‘Development of fire sprinkler system design for buildings with exposed timber surfaces’

by

Dale Kinnersley

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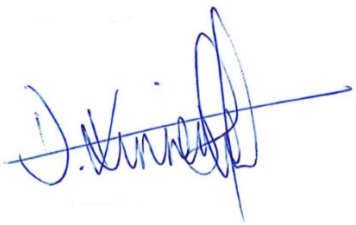

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Print name: Dale Kinnersley

Abstract

This thesis presents an experimental investigation into the optimization of fire protection to mass timber construction, with particular focus on the performance of sprinkler systems with consideration to the fixing of pipe networks and other services to cross laminated timber (CLT) ceilings, in order to ensure fire safety.

The built environment accounts for 25% of the UK's annual carbon footprint which is largely attributed to the significant dependence upon concrete and steel. The government's roadmap, "Timber in Construction Roadmap 2025", sets out an ambition for timber to play a significant role in reducing the use of concrete and steel in construction.

The first phase of the study focused on optimizing the wetting potential of sprinkler systems in rooms with exposed timber surfaces as might be found in CLT buildings. Testing was undertaken to assess the capability of an assortment of currently available sprinkler head types, operating pressures, and mounting orientations. Experimental test facilities were created to measure water distribution to the floor and walls, and ceiling wetting patterns were measured and recorded photographically for subsequent analysis. The results demonstrate that effective wetting of exposed ceilings and walls can be achieved with currently available equipment without compromising water delivery to room contents. These findings suggest that crucial modifications to sprinkler system design, particularly in head selection and placement, can significantly enhance fire suppression performance in timber buildings. The data generated support the need for updates to UK sprinkler standards to accommodate the unique challenges posed by exposed combustible timber surfaces, due to their combustibility. Further improvements might be possible if new sprinkler head designs were developed specifically for this application.

The second phase examined the structural integrity of screw fixings used to suspend mechanical and electrical (M&E) services from CLT ceilings, including sprinkler systems, at ambient (pre-fire), under fire and post-fire conditions. Pull-out tests were conducted to evaluate load capacity in non-fire conditions, and these measurements were used as baseline fire test results. Using a purpose-built test rig, fire tests were conducted to evaluate pull-out strength, both during and after fire exposure. Variables included screw embedment depth, shank diameter, and CLT adhesive type. Fire test results indicated that load capacity degradation could be both sudden and catastrophic, primarily driven by surface charring along the screw thread driven by thermal conduction of heat from the flame zone deep into the timber through the shank of the fixing. Both mechanisms greatly reduced the timber's ability to hold fixings under load demonstrating 'strength-under-fire' to have a different relationship to the fixing embedment depth than for the non-fire situation. These effects were found to intensify with increased screw diameters which facilitated conduction of heat.

Whilst the presence of a sprinkler system will inherently protect fixings from experiencing extreme heating, the ability of other M&E to remain in place must be considered as another layer of protection. It is common practice to run heavy ducting, electrical cable trays, and service pipework from the ceiling of mass timber buildings to create an attractive industrial aesthetic, or because it is the only option. Early and rapid detachment of these services could at best impede evacuee egress and firefighter access, and at worst lead to life-loss and injury

through entanglement, crush, and electrocution. Detachment may additionally cause the breakdown of building compartmentation allowing fire spread between connected compartments. This situation could be considered analogous to the Shirley Towers fire where firefighter lives were lost through entanglement with fallen services – in that instance the detachment was due to weak fixings (plastic) in a strong substrate (concrete), here the fixings are strong (steel), but the substrate (timber) weakens significantly in fire. The data will underpin the development of new standards for fixing M&E services into timber, due to the loss of strength during and after fire.

Together, these findings provide critical insights into the fire resilience of mass timber buildings and offer practical recommendations for improving fire protection strategies through sprinkler system optimization and revised guidance on M&E screw fixing performance.

Publications during this candidature

Peer-review papers:

Reduction of load capacity of screw fixings into a timber soffit during and after fire.

Dale Kinnersley[ab]*, T.Richard Hull[b], James L D Glockling[b], Stuart Campbell[a]

[a]Fire Protection Association, London Road, Moreton in Marsh, Gloucestershire, GL56 0RH, UK, dkinnersley@thefpa.co.uk, stuart.c.campbell@outlook.com

[b]Centre for Fire and Hazard Science, University of Lancashire, Preston, PR1 2HE, UK,

TRHull1@lancashire.ac.uk, Jim@glockling.co.uk

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Investigation of sprinkler wetting patterns for fire protection of exposed timber

Dale Kinnersley[ab]*, T. Richard Hull[b], James L. D. Glockling[b], Stuart Campbell[a]

[a] Fire Protection Association, London Road, Moreton in Marsh, Gloucestershire GL56 0RH, UK, dkinnersley@thefpa.co.uk, stuart.c.campbell@outlook.com

[b] Centre for Fire and Hazard Science, University of Central Lancashire, Preston PR1 2HE, UK, TRHull1@lancashire.ac.uk, Jim@glockling.co.uk

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Glossary of terms and abbreviations

CLT	Cross Laminated Timber
GLT	Glue Laminated Timber
LVL	Laminated Veneer Lumbar
M&E	Mechanical and Electrical
ERD	Euclidean Relative Difference
FDS	Fire Dynamics Simulator
CFD	Computational Fluid Dynamics
ADD	Actual Delivered Density
SD	Standard Deviation
RTI	Response Time Index
HRR	Heat Release Rate

List of symbols

q_{HC}	Heat release rate (kJ/s)
ΔH_C	Heat of combustion ($MJ.kg^{-1}$)
m_{fuel}	Fuel mass flow rate (g/s)
$\dot{m}''_{(crit)}$	Critical mass loss rate (kg/s)
C	Conduction factor ($m/s^{1/2}$)
RTI	Response Time ($m.s^{1/2}$)
ρ	Density (kg/m^3)
Q̇	Flow ($min^{-1}\ bar^{-1/2}$)
P	Pressure (bar)
K	K-Factor (coefficient of sprinkler head)
mm/min	Density measurement ($mm\ min^{-1}\ m^{-2}$)

Chapter 1 : Introduction

1.1 Motivation

The use of engineered timber in the built environment is gaining popularity in construction due to its availability in various forms such as cross laminated timber (CLT), glue laminated timber (Glulam or GLT), and laminated veneer lumber (LVL). These engineered timber products have allowed structural engineers and architects to push the boundaries of what is possible in timber design appreciating the visual appearance of structure and exposed internal surfaces [1-5]. Timber is replacing materials such as steel and concrete which are non-combustible and have well understood structural fire performance. The increased use of timber in the UK has been driven by government [6-9] helping their vision to tackle climate change by reducing carbon dioxide (CO_2)emissions in UK construction. It is also seen as conferring enhanced sustainability to a building and the businesses that might operate from it, and so internal surfaces are likely to be exposed to create the aesthetic visual qualities demanded by modern habitation.

Substituting steel and concrete for timber brings new challenges for fire protection. Timber is a combustible material and in the event of fire will lose its structural capacity. Timber loses strength through heating [10]. Within a temperature range of -20 to +200°C and at constant moisture content, the strength of timber is almost linearly related to temperature, where strength decreases with increasing temperature. In addition, flaming and smouldering combustion lead to charring, which reduces the cross-section of the timber irreversibly, compromising stability.

The wider use of timber presents many potential challenges for fire safety and building resilience that need to be addressed if they are to achieve parity in performance with traditional forms of construction:

- The structure of the building may add to the fuel load that is normally limited to being the contents of the compartments – fires may be bigger and develop more rapidly.
- Loss of structural strength may greatly impact the ability of the fire and rescue service to respond and meaningfully intervene in determining the fire's outcome. Repair of structural damage will also be more complex and costly.
- Loss of timber strength may also manifest in its ability to maintain ceiling suspended services in place which might directly impair the performance of required systems, breakdown compartmentation, and cause risk of crush and entanglement of evacuees and firefighters alike.
- Timber is able to sustain burning in the form of smouldering after flaming combustion has stopped. This it can do with dogged determination over many hours consuming its way through significant thicknesses of timber at seams and joins to access hidden combustible voids and reemerge as flaming combustion when circumstances allow. Out of reach of suppression systems or fire service hoses, this situation must be prevented at source otherwise the question of 'what stops the fire?' becomes very difficult to answer making potential loss very difficult to quantify for insurance purposes.

Protection comes in many forms, and each will have their level of relevance to life-safety (supporting evacuation), and property protection (saving the building). In respect of timber,

some protection is afforded natively by charring which, under certain conditions may cause self or auto-extinguishment of flaming combustion [11]. Passive fire options using retardants and encapsulation may be used to provide more dependable and longer durations of compartmentalisation. In association with good compartmentation, an appropriately adapted sprinkler system offers the best opportunity to address most of the key challenges, including eliciting the vitally important level of intervention required from the Fire & Rescue service.

1.2 Fire Suppression and mass timber buildings

Fire sprinklers are an automatic means of supplying water to the seat of a fire and surrounding areas in the shortest time possible without the need for human intervention. They are noted for their reliability and form the backbone of commercial property protection worldwide which has been achieved through a process of continuous development, adapting to changes in construction detailing and storage methods as new situations arise. The aforementioned challenges presented by mass timber building are no exception and need a response – the subject of this study.

Fire protection of buildings with internal timber surfaces using sprinkler systems is not a new concept. In Victorian Britain, sprinkler systems, and the type of sprinkler head used, were designed to protect timber mill floors and ceilings. Sprinkler heads provided water upward to the ceiling and downward to the fuel load below.

Suppression systems are already fitted into many types of construction to support life-safety and for property and business protection [12-18]. However, it is not widely understood that installation rules have been developed around quite different types of buildings. Suppression systems are being fitted into timber buildings without consideration of the suitability of current installation standards and if these systems can comply to the standard adopted or, meet stakeholder expectations. Current sprinkler standards are limited in scope by only considering the movable fuel load within compartments and not the potential additional fuel load arising from combustible internal linings.

Sprinkler system requirements for massive timber constructed buildings with exposed combustible linings including the exposed ceiling and walls will need careful consideration. Conformity to current UK standards does not guarantee appropriate levels of protection. The combustible nature of timber will contribute to the total fuel load [19] and increase the heat release rate within a compartment fire [20]. Therefore, enhancements to the sprinkler system need to be established.

Where combustible surfaces are exposed, sprinklers have been shown to be effective provided the sprinkler system is appropriate for the risk and has been serviced and maintained correctly. Activation in the early stages of fire will provide control and cooling from the sprinklers to adjacent surfaces limiting fire spread [21-24].

Sprinkler systems are generally installed in order to comply with the following requirements:

1. The Building Regulations depending upon risk/height triggers: Life-Safety standards.
2. The building insurer: Property Protection standards.
3. To satisfy a Fire Risk Assessment: Life-Safety standards.
4. The building owner/occupier: Life-Safety or Property Protection standards.

Life-Safety sprinkler standards [12-14] are minimum standards that aim to ensure safe occupant evacuation of the building before structural collapse occurs in line with mandatory

requirements from UK Government. UK Regulations do not consider the saving of the building or businesses that operate from it and are 'agnostic' on construction material except to say that 'complex' buildings need to be specifically engineered to meet the life-safety brief.

Property protection standards [18] incorporate additional requirements from the sprinkler system to enhance the fire protection and resilience of the building but are not mandated. Neither Life-Safety nor Property Protection standards consider the mass timber situation, but it is essential that going forward to stay relevant, both standards are adapted.

Sprinklers are considered the most viable suppression system option because they have more stringent design standards than other suppression systems (such as watermist), alongside third-party certification, product approvals, guidance, history, interchangeable components, and they are not limited to specific contractors or manufacturers.

Sprinkler heads differ in design, and their spray characteristics have evolved over the decades to meet changing protection scenarios. This testing reviewed which head types could best meet the challenges of the protection of timber surfaces with a view to supporting the adaption of installation rules so that they stay apace with new construction methods.

Unwanted water exposures from flood and escape of water events may detrimentally impact the timber elements of the building both structurally and aesthetically. Mitigation for these types of events is covered by insurance guidance [25] and will need to be considered as part of the overall water-based suppression system design.

1.3 Fixing to mass timber ceilings

A significant component of sprinkler system design relates to the requirements for the securing of the sprinkler pipe array to the ceiling to ensure that it remains in place to perform its function of water distribution when a fire occurs. A major change component of mass timber is that this support will now be required from a timber anchorage point. As previously discussed, the known weakening of timber under the action of heat may require adaption of fixing method to ensure continued correct function.

Fixing to exposed timber structure currently has no recognized national standards. The most relevant industry standard BS 8539 [26] covers fixings into concrete. Industry guidance from (BESA) Building Engineering Services Association [27] provides best practice advice and test requirements for fixings/support assemblies which can be applied to timber construction.

1.4 Aim of the Research

The aim of this research is to inform guidance through the production of an LPC Technical Bulletin, for use by the sprinkler industry, insurers, consultants, fire engineers, and specifiers on the adaptation of sprinkler systems for protection of mass timber construction, particularly with exposed combustible surfaces. This aim is broken down into two specific objectives which will provide sufficient insight into understanding how best to locate sprinklers within a combustible compartment, including specific sprinkler head selection, and how to fix directly to the underside of exposed CLT ceilings in the absence of national and European guidance.

Objective 1:

To determine the spacing requirements of sprinklers for protection of exposed timber surfaces, and the selection of the correct spray characteristics from the sprinkler head.

This part of the research will focus on the spray characteristics from sprinklers to evaluate the correct specification which will assist in reducing the additional fuel load from the exposed timber surfaces to the compartment's moveable fuel load(s).

Sprinklers act on a fire directly by removing heat, they also pre-wet surrounding fuel, reducing its ignitability and thereby limit the rate of flame spread. However, sprinkler heads differ in design, and their spray characteristics have changed over the decades. The following types of sprinkler heads were investigated.

- Conventional (Upright and Pendant) sprinkler (CUP): The CUP sprinkler has a spherical water distribution directed towards the ground and the ceiling over a definite protection area. A conventional sprinkler discharges ~40% upward and 60% downward. The upward moving water typically but not consistently, strikes the ceiling and then drips downward, adding to the water below.

- Spray Sprinkler Pendant (SSP) sprinkler: This has a paraboloid water distribution directed towards the ground over a definite protection area. An SSP discharges 80–100% of the total water flow downward. SSP sprinklers give the specified distribution by having the jet of water directed downward against the deflector.

- Spray Sprinkler Upright (SSU) sprinkler: This has a paraboloid water distribution directed towards the ground over a definite protection area. An SSU also discharges 80–100% of the total water downward. SSU sprinklers give the specified distribution by having the jet of water directed upward against the deflector.

The study investigated water spray patterns, sprinkler size ('K' factor coefficients), distribution above and below the sprinkler deflector, and the potential for wall and ceiling wetting, in addition to providing the specified water density at floor level based on the associated hazard and risk of occupancy for common types of commercial buildings.

Spacing of sprinklers relative to combustible surfaces was examined. This area of research focuses on wetting capabilities of current sprinkler head types to timber surfaces optimising water delivery:

1. To assess density of discharge (depth of water) from sprinklers at floor level, as detailed in current standards, appropriate to the risk occupancy classification of the building.
2. To assess wall wetting from adjacent sprinklers up to ceiling level to assist in preventing and slowing surface spread of flame up compartment boundaries (walls).
3. To assess ceiling wetting from sprinklers, which will contribute to slowing or halting surface spread of flame at ceiling level.

Detailed graphical data is presented to ensure that proposed changes to current sprinkler standard requirements have been addressed through research and testing.

Data produced from experiments demonstrates that the objectives have been achieved providing evidence and data for the industry to optimise sprinkler system performance for greater safety to life and property for mass timber construction.

Objective 2:

To investigate key relationships between screw fixing diameter and embedment depth into exposed CLT for suspension of sprinkler systems and M&E services in ambient, fire and post-fire conditions.

This research looked at common industry screw fixings and loading capacities under ambient (pre-fire), fire, and post-fire conditions to provide information enabling considered decisions to be made for screw fixing into timber. It is very much needed, as lack of knowledge increases the risks that substantial loads may fall in the event of fire which might impede evacuation and response actions, allow fire spread across passive boundaries through broken ductwork, and increase consequential damage as fluid and gas bearing pipes incur mechanical damage. The relevance of this extends to all M&E suspended from timber ceilings, not just sprinkler pipework.

This was accomplished by load capacity testing during and post-fire testing. Test results captured data on pull-out forces, embedment depths, CLT ply depths, and local temperatures. Graphical data is presented to confirm the relationship between embedment depth and load capacity enabling engineers' measurable assessment for use in installation.

1.5 Thesis Structure and Outline of Chapters

This thesis contains nine chapters and five appendices. A brief description of each chapter, aside from this introductory chapter is presented below.

Chapter 2 : Background

This chapter outlines the evolving challenges in property protection due to changes in construction materials and methods, particularly the increased use of combustible timber elements. The chapter highlights the risks posed by smouldering fires, timber voids, and structural instability, highlighting that fire must be prevented from entering concealed spaces. It discusses the limitations of current sprinkler systems for combustible surfaces and structural sensitivity to water. The chapter also explores the implications for fire service intervention and insurance availability. These changes necessitate a re-evaluation of existing fire protection strategies, especially in terms of resilience and the role of sprinklers in controlling fire spread and supporting fire service operations.

The chapter further distinguishes between life safety and property protection, stressing that while sprinklers are typically specified for life safety, their role in property protection is more demanding and less regulated. It stipulates that only direct fire service intervention can fully extinguish fires in timber structures due to smouldering risks. The chapter concludes by examining the variables in sprinkler and construction design that must adapt for mass timber construction.

Chapter 3 : Proposal of attributes of the ideal sprinkler system

This chapter combines key elements required for an effective sprinkler system tailored to the challenges of modern timber construction. It proposes a sprinkler system that ensures comprehensive wetting of walls, ceilings, and moveable fire loads to suppress fire effectively at its origin. The chapter highlights the importance of robust ceiling fixings and strategic void controls to prevent fire ingress into concealed timber cavities. It also addresses water management, advocating for safe drainage solutions to mitigate both accidental and operational water exposure. Finally, the extent of protection is considered, aiming for a

balance between technical efficacy and practical implementation, forming the basis of the hypothesis for an ideal property protection sprinkler system.

Chapter 4 : Literature Review

This literature review explores the evolution and challenges of using timber in modern construction, particularly in the UK's push toward sustainable building practices. It traces historical fire regulations from the Great Fire of London to current government strategies promoting timber to reduce carbon emissions. The review compares traditional materials like steel and concrete with engineered timber products such as CLT, LVL, and GLT, highlighting timber's benefits and fire-related vulnerabilities. It explores the chemical and physical properties of wood, its combustion behaviour, and the risks of flaming and smouldering combustion. Key concerns include charring rates, adhesive failures, delamination, and increased heat release rates from exposed timber surfaces. The review critiques current fire regulations and questions the viability of self-extinguishment, and underlines the importance of both passive (encapsulation, retardants) and active (sprinklers) fire protection. The chapter concludes by advocating improved sprinkler system design and fixing methods to enhance resilience, life safety, and insurability of timber buildings, supporting the UK's net zero goals.

Chapter 5 : Regulatory Implications and relevance

This chapter reviews the regulatory landscape surrounding sprinkler systems across the UK, highlighting where they are mandated in England, Wales, Scotland, and Northern Ireland. It confirms that current regulations which address life safety, fall short in supporting property protection, especially in the context of timber construction, and highlights the disconnect between regulatory requirements and the needs of insurers. It calls for a change in regulations that not only mandate sprinkler systems but also ensure the design and implementation supports both life safety and property protection.

Chapter 6 : Sprinklers

This chapter describes the investigation of the role of sprinkler systems in enhancing fire safety in mass timber buildings. Traditional fire protection methods like fire retardants and encapsulation for passive fire have limitations, underlining the need for updated sprinkler systems. The chapter details the experimental study evaluating various sprinkler head types for their effectiveness in wetting exposed timber ceilings, walls, and floors. Sprinkler head testing assessed water distribution patterns, discharge densities, and the impact of sprinkler orientation and pressure. Results showed that certain sprinkler heads provided superior ceiling and wall wetting, especially when installed in a specific orientation and pressure. The chapter concludes that with minor design adaptations, sprinklers can significantly improve fire protection in timber buildings and address the specific challenges of exposed combustible surfaces.

Chapter 7 : Fixings

This chapter explores the structural performance of screw fixings used to suspend sprinkler pipework and mechanical & electrical (M&E) services from timber ceilings at ambient and in fire conditions. A lack of guidance for fixings in timber, prompted a detailed experimental study exploring cross-laminated timber (CLT) panels and various screw types to sustained flaming. The chapter evaluates the pull-out strength of fixings under ambient, fire, and post-fire conditions. Evaluation of larger diameter screws, which would conduct more heat are

investigated together with smaller thinner screws. In conclusion the chapter indicates embedment depth, screw geometry, and charring which critically influence performance.

Chapter 8 : Conclusion

This chapter covers the main conclusions of the thesis culminating in confirmation of the original hypotheses.

Chapter 9 : Future Work

This chapter focuses on what additional changes can be made to sprinkler standards to better protect mass timber construction from the perils of fire. It provides suggestions into sprinkler head development for manufacturers to pursue with relation to spray pattern discharge characteristics for better surface wetting at varying pressures.

In addition to sprinkler changes, this chapter provides information to the on-going fire-testing of standard industry fixings into the underside of CLT at various embedment depths, angles of insertion and differing loads. The follow-on testing has alerted the UK national standards body (BSI committee FSH/0) on the requirements for fixing into timber which may lead to a national standard.

1.6 Limitations of the Study

Timescales and funding are critical to the full evaluation of this study. However, neither are limitless, and this study was restricted to underpinning an appropriate guidance document on completion.

This study has focussed on fixings into timber for the construction industry to ensure stability of building services in the event of a fire for both life-safety and for property and structural performance. Sprinkler head performance evaluation within a combustible compartment will provide valuable design information when considering the correct selection of sprinkler system performance and effectiveness.

Chapter 2 : Background

2.1 The changing landscape of construction materials

2.1.1 Changes in materials

To meet net zero targets by 2050 set out by UK government, the construction industry is required to change and adapt to using materials that sequester and minimize carbon emissions in their production. This change in material use also includes re-use of the building materials through and at the end of the life cycle. To meet these targets, steel and concrete will increasingly be substituted for engineered timber which is seen as conferring enhanced sustainability to a building.

Engineered timber as a material is gaining popularity in construction due to its availability in various forms, sustainability credentials, strength for primary structure, and visual appearance of structural components and exposed internal surfaces. Timber construction projects are currently underway for buildings of mixed occupancy including office, recreation, residential and retail which all have different risk profiles associated with fire and water exposure events.

In comparison to concrete and steel which are non-combustible, have well understood fire performance properties, and are water resilient, timber is combustible, and both fire and water exposure can have profound implications for its structural performance.

The principal challenges in these material changes therefore stems from:

- Timber's ability to burn in both flaming and smouldering form.
- Timber's structural sensitivity to water exposure

Both of these can radically change timber's ability to support load and loss of strength can happen out of sight in respect of detection and corrective systems causing critical damage that might lead to loss of the building on unfamiliarly short timescales.

2.1.2 Changes to methods of construction

Primary structure using various forms of engineered timber and internal surfaces are likely to be exposed to create the aesthetic visual qualities demanded by modern construction. These exposed surfaces will contribute to the fuel load associated with the building occupancy. Without considering fire protection, exposed combustible walls, floors, and ceilings will increase spread of flame and voids created during the construction will have the ability to hide combustion within.

To overcome the potential threat to the vulnerability of modern timber construction, fire protection in various forms should be considered including, passive fire protection in the form of fire retardants and encapsulation, detection, active fire suppression, and material hybridisation (including the limited use of concrete) in areas where solutions demand.

2.1.3 What are the impacts of the changes

The increase in risk has been realised by the insurance industry. Insurance provision demands the ability to quantify risk in terms of (amongst many other factors) expected extent of damage, types of damage, means of repair, and costs associated with repair. Whilst much experimental testing is currently being undertaken, a view is that construction is running ahead of knowledge; the experimental testing that is ongoing is still at the stage of showing the

issues rather than providing solutions; and Building Codes are yet to respond satisfactorily to this change. Against a backdrop of some exceptionally large insurance claims around some high-profile mass timber projects, these concerns are recognised as a reality and in some cases even insurance policy wordings have been found to be inadequate.

Structural stability under fire and water exposure is fundamental to insurability for many obvious reasons and includes eliciting the required level of intervention from the fire and rescue services. Their ability to respond and intervene, along with other factors such as having adequate access and water supplies is a contributing factor to the estimation of potential loss.

2.2 What are the changes for improvement of sprinkler protection

A sprinkler system is designed to control the fire at the point of origin and stop, or halt fire spread, with final extinguishment conducted by the fire and rescue services. Existing sprinkler standards consider the building to be constructed with non-combustible or limited combustible materials. Mass timber construction will feature a combustible structure and linings with exposed timber to the walls, floors, and ceilings.

Current sprinkler heads are designed and installed to discharge 80-100% of the water downwards to the floor level, where the expected fuel load is located. Current UK and European sprinkler standards do not consider the additional fuel load from the exposed surface(s). In addition to this, suspension of sprinkler pipework and M&E services are not considered for attachment to the underside of a timber substrate. Standards only consider fixing to steelwork and concrete structures.

The changes needed to ensure successful sprinkler control of fire in a timber lined compartment, should take into consideration:

- Surface wetting – to slow or halt flame spread.
- Fixings – to allow adequate suspension of services.
- Sprinkler discharge – to maintain effective density levels for the associated risk.
- Fire control – to allow the Fire & Rescue service to extinguish in a safe compartment and reduce building damage for insurance purposes.
- Water control – reduction of consequential damage to water sensitive materials (from accidental and deliberate discharges).

Any adaptation will need to be cost effective (no major changes), be achievable with existing equipment, allow for ease of adoption and implementation by contractors, and enable insurance providers enough comfort (in association with other measures) to offer the demanded insurance capacity.

2.3 Life safety and Property Protection

2.3.1 Life safety

The purpose of health and life safety with regards to construction and the ongoing maintenance of property in the built environment is mandated through government law in statutory guidance for the devolved administrations making up the United Kingdom. Buildings designed for health and life safety extends only to provide evacuation before collapse for all occupants within and in the vicinity of the building or buildings as a legal duty. Successful evacuation is based on timescale where the building is required to meet minimum performance objectives and be deemed fit for purpose.

To ensure life safety objectives are met, detailed design and construction of any building will be required to meet prescriptive guidance. Guidance documents are written through the various administrations to cover the safety of life from fire. Within the England, the statutory guidance for fire is Approved Document B (fire safety) volume 1: Dwellings, 2019 edition incorporating 2020 amendments [28], and Approved Document B (fire safety) volume 2: Buildings other than dwellings, 2019 edition incorporating 2020 amendments [28]. However, the documents only consider 'common building situations' detailed in HM Government – Manual to the Building Regulations July 2020 – A Code of Practice for use in England [29]. Exclusions listed within the document include:

- Difficult ground conditions
- Buildings with unusual occupancies or high levels of complexity
- Very large or very tall buildings
- Large timber buildings
- Some buildings that incorporate modern construction methods

The above specifies very large or very tall buildings and large timber buildings. Therefore, fire performance covering life safety for timber construction will need to be navigated through alternative codes and standards. This can be through national codes in the form of British Standards (BS) and British Standard European Norm (BS EN) documents such as, BS 9991:2015 - Fire safety in the design, management and use of residential buildings - Code of practice [30], BS 9999:2017 - Fire safety in the design, management and use of buildings – Code of practice [31], and BS 7974:2019 - Application of fire safety engineering principles to the design of buildings - Code of practice [32]. These alternative standards provide solutions for protection against fire for life safety that are equal to or higher than the statutory guidance.

However, meeting minimum standards to ensure compliance with law does not infer that the building has resilience to fire and will perform as intended to all stakeholders. Additional measures may be needed to be factored into the design of mass timber buildings for the safety of life, which are not currently considered by UK standards.

2.3.2 Property Protection

When the additional requirement for property protection is needed, insurers and owners/investors might seek to protect the asset through mitigating losses from fire, flood, and escape of water. This can be accomplished by enhancing minimum Government requirements by embracing measures to enhance building resilience, property protection, and business continuity.

Through the Fire Protection Association, an insurer research division known as RISCAuthority, an insurer funded research scheme made up from a large number of UK insurance companies, together with various participants including suppliers, industry experts and trade organisations collaborate to produce guidance documentation and information for property protection to ensure buildings and the business' that operate within them, are more resilient to fire and escape of water.

January 2022, saw RISCAuthority produce a white paper, "Insurance challenges of massive timber construction and a possible way forward" - Revision 1.0 January 2022 [33], to raise awareness of the challenges mass timber brings to property protection. This paper is discussed further in section 2.5.3.

Property protection cannot be assured or relied upon through statutory guidance or relevant standards listed above. Buildings need to be more resilient by enhancing both passive and active measures. Passive enhancements can be adopted by increasing the fire resistive construction of the building. Active measures can be enhanced by implementing recognised property protection suppression guidance. Both enhancements are covered by insurer guidance in the guise of Approved Document B incorporating insurer requirements 2015 [34 & 35], BDM01 - A to Z of Essential Principles for the protection of buildings, 2023 [36], Approved Document G incorporating insurer requirements, 2021 [25], and LPC Rules for Automatic Sprinkler Installations 2015 Incorporating BS EN 12845 [18].

National sprinkler and watermist system standards are aimed at life safety and have little relevance to ensuring recoverability of the building or the business' that operate within. The adoption of the LPC Rules for Automatic Sprinkler Installations 2015 incorporating BS EN 12845 for commercial and industrial occupancies, specifically addresses property protection through insurer's requirements in the form of the Technical Bulletins. However, all UK sprinkler and watermist standards for life-safety or property protection make the basic assumption that the building has an inherent level of robustness through being constructed of steel and concrete, but this is not the case for mass timber construction and adaptation is needed to remain relevant.

Property protection for timber construction will need to at best put the fire out in the compartment of origin, or to control the fire to the compartment of origin, but always to elicit the assistance needed from the fire service, that they are under no obligation to give, by maintaining safety (fire spread, size, and building and fixture structural stability), as only the fire service can assure a fire is out in a timber building because of timber's ability to smoulder.

2.4 Suppression Standards

There are a number of available suppression standards that are considered for numerous building types/occupancies and are used throughout Europe. In over half the countries the national insurance or European insurance standard is accepted by the authorities as a design standard. However, authorities in a number of countries do not accept insurance standards or American NFPA standards. Instead, they accept national or European (CEN) standards.

For insurance markets the design standard used in a number of countries is the European insurers standard CEA 4001 [37], although many countries have their own insurance design standard. Insurers in all countries allow the use of the internationally recognised NFPA or FM design standards. All of these standards are based upon many years of experience and full-scale testing and show that if a system is designed in accordance with the standard and maintained ready to function, it will control or extinguish fire in all but the most exceptional circumstances.

Table 1 provides an insight into sprinkler standards used throughout Europe.

Table 1 - Sprinkler standards used in Europe.

Country	Main Standard(s)	Alternative Standard(s)
United Kingdom	LPC Rules for Automatic Sprinkler Installations 2015 BS EN 12845:2015 [13] BS 9251:2021 [12] BS EN 16925:2018 [14]	NFPA 13 [38] F.M. Global [39]
Belgium	CEA 4001	EN 12845:2015 NFPA 13 NFPA 15 [40] F.M. Global
Czech Republic	EN 12845:2015	CEA 4001 NFPA 13 F.M. Global
Denmark	DBI 251 [41]	EN 12845:2015 NFPA 13 F.M. Global
Finland	CEA 4001	EN 12845:2015 NFPA 13 F.M. Global
France	APSAD R1 [42] and CEA 4001	EN 12845:2015 NFPA 13 F.M. Global
Germany	CEA 4001 / VDS [43]	EN 12845:2015 NFPA 13 F.M. Global
Ireland	LPC Rules for Automatic Sprinkler Installations 2015 BS EN 12845:2015 BS 9251:2021 BS EN 16925:2018	NFPA 13 F.M. Global
Netherlands	EN 12845:2015	CEA 4001 NFPA 13 F.M. Global
Norway	EN 12845:2015	-
Romania	P 118-99 [44]	-
Spain	EN 12845:2015	-
Sweden	SBF 120:6 [45]	EN 12845:2015 NFPA 13 F.M. Global
Switzerland	VKF [46]	CEA 4001 NFPA 13 F.M. Global

The most widely recognised suppression standard used in the UK is the LPC Rules for Automatic Sprinkler Installations 2015 incorporating BS EN 12845 for commercial and industrial occupancies. The document covers both life-safety and property protection and is the only UK standard accepted by insurers. The document comprises the UK adopted European sprinkler standard BS EN 12845 covering life-safety and enhances this to property protection through a series of LPC Technical Bulletins.

Commercial sprinkler systems to the LPC Rules have an enviable record of operation since their specification and use is highly research and implemented/maintained without compromise. Alternative sprinkler standards such as BS 9251:2021, BS EN 16925:2018, and watermist standards BS EN 14972-1:2020 [17], BS 8458:2015 [15] and BS 8489-1:2016 [16] only consider life safety and are limited in their use and will not be considered in this research project.

2.5 Government, Commerce, and insurer requirements

2.5.1 Government

In England, the Secretary of State exercises authority under the Building Act 1984 [47] and Building Regulations 2010 [48], focusing primarily on life safety rather than property protection. Scotland, Wales, and Northern Ireland have similar but distinct legislative frameworks, such as the Building (Scotland) Act 2003 [49] and the Building Regulations (Northern Ireland) Order 1979 [50] . Each administration supplements its regulations with statutory guidance such as Approved Documents in England and Wales, Technical Handbooks in Scotland, and Technical Booklets in Northern Ireland to assist in compliance with legal standards.

Recent legislative developments in England are aimed at enhancing fire safety and building standards. The Fire Safety Act 2021 [51] and Fire Safety (England) Regulations 2022 [52] expand the scope of the Regulatory Reform (Fire Safety) Order 2005 [53] to include structural elements like cladding and flat entrance doors in multi-occupancy buildings. The Building Safety Act 2022 introduces a new regulatory framework, including the establishment of a Building Safety Regulator and specific duties for accountable persons in high-risk buildings. These laws collectively aim to improve safety for occupants and ensure that responsible parties maintain compliance through risk assessments, training, and necessary building upgrades. Further analysis of the regulatory landscape is detailed in chapter 5.

2.5.2 Commerce

The clients' obligations under The Regulatory Reform (Fire Safety) Order are for the protection of the staff/operatives, and to meet minimum specified legal requirements for safety. Accomplishing this will cover life-safety requirements. However, the client's remit should go further with respect to ensuring business continuity and property protection through taking resilient measures. Voluntary measures can include sustainability, business reputation, flexibility, and growth. This is usually achieved and detailed within the business continuity plan and can be accommodated using correct passive and active fire protection measures. Embracing these factors and considering real-life credible worst-case challenges will provide a more resilient building in respect of property protection in lieu of meeting minimum requirements stipulated in legislation.

2.5.3 Insurance Requirements

Where a building is considered for insurance, the insurers seek to protect the asset through mitigating losses from fire, flood, and escape of water. This is accomplished by enhancement of Government requirements of life-safety by embracing measures to enhance building resilience, property protection, and business continuity.

Insurers are increasingly concerned about the risks posed by mass timber construction due to the combustible nature of timber and the evolving scale and complexity of such buildings. Key

challenges include heightened fire risks from concealed combustible voids that can facilitate rapid fire spread beyond the reach of firefighting efforts, and vulnerability to water damage, which is the leading cause of loss in residential sectors. The lack of resilience in timber structures, particularly during construction and in the face of long-term deterioration, raises concerns about disproportionate collapse and repairability. Insurers struggle with quantifying risks due to limited data and scientific understanding of timber performance. Many insurers prefer hybrid construction methods that combine timber with non-combustible materials to mitigate risks.

Provision of insurance for massive timber buildings is challenging due to the difficulty in quantifying risks associated with fire, water damage, and structural resilience. Insurers require detailed information on building design, materials, risk mitigation measures, and potential loss scenarios such as Estimated Maximum Loss (EML) and Maximum Foreseeable loss (MFL), but current timber construction proposals often outpace available research and testing, making insurability uncertain and sometimes economically unviable.

For building resilience, insurers require designs that minimize susceptibility to fire and water damage, reduce vulnerability through features like robust compartmentation and sprinkler systems, and support rapid recoverability after an incident. This includes using non-combustible materials where possible, implementing effective detection and suppression systems, ensuring ease of repair, supporting fire service intervention, and incorporating flood protection and escape of water mitigation strategies from the outset of the design process.

2.6 Chapter summary

The construction industry is undergoing a significant transformation to meet the UK's net zero carbon targets by 2050, with engineered timber emerging as a sustainable alternative to traditional materials like steel and concrete. While timber offers aesthetic and environmental benefits, its combustibility and sensitivity to water introduces new fire and water damage risks, especially when used in exposed structural and internal finishes. These risks are compounded by the lack of comprehensive fire testing and performance data, raising concerns among insurers about the viability and safety of mass timber buildings.

Current sprinkler systems and standards, designed for non-combustible or limited combustible structures, are inadequate for timber buildings, necessitating changes to address surface wetting, provide effective discharge, secure fixings, and reduce the potential for consequential damage. Life safety regulations focus on evacuation before collapse but often exclude large or complex timber buildings, requiring alternative standards to ensure fire safety.

Suppression standards vary across Europe, with the UK primarily relying on LPC Rules, which address both life safety and property protection. Government legislation, including the Building Safety Act 2022 and Fire Safety Regulations 2022, aims to improve fire safety oversight, while commercial clients are encouraged to go beyond legal compliance by integrating resilient design strategies.

Beyond life safety, property protection is a growing concern for insurers, who advocate for enhanced passive and active fire protection measures to improve building resilience and business continuity. Insurer-led initiatives, such as RISCAuthority's white paper, highlight the challenges of insuring mass timber buildings due to their susceptibility to fire and water damage, hidden voids, and long-term deterioration. Insurers require detailed risk assessments and mitigation plans to consider coverage, often favouring hybrid construction methods that

combine timber with non-combustible materials to reduce exposure and enhance recoverability.

Chapter 3 : Proposal of attributes of the ideal sprinkler system (hypothesis 1 & 2)

This study investigates the potential to adapt current commercial sprinkler system design requirements to better protect mass timber buildings with exposed combustible surfaces and focuses on:

- Ceiling, floor, and wall fire load wetting
- Fixing to the underside of a timber ceiling/soffit

The data collected from the research and testing, allows for the extrapolation of:

- Sprinkler protection to voids
- Control of system for unintended escape of water
- Extent of sprinkler protection to the building

3.1 Hypothesis 1

The initial investigation was to assess current sprinkler system design requirements for buildings constructed of limited or non-combustible materials, to be adapted for buildings with exposed combustible timber finishes. By reviewing domestic and residential, and commercial and industrial sprinkler standards, this confirmed that with minor changes, sprinkler systems can potentially provide a more resilient option to mass timber construction through sprinkler head selection, spacing, and location from timber or combustible surfaces.

3.1.2 Ceiling, floor, and wall fire load wetting

Current sprinkler system standards only consider the moveable fire load located at floor level. Modern sprinklers provide 80-100% of the water directly to the floor. Research conducted shows that previous historical sprinkler head design, allowed for water to be directed both upwards and downwards. The benefit of these historic sprinklers known as Conventional style, would allow for surface wetting of the ceiling in addition to providing water to the floor fire load.

The location of sprinklers from walls varies in sprinkler standards depending on the combustibility of the wall construction and the distance spacing of sprinklers within a compartment. In commercial standards, a maximum distance of 1.5 m from walls containing combustible materials is a prerequisite. This distance is assumed to be reasonable and is considered to be the basis for testing requirements for mass timber.

To establish a basis for sprinkler selection criteria and to evaluate sprinklers in different orientations, pressures, and locations, three criteria were considered. The first criterion was wall wetting. A fire located adjacent to a combustible wall has been shown to be larger than a fire in the middle of a compartment where the initial fire is equivalent. Potential surface spread of flame upward to the ceiling was deemed to be a significant threat. Therefore, wall wetting is an important fire protection requirement. The next criterion was involvement and surface spread of flames on the ceiling above sprinklers with the final criteria being water flow to floor level for the general contents fuel loads. Current sprinkler rulesets consider sprinkler water discharge to the floor (moveable fuel load) by specifying a minimum design density of discharge from the sprinklers, which is based on occupancy classification.

To ensure optimised water delivery within a timber enclosure can be proven, three discreet phases were considered:

1. To assess density of discharge (depth of water) from sprinklers at floor level, as detailed in current standards, appropriate to the risk occupancy classification of the building.
2. To assess wall wetting from adjacent sprinklers up to ceiling level in order to assist in reducing surface spread of flame up compartment boundaries (walls).
3. To assess ceiling wetting from sprinklers, which will contribute to slowing or halting surface spread of flame at ceiling level.

3.1.3 Sprinkler protection to voids

Current commercial sprinkler standards covering ceiling and intermediate floor spaces differ in sprinkler protection requirements of voids. The differences relate to void depth, combustibility of void construction and combustibility of services within the void(s).

Unprotected voids have the potential to hide and transfer fire through a building, be it flaming or smouldering combustion. The fire protection of combustible voids is certainly essential but the use of sprinklers to do this can be hindered by depth preventing spray pattern development. The use of specialist flat spray pattern sprinklers can protect voids that are ≥ 300 mm deep but where the void depth is less than 300 mm voids shall be compartmentalised into areas of 72 m^2 and not exceeding 250 m^2 as per current sprinkler requirements, or other passive solutions can be used to make the void sterile including encapsulation of combustible surfaces, fuel removal, or packing the void with non-combustible insulation.

3.1.4 Control of system for unintended escape of water

Sprinkler systems are designed to allow the entire arrangement of pipework to be self-draining. This is accomplished through sloping the pipework back to the main installation control valve drain. Where trapped water is present, additional drain valves are installed and sized to cater for the diameter of the pipework needed to be drained.

Unwanted escape of water events in any form is detrimental to timber construction through damage of surfaces and wet rot. By considering the use of intermediate zone valves (per floor or per tenant), individual isolations can reduce the impact of water damage and allow for a smaller pipe network to be locally drained. The locations of drain valves are based on the pipe routing system located around the building construction and other Mechanical and Electrical (M&E) services. Trapped water in the sprinkler pipework shall be piped to main drain locations, such as bathrooms, kitchens or externally routed.

3.1.5 Extent of sprinkler protection to the building

Commercial and industrial, and domestic and residential sprinkler standards differ in the requirements for sprinkler protection locations within the building envelope. Commercial standards require all areas of a building to be sprinkler protected. There are permitted and necessary exceptions listed within the standard, detailed below:

Permitted exceptions (following a suitable and sufficient risk assessment)

- rooms protected by other automatic fire suppression systems (such as inert gas, powder, or water spray)
- wet processes, such as the wet end of paper-making machines.

- lift enclosures.

Necessary exceptions (alternative suppression systems considered)

- silos or bins containing substances that expand on contact with water.
- in the vicinity of industrial furnaces or kilns, salt baths, smelting ladles or similar equipment if a risk assessment indicates that the hazard would be increased by the use of water in extinguishing a fire.
- where water discharge may present a hazard (which is generally not considered to be the case on LV electrical equipment; if continuity of service is the concern, electrical equipment IP ratings should be uprated or alterative firefighting media used), omission of sprinkler protection shall be agreed and discussed with the building insurer.
- rooms or compartments containing High Voltage (HV) electric power distribution apparatus such as switch gear and transformers and used for no other purpose(s).

Domestic and residential standards confirm that sprinkler protection should be provided in all parts of the premises. Sprinkler protection may be omitted from the following areas, unless required by a fire risk assessment or the fire strategy.

- Bath and shower rooms < 5 m^2
- Enclosed staircases
- Ceiling voids
- Enclosed vertical lift shafts
- Cupboards and pantries < 2m^2
- Roof/loft voids
- Water closet
- attached buildings
- Crawl spaces
- External balconies

Mass timber construction covers buildings that embrace different occupancy classifications that consider both commercial and industrial, and domestic and residential sprinkler standards. For this study only commercial and industrial sprinkler standards will align to the active fire protection requirements of mass timber construction.

Sprinkler protection is required to be installed to all areas of a timber building. Water sensitive areas, which would not require sprinkler protection, will need to be adequately protected through passive fire protection (encapsulation) and consider alternative fixed firefighting suppression. Non-sprinklered areas shall be fire risk assessed and accepted within the fire strategy document and signed off by the authorities having jurisdiction.

3.2 Hypothesis 2

Following the development of hypothesis 1, a second hypothesis was considered which reviewed fixing requirements into timber ceilings/soffit. The research showed that current requirements for fixing a sprinkler system and/or M&E services directly to the underside of a timber ceiling are limited within UK National Standards. European sprinkler standards only cover fixing into concrete, industry guidance provides best practice for concrete, but does not cover timber, and national standards only consider concrete. Eurocode 5 [54] provides structural guidance for erection of the structure, together with a multitude of calculations, but does not provide standard fixing guidance for the suspension of services.

To compliment the research for adaption of sprinkler systems for mass timber construction (hypothesis 1), and to provide a comprehensive standard for the sprinkler industry, research, and development of fixing requirements for timber was a crucial additional investigation.

3.2.1 Fixing to the underside of a timber ceiling/soffit

Current sprinkler and M&E services are suspended using mechanical assemblies fixed to the underside of the structure. For concrete this is achieved using anchors that connect to drop rods. Clamps are used for steel beams that also connect to drop rods where the services will be fixed using approved components, such as mild steel loop bands for pipework, or slotted channel systems for other services.

Structural load capacity of bracket assemblies and individual fixings need to be considered for all services supported from timber ceilings as shown in Figure 2.1.

Figure 2-1 : M&E service fixed to the underside of a CLT ceiling (Photograph by D.Kinnersley, Nov 2022)

Fixings used to secure M&E services to timber are of the metal screw type. The ability of a screw fixing to hold a load is determined at the contact surface between the threads and substrate into which it is embedded. Metal is a good conductor of heat, and in a fire, screw fixings can transmit heat turning timber to char and weakening the contact surfaces that assure its retaining capability. When a screw fixing is used to secure other metal framings in place, such as channel, brackets, or hanger rod this can increase the rate of heat uptake by the screw fixing, by substantially increasing the area for heat collection and conduction.

In current sprinkler standards, larger diameter screw fixings are used to support larger loads as opposed to using more numerous or longer fixings. For timber ceilings, this may be counterintuitive realizing the need to investigate other options.

Without sprinkler systems providing cooling and wetting to services suspended at the ceiling, the load contribution of all M&E services will need to be measured. The load capacity of M&E services will need to be researched at three different conditions, ambient, during fire and post-fire.

3.2.2 Ambient, fire and post-fire testing

To fully assess the load capacity of fixings into timber, a test arrangement is needed that allows for fixings to be embedded into timber and evaluated in different environments. The evaluation of fixing load capacities at ambient, during fire and post fire will provide the data to specify the fixing requirements for sprinkler and M&E services for mass timber incorporating a safety factor that will provide guidance to designers and engineers.

3.3 Chapter summary

Hypothesis 1 focuses on modifying existing sprinkler designs to address fire risks associated with timber structures, emphasizing the need for ceiling, wall, and floor wetting to prevent flame spread. It proposes using conventional style sprinkler heads for better surface coverage and outlines criteria for evaluating sprinkler performance.

The importance of protecting voids, controlling water discharge to prevent timber damage, and ensuring comprehensive sprinkler coverage throughout the building is a requirement. Commercial standards are deemed more suitable than residential for mass timber applications, with exceptions requiring risk assessments and alternative fire protection strategies.

Hypothesis 2 investigates the structural challenges of fixing sprinkler and mechanical systems to timber ceilings, noting the lack of guidance in UK and European standards. The vulnerability of metal screw fixings in fire conditions due to heat conduction and char formation in timber, compromises load-bearing capacity are duly noted. The study requires testing fixings under ambient, fire, and post-fire conditions to establish safe load capacities and develop reliable installation practices.

The outlining attributes of an ideal sprinkler system:

- The systems must act swiftly to prevent fires from spreading into combustible voids and manage both surface and content fuel loads, while maintaining structural integrity.
- They should protect mechanical and electrical installations, including themselves.
- Crucially, they must operate reliably without leaks or accidental discharges, minimize damage, and have low environmental and financial impact.

Key design and installation factors include sprinkler head selection, firestopping, pipe routing, pipe fixing and damage mitigation strategies which should highlight the vulnerability of wood to water damage, which can lead to aesthetic and structural deterioration, biological infestation, and mechanical failure.

Chapter 4 : Literature Review

4.1 Introduction

Following the Great Fire of London 1666, the first UK fire regulations were introduced, where King Charles II banned wooden buildings and widened roads. In the following year, the Act for rebuilding the City of London was passed, which stated that all new buildings shall be constructed of brick and stone to protect against fire spread.

Today, in the reign of King Charles III, the UK government wish to embrace the increased use of timber in construction, detailed through publications such as Net Zero Strategy: Build Back Greener [6], which promotes the replacement of materials such as steel and concrete with timber. This, however, brings back the fire hazards associated with these natural materials.

Developments in the construction of tall residential and commercial building using biophilic materials such as timber are progressing apace and supported by the UK government and construction industry alike. This shift in material usage is seen as a means of reducing the UK carbon footprint in an effort to tackle global warming [7]. This is also recognised in USA, where Nepal et al [8] confirm the carbon benefits of mass timber construction [55] to be twofold: avoided emissions through material substitution, and biogenic carbon storage in timber materials during and after use. However, future impacts will be dependent on forest management, market dynamics, and end-of-life treatment of the timber.

The UK government has fully committed to the timber in Construction (TIC) roadmap 2025 [9, 56], embracing timber and recognising the challenges associated with the material. With 25% of the UK's annual greenhouse gas emissions coming from the built environment, the road map emphasizes timber's role in reducing both operational and embodied carbon. Mass timber has been recognised as an engineered wood product known for strength and consistency and has been highlighted as the key enabler of larger open spaces in commercial buildings. This comes with concern for the UK insurance industry, detailed in the RISCAuthority publication 'Insurance challenges of massive timber construction and a possible way forward' (January 2022) [33]. With tensions already heightened over fire following the Grenfell Tower tragedy, timber construction methods give rise to further concerns for insurers on fire risks, including smouldering combustion, delamination, water damage, and long-term durability.

For insurers to embrace mass timber, the Mass Timber Insurance Playbook [57] is referenced through the TIC. Early collaboration with insurers and interested stakeholders will enable fire safety, property protection (building resilience), and water damage concerns to be addressed and embedded at the time of design, to ensure their insurability through life and thereby supporting the longer term adoption of mass timber.

One area that can assist in overcoming the increased fire threat to new construction methods and materials [7], is an active fire suppression system, featuring new design guidelines that cover life safety, property protection, and business resilience.

This literature review covers multiple various aspects of the fire protection of timber and seeks to understand its structural properties, the impact of fire and water exposure, suppression research, and identify gaps in knowledge that need to be addressed.

4.2 Materials in construction

4.2.1 Existing materials

Common building materials that have been used in construction over the last few decades that could be replaced by timber include steel, concrete, and plasterboard. Steel is used to provide structure; concrete is used for its robustness and versatility in addition to structure, and plasterboard is lightweight, easy to install and used as a covering for non-structural interior stud walls and ceilings.

The fire performance of these materials is well established through standards testing. Steel is the most comprehensively fire-tested of all structural framing materials with extensive large-scale tests replicating the behaviour of steel in real buildings. Whilst much is made of the vulnerability of steel to fire, with the exception of the World Trade Centre, there have been no recorded structural failures of high-rise steel-framed buildings collapsing due solely to fires [58], suggesting the passive protection strategies appear adequate. The behaviour under fire conditions varies depending on the exact type of steelwork, however in general, hot finished carbon steel begins to lose strength at temperatures above 300^0C to 800°C with a melting temperature of 1500°C, which is comparable with hot rolled steel.

Fire-resistant steel has a higher yield strength at elevated temperatures. At normal ambient temperatures, the performance is similar to that of carbon steel but has an improved yield-strength at higher temperatures due to the addition of chromium, molybdenum, and other beneficial alloying elements.

Steel columns are normally protected from fire by using intumescent coatings or by encasement in fire resisting materials. Intumescents are painted on coverings that are inert at low temperatures but expand under the action of fire at a ratio of typically 50:1 (1 mm coating will expand to 50 mm) [59]. Once expanded at temperatures of approximately 200-250^0C they protect the steel by providing an insulating layer with low thermal conductivity. Alternatively, the steel can be encapsulated by non-combustible panels.

Concrete has an inherently low thermal conductivity, 50 times lower than that of steel [60] and heats up slowly in fire providing good fire resistance. High Strength Concrete (HSC) has more susceptibility to explosive spalling during a fire but as a material has superior structural strength with a compressive load strength of at least 50 MPa which provides good stiffness and durability.

The strength properties of concrete lie within the strength of the cement matrix. The compressive strength of Normal Weight Concrete (NWC) is inversely related to the water-cement ratio. Recent material technological advances have led to higher performing concretes ranging in strength from 35 MPa to 140 MPa [61]. HSC is achieved by introducing water reducing admixtures to achieve a lower water-cement ratio or by the addition of silica fume, which is a fine non-crystalline silica, grey coloured powder (similar to Portland cement).

Plasterboard used for partitioning, ceilings and encasement provides fire performance characteristics appropriate to national regulations or to suit project specific requirements. Plasterboard has a reaction to fire performance characteristic that is related to the combustibility and behaviour in the early stages of fire and is generally tested as part of a built up walling systems to confirm the construction as a whole meet with building regulation.

Plasterboard is commonly used today for encapsulating mass timber to meet fire resistance requirements for compartments in commercial buildings.

4.2.2 Timber

Timber is an adaptable material that can be manufactured into various forms providing architectural freedom to offer buildings of different proportions and use from source material that may be quickly grown, weak, geometrically small, and non-homogeneous. Commercial buildings may use the raw material itself or composite forms capable of spanning large floor distances and supporting great weight in columns suitable for replacing steel and concrete.

Timber is easy and quick to erect reducing costs, has good insulation properties, is recyclable, has high strength to weight ratio, is sustainable and ultimately has aesthetic appeal. Some of the disadvantages of using timber are its susceptibility to water exposure that may result in mould growth, infestation, discolouration, and dimensional change, but importantly the threat of fire. Timber is a combustible material and will need specific fire protection measures to enable its wider use in all localities of a building. Figure 4-1 shows how far timber has gone in replacing steel and concrete.

Figure 4-1 : London's tallest mass timber office building (The Black and White Building) during construction 2022 (Dale Kinnersley)

4.3 Timber in construction

4.3.1 Structure of wood

The chemical structure of wood is made up of a mixture of natural polymers. Polymers are individual molecules which are chains made of repeated units derived from simpler molecules known as monomers [62].

Wood typically contains polymers of cellulose, hemicellulose (carbohydrates), lignin, and small amounts of extraneous materials (organic materials and inorganic minerals). Proportions of these polymers vary in different species of wood such as hard and softwood but are typically proportioned as detailed in Figure 4-2.

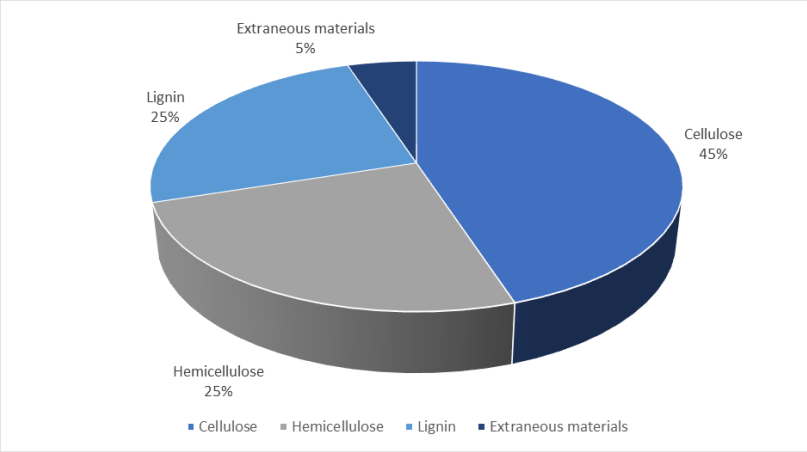


Figure 4-2 : Typical polymer proportions of wood

Cellulose is made up of numerous monosaccharide monomers shown in Figure 4-3, which is a type of sugar (D-glucose) and presents as a linear structure providing structural strength to the cell wall.

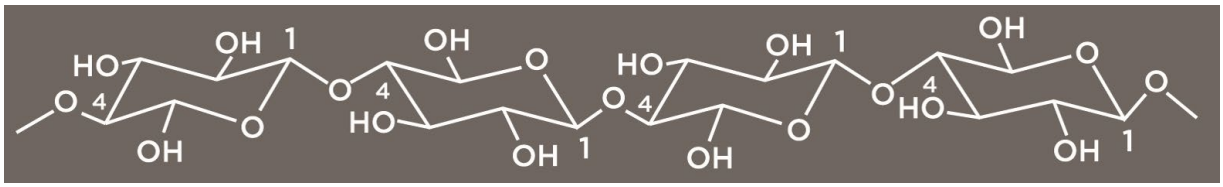


Figure 4-3 : Chemical chain of cellulose

Hemicellulose is similar to cellulose and is based on pentose sugars which are smaller and have a cross linked type structure shown in Figure 4-4.

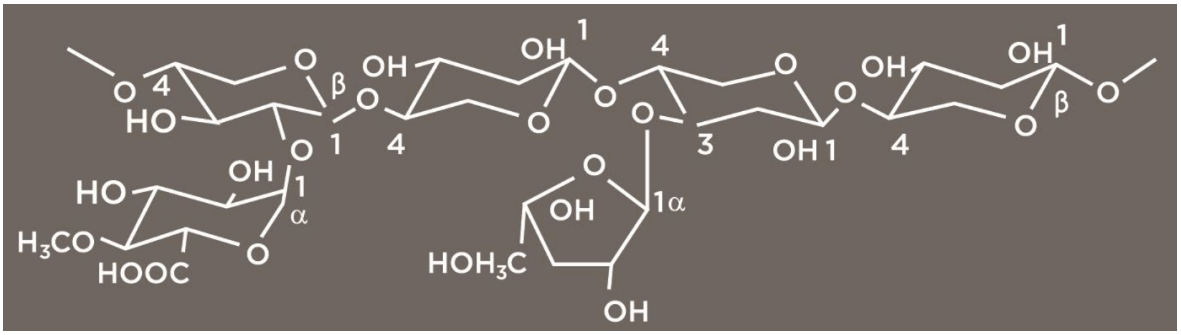


Figure 4-4 : Chemical chain of Hemicellulose

Lignin is more complex of the three main constituents acting as an encrusting material in the cell wall shown in Figure 4-5.

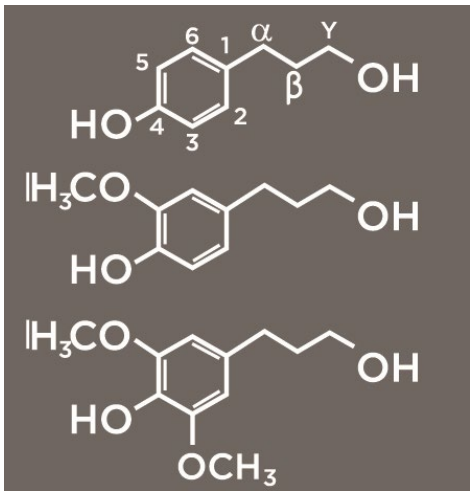


Figure 4-5 : Chemical chain of Lignin

Hemicellulose links lignin and cellulose to make a unified whole in the layers of the cell wall.

Analysis of the degradation of wood confirms that the constituents of lignin and cellulose release volatiles at different temperatures and are typically:

- Hemicellulose 200-260^{0}C
- Cellulose 240-350^{0}C
- Lignin 280-500^{0}C

The denaturing (pyrolysis) of wood commences at 100^{0}C, with water loss. At around 160-200^{0}C the three constituents slowly decompose. 200-225^{0}C the majority of gases produced are non-combustible. As pyrolysis continues and temperatures reach 225-275^{0}C flaming combustion can occur if an ignition source is introduced. At 280-500^{0}C gases produced are combustible. Smoke is produced and a char layer begins to form on the surface of the wood. When temperatures increase further above 500^{0}C volatile production is complete and char continues to smoulder and oxidise producing CO, CO_2, and H_2O. General temperatures shown above will vary amongst species of timber and temperatures of decomposition will change as confirmed by Dietenberger et al [10].

In addition to polymers, wood contains absorbed moisture. This can vary in percentage based on its location and relative humidity which is held in the wood in the natural voids created in the

structure. Moisture can also be present in the cell walls and in the protoplasmic contents of the cells and in ambient conditions can achieve an equilibrium with the surroundings known as the Equilibrium Moisture Content (EMC). The strength of timber is a function of its moisture content. It is weaker at 0% water, and optimal at around 8-10% water. Above 20% water it is susceptible to fungal decay.

The physical structure of wood, grain structure and properties vary with direction. Wood can be classed as a structural tissue and natural composite which contains cellulose fibres that are strong in tension. These fibres are embedded in the matrix of lignin that resists compression. Wood is heterogeneous, hygroscopic, cellular, and anisotropic and varies in structure between soft and hard woods. The difference between hardwood and softwood is reflected in the composition of lignin. Figure 4-6 illustrates the make-up of wood depicting the cell wall structure.

Dimensional properties of wood vary depending on moisture content (MC). The fibre saturation point (FSP) is the moisture content level at which all free water has evaporated from the wood's cell cavities, but the cell walls remain saturated with bound water. The majority of woods have an FSP of between 25 and 30% at which the physical properties transition from moisture dependant to constant. At >30% FSP, added water occupies cell lumens which increases weight, but the wood remains dimensionally stable. At < 25%, loss of bound water from cell walls causes the wood to either shrink or swell resulting in dimensional changes.

Due to the cellular structure of wood, dimensional changes through expansion and shrinkage will differ. By reducing the MC from the FSP, reflecting an oven-dry condition, shrinkage and warping would be common features observed. Shrinkage can include tangential (~6% - 12%), radial (~3% - 6%), and longitudinal (~0.1% - 0.3%).

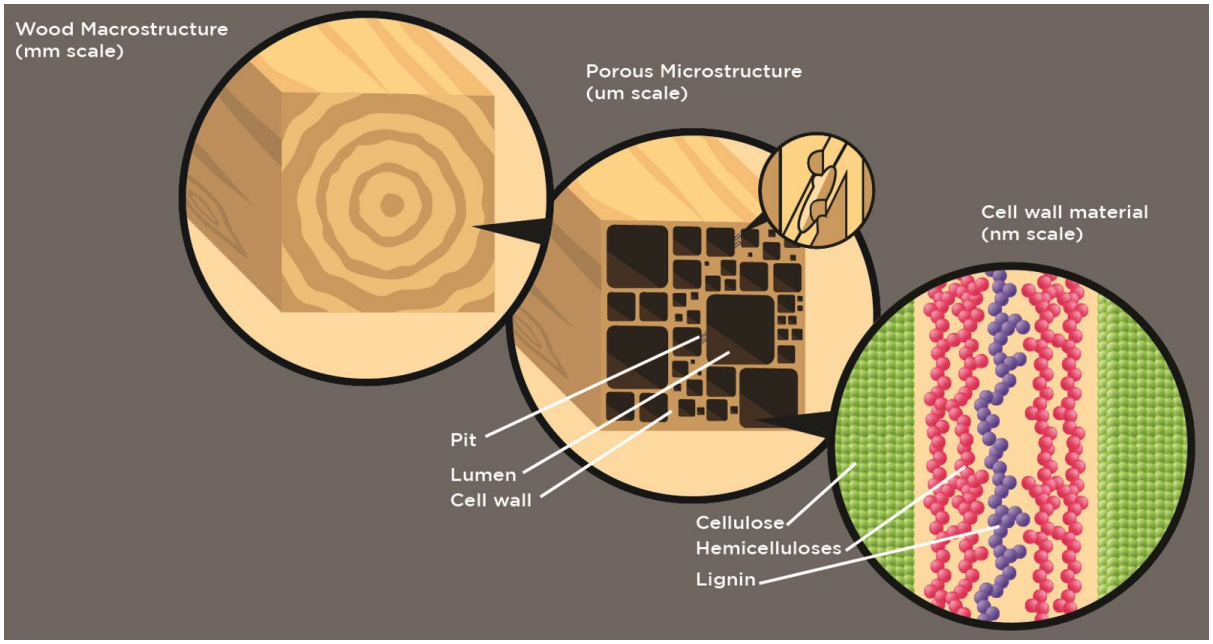


Figure 4-6 : In-depth detail of the structure

Wood is non-homogeneous and non-isotropic, meaning the properties vary with direction where measurement is made. Examples include the thermal conductivity of wood which when measured parallel to the grain is twice that perpendicular to the grain. Gas permeability

exhibits greater differences still to the order of 10^3. The porosity of the materials cellular structure changes with water content.

As moisture content increases from dry up to the FSP, structural strength, including shear, tensile, bending, and compressive, declines. Where water is present above the FSP there is minimal impact on the mechanical properties. However, below the FSP, water content in the cell walls plasticizes the lignin-cellulose matrix which reduces strength and stiffness. Loss of strength due to MC are as follows:

- Shear strength parallel to grain diminishes in line with compressive and bending strengths, often losing 30–50 % of dry strength by the FSP.
- Tensile strength (parallel to grain) is less sensitive but still declines by roughly 10–20 % from dry to 15 % MC, and up to 40 % at FSP.
- Bending strength from dry condition to 12 – 15% MC (a typical EMC for temperate climates), bending strength drops to 85 – 90% of its dry strength and reduces to 60 – 70% as the FSP is approached.
- Compressive strength from dry condition (~2% MC) to 16% MC, strength drops by around 50% (18 - 39 MPa (dry) to ~9 – 19.5 MPa (16%))

The strength of wood is not just affected by moisture. Increased temperature is known to reduce strength [10] as the wood dries, and at higher temperatures pyrolysis results in weakening of the of the structural components and eventually combustion (~225-275^{0}C) where timber chemically changes and starts to char. Char has no structural integrity and leads to loss of cross section area of the wood, reducing the original structural capacity.

4.3.2 Composites

Engineered timber in composite form include Cross-Laminated Timber (CLT), Laminated Veneer Lumber (LVL), and Glue Laminated Timber (GLT). These composites can be used to produce large dimensionally stable buildings that can be erected faster and more economically than using traditional building materials detailed in section 4.2.1 [63]

Composite building components produced bespoke at the factory, can form a high tolerance kit of parts which enables greater freedoms for the design of large enclosures with long spans of structure that permit heavy loads and scale, having improved efficiency and sustainability.

4.3.2.1 Cross Laminated Timber (CLT)

CLT was originally developed in Switzerland in the early 1990's with further development coming from Austria and Germany [64]. It is estimated that 80% of the timber used in UK construction comes from these countries. Plans are in place through the Timber in Construction Road Map (TIC), backed by UK government, to plant and manage timber forests in the UK to furnish the construction industry, but this will not be available for at least ~25 years.

CLT is an engineered wood product seen as an alternative to steel and concrete in construction [65 - 69] but used in panelised form. It has excellent load-bearing qualities and is a sustainable material that can be used throughout a building's life cycle and reduce CO_2 [70].

CLT is formed of parallel timber planks laid out orthogonally to the adjacent layer and bonded together in odd numbers, typically, three, five or seven, to produce wall and floor panels, but can be more, shown in Figure 4-7. The thickness of ply layers varies, but typically range from 20 to 50 mm, with the overall thickness of a slab being specified for structural requirement.

Adhesives used between the layers vary between manufacturers and are selected to suit functional requirements. It is the combination of the timber and the bonding of the layers that provides strength and locks the timber together to produce strong panels used for floors, walls, and ceilings [64, 70]. Adhesives are normally only applied between ply layers as shown in Figure 4-7, however, glue can be applied between individual planks if needed for a specific project requirement.

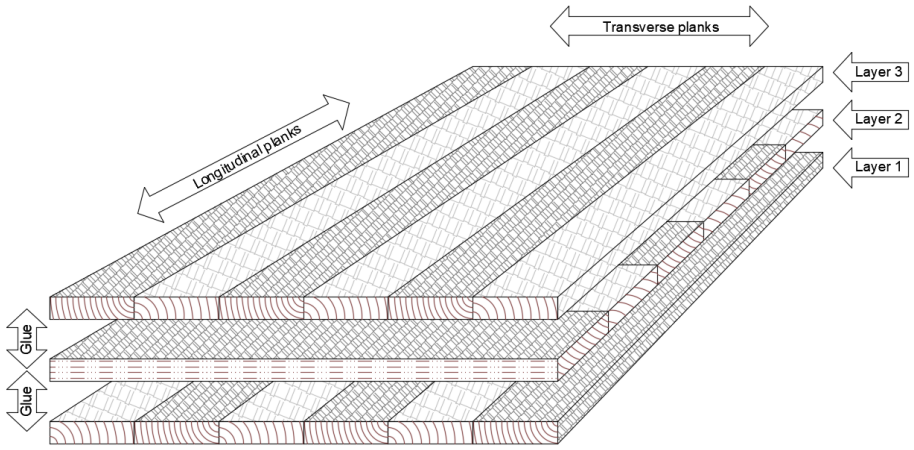


Figure 4-7 : Configuration of CLT Panel

4.3.2.2 Laminated Veneer Lumber (LVL)

Laminated Veneer Lumber (LVL) is used for beams and columns due to its high strength to weight ratio. LVL is lightweight and very strong in comparison to steel and has high load-bearing capacity.

LVL is formed from multiple veneers (typically 25 veneers, 3 mm thick) that are strength graded and bonded together and sized to cater for load requirements. It is a material that is dimensionally stable and used for post and beam construction with non-structural infill. LVL is different from CLT utilising multiple veneers to a thickness of ~75 mm bonded together with high strength adhesive which provides a straight and uniform component that incorporates high strength and stiffness.

4.3.2.3 Glue Laminated Timber (GLT)

Glue Laminated Timber (GLT) or glulam is used for long span beams replacing steel, concrete, and other load-bearing structures. GLT is often produced in different shapes to cater for architectural aesthetics, retaining structural capacity.

GLT is made from strength graded timber, finger-jointed in multiple layers and bonded together under pressure. It is a solid wood product that has the flexibility to be adapted to suit the building architecture. It is used for similar post and beam construction as LVL, but its fabrication involves fewer leaves of thicker timber (typically 20 – 45 mm lamella thickness and glued together to a size requirement for the structure)

4.3.3 Burning characteristics of wood

4.3.3.1 Heat transfer

There are three mechanisms for heat transfer, convection, conduction, and radiation. All three contribute during fire with radiation being dominant. Spread of fire is dependent on many features including the combustibility of the compartment/building, the materials present, how the materials are located within the compartment/building, the efficacy of compartmentation, ventilation arrangement, and type/size of the initiating event. Contents aside, the combustibility can be based on the primary (structure) and secondary construction materials within the building such as decorations and acoustic linings, architectural features etc. which would assist in the spread of fire in the compartment [71].

Conduction is heat flow through a solid material. Fire in a compartment with insufficient insulated linings can conduct heat to start fires in locations remote from its origin.

Convection is the exchange of heat from a gas or liquid and a solid involving movement of the fluid medium. Convection occurs at all stages within a fire and is specifically important in the early stages when thermal radiation levels are low. For natural fires, the movement of gases is dominated by buoyancy, which influences the shape and behaviour of the flames and can be summed up as the transfer of heat through the motion of heated matter such as smoke, air and gases produced by the fire.

Radiation requires no intervening medium from the source and the receiver and transfers via electromagnetic waves. This type of heat transfer is the dominant mode in larger, unwanted fires. When the fuel bed diameter increases, the growth and spread of fires in a compartment increases [62]. A substantial amount of heat released in flames is transmitted by radiation to the surroundings, most is emitted by minute solid soot particles formed in diffusion flames and characterised by their yellow luminosity. Radiation allows the transfer of heat from a fire across an intervening space to an object which in turn absorbs, transmits, or reflects this energy. If sufficient is absorbed by the target surface it will heat up until combustion commences and spreads the fire further.

The three mechanisms are shown in Figure 4-8.

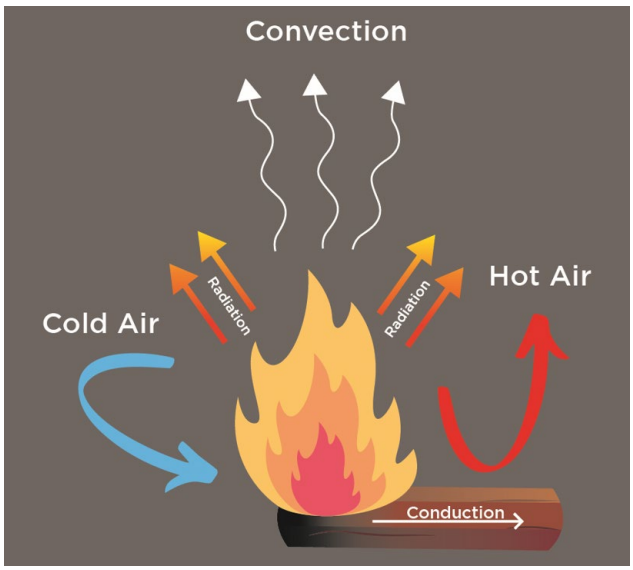


Figure 4-8 : The three mechanisms of heat transfer

Where primary and secondary structure are timber, they may become part of the fuel contribution increasing the Heat Release Rate (HRR) above that which the contents alone would recognise.

4.3.3.2 Pyrolysis

Thermal decomposition also known as 'gasification,' 'depolymerisation' or 'pyrolysis' is a chemical decomposition and change from original state of a material through heat. At a specific temperature known as the decomposition temperature, a solid chemically decomposes. Wood decomposes and changes physically releasing volatile gases that, once mixed with air, burn above the solid leaving a residual char. Chemical change through heat breaks down chemical bonds that are responsible for the release of volatiles.

Wood is a polymeric solid and is involatile (available water aside) in normal state. To burn, the molecular structure of wood needs to be broken down into smaller molecules to enable them to vaporise from the surface of the material. The various polymers of wood break down at different temperatures, shown in Figure 4-9. As heat is conducted into the wood, chemical breakdown accelerates the change of state allowing wood to pyrolyse more easily. Cellulose polymers of wood also have a semi-physical change through heating, which is desorption of absorbed water that commences at temperatures ~100^{0}C.

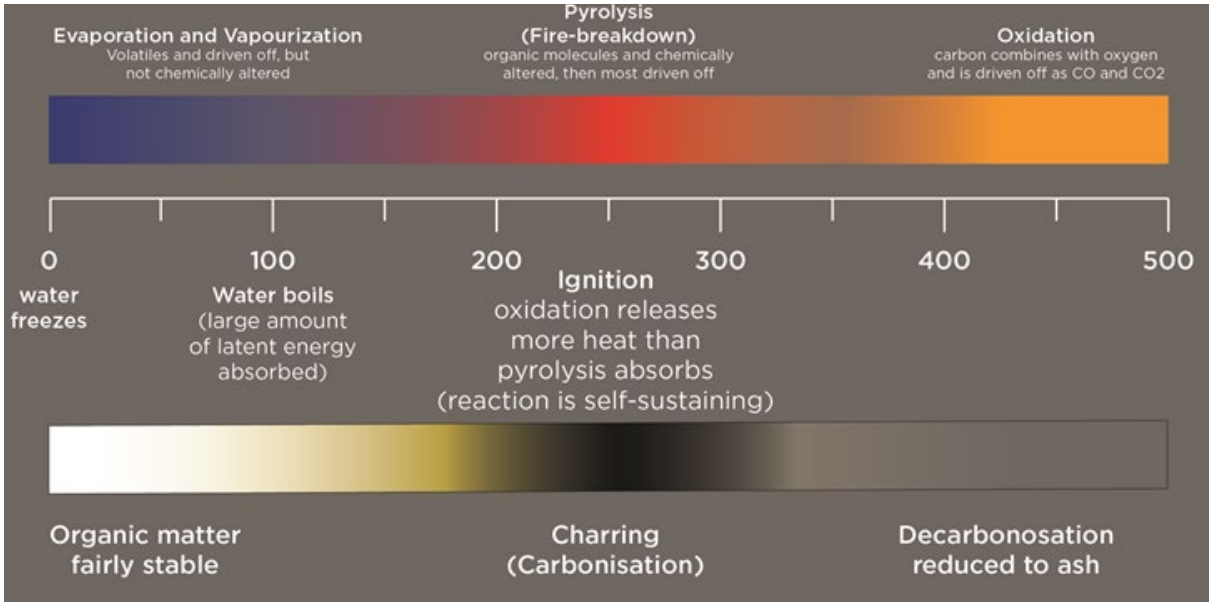


Figure 4-9 : Thermal decomposition of organic matter

Within the temperature range of 100^{0}C up to 500^{0}C common organic molecules undergo decomposition reactions and break down into smaller molecules/volatile fragments (known as pyrolysate) where it is not uncommon for the smaller molecules to participate in chemical reactions forming larger molecules.

4.3.3.3 Combustion

Combustion is an exothermic chemical reaction that results in a high temperature output involving fuels and oxidant (oxygen (O_2)) producing oxidized gaseous products. Smoke contains solid or liquid droplets of unburned oxidized products. Flames are normally a visual indicator of fire when substances in combustion vaporize. Combustion involves a complicated sequence of events known as radical reactions. Wood undergoes pyrolysis to produce gaseous fuels for

combustion which in turn uses the heat to produce more gaseous fuels to extend the combustion process. When wood reaches a high enough temperature during combustion, there is production of incandescent light in the form of glowing from char or visual flame in the gas phase.

Complete combustion requires perfect stoichiometric involvement of fuel and oxygen leaving no remaining fuel or oxidant. Complete combustion is almost impossible to accomplish in anything, but a pure oxygen environment and chemical equilibrium is never attained resulting in unburnt products such as carbon monoxide (CO), hydrogen (H), and carbon (C) (soot or ash) in addition to carbon dioxide (CO_2) and water (H_2O). Incomplete combustion yields a lower heat output to that of carbon dioxide.

Most common building fires involve hydrocarbons releasing heat from the combustion process producing water and carbon dioxide represented below in Equation 1 (for propane).

Equation 1

$$C_3H_8+5O_2 \Rightarrow 3CO_2+4H_2O+Heat$$

Flaming combustion occurs when fuel is in the gas phase. Flaming combustion is visual by the indication of flame, which has the characteristic yellow luminosity rising from the surface of the fuel. There are two types of flames, pre-mixed and diffusion. Pre-mixed flames occur where the fuel is mixed with oxygen or air prior to burning. Diffusion flames are when the fuel and oxygen are initially separated but burn together in the location where they have mixed. Common accidental building fires emit diffusion flames.

Combustion of solid fuels that burn with a diffusion flame is best described by burning rate. Burning rate is the rate at which the mass of a solid is vaporized or oxidised and is expressed as mass loss unit per time measured in kg/s.

For flaming combustion to occur, there needs to be an initial ignition (piloted ignition or spontaneous ignition). Piloted ignition is when the process is initiated by a spark or independent flame such as a match applied to the fuel that is mixed with the surrounding oxygen or air. Fuels have a flash point which is best described as the lowest temperature at which there is sufficient vapour to form an ignitable mixture with air near the surface of the fuel when an ignition source is applied. At this temperature flames would flash over the surface area, but combustion would not be sustained as there are insufficient vapours available to support combustion.

Spontaneous ignition occurs at a higher temperature. The application of an external heat flux will raise the temperature to produce sufficient volatiles that on mixing with the air react quickly enough to increase the temperature to ignite the fuel. Scientific papers reviewed confirm there is also a critical heat flux (CHF) for ignition, or extinction. Bartlett et al [72] reviewed complex burning behaviour of engineered timber products CLT and GLT. Pyrolysis, ignition, and combustion were considered, and it was confirmed the most dominant factor effecting burning behaviour was incident heat flux.

In some situations where large timber elements are concerned it has been found that the continued flaming combustion of wood requires a constant external heat flux to maintain high temperatures at the surface. Where the external heat flux drops below a predetermined temperature, flaming combustion ceases, this is not extinguishment, but a transfer from flaming to smouldering. Self or Auto-Extinguishment is covered in more detail in chapter 4.4.3.

Emberley et al [73] conducted small and large-scale testing of CLT for self-extinguishment. Results confirm a critical threshold heat flux level ~45 kW/m^2 where flaming combustion ceases due to insufficient energy. This critical threshold level was also confirmed in tests undertaken by Hopkin et al [74]. However, a lower level of heat flux for flaming combustion was found to be ~18.5 kW/m^2 for tests undertaken by Madden et al [75]. Bartlett et al [76] found that sustained flaming of CLT fell in between levels quoted by Emberley, Hopkin and Madden, which was confirmed at ~31 kW/m^2. For non-charring materials, the CHF would be expected to show consistently. For materials such as wood, the extent of charring will affect the CHF. This suggests an explanation for these inconsistencies.

Madden et al [77] investigated the ignition of a timber ceiling analysing the convective and radiant heating effects. Findings confirm that ignition is not solely dependent on peak heat flux but also on the duration and distribution of thermal exposure. Hopkin et al [78] experimented on commercial enclosures with CLT conducting three experiments to determine whether glue-line integrity failure (GLIF) must be avoided to achieve auto-extinction and to understand how combustible ceilings affect fire dynamics. Results showed that combustible ceilings increase radiative heat flux, potentially accelerating fire spread. Bartlett et al [79] investigated fire-induced delamination of CLT by exposing samples to a modified flame spread test and constant heat flux. Delamination occurred exposing fresh wood to flames and accelerated flaming combustion.

Under a sufficient external heat flux, wood produces enough volatiles at the surface, irrespective of the insulating properties of the char, to maintain flaming combustion. In common building fires wood would receive this heat flux from radiation from other hot objects involved in the fire as confirmed by Hopkin et al [78] and Bartlett et al [79].

Smouldering combustion is a slow, lower temperature and flameless form of combustion that is sustained by the heat evolved as oxygen attacks the surface of a condensed phase fuel and is more persistent. The main difference between flaming and smouldering combustion is that smouldering occurs on the surface of a porous solid fuel rather than in the gas phase. Temperature and heat release rates are lower in smouldering which propagates at around 0.1 mm/s, ten times lower than flame spread over a solid. The reaction can be prevalent over many hours [80] and produces toxic gases as products of incomplete combustion. Ohlemiller et al [81] investigated smouldering propagation in relation to air flow velocity and confirm that smouldering was prone to transition back to flaming combustion at an air flow velocity of 20 – 25 cm/sec.

Smouldering tends to follow flaming combustion in many cellulosic materials if the flame is extinguished without cooling the fuel. Examples of materials that may smoulder are timber, coal, sawdust, biomass, and tobacco foams. These materials are porous, permeable to flow and formed with cellular structure or of particulates, grains and fibres which facilitate surface reaction with oxygen allowing gas flow through the fuel. Gas flow through the fuel allows for a large surface area per unit volume which acts as thermal insulation reducing heat losses.

When flaming combustion of wood ceases, the char on the solid can continue to smoulder and oxidize, provided the temperature is high enough. Liang et al [82] investigated ignition behaviour and emission characteristics of smouldering combustion in beech wood under low-intensity, long-duration radiant heating (5–10 kW/m^2), to determine the conditions for self-sustained smouldering after the heat source is removed. Experiments conclude that self-sustained smouldering requires a surface temperature ≥ 350 ± 20°C. Below 5 kW/m^2, ignition did not occur even after 400 minutes. In concluding their research, wood can smoulder under

lower heat fluxes than previously thought, given sufficient time. Self-sustained smouldering is possible without continued irradiation, but only if specific thermal and physical thresholds are met.

Rein et al [83 & 84] confirms that smouldering combustion is the most persistent type of combustion phenomena. Smouldering results from oxidation in the solid phase, whereas flaming only occurs in the gas phase. Rein confirms smouldering can be initiated with weaker ignition sources and is more difficult to suppress and the potential transition from smouldering to flaming combustion is a significant threat. Zhang et al [85] studied smouldering to flaming (StF) transition of solid timber under varying air flow conditions with different sample thicknesses of wood. Findings show that as air velocity increases, both smouldering and surface temperature increases speeding up the transition to flaming combustion. It was confirmed that weak and glowing smouldering was measured at low temperatures of 300 – 500 ^{0}C, the same measurements confirmed by Liang et al [82], and had elevated temperatures of 600 – 800 ^{0}C.

Mitchell et al [86] looked at smouldering and/or the cessation of flaming in the context of structural impact to mass timber construction. Mitchell used data from wildfire fires and linked them to compartment fires; it is seen that smouldering of solid timber increases linearly with air velocity which leads to the transition of flaming in forward flowing smouldering. However, small scale testing also confirmed that smouldering cannot self-sustain without sufficient heat flux and airflow. Smouldering is identified as a hazard to mass timber construction in the context that it is difficult to detect and suppress and can transition back to flaming combustion as described earlier by Rein et al [83 & 84]. The research by Mitchell, recognizes insurers concerns, referencing RISCAuthority White Paper [33]. The white paper reflects the concerns of smouldering combustion spreading into hidden and exposed voids (horizontally and vertically) leading to prolonged periods without detection and potentially spreading to adjacent compartments or other floors, where transition to flaming could initiate multiple fire seats with new fuel sources.

4.3.3.4 Charring

The following section is based on the work of Drysdale [62]. Cellulose, hemicellulose, and lignin have different properties that alter with increasing heat at different temperatures. When lignin is heated to higher temperatures ~ 400 – 450 ^{0}C, ~50% volatilizes and the remnants are char residue. In standard conditions when the temperature of wood is heated above 450 ^{0}C, 15-25% normally remains as char. The majority of char is from the lignin content which varies between species from soft to hard woods. Cellulose and hemicellulose contributions to char are variable dependent on temperature or rate of burning.

Whilst higher temperatures are associated with char formation, prolonged lower temperatures or lower rates of heating appear to affect char forming reaction and char yields. The consequence of variable heat to charring behaviour is different for every fire and the surrounding conditions of the environment.

Char is a carbon rich residue left behind on the surface of wood following combustion. Char is formed during thermal decomposition when not all of the wood transitions from the solid phase into the gas phase leaving char residue at the surface. As char builds up in depth, burning conditions of the wood change. Pyrolysis of the wood beneath the char still occurs and penetrates through the char to the virgin wood below, shown in Figure 4-10.

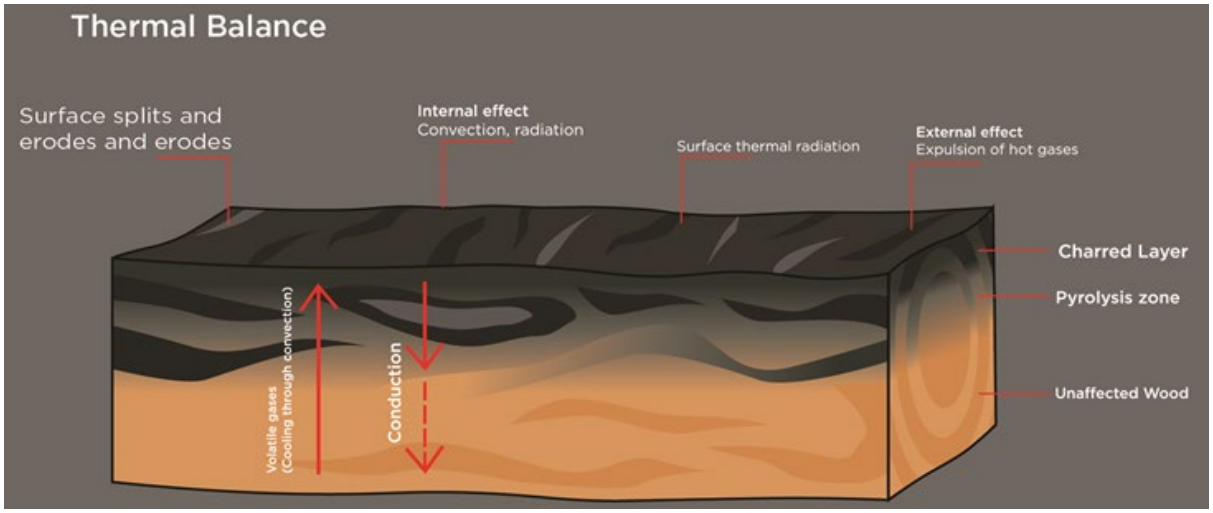


Figure 4-10 : Burning wood indicating char formation.

Visually, char appears at the surface in the form of small, discoloured cracks which are perpendicular to grain direction. The cracks allow volatiles to escape through the surface of the affected layer and widen as char depth increases. The appearance is described as 'crocodiling' or 'alligatoring.' As char increases in thickness the release of volatile gases from the wood is impeded reducing supply of fuel to the flame and slowing down the rate of combustion.

Char typically has low density and high porosity which results in it becoming an exceptionally good thermal insulator acting as a barrier to slow down heat transfer into the wood.

As char starts to form on the surface, the thermal barrier grows slowly between the flame and the solid, the wood undergoes flaming combustion. As the char thickens heat radiated back into the wood decreases, char insulates virgin wood below, flame extinction usually follows with transition to smouldering combustion. Lucherini et al [87] estimated effective char depth in structural timber elements exposed to natural fires, considering the heating and cooling phase. They conclude that approximately 75% of the char depth develops during the heating phase, the cooling phase contributes the remaining 25% and plays an even more critical role in the formation of the zero-strength layer whose thickness can be 2–3 times greater after cooling than at the end of heating. Their study highlights current Eurocode 5 (EC5) (EN 1995-1-1:2004) [54] simplified methods, underestimate the impact of the cooling phase, potentially leading to unsafe structural assessments.

Girompaire et al [88] investigated fire dynamics of mass timber compartments with exposed surfaces looking at HRR and char depths. They validated their study against 20 experimental fire tests, which demonstrates strong alignment with observed HRR, temperature trends, and mostly conservative char depth estimates. This is in stark contrast to validated tests undertaken which confirm that conservative charring rates detailed in EC5 are vastly underestimated.

Conservative charring rates predicted in EC5 are 0.65 mm/min. Ronquillo et al [89] confirm that charring rates in natural fires are generally higher than in standard furnace tests which is also confirmed by Pečenko et al [90] who modelled charring of timber through exposure to natural fire. Modelling used the advanced heat–mass–pyrolysis model (PYCIF) to simulate the charring behaviour of timber under natural fire conditions. They conclude natural fires are often more severe than standard ISO fire exposures. Xu et al [91] investigated the combustion and charring

behaviour of five commonly used constructional wood species. Charring depth and rate were found to increase with heat flux and exposure time but stabilize after 30 minutes. When comparing with predictions from EC5 and Australian (AS1720.4) [92] standards, find that both generally underestimate charring, especially for denser woods. Amin et al [93] introduced a novel database (VAQT) of 231 fire resistance tests to improve the prediction of timber charring rates by comparing EC5 methods with data-driven approaches including statistical models and machine learning algorithms. They demonstrate that EC5 underperforms with a 27% error rate and advocate for integrating AI-driven models into fire engineering to enhance safety and precision in timber structure design.

Fire tests show numerous variances in charring rate from EC5 but need to be considered separately based on exact test requirements. Xu et al [94] conducted charring rates of five varied species of timber using cone calorimetry at three levels of heat flux, 25, 50 and 75 kW/m^2. Samples were heated for different time periods ranging from 5 – 60 min in increments of 5 min. Results show measured average char rates range from 0.41 – 1.11 mm/min, higher than predicted which ranged between 0.50 – 0.89 mm/min. Charring depth was shown to be approximately linear with exposure time, resulting in the charring rate being calculated as the charring depth divided by the fire exposure time. In conclusion, charring depth was observed to increase with fire exposure time and increasing heat flux. Albert et al [95] investigated the fire performance of CLT made from densified Paraserianthes falcataria laminas (species of fast-growing tree from Southeast Asian countries), focusing on mass loss and charring rates during a 120-minute open burning test. Laminas were compressed at 40%, 50%, and 60% ratios, and CLT panels were assembled using polyvinyl acetate (PVAc) adhesive. The results showed that the control sample had the highest charring rate (0.2085 mm/min), while 50 and 60 compression rates (test samples) had the lowest (0.1638 and 0.1634 mm/min), all within the EC5 limit. Sun et al [96] investigated moisture transfer, burning, and charring behaviour of glue laminated larch. Results show that charring and colouring temperatures averaged 380°C and 260°C respectively, higher than previously reported values. Charred depth, coloured depth, and burnt-out depth increased according to heating duration. Charring rate was 0.72–0.76 mm/min. Colouring rate was 0.98–1.00 mm/min. Bøe et al [97] conducted large-scale experiments on a CLT compartment and an adjacent corridor. Charring rate measurements varied but were confirmed at ≥1.1 mm/min. However, variations of 1.45, 0.95 and 0.69 mm/min at various CLT depths (25 mm intervals) were also confirmed with the conclusion that charring rates are dependent on temperature such that at ≤ 463°C a lower charring rate of 0.67 mm/min was recorded. Dietenberger et al [10] reviewed thermal degradation of wood in fire and confirm a typical charring rate at 0.6 mm/min. Kim et al [98] recently investigated the fire performance of CLT wall panels by examining charring depth under non-load-bearing fire conditions (two uncladded CLT panels and two panels clad with fireproof gypsum boards). Tests were conducted using a vertical furnace and the ISO 834-1 [99] standard fire curve, with charring depth measured by core sampling. Unclad CLT walls experienced a linear increase in charring depth of 0.87 mm/min after 1 hour and 0.94 mm/min after 2 hours. Cladding with fireproof gypsum board reduced charring depth by about 29%. Maharjan et al [100] looked at the fire performance of mass timber structures, including compartments, beams, and columns/walls. Findings show that peak temperatures in mass timber compartments increase linearly with both the exposed timber area and duration of fire exposure. Charring rates in compartments are significantly higher (average 1.22 mm/min) and more variable than those observed in standard fire tests on beams and columns/walls (typically 0.60–0.70 mm/min). For beams, columns, and walls, charring rates generally fall within ±20% of EC5 (0.65 mm/min). These results are also confirmed by tests undertaken by Hopkin et al [74] who conducted full-scale

fire experiments on CLT residential enclosures with different lining protection configurations. Results confirm that HRR increased proportionally with the area of exposed CLT and its charring rate. Charring rates were generally higher for walls than ceilings, likely due to differences in oxygen and heat distribution.

Char fall off was investigated by Makino et al [101]. They explored how char layers on glue-laminated timber walls behave under ISO 834 standard fire exposure for durations of 30 to 120 minutes, followed by cooling periods of 0, 60, or 180 minutes, using specimens of Glue-laminated larch walls, 100 mm, or 150 mm thick. Measurements of surface geometry (cracks and fallout) were conducted using laser displacement meters, internal temperatures, and moisture content. Crack formation was found to increase with heating duration and cooling slightly increases crack width. Fallout of char becomes significant after 60 minutes of heating and cooling increases fallout severity.

In conclusion, charring rates vary depending upon heat flux, duration, exposure area, compression, species (hard and soft woods), and orientation, which all have a significant role. It can be derived from the research conducted which shows that the conservative charring rate of 0.65 mm/min within EC5 is outdated and needs to be reconsidered for the safety of mass timber construction. Finally, Bartlett et al [72] state that the most dominant factor affecting burning behaviour is the incident heat flux, which can cause up to an 800% variation in charring rate.

4.3.3.5 Fuel contribution and Heat Release Rate (HRR)

The inclusion of exposed timber linings within a compartment (walls, floors, and ceilings) adds to the fuel load (contents), presenting greater fire potential, since timber boundaries in a compartment contribute to fuel load, potentially leading to longer and more severe fires [102].

HRR is used in association with flame height, smoke production, and temperature in compartment fires to assess the potential for flashover conditions (the time at which radiative heat transfer causes all combustible materials in the compartment to become involved in the fire). Energy released by a fire needs to be quantified and understood. However, fuel quantity, type, orientation, enclosure volume, and ventilation play significant factors in determining the HRR. Most fire calculations only consider the contents of the compartment and if the fire will be ventilation or fuel controlled. The introduction of timber in primary and secondary exposed structure needs to be carefully considered and factored into the HRR calculations.

Heat Release Rate (HRR) is the rate of heat generation by fire, measured in Joules per second (J/s) or Watts (W), but more normally reported as megawatts (MW) or kilowatts (kW). It can be simply defined as how big the fire is, for example a wastepaper bin fire is circa 50 kW and a common two-seater sofa circa 3.5 MW.

A simple approximation calculation for calculating HRR can be seen in the equation below. However, there are several ways to calculate HHR of materials:

Equation 2

$$q_{Hc} = \Delta H_c \times m_{fuel}$$

where:

q_{Hc} = the heat release rate (kJ/s)

ΔH_c = the heat of combustion (MJ.kg-1)

m_{fuel} = the mass flow rate of the fuel (g/s)

The increase in HRR related to exposed timber surfaces has been summed up by Xu et al [94] stating that HRR increases with increasing heat flux. Brandon et al [103] confirms an 80% increase from unprotected CLT surfaces, whereas Weisner et al [104] confirms approximately double the HRR with three surfaces exposed (2 x walls and 1 x ceiling) ,similar in findings to Kotsovinos et al [80], with Hadden et al [105] stating higher than expected HRR from initial predictions. Tests undertaken by Zelinka et al [106] used varying exposed CLT surfaces and found HRR to reach up to 23 MW with increased fire severity and duration, which was also confirmed by Brandon et al [107] and Mitchell et al [108].

Ni et al [102 & 109] confirmed that exposed timber surfaces in mass timber buildings increased HRR and extended fire duration. Their study confirmed that exposed timber from 0% - 100% can increase HRR by 47% and extend fire duration by 64%. Tests show a near-linear relationship between the percentage of exposed timber and the total HRR, with values reaching up to 100 kW/m^2 of exposed CLT. Tests undertaken by Hasburgh et al [110] show how exposed CLT significantly influences fire dynamics and increases HRR. Mitchell et al [24] confirm that exposed timber ceilings increase HRR and Hoehler et al [111 & 112] confirm a general increase in HRR from exposed CLT surfaces, which is also confirmed by Ronquillo et al [5] and Hopkin et al [113].

Findings by Ohlemiller et al [81] confirm that increased air flow improved the rate of transfer of oxygen to the wood increasing HRR. Hopkin et al [4] conducted three tests on loaded CLT slabs reviewing common CLT adhesives. Results show an exposed CLT ceiling increased heat release rate by three times over encapsulated ceilings using plasterboard, with Nothard et al [114] also confirming higher HRR from involvement of a CLT ceiling.

Testing undertaken by Hoehler et al [115] show how exposed CLT increases HRR and extends fire duration. Results also show that large openings also increase HRR. Sanned et al [116] investigated the second/end peak in heat release rate. Sanned et al, demonstrate that the second HRR peak is primarily caused by burn-through, where heat reaches the rear unburnt side of the timber, which is then involved. Moisture transport also plays a role, with drier samples igniting faster and producing higher HRR.

CFD modelling was investigated by Perković et al [117], who confirm through simulation that exposed CLT significantly increases HRR, gas and surface temperatures, and smoke production.

In some instances, delamination of CLT timber slabs lead to secondary flashovers when the lamella detaches from the panel at the first glue line, exposing fresh timber to the fire. This was confirmed by Brandon et al [107 & 118] who conducted a full literature review related to fire challenges of tall wood buildings. Key findings indicate that exposed CLT significantly increases fire intensity and duration, while encapsulated timber (e.g., protected with gypsum board) may not contribute unless the protective layer fails. The study highlights the risk of secondary flashover events due to delamination of CLT, particularly when thermoplastic polyurethane adhesives are used. Su et al [119] found that exposed CLT surfaces in tall wood buildings significantly increase fire severity by contributing additional fuel load, accelerating flashover (by 3–5 minutes), and extending the duration of fully developed fires. Tests revealed that delamination of CLT plies, especially the first and second layers was a key mechanism for fire regrowth. Hoehler et al [115] demonstrated that CLT can significantly influence fire

dynamics in tall wood buildings, especially when exposed and under limited ventilation. Testing shows exposed CLT significantly increases HRR and fire duration with delamination of CLT (due to heat) causing re-ignition in the decay phase.

Bateman et al [19] investigated how fuel load and the configuration of exposed CLT surfaces affect fire dynamics in reduced-scale compartment experiments. Sustained burning is primarily influenced by the configuration of exposed surfaces, with back and side wall exposure consistently leading to continued combustion due to delamination and increased heat flux, while back wall and ceiling exposure generally resulted in auto-extinction except at the highest fuel load. Delamination, driven by thermal penetration reaching the glue line, plays a critical role in reigniting flames after apparent extinction. Hadden et al [105] presents five large-scale compartment fire experiments to assess how exposed CLT affects fire dynamics. Delamination of charred timber layers was identified as a key factor preventing auto-extinction, with ceiling surfaces more prone to delamination. Frangi et al [120] confirm that the fire behaviour of CLT depends on the single layers, and if these are to delaminate, then an increased charring rate needs to be applied for fire safety. This is the same for encapsulation, when it falls away during fire exposing the CLT bare surface to the fire. In addition, strength of the panels are influenced by thickness and number of layers and further research confirms vertical CLT (walls) may show better fire behaviour in comparison to horizontal CLT (ceilings). Bartlett et al [121] explored auto extinction of engineered timber which proved successful on consumption of the compartment fuel load. However, delamination was shown to disrupt this process, leading to re-ignition and preventing auto-extinction.

Ronquillo et al [89],Ni et al [102 & 109], Zelinka et al [23] Brandon et al [103] and Emberley et al [73] all confirm that delamination can lead to secondary flashovers and intensify fire behaviour. Ronquillo et al, also confirm that type of adhesive used plays a critical role, with melamine formaldehyde and phenolic–resorcinol–formaldehyde adhesives showing better resistance to delamination than polyurethane. Both Hoehler et al [111 & 112] and Bøe et al [122] identified polyurethane adhesive failure under heat as delamination was observed before the char front reached the glue line.

Glue line integrity failure is the most common cause of delamination of CLT through failure of the adhesive. Many types of adhesives have been investigated and tested over the years showing comparable results. Bartlett et al [79] investigated fire-induced delamination of CLT through two experiments using different adhesives (polyurethane and melamine formaldehyde) and lamella configurations. Delamination occurred in both cases, with temperature spikes and increased charring rates following the detachment of charred layers. The study found that delamination can occur even before the char front reaches the glue line, particularly with polyurethane adhesives, while both adhesive types can experience delamination. Brandon et al [123] also investigated delamination with specific adhesive types, confirming fire performance of CLT is significantly influenced by the type of adhesive used. CLT specimens bonded with commercial polyurethane adhesive (PU1) exhibited pronounced delamination during fire exposure, leading to increased charring, HRR, and sustained fire behaviour. In contrast, specimens using enhanced polyurethane (PU2), melamine formaldehyde (MF), and phenol resorcinol formaldehyde (PRF) adhesives showed no signs of delamination. Čolić et al [124 & 125] investigated the difference of two type of polyurethane (PU) adhesives used in CLT, noted as HB S (standard PU) and HB X (modified PU) with known improved fire performance at two different moisture levels of 9 and 14%. Testing was undertaken to understand the effects of heat induced delamination (HID) which is attributed to bond line failure using different glue types and moisture contents for different heat fluxes. Results from testing confirm that failure

temperatures for HB S adhesive are more dependent on heat flux and moisture content, and the HB X adhesive temperatures are more heat flux dependent. Heat induced delamination occurred for both adhesive types. Both adhesives showed similar trends, in that failure temperature decreased with heat flux and increased with moisture content. Findings using the same adhesives were also confirmed by Hopkin et al [4]. Investigations into PU and MF adhesives were investigated by Weisner et al [126], Zelinka et al [127] and Vihmannetal et al [128] with slightly differing results under heat. Wang et al [129] investigated the structural performance of adhesively bonded joints between spruce glulam and birch plywood, aiming to reduce reliance on metal connectors in timber construction. Three adhesives, melamine-urea-formaldehyde (MUF), phenol-resorcinol-formaldehyde (PRF), and two-component polyurethane (2C PUR), were evaluated using three pressing methods: screw-gluing, clamping, and weight loading. Tested under both dry and moist conditions using longitudinal tensile shear tests. Results showed that 2C PUR achieved the highest bonding strength (>5 MPa), while MUF and PRF performed similarly (4–5 MPa). Statistical analysis revealed adhesive type significantly influenced bonding strength, whereas pressing method did not. Wood failure predominantly occurred in spruce glulam, with PRF showing nearly 100% wood failure percentage. Moisture exposure had minimal impact on bonding performance. The study concludes that screw-gluing is a practical method for structural applications and highlights the need for further research on grain orientation effects and bonded area size. Albert et al [95] explored the fire behaviour of CLT manufactured from densified low-density wood. From experiments it was confirmed that delamination of glue lines occurred ~ 30 min due to PVAc decomposition, accelerating heat spread and influencing fire behaviour. Bartlett et al [76] reviewed fire safety challenges of tall timber buildings. Within the results delamination is confirmed even with adhesives previously considered resistant, suggesting broader implications are needed for design and due to delamination secondary flashovers and increase HRR follows.

4.4 Timber fire protection methods

4.4.1 Regulation

The government's role is to provide specifications for buildings for the protection of life. This is covered in many government regulations and guidance documents. Section 1 of the Building Act 1984 [47] gives purpose of the Building Regulations by providing the Secretary of State power to secure health, safety, welfare, and convenience of persons in or about buildings including firefighter safety. This also covers amongst others:

- Conservation of fuel and power,
- Preventing waste, undue consumption, misuse, or contamination of water,
- Protection or enhancement of the environment.

Section 8 of the Building Regulations 2010 [48] requires securing reasonable standards of health and safety of persons in or about buildings. Section 6 of the Building Act 1984 delegates power to the Secretary of State to publish statutory guidance in the form of Approved Documents. Approved Document B Parts 1 & 2 [28] is specifically related to fire protection of common buildings. Schedule 1 of the Building Regulations 2010 covers Part B Fire Safety. Approved Documents only cover common building situations.

The manual to the Building Regulations 2020 [29] assists in providing basic guidance through the complex set of legal documentation, which confirms less common building situations such as:

- Very tall buildings
- Large timber buildings.

Massive timber buildings present several potential additional risks that are not directly addressed by current building regulations or the approved documents. Therefore, this research will sit outside the scope of the Approved Documents which remain agnostic in terms of structural building materials. As a result, alternative standards are considered, such as BS 9991 [30], BS 9999 [31], and BS 7974 [32].

The Regulatory Reform (Fire Safety) Order 2005 (RR(FS)O 2005) [53] is primarily concerned with occupied or commissioned buildings. It does not stipulate the objectives of the Building Act 1984 or Building Regulations 2010, only the obligations of the building occupier and is not considered in this research.

To ensure mass timber buildings are fit for purpose and adequately protected from the perils of fire and water damage, property protection should be a consideration to the building in addition to mandatory requirements for life safety. This can be achieved in many ways and has been covered in this literature review. Notably, passive, and active fire protection play a significant role for the fire engineer when considering timber as replacement for steel and concrete. Mitigation options for the fire engineer to enhance the safety of mass timber construction are covered in the subsequent sections.

4.4.2 Design for burn-out

Timber construction will be designed to meet the requirements of the fire strategy which may incorporate 'design for burn-out,' self/auto-extinguishment (chapter 4.4.3), and passive fire resistance requirements (chapter 4.4.4). Burn-out in fire resistance refers to the phase after a fire has reached its peak intensity, when most combustible materials are consumed and the fire begins to decline. Fire-resistant structures must remain stable not only during peak heat but also throughout this prolonged burn-out period to prevent delayed collapse.

In 1928 S. H. Ingberg, Chief, Fire Resistance Section of the U.S. Bureau of Standards conducted fire resistance tests; [Smithsonian Institution Archives, Accession 90-105, Science Service Records, Image No. SIA2008-4292] [130]. Ingber's record of fire testing compartments was specific to office and record room occupancies including the associated fuel loads within the compartments. Numerous tests were conducted measuring fuel load, temperature, time, and outcome using both timber and metal furniture.

A table was produced to provide total combustible content based on fuel load and assumed BTU per sq.ft. relative to equivalent fire durations which were used to determine fire resistive periods detailed in the Post-War Building Studies 1946 [131]. Within these studies three grades of occupancy were identified: Low Fire Load, Moderate Fire Load and High Fire Load, all based on average BTU per sq.ft. of net floor area of any compartment (calorific values). Fully protected construction is also referred to in these studies:

We conclude from these results that, in a building of low fire load, a fire resistance of I hour in the elements of structure would enable the building to withstand a complete burn-out without collapse. Similarly in a building of moderate fire load a fire resistance of 2 hours would be adequate, and for high fire loads, 4 hours. We have thus obtained the necessary basis on which to formulate requirements for that grade of building which should resist a complete burn-out without failure and which we propose to call "fully protected construction."

In the studies sprinkler protection and flame retardancy of timber is acknowledged. For sprinklers in multi-storey buildings, the following is confirmed; Buildings, divisions, or compartments of buildings of fully protected construction, other than low normal fire load occupancy, should be generally equipped with an approved sprinkler system where the area on any one floor exceeds 10,000 sq. ft. In buildings not of fully protected construction, other than of low normal fire load occupancy, we propose that the cubic capacities given for unsprinklered buildings may be doubled where sprinklers are installed, and no unsprinklered floor area should exceed 7500 sq. ft. Except in the case of occupancies of low fire loads where unlimited areas are considered permissible, the cubic capacities given in Table 8 may be doubled when sprinkler systems are installed.

Where flame retardant timber is duly acknowledged it is confirmed that the treatment of timber with various solutions with the object of rendering it incombustible has been the subject of much study, and methods have been developed on a commercial scale for impregnating timber with suitable materials. Such timber is often described as "fire-proofed timber," but there is no evidence to suggest that that term can be interpreted literally, and it is preferable to adopt a term such as "flame retardant" timber. The use of created timber may, however, prevent a fire developing or at least reduce its severity in buildings where the woodwork contributes the main source of fuel.

In 1952 Post-War Building Studies No:29 Fire Grading of Buildings Part 2 Fire Fighting Equipment, Part 3 Personal Safety, Part 4 Chimneys and Flues [132] identifies both sprinklers and fire alarms, but does detail design for burn-out.

In 1974 Malhotra of the Building Research Establishment (BRE) [133] acknowledges the work of Ingberg [130] and Edwin O Sachs through Law et al [134] (where definition of fire resisting periods were devised), by reviewing various international tests for flame spread and fire resistance looking at the benefits and drawbacks of each test from their country of origin culminating in a table reflecting 'reaction to fire' tests. The research reviews ignitability, flame spread, rate of heat release and smoke production. The test basis for these periods does not confirm burnout, but defines fire resistance as, "the ability of an element of building construction to withstand the effects of fire for a specified period of time without loss of its fire separating or loadbearing function or both." Table 4 of the paper relates fire load to duration of fire exposure: 1130 MJ/m^2 - 1 hour, 1130 – 2260 MJ/m^2 - 2 hours and 2260 – 4500 MJ/m^2 - 4 hours. It is acknowledged that fire load is only one consideration in a number of factors that influence the severity of a fire.

1991 sees Law [135] review the classic fire tests undertaken by Inberg [130] on office furniture and papers. Ingberg used ventilation in fire tests, but not quantifiable ventilation, it was adjusted to ensure the severest fire was attained.

Law reviews the differing factors and calculations that contribute to fire behaviour by looking specifically at rate of burning, ventilation, heat transfer, heat balance, radiation, flames from the windows, effect of wind, effect of the type of fire load, fire grading, and design methods, building on the work of Inberg. Although not specifically related to mass timber or burnout, in 1997 D.B. Moore of the BRE [136] conducted full scale tests on a complete steel-framed building, utilising the large scale test facility at BRE Cardington. Specific testing was undertaken to confirm that scaled-down models, subassemblages and simplified tests cannot truly represent the behaviour of a complicated building in normal commercial conditions. There are so many differences in the behaviour of isolated components that when connected together perform differently from their independent testing alone.

2003 Lennon et al [137] conducted eight full-scale fire tests on compartments at BRE Cardington measuring 12 m x 12 m. The tests conducted were based on Annex B of the ENV version of Eurocode 1,2 [138]. Testing investigated the influence of compartment linings, fire load type, fully developed and flashover fires. The objective was to gather high-quality data on the behaviour of post-flashover fires in realistic compartments and use the information to validate the natural fire safety concept. The data was then to be used to consider the predictive methods of the parametric temperature-time response in the Eurocodes.

In 2016 R. H. White [139] looked at fire resistance ratings of wood members and assemblies tested to ASTM Standard E119 [140]. However, this is limited to individual assemblies and does not permit modifications. White identifies three areas to review for wood dependency starting with protective membrane (encapsulation), extent of charring and load capacity of remaining uncharred structure. There is no reference to fire resistive periods for timber and does not discuss burnout. However, different standards, adoptions, and options for determining fire resistance of structural timber for structural engineers to adopt are duly noted.

In 2020 Law et al [141] confirmed that minimum fire resistance periods were defined to allow a structure to resist burnout of the fuel in a compartment, which became legislatively empowered in the 1950's. They also claim that where statutory guidance recommends 30 min as a period of fire resistance, such buildings are not expected to resist burnout. Where guidance recommends more than 30 min fire resistance (for offices or residential buildings), it is intended that such buildings should resist burnout. However, if the structure contained elements of combustible construction, the structure itself could burn and lead to complete burnout (both fuel and structure), hence the recommendation by the Fire Grading Committee ~1946 recommended structures 'should be of incombustible material'.

In 1952 height triggers for building types were introduced, but it was not until 1992 that 'requires sprinklers' was introduced for office buildings over 30m, and within the subsequent revisions of 2019 and 2020. This introduction was a 'trade-off' to allow reduction in the recommended period of fire resistance.

In concluding the paper by Law et al, the structure should resist a total burnout of the available fuel load; or, alternatively, the structure should not resist burnout but should do something to facilitate occupant evacuation or support the fire and rescue service's activities.

Law et al unconvincingly claim that burn-out is implied in the "UK guidance." They appear to argue that when more than 30 minute fire resistance for compartmentation is identified in statutory guidance for England, Scotland, Wales and Northern Ireland, the implication is that the compartment shall hold, and full structural protection shall be provided which is not necessarily the case. Since the first Building Regulations were made law in 1964 and 1965, when the Fire Grading of Buildings – Part I 1946 were replaced by legislation, has burn-out been a legal requirement. In England there is no burn-out requirement in Schedule 1 of the Building Regulations 2010. In the English statutory guidance of Approved Documents, which follow Schedule 1 and the other Building Regulations, there is no implication to be read as an expectation or intention that burn-out shall define compartment fire resistance above a 30 minute threshold.

4.4.3 Self/Auto-Extinguishment

Over the last decade or more, timber fire testing has increased. Tests range from small to large-scale compartment testing. Scientists and the wider fire community have studied various timber species to understand physical properties and chemical make-up of timber. The

research confirms that different timber species have different physical make-up leading to different outcomes when heated. However, it is shown that all species when heated have the same potential to burn, providing additional heat release rates and an increase in compartment temperatures [102 & 109].

Self/auto-extinguishment [11] has been studied and considered but is not confirmed. Self/auto-extinguishment has been defined as moving from flaming to smouldering combustion in some scientific experiments, and smouldering combustion to no combustion in others. Crielaard et al [142] confirms self-extinguishment of CLT as the cessation of all combustion shown in Figure 4-11.

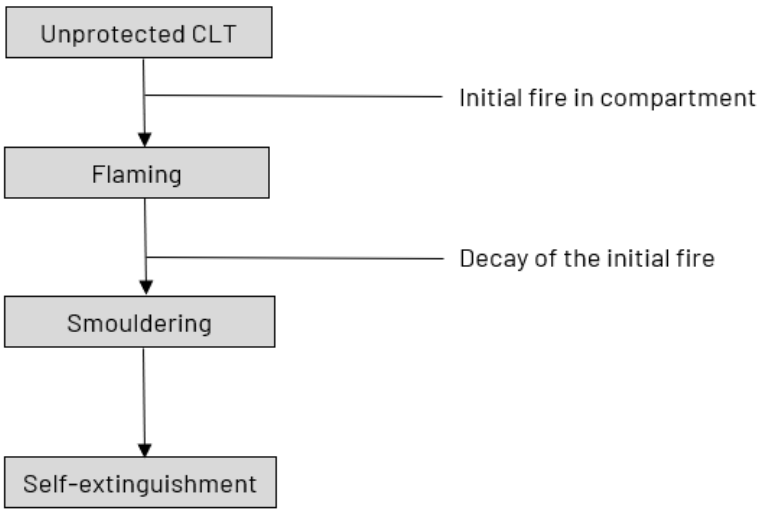


Figure 4-11 : The involvement of the CLT in flaming combustion and the transformation from flaming to smouldering taking place under the influence of an initial compartment fire [142]

Bartlett et al [143] investigates the phenomenon of auto-extinction in engineered timber through approximately 100 controlled experiments. The authors identify a critical mass loss rate of around 3.5 g/m^2/s at ambient oxygen levels, while external heat flux and airflow show minimal influence. Their study demonstrates that the firepoint theory can reliably predict extinction conditions if surface temperatures and heat transfer parameters are accurately known. These findings suggest that, with further validation, self/auto-extinction could be used as a design criterion to safely incorporate exposed timber elements in buildings, supporting architectural aspirations without compromising fire safety that is focused on occupant evacuation, though it offers no relevance to property protection. Emberley et al [144] studied the relationship between external heat flux and self-extinguishment behaviour of timber showing as heat flux increases, the mass loss rate and in-depth thermal gradient also rise until reaching a steady state. Once this steady state is achieved and the external heat flux is removed, the timber consistently self-extinguishes. Importantly, the ratio of in-depth heat flux to external heat flux stabilizes at approximately 0.06 for fluxes above 60 kW/m^2, indicating that higher fluxes do not indefinitely increase internal heating. These findings demonstrate that timber will self-extinguish under certain thermal conditions, provided delamination does not occur. Hadden et al [105] presents five large-scale compartment fire experiments to assess how exposed CLT affects fire dynamics. Results showed that auto-extinction was only achieved in one test with two exposed surfaces, and even then, not consistently. Delamination of charred timber layers was identified as a key factor circumventing auto-extinction, as it exposes fresh wood and sustains combustion. Bartlett et al [121] also investigated

compartment fires and auto-extinguishment confirming that CLT can achieve auto-extinction in compartment fires under certain conditions, notably when delamination does not occur. Results show once the compartment fuel load is consumed, exposed timber surfaces could self-extinguish due to declining mass flux of volatiles. Again, delamination was shown to disrupt auto-extinguishment leading to re-ignition and evade auto-extinguishment.

Emberley et al [145] studied the critical heat flux and mass loss rate for extinction of flaming combustion of timber. Six timber species were subjected to varying heat fluxes (20–100 kW/m^2) and it was found that self-extinction occurs when the external heat flux drops below a species-specific threshold. European Spruce and Radiata Pine (used in CLT) had critical heat fluxes of approximately 43.6 ± 4.7 kW/m^2 and 44.6 ± 0.9 kW/m^2, respectively, while Balsa required a much higher flux of 56.6 ± 2.1 kW/m^2. These results highlight that the critical heat flux for self-extinction is not dependent on timber density, but rather on the species-specific thermal and combustion properties. Debonding was also acknowledged which can lead to increased burning rates and re-ignition, undermining the self-extinction process.

Bateman et al [19] reviewed the effects of fuel load and exposed CLT surface in reduced-scale compartments. Bateman found that sustained burning is primarily influenced by the configuration of exposed surfaces, consistently leading to continued combustion due to delamination and increased heat flux. Crielaard et al [142] investigates the potential for self-extinguishment in cross-laminated timber (CLT) structures during compartment fires. Through two experimental series, one examining heat flux and airflow on small CLT samples, and another using compartment-scale fire tests, results show CLT can self-extinguish if charred lamellae do not fall off, the heat flux during smouldering remains below 5–6 kW/m^2, and airflow is limited to 0.5 m/s. It was also confirmed that increasing the thickness of the outer lamellae, effectively prevented fall-off, enabling smouldering to decay safely.

Complementing the study by Emberley et al [145], Morrisset et al [146] reviewed the thickness of timber in relation to self-extinguishment for redwood samples exposed to a constant heat flux of 35 kW/m^2. Findings confirm that both 45 mm and 95 mm thick samples consistently self-extinguished. Importantly, the heat flux measured at the regressed char surface at the point of extinction ranged from 29.5 to 30.8 kW/m^2, confirming that self-extinction occurs within this heat flux range regardless of sample thickness under the tested conditions. Also reviewing flame extinction of timber, Cuevas et al [147] examined timber combustion under three oxygen concentrations of 21%, 19%, and 17%, using controlled atmospheres created with air and nitrogen mixtures. External incident heat fluxes applied to the timber samples ranged from 30 to 50 kW/m^2 and the results showed that lower oxygen concentrations required higher heat fluxes to maintain flaming, with self-extinction consistently occurring at 30 kW/m^2 for 21% O_2, 37.5 kW/m^2 for 19% O_2, and 45 kW/m^2 for 17% O_2.

Hopkin et al [148] presents the findings from three large-scale fire experiments conducted to evaluate the fire performance of exposed CLT ceilings in office-type enclosures with different adhesives. For auto-extinction of flaming combustion, this occurred in CLT once incident heat flux dropped below ~40 kW/m^2, regardless of char fall-off severity. This shows that while adhesive type influences char detachment, the cessation of combustion is primarily governed by heat flux levels rather than char integrity. Most recently in 2024 Weisner et al [104] investigated self-extinguishment of CLT in an enclosure with varying exposed timber surfaces, using different fuel loads and time durations. Self-extinction was defined as the extinction of the gas phase flame (cessation of flaming combustion) and not smouldering. Burnout is also defined in the paper as the flameout of the moveable fuel load in the compartment. From

experiments, contribution of the exposed timber was shown to have approximately doubled the HRR where three exposed surfaces were present (2 x walls and the ceiling). A critical value of 40 kW/m^2 was noted as the threshold for self-extinction which was cited to Hadden and Hopkin in two separate papers. Ceiling threshold was approximately 70 kW/m^2 which may have been due to the limited availability of oxygen near the ceiling compared to the wall. In concluding the tests, 40 kw/m^2 aligned closely for self-extinction on the exposed CLT walls, but not for the ceiling which was 70 kW/m^2. Heat fluxes were highest with the largest amount of exposed timber surfaces once the movable fuel load had burned out.

Xu et al [149] conducted a literature review on large-scale compartment fires and self-extinction. The review confirms application at the compartment scale remains complex due to interdependent phenomena such as thermal feedback, char fall-off, encapsulation failure, and fuel load characteristics. Tests demonstrated that self-extinction can be achieved or inhibited depending on the timing and severity of these mechanisms, and that external heat flux can serve as a practical surrogate for predicting self-extinction.

While investigating CLT slabs in a standard furnace and compartment test for comparative energy analysis against non-combustible slabs, Bartlett et al [20] demonstrated that CLT slabs absorbed less heat due to lower thermal inertia and continued to burn after compartment fuel burnout, even under ventilation-controlled conditions. The findings highlight the limitations of conventional fire resistance testing for combustible materials and underscore the need to consider fire dynamics and material behaviour in real fire scenarios when designing timber structures.

This study by Arnórsson et al [150] explores the variability of the critical mass loss rate at auto-extinction in timber exposed to fire, a key factor in designing safe mass timber structures. Through controlled experiments on redwood samples under varying heat fluxes, orientations, and forced airflow conditions, the authors found that while the critical mass loss rate ($\dot{m}''_{(crit)}$) is relatively consistent (with a coefficient of variation (CV) of 16%), the time to extinction is highly variable (CV of 40%) due to stochastic factors like crack formation and edge burning. The findings highlight the importance of local flow conditions and sample orientation in predicting auto-extinction, suggesting that while $\dot{m}''_{(crit)}$ is a reliable metric, its application in design must account for variability in time to extinction and total mass loss.

Nothard et al [114] reviewed factors influencing the fire dynamics in open-plan compartments with an exposed timber ceiling. They showed that CLT ceilings delay the transition from travelling fire to growing fire due to their higher thermal inertia, which slows down surface heating. However, once ignition occurs the CLT ceiling contributes substantial additional fuel, accelerating the transition to fully developed fire. This results in higher peak HRR and more intense fire behaviour. Ceiling intrusions, such as beams, further influence this dynamic by trapping hot gases, increasing radiative feedback, and reducing ignition times. Self-extinction (ceases flaming) of the CLT ceiling was consistently observed after the burnout of the movable fuel load in all tests. This occurred when the incident heat flux to the ceiling dropped below the 45 kW/m^2 benchmark identified in bench-scale studies. The extinction was attributed to insufficient heat flux to sustain pyrolysis and flaming combustion.

Self/auto-extinguishment phenomenon can only be considered in the decay phase of a fire when all of the movable contents have been consumed by fire shown in Figure 4-12.

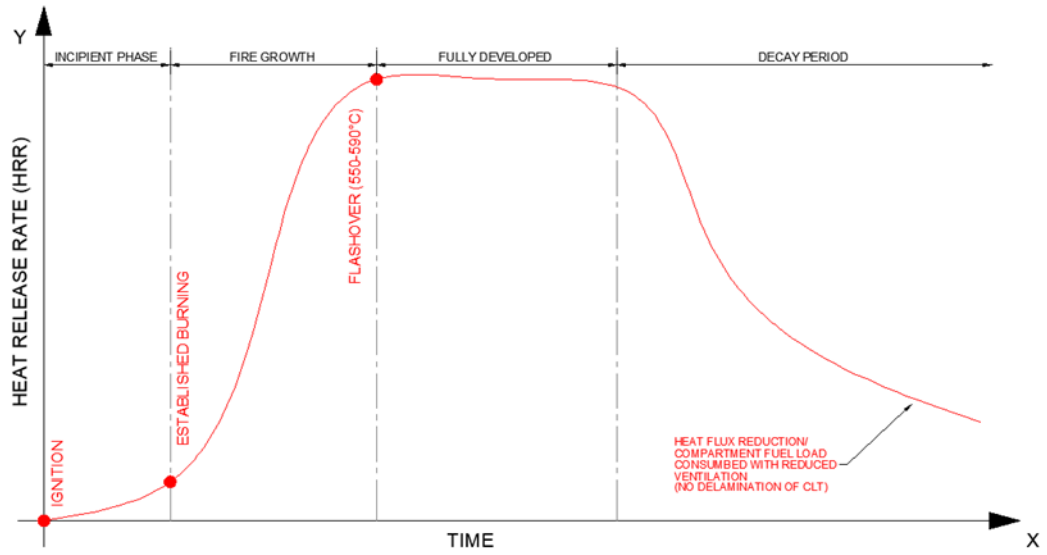


Figure 4-12 : Shows the four phases of a compartment fire.

The reliance on self or auto-extinguishment [11] of timber should not be considered as a viable option for fire protection, especially as this is only considered in the decay phase of fire. Tests conducted show different heat flux levels and air flow velocities that cannot be predicted in real fires. At design stage, the area of exposed combustible surfaces and the predicted fuel load may be known (estimated), for calculation purposes. In reality these parameters will change (upwards or downwards) reflecting different compartment dynamics that will not guarantee self/auto-extinguishment, placing greater reliance on other forms of fire protection.

4.4.4 Passive protection (encapsulation/ retardants)

In this section passive fire protection of timber looks at both encapsulation and fire retardants.

Encapsulation is the process of covering mass timber elements with limited or fully fire resistant materials. For mass timber, encapsulation is widely used to stop timber becoming involved in the fire. This is usually accomplished by encasing timber surfaces, walls and ceilings in plasterboard and cementitious materials which will provide the surfaces with a fire resistance rating. It also provides load-bearing capacity, integrity for flames and insulation by allowing the arrangement to withstand heat and load for longer periods known as the REI classification. In some instances, intumescent coating is also applied that when heated, expand to form a protective barrier to fire.

REI is a European and UK fire safety classification that measures how long a building component can withstand fire in three ways: R (load-bearing capacity), E (integrity against flames and smoke), and I (insulation against heat). For example, REI 60 means a structural element can maintain these properties for 60 minutes. These ratings are essential for passive fire protection, ensuring structural stability, compartmentalization, safe evacuation, and is achieved through tested systems such as intumescent coatings, fire-rated boards, and by certified installations required by UK Building Regulations.

The advantage of encapsulation provides improved safety and property protection which permits greater use of timber in lieu of traditional materials to reduce the overall impact on the environment. However, encapsulation can slow construction, increase cost and the carbon impact will need to be offset against the sequestered carbon benefit of timber. One of the disadvantages of concealing the timber is losing the natural aesthetic of the material which has

shown to be biophilic allowing occupants to connect with nature and making a physical statement about sustainability.

Worse, encapsulation can hide smouldering combustion. Mitchell et al [86] looked at smouldering and/or the cessation of flaming in the context of structural impact to mass timber. Research reflects concerns that smouldering can spread into hidden and exposed voids leading to prolonged periods without detection and potentially spreading to adjacent compartments or other floors, where transition to flaming could initiate multiple fire seats with new fuel sources. Frangi et al [151] investigated timber buildings (tall and medium) for the introduction of "building encapsulation". Experimental full-scale fire tests on modular timber hotel units demonstrated the effectiveness of passive fire protection using multi-layer gypsum boards, by preventing fire spread and structural damage even during full burn-out scenarios. Hoehler et al [111] examined the effects of ventilation, surface exposure, and encapsulation using gypsum boards. Results showed that gypsum boards effectively delayed or prevented CLT ignition. Buchanan et al [152] produced a White Paper on fire resistance of timber structures stating the need to move beyond prescriptive codes toward performance-based approaches that consider real fire scenarios, including complete burnout without firefighter intervention. The paper demonstrates how inclusion of encapsulation, sprinkler systems, and robust structural detailing can mitigate fire risks.

Ronquillo et al [5] reviewed large-scale fire tests concluding while exposed CLT can significantly increase HRR and prolong fire duration, especially when delamination occurs, adequate protection, such as gypsum board encapsulation, can render its contribution to fire negligible, but further research is needed to understand its reliability in larger enclosures including smouldering combustion. Ahmad et al [153] looked at new encapsulation techniques to strengthen and enhance fire resistance of mass timber structural elements. Ahmed et al introduces a novel encapsulation method using a Fabric-Reinforced Cementitious Matrix (FRCM) to enhance both the structural strength and fire resistance of mass timber elements. The study concludes that FRCM encapsulation can meet the fire safety requirements of tall timber buildings, provided moisture control measures are implemented. Again, the aesthetic quality of the timber is lost.

In contrast to successful fire testing with encapsulation detailed above, Hopkin et al [113] conducted full-scale experiments on CLT residential enclosures featuring different lining configurations. Partial protection strategies often hindered self-extinguishment by trapping heat and allowing pyrolysis gases to ignite timber behind the linings. Full encapsulation was more effective in preventing CLT involvement, though it comes with trade-offs in cost and sustainability. Overall, the findings highlight that fire safety in CLT buildings depends not just on the quantity of protection but on its reliability and interaction with enclosure surfaces during all fire phases. Lining failure (e.g., plasterboard detachment) had a greater impact on fire development than char fall-off. Secondary flashovers were observed when linings failed during the decay phase.

The Structural Timber Association document [1] focuses on life safety (not property protection) and outlines the regulatory framework and design strategies for ensuring structural stability of mass timber buildings during fire events, in line with Building Regulation B3(1) in England. The document identifies two key structural fire safety objectives: providing adequate time for evacuation and fire service intervention and ensuring the structure can survive full fire burn-out. It details that guidance based compliance (ADB) is suitable for lower-risk buildings, but performance-based approaches (e.g. BS 7974) are necessary for higher-risk or complex

buildings, especially where timber is exposed and contributes as fuel. It also introduces design solutions such as partial protection, encapsulation, and self-extinction. Appendix A of the document presents a detailed compliance roadmap for mass timber panelised construction (MTPC) in England, specifically addressing Building Regulation B3(1) concerning internal fire spread and structural stability. The appendix emphasizes that MTPC introduces unique fire safety challenges due to its combustible nature and large surface area. The roadmap stresses the importance of a Qualitative Design Review (QDR) to assess fire hazards and structural consequences. It also highlights the limitations of relying solely on fire resistance ratings and underscores the need for encapsulation or demonstration of self-extinction in higher-risk scenarios.

The merits for encapsulation enhance both structural load capacity and fire resistance of compartments against fire. However, delamination of the plaster boarding exposes fresh timber to fire, resulting in potential secondary flashovers and increased fire severity within the compartment.

Fire retardants and timber treatments for dry rot and termite infestations can be applied to timber and within the hidden voids/structure by vacuum pressure/impregnation. It is however appreciated that application of treatments may impact recycling the material at the end of the building's lifespan. Treatment of timber with fire retardants may also be required to be re-applied at specified future timeframes.

Flame-retardant treatments for timber products can be applied in three main ways: incorporation during manufacture, post-manufacture impregnation, and site-applied surface coatings. Incorporation during manufacture embeds flame-retardant chemicals throughout engineered timber products, ensuring durability and resistance to removal by machining or leaching. Post-manufacture treatments involve vacuum-pressure impregnation of solid wood or plywood at specialized facilities, offering deep penetration and long-lasting protection. Site-applied coatings, such as intumescent or chemical paints and varnishes, are the easiest and cheapest to apply on location, with decorative benefits, but they rely heavily on correct application and are more vulnerable to damage, moisture, and inconsistent performance. Each method varies in longevity, cost, and suitability for different timber types and end-use conditions [154].

Fire retardant coatings are applied to combustible and flammable materials, such as wood to retard or inhibit the combustion process. Fire retardant coatings are classified into two groups, non-intumescent and intumescent. Non-intumescent coatings reduce rate of flame spread and smoke development. Intumescent coatings swell up-to 50 times the original thickness of the coating producing a char layer which acts as an insulating barrier.

Flame retardant timber is acknowledged in the Post-War Building Studies No:20 (1946) [131]. The treatment of timber with various solutions with the object of rendering it incombustible was the subject of much study. Such timber was often described as "fire-proofed timber," but there is no evidence to suggest that that term can be interpreted literally, and it is preferable to adopt a term such as "flame retardant" timber. However, treatment of timber may reduce the likelihood of ignition and prevent a fire developing or at least reduce its severity in buildings where the woodwork contributes the main source of fuel.

The 1950 article by S.H. Clarke [155] explores the challenges and developments in fire retardant treatments for textiles and timber, emphasizing their role in reducing fire hazards in buildings. Drawing on catastrophic fire incidents like the Winecoff Hotel and Hartford Circus disasters,

Clarke outlines the chemical and physical behaviour of wood and cotton-based textiles during combustion and evaluates various chemical treatments, particularly phosphate-based compounds for their effectiveness in reducing flaming and glowing combustion. While such treatments can delay ignition and slow early fire spread, they offer minimal benefit in fully developed fires due to limited impact on thermal properties and fire endurance. The article concludes that fire retardant treatments are most useful for lightweight materials in temporary structures but are impractical or unnecessary for large timber unless more cost-effective methods are developed.

Fifty-five years later, Ming et al [156] investigated guanidine dihydrogen phosphate (GDP), diguanidine hydrogen phosphate (DHP), guanidine carbonate (GC), and guanidine nitrate (GN) compounds. They confirm that some of the guanidine compounds are one of the most effective and economical flame retardants for wood and claims that these could improve flame retardance and accelerate the formation of a carbonized layer. Sample decomposition in the second stage plays a key role in the pyrolysis attributed to flame retardance. At lower temperatures < 300 ºC samples had lower flammability, but at higher temperatures >300 ºC samples have poor higher flammability. In 2013, Lowden et al [157] reviewed the flammability behaviour of wood and reviewed the methods for reducing fire risk. Formation of char plays a critical role in slowing decomposition and reducing heat release. The study outlines how fire retardants can alter the process by promoting char formation, reducing volatile emissions, and acting as thermal or physical barriers. It also highlights the importance of understanding wood's combustion mechanisms and the influence of factors like heating rate, oxygen availability, and sample geometry on fire behaviour. The authors conclude that no single method suffices for assessing fire retardancy, and a combination of tests and predictive models is necessary. They emphasize the need for environmentally sound, effective treatments that balance fire performance with wood's structural and aesthetic properties. Three years later in 2016 White [158] discusses the limited amount of timber fire retardants available and how these are designed to reduce the spread of flames over the surface. The thickness and durability of the coating may merely delay the ignition of the timber for a few minutes or may provide an insulative layer that reduces charring. In the same year Dietenberger et al [10] explores flame retardants in depth, showing how they alter degradation pathways to increase char yield and reduce flammable emissions, though often at the cost of mechanical strength and increased hygroscopicity. The research shows FRTs improve fire resistance by promoting char formation and reducing volatile emissions, though they may compromise mechanical strength and increase moisture sensitivity.

A year later and Mariappan [59] argues that fire retardant coatings are the oldest and easiest method to apply to a combustible surface to protect against fire. The effectiveness of the coating depends on the coating thickness and the efficiency of the formulation, but coatings with indefinite lifetimes have not been demonstrated and many may need to be reapplied at various stages. Fire retardant coatings do not cause chemical modification to the substrate, they provide a protective layer to alter the heat flux to the substrate and inhibit its thermal degradation, ignition, or combustion. Mariappan identifies boron-based, phosphorus-based, intumescent, synergistic flame coatings, transparent coatings, nanocomposite, and sol-gel methods for the protection of timber. However, timber structures may need different solutions for different installations or assemblies and finishes.

2020 saw Popescu et al [159] review current fire retardant and intumescent coating materials to treat wood against fire through mechanisms that reduce combustion. Popescu et al, identified the following compounds: halogen-based, inorganic salts-based, boron-based,

phosphorus-based, nitrogen-based, phosphorous-nitrogen–based, silicon containing fire retardant compounds, nanocomposite, and Intumescent fire-retardant systems. In conclusion, different possibilities to improve reaction to fire exist and that pure wood modification is not entirely suitable for significant improvement. Depending on modes of action combined strategies may provide a higher level of fire protection.

Three different studies were reviewed in 2023. Hansen-Bruhn et al [160] investigated the toxicity of fire-retardant treatments on timber using different phosphorus loadings. Fire retardants were applied in two separate ways. Surface treatment and pressure impregnation. Surface treatment is applied through painting, spraying, or dipping into the treatment and a small amount is needed for fire protection. However, with this form of treatment, re-application may be needed over time, which can be difficult and expensive. Pressure impregnation treatment allows the retardant to be driven into the cell structure of the timber. However, the application of this treatment makes surfaces difficult to varnish, and external conditions may lead to leaching. Impregnation inhibits pyrolysis of wood, increases char and water formation. In concluding the testing, Hansen-Bruhn et al, show that both treatments in the tests showed effective fire protection toward developing fires, with less than 50% mass loss during non-flaming oxidative pyrolysis and resisted steady flaming. Hansen-Bruhn et al [161] also investigated flammability and burning behaviour of fire protected timber looking at how to effectively reduce timber's reaction to fire for passive fire protection, by using fire retardant surface coatings and impregnation treatments. Numerous small-scale tests were undertaken resulting in both treatments reducing total HRR. The water-based melamine-free fire-retardant intumescent coating reduced HRR by 21% and the impregnated wood (boric acid free phosphorus based to Euroclass Bs1, d0) reduced by 47%. In conclusion, phosphorus-based treatments (surface and impregnation) were highly effective in reducing timber flammability. Lin et al [162] presented a novel method for enhancing the fire resistance and water-leaching durability of Scots pine wood through in-situ phosphorylation and carbamylation using ammonium dihydrogen phosphate (ADP) and urea. The treatment involves vacuum-pressure impregnation followed by thermal curing at 150 °C, resulting in covalent bonding of phosphate and carbamate groups to wood polymers. Characterization techniques demonstrated successful chemical modification and diffusion into the cell wall. The modified wood exhibited significantly improved fire performance, including a limiting oxygen index (LOI) above 70%, reduced HRR, and enhanced char formation, even after a rigorous 14-day water-leaching test. Mechanical properties were also improved, with a 40% increase in modulus of elasticity and minimal impact on strength, making this approach promising for exterior fire-retardant timber applications.

Most recently in 2024, Rantuch et al [163] report that significant changes are being made in wood modification for environmental concerns including wood preservatives and looking specifically at furfurylation which is a chemical process enhancing wood properties with furfuryl alcohol. Using thermogravimetry and a cone calorimeter, Rantuch et al, studied biochar preparation of biochar-furfurylated wood. A solution was impregnated into samples of timber using a standard vacuum method. Three samples of unmodified spruce wood, furfurylated wood and biochar-furfurylated wood were subjected to a heat flux of 50 kW/m^2. Results show furfurylation decreases effective heat of combustion and carbon monoxide yield. However, the treatment also causes significant increase of virtually all key flammability parameters (mainly HRR and smoke production). It was also concluded that the use of biochar is effective in synthetic polymer flammability reduction and heat of combustion.

From 1950 to present, flame retardants for timber have been successfully evaluated, albeit with some trade-offs in mechanical performance and moisture retention. However, treatments are only a part of the passive solution.

4.4.5 Active protection (sprinklers)

The Post-War Building Studies No:20 Fire Grading of Buildings Part 1 General Principals and Structural Precautions [131] states that the installation of a sprinkler system reduces greatly the chances of an outbreak developing into a large fire, whilst a fire alarm system ensures early warning of an outbreak. These are factors which do not affect the potential hazard once the fire develops, but by minimizing the chance of the fire developing, reduce the overall hazard. For example, if every building were equipped with a sprinkler installation, serious fires might be reduced in number.

In later years, the 1952 Post-War Building Studies No:29 Fire Grading of Buildings Part 2 Fire Fighting Equipment, Part 3 Personal Safety, Part 4 Chimneys and Flues [132] acknowledges both sprinkler and fire alarms stating, buildings may be equipped with both automatic sprinklers and automatic fire alarms. In addition to their function of extinguishing a fire, sprinkler systems are designed also to raise the alarm, usually at one of the entrances to the building, and this alarm is sometimes connected electrically to a point from which help can be summoned. Sprinkler systems which automatically discharge water direct on to the seat of a fire are considered the most efficient means of dealing with the initial stages of fire in ordinary combustible materials. Experience has shown that it is essential to protect all parts of a building not only those parts where a fire is more likely to occur.

Suppression systems are already fitted into many types of construction to support life-safety and for property and business protection [12-18]. However, it is not widely understood that installation rules have been developed around quite diverse types of buildings, and the move to construction in larger volumes with combustible surfaces demands a grass roots review and significant research if this new scenario is to be adequately protected. Suppression systems are being fitted into timber buildings without consideration of whether the installation standards meet the additional requirements of combustible exposed surfaces. Buildings of particular interest include multi-storey structures built of CLT or other structural systems with significant bare wood surfaces.

Current sprinkler standards only consider the movable fuel load (contents) within compartments and not the potential additional fuel arising from the choice of internal linings. Residential and domestic standards [12 & 16] do consider protection of internal walls within a compartment by 'wetting' the surfaces up to 0.7 m from the ceiling in addition to providing water discharge to the floor area/moveable fuel load to accommodate the significant fuel present in curtains and wall hangings. Commercial and industrial sprinkler standards do not specifically require direct wetting of the perimeter surfaces of compartments, although spacing limitations are required for external combustible walls. These standards predominantly consider fuel loads located at floor level or within storage systems. Historically, sprinkler head types installed within the UK were of the 'conventional' style. These types of sprinkler heads provide a multi-directional spray pattern which includes an upwards spray of water to the soffit. These specific head types were designed to cater for combustible warehouse soffits, a revisited feature of present mass timber construction.

Sprinkler system requirements for mass timber constructed buildings with exposed combustible linings including the ceiling/soffit needs careful consideration. Conformity to

current UK standards does not guarantee appropriate levels of protection. The combustible nature of timber will contribute to the total fuel load and increase the heat release rate (HRR) within a compartment fire as previously covered.

The future design of sprinkler systems for massive timber buildings needs to be adapted to accommodate combustible internal surfaces. The system will also need to address the concerns of the insurance industry by providing system resilience for property protection in addition to mandatory life safety requirements.

When considering resilience and risk analysis, it is common to consider both the likelihood of an event occurring and the consequences following the event. Current legislation recognizes simple internal fires. However, worst case events in the commercial environment (Lithium batteries/social unrest, firebombs/dense storage/hazardous materials/explosion etc.) need to be considered for the protection of the building. The start point for 'resilience' is the assumption that 'what can go wrong, will go wrong' which then steers the solution. Tools to prevent failures occurring can be a part of the solution, but even preventative measures have failure rates attached to them. Sprinkler systems can improve the resilience of buildings by protecting them from fires that break out in spite of preventative measures. But the effectiveness of such systems can be compromised if they are not carefully and correctly designed to suit each specific environment in which they are installed. Combustible walls and ceilings pose additional or different risks to non-combustible buildings and need additional consideration.

Sprinkler system effectiveness has been documented over the decades providing an excellent 96% effectiveness, shown in Figure 4-13.

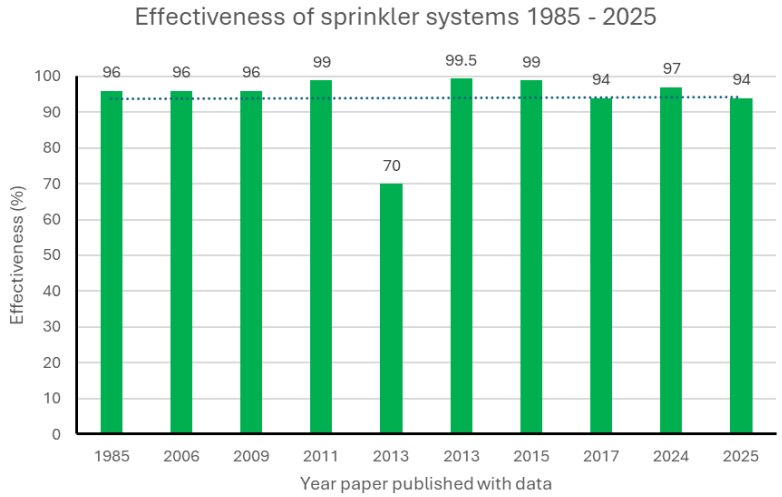


Figure 4-13 : Chart showing sprinkler system effectiveness from studies (1985 - 2025)

In 1985 Richardson [164] reviewed the reliability of automatic sprinkler systems on behalf of the National Research Council Canada. Findings show reliability to be in excess of 96% and with proper design, inspection and maintenance can improve to 99% Reliability is understood to be the percentage of times that they have satisfactorily provided performance in controlled fires, in other words prevention of excessive fire spread. Causes of failure were understood to be due to poor design, poor maintenance, and closed valves. Incomplete sprinkler protection of buildings (unsprinklered compartments) inadequate water supply, poor fire stopping allows fire spread within concealed spaces out of sprinkler range, and human error, such as isolating the water supply before control is another failure point.

2006 saw J. R. Hall Jr [165] analyse sprinkler system reliability for the US National Fire Protection Association (NFPA). The report: An Analysis of Automatic Sprinkler System Reliability Using Current Data, presented a comprehensive evaluation of sprinkler system performance using updated data from NFIRS Version 5.0 (1999–2002) concluding, when sprinklers did operate, they were effective in 96% of cases, with effectiveness decreasing slightly as more sprinkler heads activated, suggesting that smaller, localized activations are more successful in fire suppression. The findings support the reliability of sprinkler systems when professionally installed and maintained and emphasize the critical role of human factors in system failure. In 2009 J. R. Hall Jr [166] updated the NFPA report confirming sprinklers operated in 95% of structure fires large enough to activate them and were effective 96% of the time. In homes, where most fire deaths occur, the presence of sprinklers reduced the death rate by 80% and property damage by up to 70%.

On behalf of the UK Department for Communities and Local Government, Entec UK Limited [167] reviewed effectiveness of sprinklers in housing, commercial, public, and other buildings. The report finds that sprinkler systems are highly effective in controlling or extinguishing fires. Successfully doing so in 99% of cases where they activate, and significantly reduce fire-related deaths, injuries, and property damage. Despite this, their adoption is limited due to persistent misconceptions about cost, aesthetics, and reliability, as well as inconsistent insurance incentives and a lack of training among architects and building designers. Sprinklers are highly effective and can be cost-beneficial, especially in high-risk buildings. Most fires were controlled by 4 or fewer sprinkler heads. Accidental activations are extremely rare (1 in 500,000 per year).

2011 saw RISCAuthority publish document BDM01 [168] which reviewed sprinkler protection for Light Timber Frame buildings (LFT) in United Kingdom and the United States. The publication shows the disparity between sprinkler protection in residential occupancies, with significant implications for fire safety in LTF construction. While domestic sprinkler systems are on the increase in the UK, the United States mandated their installation, initially in multiple-occupancy dwellings during the 1980s and, following the adoption of revised building codes by 48 states, in all new single-occupancy homes from January 2011. Despite these regulatory advances, historical data indicate that prior to 2008 fewer than 3% of new single-occupancy homes incorporated sprinklers, and in 1998 such systems were present in only 2.5% of recorded residential fires, suggesting an overall penetration of less than 5% of the housing stock at that time. Empirical evidence underscores the efficacy of sprinkler systems in mitigating fire spread, property damage, and fatalities, particularly in LTF buildings, which exhibit heightened vulnerability to rapid fire development and catastrophic loss when unprotected. This contrast highlights the critical role of active fire suppression in safeguarding life and property within combustible construction environments.

In 2013 Frank et al [169] conducted a review of sprinkler system effectiveness looking in greater detail at sprinkler system failures. The study picks up on failures associated with components and poor on-going regular servicing. Data collected from New Zealand show the highest component failure is pump performance and pump starters for all building types. Inadequate water supply and unprotected areas for all building types show the largest failure of sprinklers which can be attributed to poor design. Effectiveness varies across different risks i.e. Light, Ordinary and High Hazard which changes with fuel package configuration and would now include the additional fuel load provided by bare timber surfaces.

The British Automatic Fire Sprinkler Association (BAFSA) produce technical report documents BIFs (BAFSA Information Files). In 2014 and 2015, BAFSA published two separate documents. Fire sprinkler systems in timber framed buildings (BIF 18) Richmond House [170] and BIF 19: Sprinkler reliability [171], respectively. BIF 18 emphasises that sprinklers are a critical fire safety measure in timber framed buildings due to their ability to significantly reduce the risk of fire-related injuries, fatalities, and property damage. Given the rapid spread and intensity of fires in timber construction, especially during the build phase, sprinklers offer essential protection by controlling or extinguishing fires early, minimizing threats to occupants and firefighters, and reducing environmental and economic impacts. Their use is increasingly advocated by fire safety authorities and supported by international evidence, with calls for their installation to be mandated in large or high-rise timber framed developments. BIF 19 refers to sprinkler system effectiveness confirming that automatic fire sprinkler systems are highly effective, with over 92% operational performance and 93% effectiveness in real-world fire incidents. Historical and contemporary data consistently show reliability rates between 85% and 99.8%, reinforcing the importance of proper design, installation, and upkeep. Case studies further demonstrate that sprinklers significantly reduce fire damage, save lives, and support business continuity, often controlling fires with just one or a few activated heads.

An optimal economics review of efficiency and effectiveness of sprinkler systems in the United Kingdom [172] was conducted on behalf of National Fire Chiefs Council (NFCC) and National Fire Sprinkler Network (NFSN) in 2017. The review confirms that between 2011 and 2016, data from 2,294 UK fire incidents involving sprinkler systems revealed that sprinklers operated in 945 cases and successfully controlled or extinguished fires in 99% of those, demonstrating high performance effectiveness. Operational reliability was also strong at 94%. Additionally, 95% of incidents required five or fewer sprinkler heads, with 65% needing only one, underscoring the systems' efficiency and targeted response. The report supports wider adoption of sprinklers in UK buildings.

Specifically timber related, Brandon et al [173] conducted statistical analysis of fires in timber structures. Older or unsprinklered low-rise timber buildings showed higher fire spread risk. Analysis of 33 high damage fires revealed that attics, façades, and wall cavities are the most critical paths for fire spread. Sprinklers were shown to be highly effective in limiting fire development and property loss, with no evidence that sprinkler water damage exceeds that caused by manual firefighting.

In 2023 RISCAuthority published their document, BDM01 A to Z of Essential Principles for the Protection of Buildings (Rev. 3)[36]. BDM01 emphasizes that sprinkler systems are a critical component of a building's Resilience Strategy, particularly for reducing fire severity within compartments. When installed to the LPC Sprinkler Rules, they are highly effective, controlling fires in 99% of the 94% of cases where they operate as intended. While sprinklers suppress fire growth and delay flashover, they do not guarantee extinguishment, which still requires intervention by the Fire and Rescue Service. Their value lies in limiting damage, supporting safe evacuation, and reducing business interruption costs. The document encourages early consultation with insurers and fire services to confirm the benefits of sprinklers, especially in high-risk or complex buildings, and integrates them into broader strategies for compartmentation, structural stability, and fire safety management.

Up-to-date statistics (2024) were recently released from the NFPA [174]. In simplistic language, the document presents data from 2017 – 2021 confirming an average of 52,948 structural fires per year (11% sprinklered). Deaths reduced when sprinklers were present. Fire

fighter injuries per fire were 35% lower. Where sprinklers were present, fires were confined to the object or room on 94% of fires reported and sprinklers operated on 92% of fires and were effective in 97% controlling the fire.

BAFSA produce a biannual report "sprinkler saves," the latest newsletter Spring 2025 [175] features case studies of successful sprinkler activations in residential, public, and industrial buildings. Statistical evidence shows sprinklers are 99% effective in controlling fires and 94% reliable in operation. It also includes data from London Fire Brigade and other fire services, reinforcing the call for wider adoption of sprinklers in the built environment to enhance fire safety and protect lives.

It cannot be understated that sprinkler systems are highly effective in controlling and even extinguishing fires. However, to meet climate restrictions in the aim for net zero, sprinkler systems can assist and become an enabler. In the European Fire Sprinkler Network (ESFN) Sprinkler Outlook: Issue 4/2024 [176], national updates from the UK, Belgium, Italy, France, Spain, and the Netherlands, show growing momentum for sprinkler adoption in response to new risks and sustainability goals. Fire sprinklers are seen as essential enablers of Net Zero construction, particularly in timber buildings. Environmental scoring systems like BREEAM for rewarding combustible materials while penalising sprinklers, despite their role in mitigating fire risk is critiqued. The article argues that without sprinklers, many timber based designs become uninsurable and therefore unbuildable. A call for a fair carbon-accounting baseline, which compares timber buildings with sprinklers to traditional concrete or steel structures, would show that sprinklers can unlock sustainable design without compromising resilience. Adapting Net Zero scoring frameworks to reflect this balance, positioning sprinklers not as a carbon burden but as a vital component of low-carbon, insurable construction is advocated.

Frank et al [169] references sprinkler system effectiveness which changes across different hazard risks, listing Light, Ordinary, and High Hazard occupancies. There is a vast difference amongst hazard occupancies in terms of sprinkler system requirements which were evaluated in the late 1960s early 1970s confirmed by Baldwin et al [177] in 1971 in the paper: "The number of sprinkler heads opening in fires". The document analyses fire incidents involving sprinkler systems to understand how many sprinkler heads typically activate and what factors influence this number. It finds that the number of heads opening follows a consistent statistical distribution across both U.S. and U.K. data, and that more heads tend to activate in fires with higher financial losses. Factors such as building age, hazard classification, and system type (wet vs. dry) significantly affect sprinkler performance. The study also explores theoretical models to explain these patterns, suggesting that fire growth prior to sprinkler activation can be exponential, and that delays in response can substantially increase the number of heads required to control a fire. For the purpose of this study and in line with current timber construction, the focus will be based around Ordinary Hazard occupancies, such as schools, offices, and other commercial-type buildings.

Watermist has not been considered in this study. However, Arup Fire in conjunction with CERIB successfully conducted full-scale timber compartment tests with and without watermist as the active fire suppression system. The CodeRed #03 experiment [178 & 179] demonstrated that a standard low-pressure water mist system, designed to the Ordinary Hazard Group 1 standard, can effectively control fire growth in a large open-plan compartment with an exposed CLT ceiling, even under challenging conditions such as open windows and a high fuel load. Five nozzles activated within 5.5 min of ignition, limiting flame height to 2.76 m, peak heat release rate to between 762–1205 kW and temperatures near the ignition peaked at 185°C. No charring

of the timber ceiling was observed, only minor discoloration. Findings suggest that water mist systems can be a viable fire suppression solution in mass timber buildings, subject to approval by relevant authorities and insurers. In 2025 Arup Fire published their 'Fire safe design of mass timber buildings' guide [180]. The guide emphasizes the importance of automatic fire suppression systems, such as sprinklers designed to EN 12845, NFPA 13, or equivalent standards, which have been shown to reliably control fire growth and prevent ignition of timber surfaces. The guide recommends integrating suppression systems with careful control of exposed timber areas and selection of CLT with proven bond line integrity to ensure predictable fire decay and structural resilience.

Mitchell et al [108] reviewed 63 fire experiments in mass timber compartments, primarily involving CLT, to assess fire dynamics and structural performance. Mitchell highlights sprinklers can be an effective method for mitigating fire spread in mass timber compartments.

Simulated sprinkler tests have also shown the positive benefits of sprinklers in timber construction. Su et al [119] states that simulated sprinkler elements consistently activated before flashover, indicating that sprinklers would likely mitigate fire growth in real world applications. Khoat et al [181] presents a numerical analysis of fire behaviour following sprinkler activation in a compartment fire using Fire Dynamics Simulator (FDS). Sprinkler spray significantly lowered smoke temperature, velocity, and mass flow through doorways, demonstrating its impact on improving tenability conditions, and Hoehler et al [115] demonstrated through simulation that if sprinklers had been installed, they would have activated within 5.8 minutes, early enough to prevent flashover, highlighting the vital role of sprinkler systems in mitigating fire risks in CLT structures.

Recommendation for the inclusion of sprinklers for mass timber construction is evident in plentiful scientific papers [21, 23, 152, 182 & 183]. The National Fire Chiefs Council (NFCC) paper [183] recommends mandatory installation in high-risk buildings such as residential flats, schools, care homes, hospitals, car parks, warehouses, waste facilities, and timber-framed structures.

Sprinkler heads have evolved over many years. The speed of response of sprinklers ranges from slow to fast based on what is known as Response Time Index (RTI) values. Sprinklers are currently listed based on conduction factor (C) in $(m/s)^{1/2}$, and response time (RTI) in $(m.s)^{1/2}$ shown in Figure 4-14.

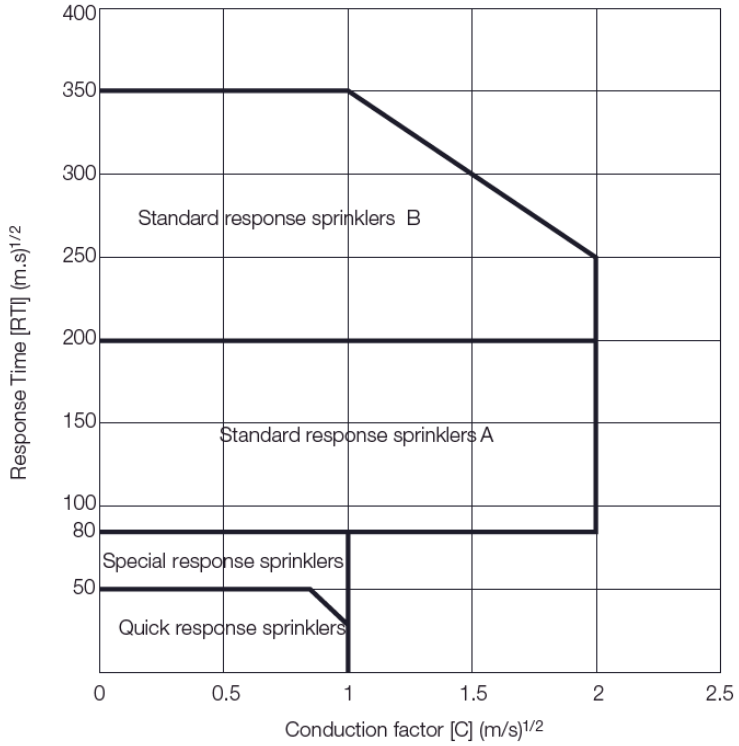


Figure 4-14 : Sprinkler thermal sensitivity ratings, Response Time Index (RTI), and conduction factor (C)- Taken from LPC Rules 2015 by permission.

Östman et al [184] reported that testing with sprinklers in timber compartments showed that with fast response sprinklers (quick), fire safety objectives were achieved. Östman et al, goes further stating 'Automatic fire sprinkler systems are probably the most effective way of improving the fire safety in all buildings' as they will extinguish or control the fire well before the timber structure is at risk of being involved in the fire.

Tsui et al [185] reviewed variability of sprinkler response time index and conduction factor. Findings show that RTI is significantly influenced by sprinkler orientation and bulb size, with 3 mm bulbs (fast (quick) response) showing lower RTI but greater variability than 5 mm bulbs (standard response), and perpendicular orientations yielding faster activation than parallel ones. The conduction factor, which accounts for heat loss through the sprinkler body, was found to be lower than manufacturer estimates. Hopkin et al [186 & 187] 2018 and 2019 evaluated sprinkler actuation times for use in Fire Dynamics Simulator (FDS). The study investigates the predictive accuracy of Fire Dynamics Simulator (FDS) for sprinkler actuation times by benchmarking against 22 controlled fire experiments. Results showed that FDS could predict sprinkler actuation times with a Euclidean relative difference (ERD) of 0.13 to 0.15 and an average overprediction of 6.4% to 9.7%. The 2019 the study by Hopkin and Spearpoint compares the accuracy of sprinkler actuation time predictions using two fire modelling tools, FDS (a CFD-based model) and B-RISK (a zone model). Findings show that while both models tend to overpredict activation times, FDS generally provides more accurate results.

There is plenty of guidance documentation published requiring or requesting sprinkler provision for mass timber construction. Östman et al [21] presented 'Fire safety engineering in timber buildings' at the Seminário Casas de Madeira, which states that a key component of timber fire safety is the integration of active fire protection systems, particularly sprinklers. These systems allow for more flexible design approaches and enable the safe use of exposed

timber surfaces. Brandon et al [107] conducted a literature review of fire safety challenges of tall wood buildings. Among the 45 compartment fire tests reviewed, several included sprinkler systems, particularly the pre-flashover tests by Frangi and Fontana (2005), which demonstrated that sprinklers activated within 2–3 min and effectively prevented flashover, regardless of ventilation conditions or combustible linings. The findings underscore the importance of robust encapsulation and active fire protection systems in mitigating fire risks in tall timber buildings. In 2022 Buchanan et al [188] published a global design guide 'Fire safe use of wood in buildings' in which chapter 10 relates to sprinkler systems. It shows different countries have differing requirements which require sprinklers in taller timber buildings to offset the combustibility of wood used in structural, lining, and façade applications. Sprinklers also support performance based design by allowing trade-offs in passive fire protection measures, such as reduced fire resistance ratings or larger compartment sizes. Ultimately, sprinklers are presented not just as a technical solution but as a strategic enabler for the broader adoption of timber in modern, safe, and sustainable buildings. Prior to the publication of the global design guide, Buchanan et al [189] published a white paper on fire resistance of timber structures for US National Institute of Standards and Technology (NIST). The paper highlights the importance of automatic sprinkler systems as a highly effective active fire protection measure. However, the reliability of sprinklers must be considered alongside passive measures.

A publication from Waugh Thistleton Architects of '100 Projects UK CLT' in 2018 [190] showcases adoption of timber for construction. The document explains that while automatic fire sprinkler systems are widely recognized as the most effective fire protection measure, with no recorded multiple fatalities in buildings equipped with properly maintained systems, they are not infallible and should be considered supplementary to other fire safety strategies. Sprinklers primarily slow fire growth rather than extinguish it, so designs must account for potential system failures.

Fire tests with active sprinkler systems have been successfully conducted over the last two decades. In 2005 Frangi et al [191] conducted two series of full-scale testing known as series BE and BÜ. BE focused on technical measures like sprinkler systems, whilst BÜ focused on structural fire safety without sprinklers. Tests were conducted on modular hotel rooms built with different wall and ceiling linings (combustible vs. non-combustible). Series BE, sprinklers activated within 2–3 minutes, effectively controlling the fire and minimising damage. Series BÜ, flashover occurred within 4–7 minutes depending on linings, which led to more intense external burning and faster window failure. It is confirmed that fast-response sprinkler systems were highly effective in controlling fires during the initial stages, preventing considerable damage even in rooms with combustible linings. Three years later Frangi et al [151] conducted further experiments which demonstrated that activated sprinkler systems are highly effective, detecting fires within 2 min and suppressing them before flashover. In contrast, tests without sprinklers showed rapid fire growth and flashover within 4–7 min, with combustible linings significantly increasing fire severity and external flame spread. In 2018 Zelinka et al [106] conducted five tests with and without sprinklers in a two-storey mass timber building. Results from tests 4 and 5 confirm automatic fire sprinklers effectively suppressed fire development, even when CLT surfaces were fully exposed. Test 5 simulated a delayed sprinkler response and still managed to control the fire before flashover occurred in the main living areas. The review by Ronquillo et al [89] explores the fire performance of CLT through a comprehensive analysis of large-scale fire tests. Sprinkler systems were found to be highly effective in controlling CLT compartment fires. In tests where sprinklers were installed, they

activated early and significantly reduced HRR and room temperatures. The presence of sprinklers allowed for safe burnout of fuel loads without firefighter intervention and helped maintain the integrity of CLT structures.

In 2024, Bøe et al [97] conducted two large scale experiments on a fully sprinklered timber student bedsit with an adjacent corridor. Experiment 1 had active sprinklers in both compartments. Experiment 2 had sprinklers active in the corridor. For both experiments the fire commenced in the bedsit. Results for experiment 1 confirm that the sprinkler system successfully activated within 2 min and controlled the fire until manual extinguishment. For experiment 2 the bedsit (no sprinklers) reached flashover conditions in 5 min with temperatures recorded at 1000^0C. There was rapid fire spread up the walls onto the ceiling. Fire travelled into the corridor (the door between bedsit and corridor was open) and activated the corridor sprinklers within 3 to 4 min but failed to have any impact on the fire and temperature reduction. The sprinklers were left to run for a period of 12 min; at this point, the flowing pressure was increased from 0.35 bar to 2.0 bar to deliver more water for fire control. This had no effect or fire control, and manual intervention was needed.

The failure (overrunning) of the corridor sprinkler system was considered to derive from large flames from the bedsit entering the corridor and an inability of the system to prevent the involvement of the corridor CLT. In the corridor post-fire, large parts of the CLT walls remained standing due to cooling from the colder air and water from the closest sprinkler (surface wetting). However, with no water application to the upper walls and ceiling provided by the spray type sprinklers (100% water downward), damage was significantly greater as the system failed to stop the production of combustible gases that fed the existing flames and contributed to the uncontrolled fire spread along the corridor. Results suggest that an appropriate sprinkler head that can wet surfaces will suppress the fire preventing CLT becoming involved, and slow or halt flame spread.

The inclusion of sprinklers for mass timber is commended by the insurance industry. Ronken [192] discusses the challenge facing insurers with respect to mass timber construction. The article considers the types of timber construction, the challenges posed by flammable materials, and the increased insurance premiums associated with wooden buildings due to higher repair costs. Notably, it emphasizes the importance of preventive measures, such as sprinkler systems to mitigate risks and reduce damage. These concerns are also echoed in other articles from insurers [33 & 193].

4.4.5.1 Fixing sprinklers and M&E services to timber

Little guidance for fixing fire sprinkler and M&E services directly to the underside of timber ceilings is provided within standards. European sprinkler standards only cover fixing into concrete [13], industry guidance provides best practice for concrete, but does not cover timber [27], and British standards only consider concrete [26]. Sprinkler and M&E services are suspended using mechanical assemblies fixed to the underside of the structure. For concrete this is achieved using anchors (also known as expansion fixings) that connect to vertically threaded "drop rods." Clamps are used for steel beams that also connect to drop rods where the services will be fixed using approved components, such as mild steel loop bands for pipework.

Most fixings used to secure M&E services to timber ceilings are of the metal screw type. The ability of the screw fixing to hold load is determined at the contact surface between the threads and wood into which it is embedded. Metals are good conductors of heat and in fire screw fixings can transmit heat within, heating the timber and eventually turning timber to char

and weakening the contact surfaces that assure its retaining capability. When a screw fixing is used to secure other metal framings in place, such as channel, brackets, or hanger rod this can increase the rate of heat uptake by the screw fixing, by substantially increasing the area for heat collection and conduction. For mounting services below a timber ceiling, larger diameter screw fixings are currently used to support larger loads as opposed to using more numerous or longer fixings.

Moraes et al [194] reviewed the influence of temperature on embedding strength of 8 mm dowels using Pinus sylvestris L (evergreen coniferous) timber. Results show that moisture content decreases linearly with temperature, and at 140^{0}C samples tested, all moisture had been driven off. Above this temperature, mass is lost irreversibly. At temperatures in the range between 60 – 90^{0}C, moist lignin softens within the structure, leading to reduction in embedding strength, and at temperatures ranging between 90 – 140^{0}C strength decreases due to wood drying and elimination of bond water. When reviewing the results it is concluded that the lignin is responsible for resistance variation as a function of temperature and shear is affected in an equivalent way to compression by the lignin as a function of temperature and moisture content.

Peng et al [195] used a three-dimensional thermal model to analyse heat transfer within timber connections exposed to a standard fire and reviewed the output against experimental results. The weakest link in any timber structure is the connection during fire as it conducts heat deep into the wood through the metal fastener causing wood charring. It is also understood that fire performance of these connections is complicated due to differing geometries, fasteners, and connection types. It was observed that temperatures inside the steel fixings were much higher than the temperature of the wood at the same depths and even higher where steel nuts and heads were used as these contributed to a larger fire area exposure. The major failure occurs in the side members and fasteners under fire. It was also found that the thickness of the wood side members played a key role on load-carrying capacity of connections under fire rather than fastener diameter.

Uibel et al [196] found that embedment strength is dependent in the diameter of the fixing, the density of the material (substrate) and the angle between the load and grain direction of the layer(s) of the CLT.

In 2015 BRE ran a series of experiments to assess the effect of fire on a selection of electrical cable supports and fixings [197]. Following fires at Harrow Court (02.02.2005), Atherstone-on-Stour (02.11.2007) and Shirley Towers (06.04.2010) where firefighters lost their lives from entanglement with falling cables and fixings. BRE investigated different cable supports and fixings under fire conditions, focusing on their ability to hold cables in place during compartment fires. A fire test rig with an ISO 9705 fire test room and a corridor was used. Cables were supported by five types of supports (1 plastic, 4 metal) and fixed to timber and concrete lintels. 6 mm screws were used for testing. Two experiments were conducted with different compartment temperatures. Experiment 1: Peak temperature ~397°C. Experiment 2: Peak temperature ~820°C. Concluding their report, metal supports remained intact, while plastic clips failed at temperatures between 212°C and 486°C. Some failures were due to fixings melting. This would not be the same outcome for metal clips used in timber soffits. In the same year, Boadi et al [198] investigated the fire resistance of hybrid steel-column and glulam-beam connections, specifically Concealed (CN), Exposed (EX), and Seated (SE) types, under real fire conditions using full-scale furnace tests. Results show that failure typically involved multiple modes, with CN and EX connections dominated by joint splitting and bolt embedment, while SE

connections exhibited tensile cracking and torsional buckling. CN connections showed higher charring rates due to internal steel plates. The study concludes that using cumulative radiant heat energy to predict fire severity is inadequate for timber connections due to complex influencing factors and highlights the need for more refined design provisions in building codes.

Ringhofer et al [199] identifies that there are gaps in CLT which could affect fasteners embedded within. To reduce this impact, they recommended that fasteners penetrate three layers of CLT. In addition, they also stated that fasteners should be located at a set distance from the edge of panels based on location and diameter of fastener type.

Kinder et al [200] looked at mass timber connections and emphasizes that selecting optimal mass timber connections involves balancing structural performance with considerations like moisture, shrinkage, and fire rating. Moisture fluctuations can cause wood to swell or shrink, potentially leading to structural issues such as screw tension, bolt-induced cracking, or aesthetic damage; thus, careful detailing such as screw placement, countersinking, and moisture barriers is essential.

Khai et al [201] tested the withdrawal capacity and strength of self-tapping screws in CLT. 20 tests were undertaken in CLT with screws ranging from 5 – 11 mm in diameter and penetration depths (embedment) ranging from 33 – 130 mm. Results from testing show load capacities were decreased when screw diameter was increased. Results show that greater screw diameter, increases screw-timber contact area but reduces screw-timber contact capacity and a slight increase of 10 mm penetration depth could significantly improve load capacity. The larger screw diameter could reduce load strength by damaging the contact surface. Longer screw penetrations increase the screw-timber contact area and remained or increased the screw-timber contact capacity, finally concluding that increasing screw length over diameter enhances withdrawal capacity and should be the first choice.

Abdoli et al [202] looked at a range of fixing types including steel and concrete nails and their pull-out capacity in different CLT wood species of different densities. Results show steel nails had the lowest load capacity of 13.13 N and lag screws had the highest resistance at 145.77 N. It was also confirmed that nails simply spread fibres and screws cut fibres embedding them into the substrate which provided the better pull-out resistance. Diameter also had a profound influence on performance. Greater diameter fasteners produced the highest damage to the substrate but provided the greater resistance to withdrawal of the fastener.

Hoelz et al [203] investigated wood screw connections for load capacity based on test set up BS EN 1382 [204] using different geometries in two different planes in spruce timber. Hoelz et al, reviewed flank distance (distance between threads) 3.04 and 6.08 mm, root depth (thread thickness), thread height (thread diameter less shank diameter) 1.0 and 1.48 mm, thread angle (angle of thread inserted into the wood) 30 and 55^0, and lead angle (angle of bottom of thread from horizontal) 6.8 and 13.6^0. The diameter of the threaded bar was 10 mm and was inserted in the test specimens to ~ 50 mm. Pull-out results (withdrawal capacity) varied between RT (Radial-Tangential insertion) and TL (Tangential-Longitudinal) but ranged between 4.107 – 10.140 kN for RT and 2.929 – 7.905 kN for TL insertions. However, these tests were conducted in ambient conditions and do not consider variables such as inner diameter, embedment depth or in elevated temperatures, but do show the influence of screw design optimization for maximum load capacity.

Horne et al [205] conducted two tests on timber connections using standard steel plates connecting timber beams to timber columns. The difference in the tests was the duration of the cooling phase, short and long. The exposed steel plates absorbed heat from the fire and conducted it into the timber. The thermal energy was quick to be absorbed by the connection, but slower to be transmitted from it. It was acknowledged that the findings from the experiments have implications for firefighter intervention in timber structures. Timber has low thermal conductivity; therefore, the quicker water can be applied to the structure, the quicker it can reduce the thermal wave.

In 2024 the Building Engineering Services Association (BESA) published their document TB58 Alternative systems for building services supports – Version 1 [27]. The document provides alternative suspension systems from traditional rod and channel fixing systems and proposes lightweight wire suspension systems. However, this could not be considered for heavier M&E services and sprinkler pipework. The document confirms that using alternative support systems should be independently fire tested by the manufacturer in accordance with BS EN 1363 [206] and states that load bearing capacity can be lower under fire conditions more than traditional systems. In the same year BESA published their guidance, Saito et al [207] confirm that fixings (dowels) transfer heat and elevate the temperature of the adjacent timber, and the strength is the resistance of the timber and not the fixing. The strength of timber decreases to 50 % at 100 ^{0}C and 0 % at 300 ^{0}C as previously noted by Moraes et al [194].

In 2025 Fischer et al [208] found that the presence of steel within wood connections increases the complexity of heat transfer mechanisms and char rates. It also shows that during the cooling phase of fire, thermal wave propagation can continue through joints. At elevated temperatures thermal degradation of timber occurs decreasing the strength and with temperatures above 300 ^{0}C char forms. Steel has high thermal conductivity which transfers the heat into the wood through the connections such as screws and could cause embedment failure leading to failure of the connection itself. Where steel plates were used on the wood, charring rates were lower as the plates provided protection of the wood and acted as a barrier for water vapour leading to lower charring rates. Where screws were used there was slight charring around the screw past the char line. In some instances, the char along the screw propagated from 25 – 38 mm beyond the char line. The increased char depths reduced the depth of the screw embedment within the timber which could influence structural capacity.

Dissanayake et al [209], Verki et al [210] and Wang et al [211] confirmed in their 2025 investigations that careful design considerations for timber connections were crucial. Dissanayake et al and Verki et al, identified key gaps in timber fixing requirements and both referred to the requirement for design standards for fixings and a focus on standardization.

4.5 Conclusions

Timber has returned! In both panelised and post-and-beam construction forms it has the structural capability to replace significant quantities of steel and concrete through its adaptability, cost effectiveness, reduced construction timescales, and its renewable and sustainable profile helping achieve net zero aspirations.

Timber burns and at just 100^{0}C can lose 50% of its structural capacity. It has two main burning characteristics: flaming combustion; and smouldering combustion. Flaming combustion is well understood and visually obvious. Through reduction of applied heat flux, and air flow, flaming can extinguish. Smouldering combustion is less well understood. It can go unnoticed in hidden voids and transition back to flaming combustion in different compartments spreading fire

within a building burrowing through significant thicknesses of timber with dogged determination.

Charring follows combustion, reduces the cross sectional area of the timber, weakening the structure. It has been shown in the literature that char rates vary, partly as a function of the test method. Common assessments in the literature state that Eurocode EC5 char prediction rate is an underestimate.

Mass timber with exposed internal timber surfaces provides increased compartment heat release rates and adds more fuel to the moveable fuel load, leading to longer and more sever fires.

Adhesive failures, known as glue line integrity failure, is common amongst some adhesive types. At ~ 100^0C standard PU adhesives can fail leading to delamination of the CLT ply and accounting for secondary flashover conditions. Alternative adhesives that have been modified to perform at higher temperatures should be considered.

Regulatory requirements in the UK only seek life-safety and do not address property protection required by the insurance industry. Statutory guidance documentation such as Approved Document B (ADB) does not cover mass timber construction. Alternative fire engineering guidance to meet the requirements of the Building Regulations is currently the only option for mass timber construction.

The requirement or not for buildings to be designed for burn-out is somewhat lost to history. At inception of the Regulations, it was a defining criterion that supported non-combustible construction for buildings demanding protection over 30 minutes. Referencing since then has been conveniently lost with conflicting data now appearing in literature. Schedule 1 of the Building Regulations 2010 does not require burn-out of a building contrary to the literature review leaving a question on whether original intentions have been forgotten or quietly discarded in favour of a timber future.

Self/auto-extinguishment is not meaningful to property protection and can only be considered in the decay phase of a fire. The definition can be two different requirements: flaming combustion to smouldering and smouldering to no combustion. Conflicting data has been identified relating to heat flux values and air flow velocities that provide auto extinguishment.

Passive fire protection is a solution through encapsulation of the timber structure and by use of chemically enhancing the timber with retardants. There does not appear to be any published studies on the effect of vacuum-pressure impregnation of fire retardants on the integrity of glue-lines in CLT, either in normal use or in fires. The vacuum-pressure impregnation process requires large pressure vessels and takes hours to days for a treatment. Future modifications such as partition changes, service penetrations etc. can alter the passive protection of a compartment which in turn compromises the fire strategy of the building leading to multiple seat fires if not correctly addressed at the time of modification.

Active fire protection in association with passive fire protection will require adaptation to stay optimised for the mass timber environment. However, the performance statistic of 96% effectiveness must be retained through the logical and scientifically proven modification of system design for mass timber construction. The literature review highlights the reputation of sprinkler systems and through the testing conducted by the many researchers, has shown that the presence of sprinklers dramatically improves fire protection of the building. Small modifications can also provide resilience, property protection, and business continuity in

addition to the already known life-safety benefits. As with passive fire protection, on-going service and maintenance and upkeep of the system will ensure it remains fit for purpose for the lifetime of the building.

There is little guidance on the correct selection of fixings for timber buildings. The little testing that has been conducted shows that heat conduction through the metal fixings penetrates into the timber substrate leading to internal charring and potential failure. The literature review shows that the research conducted to date centres mainly around fixings that hold the timber structure together and does not consider the suspension of services below such as Mechanical & Electrical (M&E) services and sprinkler pipework.

Going forward sprinkler systems need to adapt by providing surface wetting of exposed internal timber surfaces. Full coverage throughout the building should be a requirement and subtle changes in sprinkler head selection and spacing can provide adequate coverage of all areas of the building and individual compartments.

For fixings to the underside of timber, load testing at ambient, during fire and post-fire will allow for evaluation of the data to provide the solutions for the suspension of sprinkler pipework and M&E services.

Together, both research areas can successfully provide a resilient sprinkler system design that enables safer use of mass timber, assisting in net zero aspirations, provides life safety to occupants and fire and rescue personnel, delivers property protection and business continuity, and satisfies all stakeholders.

Chapter 5 : Regulatory Implications and relevance

5.1 Introduction

Building regulations within the United Kingdom share a commitment to fire safety and information transparency, yet their implementation reflects distinct national frameworks. England's Building Regulations 2010 (as amended) [48] and the Building (Higher-Risk Buildings Procedures) Regulations 2023 [212] have emerged as a benchmark, introducing concepts such as the "Golden Thread" of information and mandatory handover protocols. Wales, Scotland, and Northern Ireland maintain similar principles but adapt them to local governance structures, such as Scotland's Building Warrant system and Northern Ireland's reliance on the Fire and Rescue Services Order 2006 [213]. These differences highlight a broader trend of regulatory coming together, driven by post-Grenfell safety requirements and sustainability objectives, with England's model likely shaping future reforms across devolved administrations.

5.1.1 Timeline of notable legislation changes

The Great Fire of London in 1666 was a pivotal event that transformed approaches to fire safety. In the aftermath, Parliament enacted the Rebuilding Act of 1667 [214], mandating the use of non-combustible materials such as brick and stone, widening streets to limit fire spread, and forbidding the mass use of timber, marking the first legislative effort to mitigate fire risk through building design rather than firefighting alone. Simultaneously, the disaster prompted the emergence of organized firefighting in the UK, initially driven by insurance companies that operated private brigades until inefficiencies and public pressure prompted government intervention. This transition culminated in the establishment of the publicly funded Metropolitan Fire Brigade in 1866 under the Metropolitan Board of Works, followed by nationwide municipal control in the late 19th century. The Fire Brigades Act of 1938 [215] standardized services under local authorities, and the disbandment of the last insurance brigade in 1929 (Norwich Union of Worcester) signalled the end of direct insurer involvement, embedding fire protection firmly within public governance (life-safety).

The Fires Prevention (Metropolis) Act 1774 [216], introduced measures aimed at safeguarding human life, including requirements for ladders and improved means of escape. It also regulated wall thickness and construction standards, showing an early recognition of structural integrity as a fire safety measure.

Following fatal fires in theatres and workplaces, the Manual of Safety for Theatres (1934) [217] and the Factories Act 1937 [218] introduced mandatory fire escapes and safety provisions for public venues and industrial settings. These measures extended fire safety beyond residential buildings to commercial and entertainment spaces.

The Fire Services Act 1947 [219] established the modern fire brigade system and clarified its role in fire prevention and emergency response. While primarily focused on operational duties, it laid the groundwork for integrating fire safety enforcement into public services.

The introduction of national Building Regulations in 1965 [220] replaced thousands of local bylaws, creating a unified framework for construction standards, including fire safety provisions. This was a critical step toward consistency in building design and fire protection across England.

The Fire Precautions Act 1971 [221] marked a major legislative advance by requiring fire certificates for hotels, offices, and public buildings. It mandated alarms, signage, and escape routes, shifting fire safety from passive design to active management.

The Regulatory Reform (Fire Safety) Order 2005 [53] consolidated previous legislation and placed responsibility for fire risk assessment on building owners and employers. This risk-based approach emphasized prevention and accountability rather than prescriptive compliance.

In 2017 the Grenfell Tower tragedy exposed general failures in fire safety enforcement and building design, prompting widespread public inquiry and legislative reform. It highlighted the dangers of combustible cladding and inadequate evacuation strategies. Post-Grenfell reforms included the Fire Safety Act 2021 [51], which extended the scope of the 2005 Order to external walls and flat entrance doors, and the Building Safety Act 2022 [222], which introduced a Building Safety Regulator and banned combustible cladding on high-rise buildings. These acts represent the most comprehensive overhaul of fire safety law in modern UK history. However, the Building Safety Act 2022 does not explicitly authorize the use of PAS 9980 [223] Fire Risk Appraisals of External Walls (FRAEWs), yet the Building Safety Regulator (BSR) has adopted them as a practical tool for prioritizing remediation of existing Higher-Risk Buildings (HRBs). Formalized through the Developer Remediation Contract, FRAEWs allow certain timber elements to be deemed "tolerable," contrasting with strict Regulation 7(2) requirements under the Building Regulations 2010 for new "relevant buildings."

5.1.2 Local fire acts

Local Fire Acts were provisions embedded within local building legislation in England, granting regional authorities the power to impose additional fire safety requirements beyond national standards. These measures often included mandatory sprinkler systems, enhanced means of escape, and improved firefighting access for high-risk structures such as high-rise buildings and large warehouses. Their purpose extended beyond life safety to encompass property protection and resilience, reflecting a localized approach to fire risk management.

The repeal of these provisions occurred through the Building (Repeal of Provisions of Local Acts) Regulations 2012 [224], which came into force on 9 January 2013. This legislative change removed fire safety clauses from approximately 23 local acts, including the London Building Acts (Amendment) Act 1939 [225] and similar statutes in metropolitan counties. The decision was driven by a pre-supposition of the adequacy of modern national Building Regulations and the Regulatory Reform (Fire Safety) Order 2005, which provided comprehensive and consistent fire safety standards across England, although this did mark the end of the last means of mandating for property protection in law. The repeal marked a significant shift from localized discretion to centralized regulation, restructuring compliance and reducing regulatory burdens while maintaining fire safety protections.

5.2 Devolved administrations

The four devolved administrations making up the United Kingdom, have different regulatory requirements and are each responsible for certain areas of governance.

The devolved administrations of the UK differ mainly in the extent of their powers, legal systems, and governance structures. Scotland has the widest powers, including control over health, education, justice, transport, and some taxation, and operates under its own legal system. Wales has more limited powers, focusing on areas like health, education, and

transport, and shares a legal jurisdiction with England. Northern Ireland has powers similar to Scotland but is unique for its mandatory power-sharing arrangement between unionist and nationalist parties, and it also has its own legal system. England, unlike the others, does not have a devolved government, its domestic affairs are managed directly by the UK Government in Westminster.

The legislative framework governing building construction in the United Kingdom varies across the devolved administrations. In England and Wales, the applicable standards are set out in the Building Regulations 2010, whereas Scotland operates under the Building (Scotland) Regulations 2004 [226]. Northern Ireland follows the Building Regulations (Northern Ireland) 2012 [227]. Each set of national building regulations is supplemented by non-mandatory statutory guidance, which provides recommendations for common construction scenarios, as outlined in Table 2.

Table 2 - National guidance for separate administrations

Regulations	**Guidance**
Building Act 1984 [47] The Building Regulations 2010 (as amended) - parts apply to England and/or Wales	A suite of Approved Documents including Approved Document B (Fire safety) Volumes 1 and 2, 2019 edition incorporating 2020 and 2022 amendments [28]
Building Act 1984 Building (Scotland) Act 2003 [49] The Building (Scotland) Regulations 2004	Building standards technical handbook January 2025: domestic buildings [228] Building standards technical handbook January 2025: non-domestic buildings [229]
The Building Regulations 2010 (as amended) - parts apply to England and/or Wales	A suite of Approved Documents including Approved Document B fire safety volume 1: dwelling houses Wales Approved Document B fire safety volume 2: buildings other than dwelling houses Wales [230]
Building Regulations (Northern Ireland) Order 1979 [50] The Building Regulations (Northern Ireland) 2012	Technical Booklet E Fire Safety [231]

Fire safety requirements within the United Kingdom are established through legislation; however, the devolved administrations of the four nations each implement distinct regulatory frameworks. These frameworks comprise both statutory regulations and accompanying guidance, as outlined in Table 3.

Table 3 - Fire safety guidance for separate administrations

Regulations	Guidance
The Regulatory Reform (Fire Safety) Order 2005 - applies to both England and Wales	A suite of guidance documents originally published by the Department of Communities and Local Government with occasional references to Approved Document B (volumes 1 & 2) [28]
The Fire (Scotland) Act 2005 [232] and The Fire Safety (Scotland) Regulations 2006 [233]	Guidance on carrying out a fire safety risk assessment for people responsible for non-domestic premises and houses of multiple occupation (HMO) is available [234]
The Regulatory Reform (Fire Safety) Order 2005 - applies to both England and Wales	Fire Safety Act 2021 Guidance on the roles and duties of those responsible for fire safety in buildings [in Wales] [235]
The Fire and Rescue Services (Northern Ireland) Order 2006 The Fire Safety Regulations (Northern Ireland) 2010 [236]	Non available

5.2.1 England

In England, the power to make Building Regulations is exercised by the Secretary of State of the Ministry responsible, through the Building Act 1984 and Building Regulations 2010. They have the power to secure the health and safety, welfare, and convenience of persons in or about buildings. Through various other statutory regulations and standards, the safety of persons from fire within buildings is enshrined in law.

The 2010 Building Regulations use the 1984 Building Act to require buildings to be designed to secure reasonable standards of health and safety for persons in the event of a fire. The only legislative consideration for fire safety in building design is life safety, in that all occupants can escape to a place of ultimate safety should there be a fire. The focus on life safety often results in fire safety design considerations applying minimum fire protection requirements to ensure evacuation before collapse.

Currently, there is no dedicated legislative category that adequately addresses the case for 'Property Protection' within fire safety frameworks. This absence has posed a significant challenge over the years. While the destruction of important buildings such as shopping centres, schools, or hospitals represents a severe loss, lobbying efforts have often been constrained by stating such events as an 'inconvenience' to the public. This portrayal fails to capture the consequences, including large-scale financial losses, operational disruption, personal distress, irreparable damage to businesses, and broader economic impacts on the UK. Without the establishment of a distinct category within legislation, it remains difficult to construct a compelling and equitable argument for property protection as a legal priority.

Section 1 of the Building Act 1984 establishes the purpose of building regulations, reflected in Regulation 8 of the Building Regulations 2010, which limits certain provisions to securing reasonable standards of health and safety for persons in or around buildings. Complementary legislation includes the Fire Safety Act 2021, the Fire Safety (England) Regulations 2022 [52], the Building Safety Act 2022, and the Regulatory Reform (Fire Safety) Order 2005 (FSO) for completed or existing buildings. The Fire Safety Act clarified that the FSO applies to structural

elements, external walls, including cladding and balconies and flat entrance doors in multi-occupied residential buildings. The Fire Safety (England) Regulations 2022, introduced under Article 50 of the FSO, impose duties on responsible persons to manage fire safety risks in residential premises. The Building Safety Act, comprising six parts, enhances safety standards and accountability, establishing the Building Safety Regulator and introducing new roles and registers for building control.

These legislative changes were driven by failures exposed by the Grenfell Tower fire in June 2017, which claimed 72 lives and revealed critical shortcomings in building regulations, enforcement, and material safety. The tragedy highlighted inadequate fire risk assessments, combustible cladding, and weak accountability mechanisms. In response, the government implemented sweeping reforms to prevent recurrence, focusing on stronger regulation, clearer duty-holder responsibilities, and improved oversight throughout a building's lifecycle. The Building Safety Act and Fire Safety Act embody these reforms, aiming to create a culture of safety, transparency, and resident empowerment.

5.2.2 Wales

In Wales, the authority to make building regulations under Section 1(1) of the Building Act 1984 was transferred to the Welsh Ministers through the Welsh Ministers (Transfer of Functions) (No. 2) Order 2009 [237].

5.2.3 Scotland

Under Crossheading 1 of the Building (Scotland) Act 2003, the stated purposes are: (a) securing the health, safety, welfare, and convenience of persons in or around buildings and others affected by buildings or related matters; (b) promoting the conservation of fuel and power; and (c) supporting the achievement of sustainable development. These objectives closely align with those in England and Wales, where the primary purpose is also to ensure health and life safety.

5.2.4 Northern Ireland

The Building Regulations (Northern Ireland) Order 1979 serves as the primary legislation governing building regulations in Northern Ireland and has been amended by the Planning and Building Regulations (Amendment) (NI) Order 1990 [238] and the Building Regulations (Amendment) Act (Northern Ireland) 2009 [239]. Article 3 of the 1979 Order grants the Department of Finance the authority to make building regulations and determine their purpose.

5.3 Where sprinklers are mandated through legislation

Sprinkler system requirements are mandated for certain building types based on risk; these requirements only consider life safety and differ throughout the four devolved administrations.

Sprinkler system specifications are mandated for designated building classifications based on calculated fire risk. These provisions are primarily oriented toward life safety objectives and exhibit regulatory divergence across the four devolved administrations.

5.3.1 England

In England, the requirement to fit automatic fire sprinklers to buildings is not uniform and falls under various legislation including:

- Fire Safety (England) Regulations 2022
- Building (Inner London) Regulations 1985 [240]

- Fire Precautions (Sub-surface Railway Stations) Regulations 1989 [241]
- Regulatory Reform (Fire Safety) Order 2005 – Fire Safety in Non-Domestic Premises and Common Areas of Residential Buildings.
- Building Regulations - Approved Document B: Fire Safety Volume 1: Dwellings
- Building Regulations - Approved Document B: Fire Safety Volume 2: Buildings other than Dwellings
- Crown Fire Standards - Ministry of Defence establishments, Crown premises, and Government buildings [242]
- HM Prison Design Brief PF24 - Fire Standards in Prison Establishments [243]
- Health Technical Memorandum 05-02: Firecode Guidance in support of functional provisions (Fire safety in the design of healthcare premises) [244]
- Building Bulletin 100: design for fire safety in schools [245]

In England and Wales, requirements for fire sprinkler installations are primarily outlined in Approved Document B (ADB). ADB stipulates that sprinklers must be installed in uncompartmented warehouses exceeding 20, 000 m^2, care homes with multi-bed rooms, new residential buildings with a height greater than 11 m above ground level, and uncompartmented retail or self-storage facilities with open-plan areas exceeding 2, 000 m^2.

For educational premises, the government adopts a largely laissez-faire stance on sprinkler protection, relying on fire risk assessments guided by BB100 (the schools' fire safety design guide). BB100 recommends sprinkler installation in medium to high risk buildings.

It is important to note that ADB and BB100 are advisory documents, and compliance with sprinkler provisions can be circumvented under certain conditions. Furthermore, ADB does not address uncommon building situations. Such cases fall under the scope of BS 9991 [30], BS 9999 [31], and BS 7974 [32], which provide life safety standards. The Manual to the Building Regulations 2020 [29] defines 'uncommon building situations' as including:

- *Difficult ground conditions*
- *Buildings with unusual occupancies or high levels of complexity*
- ***Very large or very tall buildings***
- ***Large timber buildings***
- ***Some buildings that incorporate modern methods of construction***

Following the Grenfell Tower fire, UK Government introduced the Building (Amendment) Regulations 2018 [246], banning structural timber in external walls under Regulation 7(2), despite the exclusions list of Regulation 7(3), for "relevant buildings" under Regulation 7(4). This replaced reliance on non-mandatory guidance in Approved Document B and prohibited fire engineering approaches such as BS 8414 [247] and BS 476 [248] tests. Compliance now requires materials to achieve Class A2-s1,d0 under BS EN 13501-1 [249] to meet Requirement B4(1) of the Building Regulations 2010. While Regulation 7(3) allows limited exclusions, it does not permit structural timber, effectively restricting loadbearing CLT external walls to column and beam frames. The unresolved issue of CLT floor slab penetration into external walls remains, and the timber industry continues to seek an exclusion under Regulation 7(3) to re-enter the high-rise residential market.

Regulation 7(2) of the Building Regulations 2010, aimed to address shortcomings in fire safety requirements for external walls of "relevant buildings." While it prohibited certain timber-based structural elements like loadbearing timber frames, SIPs, and CLT in external walls, it allowed

timber structures under Approved Document Part A if separate from the wall. The regulation was not applied retrospectively to existing high-risk buildings, leading to reliance on PAS 9980 for retaining timber in renovations, a practice now facing legal challenges. Despite restrictions, timber solutions remain viable in non-relevant new builds, and the market for CLT floor slabs is undiminished. Which is the subject of this study.

5.3.2 Wales

In Wales, the legislative framework for fire safety, under the Domestic Fire Safety (Wales) Measure 2011 [250] and amendments to the Building Regulations 2010 – Approved Document B: dwelling houses and Approved Document B: buildings other than dwelling houses, mandates comprehensive sprinkler protection in all new and converted residential properties. This requirement extends beyond houses and flats to include new schools, sheltered housing, residential care homes, and hostels, ensuring that these buildings are sprinkler protected throughout. Unlike England, where height thresholds apply, Welsh regulations impose universal coverage regardless of building size or height.

5.3.3 Scotland

In Scotland, the obligation to install automatic fire sprinkler systems is established under the Building (Scotland) Regulations 2004 and the Fire Safety (Scotland) Regulations 2006, supported by guidance in the Building Standards Technical Handbooks. Current requirements stipulate that all social care homes, flats, shared multi-occupied residential buildings, new schools, and new social housing must be fitted with sprinkler systems throughout. In addition, covered shopping centres and warehouses exceeding 14, 000 m^2 are expected to incorporate sprinkler protection. These measures aim to enhance life safety by controlling fire growth, providing additional escape time, and reducing property damage.

5.3.4 Northern Ireland

In Northern Ireland, the requirement to install automatic fire sprinkler systems is governed by the Fire and Rescue Services (Northern Ireland) Order 2006 and the Fire Safety Regulations (Northern Ireland) 2010, alongside supporting guidance in the Building Regulations and Technical Booklet E. Current expectations require that all social care homes, flats, shared multi-occupied residential buildings, new schools, new social housing developments, covered shopping centres, and warehouses exceeding 14, 000 m^2 should be fitted with sprinkler systems throughout.

5.4 Summary of legislative requirements

Fire sprinkler requirements across the UK vary significantly by jurisdiction, reflecting differing legislative priorities for life safety and property protection. In England, guidance is primarily advisory through Approved Document B (ADB) and BB100, mandating sprinklers in specific high-risk scenarios such as large warehouses, care homes, and tall residential buildings, while educational premises rely on risk-based assessments. ADB's limitations in addressing uncommon building situations necessitate reliance on standards like BS 9991, BS 9999, and BS 7974.

Conversely, Wales enforces universal sprinkler coverage in all new and converted residential properties, schools, and care facilities under the Domestic Fire Safety (Wales) Measure 2011, regardless of building height or size. Scotland and Northern Ireland adopt similar prescriptive approaches, requiring sprinklers in social care homes, flats, multi-occupied residences, new

schools, social housing, and large commercial premises, with thresholds for warehouses and shopping centres.

This divergence underscores a fragmented regulatory landscape where England's risk-based, advisory model contrasts with the mandatory, comprehensive frameworks in Wales, Scotland, and Northern Ireland, raising questions about consistency, enforcement, and the balance between life safety and property protection.

The post-Grenfell regulatory landscape prioritizes enhanced accountability and systemic resilience, particularly for higher-risk buildings. Key innovations include Gateway approval stages, rigorous change control mechanisms, and mandatory occurrence reporting, all underpinned by digital information management requirements. The classification of higher-risk buildings necessitates compliance with stringent safety protocols throughout the building lifecycle. These measures aim to mitigate systemic vulnerabilities by embedding transparency and traceability into design, construction, and operational phases, thereby reinforcing the principle that safety is a continuous obligation rather than a static compliance exercise.

Complementary standards such as Regulation 38 [48] and BS 8644-1 [251] further institutionalize the management of fire safety information. Regulation 38 mandates the timely provision of comprehensive fire safety data, including escape routes, detection systems, and maintenance instructions, to the designated responsible person. BS 8644-1 operationalizes the "Golden Thread" concept through a standardized framework for digital recordkeeping, ensuring that critical safety information remains accurate, accessible, and transferable throughout a building's lifecycle. Collectively, these reforms demonstrate a shift toward integrated, data-driven governance in the built environment, promoting a culture of safety, accountability, and collaborative risk management.

Legislative requirements governing the installation of fire sprinkler systems are primarily enforced through two mechanisms:

- Building Control, ensuring compliance with the Building Regulations.
- Fire Risk Assessment, conducted in accordance with the Regulatory Reform (Fire Safety) Order 2005 (FSO) for England and Wales. In Scotland and Northern Ireland, a Fire Risk Assessment is similarly mandated under respective legislation.

The Regulatory Reform (Fire Safety) Order 2005 removed the Fire and Rescue Service's statutory duty to inspect buildings at handover or "Practical Completion," introducing instead the concept of the "responsible person" as the duty holder for occupant fire safety. To support this, Regulation 16B (later renumbered as Regulation 38 under the Building Regulations 2010) required contractors to provide building owners with fire safety information. However, this obligation was often ignored in practice, a failure highlighted by the Grenfell Tower fire. The subsequent "Building a Safer Future" review emphasized that without this information, responsible persons could not effectively discharge their duties under the Fire Safety Order.

The Building Safety Act 2022 created the Building Safety Regulator and introduced the "accountable person" role for Higher-Risk Buildings (HRBs), with enhanced oversight at Gateway 3. Secondary legislation established distinct regulatory frameworks for HRBs and non-HRBs, leading to two versions of Regulation 38: one for HRBs under accountable persons and another for non-HRBs under responsible persons. The Building Regulations etc. (Amendment) (England) Regulations 2023 disapplied the original Regulation 38 for HRBs, replacing it with strengthened provisions under the Building (Higher-Risk Buildings

Procedures)(England) Regulations 2023. These dual requirements are particularly critical for structures involving timber, where temporary suspension of fire safety measures may occur, making it essential for both accountable and responsible persons to understand compliance methods to ensure occupant safety.

Figure 5-1 illustrates the combined legislative standards applicable in England. These requirements clearly demonstrate that the primary purpose of sprinkler systems is to safeguard life. They are designed to facilitate safe evacuation prior to structural failure. From a regulatory perspective, if all occupants evacuate safely during a fire, even if the building is subsequently destroyed, the outcome is considered a success.

Figure 5-1 : requirements showing where fire sprinklers are covered within guidance:

Legislation Diagram - Rev D-Model.pdf

The legislation diagram (Figure 5-1) can be found at the end of the references section.

5.5 Property Protection and Insurance requirements

Where sprinkler systems are implemented by businesses to protect commercial operations, storage of stock, or ensure continuity while safeguarding life, they must be designed in full compliance with recognised property protection standards, such as the LPC Rules for Automatic Sprinkler Installations (2015) [18].

Beyond legislative requirements, property protection considerations typically include:

- Mitigating fire risks to reduce insurance premiums
- Ensuring business continuity and minimising fire-related losses
- Enhancing building resilience during fire events
- Supporting fire and rescue service operations

For property protection purposes, sprinkler systems often incorporate additional measures outlined in BS EN 12845:2015 Annex F [13], which extend life safety provisions and are applicable to most business types. However, property protection requirements are particularly relevant for premises storing high-risk goods or where insurers act as the primary authority.

Typical examples include storage warehouses, manufacturing facilities, office complexes, shopping centres, hotels, educational institutions, car parks, and multi-occupancy buildings. These may not fall under statutory requirements but often require sprinkler protection to satisfy insurance conditions.

Sprinkler standards addressing property protection are widely recognised by UK insurers because they exceed minimum life safety requirements and provide enhanced fire resilience for buildings. From an insurance perspective, life safety alone does not address financial risk.

Emerging construction trends such as mass timber, modern methods of construction, and very large or tall buildings, fall outside the scope of national building regulations and guidance. The substitution of non-combustible materials (e.g., steel and concrete) with timber is a significant concern for insurers. While insurers are willing to support timber construction, this is contingent upon proven fire protection systems and a clear understanding of associated risks to mitigate potential losses.

To address these concerns, The Mass Timber Insurance Playbook [57] provides guidance for stakeholders on integrating timber successfully into construction projects. The document emphasises that compliance with building codes does not guarantee insurability. It advocates hybrid construction as a key advantage and identifies robust passive and active fire protection measures as mandatory.

Ultimately, reconciling differences in sprinkler system requirements and fostering collaboration among stakeholders, including government bodies and insurers, necessitates a dual focus on property protection and life safety. This approach will encourage wider adoption of sprinkler systems, ensuring buildings across all construction types are designed to withstand fire events.

5.6 What changes are needed for timber construction

Contemporary sprinkler standards, addressing both life safety and property protection, have evolved in response to modern construction practices and materials that inherently restrict fire spread and do not significantly contribute to the overall fire load.

The concept of using sprinkler systems to protect buildings with exposed timber surfaces is not new. In Victorian Britain, sprinkler systems and the design of sprinkler heads, were specifically developed to safeguard timber mill floors and ceilings. Early sprinkler heads discharged water both upward toward the ceiling and downward toward the combustible materials below.

In contrast, modern construction techniques and material choices have driven the development of sprinkler systems that deliver water exclusively downward, targeting the primary fuel load at floor level.

Future enhancements to sprinkler system design, including adjustments to sprinkler head type, positioning, spacing, and fixing, offer opportunities to optimize performance for buildings featuring exposed timber finishes on floors, walls, and ceilings. Such improvements will strengthen property protection while maintaining the fundamental objective of life safety which is mandatory in legislation.

Chapter 6 : Fire Sprinklers

6.1 Introduction

Timber is a combustible material that will need to be protected against fire. This can be achieved with fire retardants [10, 59, 154,156 – 163], encapsulation using plasterboard, or with the installation of an active fire suppression system. Of these options only sprinklers attack the fire itself thereby offering the possibility of resolving the fire event itself: retardants may slow the rate of involvement of the timber 'for a period of time' only, and the extent to which this contributes to supporting evacuation, or ending the fire event will be very much dependent on the local situation and other protection measures present. All forms of protection increase initial costs but there will be ongoing costs for periodic reapplication of retardant coatings (which may be difficult in existing buildings), and sprinkler system testing and maintenance. Encapsulation removes the visual aesthetics of the raw material and has the potential to allow and hide smouldering combustion [5, 24, 80, 82, 84, 86, 100, 252, 253].

As fire safety and sustainability goals converge, fire sprinkler systems are increasingly seen as a carbon-conscious investment in resilient, low-impact timber building designs. That said, adaptation of the design of fire sprinkler systems is required to ensure that both contents and any exposed timber surfaces are appropriately protected. The additional fuel load and propensity for timber to smoulder and later re-ignite, means an optimised response from the fire sprinkler system is required to ensure containment and prevent spread to inaccessible seams and voids.

Sprinkler systems have been around for over two centuries, with the first known system being installed at Drury Lane Theatre, London, in 1812 [18]. Sprinklers work through heat activation of the thermal sensing element located in the head itself. In the event of fire, heat accumulating at the ceiling (where the sprinklers are located) activates the sprinkler(s) when the temperature reaches a specified value. Sprinkler head(s) closest to the fire will activate, providing water to the fire below with others operating as required if the fire grows or moves.

Fire protection of buildings with internal timber surfaces using sprinkler systems is not a new concept. In Victorian Britain, sprinkler systems, and head type were designed to protect timber mill floors/ceilings. Sprinkler heads were designed to provide water upward to the ceiling and downward to the floor. These sprinklers are known as 'Conventional' type and manufacturers still produce these sprinklers today, known as 'old-style conventional sprinklers.' However, due to changes in building methods and materials, modern sprinklers have been developed to provide 80-100% of the water discharge downward to cover the fuel load at floor level, based on the assumption that modern buildings have essentially limited or non-combustible walls and ceilings (this is accepted in current sprinkler installation rulesets).

Sprinkler statistics [36, 164, 165, 166, 167, 169, 171, 173, 174, 145, 177, 254] confirm that the effectiveness of sprinklers to control fires and halt fire spread is over 96%, and with proper design, inspection, and maintenance this can improve to 99%. Studies show that from 2017–2021, deaths were reduced by 90% when sprinklers were present, and firefighter injuries per fire were 35% lower. Where sprinklers were present, fires were contained to the room of origin or object in 94% of fires reported, and sprinklers operated in 92% of fires recorded and were 97% effective in controlling the fire. However, there is concern that this track record will be impacted if the same design and installation rulesets are not adapted for buildings with combustible walls and ceilings.

In this experimental study, a range of sprinkler head types were tested to evaluate the wetting potential of exposed timber ceilings and walls in addition to providing water to the room's contents. Water distribution tests were conducted using standard single sprinklers at high and low pressures with different mounting orientations. Water captured below the sprinklers allowed the assessment of actual delivered density (ADD) against requirements. A specifically designed test arrangement was used to evaluate water delivery rates to walls, and ceiling wetting patterns were captured photographically and measured for later analysis.

The aim of this study is to provide data to inform organisations/standards bodies of changes that are required to optimise sprinkler systems for the protection of mass timber buildings with exposed internal combustible timber surfaces. The results presented demonstrate that, through careful consideration of sprinkler head type and positioning, effective surface wetting of ceilings and walls can be achieved without compromising water delivery to the contents/fuel load. It is estimated that minor changes to system design will greatly improve system performance for mass timber construction at minimal cost and preserve the reputation of sprinkler systems as the most reliable protection system for high value commercial assets.

This work is presented with a view to support changes to current UK sprinkler standards to improve wetting of combustible surfaces.

6.2 Occupancy risk classifications

There are a number of suppression standards that can be applied to different building types and occupancies in the UK today. The most commonly used standards are for sprinkler systems, which separately cover Commercial and Industrial [13, 18] and Residential and Domestic [12, 14] premises.

Standards used for sprinkler head testing vary, from commercial to residential. Table 4 provides general details of test standards and their specific requirements.

Table 4 - Summary of sprinkler head test standards

Standard	Container Size (WxDxH) (mm)	Ceiling height above container (mm)	Sprinkler Flow Rate (L min^{-1} bar$^{-1/2}$)	Wall Wetting Distance from ceiling (mm)	Head Pressure (bar)	Test Duration (mins)	Permitted containers less than 50% (qty)	Sprinkler coverage (mm)	Discharge Downwards (%)
BS EN 12259-1 *	H – 500	2700	61.3	N/A	0.59	Satisfactory average time	5	N/A	40-60
BS 9252 **	H – 300	2500	56.6	700	0.5	6	N/A	N/A	80-100
BS EN 12259-14 **	300x300, 500x500	2400	56.6	711	0.5	20/10	N/A	N/A	80-100
UL 199 *	300 x 300 x 300	2300, 3050, 1200	57	N/A	0.5	10	5	3050	40-60
UL 1626 **	300 x 300 x 300	2440, 2080	57	710	0.5	20/10	N/A	N/A	80-100
FM 2000 *	305 x 305	2300	57	N/A	0.5	10	5	3050	40-60
FM 2030 **	300 x 300	2400, 2030	57	711	0.5	20/10	N/A	N/A	80-100
LPS 1039 *	H – 500	2700	60	N/A	0.59	N/A	5	N/A	40-60
* Indicates Commercial Standard				** Indicates Residential Standard					

Table 4 highlights differences between used standards. Sprinklers installed in the UK are typically approved to European and American standards and are subjected to numerous tests shown in the table.

The same distinction is applied to watermist standards [15–17]: however, watermist is not generally considered appropriate for property protection by UK insurers and is therefore not considered in this study[1] . There are also an extremely limited number of approved watermist nozzles available.

The selection of the correct sprinkler system for the risk is based upon the perceived hazard classification of the building. For sprinkler systems designed to the current BS EN 12845 [13], there are numerous occupancy classifications depending on building use. These classifications are split into three groups:

- Light Hazard (low fire loads and low combustibility)
- Ordinary Hazard (medium fire loads and medium combustibility)
- High Hazard (high fire loads and high combustibility)

For light hazard this would include premises such as schools, offices and prisons with no compartment exceeding 126 m^2. Ordinary hazard classifications are grouped into 4 groups (OHI, OH2, OH3 & OH4). These range from hospitals, offices, retail, cinemas, sawmills, bakeries, and breweries. High hazard classifications are split further into production facilities and storage facilities. Production classifications (HHP1, HHP2, HHP3 & HHP4) range from printing works, tar distilling, rubber goods manufacturer, and firework manufacturer. High hazard storage (HHS1, HHS2, HHS3 & HHS4) covers all storage risks. The relevance of the numerical reference relates to the hazard category of the stored product, with HHS1 being the lowest.

Occupancy classifications require different sprinkler design spacings, type of sprinkler heads and amount of water needed to be discharged from the system to cover the assumed fire area.

Sprinkler heads come in varied sizes having a range of 'K' factor constant coefficients that relate the orifice diameter, depth, and shape, to the operational pressure and output flow. Equation 3 shows the relationship between 'K' factor, pressure, and flow rate.

Equation 3

$$K = Q/\sqrt{P}$$

where Q is the flow of water (L min^{-1} $bar^{-1/2}$)

P is pressure (bar), and

K is the 'K' factor coefficient of the sprinkler head, which is directly proportional to Q and inversely proportional to the square root of the pressure.

[1] Watermist is perceived by some to be an alternative to sprinklers but is a relatively new form of suppression. The technology was developed for quite different environments derived from offshore needs, such as protecting engine bays in ships. Watermist is a more three-dimensional system than sprinklers, using heat absorption and oxygen displacement. It has more in common with gaseous fire protection systems in its mode of operation than with sprinkler systems.

Thermal sensitive elements in sprinkler heads differ in terms of type, and sensitivity and are chosen to suit the needs of the risk. They can take the form of a metal fusible link (soldered strut) or a thermal glass bulb containing a liquid that expands with heat to break the glass, as shown in Figure 6-1. In each case, once activated, the valve opens, allowing water to flow onto the sprinkler deflector to create the required spray pattern and coverage.

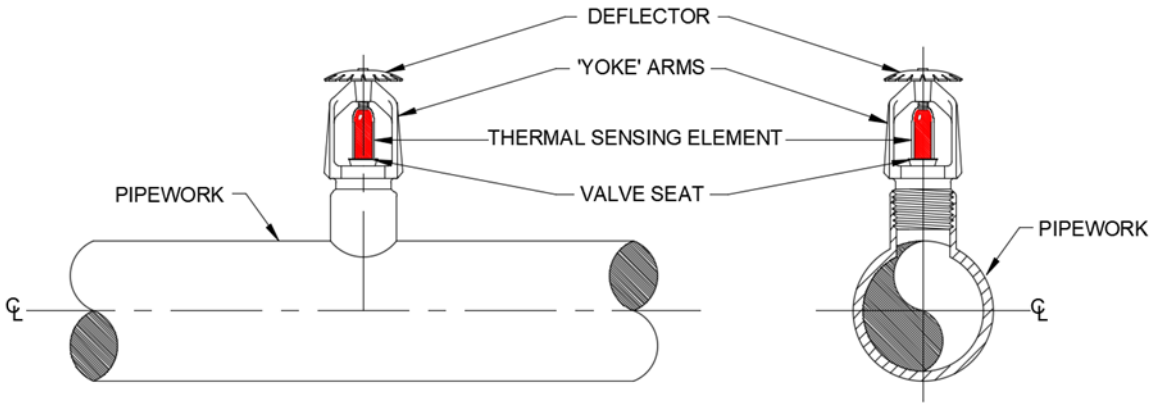


Figure 6-1 : Main components of a sprinkler head with feed pipework (shown in the 'upright' position)

Figure 6-1 shows a typical commercial sprinkler with glass bulb thermal sensing element connected onto a sprinkler range pipe through a welded socket, sized to match the sprinkler head (15 mm, K80 sprinkler).

In commercial sprinkler systems [13], sprinklers are spaced to ensure adequate floor coverage is achieved. Spray onto the walls and ceiling is not a consideration. However, there is a maximum spacing limitation of 1.5 m from external walls containing combustible material. Residential sprinkler standards allow for a greater area per sprinkler (~25 m^2) and at lower design densities (≥2.04 mm min^{-1} m^{-2}). Residential sprinklers are designed to provide an element of wall wetting 0.7 m below the ceiling, to cater for fires involving common household furnishings (curtains, cupboards, sofas, beds, etc.) that are located on the perimeter of rooms, but they are not required to wet the ceiling. Residential sprinkler systems [12] are not specifically considered further in this study.

Knowledge of sprinkler head spray patterns has led this study to focus on Conventional sprinklers due to their ability to provide both an upward and a downward spray pattern, irrespective of whether the sprinkler is installed in a downward (pendant) or upward (upright) position.

The amount of water discharged, based on the risk profile or occupancy hazard classification, is specified according to the standard adopted. Water discharge from sprinkler heads is measured as density of water (depth) in mm min^{-1} m^{-2} (~5–30 mm min^{-1} m^{-2})[2], over an estimated fire area (confirmed by the hazard classification, usually between 72 and 300 m^2). Sprinklers are located where the hottest gas layer would be expected at ceiling level (75–150 mm below the ceiling), to ensure early activation. Commercial/industrial sprinklers are spaced between 2 m (minimum) and 3.7/4 m (maximum) apart to cover an area of 9 to 12 m^2 per sprinkler depending on hazard classification. Each sprinkler is designed to discharge in a circular spray pattern,

[2] Within the sprinkler industry, density measurement is normally expressed as mm/min/m^2, which represents the depth of water in mm over an area of 1 m^2, for 1 min after activation.

covering the fire area at floor level. The droplet size distribution for sprinkler systems is deliberately large (>1 mm), so droplets penetrate the fire plume to provide cooling and pre-wetting of the fuel load without cooling the ceiling gas layer (which would inhibit subsequent sprinkler heads from opening). Using sprinkler water to wet timber linings (walls, floors, and ceilings) will help to prevent flame spread within a compartment.

With the objective of this investigation being to ensure optimised water delivery within timber enclosures, the discreet phases were as follows:

1. To investigate the suitability of commercially available sprinkler head designs.
2. To assess density of discharge (depth of water) from sprinklers at floor level, as detailed in current standards, appropriate to the risk occupancy classification of the building.
3. To assess wall wetting from adjacent sprinklers up to ceiling level in order to reduce surface spread of flame up compartment boundaries (walls).
4. To assess ceiling wetting from sprinklers, which could potentially contribute to slowing or halting surface spread of flame at ceiling level.

Each investigation, and its corresponding results are discussed in sections 6.3 to 6.6, respectively below.

6.3 Investigation into sprinkler system design

This study investigated the potential to adapt commercial sprinkler system design requirements for buildings that are considered non-combustible or of limited combustibility, to be suitable for mass timber CLT buildings with exposed timber surfaces. The shift to using increased quantities of timber and other low-carbon combustible materials, has underlined the importance of active fire protection for mass timber buildings, irrespective of height, but what is a suitable system?

For this study, sprinklers were considered as they have more stringent design standards than other suppression systems, alongside third-party certification, product approvals, guidance, history, interchangeable components, and they are not limited to specific contractors or manufacturers.

Sprinklers act on a fire directly by removing heat, and they also pre-wet surrounding fuel, reducing its ignitability and thereby limit the rate of flame spread. However, sprinkler heads differ in design, and their spray characteristics have changed over the decades. The following types of sprinkler heads were investigated, and their typical spray patterns are shown in Figure 6-10.

- Conventional (Upright and Pendant) sprinkler (CUP): The CUP sprinkler has a spherical water distribution directed towards the ground and the ceiling over a definite protection area. A conventional sprinkler discharges ~40% upward and 60% downward. The upward moving water typically but not consistently, strikes the ceiling and then drips downward, adding to the water below.
- Spray Sprinkler Pendant (SSP) sprinkler: This has a paraboloid water distribution directed towards the ground over a definite protection area. An SSP discharges 80–100% of the total water flow downward. SSP sprinklers give the specified distribution by having the jet of water directed downward against the deflector.
- Spray Sprinkler Upright (SSU) sprinkler: This has a paraboloid water distribution directed towards the ground over a definite protection area. An SSU also discharges 80–100% of the total water downward. SSU sprinklers give the specified distribution by

having the jet of water directed upward against the deflector (as shown in Figure 6-10 D).

Sprinkler heads are configured in various ways to meet architectural requirements and minimize the risk of mechanical damage. Upright sprinklers (SSU) are typically installed in areas with exposed soffits, mounted above the pipe to prevent damage. Pendant sprinklers (SSP) are commonly used in false ceilings where services are hidden, but they can also be fitted under exposed soffits to reduce interference from M&E services by minimizing the number of sprinklers needed around obstructions. Additionally, SSP sprinklers are often placed within storage racks to protect stock below. Conventional sprinklers (CUP) offer the greatest flexibility and can be installed in most settings, including exposed soffits, false ceilings, and ceiling voids.

Contemporary architectural designs often leave building services exposed beneath timber soffits, as illustrated in Figure 6-2. This approach, commonly referred to as the "industrial look," necessitates careful consideration of sprinkler spacing and head selection to ensure full coverage within the compartment. One advantage of suspending services below the ceiling is that it eliminates the need for individual sprinkler pipe penetrations through the soffit, thereby preserving the compartment's integrity.

Figure 6-2 : Exposed CLT ceiling with suspended services (the 'industrial look')

Sprinkler system constraints were reviewed to see what changes were needed to head type selection and spacing arrangements to improve water distribution to assist in protection of exposed combustible surfaces.

The study investigated water spray patterns, sprinkler size ('K' factor coefficients), distribution above and below the sprinkler deflector, and the potential for wall and ceiling wetting, in addition to providing the specified water density at floor level based on the associated hazard and risk of occupancy for common types of commercial buildings (Ordinary Hazard).

In the UK water to sprinkler systems is generally supplied by centrifugal-type pumps as flow and pressure from town's mains are limited. Pumps are specified so they deliver water at not less than 0.35 bar to the most hydraulically remote sprinkler head when the maximum number of heads are operating, as specified in BS EN 12845:2015 for Ordinary Hazard classifications. When fewer heads are operating, supply water pressures will be higher, as defined by the pump's pressure/flow curve. To this end, in addition to 0.35 bar, the sprinklers were evaluated at 3.0 bar, a conservative pressure typical of the first head operating. The number of sprinklers operating within a specified fire area (known as the assumed area of operation) differs based on system classification ranging from 6 to 18 sprinklers (72 – 216 m^2). The minimum head pressure of 0.35 bar is based on the maximum number of sprinklers operating in the fire area, otherwise known as failure pressure.

6.4 Preliminary sprinkler dispersal patterns, 'K' factor, and vertical distribution investigation

6.4.1 Methodology

6.4.1.1 Equipment and materials

All sprinkler head testing was carried out at The Fire Protection Association, Northcot Park, Station Road, Blockley, Gloucestershire. GL56 9LH (Unit 1 Test Building) using the variable height ceiling, sprinkler pump, tank, and pipework suspended below the ceiling shown in Figure 6-3.

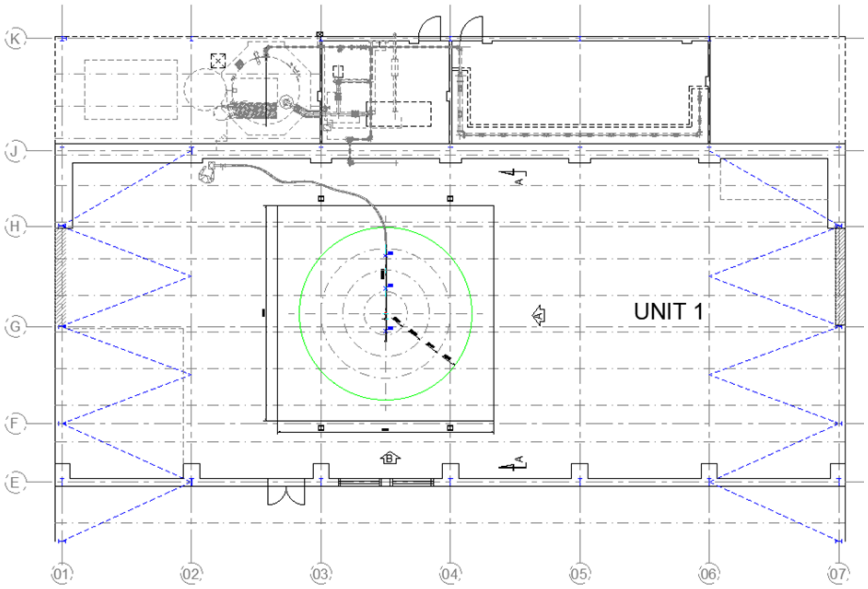


Figure 6-3 : Plan layout of FPA test facility (unit 1)

The ceiling height was set at 2600 mm above the water collection buckets, shown in Figure 6-4.The centreline distance of the pipework below the ceiling varied depending on sprinkler head manufacturer as these were variable as shown in Figure 6-5 and 6-11.

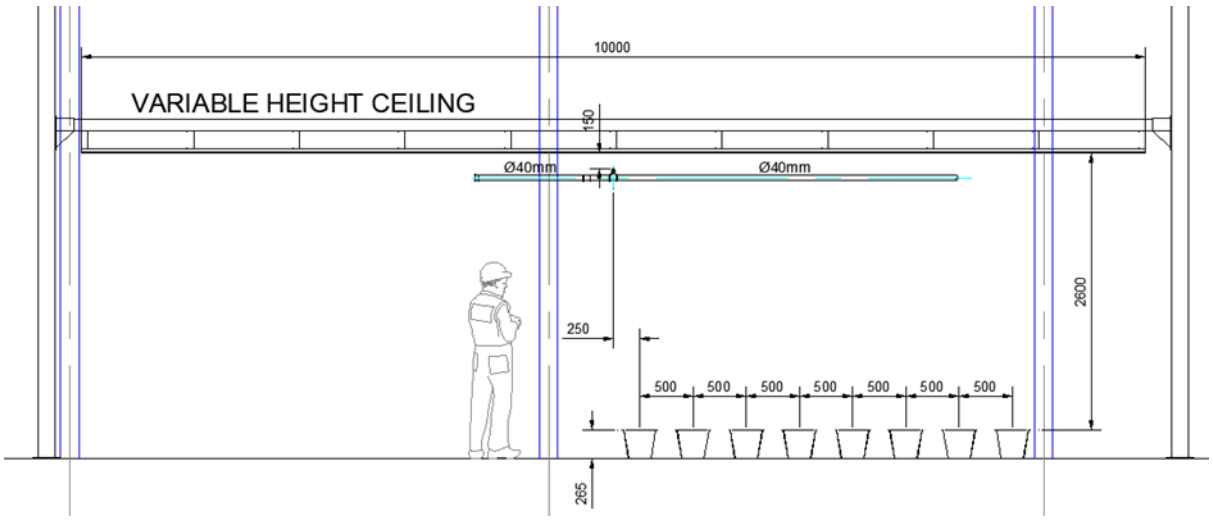


Figure 6-4 : Set height of the ceiling above water collection buckets.

Figure 6-5 : Pipework installed below the variable height ceiling.

The floor of the unit was marked up with a 500 x 500 mm grid on one half of the sprinkler head to a radius of 4 000 mm. Each intersection was sprayed with a yellow identification mark and numbered for location of water collection buckets shown in Figure 6-6.

Figure 6-6 : Left: 500 x 500 mm grid. Right: Grid with water collection reference locations

108 standard buckets were used and located at the grid intersections for water collection to one half of the sprinkler head for each test. Each water collection buckets was individually numbered and laid out on the grid as shown in Figures 6-7 and 6-8.

Figure 6-7 : Numbered water collection buckets

Figure 6-8 : Full layout of water collection for test

The sprinkler pump was fed from a Franklin Hodge LPCB approved sprinkler water storage tank with a volume of 17 000 litres. The pump shown in Figure 6-9 provided a variable discharge ranging from 75 – 225 L min^{-1} $bar^{-1/2}$ at a maximum pressure of 3.5 bar.

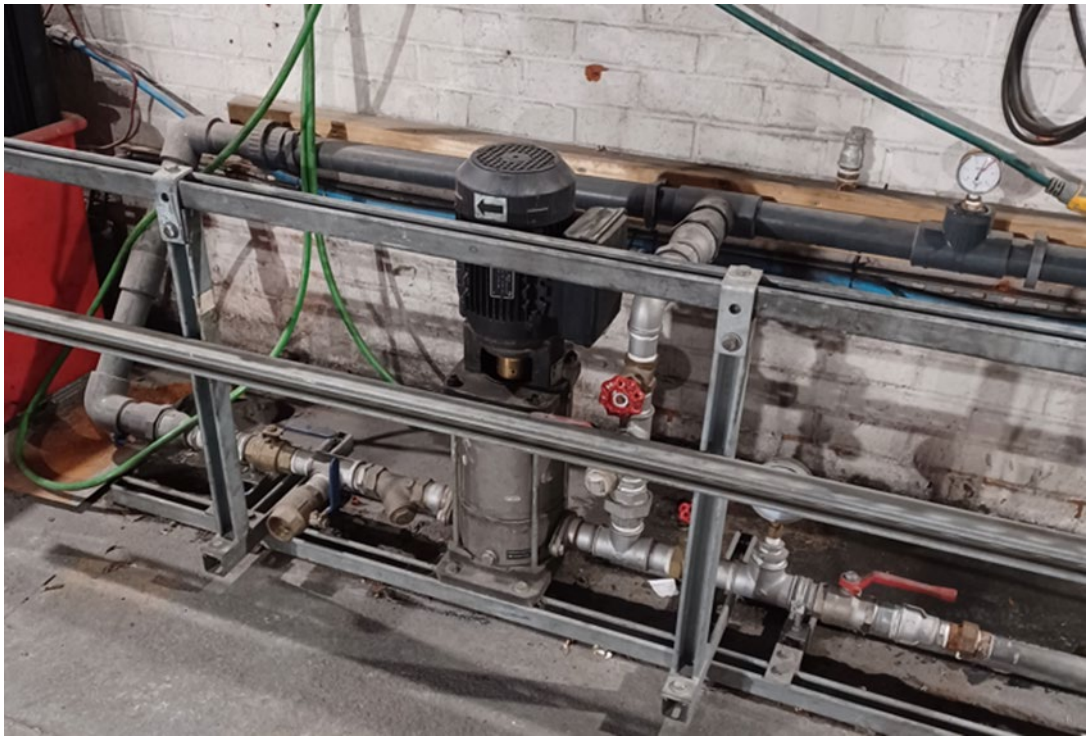


Figure 6-9 : Sprinkler Pump (Ebara Type EVMW 8 6N)

6.4.1.2 Sprinkler dispersal patterns

An evaluation of different sprinkler head types to determine spray characteristics was conducted. Common sprinkler types were SSU (upright (upward)), SSP (pendant (downward)) and CUP (upright/pendant (ratio 40:60)), shown in Figure 6-10. Testing used 15 mm sprinklers with a 'K' factor of 80 at a delivery pressure of 0.35 bar, representing minimum head pressure of the system, and 3.0 bar, representing a single sprinkler head operating in the initial stages of a fire. Sprinklers were visually screen-tested to identify which heads provided a good proportion of upward spray.

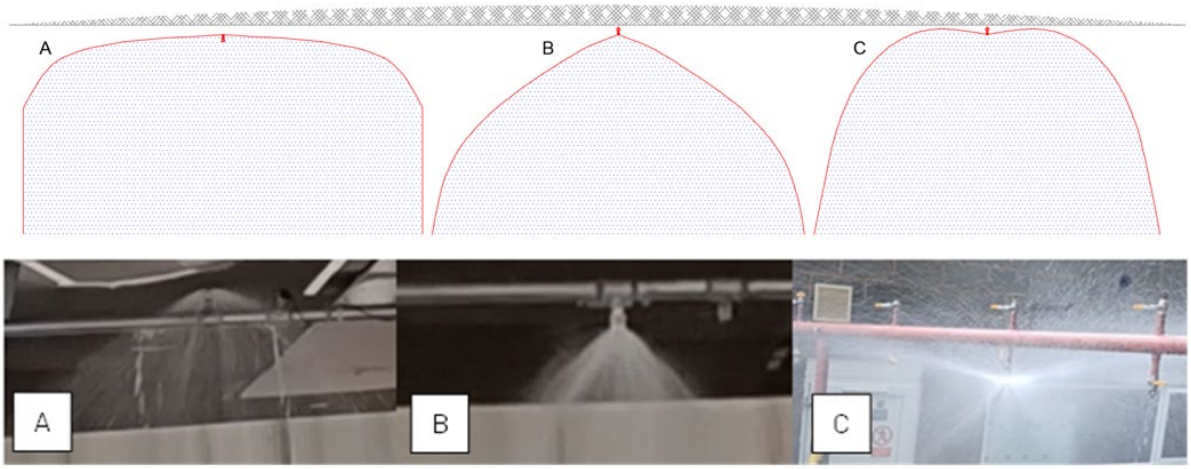


Figure 6-10 : 2-dimensional representation of sprinkler distribution patterns (manufacturers) together with photographic details. A - An SSU sprinkler. B -An SSP sprinkler. C - A CUP sprinkler

Based on visual testing which complemented Figure 6-10, Conventional sprinkler head (CUP) types were selected for these specific tests as they provided an upward and downward spray characteristic, confirmed by manufacturers' data sheets. Sprinklers were obtained from five manufacturers with the same characteristics (CUP 15 mm, K80), referenced in this study as manufacturer A (Rapidrop), B (Reliable), C (Tyco), D (Victaulic) & E (Viking). These sprinklers have been shown to perform for the specific spray pattern/test for which they were originally produced.

Figure 6-11 : CUP sprinklers evaluated. Top, left to right: Rapidrop (A), Reliable (B), Tyco (C). Bottom, left to right: Victaulic (D), and Viking (E).

6.4.1.3 'K' factor testing

The accuracy of 'K' factors was measured, as it is known that 'K' factors can vary from specified values. This provided an essential baseline so that accurate flow rates could be obtained during distribution testing through water pressure monitoring at the sprinkler head.

Manufacturers' data provided with the sprinkler samples confirm that the 'K' factor for each was 80. Testing to BS EN 12259-1:1999 [255] was used to obtain actual 'K' factors for each sprinkler.

Testing consisted of a water pump, pipework, sprinkler(s), pressure transducer, and water container. Volume of water collected, test duration and accurate pressure readings at the sprinkler allowed 'K' factors to be established using Equation 3. Results showed variations in 'K' factors from all manufacturers and are reported in section 6.4.2, Table 6.

Sample sprinkler heads were tested at various pressures with volumes of water collected and recorded. Using Equation 3 a table was produced providing 'K' factor results for each different test. On completion of numerous tests, the resultant 'K' factors were inserted into a graph, to provide accurate results. An example of this can be seen in Table 5 and Figure 6-12 for sprinkler E.

Table 5 - Sprinkler E - 'K' factor results

Nominal pressure (bar)	Actual pressure (bar)	SQRT (P)	Vol collected (L)	Collection period (min)	(sec)	Collection Time (min)	Vol flow Q (L/min)	K factor
0	0	0	0	0	0	0	0	n/a
0.5	0.510	0.714	121.5	2	0	2.00	60.75	85.04
0.5	0.510	0.714	121.5	2	0	2.00	60.75	85.10
1	1.011	1.006	115	1	30	1.50	76.67	76.23
2	2.025	1.423	121	1	0	1.00	121.00	85.02
2	2.018	1.420	121	1	0	1.00	121.00	85.18
4	4.044	2.011	112	0	40	0.67	168.00	83.54

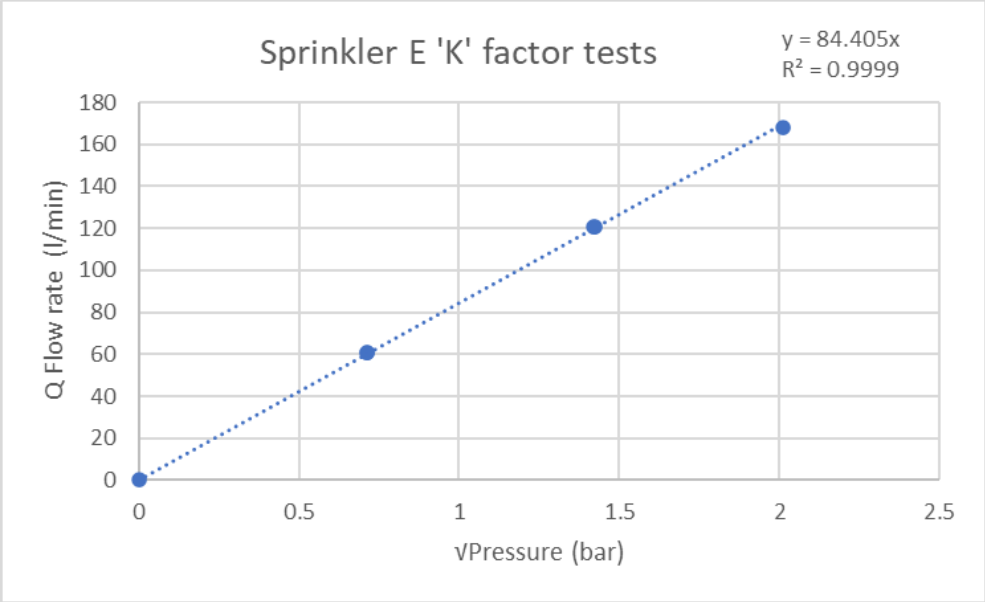


Figure 6-12 : Sprinkler E results plot for 'K' factor accuracy

6.4.1.4 Vertical distribution (above and below) water collection

Manufacturers' data confirms that 40% of water delivered to a CUP sprinkler is distributed upward and 60% downward. To evaluate accurate above and below water distribution, a simplified test set-up based on BS EN 12259-1:1999, Annex D.3 test rig was used, shown in Figures 6-13 and 6-14. This used the same components as the 'K' factor tests, with the addition of the above/below water deflector plate.

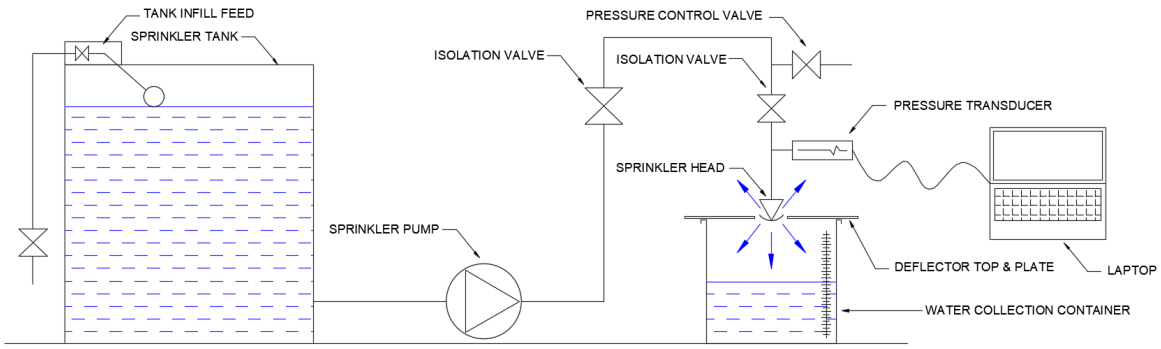


Figure 6-13 : Schematic representation of test set-up for sprinkler water collection below the deflector

Using sprinkler head pressure and actual 'K' factors, the flow rate through each of the sprinklers was established through calculation (Equation 3). To evaluate above and below water distribution, measurements were taken from water collected in the container below the sprinkler over a period of time. This allowed water flow calculated below the sprinkler deflector to be deducted from the total flow of water being delivered through the sprinkler head, allowing the above/below ratio to be calculated. Tests were conducted at a range of different pressures over a range of time periods. Results for above and below water distribution are presented in section 6.4.2, Table 7.

Figure 6-14 : Simplified test set-up recording below water distribution from the sprinklers. A - test set-up. B - water capture.

Figures 6-13 and 6-14 show the modified version of BS EN 12259-1:1999 Annex D3 set up. The board on top of the container was fitted with a thin metal plate ~2 mm thick which contained a hole that was ~1 mm larger than the sprinkler deflector shown in Figure 6-14A. The sprinkler deflector was located at the same level as the top of the plate to allow water to be collected in the container below the deflector. The water delivered above the container flowed away and was not collected.

6.4.2 Preliminary investigation sprinkler results

6.4.2.1 'K' factor testing

Testing was conducted with CUP sprinklers from five manufacturers. Data sheets confirmed a minimum 'K' factor coefficient of 80. Testing was undertaken as described in section 6.4.1.3 and using Equation3, results for accurate 'K' factors were obtained, confirmed in Table 6.

Table 6 - 'K' factor test results

Manufacturer reference	Specified 'K' factor (L min^{-1} $bar^{-1/2}$)	Measured 'K' factor (L min^{-1} $bar^{-1/2}$)	Tolerance value
Sprinkler A	80	85.45	+ 5.45
Sprinkler B	80	82.52	+2.25
Sprinkler C	80	80.27	+0.27
Sprinkler D	80	84.22	+4.22
Sprinkler E	80	84.41	+4.41
Note: In BS EN 12259-1:1990, Table 3's error range is 80 ± 4			

Table 6 shows variance between all manufacturers (sprinklers A to E). All sprinklers had slightly higher 'K' values, which would result in higher sprinkler flow rates. Two sprinklers fell within tolerance requirements of BS EN 12259-1:1990; three sprinklers fell outside tolerance values. At a consistent pressure provided to sprinklers assessed, those measured with a higher 'K' factor would provide higher flow rates. For example, at a pressure of 1 bar, Sprinkler A would provide a flow rate of 85.45 L min^{-1} $bar^{-1/2}$, Sprinkler C would provide a flow rate of 80.27 L min^{-1} $bar^{-1/2}$.

6.4.2.2Vertical distribution testing (above and below)

Water distribution tests for above and below the sprinkler deflector were generally undertaken in accordance with BS EN 12259-1:1999 Annex D.3 using a modified test rig as detailed in section 6.4.1.3. with each sprinkler flowing at 4.0 bar pressure. Results shown in Table 7 demonstrate that a good proportion of upward spray was achieved from all sprinklers. Results show different distribution ratios from each sprinkler when considering manufacturers' data, where more water is distributed above the deflector, which will support ceiling wetting.

Table 7 - Above and below water distribution results

Manufacturer reference	Specified distribution (%)		Measured distribution (%)	
	Above	Below	Above	Below
Sprinkler A	40	60	56.1	43.9
Sprinkler B	40	60	52.8	47.2
Sprinkler C	40	60	52.1	47.9
Sprinkler D	40	60	45.2	53.8
Sprinkler E	40	60	54.5	45.5

Table 7 shows different distribution ratios from each sprinkler when considering manufacturers' data. Results show more water is distributed above the deflector, which supports ceiling wetting.

6.4.3 Preliminary investigation sprinkler discussion

Three sprinkler types were initially assessed, to recognize spray characteristic patterns. Testing showed that upward (SSU) and downward (SSP) sprinklers discharged 100% water downward, consistent with the manufacturers' literature. Conventional sprinklers (CUP) demonstrated both upward and downward spray, which would benefit exposed combustible timber ceilings.

To establish a basis for sprinkler selection criteria and to evaluate sprinklers in different orientations, pressures, and locations, three criteria were considered, shown in Figure 6-15. The first criterion was wall wetting. A fire located adjacent to a combustible wall has been shown to be larger than a fire in the middle of a compartment [257] where the initial fuel package is equivalent. Potential surface spread of flame upward to the ceiling was deemed to be a significant threat. Therefore, wall wetting is an important fire protection requirement. The next criterion was involvement and surface spread of flames on the ceiling above sprinklers. The final criterion was water flow to floor level for general contents fuel loads, which current sprinkler rulesets consider by specifying a minimum design density of discharge below sprinklers, based on occupancy classification.

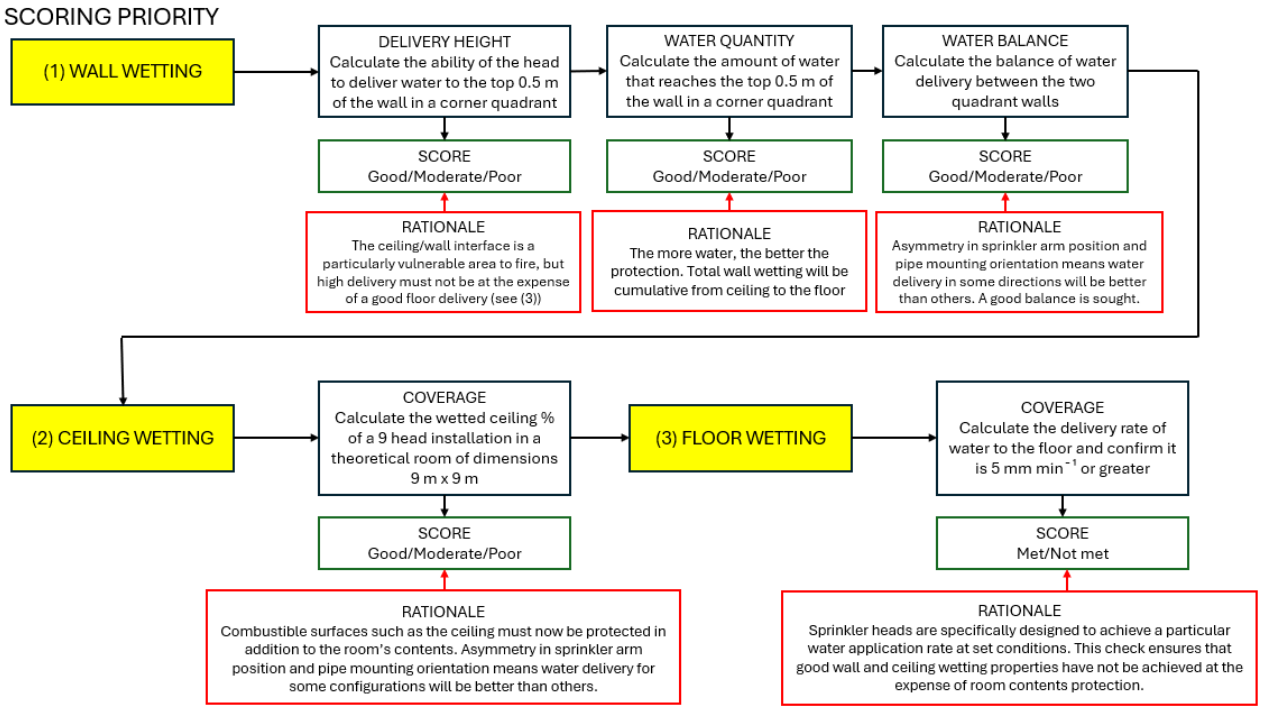


Figure 6-15 : Flow chart for sprinkler head characterisation selection.

Thirty-nine individual water distribution tests were conducted to evaluate the performance of each sprinkler (A – E) against the criteria set out in Figure 6-15 and are summarised in Table 8. The complete set of results can be found in Appendix B.

As previously described, automatic sprinkler systems are engineered to limit fire development through direct suppression and by pre-wetting adjacent combustible fuels to inhibit secondary ignition. Water remains the predominant suppression agent due to its favourable thermophysical properties, including a high latent heat of vaporisation and substantial specific heat capacity, which enable efficient absorption of thermal energy from the fire environment and attenuate heat transfer to nearby materials. Historically, conventional 'Victorian-era' sprinkler configurations have demonstrated effective wetting of exposed timber surfaces (ancestral mill floors and ceilings), contributing to reductions in incident heat flux and suppression of surface pyrolysis. This pre-wetting action delays ignition and decreases the rate of flame spread across timber substrates, thereby enhancing overall compartment fire resilience.

6.5 Ceiling and floor wetting

6.5.1 Methodology

A hybrid test was established to evaluate water distribution, capture water volume at floor level and measure ceiling surface wetting. It was decided to use elements of the different standards shown in Table 1 and Table 4 to optimise testing for this study.

The test set-up consisted of a tank, pump, pipework, fixings, pressure transducer, sprinkler(s) (CUP), water collection buckets, load cell, and laptop for recording data, shown in Figure 6-16.

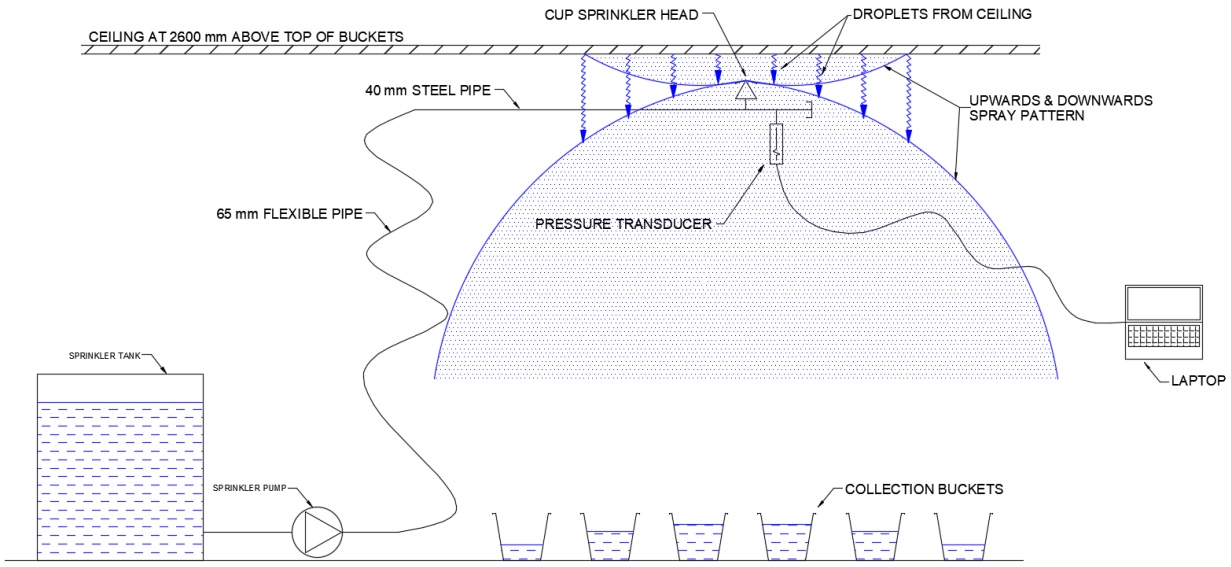


Figure 6-16 : Schematic of water collection layout and major components.

The design layout for water collection is shown in Figure 6-19 and 6-20: 108 identical buckets were located at 500 mm centres on a semi-circle layout with a maximum radius of 4 000 mm to capture water. The CUP sprinkler head(s) were located between 150 and 180 mm below the ceiling. Location of sprinkler deflector below the ceiling is critical in terms of response time activation. Ideal locations for sprinkler thermal element (glass bulb) are 75–150 mm below the ceiling. Sprinklers were installed with the yoke arms running perpendicular to the sprinkler pipe. Using standard industry bracket material, allowed the sprinkler to be installed at 150 mm below the ceiling when tested in the upward position. However, due to physical bracketry size, when tested in the downward position, a range of 150–180 mm was achieved, depending on sprinkler head design shown in Figure 6-17.

Table 4 summarizes the various sprinkler test standards, which specify ceiling heights ranging from 2030 mm to 3050 mm. For this study, a ceiling height of 2600 mm above the tops of the buckets was selected, corresponding to the mean value of the surveyed standards. Based on these standards, it was assumed that this height provides sufficient clearance beneath the sprinkler to allow full development of the intended spray pattern. A ceiling height of 2600 mm is also representative of typical floor-to-ceiling heights in buildings without suspended ceilings, where mechanical and electrical services remain exposed. The experimental configuration further assumed the absence of any service-related obstructions to water discharge, ensuring that the resulting spray characteristics could be observed and recorded without interference.

Figure 6-17 : Sprinkler deflector location below the ceiling in both downwards (pendant)(left) and upwards (upright)(right) orientations.

To enable sprinkler wetting patterns to be quantified, the open area and the lip of a standard bucket was measured. Water droplets hitting the lip were predicted to have a 50% chance of entering the bucket. The area of the bucket, including half of the lip, was used as the area of capture for water discharge from the sprinkler(s). The standard water collection bucket had an open area of 300 mm with a 15 mm lip equating to an area of 0.078 m^2.

A total of 108 identical collection buckets were positioned at predetermined locations beneath each sprinkler to quantify spatial water distribution. Following each test, the volume of water collected in every bucket was determined gravimetrically by weighing the captured water as shown in Figure 6-18. The recorded weights, corresponding to each bucket's geographic location, Figure 6-19, was entered into Microsoft Excel to generate a 180° distribution profile of water application.

Assuming radial symmetry of sprinkler discharge, the 180° dataset was mirrored within the spreadsheet to produce a complete 360° water-distribution representation. Cartesian X, Y, and Z coordinates were assigned to each bucket position to facilitate spatial analysis.
To determine the application density, the measured water mass was divided by both the test duration and the surface area of the bucket aperture, yielding a water delivery rate expressed as mm min^{-1} m^{-2}. Conversion from mass to density was performed within Excel, resulting in an independent 360° density distribution. A plan-view density map was subsequently generated using Microsoft Excel's charting functions.

For enhanced spatial visualisation, the density data was imported into Microcal Origin. The dataset was initially arranged on an 8 × 16 grid, which was mirrored to create a plot-ready 16 × 16 matrix. Interpolation was used to increase the spatial resolution of the sprinkler distribution

dataset after the original measurements were arranged on a 16 × 16 grid. Because the physical bucket layout produced a relatively coarse sampling matrix, the data was up-scaled by a factor of four in each dimension to create a 64 × 64 grid for improved graphical representation. Up-scaling was performed using the software's built-in grid interpolation function. The procedure estimates new data values at intermediate positions between the original measurement points by fitting a smooth surface across the dataset. Although the software does not alter the underlying measured values, it uses them as control points to calculate intermediate values. This produces a continuous surface that retains the structure of the original data while providing a higher-density matrix suitable for contour plotting than was achievable through Excel alone.

This methodology was applied consistently across all sprinkler models evaluated in the study, shown in section 6.5.3.

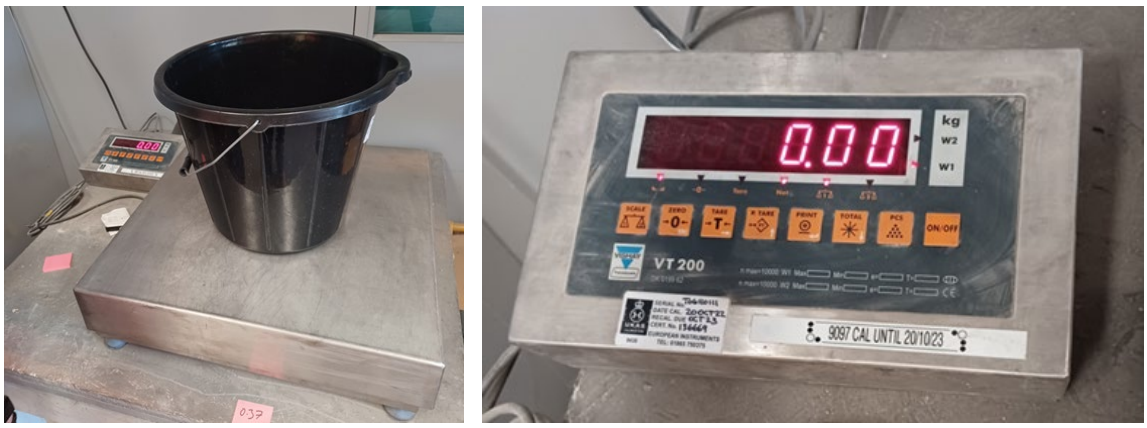


Figure 6-18 : Calibrated load cell for water weight measurements.

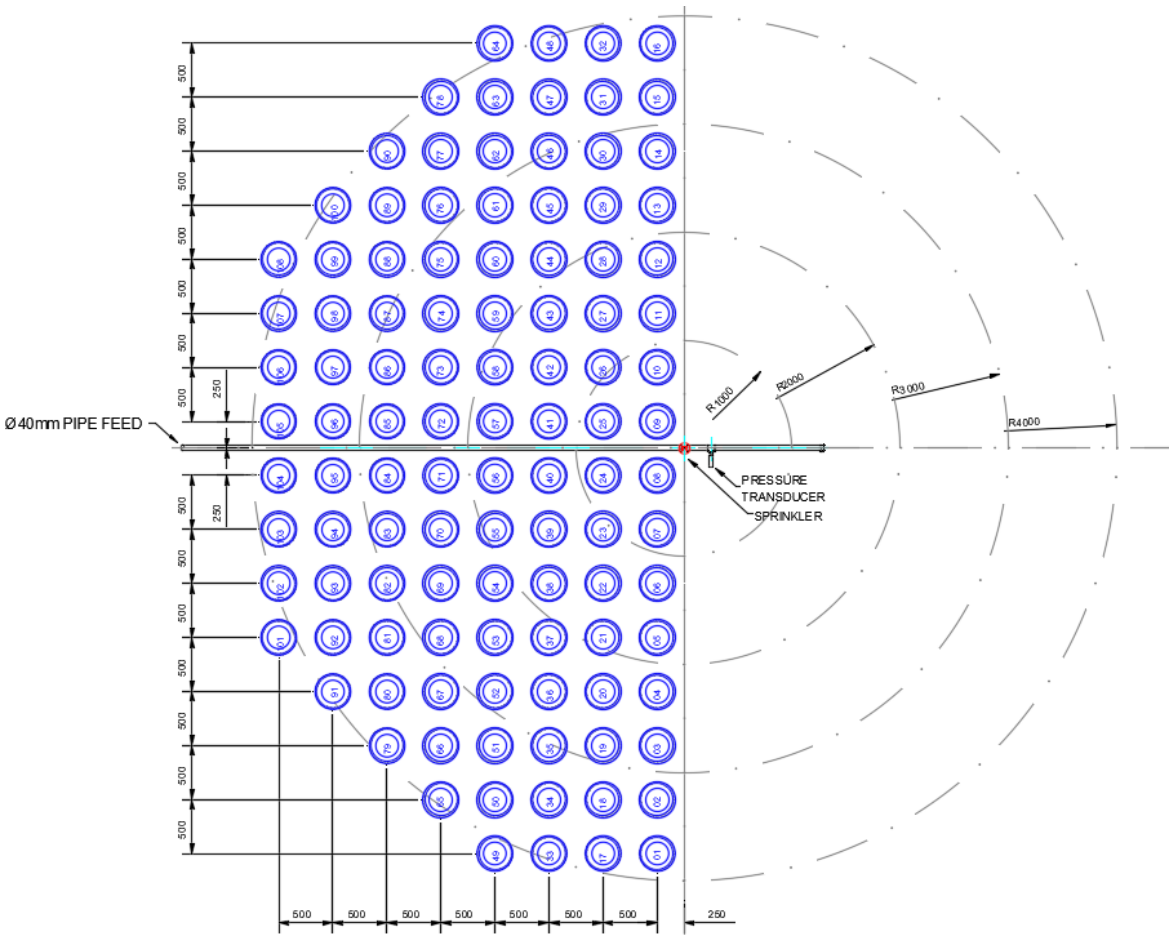


Figure 6-19 : Test set-up for water distribution capture and ceiling wetting analysis. The blue concentric circles represent buckets.

The ceiling was marked up at 500 mm intervals, north–south and east–west from the centre point of the sprinkler, so that wetting patterns at ceiling post-test could be measured, photographed, and simulated. Figure 6-20 shows the test set-up with the buckets located below the ceiling, with pipework and sprinkler head above.

Given the optimum distance of sprinkler deflector below ceiling is 75–150 mm, testing at the lower level of 150/180 mm allowed space for the sprinkler to spray upward and develop a wetting pattern on the ceiling. This lower level would increase the activation time of the sprinkler slightly, but this would be offset by more efficient wetting of the timber ceiling.

Results for ceiling wetting were photographed, measured, and visually replicated in AutoCAD showing 'wetted' areas.

Figure 6-20 : Water collection buckets in a semi-circular layout below the sprinkler.

Table 8 shows the summary of the varying tests undertaken with sprinklers located in an open area (tests 01-16), shown in Figures 6-16 and 6-19, and in a corner wall location prefixed with the letter W,(tests W01-W17) shown in Figures 6-31 and 6-32 where sprinklers were located at 1.5 m from each wall. For tests 17, 18, W18, W19, W20 and W21, sprinklers were selected based on best/worst performance and were tested where only the sprinkler head is exposed below the ceiling/soffit. Due to availability of the test laboratory, sprinkler performance was evaluated during testing and results obtained at lower pressures were used to select and rank sprinklers for testing at the higher pressure of 3.0 bar. Sprinklers A, B & C were chosen as best, average, and worst performing. Sprinklers D and E were not tested at 3.0 bar as they fell in-between best/worst ranking at the lower pressure.

Table 8 - Summary of water distribution tests.

Test Reference	Sprinkler head manufacturer (A, B, C, D & E)	Target test pressure (bar)	Orientation tested (Downwards / Upwards / Ceiling)	Recorded Pressure (bar)
01	A	0.35	Upwards	0.35
02	E	0.35	Upwards	0.35
03	A	0.35	Downwards	0.33
04	A	3.0	Downwards	3.02
05	C	0.35	Downwards	0.35
06	D	0.35	Downwards	0.35
07	B	0.35	Downwards	0.35
08	E	0.35	Downwards	0.35
09	B	3.0	Downwards	3.11
10	C	3.0	Downwards	3.10
11	C	0.35	Upwards	0.34
12	B	0.35	Upwards	0.35
13	D	0.35	Upwards	0.34
14	B	3.0	Upwards	3.12
15	A	3.0	Upwards	3.03
16	C	3.0	Upwards	3.11
17	C	3.0	Ceiling	2.85
18	C	0.35	Ceiling	0.35
W01	C	3.0	Upwards	3.13
W02	A	3.0	Upwards	2.99
W03	E	3.0	Upwards	2.98
W04	D	3.0	Upwards	3.05
W05	B	3.0	Upwards	3.09
W06	B*	3.0	Upwards	3.10
W07	B	0.35	Upwards	0.34
W08	A	0.35	Upwards	0.35
W09	C	0.35	Upwards	0.35
W10	C	3.0	Downwards	3.12
W11	A	3.0	Downwards	3.00
W12	E	3.0	Downwards	3.02
W13	B	3.0	Downwards	3.10
W14	D	3.0	Downwards	3.05
W15	B	0.35	Downwards	0.34
W16	A	0.35	Downwards	0.34
W17	C	0.35	Downwards	0.36
W18	C	3.0	Ceiling	2.85
W19	C	0.35	Ceiling	0.37
W20	B	0.35	Ceiling	0.35
W21	B	3.0	Ceiling	2.80
Note: Test W06 (*) sprinkler was located at 1.5 x 1.1 m spacing				

Table 8 shows all water distribution testing undertaken for each sprinkler, in different orientations at different pressures.

6.5.1.1 Distribution criteria (ceiling and floor)

Ceiling wetting distribution is not a requirement in current sprinkler standards and was assessed purely on physical wetted area measured to the nearest m^2. The largest wetted area was considered a property of the best performing sprinkler, and smallest measured area considered the worst performing sprinkler for each orientation and pressure.

Sprinkler water distribution was evaluated at the floor using actual measured density. The largest area covered within the minimum design density of 5 mm min^{-1} m^{-2} was considered to have the best performance, the smallest area meeting the minimum design density was considered worst performance.

6.5.2 Ceiling wetting results

Tests undertaken at a pressure of 3.0 bar confirm that a good proportion of the ceiling can be wetted. Results shown in diagrammatic format, replicate area of wetted ceiling in both orientations. Figures 6-21, 6-22, 6-23 and 6-24 summarise measured and photographed ceiling patterns, providing a visual representation of surface wetting and approximate area of coverage from sprinklers.

6.5.2.1 Conventional Pendant (downward) patterns

Results show sprinklers installed in the downward position produce slightly smaller wetted areas than sprinklers in the upward position. In downward orientation, it can clearly be seen how the pipework feeding the sprinkler (above the sprinkler head) impacts water distribution and coverage directly above, with a 'dry' area of ceiling shown in Figures 6-21 and 6-22. This is known in the sprinkler industry as *pipe shadowing* and would produce a larger 'dry' area with a larger-diameter sprinkler pipe.

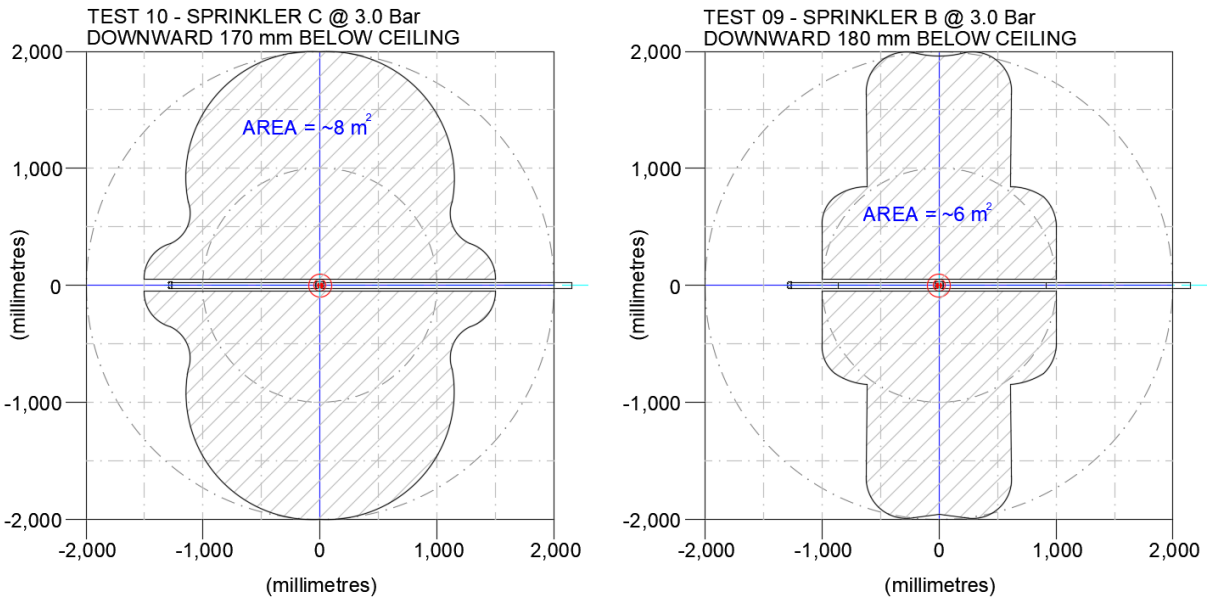


Figure 6-21 : Representation of ceiling wetting patterns at 3.0 bar in downward position. Left: shows best results (sprinkler C). Right: shows worst results (sprinkler B).

Figure 6-22 : Actual ceiling wetting patterns at 3.0 bar in downward position. Left: sprinkler C (best). Right: sprinkler B (worst).

Figure 6-21 shows the ceiling pattern has an elongated shape, potentially due to the location of the sprinkler yoke arms causing an obstruction to the spray pattern. This complemented results from wall tests where better water distribution was achieved where the sprinkler yoke arms did not impact directional spray.

6.5.2.2 Conventional Upright (upward) patterns

Ceiling wetting patterns for sprinklers in the upward orientation are more circular than those in the downward orientation. Figures 6-23 and 6-24 show the best and worst ceiling wetting patterns.

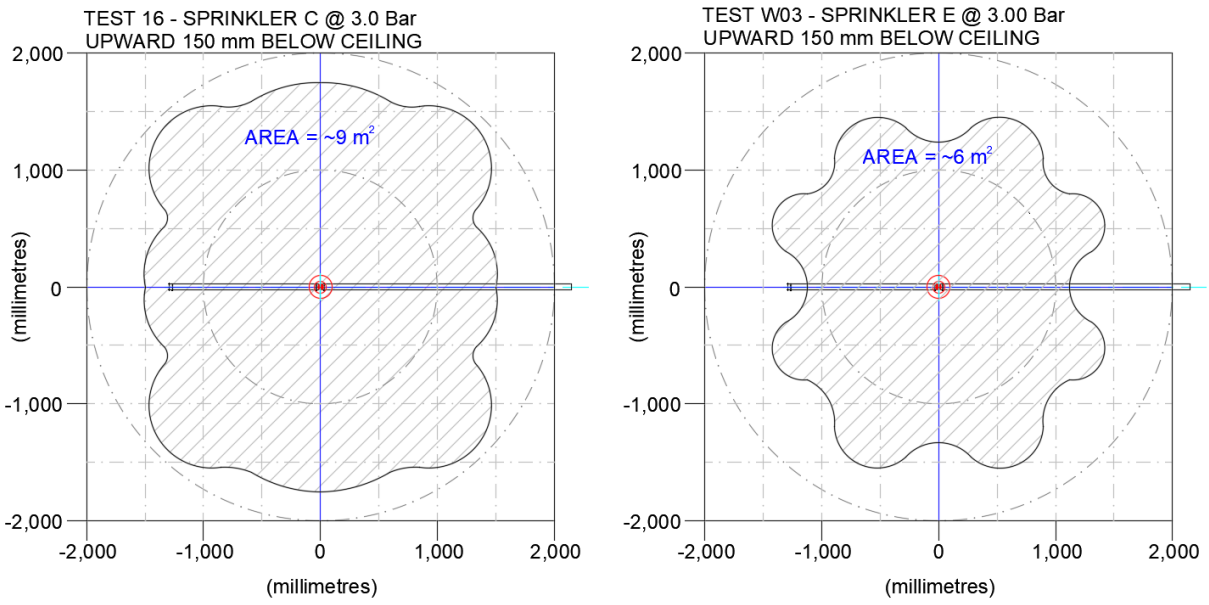


Figure 6-23 : Representation of ceiling wetting patterns at 3.0 bar in the upward position. Left: shows best results (sprinkler C). Right: shows worst results (sprinkler E).

Figure 6-24 : Actual ceiling wetting patterns at 3.0 bar in upward position. Left: Sprinkler C (best). Right: sprinkler E (worst).

Figure 6-23 shows a more circular wetted ceiling area directly above the sprinkler head from the upward orientation of the sprinkler. When comparing both orientations, it is clear from the results that the surface area of wetted ceiling from sprinklers in the upward position would allow a more uniform spacing of sprinklers to cover ceiling area than those in the downward position which is simulated in Figure 6-41. For the full range of wetting patterns, see Annex B for supplementary material.

6.5.3 Floor distribution results

A requirement for all sprinklers, irrespective of type and orientation, is to provide water discharge to cover the floor where the contents fuel load will be present. A specified density of discharge from sprinklers is required to cover the contents and is based on occupancy classification. Current requirements for standard type commercial occupancies (Ordinary Hazard) require a design density of discharge of 5 mm min^{-1} m^{-2} over an assumed floor area varying from 6 to 18 sprinklers (72–216 m^2). Results at floor level shown in sections 6.5.3.1 and 6.5.3.2 have been capped at an adequately compliant density of 6 mm min^{-1} m^{-2}. These areas are shown in elevated black sections in Figure 6-25.

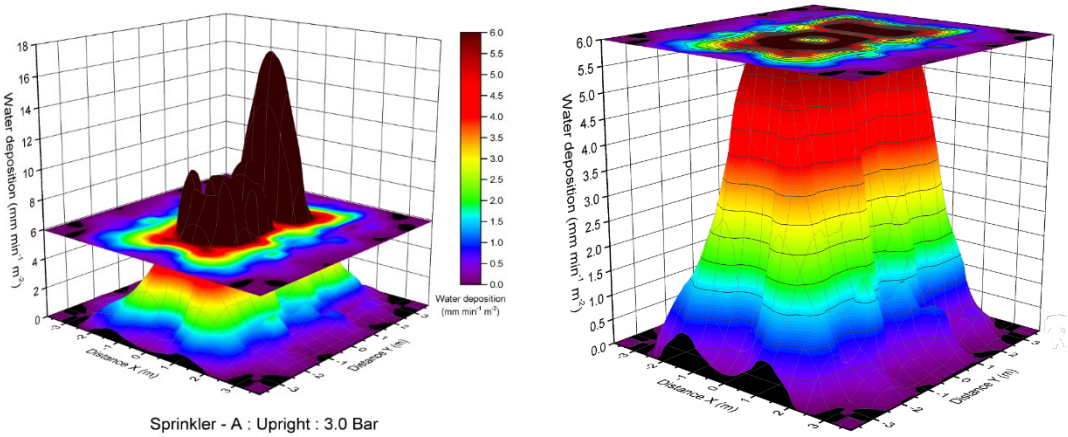


Figure 6-25 : Delivery of water density at 3.0 bar in 3-D. Left: showing a density of discharge with higher densities 6-16 mm min^{-1} m^{-2} shown in black. Right: discharge results capped at 6 mm min^{-1} m^{-2}.

Figure 6-25 shows the actual density of water delivered from sprinkler A at a pressure of 3.0 bar. The peak recorded density is at ~16 mm min^{-1} m^{-2} over a small area. At ~5 mm min^{-1} m^{-2}

(minimum requirement) the results show that the area adequately covered by the sprinkler is ~12 m^2 (3 x 4 m).

6.5.3.1 CUP in the Pendant (downward) position

Figures 6-26 and 6-27 show the best and worst results for actual density delivered at a pressure of 3.0 bar for sprinklers located in the downward orientation.

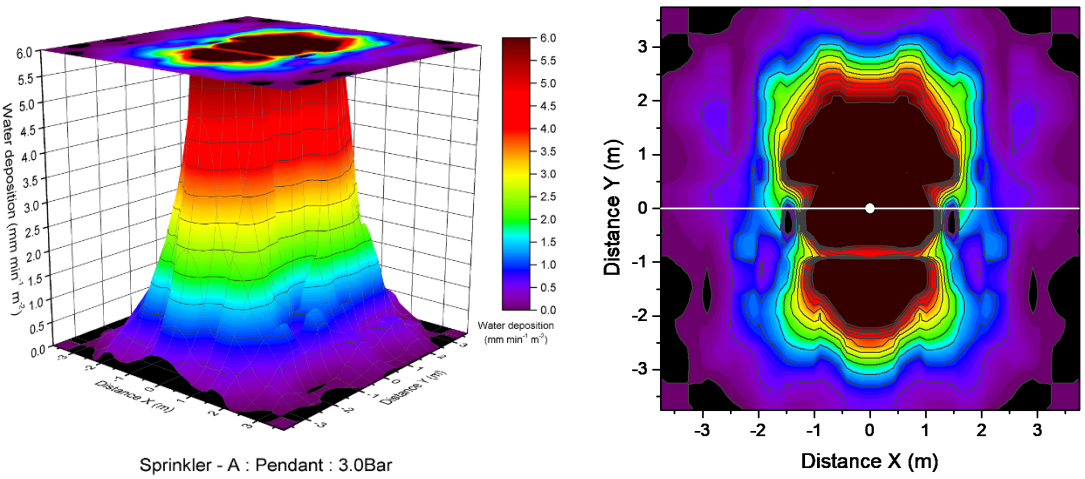


Figure 6-26 : Best results of delivery of water density in downward orientation from sprinkler A at 3.0 bar in 3-D and 2-D.

Figure 6-26 demonstrates >6 mm min^{-1} m^{-2} density of discharge over an area of ~8 m^2 and an average density of 2.5–5.0 mm min^{-1} m^{-2} for the remaining area up to ~12 m^2. The red and black areas in the right-hand figure correspond to the area that complies with the standard for Ordinary Hazard.

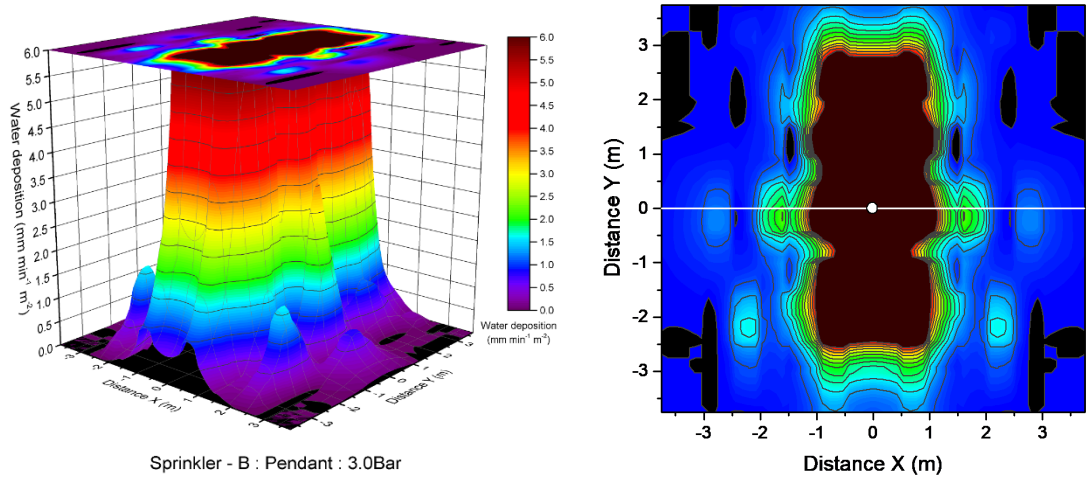
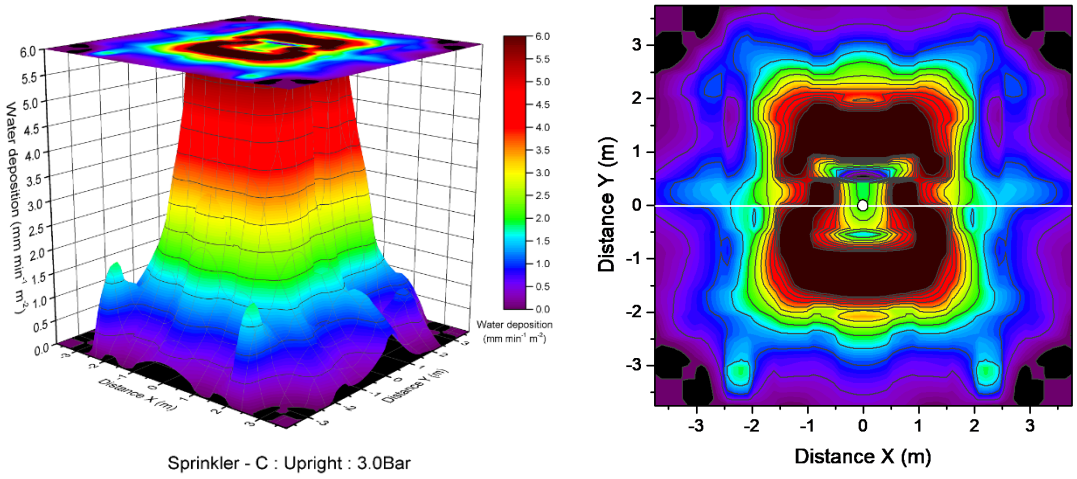


Figure 6-27 : Worst results of delivery of water density in downward orientation from sprinkler B at 3.0 bar in 3-D and 2-D.

Figure 6-27 demonstrates >6 mm min^{-1} m^{-2} density of discharge over an area of ~7 m^2 and an average density of 1.0–3.0 mm min^{-1} m^{-2} for the remaining area up to ~12 m^2.

6.5.3.2 CUP in Upright (upward) position

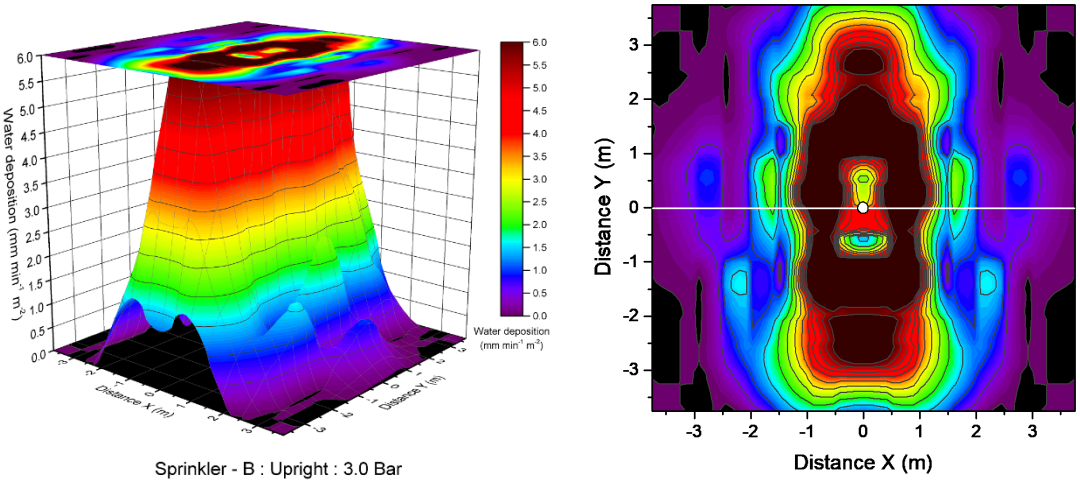
Figures 6-28 and 6-29 show the best and worst results for actual density delivered at a pressure of 3.0 bar for sprinklers located in the upward orientation.



Sprinkler - C : Upright : 3.0Bar

Figure 6-28 : Best results of delivery of water density in upward orientation from sprinkler C at 3.0 bar in 3-D and 2-D.

Figure 6-28 demonstrates >6 mm min^{-1} m^{-2} density of discharge over an area of ~8 m^2 and an average density of 2.5–5.0 mm min^{-1} m^{-2} for the remaining area up to ~12 m^2.



Sprinkler - B : Upright : 3.0 Bar

Figure 6-29 : Worst results of delivery of water density in upward orientation from sprinkler B at 3.0 bar in 3-D and 2-D.

Figure 6-29 demonstrates >6 mm min^{-1} m^{-2} density of discharge over an area of ~6 m^2 and an average density of 1.0–5.0 mm min^{-1} m^{-2} for the remaining area up to ~12 m^2.

Results in both orientations show the actual delivered density of discharge for single sprinklers operating at 3.0 bar. It is difficult to confirm from a single head test if the appropriate density is achieved: however, results confirm that >6 mm min^{-1} m^{-2} is achieved directly below the sprinkler head in areas ≥6 m^2 and lower densities are confirmed for areas up to ~12 m^2. An overall density requirement of 5 mm min^{-1} m^{-2} can be considered achieved from these tests.

Figure 6-30 shows a simulation from a group of four sprinklers spaced at 3 m × 3 m, at a minimum pressure (0.35 bar).

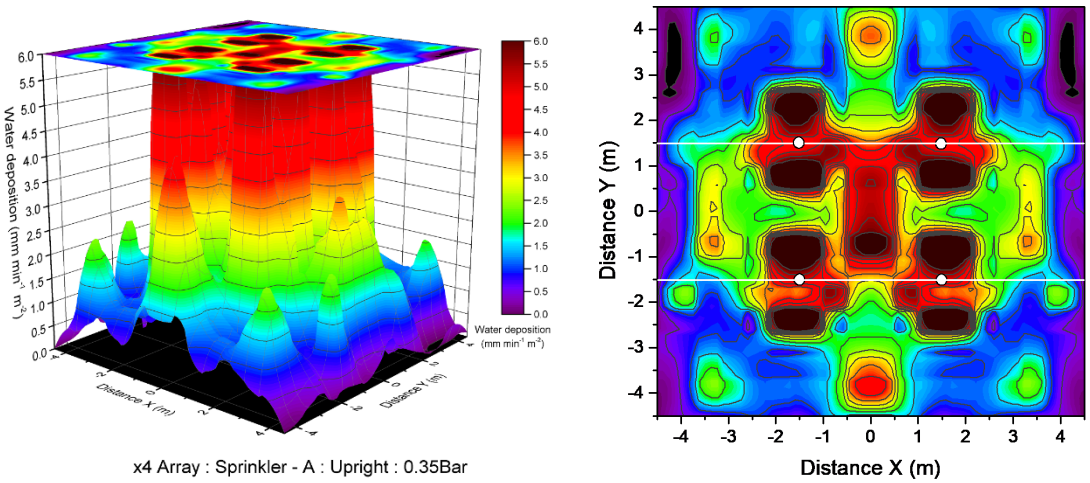


Figure 6-30 : A simulated density of discharge from a group of four sprinklers in the upright orientation at a minimum pressure of 0.35 bar.

Figure 6-30 shows the density within the area of four sprinklers (9 m2) ranges from ~2.5 to >6 mm min^{-1} m^{-2}. The capture area shown can be assumed to be ~5 mm min^{-1} m^{-2} at 0.35 bar as an average mean collective. Smaller peaks of intensity shown in the figure are not artifacts of the software, they are the product of actual measurements. Results shown are for collected densities at precise locations below the sprinkler, and do not consider full collective mean density at floor level.

6.5.4 Ceiling and floor wetting discussion

Subjective analysis has been conducted confirming ceiling wetting and floor density from sprinklers ranging from best to worst. Results for tests shown in Table 8 can be found in Annex B.
Ceiling wetting results confirm that CUP sprinklers will provide an upward spray pattern to the ceiling. Results at minimum operating pressure of 0.35 bar, with sprinklers located ~150 mm below the ceiling show surface area of wetted ceiling is reduced. This is also evident from tests where the sprinkler was located within the ceiling irrespective of test pressure. At the higher pressure of 3.0 bar, with sprinklers located ~150 mm below the ceiling, wetting was optimised providing a larger wetted ceiling area.

To optimise the area of ceiling wetting, sprinklers could be located using different spacing arrangements to limit potential surface spread of flame. An acceptable level of performance would be where the shape and area of wetted ceiling assist in the reduction of surface spread of flame. An example of this can be seen in the concluding section 6.7.

Actual density delivered to the floor at a sprinkler head pressure of 0.35 bar shows that the minimum required density is achieved from all sprinklers in the upward position. However, in downward position, sprinklers B and C do not provide adequate density. At 0.35 bar all sprinklers show reduced floor area coverage at 5 mm min^{-1} m^{-2}. Sprinklers A, B and C were evaluated at 3.0 bar in both orientations and met minimum density requirements. Sprinklers D and E were not assessed at 3.0 bar. However, it could be assumed that as these fell within best/worst performance at 0.35 bar, they would provide minimum density requirements at 3.0 bar.

Floor water distribution results at reduced sprinkler head spacing ~9 m^2 (based on 3m x 3m), at the minimum design pressure of 0.35 bar, show that the minimum design density requirement of 5 mm min^{-1} m^{-2} can be achieved.

In the early stages of fire with a single sprinkler operating, a higher pressure will provide a greater density of water directly over the fire area and simultaneously provide a larger ceiling wetting pattern.

6.6 Wall wetting

6.6.1 Methodology

The test set-up for wall wetting incorporated a corner wall scenario, using MDF panels and 100 × 50 mm structural timber batons shown in Figures 6-31 and 6-32. Walls were painted with a water-repellent paint and fitted with a lightweight metal L-shaped 90° angle. The angle was attached to the face of the wall and foil tape was used to seal and create a 5 mm × 5 mm trough. The troughs were located at 500 mm intervals up the wall, and on the surface. Each 0.25 m^2 area of wall was numbered, with all water touching the surface being collected in the trough below (Figures 6-32a and 6-32b). The troughs were sloped feeding hoses through to the rear of the wall (Figures 6-32c and 6-32d). Hoses were glued and sealed into position and fed into corresponding numbered buckets for water capture from the respective section.

Sprinkler pipework and the arms of the sprinkler heads, known as the yokes, are known to contribute to shadowing of the sprinkler discharge spray pattern observed in ceiling wetting results. To prevent double shadowing, yoke arms were aligned with the sprinkler pipework which is the requirement for sprinkler head installation. Results shown in section 6.6.2 demonstrate the effect of shadowing.

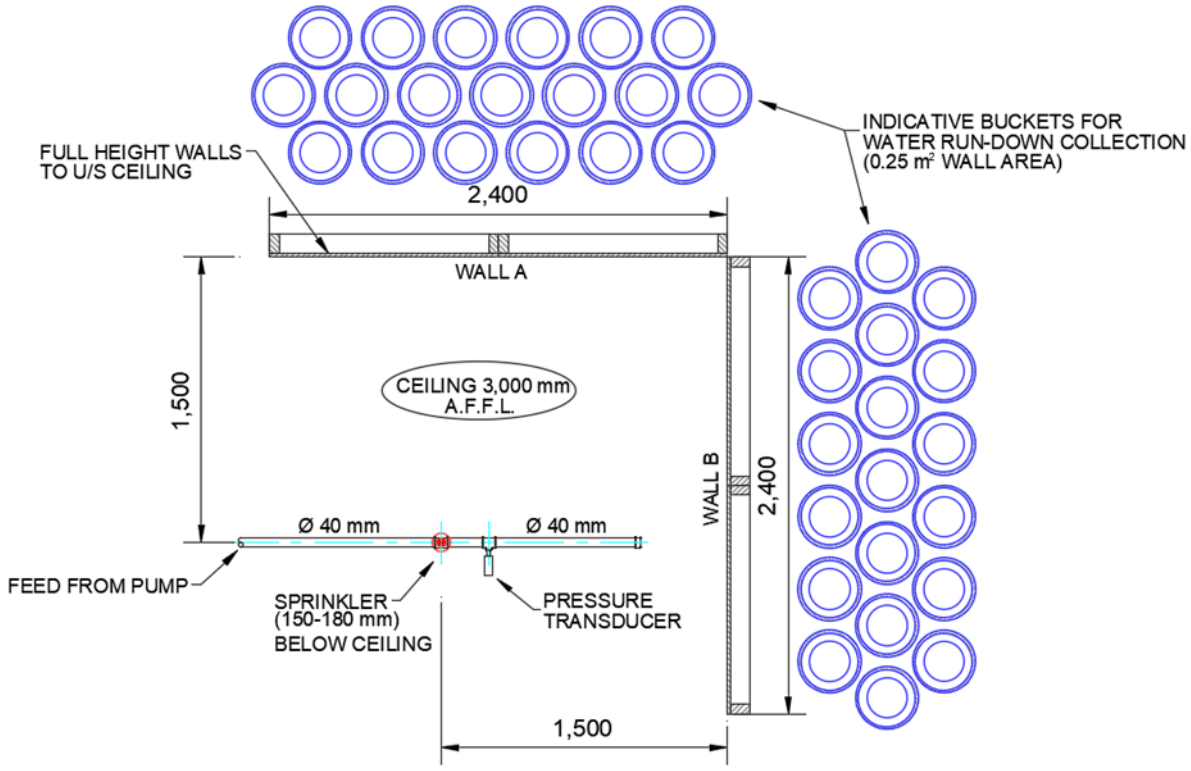


Figure 6-31 : Design of water collection for water run-down. Hoses have not been shown for clarity.

The orientation of yoke arms running with the pipework ensures that spray from the sprinkler is not impeded by either. Running the yoke arms with the pipework allowed for unimpeded spray onto Wall A. Spray to Wall B would be interrupted by both the pipework and the yoke arms. The impact of the interference of water spray onto Wall B from the yoke arms is shown in section 6.6.2.

An acceptable level of performance from each sprinkler is considered to be the ability to provide sufficient water to the top 0.5 m section of the wall at the intersection of the ceiling, in addition to providing a similar distribution to both walls. This is not defined as a requirement in current standards for commercial sprinkler systems. Fire spread over the walls is likely to reach and involve the ceiling very quickly. The potential for sprinkler spray to reach the top 0.5 m section of the wall will provide wetting to both planes to assist in reducing the impact of surface spread of flame.

Figure 6-32 : A: Corner wall set-up. B: –0.5 × 0.5 m (0.25 m^2) measured area. C: Water collection trough. D: Water collection buckets with clear tube feed pipes at the rear.

Water captured was weighed and converted into volume. The volume was divided by the area of each panel and test duration to provide a density in mm min^{-1} m^{-2}. Results are represented in graphical form in section 6.6.2.

6.6.1.1 Distribution criteria (walls)

Sprinklers were evaluated for wall wetting by using density of discharge to each 0.25 m^2 section of wall in mm min^{-1} m^{-2}, which is not a requirement in current commercial sprinkler standards. The sprinkler providing the most even proportional density and coverage to both walls was considered best performing sprinkler, and least even density with disproportionate coverage on both walls considered worst performing sprinkler.

6.6.2 Results

6.6.2.1 Area density collection

Twenty-one wall wetting tests were conducted using CUP sprinklers in downward and upward configurations at both 0.35 and 3.0 bar pressure. Measurement and capture of water to each 0.5 × 0.5 m (0.25 m^2) area was recorded and converted into actual density discharge per unit area of wall on each panel, to establish whether water reached the top wall area intersecting with the ceiling. Figures 6-33, 6-34, 6-35 and 6-36 show the results for both walls from the sprinkler located at 1.5 m from each wall, indicated as a yellow oval at the top of the wall.

Figures 6-33, 6-34, 6-35 and 6-36 show two sprinkler positions (upward and downward), delivering water at a pressure of 3.0 bar. Irrespective of orientation, wall wetting is achieved from all sprinklers, with significant differences between individual heads. However, adequate performance was observed for all sprinkler heads.

Actual densities are recorded per 0.25 m^2 panel (Figures 6-33, 6-34, 6-35 and 6-36). These figures show average density horizontally and vertically on Walls A and B. However, water run-down through cumulative density is a more important consideration. Colour shading is included to indicate actual density of water delivered to each individual panel. Light green/blue indicates a low delivery of water. The blue range indicates good water delivery, with darker shading delivering more water.

Side Wall Test Sprinkler C Upright 3.0 bar

8.4	12.2	9.5	7.6	3.1	7.6	8.6	6.2
3.3	1.8	2.9	2.2	5.0	2.8	4.7	3.6
1.2	0.8	0.8	0.3	1.3	0.8	1.0	1.1
0.8	0.3	0.5	0.3	0.9	0.3	0.3	0.5
0.8	0.6	0.6	0.1	0.6	0.3	0.1	0.2

Wall A Wall B

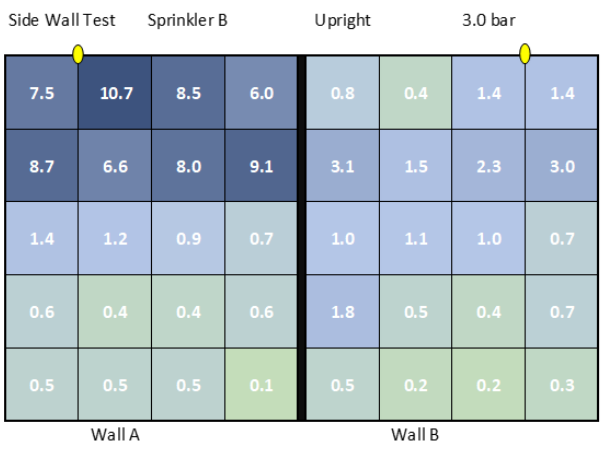
Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	2.9	3.1	2.8	2.1	2.2	2.4	2.9	2.3

	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	9.4	6.4
Row 4	2.5	4.0
Row 3	0.8	1.1
Row 2	0.5	0.5
Row 1	0.5	0.3

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	2.8	2.5

Figure 6-33 : Measured densities from test W01, sprinkler C, for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling.

Figure 6-33 shows sprinkler density in near symmetry to both walls. Whilst there are slight differences in the density per 0.25 m^2 panel on walls A and B, the mean density per wall is very close. The effect of the yoke arm position can be clearly seen in the density recorded in the upper sections of the wall located closest to the sprinkler.



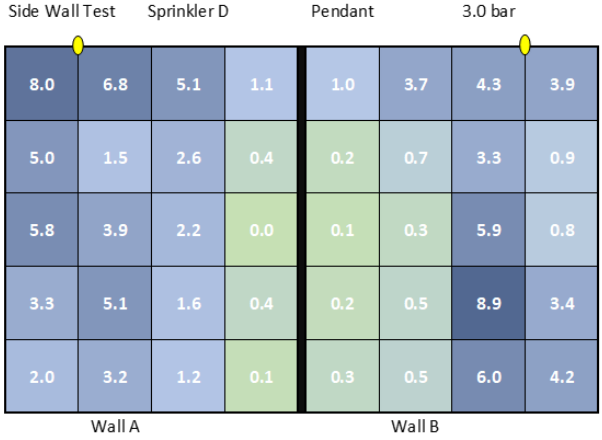
	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	8.2	1.0
Row 4	8.1	2.5
Row 3	1.1	0.9
Row 2	0.5	0.8
Row 1	0.4	0.3

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	3.7	3.9	3.7	3.3	1.4	0.7	1.1	1.2

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	3.7	1.1

Figure 6-34 : Measured densities from test W05, sprinkler B, for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.

Figure 6-34 shows a disproportionate delivery of sprinkler density to each wall. Wall A is provided with greater density at the top two levels. Wall B follows a similar pattern in that more water is delivered to the top two sections of wall, but at much lower densities.



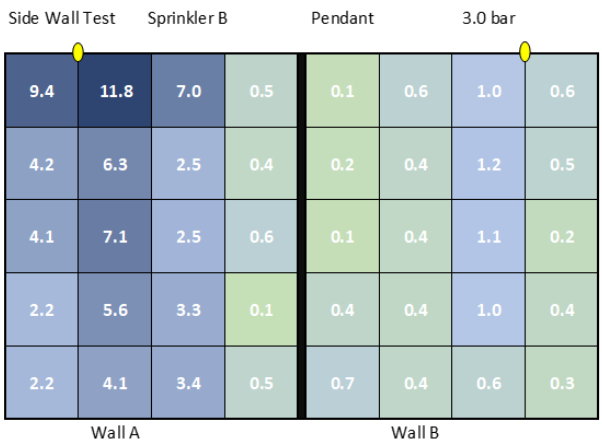
	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	5.2	3.2
Row 4	2.4	1.3
Row 3	3.0	1.8
Row 2	2.6	3.2
Row 1	1.6	2.8

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	4.8	4.1	2.5	0.4	0.4	1.1	5.7	2.6

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	3.0	2.5

Figure 6-35 : Measured densities from test W14, sprinkler D, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling.

Figure 6-35 shows the closest sprinkler density on both walls for sprinklers in the downward orientation. The figure shows that the lowest density recorded is the intersection between wall A and B which is confirmed in the average density of both columns 1.



	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	7.2	0.6
Row 4	3.3	0.6
Row 3	3.6	0.5
Row 2	2.8	0.5
Row 1	2.5	0.5

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	4.4	7.0	3.7	0.4	0.3	0.4	1.0	0.4

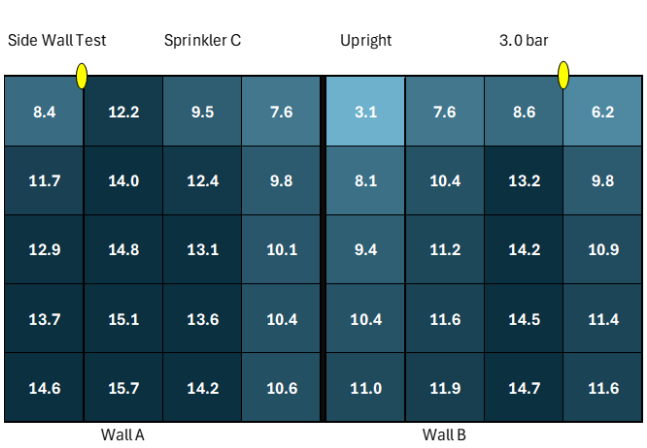
Mean water density per wall (mm min^{-1})	Wall A	Wall B
	3.9	0.5

Figure 6-36 : Measured densities from test W13, sprinkler B, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.

Figure 6-36 shows a significant disproportionate delivery of sprinkler density to each wall. Wall A has a significant quantity of the water flow from the sprinkler with good density in columns 2, 3 and 4. Wall B has extremely low densities and the intersection of both walls has the lowest density recorded.

6.6.2.2 Cumulative density collection

Cumulative density reveals the beneficial effect of water run-down from the top of the wall, providing more than adequate wall wetting towards the floor. Figures 6-37, 6-38, 6-39 and 6-40 show cumulative recorded densities and water distribution proportions for each wall. Colour shading shows water delivery differences, with darker shading indicating greater water delivery.

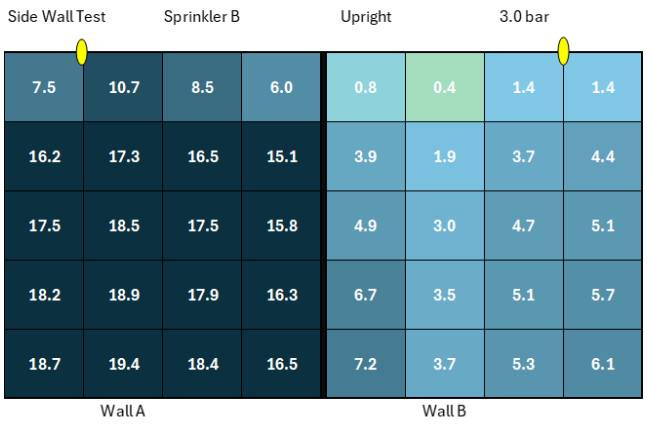


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	9.4	6.4
Row 4	12.0	10.4
Row 3	12.7	11.4
Row 2	13.2	12.0
Row 1	13.8	12.3

% wall wetting from sprinkler	Wall A	Wall B
	53%	47%

Figure 6-37 : Cumulative densities from test W01, Sprinkler C, for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling.

Figure 6-37 shows the close ratio of water delivery to both walls confirming that sprinkler C in the upward position has good symmetry and water run down to floor level.

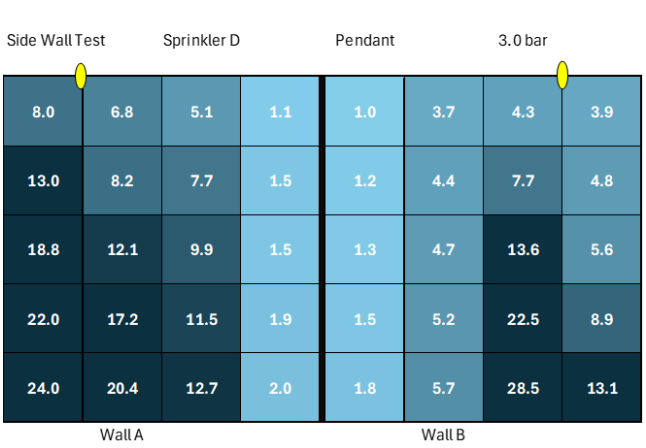


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	8.2	1.0
Row 4	16.3	3.5
Row 3	17.3	4.4
Row 2	17.8	5.3
Row 1	18.3	5.6

% wall wetting from sprinkler	Wall A	Wall B
	77%	23%

Figure 6-38 : Cumulative densities from test W05, Sprinkler B for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.

Figure 6-38 shows the inferior performance of sprinkler B in the upward position providing less water delivery to wall B and poor water run down capability.

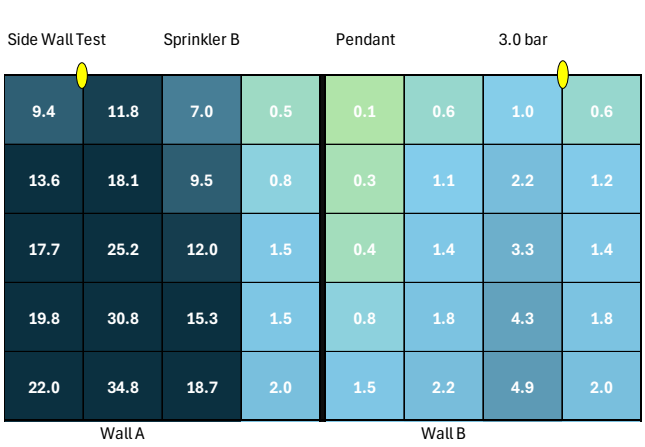


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	5.2	3.2
Row 4	7.6	4.5
Row 3	10.6	6.3
Row 2	13.2	9.5
Row 1	14.8	12.3

% wall wetting from sprinkler	Wall A	Wall B
	55%	45%

Figure 6-39 : Cumulative densities from test W14, Sprinkler D, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling.

Figure 6-39 shows the close ratio of water delivery from sprinkler D in the downward orientation. Results from the figure show that less water is delivered to the intersection of walls A and B.



	mm/min per row	
Vertical Level	Wall A	Wall B
Row 5	7.2	0.6
Row 4	10.5	1.2
Row 3	14.1	1.6
Row 2	16.9	2.2
Row 1	19.4	2.6

% wall wetting from sprinkler	Wall A	Wall B
	88%	12%

Figure 6-40 : Cumulative densities from test W13, Sprinkler B, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.

Figure 6-40 confirms the worst results obtained showing disproportionate water delivery from the sprinkler head. The intersection of wall A and B suffer from poor water delivery in the downwards orientation.

6.6.3 Wall wetting discussion

The results indicate a difference in performance of sprinklers based on location of the yoke arms relative to the facing wall. Proportionate distribution irrespective of yoke arms is achievable in some sprinklers, but not others. Pipework shadowing is also a contributing factor in reduced distribution when sprinklers are installed in the pendant (downwards) position.

Water run-down has been shown in density (mm min^{-1} m^{-2}) for visual ease: however, this method of measurement is for depth of water at floor level over a specified area, which is captured in section 6.5.3. Irrespective of water measurement, it can be observed from Figures 6-33 to 6-40 inclusive, that the top 0.5 m of the wall is wetted. However, results also show significant differences between sprinkler heads.

Experimental testing undertaken in this study demonstrates that, when sprinkler heads are arranged at 1.5 × 1.5 m spacing from corner sections and positioned 150–180 mm below the ceiling, the resulting discharge reliably reaches the ceiling–wall interface. The findings further show that water run-down from the upper wall surface produces sustained wetting, ensuring adequate distribution to lower interface regions. This wetting behaviour is expected to limit fire penetration into unsealed gaps or openings within the wall construction and thereby reduce the likelihood of smouldering.

All results for sprinkler discharge testing (floor, walls, and ceiling) can be found in Annex B.

6.7 Conclusions

This study investigated the performance of CUP-type commercial sprinklers protecting exposed timber surfaces by evaluating their ability to wet ceilings, walls, and floors under varying orientations and pressures. Initial tests confirmed that CUP sprinklers uniquely discharge water both upward and downward, regardless of orientation. All tested models met or slightly exceeded the required 'K' factor, ensuring sufficient water discharge. Water distribution patterns showed better than expected ceiling wetting at distances of 150–180 mm below the ceiling, and wall wetting was achieved across all tests, even at lower pressures, although performance varied, especially in corner areas.

Ceiling wetting results ranged from excellent to poor, with the best coverage observed in upright orientation and the worst in pendant orientation, both at 3.0 bar shown in Figure 6-41. These extremes highlight the importance of sprinkler orientation and pressure in achieving effective coverage, albeit testing was undertaken without a fire where the upward velocity from the fire plume could affect results shown.

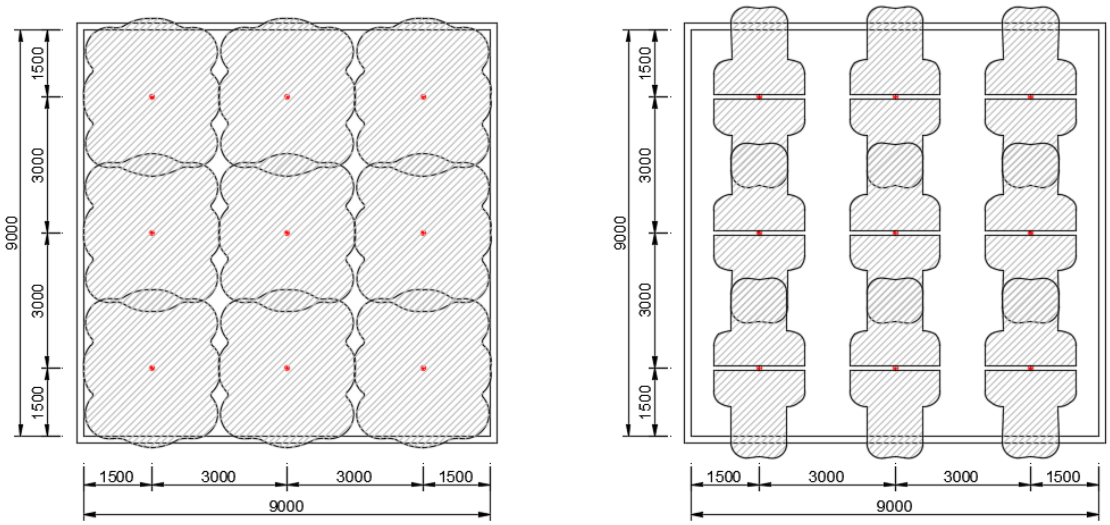


Figure 6-41 : Left: Sprinkler C upright at 3.0 bar – good coverage. Right: Sprinkler B pendant at 3.0 bar – acceptable coverage.

The results suggest that staggered sprinkler spacing, as per BS EN 12845:2015, could improve ceiling wetting to help prevent surface flame spread. Floor wetting met the required minimum discharge density for Ordinary Hazard classifications, confirming that CUP sprinklers can provide adequate protection for typical commercial and institutional occupancies.

Figure 6-42 shows the improvement in ceiling wetting from staggered spacing for sprinkler B in a pendant orientation at 3.0 bar. At failure pressure of 0.35 bar, sprinkler C in a downward orientation exhibits wholly inadequate ceiling coverage. All other recorded sprinkler coverage tests fell between these two extremes and can be found in Annex B.

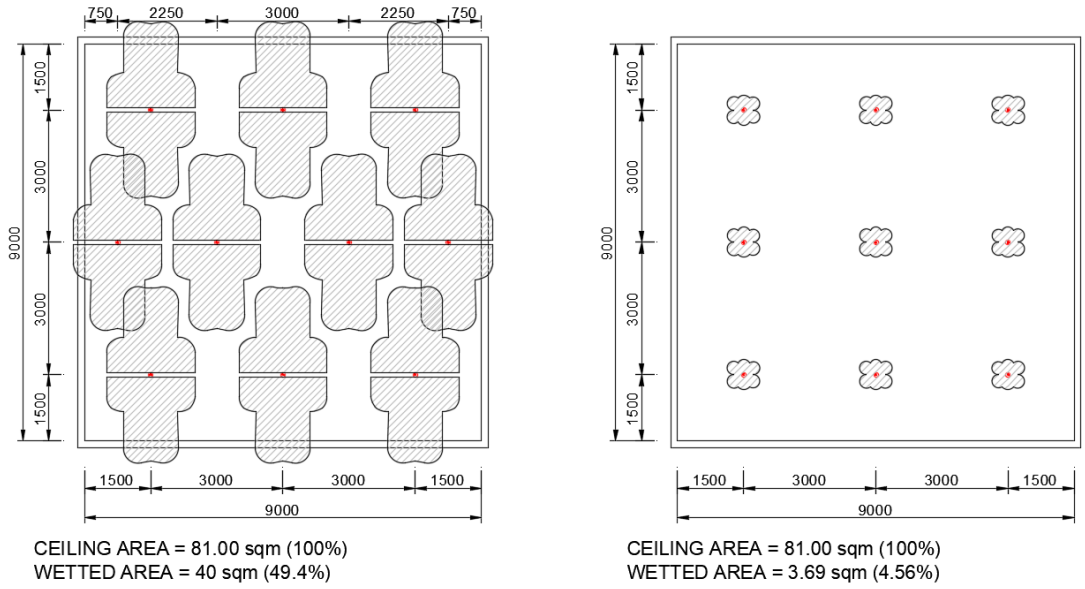


Figure 6-42 : Left: Sprinkler B pendant at 3.0 bar – acceptable coverage through staggered spacing. Right: Sprinkler C pendant at 0.35 bar – inadequate coverage.

The findings emphasize the need for tailored sprinkler strategies in timber buildings, which have higher fuel loads and fire spread potential compared to traditional construction. Effective wetting of timber surfaces can slow fire development, aid evacuation, and improve firefighting conditions. The study concludes that with appropriate sprinkler selection, orientation, and spacing, CUP-type sprinklers can meet the necessary criteria for protecting exposed combustible surfaces and calls for updates to standards and manufacturer designs to optimize performance in timber structures.

Chapter 7 : Fixings

7.1 Introduction

Guidance for fixing fire sprinkler and M&E services directly to the underside of timber ceilings is not specifically covered in standards. European sprinkler standards cover fixing into concrete [13], industry guidance provides best practice for concrete, but does not cover timber [27], and British standards only consider concrete [26]. Guidance has been provided for suspension of sprinkler pipework in the LPC Rules, Technical Bulletin TB229 [18]. This does refer to timber but only in respect of side entry of pipework to structural timber beams and not fixed to the underside of a timber soffit.

Sprinkler and M&E services are suspended using mechanical assemblies fixed to the underside of the structure. For concrete this is achieved using expansion anchors that connect to vertically threaded drop rods. Clamps are used for steel beams that also connect to drop rods where services are fixed using approved components, such as mild steel loop bands for pipework. Figure 7-1 shows typical sprinkler fixings into the structure and attached to the steel structure.

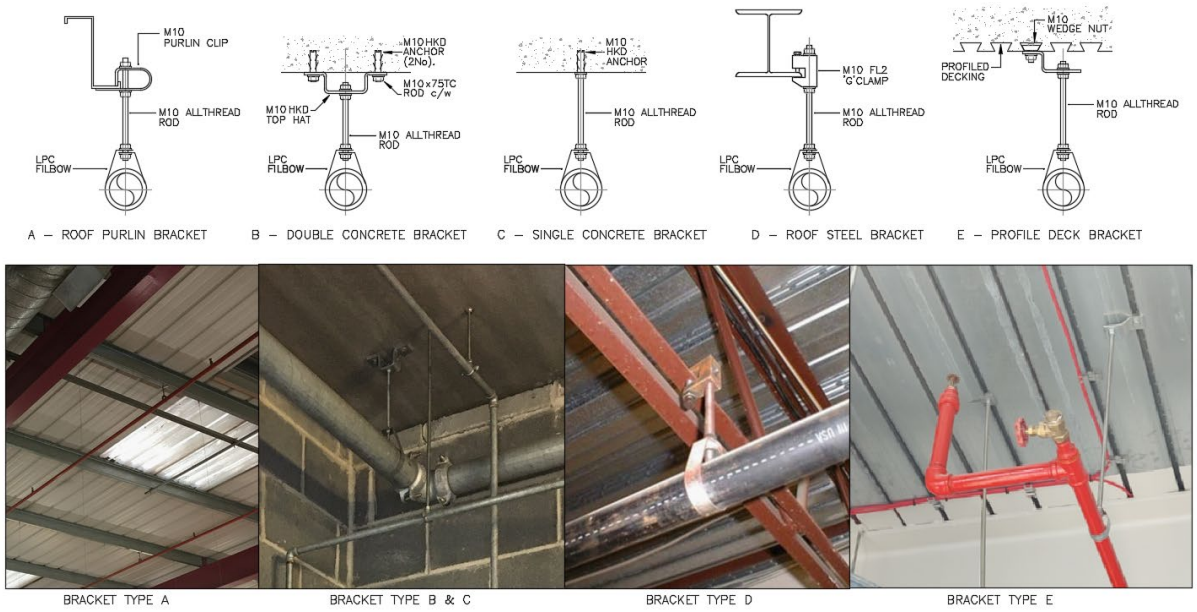


Figure 7-1 : Typical sprinkler fixings. A & D show pipe supported from the structural steel frame. B, C and E show fixings from the underside of the floor structure.

Structural load capacity, bracket assemblies, and individual fixings need to be considered, not just for sprinkler systems, but for all services supported from timber ceilings.

In this study, samples of standard industrial CLT were tested with two distinct types of adhesives with typical construction industry screw fixings used for the suspension of M&E services. A fire-test rig was designed to expose screw fixings embedded into CLT to a fire in a ceiling mounted configuration. A series of eight fire tests were conducted, and pull-out strength of each screw fixing was assessed during and after fire.

Load capacity of screw fixings was tested in ambient conditions (pre-fire), during, and after exposure to fire to investigate risk of detachment of sprinkler systems and Mechanical and

Electrical (M&E) services. The following key variables were analysed in relation to pull-out strength versus embedment depth:

1. Pull-out strength of screw fixing in ambient conditions.
2. Pull-out strength of screw fixing during and post-fire.
3. The relationship between screw fixing embedment depth and pull-out strength.
4. Relationship between embedment depth, screw dimensions, and char formation.

7.2 Potential contributing mechanisms of timber strength loss

Wood is known to lose strength under the action of heat which can impact its ability to both support weight (loads in compression and tension), or hold in place devices attached by frictional fit, such as screws. Depending upon the temperatures reached some of these may result in reversible or irreversible loss of strength. The key mechanisms are:

- Water evaporation
- Thermal degradation of the polymer components of wood
- Char formation

Wood contains 'free' water in cell lumens (transit routes), and 'bound' water in the cell walls. When heated to 100°C, free water can boil resulting in internal vapour pressure. Up to 150°C bound water vaporises causing cell-wall shrinkage and the formation of micro-cracks; defects which act to reduce the wood's capacity to carry load.

The incremental loss of strength due to polymer degradation is as follows:

- Between 200°C and 300°C hemicellulose, the flexible supporting mesh between plant fibres, loses rigidity.
- On further heating (300°C to 400°C) the main load-bearing polymer cellulose degrades
- Between 250°C and 500°C lignin, the 'glue' that binds together all fibres, softens and chars.

Char formation usually occurs between 300°C and 400°C during which time volatile gases escape leaving a smaller brittle carbonaceous char that cannot support compressive loads effectively. The loss of material during this process also contributes to overall loss of strength.

Table 9 shows approximate retained bending strength for a dry softwood (e.g., pine) under standard test conditions. Exact values will vary by species, moisture content, and loading mode.

Table 9 - Typical temperature to strength relationship for dry softwoods.

Temperature (°C)	Retained Bending Strength (%)	Dominant Polymer Change
20 (room temp)	100	none
100	90–95	moisture loss
150	75–85	hemicellulose softening
200	50–70	hemicellulose degradation starts
250	30–50	rapid cellulose weakening
300	10–20	cellulose pyrolysis
>350	<5	residual char, negligible strength

An additional consideration specific to cross laminated timber is the role played by the composite layers and the type of glue used to bond them together. Some glue types soften and melt under the action of heat (thermoplastic), and some decompose and char (thermoset). Both can be used for CLT assembly. A fixing into CLT could conceivably fail due to the premature loss of strength of the glue holding the lamina in place into which it is fixed, or the wood itself weakening.

7.3 Methods and materials

7.3.1 Preliminary test rig development

A review was conducted of existing fire test standards for the evaluation of the performance of fixings into CLT. This considered furnace testing with an ISO 834 [99] fire curve, and full compartment configuration to ISO 9705 [257] and LPS1181 [258]. All tests had advantages and disadvantages associated with them including timescales and costs. It was therefore decided to develop a medium-scale test that would be manageable, relative, and repeatable.

Different configurations, burners, fire outputs, and arrangements were considered. Twelve preliminary tests were conducted shown in Table 10 below.

Table 10 - Preliminary fire test development for test rig.

Initial configuration (ceiling with down-stands, burner directly below it)	
Test No:	**Description of test arrangement**
T01	100 kW, top of burner 1500 mm below ceiling, solid 150 mm down-stands on all four sides
T02	100 kW, top of burner 1500 mm below ceiling, 150 mm down-stands on all sides (2 ends with 3 x 50 mm holes)
T03	100 kW, top of burner 1200 mm below ceiling, 150 mm down-stands on all sides (2 ends with 3 x 50 mm holes)
T04	100 kW, top of burner 900 mm below ceiling, 150 mm down-stands on all sides (2 ends with 3 x 50 mm holes)
T05	100 kW, top of burner 900 mm below ceiling, 150 mm down-stands on 2 sides only
Test modified to simulate 'corridor' arrangement	
T06	100 kW, top of burner 1100 mm below ceiling with 150 mm down-stands on 2 sides only, plain backing wall behind burner with 45 deg slope above
T07	Same as T06 but added in baffles on either side of burner backing wall
T08	Same as T07 but added back the baffle with holes (now 5 holes) to the 'open' end of ceiling panel
T09	Same as T08 but raised burner by 200 mm
Test set up similar to tests T01-06, but gravel bed burner replaced by and array of 3 x 4 gas torch burners (total output of 75 kW)	
Multi burners 01	Burners initially placed 180 mm below the ceiling
Multi burners 02	Burners lowered to 300 mm below the ceiling (appeared to be the best position)
Multi burners 03	Burners lowered to 400 mm below the ceiling (started at 75 kW but then turned up to 100 kW as temperatures were low)

On reviewing the results from preliminary testing, it was decided to proceed with a corridor arrangement using a gravel bed burner from ISO 9705 with a 100 kW fire. A preliminary rig was

set-up with a timber ceiling, and sixteen thermocouples were installed to ensure that there was adequate spread of flames across the whole ceiling. Temperature results can be seen in Figure 7-2.

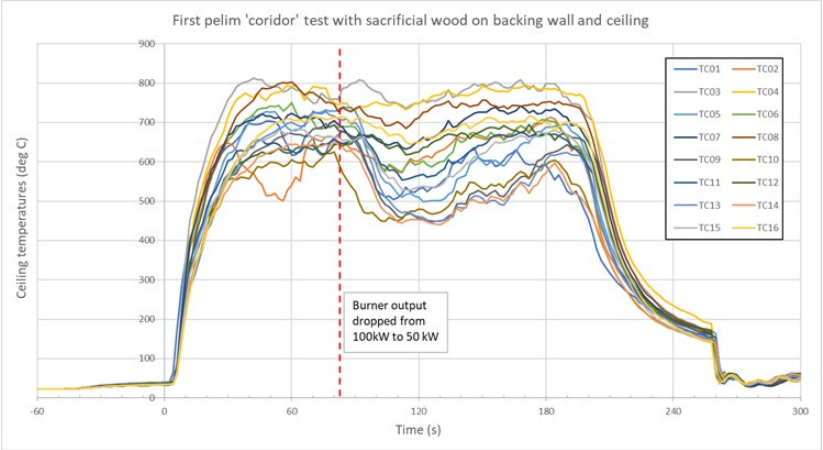


Figure 7-2 : Preliminary temperature test results for corridor arrangement.

Figures 7-3 and 7-4 show the layout of the thermocouple arrangement used to establish the adequacy of the test rig for surface spread of flame across the whole ceiling and photographs showing the test.

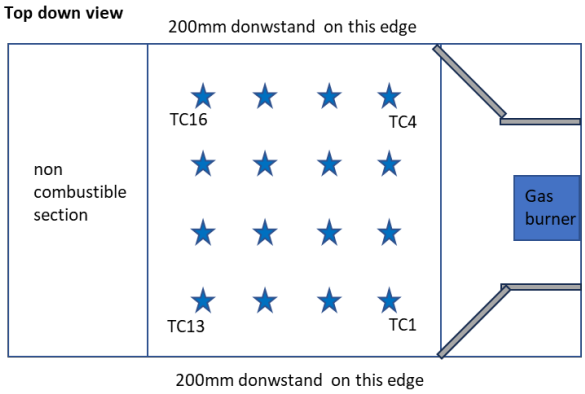


Figure 7-3 : Preliminary test rig showing thermocouple locations to establish adequate surface spread of flame.

Figure 7-4 : Photographs showing preliminary fire temperature test in corridor arrangement.

7.3.2 Development of test rig

Following preliminary testing, a medium scale test rig was developed to expose embedded fixings into the underside of the CLT ceiling to temperatures consistent with a fully developed fire. The frame for the test rig was constructed from 41 x 21 mm slotted channel, incorporating a CLT ceiling, plywood rear wall panel, plasterboard down-stands, and an ISO 9705 propane burner.

The scale of the test rig allowed for an exposure area of 0.81 m^2 of CLT ceiling. The ISO 9705 heat source consisted of a 170 x 170 x 170 mm gravel bed gas burner, fuelled with propane gas via a Bronkhorst mass flow controller to provide a constant 100 kW output. Propane was supplied from 1 – 2, 47 kg gas cylinders. The burner was fixed to a rear wall consisting of sheets of 18 mm plywood which were consumed during each test. Directly over the burner was a sacrificial CLT ceiling and together with the plywood rear wall ensured that the CLT sample was exposed to flames throughout each test. To ensure flames were channelled up the rear wall to the underside of the ceiling, and minimise the influence of drafts within the laboratory, the burner was framed with vertical plasterboard baffles. Figure 7-5 shows the design of the test rig and Figure 7-6 shows the completed rig in preparation for testing.

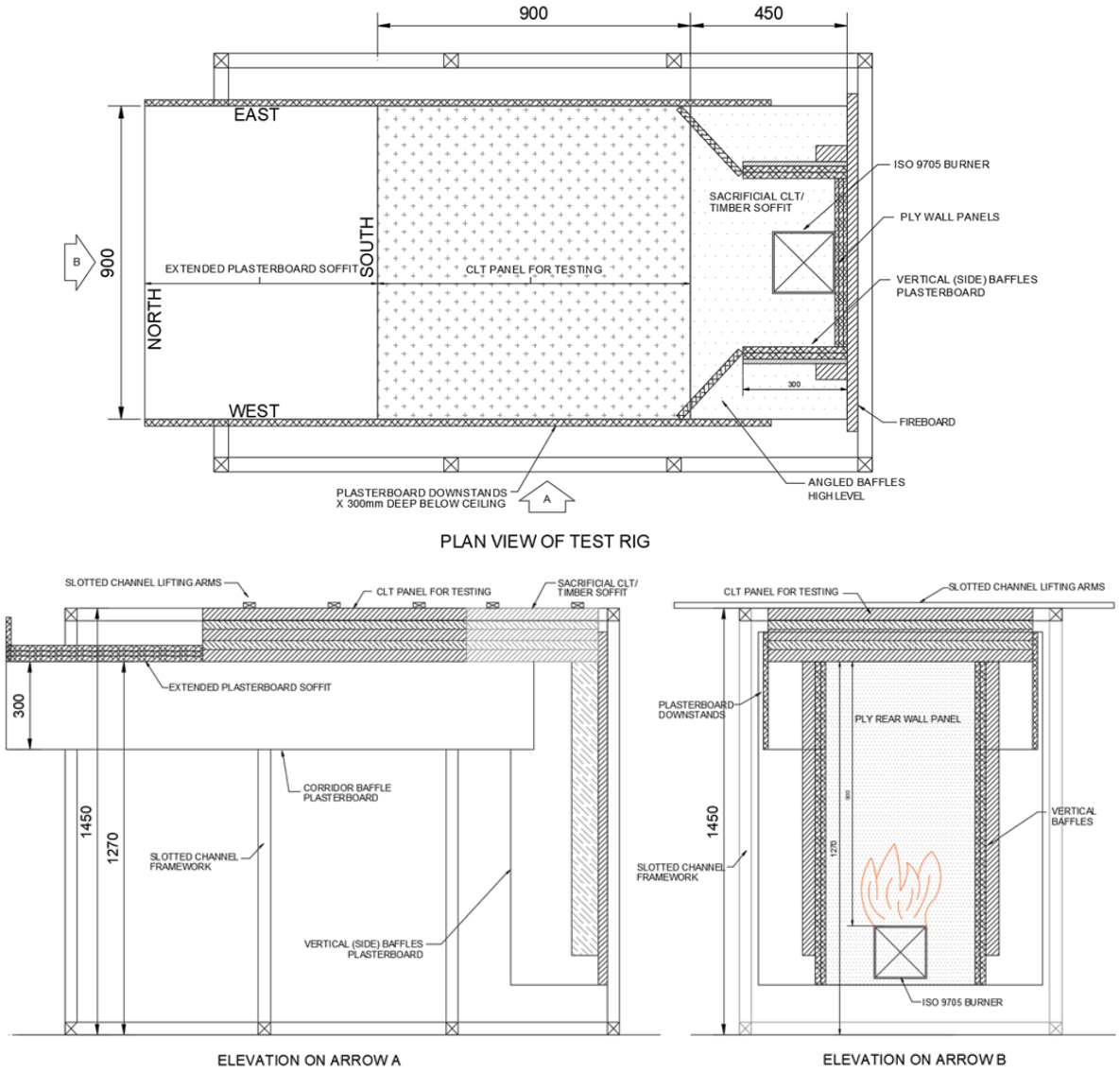


Figure 7-5 : Design of the bespoke test rig. Plan view and elevation on arrow 'A' and 'B.'

Figure 7-5 shows the test rig design which measured 2050 mm (L) x 1200 mm (W) x 1450 mm (H) overall. Figure 7-6 shows the built test rig in readiness for a test.

Figure 7-6 : Completed rig prior to testing.

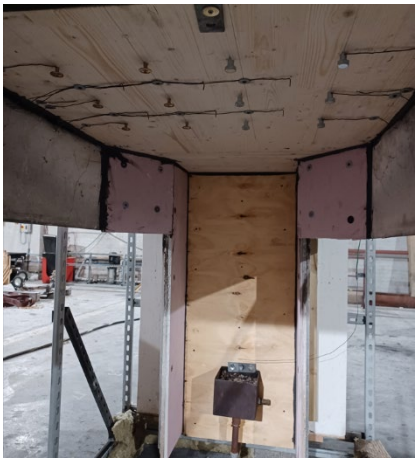
7.3.3 Instrumentation

The flow rate of the gas required to achieve the desired heat output was controlled by the mass flow controller. To monitor the temperatures in the gas layer and within the CLT, 41 Type 'K' 1.5 mm x 300 mm long mineral insulated thermocouples were used at a frequency on 1 Hz via a DataTaker data logger which in turn was connected to a PC for data recording. Thermocouples were mounted below the CLT ceiling, within the CLT at the glue line, general ply depths and around the screw fixings. The ISO 9705 burner was located at 900 mm below the CLT, measured from the top of the burner to the underside of the CLT. Instrumentation used can be seen in Figure 7-7.

47 kg propane gas cylinder

Mass flow controller

Thermocouples located within the CLT



Thermocouples below the CLT

Figure 7-7 : Photographs of instrumentation and materials used for testing.

Thermocouples were installed parallel and perpendicular to the exposed heated surface to record ceiling gas, screw (tip, mid-point, head), glue line and general ply temperatures. It is acknowledged that thermocouple output can be impacted through installation positions and orientations [259 - 261]. With the exception of gas measuring thermocouples, all other thermocouples were installed on the non-fire side to reduce errors associated with conduction along the metal sheathing. To ensure thermocouples were touching the fixings at the mid-point and the tip, a jig was used for drilling accuracy until the drill tip contacted the embedded fixing. The thermocouple was then fully inserted, and contact was confirmed by metal-on-metal sound. The thermocouple was then retracted and insertion depth compared through measurement against drilling depth as a secondary check. Durations for fire testing were 30 and 60 minutes. Figure 7-8 and Table 11 show the locations of the thermocouples.

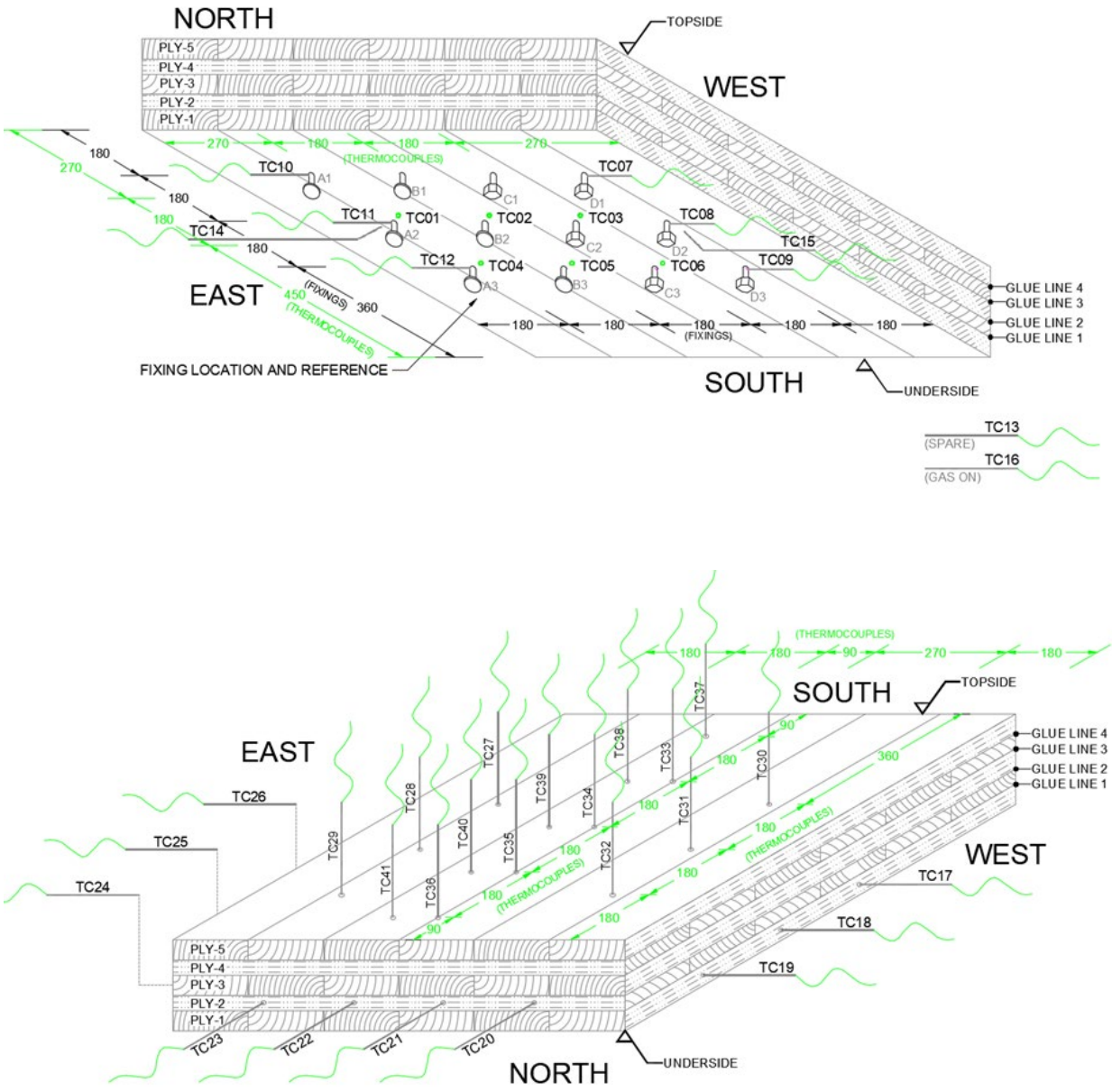


Figure 7-8 : Locations of thermocouples, Top: Exposed/below the CLT panel. Bottom: Internal locations. The depth of thermocouples are detailed in Table 11.

Table 11 - Location of thermocouples.

Thermocouple Number	Insertion Top/Side/Below	Distance from exposed surface (mm)	Location Glueline/Mid-ply	Screw location Head/Midpoint/Tip	Comments
TC01	Below	15	N/A	N/A	Gas temperature measurements
TC02	Below	15	N/A	N/A	Gas temperature measurements
TC03	Below	15	N/A	N/A	Gas temperature measurements
TC04	Below	15	N/A	N/A	Gas temperature measurements
TC05	Below	15	N/A	N/A	Gas temperature measurements
TC06	Below	15	N/A	N/A	Gas temperature measurements
TC07	Below	N/A	N/A	Head	Fixing D1 (M12 x 120)
TC08	Below	N/A	N/A	Head	Fixing D2 (M12 x 120)
TC09	Below	N/A	N/A	Head	Fixing D3 (M12 x 120)
TC10	Below	N/A	N/A	Head	Fixing A1 (M10 x 120)
TC11	Below	N/A	N/A	Head	Fixing A2 (M10 x 120)
TC12	Below	N/A	N/A	Head	Fixing A3 (M10 x 120)
TC13	Spare	Spare	Spare	Spare	Spare
TC14	Below	N/A	N/A	Midpoint	Fixing A2 (M10 x 120)
TC15	Below	N/A	N/A	Midpoint	Fixing D2 (M12 x 120)
TC16	Side	N/A	N/A	N/A	Gas burner on measurement
TC17	Side	20	Mid-ply	N/A	Tip at 135 mm from Fixing D3
TC18	Side	20	Mid-ply	N/A	Tip at 90 mm from Fixing D2
TC19	Side	20	Mid-ply	N/A	Tip at 45 mm from Fixing D1
TC20	Side	55	Mid-ply	N/A	Tip at 140 mm from Fixing D1
TC21	Side	55	Mid-ply	N/A	Tip at 105 mm from Fixing C1
TC22	Side	55	Mid-ply	N/A	Tip at 70 mm from Fixing B1
TC23	Side	55	Mid-ply	N/A	Tip at 35 mm from Fixing A1
TC24	Side	90	Mid-ply	N/A	Tip at 135 mm From Fixing A1
TC25	Side	90	Mid-ply	N/A	Tip at 90 mm From Fixing A2
TC26	Side	90	Mid-ply	N/A	Tip at 45 mm From Fixing D3
TC27	Top	N/A	N/A	Tip	Fixing A3 (M10x 120)
TC28	Top	N/A	N/A	Tip	Fixing A2 (M10 x 120)
TC29	Top	N/A	N/A	Tip	Fixing A1 (M10 x 120)
TC30	Top	N/A	N/A	Tip	Fixing D3 (M12 x 120)
TC31	Top	N/A	N/A	Tip	Fixing D2 (M12 x 120)
TC32	Top	N/A	N/A	Tip	Fixing D1 (M12 x 120)
TC33	Top	140	Glueline	N/A	General measurement from exposed surface
TC34	Top	110	Glueline	N/A	General measurement from exposed surface
TC35	Top	70	Glueline	N/A	General measurement from exposed surface
TC36	Top	40	Glueline	N/A	General measurement from exposed surface
TC37	Top	160	Mid-ply	N/A	General measurement from exposed surface
TC38	Top	125	Mid-ply	N/A	General measurement from exposed surface
TC39	Top	90	Mid-ply	N/A	General measurement from exposed surface
TC40	Top	55	Mid-ply	N/A	General measurement from exposed surface
TC41	Top	20	Mid-ply	N/A	General measurement from exposed surface

7.3.4 Test Samples

7.3.4.1 Cross Laminated Timber (CLT)

CLT test panels were 900 mm x 900 mm x 180 mm thick, 5-ply (consisting of layers 40, 30, 40, 30, 40 mm thick), replicating a typical floor/ceiling composition. The CLT was made from European spruce having a density ρ of 385 kg / m^3 and was commercially available in Industrial Visual Quality (IVI) suitable for visually exposed applications. Panels were supplied with two different adhesive types consisting of standard Polyurethane (PU) adhesive, code HB S, and a heat-resistant modified-PU adhesive, code HB X which retains surface bonding at higher temperatures. CLT panels in the conditioning chamber are shown in Figure 7-9

Figure 7-9 : CLT panels in the conditioning chamber prior to testing.

All panels including those for the ambient (baseline) tests were conditioned for a minimum of 4 weeks prior to testing in an enclosure controlled to 23 (+/-2) °C and 50 (+/-5)% relative humidity. Moisture content was measured and recorded in numerous locations on each panel and on the plywood rear wall before each test to ensure a common starting point for repeatability. Measurement of moisture content was used as a cross reference to appreciate

potential differences in results. Table 12 shows recorded moisture content of panels used prior to testing.

Table 12 - Moisture levels taken prior to testing.

Moisture levels taken prior to each test				
Panel Number	Panel Type	Moisture levels recorded		
		Location A	Location B	Location C
1	HBS	X	X	X
2	HBS	X	X	X
3	HBX	0.0	0.0	0.0
4	HBX	9.4	11.7	11.2
5	HBX	0.0	0.0	0.0
6	HBX	9.1	8.3	0.0
7	HBX	X	X	X
8	HBX	0.0	0.0	0.0
9	HBS	0.0	0.0	0.0
10	HBS	X	X	X
11	HBS	X	X	X
12	HBS	X	X	X
13	HBS	0.0	0.0	0.0
14	HBS	8.5	8.4	8.3
15	HBS	0.0	0.0	0.0
16	HBS	8.5	9.1	9.0
17	HBS	0.0	0.0	0.0
18	HBS	7.8	0.0	0.0
19	HBS	X	X	X
20	HBS	0.0	0.0	0.0
0.0 Represents a reading lower than 7.8% (lowest reading of probe) X - Unused panel				

7.3.4.2 Fixings

Fixings selected reflect the requirements of BS EN 12845:2015+A1:2019 [13] for sprinkler systems affixed into concrete. Table 40 in BS EN 12845 identifies minimum cross section area of fixing based on minimum load capacity, reflecting different pipe diameters/loads. The minimum length of fixing is also specified for concrete.

Using Table 40, 10 mm (M10) and 12 mm (M12) diameter screw fixings were selected based upon a minimum load capacity of 500 kg at 20 °C. This will support pipework up to 150 mm diameter. Screw fixings chosen for testing were M10 and M12 coach screws at 100 mm and 120 mm long respectively.

In addition to M10 and M12 coach screws, hanger-type industrial screw fixings, known as stud screws and rod hangers (M10 and M12), were also evaluated and thinner 8 mm (M8) coach screws at 100 mm long were also tested, shown in Figure 7-10.

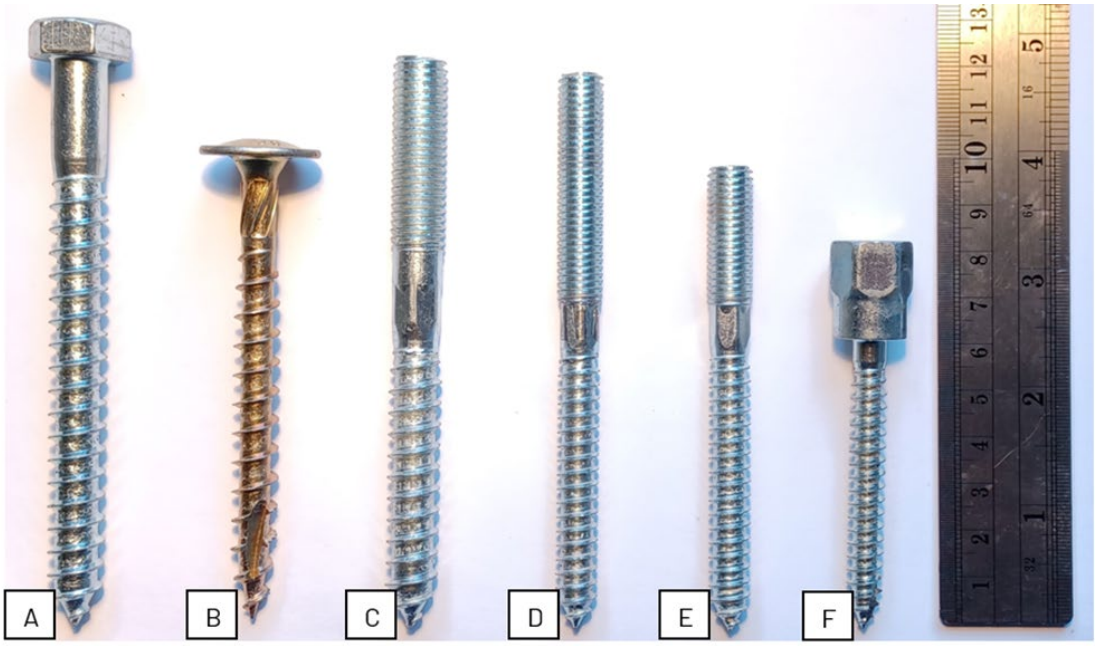


Figure 7-10 : Screw fixings tested A - M12 coach screw, B – M10 (M8) coach screw, C – M12 stud screw, D – M10 stud screw (long), E – M10 stud screw (short) and F – M10 rod hanger (M6 thread) supplied by Midfix.

Screw fixings A, C, D, E and F are carbon steel with zinc coating to a thickness of 5µm. Screw fixing B is hardened carbon steel, finished in zinc plating with a yellow chromate passivation to a thickness of 5µm. It is acknowledged that there are a multitude of different screw types for use in timber that have different shank to thread ratios, including pitch angle and tip shapes.

The ability of a screw fixing to withstand an extractive force is dependent on the contact area of the thread with the wood, the amount of compression it exerts on the surrounding wood on insertion, and insertion angle in relation to the extraction force direction. Screw fixing engagement is also affected by the pilot hole (diameter and depth), shank diameter, thread diameter, and pitch, all of which are variables which were investigated. M8 screw fixings were not piloted as advised by the fixing's supplier. Pilot details for coach screw fixings were as follows:

- M10 screw fixings; 5.5 mm pilot hole – drilled full screw depth, 6.5 mm screw shank, 9.9 mm screw thread and 6.0 mm thread pitch.
- M12 screw fixings; 7.0 mm pilot hole – drilled full screw depth, 8.8 mm screw shank, 11.7 mm screw thread and 5.0 mm thread pitch.

Embedment depths were chosen to allow for maximum penetration into the CLT with 100 mm screw fixings embedded at 90 mm and 120 mm screw fixings embedded at 110 mm (into 3-ply layers) [196]. Smaller embedment depths were evaluated using M10 and M12 screw fixings at 70 mm and 50 mm (into 2-ply layers), respectively. Hanger-type industrial screw fixings were evaluated at their full embedment depth of 60 mm.

7.3.5 Measurements

7.3.5.1 Pull-out force testing in ambient conditions

With screw fixings inserted into the samples, pull-out forces were recorded for all CLT panels. Figure 7-11 shows load testing conducted using the Staht t25 digital pull tester to BS 8539 [26].

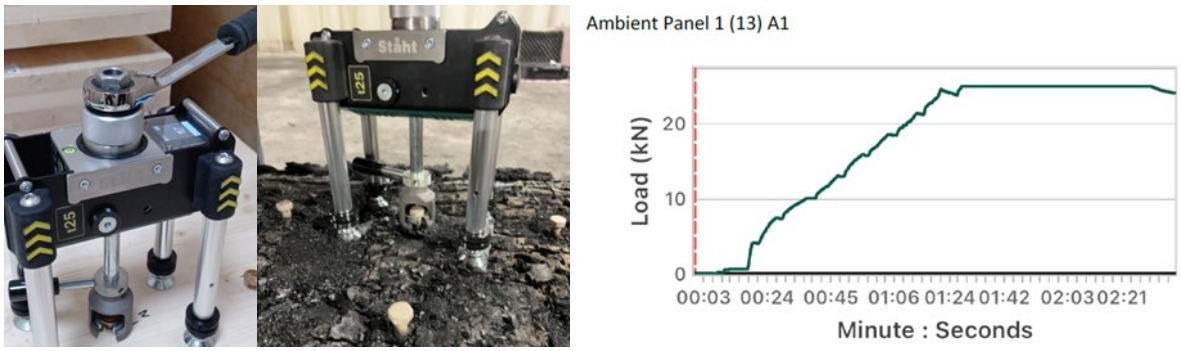


Figure 7-11 : Staht t25 digital pull tester device at ambient and post-fire testing with individual result print-out.

Table 13 shows the tests performed at both ambient and fire/post-fire condition for each combination of glue type, fire exposure duration, and fixing types. 13 tests in total were conducted, 5 ambient tests and 8 fire tests in order to allow pull-out force testing to be evaluated.

Table 13 - Experimental tests undertaken at both ambient and post-fire conditions.

Test Reference	Test Condition (Ambient / Fire / Post-fire)	Glue Type (HB S / HB X)	Fire Test Duration (min)	Fixings Tested
AT1	Ambient	HB S	N/A	M10 & M12 Coachscrews
AT2	Ambient	HB X	N/A	M10 & M12 Coachscrews
AT3	Ambient	HB S	N/A	Stud-bolts & Rod-hangers
AT4	Ambient	HB X	N/A	M10 & M12 Coachscrews
AT5	Ambient	HB S	N/A	M10 & M12 Coachscrews
FT1	Post-fire	HB S	30	M10 & M12 Coachscrews
FT2	Post-fire	HB X	30	M10 & M12 Coachscrews
FT3	Fire / Post-fire	HB S	30	M10 & M12 Coachscrews
FT6	Post-fire	HB S	30	M8 Coachscrews, Stud-bolts & Rod-hangers
FT7	Post-fire	HB S	30	M8, M10 & M12 Coachscrews, with bracket components
FT4	Fire / Post-fire	HB X	60	M10 & M12 Coachscrews
FT5	Fire / Post-fire	HB S	60	M8 ,M10 & M12 Coachscrews
FT8	Fire / Post-fire	HB X	60	M10 & M12 Coachscrews

Three fixings of each type were evaluated for each test.

7.3.5.2 Fire conditions

Of the 13 tests conducted, five used high temperature adhesive (HB X), and four tests FT3, FT4, FT5 and FT8, incorporated weighted testing of coach screws to a value of 150 kg. Tests FT3 and FT4 used M12 x 100 mm coach screws, and tests FT5 and FT8, M10 x 100 mm coach screws as detailed in Table 13 (above).

A weight of mass 150 kg (1.471 kN) was selected for testing. This load represents a 150 mm diameter steel pipe 3.2 m long filled with water, commonly used in the sprinkler industry utilising a single bracket, meeting the requirements of BS EN 12845.

Typical M&E service loads would also include ductwork, cable trays, conduit, filter units, sewerage pipework and potentially assemblies supported from the structure with different load requirements but were not specifically investigated in the current work.

Panels that were fire tested were subjected to a 100 kW output from the ISO 9705 gravel bed burner. Gas temperatures and specific measurements from the fire are detailed further in results, section 7.4.

7.3.5.3 Post-fire conditions

Post-fire test measurements included pull-out force and char depths. Pull-out forces were measured once the sample had been allowed to cool for 60 minutes and took around 30 minutes to complete. Following pull-out testing, char was removed, and surface char depths were measured local to the screw fixings and in areas between the screw fixings. Results for screw fixing load capacities were tabulated and averaged with a ± 1 Standard Deviation (SD) showing the amount of variation in the measured results from the mean value.

7.4 Results and discussion

7.4.1 Benchmark ambient pull-out test results

7.4.1.1 Coach screws

To provide baseline pull-out-force measurements, four tests were initially conducted using pristine (non-fire tested) examples of both the HB S and HB X panels. For each panel, three of each screw fixing type (M10 x 100 mm, M10 x 120 mm, M12 x 100 mm and M12 x 120 mm) were embedded and then pull-out force determined at penetration depths of 50 mm, 70 mm, 90 mm, and 110 mm. All screw fixings were equidistantly spaced and positioned so as not to lie along the joint of two wood segments shown in Figure 7-12.

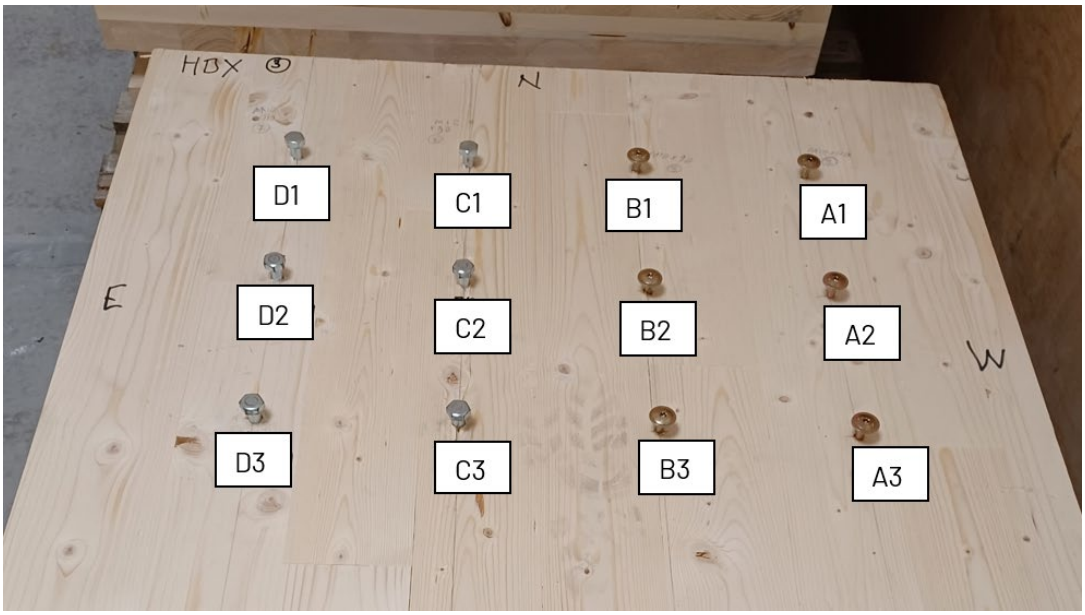


Figure 7-12 : Pristine CLT panel embedded with M10 & M12 fixings prior to pull-out testing.

Pull-out forces measured as a function of embedment depth are shown in Table 14 and Figures 7-13 and 7-14. These illustrate the positive linear relationship between pull out force and embedment depth for the two panel types and two coach screw diameters. The increased pull-

out resistance of the M12 coach screw relative to M10 coach screws is also evident for embedment depths greater than 50mm. It is apparent that there is very little difference in results between the two different adhesives shown in the graphs. For full tabulated test results, see Appendix C – Supplementary material – Fixings.

Table 14 - Average pull-out results for M10 and M12 screw fixings (showing uncertainty expressed as a ± 1 Standard Deviation (SD) showing the amount of variation in the measured results from the mean value).

Fixing reference and embedment depth	Test AT1 (kN) ± 1SD	Test AT2 (kN) ± 1SD	Test AT4 (kN) ± 1SD	Test AT5 (kN) ± 1SD
Fixing type D M12 x 120 mm Embedment depth @ 110 mm	25.1 + 2.6	23.7 + 2.4	N/A	N/A
Fixing type A M10 x 120 mm Embedment depth @ 110 mm	19.1 + 2.3	16.1 + 0.8	N/A	N/A
Fixing type C M12 x 100 mm Embedment depth @ 90 mm	19.6 + 1.8	16.4 + 0.8	N/A	N/A
Fixing type B M10 x 100mm Embedment depth @ 90 mm	17.0 + 1.9	13.9 + 0.7	N/A	N/A
Fixing type B M12 x 100mm Embedment depth @ 70 mm	N/A	N/A	14.0 + 0.3	16.1 + 0.4
Fixing type B M10 x 100mm Embedment depth @ 70 mm	N/A	N/A	14.3 + 2.4	12.0 + 0.6
Fixing type C M12 x 100mm Embedment depth @ 50 mm	N/A	N/A	8.9 + 0.6	9.2 + 0.4
Fixing type B M10 x 100mm Embedment depth @ 50 mm	N/A	N/A	8.8 + 1.0	8.1 + 1.0

It is assumed that the observed variability in pull out force at each depth is attributed to intrinsic variations in the physical properties of the wood (density, resin content, moisture content, structural inhomogeneity) and the panel's construction (multiple wood lengths glued into multiple layers). Sub-surface knots may also have been a factor.

Results indicate that prior to fire exposure, the capacities of the coach screws are capable of supporting the specified water filled sprinkler pipework (i.e. 4.9 kN (500 kg) at 20 °C (ambient) conditions detailed in Table 40 of BS EN 12845).

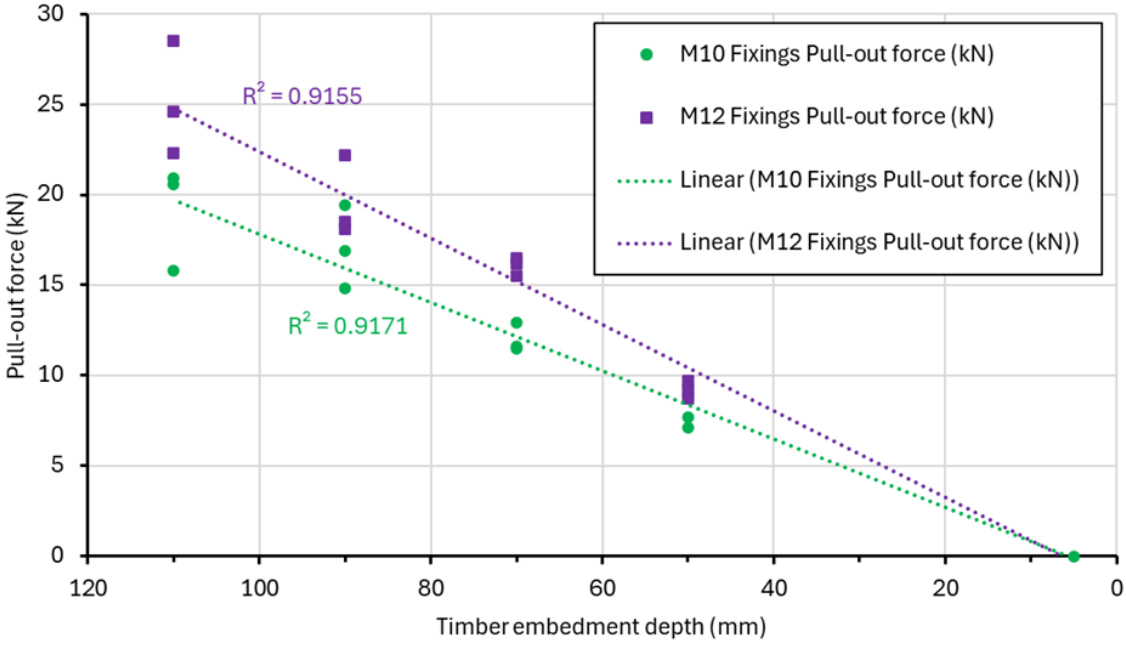


Figure 7-13 : Pull-out force versus embedment depth for HB S adhesive, ambient conditions.

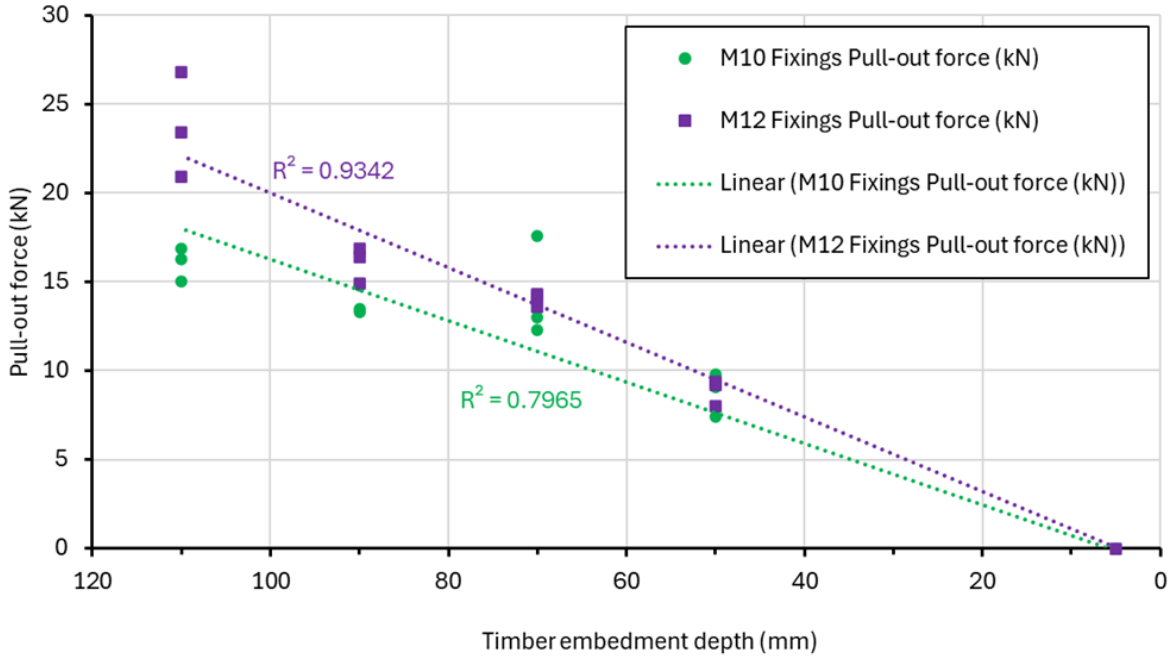


Figure 7-14 : Pull-out force versus embedment depth for HB X adhesive, ambient conditions.

The linear line of best fit has been extended to reach an embedment depth of 5 mm with zero load capacity; at this embedment depth the fixing holds its own weight.

7.4.1.2 Stud screws and rod hangars

Stud screws and rod hangers were assessed at their maximum embedment depth of 60 mm with holes pre-drilled as advised by the supplier (see Figure 7-10 (C-F), Figure 7-15, and Table 15). These screw fixing types are currently supplied for suspension of M&E services in timber construction. Figure 7-15 shows the pull-out force results for each stud screw and rod hanger

at ambient temperature. References/naming convention (A1 to D3) shown in Figure 7-15 relate to location on the test panel not the fixing types detailed in Figure 7-10.

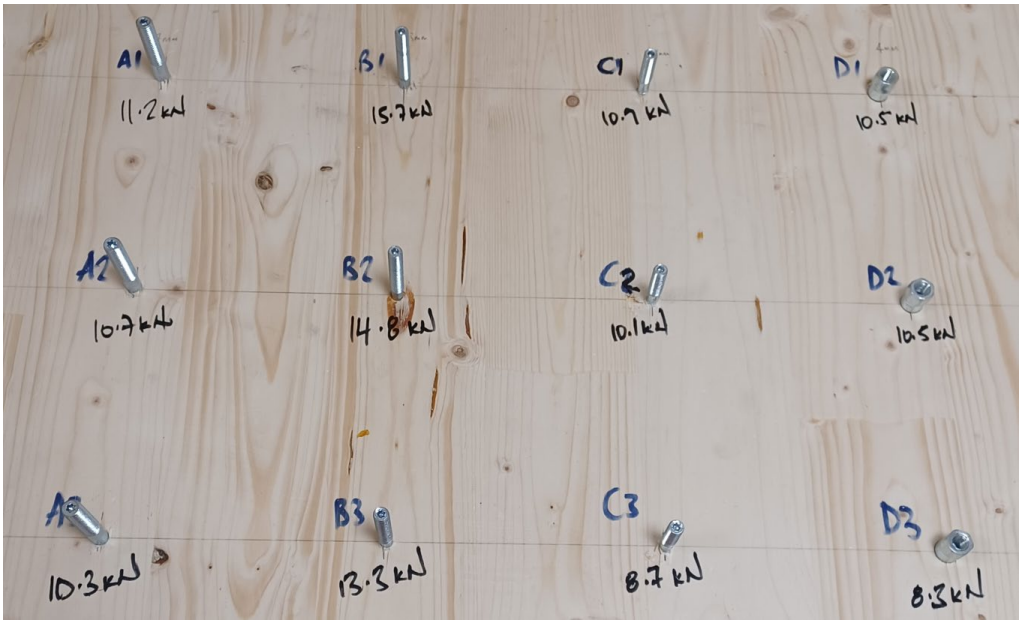


Figure 7-15 : Standard Industrial-type screw fixings for M&E services (ambient conditions)(A1-3 M12 stud screw, B1-3 M10 stud screw-long, C1-3 M10 stud screw-short, and D1-3 M10 rod hanger).

Table 15 shows average pull-out results for both ambient and post-fire testing of the industrial screw type fixings with a standard deviation. Results show the difference from original embedment depths of 60 mm to the measured embedment depths taken post-fire providing and equivalent charring rate based on the 30 min fire test.

Table 15 - Average pull-out results for standard industrial stud screw and rod hanger fixings (showing uncertainty expressed as a ± 1 Standard Deviation (SD) showing the amount of variation in the measured results from the mean value).

Fixing type	Initial embedment depth (mm)	Mean ambient pull-out force (kN) ± 1 SD	Post-fire embedment depth (mm)	Mean post-fire pull-out force (kN) ± 1 SD	Equivalent charring rate mm/min
M12 Stud bolt	60	10.7 ± 0.5	39	< 0.1	0.7
M10 Studbolt-long	60	14.6 ± 1.2	43	0.7 ± 0.6	0.57
M10 studbolt-short	60	9.9 ± 1.1	39	0.1 ± 0.1	0.7
M10 Rod hanger	60	9.8 ± 1.6	43	2.5 ± 1.7	0.57

Results show load capacities at both ambient (baseline) and post-fire in Table 15. Most notable from the results are:

- The loss of strength from ambient to post-fire in the stud screws, with M12 screws losing 100% load capacity and all others greatly reduced.
- The variation that can exist in pull out force between screw fixing of identical diameter and embedment depth.
- Equivalent charring rate is higher than standard screw fixings (see section 7.4.2.2).

7.4.2 Fire challenge assessment and charring

Ideally the fire challenge tests would mimic the conditions of a fully developed fire in a full-scale compartment. Gas temperatures alone cannot describe the heat transfer into the CLT surfaces. Full-scale testing of CLT compartments and the potential for a different fuel source (propane) would provide a different thermal contribution from the fuel and re-radiation from adjacent surfaces. However, combining gas temperature data with the resulting char rates gives some indication of how the rig approximates to reported full-scale referenced tests.

7.4.2.1 Gas Temperatures

Gas/flame temperatures were measured 15 mm below the wood sample around the screw fixings shown in Figure 7-8, (TC01 – TC06 inclusive). Temperature results for fire tests were all very similar. Figures 7-16 and 7-17 show average temperature data for 30 and 60 min fire durations respectively, consistent with a fully developed compartment fire (i.e. >600 °C). Temperatures were approximately consistent for 30 min for tests FT1, FT2, FT3, FT6 & FT7 and 60 min for tests FT4, FT5 & FT8. Gas temperatures were observed to be around 100 °C greater closer to the burner at TC04, 05 & 06, than those further from it at TC01, 02 & 03. This resulted in lower pull-out forces for the screw fixings located closer to the burner. For example, in FT1, three M10 x 120 mm screw fixings experienced pull-out forces of 9.1, 9.5 and 12.5 kN with locations 360, 540 and 720 mm from the S edge (see Figure 7-8) moving away from the burner. These results are presented as an average value of 10.4 kN ±1.5 Standard Deviation (SD).

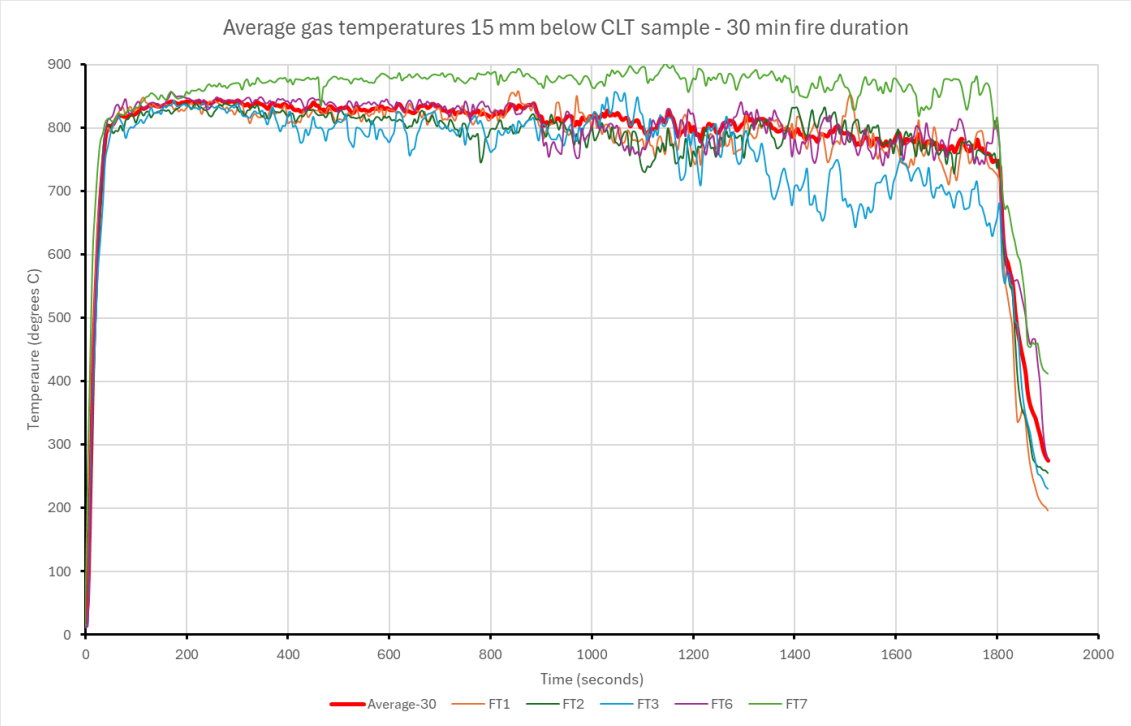


Figure 7-16 : Average gas temperatures measured 15 mm below the underside of the CLT sample for 30min, tests (FT1, 2, 3, 6 and 7).

It can be seen from Figure 7-16 that the temperature for FT3 is lower than other 30 min fire tests. This was caused by frost developing on the cylinder affecting gas supply pressure, causing a drop in output temperature (< 100kW) from the burner at ~700 seconds. FT7 shows a higher temperature output which resulted from warming the cylinder during the test, providing a very steady burner output of 100kW. This is also reflected in test FT8 shown in Appendix C.

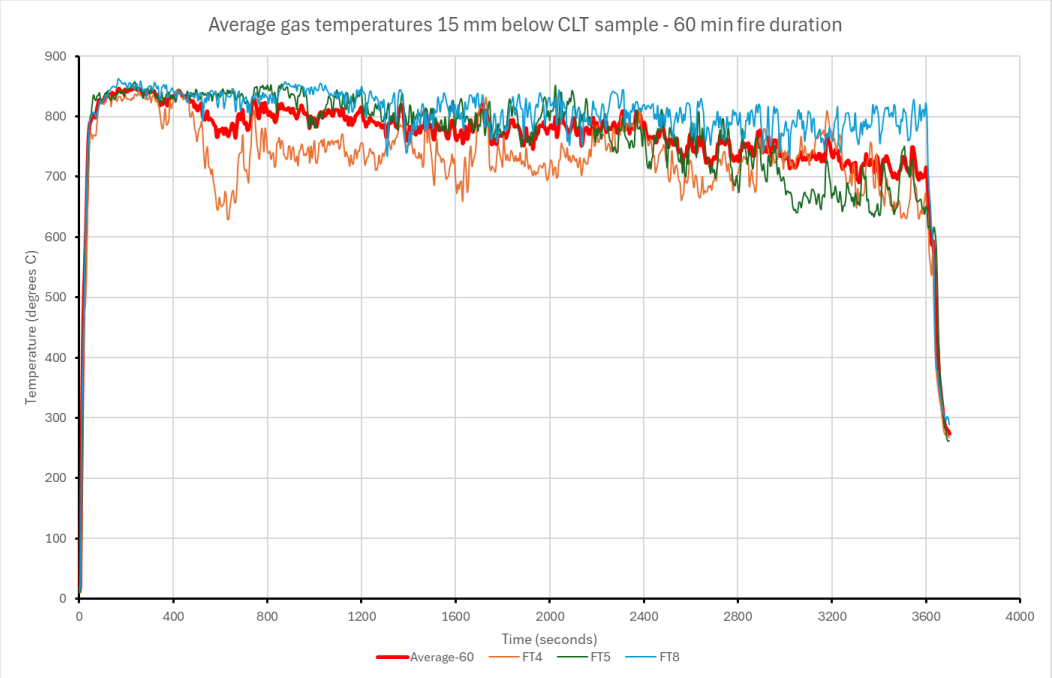


Figure 7-17 : Average gas temperatures measured 15 mm below the underside of the CLT sample for 60min, tests (FT4, 5 and 8).

Test FT4 shows a lower than average gas temperature for the 60 min duration and a drop off at ~500-700 seconds. Burner output remained constant at 100 kW for 45 mins until a drop off due to frost build up on the cylinders. The drop off at ~500 seconds could potentially be due to early char formation, slowing contribution from the wood, but this is not proven in these experiments. For a full review of the temperature profiles for all fire tests, see supplementary material in Appendix C.

7.4.2.2 Char formation

Char depths were measured following pull-out tests. Each sample had char carefully scraped away as shown in Figure 7-18, using a wallpaper scraper and hand brush.

Figure 7-18 : CLT panel with the char removed around the screw fixings (left) and pilot drill holes for remaining slab thickness measurements (right).

To determine embedment depth on the resulting uneven surface, pilot holes were drilled through the full depth of the sample and measurements were taken of the remaining timber depth to provide char depth measurements shown in Figure 7-19, not dissimilar to the procedure used by Brandon et al [263].

Measuring consisted of using a 3 mm diameter rod pushed through the pilot hole to a small flat circular plate ~15 mm diameter that sat on the face of the charred surface. The depth of insertion from the opposite face from the fire was marked on the rod then measured and recorded with digital callipers. Where screw fixings were removed from the sample, the circular plate was inserted into the depth of the 'dishing' and the same measuring principal applied. Figure 7-19 shows the details for char measurements taken.

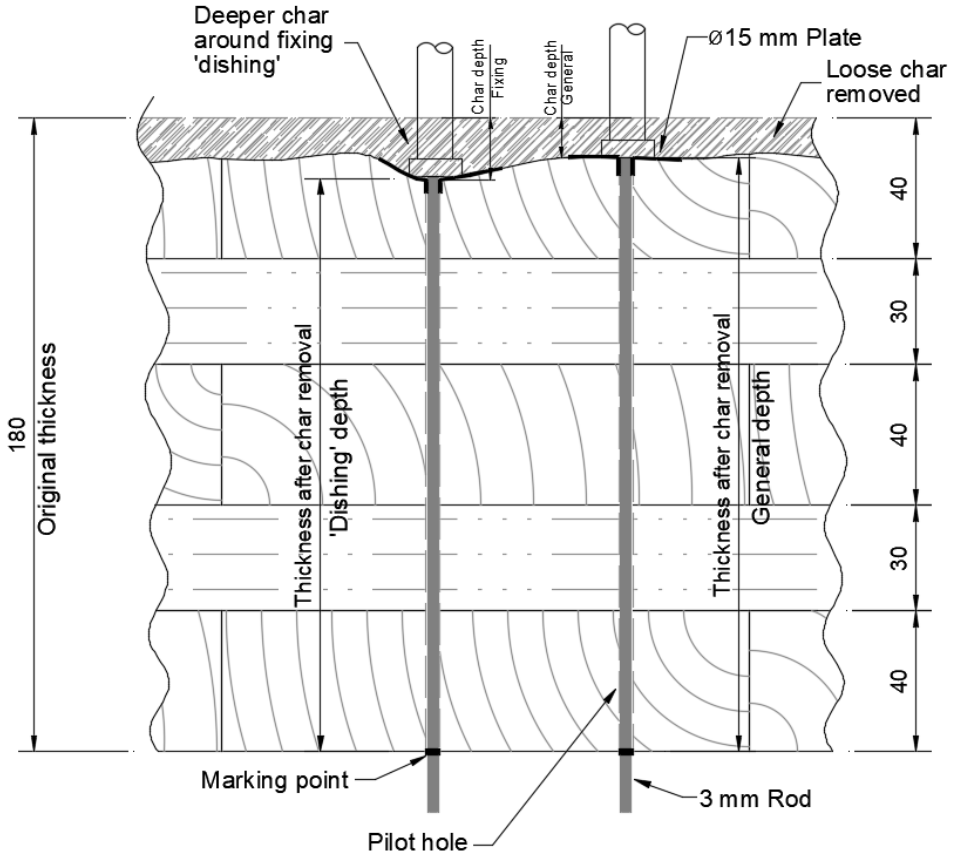


Figure 7-19 : Shows how the char depths were measured with a 3 mm diameter rod pushed through pilot holes to the 15 mm diameter plate with marking point.

Figures 7-20 and 7-21 show loss of structural material (char) from the surface of the sample. They also show the 'dishing' effect at the surface and blackening internally where screw fixings were installed. The extent of charring with depth is difficult to define, but internal temperatures measured (Table 18 and Figure 7-25) confirm discolouring and charring, as described by Drysdale [62]. However, reduced pull-out results indicate that less unburnt timber is present around the M12 screws than M10.

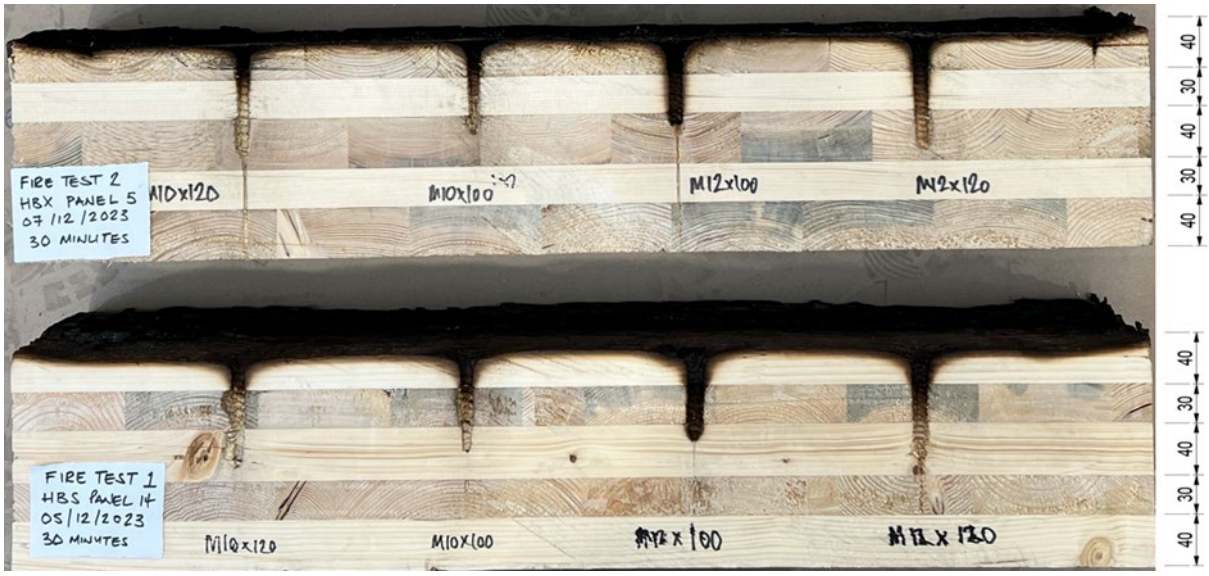


Figure 7-20 : Cross section of tests FT1 and FT2 showing loss of material at the surface of the CLT panel and the 'dishing' effect localised around the screw fixings after 30 min fire exposure.

Figure 7-21 : Cross section of tests FT4 and FT5 showing loss of material at the surface of the CLT panel and the 'dishing' effect localised around the screw fixings after 60 min fire exposure.

Figure 7-22 shows a close-up of the charring effect of heat conduction through the screw fixings, with greater charring at the M12 coach screws than the M10 coach screws, which was observed across all fire tests. The M10 coach screw shows partial charring through the screw embedment and rupture of the wood fibres towards the location of the tip.

Figure 7-22 : Enlarged view of internal charring through heat conduction at the coach screws.

Table 16 (general) and Table17 (at fixings) show loss of material due to char formation on the surface, which are slightly less than measurements recorded at the ceiling by Hadden et al [105].

Table 16 - Average loss of structural material measured in locations between screw fixings for both adhesive types after the fire.

Location of measurement (Figure 11)	Average loss (mm) ± 1 SD at 30 min	Average loss (%) from sample (180 mm) at 30 min	Equivalent charring rate mm/min	Average loss (mm) ± 1 SD at 60 min	Average loss (%) from sample (180 mm) at 60 min	Equivalent charring rate mm/min
Location 01 (general area)	11 ± 1.2	6	0.37	18 ± 0.8	10	0.3
Location 02 (general area)	14 ± 1.6	8	0.47	20 ± 2.4	11	0.33
Location 03 (general area)	11 ± 0.9	6	0.37	18 ± 1.2	10	0.3
Location 04 (general area)	12 ± 1.4	7	0.4	20 ± 2.6	11	0.33
Location 05 (general area)	9 ± 1.2	5	0.3	21 ± 2.4	12	0.35
Location 06 (general area)	11 ± 1.6	6	0.37	20 ± 0.5	11	0.33
Note: 0.6 -0.7 mm/min is typical of the literature mass loss rates for timber [72 & 78]						

Table 17 - Average loss of structural material measured at screw fixing positions for both adhesive types after the fire.

Fixing reference and embedment depth (Figure 11)	Average loss at fixing (mm) ± 1 SD at 30 min	Average loss (%) from sample (180 mm) at 30 min	Equivalent charring rate mm/min	Average loss at fixing (mm) ± 1 SD at 60 min	Average loss (%) from sample (180 mm) at 60 min	Equivalent charring rate mm/min
A1 M10 x 120 mm (110 mm Embedment)	15 ± 1.7	8	0.5	24 ± 1.9	13	0.4
A2 M10 x 120 mm (110 mm Embedment)	17 ± 1.7	9	0.57	27 ± 1.6	15	0.45
A3 M10 x 120 mm (110 mm Embedment)	17 ± 3.3	9	0.57	30 ± 2.11	17	0.5
B1 M10 x 100 mm (90 mm Embedment)	15 ± 1.6	8	0.5	23 ± 0.9	13	0.38
B2 M10 x 100 mm (90 mm Embedment)	16 ± 0.5	9	0.53	29 ± 1.7	16	0.48
B3 M10 x 100 mm (90 mm Embedment)	17 ± 1.2	9	0.57	30 ± 1.2	17	0.5
C1 M12 x 100 mm (90 mm Embedment)	16 ± 2.6	9	0.53	29 ± 3.6	16	0.48
C2 M12 x 100 mm (90 mm Embedment)	19 ± 2.6	11	0.63	27 ± 3.6	15	0.45
C3 M12 x 100 mm (90 mm Embedment)	20 ± 2.4	11	0.67	32 ± 1.6	18	0.53
D1 M12 x 120 mm (110 mm Embedment)	16 ± 1.4	9	0.53	28 ± 1.6	16	0.47
D2 M12 x 120 mm (110 mm Embedment)	19 ± 1.7	11	0.63	32 ± 3.1	18	0.53
D3 M12 x 120 mm (110 mm Embedment)	18 ± 0.7	10	0.6	29 ± 7.3	16	0.48
Note: 0.6 -0.7 mm/min is typical of the literature mass loss rates for timber [72&78]						

Post-fire test results suggest that the larger diameter of the screw fixing, the greater the loss of char local to its insertion area.

Whilst tables 16 and 17 reference a typical charring rate between 0.6-0.7 mm/min, it is acknowledged that charring rates are higher in the initial stages of a fire and reduce as the char layer forms. It is confirmed that charring rates differ between wood species and fire exposure, where charring rate increases with heat flux [91].

7.4.2.3 Fire challenge conclusions

Mean gas temperatures of ~800°C show the fire to be significant, but the average charring rate at locations remote from the screw fittings of 0.32 mm/min is less than that measured during full-scale tests conducted by Haddon [105] of 0.6 mm/min at the ceiling. This would suggest that the fire conditions in this study are less severe than for a typical well-developed fire. This may be due to the design of the test rig and the lack of oxygen (needed for char oxidation) at the timber surface. This deviation needs to be considered as a significant factor in the overall conclusions drawn from this study.

7.4.3 CLT fixings and temperatures

7.4.3.1 CLT temperatures

Measurements within the sample show an increase in temperature in all 5-ply layers. After cut-off of the burner gas supply, internal temperatures continued to rise slowly which may contribute to further loss of load capacity post-fire extinguishment. This can be seen in Figure 7-23 for measurements at 20 mm above the exposed CLT and is consistent with findings by Gernay et al [263] and general locations of thermocouples are shown in Figure 7-24. It is also noticeable for tests FT1, 2, 3, 4, 7 and 8 that temperature remains at a constant 100°C for a period of time, until the moisture is driven off, before temperature starts to increase. Tests FT5 and FT6 show inconsistent results which could be due to the inconsistencies in CLT moisture condition at the time of the test.

In all but one fire test, no fragments of char were seen to fall off the test panels. Fire test 8 had small fragments of ~10 mm depth of char, fall from a small area of the panel < 10 %. In test FT4 (a 60 minute test), delamination at the glue line in a sacrificial HB S specimen (directly above the burner and not part of the test sample) was observed.

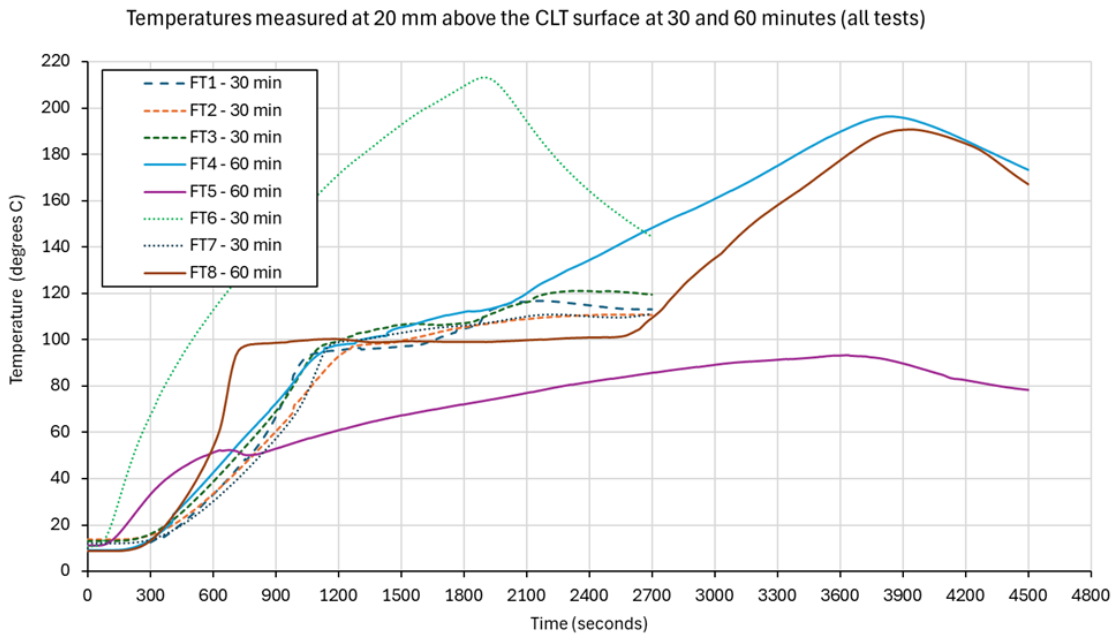


Figure 7-23 : Measurements of temperature within the CLT test sample at 20 mm above the exposed CLT surface at 30 and 60 min.

For a full review of the temperature profiles for all fire tests, see supplementary material in Appendix C.

7.4.3.2 Screw fixing temperatures

Tests FT1, 2, 3, 4, 5 and FT8 utilised coach screws shown in Figure 7-24. A consistent temperature rise from exposed screw head shank to the embedded screw tip was observed as shown in Table 18 and Figure 7-25.

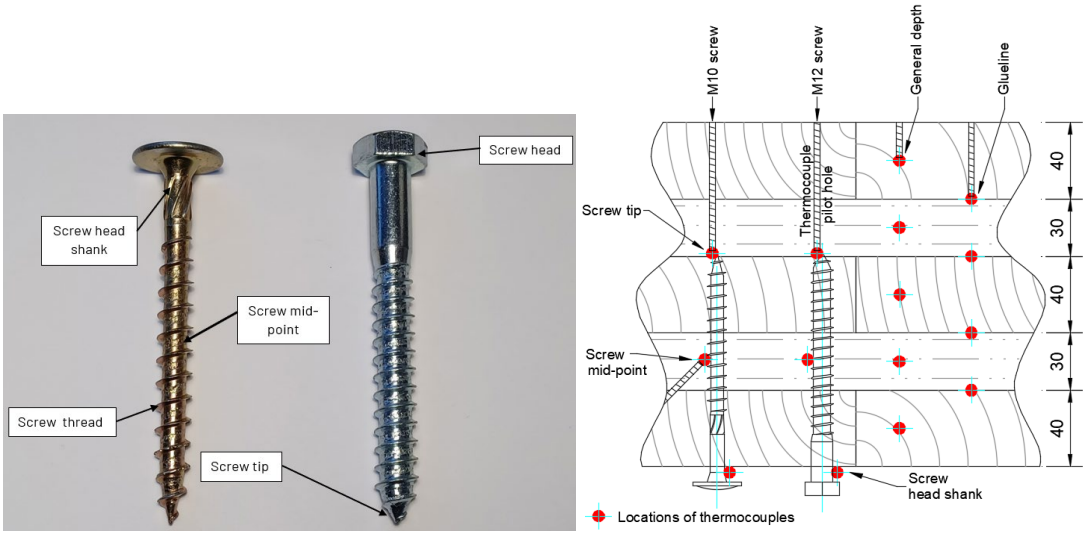


Figure 7-24 : Shows coach screws under test (left) and locations for thermocouples at different screw fixing locations, general ply depths, and glue line (right).

Measured temperatures at the screw head shank, mid-point, and tip for coach screws (M10 and M12) for tests FT1, 2, 3, 4, 5 and 8 are shown in Table 18 and Figure 7-25 at 30- and 60-min fire

durations. At 30 mins, screw head shank temperatures ranged from 554 - 717 ^{0}C, mid-point ranged from 133 – 292 ^{0}C, and tip ranged from 42 - 167^{0}C, with an average gas temperature ranging from 658 - 811^{0}C. At 60 mins, screw head shank temperatures ranged from 583 - 690^{0}C, mid-point ranged from 243 – 345^{0}C, and tip ranged from 57 - 127^{0}C, with an average gas temperature ranging from 651 - 823^{0}C. In stark contrast to the lower thermal conductivity of timber, much higher temperatures were reached adjacent to the screws which would account for the degradation of the load capacity of the timber as detailed by Khelifa et al [264]. The mid-point screw temperatures at a depth of 55 mm, are observed to be much greater than for the timber at the same time and depth shown in Table 18 and Figure 7-25. Measurements within the timber prove larger diameter M12 screws consistently result in higher temperatures than M10.

Table 18 - Average gas temperatures, wood temperatures at 55 mm above the exposed CLT sample and fixing temperatures in three locations at 30 and 60 min.

Test Reference/Measurement location	**FT1 M10 / M12**	**FT2 M10 / M12**	**FT3 M10 / M12**	**FT4 M10 / M12**	**FT5 M10 / M12**	**FT8 M10 / M12**
Average gas temperature @ 30 minutes (^{0}C)	725	736	658	718	773	811
Wood temperature, 55 mm depth @ 30 minutes (^{0}C)	13	20	19	19	15	20
Fixing head/shank temperature @ 30 minutes (^{0}C)	717 / 633	662 / 649	610 / 554	625 / 626	641 / 635	600 / 675
Fixing mid-point (55 mm) temperature @ 30 minutes (^{0}C)	133 / 224	217 / 206	197 / 250	182 / 238	216 / 292	212 / 262
Fixing tip temperature @ 30 minutes (^{0}C)	65 / 87	51 / 167	59 / 104	42 / 117	44 / 73	55 / 110
Average gas temperature @ 60 minutes (^{0}C)	X	X	X	673	651	823
Wood temperature, 55 mm depth @ 60 minutes (^{0}C)	X	X	X	52	43	55
Fixing head/shank temperature @ 60 minutes (^{0}C)	X	X	X	602 / 596	644 / 583	616 / 690
Fixing mid-point (55 mm) temperature @ 60 minutes (^{0}C)	X	X	X	243 / 302	282 / 335	273 / 345
Fixing tip temperature @ 60 minutes (^{0}C)	X	X	X	57 / 125	58 / 99	83 / 127
Note: X represents no data recorded post 30 minutes for fire tests FT1, FT2 and FT3.						

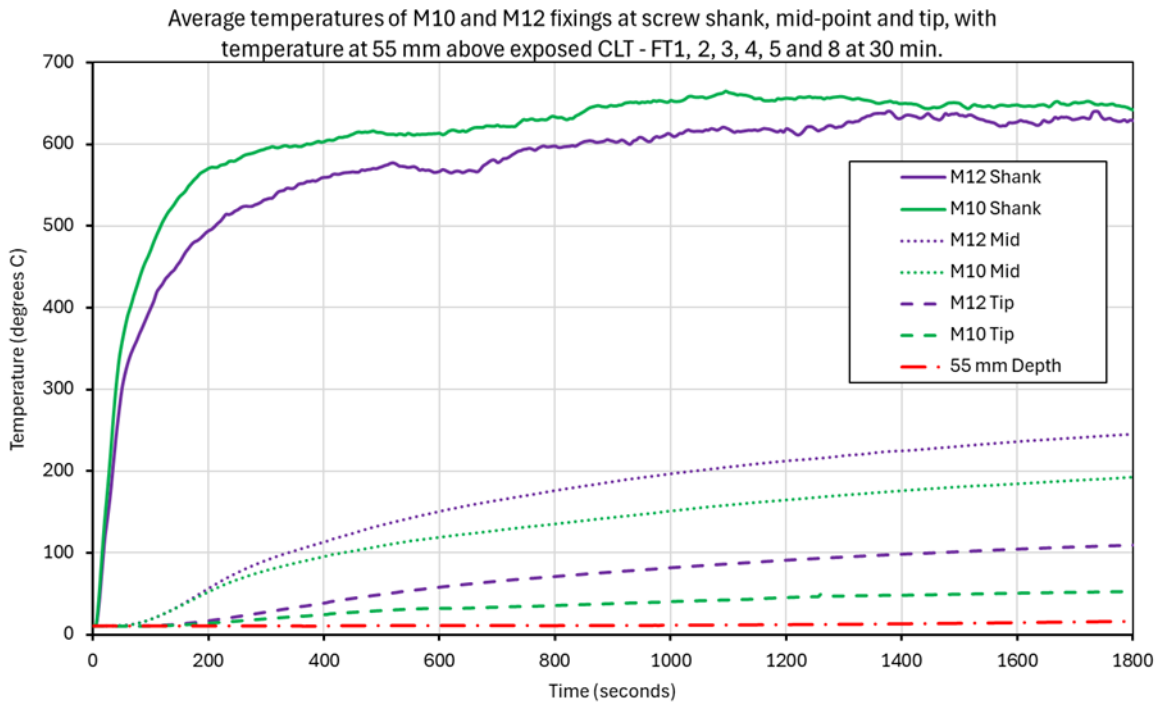


Figure 7-25 : Average screw fixing temperatures recorded as a function of depth at the CLT (screw shank), at the mid-point (internal) the screw tip (internal) and at 55 mm above the exposed CLT at 30 min.

Figure 7-25 shows the smaller M10 exposed screw head and shank heat up to a higher temperature profile within the flame than the larger M12 fixing. Internally at the mid-point and tip, M12 fixings have higher temperature profiles. This would suggest that the larger M12 fixings are conducting more heat into the CLT resulting in more localised charring and reduced pull-out force capacity.

For a full review of the temperature profiles for all fire tests, see supplementary material in Appendix C.

7.4.4 Fire pull-out test results

7.4.4.1 Pull-out forces – coach screws

Figures 7-26 and 7-27 show pull-out force versus embedment depths for each CLT adhesive type at ambient, 30 minutes and 60 minutes fire exposure. Embedment depth scatter shown in the graphs for post-fire test results derive from actual embedment depths where char has been removed. For example, after the fire actual embedment depth of 73 – 77 mm was found for pre-fire embedment depth of 90 mm.

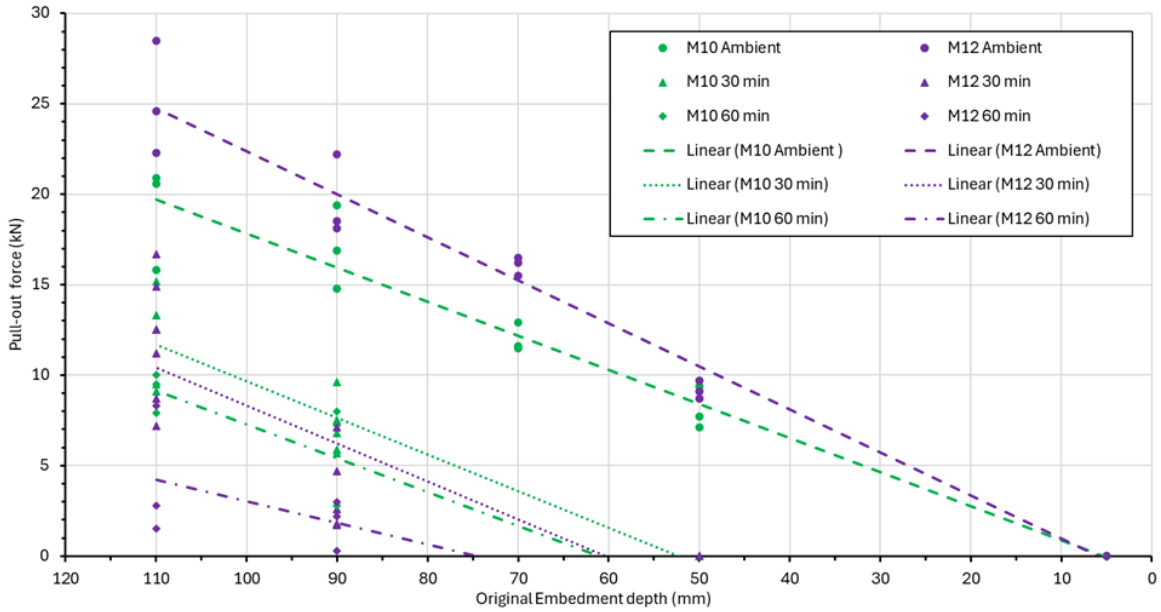


Figure 7-26 : Pull-out force versus embedment depth for HB S adhesive, ambient conditions, 30 and 60 min fire exposure.

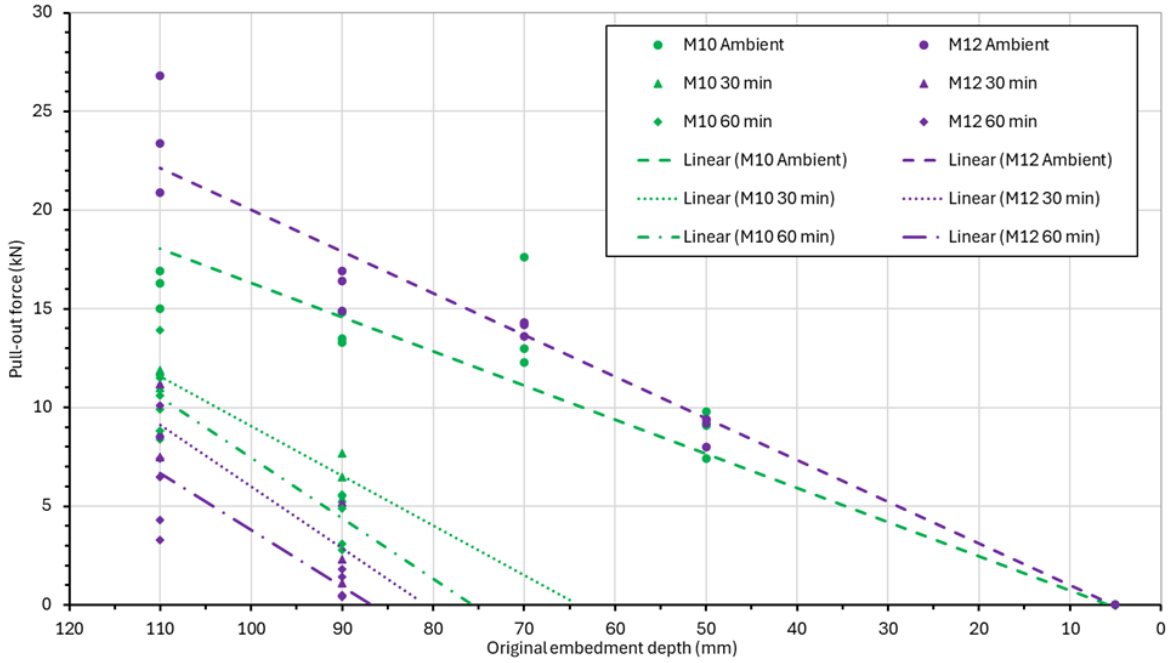


Figure 7-27 : Pull-out force versus embedment depth for HB X adhesive, ambient conditions, 30 and 60 min fire exposure.

Comparison of the two graphs (Figure 7-26 and 7-27) show a similar relationship in loss of load versus embedment depth. Above 50 mm embedment and at ambient conditions, M12 screw fixings having a greater load capacity than M10. However, post-fire results indicate the opposite, M10 screw fixings retain a greater load than M12. This result might seem counter intuitive but is believed to result from greater heat transfer into the CLT through the wider screws resulting in higher temperatures at the interface between the thread and the timber

leading to charring and loss of strength. The steeper slope of the post-fire tests shows the increased beneficial influence of embedment depth on the load capacity.

Figure 7-28 shows pull-out forces versus embedment depths for coach screws, measured across all tests (benchmark ambient, and post-fire) irrespective of CLT adhesive type.

Table 40 of BS EN 12845 requires a load capacity of 500 kg (4.9 kN) at ~20 °C, benchmark ambient loads suggest this is achievable with M10 screw fixings at an embedment depth of ~31 mm and M12 at ~25 mm (indicated in figure 7-28) assuming linear extrapolation. At ambient conditions with a minimum of 2-ply embedment ~ 70 mm, load capacity for M10 and M12 fixings is just over twice the requirement of BS EN 12845.

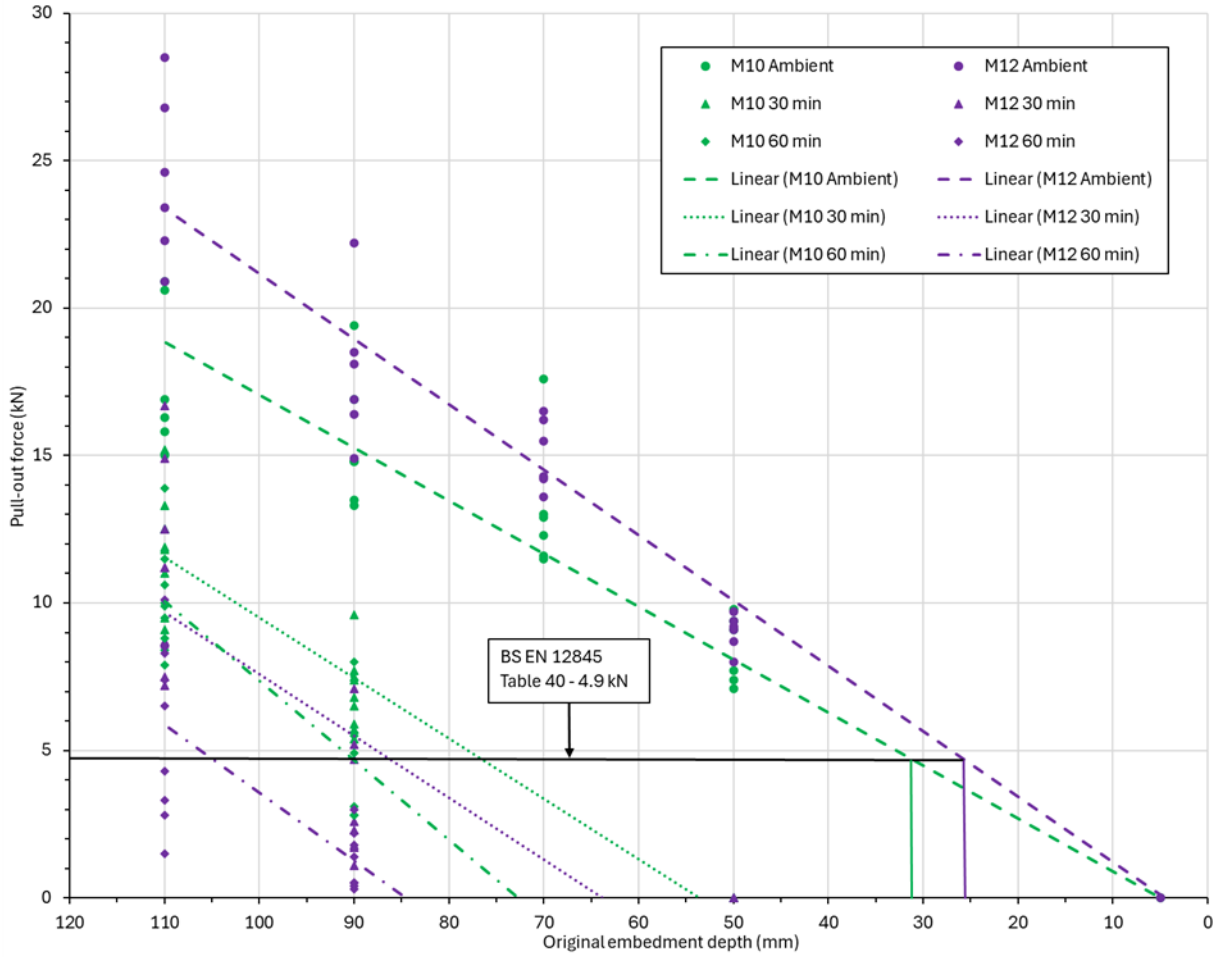


Figure 7-28 : Pull-out force versus embedment depth, all results, ambient conditions, 30 and 60 min fire exposure.

Where screw fixings were assessed at ambient conditions, load capacity exceeds the minimum specification. However, during and after fire there is significant reduction in load capacity when compared to ambient load measurements. This is due to the increase in timber temperature and char formation which leads to loss of material at the surface and loss of strength of the timber [264] and around the screw fixing. Without load, the screw fixing remains in place. However, char at these contact interfaces will increase in thermal conductivity as temperature rises [265] leading to increased heat conduction through the screw.

Four fire tests were conducted with screw fixings statically loaded replicating common sprinkler service loads. Results from these tests are discussed further in section 7.4.4.2.

7.4.4.2 Statically loaded, during fire tests

With screw fixings loaded, char formation at the contact point through the screw thread will be under compression, pulling the screw fixing in the direction of the force and leaving a small char void above the thread and compressing the char layer below, shown in Figure 7-29. Contact surfaces between the wood and screw thread are reduced. Once the char extends to the outer circumference of the screw thread, the effective embedment depth is reduced to a point where detachment occurs.

This is evident in the two statically loaded tests (FT3 & FT4) which recorded catastrophic failure of the screw fixing at ~ 20 min (full pull-out). In the other two loaded tests (FT5 & FT8) the cable failed at ~10 min and ~19 min respectively, with the screw fixing remaining in place. However, pull-out forces of the loaded screw fixings were significantly reduced. The average capacity of the same unloaded screw fixings in tests FT5 & FT8, were recorded at 5.4 kN and 4.4 kN, indicating a significant loss from ambient test results. Loaded fixings were recorded at 3.0 kN and 1.4 kN respectively, representing a 56% and 47% loss from unloaded screws due to load.

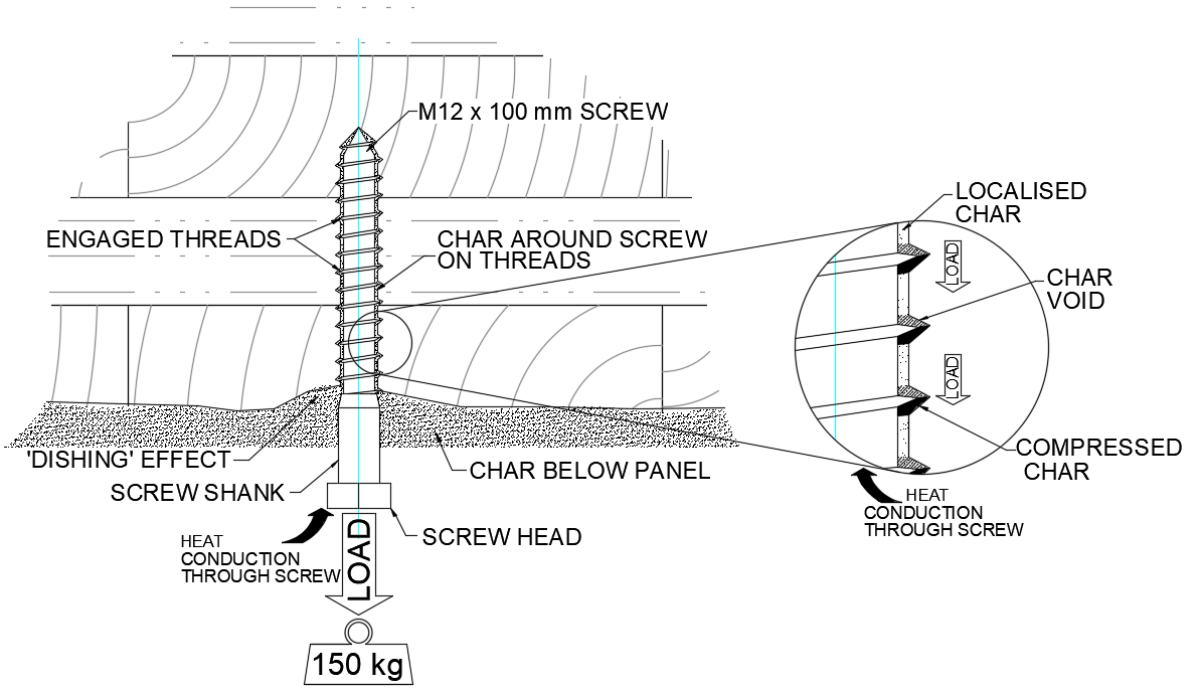


Figure 7-29 : Shows a coach screw under load, heat conduction through the fixing leading to char formation at the contact point between screw thread and timber.

At temperatures above 200-250 °C, and through prolonged heating at lower temperatures ~>120 °C, wood discolours and chars, described by Drysdale [62]. Screw fixings A2 (M10 x 120 mm) and D2 (M12 x 120 mm) shown in Figure 7-12 and Figure 7-18, included thermocouples located at the screw head shank, mid-point, and tip. Temperatures were recorded in fire tests FT1, FT2, FT3, FT6 and FT7 at 30 minutes. The results have been averaged showing uncertainty expressed as a standard deviation for each screw fixing type.

Using ambient baseline results, the remaining capacity for the coach screws once cooled is shown in Table 19. This highlights the severity of the load capacity reduction for M12 screw fixings. This has significant implications for the M&E industries fixing into timber.

Table 19 - Capacity of M10 and M12 (coach screws) post-fire at various embedment depths.

Fixing Type	Embedment depth (mm)	Ambient mean pull-out force (kN) ± 1 SD	30 min fire exposure mean pull-out force (kN) ± 1 SD	60 min fire exposure mean pull-out force (kN) ± 1 SD
M10 coach screw (A2)	110	17.6 ± 2.3	11.9 ± 1.8	10.1 ± 1.7
	90	15.5 ± 2.1	6.9 ± 1.2	4.7 ± 1.8
	70	13.2 ± 2.1	-	-
	50	8.4 ± 1.1	0#	-
M12 coach screw (D2)	110	24.4 ± 2.6	11.0 ± 3.1	5.9 ± 2.8
	90	17.8 ± 2.3	3.3 ± 2.0	1.3 ± 0.9
	70	15.1 ± 1.1	-	-
	50	9.0 ± 0.6	0#	-
Note: 70 mm embedment depth and 50 mm embedment for 60 min was not fire tested.				
0# Based on recorded pull-out force of 0.				

M8 x 100 mm screw fixings were assessed after 30 and 60 minutes fire exposure. Screw fixings were embedded to a depth of 90 mm. After fire testing, pull-out forces after 30 and 60 minutes were measured as 7.6 kN and 7.7 kN, respectively. For comparison, both M10 and M12 screw fixings embedded at 90 mm, M10 measured (averaged) at 6.9 kN and 4.7 kN respectively, with M12 screw fixings measuring (averaged) 3.3 kN and 1.3 kN, respectively. The smaller diameter of the M8 screw fixings will conduct less heat which has been shown to reduce the loss of load capacity.

7.4.4.3 Bracket assemblies

On completion of tests incorporating individual screw fixings and evaluating the data available from all tests, a single test (FT7) incorporated bracket assemblies common with the M&E industry. Using a mixture of M8, M10 and M12 coach screws together with 41 x 41 mm slotted channel, top-hat brackets and M10 allthreaded rod, a CLT test panel was prepared for fire testing. Figure 7-30 shows the design layout of the CLT test panel with the different bracket components and confirmation of screw fixing placements. Each bracket component had 2 x fixings into the CLT with the exception of bracket assemblies P,Q, R, S, T and U.

Due to the physical size of the 41 x 41 mm slotted channel and the size of the coach screw heads, the embedment depth was significantly reduced for M10 and M12. The smaller M8 coach screw heads were installed in-between the slotted channel as detailed in Figures 7-31 and 7-32. For top-hat brackets, all coach screws were fully embedded.

Assemblies A to K employed top-hat brackets. L, M and N employed 41 x 41 x 300 mm long slotted channel and P to U employed 41 x 41 x 150 mm long slotted channel.

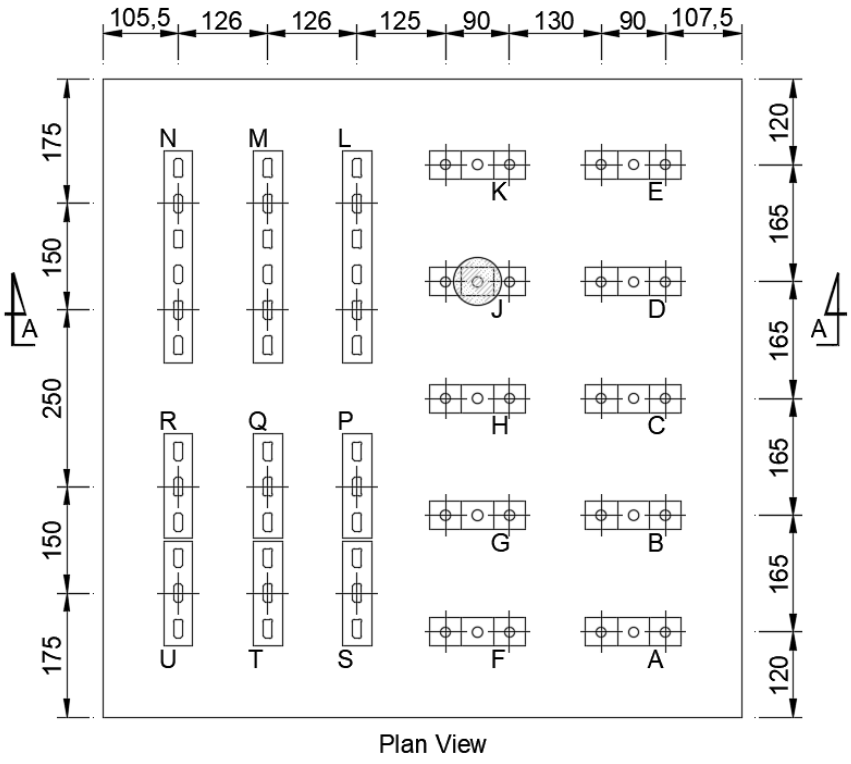


Figure 7-30 : Plan view of bracket layout A to U (bracket J incorporates 150 kg weight).

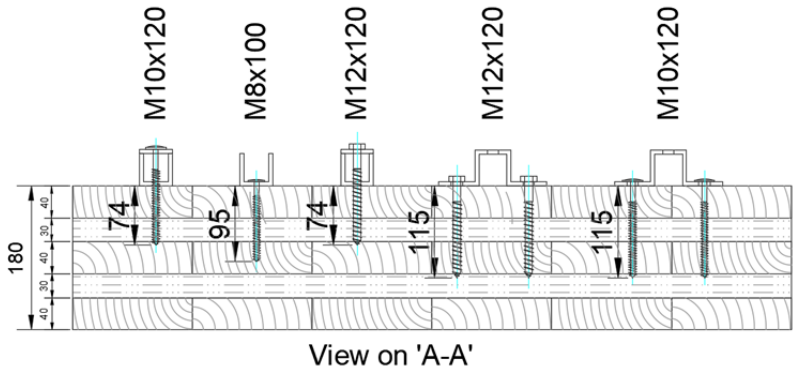


Figure 7-31 : Section through CLT bracket panel with embedment depths shown.

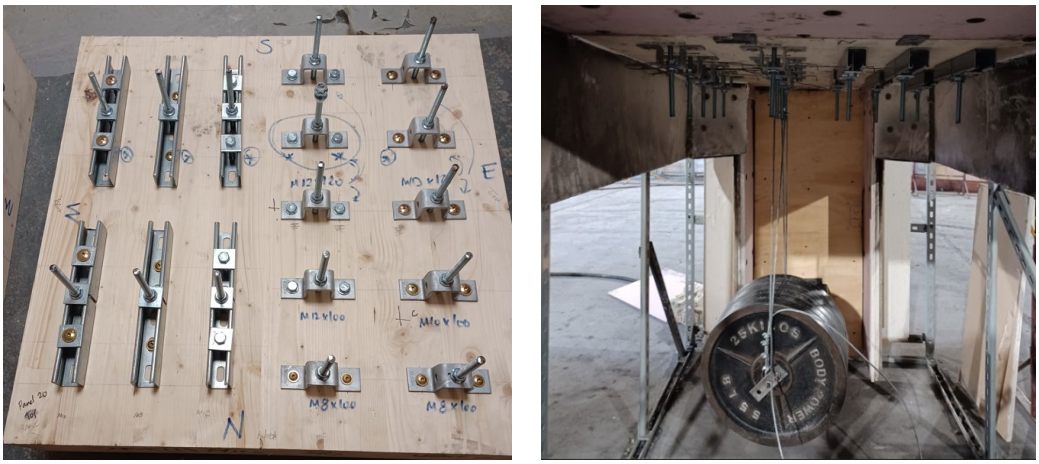


Figure 7-32 : Photograph of the completed test panel (left) and installed prior to testing with bracket J under load (right).

Test FT7 utilised a HB S CLT panel for a period of 30 minutes. On completion of the test, the panel was allowed to cool for a period of 60 minutes then followed by pull-testing. During the testing it was observed that some of the bracket components were glowing bright orange in colour and those closer to the burner were glowing white.

It was also observed as can be seen in Figure 7-33 that the bracket assembly under load has distortion of the top-hat and stretching of the M10 allthreaded rod.

Figure 7-33 : Photographs showing bracket assemblies during the test (left), and deformation of the bracket assembly post-fire (right).

The results of the test for each bracket assembly are detailed in Table 20. It is confirmed that during pull-out testing there was significant deformation of the top-hat brackets which may not represent exact full capacity of the screw fixings under test. On completion of the testing, coach screws were distorted from original shape through the central 'pulling' from the two fixings.

All results shown in Table 20 were taken to maximum capacity of the Staht t25 digital pull-out tester of 25 kN.

Table 20 - Pull-out results for full bracket assemblies.

FT7 (CLT Panel 20) 10.01.2024 - HB S - 30 Minutes			
Bracket Reference	Load (kN)	Bracket Reference	Load (kN)
A M8 x 100 mm 2 x fixings at 95 mm embedment	14.5	L M12 x 120 mm 2 x fixings at 74 mm embedment	0.8
B M10 x 100 mm 2 x fixings at 95 mm embedment	18.1	M M8 x 100 mm 2 x fixings at 95 mm embedment	17.2
C M10 x 120 mm 2 x fixings at 115 mm embedment	25+	N M10 X 120 mm 2 x fixings at 74 mm embedment	3.6
D M10 x 120 mm 2 x fixings at 115 mm embedment	24.8	P M12 x 120 mm 1 x fixing at 74 mm embedment	1
E M10 x 120 mm 2 x fixings at 115 mm embedment	25+	Q M8 X 100 mm 1 x fixing at 95 mm embedment	10
F M8 x 100 mm 2 x fixings at 95 mm embedment	16.8	R M10 x 120 mm 1 x fixings at 74 mm embedment	4.2
G M12 x 100 mm 2x fixings at 95 mm embedment	10.9	S M12 x 120 mm 1 x fixing at 74 mm embedment	3.1
H M12 x 120 mm 2 x fixings at 115 mm embedment	25	T M8 x 100 mm 1 x fixing at 95 mm embedment	12.5
J M12 X 120 mm 2 x fixings at 115 mm embedment	22.2	U M10 X 120 mm 1 x fixing at 74 mm embedment	6.2
K M12 x 120 mm 2 x fixings at 115 mm embedment	18.1		
+ Represents a value greater than 25.0kN (Tester maximum load of 25kN - No pull-out force could be measured post-fire test). Full bracket assemblies			

Results shown in Table 20 indicate that embedment depth is critical to retaining load capacity. Brackets C, D, E and H had the highest load capacity > 24.8 kN with maximum embedment depth of 115 mm.

Brackets A, B, F, G, J, K, M, Q and T had a load capacity > 10 kN up to 22.2 kN with embedment depth of ≥ 95 mm.

The lowest recorded load capacity was brackets L, M, P, R, S and U ranging from 0.8 to 6.2 kN. These brackets have embedment depths of 74 mm due to the configuration and physical size of the bracket and coach screw head.

Due to the very limited results from this individual bracket test, it cannot be confirmed what impact the mass of material of the bracket component had in relation to heat conduction into the CLT from the full assembly.

In summary of the bracket results the data suggests that embedment depth is the most crucial factor for retaining load capacity. The doubling of fixings plays a significant role in load capacity when comparing to individual results and diameter of fixing is a final consideration.

7.5 Conclusions

The study investigated the structural integrity of screw fixings used to suspend sprinkler pipework and Mechanical and Electrical (M&E) systems from timber ceilings, particularly under fire conditions. While these fixings perform well under ambient conditions by exceeding load bearing requirements and showing improved strength with larger diameters, their performance deteriorates significantly and, under load, catastrophically during fire exposure. The degradation is primarily due to char oxidation near the surface and internal weakening of the timber around the screw thread, caused by heat conduction from the metal screws.

The research highlights that screws with narrower shanks and wider threads retain more strength under fire, whereas wider shanks (M12 screws) accelerate heat transfer and charring, reducing load capacity. The failure of these fixings during fire is both rapid and structurally significant, posing potential serious risks such as falling equipment, fire spread through compromised compartment boundaries, and damage to critical systems like fire sprinklers. These findings underscore the need for further investigation and improved fixing designs to mitigate such hazards.

Importantly, the study suggests that real-world fire scenarios, especially in mass timber construction, may present even harsher conditions than those tested. The presence of additional metalwork in the flame zone could further accelerate failure. While post-fire cooling improves timber strength, the critical concern remains the performance of fixings during active fire. The inclusion of sprinkler systems can mitigate these risks, but in their absence, new standards and testing protocols are essential to ensure safety and reliability.

Chapter 8 : Conclusions

This thesis explored the performance of sprinkler systems in protecting exposed timber surfaces, particularly Cross Laminated Timber (CLT), and investigated the structural integrity of screw fixings used in timber ceilings under fire conditions for the support of Mechanical and Electrical (M&E) services, including sprinkler pipework. The study aimed to determine whether commercially available sprinkler heads and standard fixing methods could provide adequate fire protection and mechanical stability in timber buildings, which present unique challenges due to their combustible nature.

Timber use in construction has grown steadily, with engineered timber such as CLT and glulam growing at ~ 4–6% (compound annual growth rate). Mass timber projects are expanding quickly, and the global timber construction market is expected to more than double by 2035, driven by sustainability and innovation, which will require robust fire protection measures.

8.1 Sprinkler Discharge Characteristics and Timber Protection

The first part of the study focused on the discharge characteristics of CUP-type sprinklers, which are commonly used in commercial fire protection systems. These sprinklers were selected for their ability to discharge water both upward and downward, a feature critical for wetting ceilings and walls in compartments with exposed timber surfaces. Tests were conducted on CUP-type sprinklers from five manufacturers, all of which shared the same size, temperature rating, 'K' factor, and product certification credentials.

Results confirmed that all tested sprinklers met minimum discharge specifications. Interestingly, slightly elevated 'K' factors were observed across the board, indicating a marginal increase in water discharge. While this deviation from nominal values could theoretically affect system performance, the increase was not sufficient to compromise the effectiveness of the sprinklers in controlling fires in timber environments.

Water distribution analysis revealed that the ratio of discharge above and below the sprinkler head was more balanced than manufacturer specifications suggested. This finding is particularly relevant for ceiling wetting, as it demonstrates that upward water flow is sufficient to reach the ceiling surface when the sprinkler is mounted below it. Ceiling wetting was achieved at distances of 150–180 mm below the ceiling, which is critical for sprinkler response time, where it can help slow or prevent the surface spread of flame.

Wall wetting, a less commonly assessed criterion in sprinkler performance, was evaluated through bespoke testing. The study found that water was consistently delivered to the top 0.5 m of the wall at the ceiling interface, even at lower pressures provided the head was sufficiently close to the wall. A modification to the head placement rules in respect of walls being followed (half normal separation distances) is envisaged. This area is particularly vulnerable to fire spread, and effective wetting here could reduce the risk of vertical flame propagation. However, performance varied among the tested sprinklers, with the worst-performing unit providing minimal coverage in corner areas. In such cases, closer spacing to the corner wall is recommended to improve water distribution and enhance wall wetting.

Ceiling wetting results varied widely, ranging from excellent to poor coverage. These variations represent worst-case and best-case scenarios in sprinkler performance. In real fire conditions, the upward thrust of hot gases from the fire plume could assist in spreading water more effectively across the ceiling. Figure 8-1 illustrates the extremes of ceiling wetting in a 9 m × 9

m compartment using standard sprinkler spacing of 3 m x 3m with sprinklers discharging at a pressure of 3.0 bar.

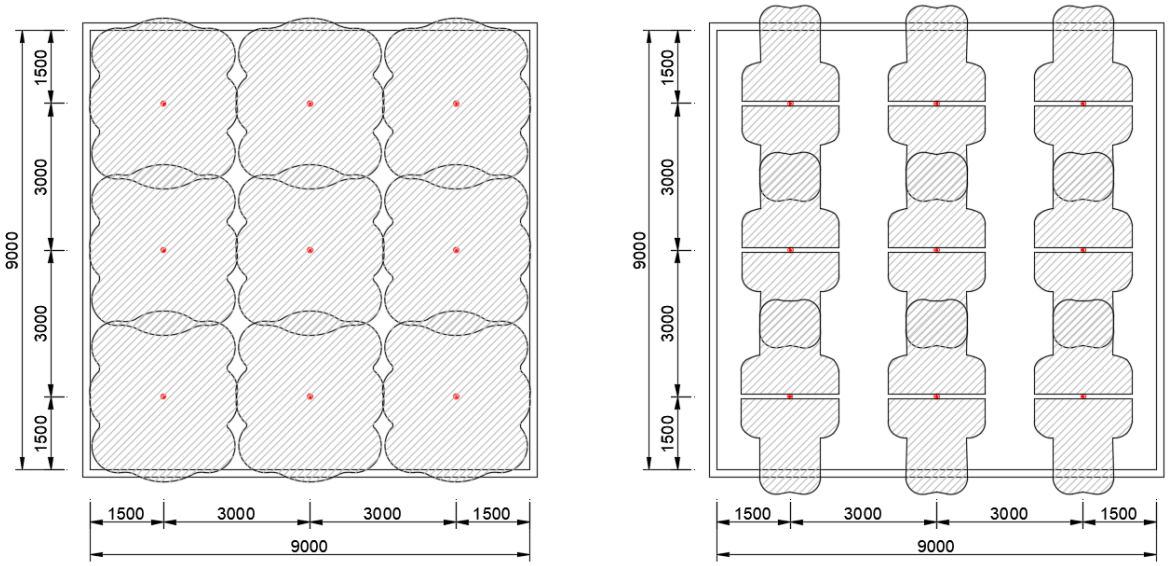


Figure 8-1 : Left: Sprinkler C upright at 3.0 bar – good coverage. Right: Sprinkler B pendant at 3.0 bar – acceptable coverage.

To improve ceiling wetting, staggered sprinkler spacing, as permitted by BS EN 12845:2015, could be employed. This approach can create a more continuous wetted line across the ceiling, helping to prevent flame spread. However, the effectiveness of this strategy depends on selecting the correct sprinkler type and orientation.

Floor wetting was also assessed, with results confirming that all tested sprinklers met the minimum discharge density of 5 mm/min over the required area. This criterion is essential for protecting contents and ensuring occupant safety in buildings classified as Ordinary Hazard occupancies, such as offices, schools, hospitals, and retail outlets.

Sprinkler selection should be guided by three key criteria:

1. **Wall Wetting**: Adequate coverage of the top 0.5 m of wall-ceiling interface, regardless of yoke arm or pipe shadowing. See Figure 8-2.
2. **Ceiling Wetting**: Maximum water distribution pattern should inform sprinkler choice. Sprinklers should be spaced to create a barrier of wetting across the ceiling to slow flame spread. See Figure 8-1 and 8-3.
3. **Floor Wetting**: Sprinklers must meet the minimum discharge density required for the occupancy classification, ensuring sufficient water delivery to the floor level. See Figure 8-3.

The study concludes that commercially available CUP-type sprinklers, when carefully selected and spaced, can provide effective protection for exposed timber surfaces. Wetting of walls and ceilings can help slow surface spread of flame, while adequate floor coverage protects contents, supporting safe evacuation and firefighting operations.

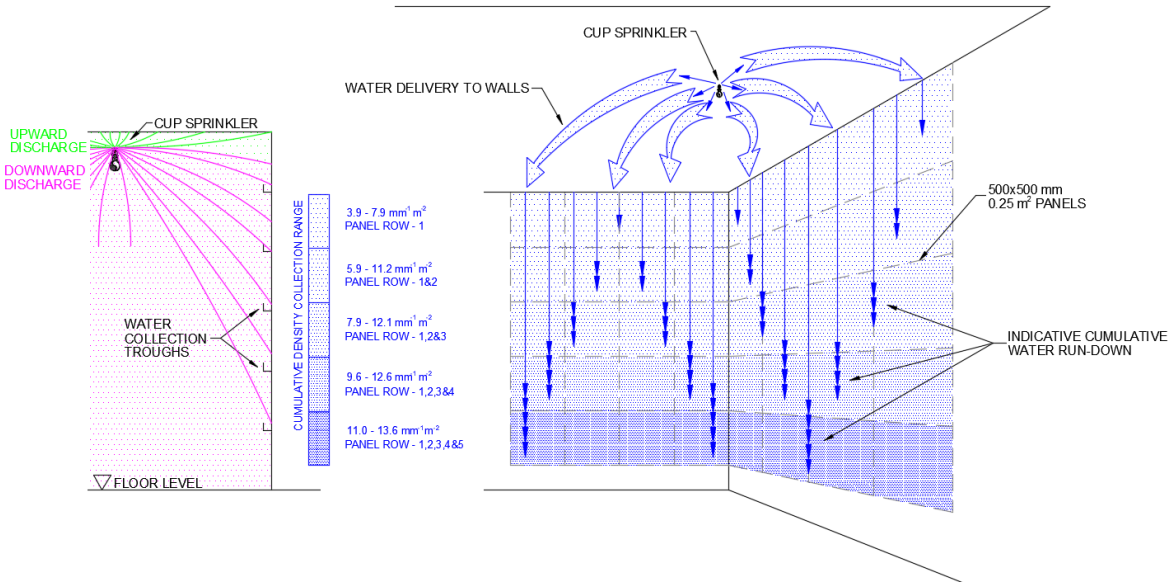


Figure 8-2 : CUP sprinkler discharge showing wall wetting.

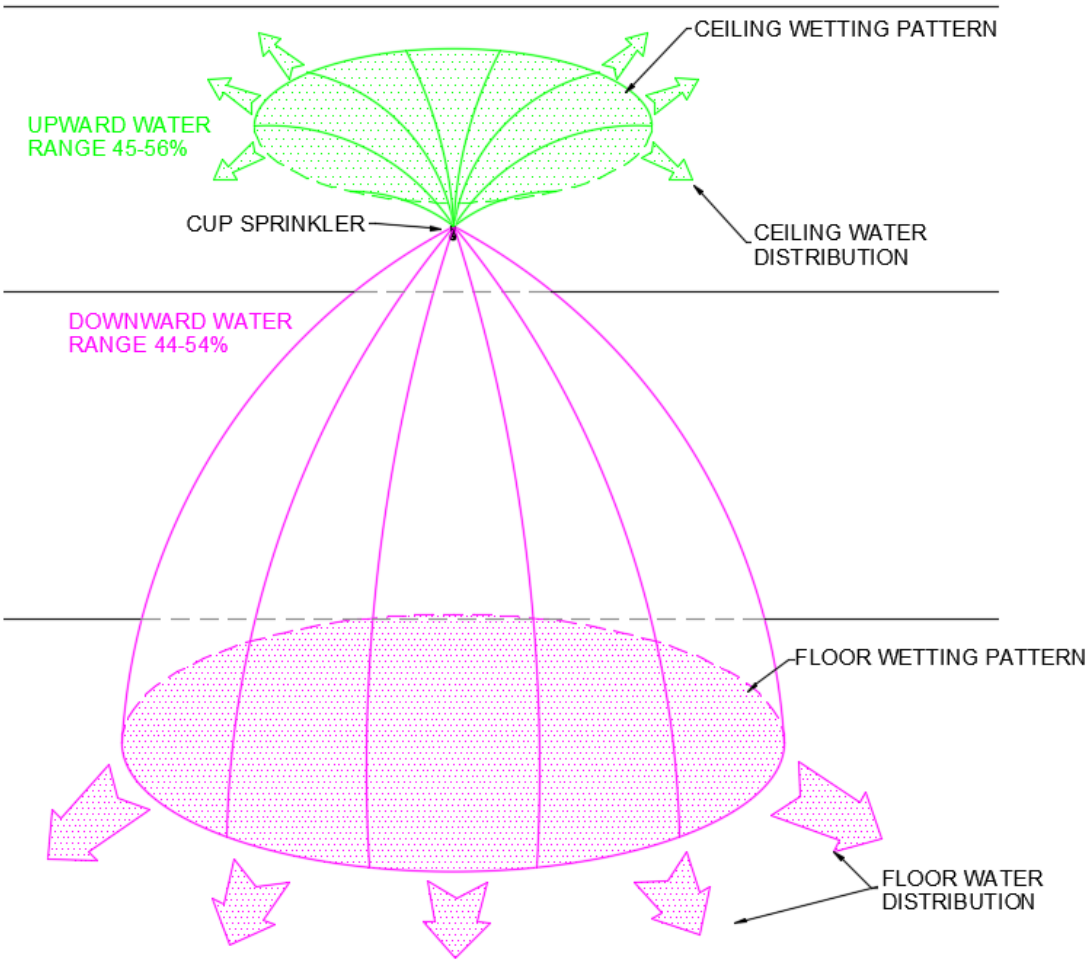


Figure 8-3 : CUP sprinkler discharge showing ceiling and floor wetting.

Timber buildings differ significantly from traditional non-combustible or limited-combustible constructions. They present higher fuel loads, increased heat release rates (HRR), and greater potential for surface flame spread. These characteristics necessitate a revised approach to active fire protection. Existing standards should be updated to account for the unique challenges posed by timber construction, including optimized sprinkler head spray patterns and strategic placement to ensure effective surface wetting.

8.2 Screw Fixings and Load Capacity Under Fire Conditions

The second part of the study examined the performance of screw fixings used to secure M&E services to timber ceilings under fire conditions. These fixings are critical for maintaining the integrity of suspended systems, including fire sprinklers, ventilation ducts, and electrical conduits. Failure of these components during a fire can lead to profound consequences, including entanglement, crush injuries, electrocution, and compromised fire compartmentation.

Under ambient conditions, screw fixings comfortably exceeded the load-bearing requirements for typical M&E applications, and larger diameter screws demonstrated greater load capacity, as expected. However, fire testing revealed significant reductions in strength due to two primary factors: surface material loss from charring and internal weakening around the screw thread caused by heat conduction. The metal screws conducted heat into the surrounding timber, increasing localised heating to the wood around the thread promoting weakening, discolouration, and charring. The extent of each was not measured but was observed as shown in Figures 7-20 to 7-22. Timber was found to be weaker during the fire than after cooling, although the data supporting this observation is limited. Screws with narrower shanks and wider threads retained more strength under fire conditions. In contrast, wider shanks (e.g., M12) conducted more heat, increasing charring and reduced load capacity. This effect was most pronounced in screws with high shank-to-thread ratios.

The rapid and significant loss of strength observed in screw fixings under fire conditions validates concerns about their reliability. In real fires involving mass timber construction, more severe conditions are likely, and the presence of additional heat-conducting metalwork could accelerate failure. Post-fire recovery of timber strength highlights the need for more detailed data on screw performance during fire exposure.

This study focused on traditional screw installation methods, specifically perpendicular placement, and considered screw diameters specified in BS EN 12845 for sprinkler systems. The findings underscore the importance of incorporating a well-designed sprinkler system into timber buildings. Such systems could reduce fire spread and gas temperatures, mitigating the impact on screw fixings and preserving the integrity of suspended services.

Without a sprinkler system, M&E services are vulnerable to rapid failure, which can result in premature detachment and increased risk to occupants and firefighters. These findings suggest that innovative approaches to screw fixings are needed, supported by updated standards and rigorous testing protocols, to ensure safety in timber buildings.

Chapter 9 : Future Work

9.1 Sprinklers

The primary goal of the sprinkler discharge study was to ensure that exposed combustible surfaces were 'wetted' from adjacent sprinklers to reduce or prevent surface spread of flame. This was achieved by reviewing sprinkler head types currently available and modifying sprinkler spacing which confirm that it is viable to optimise sprinkler systems for the specific protection of buildings with exposed timber surfaces, as might be found in mass timber construction, with existing equipment. This study has shown that location to walls, location below ceiling, spacing of sprinklers, and selection of sprinkler type are crucial factors to allow wetting of combustible surfaces.

The impact of this study may necessitate a slight increase in sprinkler head numbers, due to spacing limitations and the requirement to protect all areas of a building, but it is seen to be a balanced approach to fire protection of combustible buildings using active sprinkler protection and taking on board best engineering requirements for sprinkler protection.

Further improvements could potentially be recognised if sprinkler heads were specifically designed for optimised surface wetting and the data contained in this study could serve as a benchmark for demonstrating enhanced capability.

Future research in this area would benefit from:

1. Manufacturing/design/and testing of specific type timber sprinklers.
2. A more in-depth study of the impact of pressure on water distribution.
3. How to specify the best performing currently available conventional type head in guidance.
4. Comparative testing at full scale during fire.

9.2 Fixing into CLT

9.2.1 Potential future study

Whilst this study was originally undertaken to gain knowledge on how fixing methods for fire sprinkler systems might need adaption for the mass timber situation, it has highlighted more serious implications for M&E in general. To ensure building safety under fire conditions and to support evacuation of occupants and response by the attending fire service, better understanding of the load bearing capacity of timber in fire is needed. There are also implications for the level of consequential damage the building might incur through fire spread and damage to other ceiling supported systems (such as ducts).

Potential solutions may include the development of new types of fixings, or the use of current screw fixings in a unique way where the load is out of plane of the fixing insertion. The development of appropriate test standards and specification requirements are also required in response to these new building methods.

Based on the loss of load capacity described, it is expected that decisive action will be taken to prevent detachment of services and the foreseeable potential implications for escapee or firefighter entanglement, similar to that which occurred at Shirley Towers. In that instance it was the fixings that had a vulnerability to fire, not the substrate into which they were embedded, so whilst the outcomes could be the same, the necessary solutions will be different.

This work, in addition to a future proposed study, will provide stakeholders with information necessary to develop a new standard or guidance document for fixing M&E services into timber, which is urgently required.

9.2.2 Development of a new standard

Following on from this study, and through sponsorship from the Fire Service Research Training Trust (FSRTT) and others, a new project has been set-up to develop a new test rig shown in Figures 9-1, 9-2 and 9-3 will allow better testing of individual fixings under load and during fire.

The test rig will be redesigned for the realistic testing of mass timber fixings under load during fire. The rig will be an improved version of that used in this study designed with greater attention to repeatability, ease of use, cost of use, accuracy, and eventual standards adoption. Initial testing shall demonstrate the extent of the problem of using current fixing products and methods, producing data and video footage in a format that can be simply disseminated for presentation.

The project will involve mass timber fixing manufactures to develop products and installation methods that are not subject to losing hold under fire as readily as the current in-service equipment. The knowledge from this future work will be encapsulated in a technical report suitable for presentation by those bodies who understand and seek change (such as FRS, NFCC, and insurers), and to those who can invoke change (such as BRAC, MHCLG, BSI, Designers and Architects). Additionally, data and results from the project will be used to develop the educational and presentational tools required to invoke the change necessary to avoid 'entanglement' and 'obstruction' challenges for evacuees and fire service responders in mass timber buildings causing loss of life and injury.

This project will seek to put in place the research that will ultimately lead to methods and standards for the assurance of fixings performance during the critical periods of occupant evacuation and fire service search and rescue. The attachment of often heavy M&E services, including HVAC, pipework, and fire suppression systems, to ceilings is catered for in standards for traditional concrete floor slab structures (BS 8539), but not timber.

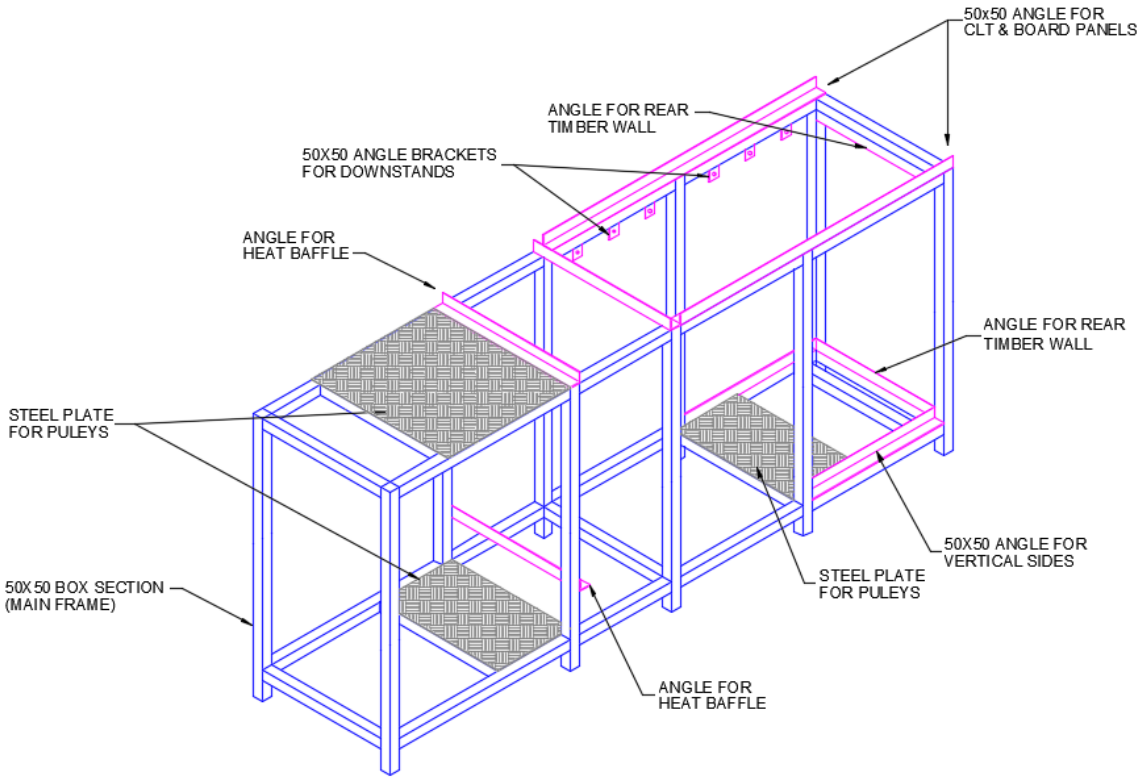


Figure 9-1 : Isometric view of the proposed new fixings test rig.

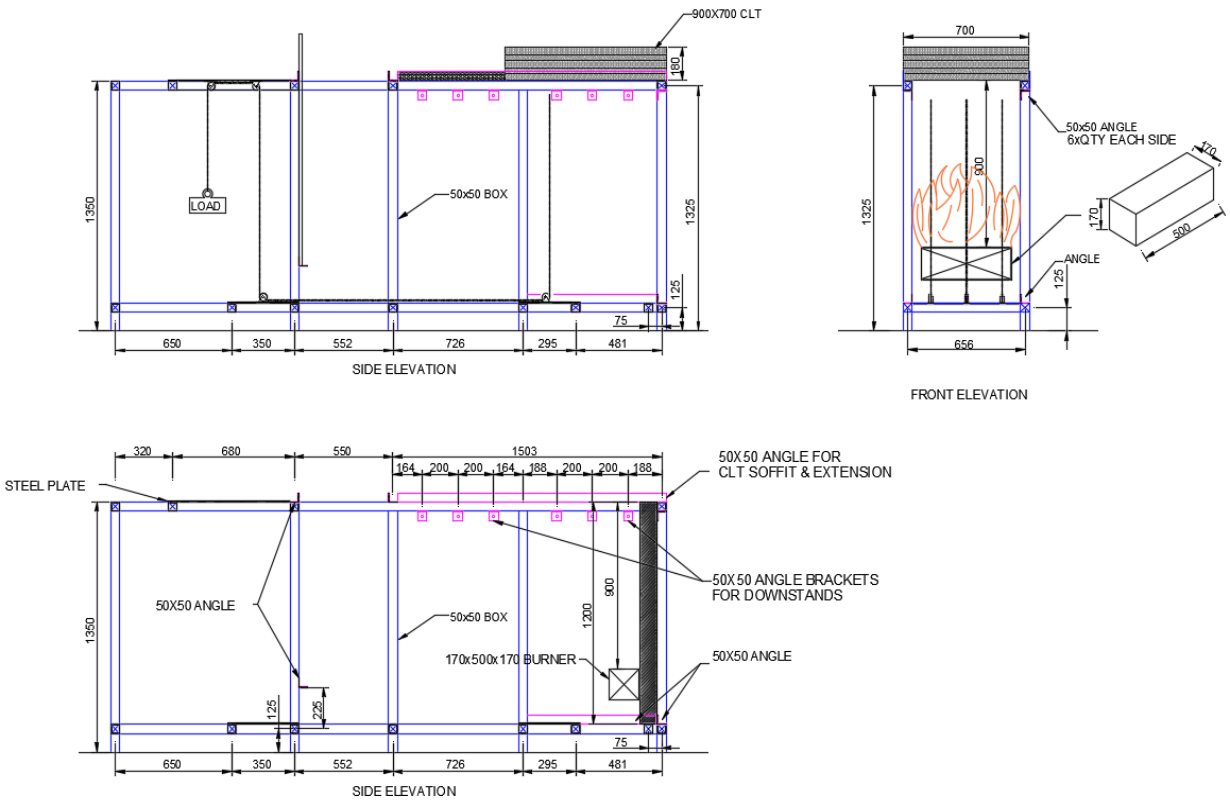


Figure 9-2 : Elevations of the proposed new test rig.

Figure 9-3 : The new test rig.

The objectives of this future study:

1. To experimentally demonstrate and publicise the extent of the problem.

    - Design and construction of a small-scale test rig that may in future serve as the basis of a test standard for fixings approval.
    - Generation of a dataset that shows the extent of the problem using the Fire Protection Association's Fire Test Laboratory.
    - Presentation of the issue through all stakeholder networks.

2. To engage with industry to find engineered solutions (fire resistant fixings into timber)

    - To work with the mass timber products supply industry to find products and methods that do not weaken so severely under the action of fire.

3. To present the test apparatus to British Standards in support of formalising the requirement.

    - Authorship of a draft technical document describing any derived experimental facilities, method of operation, and benefit, which may later be adopted as National, voluntary, or insurance standards / recommendations.

4. To educate and lobby building regulations to implement change.

    - Public speaking
    - Open webinars
    - Articles in FRS journals
    - Formal paper publication
    - Presentation to BRAC

References

[1] Structural Timber Association. (2020). Structural timber buildings: *Fire safety in use guidance (Vol. 6: Mass timber structures; Building Regulation compliance B3(1))*(Version v1.1). STA fire safety research and guidance project. https://cis.ihs.com/CIS/document/340000

[2] Hopkin, D., & Spearpoint, M. (2020). Compliance road-map for the structural fire safety design of mass timber buildings in England. *SFPE Europe*, Q4 2020. https://www.sfpe.org/publications/periodicals/sfpeeuropedigital/sfpeeurope20/europeissue20feature5

[3] Hopkin, D., Gorska, C., Spearpoint, M., Fu, I., Krenn, H., Sleik, T., Stapf, G. (2021). Experimental characterisation of the fire behaviour of CLT ceiling elements from different leading suppliers. https://doi.org/10.14264/5010564 2018

[4] Hopkin, D., W˛egrzy´nski, W., Spearpoint, M., Fu, I., Krenn, H., Sleik, T., Gorska, C., Stapf, G. (2022) Large-Scale Enclosure Fire Experiments Adopting CLT Slabs with Different Types of Polyurethane Adhesives: Genesis and Preliminary Findings. *Fire 2022*, 5, 39. https://doi.org/10.3390/fire5020039

[5] Ronquillo, G., Hopkin, D., Spearpoint, M. (2021) Review of large-scale fire tests on cross-laminated timber, *Journal of Fire Sciences*, https://doi.org/10.1177/07349041211034460

[6] Department for Business, Energy & Industrial Strategy. (2021). Net Zero Strategy: Build Back Greener. HM Government. https://www.gov.uk/government/publications/net-zero-strategy[1](https://www.gov.uk/government/publications/net-zero-strategy)

[7] Vagtholm, R., Matteo, A., Vand, B., & Tupenaite, L. (2023). Evolution and current state of building materials, construction methods, and building regulations in the U.K.: Implications for sustainable building practices. *Buildings*, 13(6), 1480. https://doi.org/10.3390/buildings13061480

[8] Nepal, P., Prestemon, J. P., Ganguly, I., Kumar, V., Bergman, R. D., & Poudyal, N. C. (2024). The potential use of mass timber in mid-to high-rise construction and the associated carbon benefits in the United States. *PLOS ONE*, 19(3), e0298379. https://doi.org/10.1371/journal.pone.0298379

[9] Department for Environment, Food & Rural Affairs. (2025, March 3). Timber in construction roadmap 2025. GOV.UK. https://www.gov.uk/government/publications/timber-in-construction-roadmap-2025/timber-in-construction-roadmap-2025

[10] Dietenberger, M, A. Hasburgh, L, E. (2016) "Wood Products: Thermal Degradation and Fire". *Reference Module in Materials Science and Materials Engineering.* https://doi.org/10.1016%2Fb978-0-12-803581-8.03338-5

[11] British Standards Institution. (2017). BS EN ISO 13943:2017 – Fire safety – Vocabulary. https://landingpage.bsigroup.com/LandingPage/Standard?UPI=000000000030277404

[12] British Standards Institution. (2021). BS 9251:2021 – Fire sprinkler systems for domestic and residential occupancies: Code of practice. https://landingpage.bsigroup.com/LandingPage/Standard?UPI=00000000030403872

[13] British Standards Institution. (2019). BS EN 12845:2015+A1:2019 Incorporating corrigenda December 2015 and January 2016 – Fixed firefighting systems – Automatic sprinkler systems – Design, installation and maintenance. https://landingpage.bsigroup.com/LandingPage/Standard?UPI=000000000030345797

[14] British Standards Institution. (2018). BS EN 16925:2018 – Fixed firefighting systems – Automatic residential sprinkler systems – Design, installation and maintenance. https://landingpage.bsigroup.com/LandingPage/Undated?UPI=000000000030310796

[15] British Standards Institution. (2015). BS 8458:2015 – Fixed fire protection systems: Residential and domestic watermist systems – Code of practice for design and installation. https://landingpage.bsigroup.com/LandingPage/Undated?UPI=000000000030295813

[16] British Standards Institution. (2016). BS 8489-1:2016 – Fixed fire protection systems: Industrial and commercial watermist systems – Part 1: Code of practice for design and installation. https://landingpage.bsigroup.com/LandingPage/Series?UPI=BS%208489

[17] British Standards Institution. (2020). BS EN 14972-1:2020 – Fixed firefighting systems: Water mist systems – Part 1: Design, installation, inspection and maintenance. https://landingpage.bsigroup.com/LandingPage/Series?UPI=BS%20EN%2014972

[18] Fire Protection Association. (2015). LPC rules for automatic sprinkler installations 2015 incorporating BS EN 12845. https://www.thefpa.co.uk/shop/lpc-sprinkler-rules-subscription

[19] Bateman, C. Bartlett, A. Rutkauskas, L. Hadden, R. (2018). "Effects of Fuel Load and Exposed CLT Surface Configuration". *World Conference on Timber Engineering*. Available:https://www.researchgate.net/publication/325319406_Effects_of_Fuel_Load_and_Exposed_CLT_Surface_Configuration_in_Reduced-Scale_Compartments

[20] Bartlett, A, I. McNamee, R. Robert, F. Bisby, L, A. (2020) "Comparative energy analysis from fire resistance tests on combustible versus noncombustible slabs". *Fire and Materials*, 44, 301-310. https://doi.org/10.1002/fam.2760

[21] Östman, B.-L., Lourenço, P. B., Branco, J. M., Cruz, H., & Nunes, L. (2013). Fire safety engineering in timber buildings. *SP Wood Technology*. Presented at the Seminário Casas de Madeira.

[22] Östman, B., Mikkola, E., Stein, R., Frangi, A., König, J., Dhima, D., Hakkarainen, T., & Bregulla, J. (2010). Fire safety in timber buildings: Technical guideline for Europe (SP Report No. 2010:19). SP Technical Research Institute of Sweden. Retrieved from https://cris.vtt.fi/en/publications/fire-safety-in-timber-buildings-technical-guideline-for-europe

[23] Zelinka, S, L., Hasburgh, L., Bourne, K., Tucholski, D., & Ouellette, J. (2018). Compartment Fire Testing of a Two-Story Mass Timber Building. https://doi.org/10.13140/RG.2.2.26223.33447

[24] Mitchell H, Kotsovinos P, Richter F, Thomson D, Barber D, Rein G. Review of fire experiments in mass timber compartments: Current understanding, limitations, and research gaps. *Fire and Materials*. 2023; 47(4): 415-432. https://doi.org/10.1002/fam.3121

[25] Approved Document G incorporating insurer requirements [Online]. Available: https://www.thefpa.co.uk/advice-and-guidance/free-documents?q=RISCAuthority%20Insurer%20Requirements%20for%20enhanced%20escape%20of%20water%20protection%20based%20on%20Approved%20Document%20G

[26] British Standards Institution. (2021). BS 8539:2012+A1:2021 – Code of practice for the selection and installation of post-installed anchors in concrete and masonry. https://landingpage.bsigroup.com/LandingPage/Standard?UPI=000000000030420417

[27] Building Engineering Services Association (BESA) – TB58 Alternative systems for building services supports – Version 1 January 2024. [online]. Available: https://publications.thebesa.com/products/alternative-systems-building-services-supports

[28] HM Government. (2019). Approved Document B (Fire safety): Volumes 1 and 2 (2019 edition incorporating 2020 and 2022 amendments). Ministry of Housing, Communities & Local Government. https://www.gov.uk/government/publications/fire-safety-approved-document-b

[29] Ministry of Housing, Communities and Local Government. (2020). Manual to the Building Regulations. Retrieved from https://www.gov.uk/government/publications/manual-to-the-building-regulations

[30] British Standards Institution. (2015). BS 9991:2015 Fire safety in the design, management and use of residential buildings: Code of practice. Retrieved from https://www.en-standard.eu/bs-9991-2015-fire-safety-in-the-design-management-and-use-of-residential-buildings-code-of-practice/

[31] British Standards Institution. (2017). BS 9999:2017 Fire safety in the design, management and use of buildings: Code of practice. Retrieved from https://landingpage.bsigroup.com/LandingPage/Standard?UPI=000000000030357099

[32] British Standards Institution. (2019). BS 7974:2019 Application of fire safety engineering principles to the design of buildings: Code of practice. Retrieved from https://www.en-standard.eu/bs-7974-2019-application-of-fire-safety-engineering-principles-to-the-design-of-buildings-code-of-practice/

[33] Insurance challenges of massive timber construction and a possible way forward Revision 1.0 January 2022 [online]. Available: https://www.scribd.com/document/812971526/RISCAuthority-Insurance-Challenges-of-Massive-and-Mass-Timber-Construction-February-2022

[34] Fire Protection Association. (2023). Approved Document B: Fire safety – Volume 1 dwellings (Incorporating insurers' requirements for property protection) (1st ed.). RISCAuthority. https://www.thefpa.co.uk/resource-download/234

[35] Fire Protection Association. (2023). Approved Document B: Fire safety – Volume 2: Buildings other than dwellings (Incorporating insurers' requirements for property protection) (3rd ed.). RISCAuthority. https://www.thefpa.co.uk/resource-download/234

[36] RISCAuthority. (2023). BDM01 A to Z of Essential Principles for the Protection of Buildings (Rev. 3). Fire Protection Association. https://www.thefpa.co.uk/resource-download/405

[37] CEA. (n.d.). *CEA 4001 Sprinkler systems: Planning and installation*. ManualsLib. Retrieved December 5, 2025, from https://www.manualslib.com/manual/1995118/Cea-4001.html [manualslib.com]

[38] National Fire Protection Association. (2025). *NFPA 13: Standard for the installation of sprinkler systems*. Retrieved from https://www.nfpa.org/codes-and-standards/nfpa-13-standard-development/13

[39] FM Global. (2025). *FM property loss prevention data sheets: Sprinklers*. Retrieved from https://www.fm.com/resources/fm-data-sheets#rbdatasheetssearch_datasheets%20product%20type=02.%20Sprinklers

[40] National Fire Protection Association. (2022). *NFPA 15: Standard for water spray fixed systems for fire protection*. Quincy, MA: National Fire Protection Association. Retrieved from https://www.nfpa.org/codes-and-standards/nfpa-15-standard-development/15

[41] Dansk Brand- og Sikringsteknisk Institut. (2021). DBI Retningslinje 251/4001: Automatiske sprinkleranlæg (3. udgave). Hentet fra https://brandogsikring.dk/udgivelser/udgivelser-fra-dbi/retningslinjer/dbi-retningslinje-251-4001-aut-sprinkleranlaeg/

[42] Cyrus Industrie. (n.d.). APSAD R1: *Automatic water sprinkler-type extinguishing installations*. Retrieved from https://www.cyrus-industrie.com/en/apsad-r1/

[43] VdS Schadenverhütung GmbH. (2021). *VdS CEA guidelines for sprinkler systems: Planning and installation* (VdS CEA 4001en: 2021-01). VdS Schadenverhütung GmbH. https://vds.de/en/certification/inspection-service/information-innovation/information-innovation/sprinkler-guideline [shop.vds.de]

[44] Ministerul Dezvoltării, Lucrărilor Publice și Locuințelor. (1999). Normativ de securitate la incendiu a construcțiilor: Indicativ P 118-99. București: MDLPL. Retrieved from http://www.mdlpl.ro/_documente/constructii/reglementari_tehnice/normativ_securitatea_incendiu.pdf

[45] Brandskyddsföreningen. (2018). *SBF 120:8 Rules for automatic water sprinkler systems*. Swedish Fire Protection Association. Retrieved from https://www.brandskyddsforeningen.se/enorm/byggnadstekniskt-brandskydd-samlade-regelverk/regelverk/sbf-120-sprinkler/

[46] Vereinigung Kantonaler Feuerversicherungen (VKF). (2015). Brandschutzrichtlinie Sprinkleranlagen (19-15de). Bern: VKF. Retrieved from https://www.gvl.ch/dokumente/praevention/wasserloeschanalgen/brandschutzrichtlinie-sprinkleranlagen.pdf

[47] Building Act 1984, c. 55. (1984). Legislation.gov.uk. https://www.legislation.gov.uk/ukpga/1984/55/contents

[48] The Building Regulations 2010, No. 2214. (2010). The Building Regulations 2010. Retrieved from https://www.legislation.gov.uk/uksi/2010/2214/contents

[49] Building (Scotland) Act 2003, asp 8. (2003). Legislation.gov.uk. https://www.legislation.gov.uk/asp/2003/8/contents

[50] Building Regulations (Northern Ireland) Order 1979, NISI 1979/1709. (1979). Legislation.gov.uk. https://www.legislation.gov.uk/nisi/1979/1709/contents

[51] United Kingdom. (2021). Fire Safety Act 2021: Chapter 24. Retrieved from https://www.gov.uk/government/publications/fire-safety-act-2021.

[52] Home Office. (2022). Fire Safety (England) Regulations 2022. Retrieved from https://www.gov.uk/government/publications/fire-safety-england-regulations-2022

[53] United Kingdom. (2005). The Regulatory Reform (Fire Safety) Order 2005: Statutory Instrument 2005 No. 1541. Retrieved from https://www.legislation.gov.uk/uksi/2005/1541

[54] European Committee for Standardization. (2004). Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings (EN 1995-1-1:2004). Retrieved from https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-5-design-timber-structures

[55] Law, C. (2025, March 1). 2025 embodied carbon data for timber products. Timber Development UK. https://timberdevelopment.uk/resources/2025-embodied-carbon-data-for-timber-products/

[56] Timber Development UK. (2023). Timber industry net zero roadmap: How the timber sector can address the climate crisis and build a net zero future (Version 1.1). Energise. https://timberdevelopment.uk/wp-content/uploads/2023/07/Timber-Industry-Net-Zero-Roadmap-v1.1.pdf

[57] The Mass Timber Insurance Playbook: A guide to insuring mass timber buildings. (2024). [online]. Available: https://asbp.org.uk/project/mass-timber-insurance-playbook

[58] Architects & Engineers for 9/11 Truth. (n.d.). FAQ #3: Has there ever been a total collapse of a steel-frame, fire-protected high-rise besides World Trade Center Buildings 1, 2, and 7? Retrieved November 21, 2025, from https://www.ae911truth.org/evidence/faqs/649-faq-3-has-there-ever-been-a-total-collapse-of-a-steel-frame-fire-protected-high-rise-besides-world-trade-center-buildings-1-2-and-7

[59] Mariappan, T. (2017). Fire retardant coatings. InTech. https://www.researchgate.net/publication/319627247_Fire_Retardant_Coatings

[60] Parthasarathi, N., Satyanarayanan, K. S., Thamilarau, V., Prakash, M., & Punnapu, A. (2019). Linear analysis of a two-dimensional multistorey reinforced concrete frame under high temperature at different column locations. *Journal of Structural Fire Engineering*, 10(3), 317–323. https://doi.org/10.1108/JSFE-03-2018-0007

[61] The Concrete Centre. (n.d.). High strength concrete. Retrieved November 21, 2025, from https://www.concretecentre.com/Specification/Special-Concrete/high-strength-concrete.aspx

[62] Drysdale, D. (Ed.). (2011). Front matter. In An introduction to fire dynamics (3rd ed.). Wiley. https://doi.org/10.1002/9781119975465.fmatter

[63] Stora Enso. (n.d.). Cross-laminated timber (CLT). Stora Enso. Retrieved November 21, 2025, from https://www.storaenso.com/en/products/mass-timber-construction/building-products/clt.

[64] Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): Overview and development. European Journal of Wood and Wood Products, 74, 331–351. https://doi.org/10.1007/s00107-015-0999-5

[65] Construction Manager. (2015, April). Hitting new heights? Construction Manager. Retrieved from https://constructionmanagement.co.uk/has-timber-hit-new-heights-hackney/

[66] DCI Engineers. (2019, March 7). Tall mass timber gets the go-ahead: IBC code change highlights. Retrieved from https://www.dci-engineers.com/news/tall-mass-timber-gets-go-ahead-ibc-code-change-highlights

[67] Think Wood. (2019). Design and construction of taller wood buildings. Retrieved from https://www.thinkwood.com

[68] Think Wood. (2021, July). Mass Timber Digest: A journal on innovations in mass timber research and design (Vol. 1). Softwood Lumber Board. https://www.thinkwood.com

[69] Elliott Wood, Waugh Thistleton Architects, OFR Consultants, & Lignum Risk Partners. (2024). Commercial timber guidebook: Industry consensus guidance for delivering robust, safe, durable and insurable mass timber buildings. https://waughthistleton.com/commercial-timber-guidebook/

[70] Brandner, R. (2013). Production and technology of cross laminated timber (CLT): A state-of-the-art report. Graz University of Technology, Institute of Timber Engineering and Wood Technology. Retrieved from https://www.researchgate.net/publication/261884030

[71] Ingberg, S. H. (1928). Tests of the severity of building fires. NFPA Quarterly, 22, 43–61.

[72] Bartlett, A. I., Hadden, R. M., & Bisby, L. A. (2018). A review of factors affecting the burning behaviour of wood for application to tall timber construction. *Fire Technology*. https://doi.org/10.1007/s10694-018-0787-y

[73] Emberley, R., Gorska Putynska, C., Bolanos, A., Lucherini, A., Solarte, A., Soriguer, D., Gutierrez Gonzalez, M., Humphreys, K., Hidalgo, J. P., Maluk, C., Law, A., & Torero, J. L. (2017). Description of small and large-scale cross laminated timber fire tests. *Fire Safety Journal*, 91, 327–335. https://doi.org/10.1016/j.firesaf.2017.03.024

[74] Hopkin, D., Węgrzyński, W., Gorska, C., Spearpoint, M., Bielawski, J., Krenn, H., Sleik, T., Blondeau, R., & Stapf, G. (2024). Full-scale fire experiments on cross-laminated timber residential enclosures featuring different lining protection configurations. *Fire Technology*, 60, 3771–3803. https://doi.org/10.1007/s10694-024-01581-1

[75] Madden, J., Kriel, M., Wiesner, F., Wu, W., Hilditch, R., Ervine, A., & Lange, D. (2024, June). Burning behaviour of a timber ceiling: A bench-scale investigation. Paper presented at the 13th International Conference on Structures in Fire, University of Coimbra, Portugal. https://www.researchgate.net/publication/382086600_BURNING_BEHAVIOUR_OF_A_TIMBER_CEILING_A_BENCH-SCALE_INVESTIGATION

[76] Bartlett, A., Gajewski, K., Lineham, S., Thomson, D., Hadden, R., Bisby, L., & Butterworth, N. (2015, December). Overcoming the fire barrier to tall timber construction. Paper presented at the Infrastructure and Environment Scotland 3rd Postgraduate Conference, Heriot-Watt University, Edinburgh. https://www.researchgate.net/publication/286937408_Overcoming_the_Fire_Barrier_to_Tall_Timber_Construction

[77] Madden, J., Weisner, F., Morisset, D., Wu, W., Hilditch, R., Ervine, A. & Lange, D. (2025). Ignition of a timber ceiling: Analysing convective and radiative heating effects. In Proceedings of the 2025 World Conference on Timber Engineering (WCTE). https://doi.org/10.52202/080513-0521

[78] Hopkin, D., Spearpoint, M., Gorska, C., Krenn, H., Sleik, T., Stapf, G., & Wegrznski, W. (2021). Update on a large-scale CLT experimental campaign for commercial enclosures. *Structural Timber Association*. https://www.researchgate.net/publication/355667853

[79] Bartlett, A., Gajewski, K., Hadden, R., Butterworth, N., & Bisby, L. (2015, October). Fire-induced delamination of cross-laminated timber. Paper presented at an academic conference. Retrieved from https://www.researchgate.net/publication/308653056

[80] Kotsovinos, P., Rackauskaite, E., Christensen, E., Glew, A., O'Loughlin, E., Mitchell, H., Amin, R., Robert, F., Heidari, M., Barber, D., Rein, G., & Schulz, J. (2022). Fire dynamics inside a large and open-plan compartment with exposed timber ceiling and columns: CodeRed #01. *Fire and Materials*, 1–27. https://doi.org/10.1002/fam.3049

[81] Ohlemiller, T, J. (1991). Smoldering Combustion Propagation on Solid Wood, FIRE SAFETY SCIENCE, PROCEEDINGS OF THE THIRD INTERNATIONAL SYMPOSIUM, pp. 565-574 [online] Available: https://publications.iafss.org/publications/fss/3/565/view/fss_3-565.pdf

[82] Liang, Z., Lin, S., Huang, X. (2023) Smoldering ignition and emission dynamics of wood under low irradiation. *Fire and Materials* V47, Iss4, 514-524. https://doi.org/10.1002/fam.3107

[83] Rein, G. (2016) Smoldering Combustion. SFPE Handbook of Fire Protection Engineering, 5th Edition, pp 581-603, *Springer*. http://link.springer.com/chapter/10.1007/978-1-4939-2565-0_19

[84] Rein, G. (2016). Smoldering combustion. In M. Hurley, D. Gottuk, J. Hall, K. Harada, E. Kuligowski, M. Puchovsky, J. Torero, J. Watts, & C. Wieczorek (Eds.), SFPE Handbook of Fire Protection Engineering (5th ed., pp. 581–603). *Springer*. https://doi.org/10.1007/978-1-4939-2565-0_19

[85] Zhang, Z., Ding, P., Wang, S., Huang, X. (2023) Smouldering-to-flaming transition on wood induced by glowing char cracks and cross wind. *Fuel*. 352.129091. https://doi.org/10.1016/j.fuel.2023.129091

[86] Mitchell, H., Amin, R., Heidari, M., Kotsovinos, P., Rein, G. (2023) Structural hazards of smouldering fires in timber buildings. *Fire Safety Journal*, Volume 140, 103861 ISSN 0379-7112. https://doi.org/10.1016/j.firesaf.2023.103861

[87] Lucherini, A., Sejnová Pitelková, D., & Mózer, V. (2025). Estimating the effective char depth in structural timber elements exposed to natural fires, considering the heating and cooling phase. *Engineering Structures*, 323, 119255. https://doi.org/10.1016/j.engstruct.2024.119255

[88] Girompaire, L., & Dagenais, C. (2024). Fire dynamics of mass timber compartments with exposed surfaces: Development of an analytical model. *Fire Technology*, 60, 1477–1501. https://doi.org/10.1007/s10694-023-01528-y

[89] Ronquillo, G., Hopkin, D., & Spearpoint, M. (2021). Review of large-scale fire tests on cross-laminated timber. *Journal of Fire Sciences*, 39(6), 1–43. https://doi.org/10.1177/07349041211034460

[90] Pečenko, R., Hozjan, T., & Huč, S. (2023). Modelling charring of timber exposed to natural fire. *Journal of Wood Science*, 69(19). https://doi.org/10.1186/s10086-023-02091-4

[91] Xu, Q., Chen, L., Harries, K. A., Zhang, F., Liu, Q., & Feng, J. (2015). Combustion and charring properties of five common constructional wood species from cone calorimeter tests. *Construction and Building Materials*, 96, 416–427. https://doi.org/10.1016/j.conbuildmat.2015.08.062

[92] Standards Australia and Standards New Zealand. (2019). AS/NZS 1720.4:2019 Timber structures – Fire resistance of timber elements (Standard No. 1720.4:2019). https://webstore.ansi.org/standards/sai/nzs17202019 [standards.govt.nz], [standards-global.com]

[93] Amin, R., Mo, Y., Richter, F., Kurzer, C., Werther, N., & Rein, G. (2024). Predicting the average charring rate of mass timber using data-driven methods for structural calculations. *Fire Technology*, 60(6), 4001–4021. https://doi.org/10.1007/s10694-024-01593-x

[94] Xu, Q., Chen, L., Harries, K, A., Zhang, F., Liu, Q., Feng, J. (2015). Combustion and charring properties of five common constructional wood species from cone calorimeter tests. *Construction and Building Materials*, Volume 96,Pages 416-427,ISSN 0950-0618. https://doi.org/10.1016/j.conbuildmat.2015.08.062

[95] Albert, C. M., & Liew, K. C. (2024). Mass loss rate and charring rate of cross-laminated timber manufactured from densified low-density wood. AIP Conference Proceedings, 3110, 020047. https://doi.org/10.1063/5.0204712

[96] Sun, A., Harada, K., & Nii, D. (2024). Experimental research on moisture transfer, burning and charring behavior of glue laminated larch under fire heating using cone calorimeter. Fire Technology. https://doi.org/10.1007/s10694-024-01545-5

[97] Bøe, A. S., Hox, K., Mikalsen, R. F., & Friquin, K. L. (2024). Large-scale fire experiments in a cross-laminated timber compartment with an adjacent corridor – Partly and fully protected with a water sprinkler system. Fire Safety Journal, 148, 104212. https://doi.org/10.1016/j.firesaf.2024.104212

[98] Kim, S., Baik, K. H., Ryu, J.-R., & Choi, Y.-J. (2025). A study on charring depth of cross-laminated timber (CLT) walls under non-load bearing fire test. Proceedings of the 2025 World Conference on Timber Engineering (WCTE). https://doi.org/10.52202/080513-0704

[99] International Organization for Standardization. (2025). ISO 834-1:2025 Fire-resistance tests — Elements of building construction — Part 1: General requirements. https://www.iso.org/standard/83943.html

[100] Maharjan, S., Gunawardena, T., & Mendis, P. (2025). Review of experimental testing and fire performance of mass timber structures. *Journal of Composite Science*, 9(6), 290. https://doi.org/10.3390/jcs9060290

[101] Makino, S., Sun, A., Harada, K., Nii, D. (2024) An Empirical Model of Fallout of Char Layer of Glue Laminated Timber Walls Heated by ISO 834 Standard Fire for Various Durations. 13th International Conference on Structures in Fire (SiF 2024). 1313-1324.

[102] Ni, S., & Gernay, T. (2022). On the effect of exposed timber on the severity of structural fires in a compartment and required firefighting resources. *Fire Technology*. https://doi.org/10.1007/s10694-022-01254-x

[103] Brandon, D., & Östman, B. (2016). Fire safety challenges of tall wood buildings – Phase 2: Task 1: Literature review (Final Report). SP Technical Research Institute of Sweden; Fire Protection Research Foundation. https://www.researchgate.net/publication/308417172_Fire_Safety_Challenges_of_Tall_Wood_Buildings_Phase_2_Task_1_-_Literature_Review

[104] Weisner, F., Xu, H., Lange, D., Gupta, V., Pope, I. Torero, J, L. (2024) Large-scale compartment fires to develop a self-extinction design framework for mass timber-Part 2: Results, analysis and design implications. *Fire Safety Journal*, Volume 152, ISSN 0379-7112. https://doi.org/10.1016/j.firesaf.2025.104346.

[105] Hadden, R. M., Bartlett, A. I., Hidalgo, J. P., Santamaria, S., Wiesner, F., Bisby, L. A., Deeny, S., & Lane, B. (2017). Effects of exposed cross laminated timber on compartment fire dynamics. *Fire Safety Journal*, 91, 480–489. https://doi.org/10.1016/j.firesaf.2017.03.074

[106] Zelinka, S. L., Hasburgh, L. E., Bourne, K. J., Tucholski, D. R., & Ouellette, J. P. (2018). Compartment fire testing of a two-story mass timber building (General Technical Report FPL–GTR–247). *U.S. Department of Agriculture, Forest Service, Forest Products Laboratory*. https://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr247.pdf

[107] Brandon, D., & Östman, B. (2016). Fire safety challenges of tall wood buildings – Phase 2: Task 1 - Literature review (Final Report). Fire Protection Research Foundation. https://www.researchgate.net/publication/308417172

[108] Mitchell, H., Kotsovinos, P., Richter, F., Thomson, D., Barber, D., & Rein, G. (2023). Review of fire experiments in mass timber compartments: Current understanding, limitations, and research gaps. *Fire and Materials*, 47(4), 415–432. https://doi.org/10.1002/fam.3121

[109] Ni, S., & Gernay, T. (2022). On the effect of exposed timber on the severity of structural fires in a compartment and required firefighting resources. *Fire Technology*. https://doi.org/10.1007/s10694-022-01254-x

[110] Hasburgh, L. E., Zelinka, S. L., Bourne, K. J., Tucholski, D. R., & Ouellette, J. P. (2018). Full-scale fire tests of a two-story cross-laminated timber structure. In Proceedings of the World Conference on Timber Engineering (WCTE 2018). *U.S. Forest Service, Forest Products Laboratory*. https://www.fpl.fs.usda.gov/documnts/pdf2018/fpl_2018_hasburgh001.pdf

[111] Hoehler, M. S., Su, J., Lafrance, P.-S., Bundy, M. F., Kimball, A., Brandon, D., & Östman, B. (2018). Fire safety challenges of tall wood buildings: Large-scale cross laminated timber compartment fire tests. Presented at SiF 2018 – The 10th International Conference on Structures in Fire, FireSERT, Ulster University, Belfast, UK, June 6–8, 2018. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:lnu:diva-77612

[112] Hoehler, M. S., Su, J., Lafrance, P.-S., Bundy, M. F., Kimball, A., Brandon, D., & Östman, B. (2018). Fire safety challenges of tall wood buildings: Large-scale cross laminated timber compartment fire tests. https://www.nist.gov/publications/fire-safety-challenges-tall-wood-buildings-large-scale-cross-laminated-timber

[113] Hopkin, D., Węgrzyński, W., Gorska, C., Spearpoint, M., Bielawski, J., Krenn, H., Sleik, T., Blondeau, R., & Stapf, G. (2024). Full-scale fire experiments on cross-laminated timber residential enclosures featuring different lining protection configurations. Fire Technology, 60, 3771–3803. https://doi.org/10.1007/s10694-024-01581-1

[114] Nothard, S., Lange, D., Hidalgo, J. P., Gupta, V., McLaggan, M. S., Wiesner, F., & Torero, J. L. (2022). Factors influencing the fire dynamics in open-plan compartments with an exposed timber ceiling. *Fire Safety Journal*, 129, 103564. https://doi.org/10.1016/j.firesaf.2022.103564

[115] Hoehler, M. S., Su, J., Lafrance, P.-S., Bundy, M. F., Kimball, A., Brandon, D., & Östman, B. (2018). Fire safety challenges of tall wood buildings: Large-scale cross laminated timber compartment fire tests. In SiF 2018 – The 10th International Conference on Structures in Fire, FireSERT, Ulster University, Belfast, UK, June 6–8, 2018. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:lnu:diva-77612

[116] Sanned, E., Mensah, R. A., Försth, M., & Das, O. (2023). The curious case of the second/end peak in the heat release rate of wood: A cone calorimeter investigation. *Fire and Materials*, 47(4), 498–513. https://doi.org/10.1002/fam.3122

[117] Perković, N., Skejić, D., & Rajčić, V. (2024). Numerical analysis of fire resistance in cross-laminated timber (CLT) constructions using CFD: Implications for structural integrity and fire protection. *Forests*, 15(11), 2046. https://doi.org/10.3390/f15112046

[118] Brandon, D. (2018). Fire safety challenges of tall wood buildings – Phase 2: Task 4 – Engineering methods (Final Report). Fire Protection Research Foundation. https://www.nfpa.org/foundation

[119] Su, J., Lafrance, P.-S., Hoehler, M., & Bundy, M. (2018). Fire safety challenges of tall wood buildings – Phase 2: Task 2 & 3 – Cross laminated timber compartment fire tests (FPRF-2018-01). Fire Protection Research Foundation. https://www.nfpa.org/foundation

[120] Frangi, A., Fontana, M., Knobloch, M., Bochicchio, G. (2008). Fire Behavior of Cross-Laminated Solid Timber Panels. Fire safety science-proceedings of the ninth international symposium pp. 1279-1290, International Association for Fire Safety Science. https://doi.org/10.3801/IAFSS.FSS.9-1279

[121] Bartlett, A. I., Hadden, R. M., Hidalgo, J. P., Santamaria, S., Wiesner, F., Bisby, L. A., Deeny, S., & Lane, B. (2017). Auto-extinction of engineered timber: Application to compartment fires with exposed timber surfaces. *Fire Safety Journal*, 91, 407–413. https://doi.org/10.1016/j.firesaf.2017.03.050

[122] Bøe, A. S., Friquin, K. L., Brandon, D., Steen-Hansen, A., & Ertesvåg, I. S. (2023). Fire spread in a large compartment with exposed cross-laminated timber and open ventilation conditions: #FRIC-01 – Exposed ceiling. *Fire Safety Journal*, 140, 103869. https://doi.org/10.1016/j.firesaf.2023.103869

[123] Brandon, D., & Dagenais, C. (2018). Fire safety challenges of tall wood buildings – Phase 2: Task 5 – Experimental study of delamination of cross laminated timber (CLT) in fire (Report No. FPRF-2018-05). Fire Protection Research Foundation. https://www.nfpa.org/foundation

[124] Čolić, A., Weisner, F., Spearpoint, M., Hopkin, D., Bisby, L. (2024) INFLUENCE OF ADHESIVE TYPE ON HEAT INDUCED DELAMINATION IN TENSION LOADED SHEAR LAP CROSS LAMINATED TIMBER SAMPLES EXPOSED TO RADIANT HEAT FLUX. SiF 2024 - The 13th International Conference on Structures in Fire. 1395 -1406.

[125] Čolić, A., Weisner, F., Hopkin, D., Spearpoint, D., Wu, W., Bisby, L. (2024) Application of microscale methods to study the heat-induced delamination in engineered wood products bonded with one-component polyurethane adhesives. *International Journal of Adhesion and Adhesives* 0143-7496. https://doi.org/10.1016/j.ijadhadh.2024.103834

[126] Weisner, F., Thomson, D., Bisby, L. (2021) The effect of adhesive type and ply number on the compressive strength retention of CLT at elevated temperatures. *Construction and Building Materials*, Volume 266, Part B, 121156,ISSN 0950-0618. https://doi.org/10.1016/j.conbuildmat.2020.121156.

[127] Zelinka, S, L., Sullivan, K., Pei, S., Ottum, N., Bechle, N, J., Douglas R, R., Hasburgh, L, E. (2019) Small scale tests on the performance of adhesives used in cross laminated timber (CLT) at elevated temperatures. *International Journal of Adhesion and Adhesives* 0143-7496. https://doi.org/10.1016/j.ijadhadh.2019.102436

[128] Vihmann, J. L., & Just, A. (2025). The influence of adhesives, wood species and manufacturing techniques on the fire performance of engineered wood. Proceedings of the 2025 World Conference on Timber Engineering (WCTE). https://doi.org/10.52202/080513-0576

[129] Wang, T., Wang, Y., Crocetti, R., Wålinder, M., Bredesen, R., & Blomqvist, L. (2023). Adhesively bonded joints between spruce glulam and birch plywood for structural applications: Experimental studies by using different adhesives and pressing methods. Wood Material Science & Engineering, 18(3), 1141–1150. https://doi.org/10.1080/17480272.2023.2201577

[130] Ingberg, S, H. (1928) Chief, Fire Resistance Section, U.S. Bureau of Standards. Testing of the Severity of Building Fires. Smithsonian Institution Archives, Accession 90-105, Science Service Records, Image No. SIA2008-4292

[131] Post-War Building Studies No:20 Fire Grading of Buildings Part 1 General Principals and Structural Precautions. By a joint committee of The Building Research Board of The Department of Scientific & Industrial Research and of The Fire Offices' Committee. (1946)

[132] Post-War Building Studies No:29 Fire Grading of Buildings Part 2 Fire Fighting Equipment, Part 3 Personal Safety, Part 4 Chimneys and Flues. By a joint committee of The Building Research Board of The Department of Scientific & Industrial Research and of The Fire Offices' Committee. (1952)

[133] Malhotra, H,L. (1974) Determination of flame spread and fire resistance. Building Research Establishment : Fire Research Station.

[134] Law, A., Bisby, L. (2020) The rise and rise of fire resistance. *Fire Safety Journal*, Volume 116, 103188, Issn 0379-7112. https://doi.org/10.1016/j.firesaf.2020.103188.

[135] Law, M. (1991) Fire Grading and Behaviour. *Fire Safety Journal* 0379-7112/91, https://www.sciencedirect.com/science/article/abs/pii/037971129190036X

[136] Moore, D, B. Structural Design Division, Building Research Establishment, UK (1997) Full-Scale Tests on Complete Buildings.

[137] Lennon, T., Moore, D. (2003) The natural fire safety concept – Full-scale tests at Cardington. *Fire Safety Journal* 38(7):623-643. https://doi:10.1016/S0379-7112(03)00028-6

[138] European Committee for Standardization. (2004). EN 1992-1-2: Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design. Brussels: CEN. Retrieved from https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-2-design-concrete-structures.

[139] White, R.H. (2016). Analytical Methods for Determining Fire Resistance of Timber Members. In: Hurley, M.J., et al. SFPE Handbook of Fire Protection Engineering. *Springer*, New York, NY. https://doi.org/10.1007/978-1-4939-2565-0_55

[140] ASTM International. (2024). ASTM E119-24: Standard test methods for fire tests of building construction and materials. ASTM International. https://store.astm.org/standards/e119

[141] Law, A., Bisby, L. (2020) The rise and rise of fire resistance, *Fire Safety Journal*, 116, ISSN 0379-7112. https://doi.org/10.1016/j.firesaf.2020.103188

[142] Crielaard, R., van de Kuilen, J.-W., Terwel, K., Ravenshorst, G., & Steenbakkers, P. (2019). Self-extinguishment of cross-laminated timber. *Fire Safety Journal*, 105, 244–260. https://doi.org/10.1016/j.firesaf.2019.01.008

[143] Bartlett, A. I., Hadden, R. M., Bisby, L. A., & Lane, B. (2016, July). Auto-extinction of engineered timber: The application of firepoint theory. Paper presented at an academic conference. Retrieved from https://www.researchgate.net/publication/303864854

[144] Emberley, R., Inghelbrecht, A., Yu, Z., & Torero, J. L. (2017). Self-extinction of timber. Proceedings of the Combustion Institute, 36(3), 3055–3062. https://doi.org/10.1016/j.proci.2016.07.077

[145] Emberley, R., Do, T., Yim, J., & Torero, J. L. (2017). Critical heat flux and mass loss rate for extinction of flaming combustion of timber. *Fire Safety Journal*, 91, 252–258. https://doi.org/10.1016/j.firesaf.2017.03.008

[146] Morrisset, D., Law, A., & Emberley, R. (2019). Effects of thickness on the self-extinction of timber. California Polytechnic State University & The University of Edinburgh, https://www.researchgate.net/publication/334898704_Effects_of_Thickness_on_the_Self-extinction_of_Timber

[147] Cuevas, J., Torero, J. L., & Maluk, C. (2021). Flame extinction and burning behaviour of timber under varied oxygen concentrations. *Fire Safety Journal*, 120, 103087. https://doi.org/10.1016/j.firesaf.2020.103087

[148] Hopkin, D., Węgrzyński, W., Spearpoint, M., Fu, I., Krenn, H., Sleik, T., Gorska, C., & Stapf, G. (2022). Large-scale enclosure fire experiments adopting CLT slabs with different types of polyurethane adhesives: Genesis and preliminary findings. *Fire*, 5(2), 39. https://doi.org/10.3390/fire5020039

[149] Xu, H., Pope, I., Gupta, V., Cadena, J., Carrascal, J., Lange, D., McLaggan, M. S., Mendez, J., Osorio, A., Solarte, A., Soriguer, D., Torero, J. L., Wiesner, F., Zaben, A., & Hidalgo, J. P. (2022). Large-scale compartment fires to develop a self-extinction design framework for mass timber—Part 1: Literature review and methodology. Fire Safety Journal, 128, 103523. https://doi.org/10.1016/j.firesaf.2022.103523

[150] Arnórsson, S. M., Hadden, R. M., & Law, A. (2021). Variability of critical mass loss rate at auto-extinction. *Fire Technology*, 57, 233–246. https://doi.org/10.1007/s10694-020-01002-z

[151] Frangi, A., Fontana, M., & Knobloch, M. (2008). Fire design concepts for tall timber buildings. *Structural Engineering International*, 18(2), 148–155. https://doi.org/10.2749/101686608784218716

[152] Buchanan, A., Östman, B., & Frangi, A. (2014). White paper on fire resistance of timber structures (NIST GCR 15-985). National Institute of Standards and Technology. https://doi.org/10.6028/NIST.GCR.15-985

[153] Ahmad, I., & Salem, S. (2025). New encapsulation technique for strengthening and enhanced fire resistance of mass timber structural elements. Proceedings of the 2025 World Conference on Timber Engineering (WCTE). https://doi.org/10.52202/080513-0033

[154] TRADA Technology Ltd. (2013). Flame-retardant treatments for timber products (WIS 2/3-3). BM TRADA. https://trada.co.uk/publications/wood-information-sheets/flame-retardant-treatments-for-timber-products/

[155] Clarke, S. H. (1950, April). Fire retardant treatment of textiles and timber. F.P.A. Journal, (9), 41–46. Fire Protection Association.

[156] Ming, G., Biaocan, L., ShouSheng, Y., Zhao, M, (2005) Flame retardance of wood treated with guanidine compounds characterized by thermal degradation behavior, *Journal of Analytical and Applied Pyrolysis*. Volume 73, Issue 1, Pages 151-156, ISSN 0165-2370. https://doi.org/10.1016/j.jaap.2005.01.006.

[157] Lowden, L. A., & Hull, T. R. (2013). Flammability behaviour of wood and a review of the methods for its reduction. *Fire Science Reviews*, 2(4). https://doi.org/10.1186/2193-0414-2-4

[158] White, R.H. (2016). Analytical Methods for Determining Fire Resistance of Timber Members. In: Hurley, M.J., et al. SFPE Handbook of Fire Protection Engineering. Springer, New York, NY. https://doi.org/10.1007/978-1-4939-2565-0_55

[159] Popescu, C-M., Pfriem, A. (2020) Treatments and modification to improve the reaction to fire of wood and wood based products—An overview. *Fire and Materials*. 44:100-111. https:// https://doi.org/10.1002/fam.2779

[160] Hansen-Bruhn, I., Hull, T, R. (2023) Smoke toxicity of fire protecting timber treatments. *Fire Safety Journal*, 141, 103977 ISSN 0379-7112. https://doi.org/10.1016/j.firesaf.2023.103977

[161] Hansen-Bruhn, I., Hull, T, R. (2023). Flammability and burning behaviour of fire protected timber. *Fire Safety Journal* Volume 140, Issn 0379-7112. https://doi.org/10.1016/j.firesaf.2023.103918

[162] Lin, C.-F., Karlsson, O., Das, O., Mensah, R. A., Mantanis, G. I., Jones, D., Antzutkin, O. N., Försth, M., & Sandberg, D. (2023). High leach-resistant fire-retardant modified pine wood (Pinus sylvestris L.) by in situ phosphorylation and carbamylation. ACS Omega, 8(12), 11381–11396. https://doi.org/10.1021/acsomega.3c00146

[163] Rantuch, P., Kvorková, V., Wachter, I., Martinka, J., Štefko, T. (2024) Is biochar a suitable fire retardant for furfurylated wood?, Composites Part C: *Open Access*, Volume 14, 100454, ISSN 2666+6820. https://doi.org/10.1016/j.jcomc.2024.100454.

[164] Richardson, J,K (1985). The reliability of automatic sprinkler systems. National Research Council Canada CBD-238 https://doi.org/10.4224/20330497

[165] Hall, J. R., Jr. (2006, March 29). An analysis of automatic sprinkler system reliability using current data. National Fire Protection Association.

[166] Hall, J. R., Jr. (2009). U.S. experience with sprinklers and other automatic fire extinguishing equipment. National Fire Protection Association, Fire Analysis and Research Division. https://www.nfpa.org

[167] Entec UK Limited. (2011). Effectiveness of sprinklers in housing, commercial, public and other buildings (Fire Research Report 27/2011). Department for Communities and Local Government. https://www.gov.uk/government/publications/effectiveness-of-sprinklers-in-buildings

[168] Fire Protection Association. (2011). BDM14: Fire in timber frame buildings – A review of fire statistics from the UK and the USA (Version 01). RISCAuthority. https://www.riscauthority.co.uk

[169] Frank, K., Gravestock, N., Spearpoint, M., & Fleischmann, C. (2013). A review of sprinkler system effectiveness studies. Fire Science Reviews, 2(6). https://doi.org/10.1186/2193-0414-2-6

[170] British Automatic Fire Sprinkler Association. (2014). Fire sprinkler systems in timber framed buildings (BIF 18, 1st ed.). Richmond House. www.bafsa.org.uk/assets/Downloads/BIF18_TimberFramedBuidlings.pdf

[171] British Automatic Fire Sprinkler Association. (2015). BIF-19: Sprinkler reliability. BAFSA. https://www.bafsa.org.uk

[172] Optimal Economics. (2017). Efficiency and effectiveness of sprinkler systems in the United Kingdom: An analysis from fire service data. National Fire Chiefs Council & National Fire Sprinkler Network.

[173] Brandon, D., Plathner, F. V., & Mikkola, E. (2021). SAFITS – Statistical analysis of fires in timber structures (RISE Report 2021:97). RISE Research Institutes of Sweden. ISBN 978-91-89385-87-0. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1651231&dswid=-8585

[174] National Fire Protection Association. (2024). US Experience with Sprinklers (NFPA Research Report SPR-003). www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/us-experience-with-saprinklers

[175] British Automatic Fire Sprinkler Association. (2025). Sprinkler Saves UK: Newsletter No. 7 – Spring 2025. https://www.sprinklersaves.co.uk

[176] European Fire Sprinkler Network. (2024). Sprinkler Outlook: Issue 4/2024. https://www.eurosprinkler.org

[177] Baldwin, R., & North, M. A. (1971). The number of sprinkler heads opening in fires (Fire Research Note No. 886). Fire Research Station, Department of the Environment and Fire Offices' Committee Joint Fire Research Organization.

[178] Kotsovinos, P., Christensen, E. G., Gale, J., Mitchell, H., Amin, R., Robert, F., Heidari, M., Barber, D., Rein, G., & Schulz, J. (2022). The effectiveness of a water mist system in an open-plan compartment with an exposed timber ceiling: CodeRed #03. Arup. Retrieved from 2022_FPE_Extra_February.pdf.

[179] Arup. (2021). Mass timber fire safety series: 2021 experimental series. Arup. https://www.arup.com/globalassets/downloads/insights/m/mass-timber-fire-safety-series-2021.pdf

[180] Arup. (2024). Fire safe design of mass timber buildings: May 2024 guide. Ove Arup & Partners Ltd. https://www.arup.com/

[181] Khoat, H. T., Kim, J. T., Quoc, T. D., Kwark, J. H., & Ryou, H. S. (2020). A numerical analysis of the fire characteristics after sprinkler activation in the compartment fire. *Energies*, 13(12), 3099. https://doi.org/10.3390/en13123099

[182] Australasian Fire and Emergency Service Authorities Council. (2018). Fire safety principles for massive timber building systems (Version 1.0, Publication No. 3081). AFAC. https://www.afac.com.au/

[183] National Fire Chiefs Council. (2020). Automatic fire suppression systems: Position statement. https://www.nationalfirechiefs.org.uk

[184] Östman, B., Brandon, D., & Frantzich, H. (2017) Fire safety engineering in timber buildings. Fire Safety Journal. Volume 91, 11-20, ISSN 0739-7112. http://dx.doi.org/10.1016/j.firesaf.2017.05.002

[185] Tsui, A., & Spearpoint, M. J. (2010). Variability of sprinkler response time index and conduction factor using the plunge test. Building Services Engineering Research and Technology, 31(2), 163–176. https://doi.org/10.1177/0143624410363064

[186] Hopkin, C., Spearpoint, M., & Bittern, A. (2018). *Using experimental sprinkler actuation times to assess the performance of Fire Dynamics Simulator*. Journal of Fire Sciences, 36(4), 342–361. https://doi.org/10.1177/0734904118772306

[187] Hopkin, C., & Spearpoint, M. (2019). Evaluation of sprinkler actuation times in FDS and B-RISK. Institution of Fire Engineers, https://www.researchgate.net/publication/333001790_Evaluation_of_sprinkler_actuation_times_in_FDS_and_B-RISK

[188] Buchanan, A., & Östman, B. (Eds.), Fire safe use of wood in buildings – Global design guide (Chapter 10, pp. 345–368). CRC Press. https://doi.org/10.1201/9781003190318

[189] Buchanan, A., Östman, B., & Frangi, A. (2014). White paper on fire resistance of timber structures (NIST GCR 15-985). National Institute of Standards and Technology. https://doi.org/10.6028/NIST.GCR.15-985

[190] Waugh Thistleton Architects. (2018). 100 Projects UK CLT. Softwood Lumber Board & Forestry Innovation Investment. https://waughthistleton.com/100-projects-uk-clt/

[191] Frangi, A., & Fontana, M. (2005). Fire performance of timber structures under natural fire conditions. In Fire Safety Science – Proceedings of the Eighth International Symposium (pp. 279–290). International Association for Fire Safety Science https://www.researchgate.net/publication/250275074_Fire_Performance_Of_Timber_Structures_Under_Natural_Fire_Conditions

[192] Ronken, L. (2025, March 4). Buildings made of wood – A challenge for insurers? Gen Re. Retrieved from https://www.genre.com/knowledge/publications/2025/march/buildings-made-of-wood-a-challenge-for-insurers-en

[193] Marsh Speciality; Insurance procurement for a mass timber project – White Paper, (2023). [online]. Available: https://www.marsh.com/en-gb/industries/construction/insights/insurance-procurement-for-mass-timber-project.html

[194] Moraes, P, D., Rogaume, Y., Bocquet, J, F., Triboulot, P. (2005) Influence of temperature on the embedding strength. Holz als Roh- und Werkstoff, 63: 297–302 https://www.doi.org/DOI 10.1007/s00107-004-0568-9

[195] Peng, L., Hadjisophocleus, G., Mehaffey, J.Mohammad, M. (2011) Predicting the Fire Resistance of Wood–Steel–Wood Timber Connections, *Fire Technology*, 47, 1101–1119. https://doi.org/10.1007/s10694-009-0118-4

[196] Uibel, T., Blass, H, J. (2013) Joints with Dowel Type Fasteners in CLT Structures. Engineering Materials Science. https://api.semanticscholar.org/CorpusID:115088766

[197] BRE (2015) A series of experiments to assess the effect of fire on a selection of electrical cable supports and fixings.[online]. Available: https://www.bre.co.uk/filelibrary/Fire%20and%20Security/FI---Cables-and-support-fixings-experiments.pdf

[198] Boadi, S. B. A., & Hadjisophocleous, G. V. (n.d.). Full scale tests on the performance of hybrid timber connections in real fires. Carleton University https://www.semanticscholar.org/paper/Full-Scale-Tests-on-the-Performance-of-Hybrid-in-Boadi-Bright/9203c0bd4d9cc48e24e555c866fe119ade9e6caa

[199] Ringhofer, A., Brandner, R., Blass, H, J. (2018) Cross laminated timber (CLT): Design approaches for dowel-type fasteners and connections. Engineering Structures 171, 849-861. https://doi.org/10.1016/j.engstruct.2018.05.032

[200] Kinder, E., & Kingsley, G. (2021). Mass timber connections index: Optimal connection considerations. WoodWorks – Wood Products Council. https://www.woodworks.org/design-and-tools/design-tools/connection-index/

[201] Khai, T, D., Young, J, G. (2022) Withdrawal capacity and strength of self-tapping screws on cross-laminated timber. Structures 37, 772-786. https://doi.org/10.1016/j.istruc.2022.01.033

[202] Abdoli, F., Rashidi, M., Rostampour-Haftkhani, A., Layeghi, M., Ebrahimi, G. (2022) Withdrawal Performance of Nails and Screws in Cross-Laminated Timber (CLT) Made of Poplar (Populus alba) and Fir (Abies alba). Polymers 14, 3129. Https://DOI:10.3390/polym14153129

[203] Hoelz, K., Dörner, P., Hohlweg, J., Matthiesen, S. (2022) Influence of thread parameters on the withdrawal capacity of wood screws to optimize the thread geometry, European Journal of Wood and Wood Products. 80:529–540. https://doi.org/10.1007/s00107-022-01792-9

[204] British Standards Institution. (2016). BS EN 1382:2016: Timber structures. Test methods. Withdrawal capacity of timber fasteners. BSI Standards Limited. https://doi.org/10.3403/30297196

[205] Horne, P., Abu, A., Palermo, A., Moss, P. (2023) Thermal response of timber connections in the cooling phase. Fire and Materials. 47: 479-497 https://doi.org/10.1002/fam.3136

[206] British Standards Institution. (2020). BS EN 1363: Fire resistance tests (multi-part document). BSI Standards Limited. https://doi.org/10.3403/BSEN1363

[207] Saito, S., Kikuchi, T., Nakayama, Y. Totsuka, M., Hirashima, T. (2024) Embedment Strength of Dowelled Connections of Glulam Timber at High Temperatures. Paper presented at the Conference on Structures in Fire. University of Coimbra, Portugal. 1359-1370. Https://doi.org/10.30779/cmm_SIF24

[208] Fischer, E, C., Bhandari, S., Sinha, A. (2025) Fire Testing of Glue-Laminated Beam-to-Column Connections. Journal of Structural Engineering. 151(4) https://www.doi.org/10.1061/JSENDH.STENG-13888

[209] Dissanayake, H., Gunawardena, T., & Mendis, P. (2025). Adaptation of connection systems for integration with engineered wood products in buildings: A systematic review. Buildings, 15(7), 1131. https://doi.org/10.3390/buildings15071131

[210] Verki, A. M., & Salem, S. (2025). Behaviour of glued-in rod connections in mass timber structures – A state-of-the-art review. Proceedings of the World Conference on Timber Engineering (WCTE 2025). https://doi.org/10.52202/080513-0352

[211] Wang, X., He, M., Li, Z., & Dong, H. (2025). Evaluation on the behavior of screwed connections between cross-laminated timber panels and steel plates. Proceedings of the World Conference on Timber Engineering (WCTE 2025). https://doi.org/10.52202/080513-0707

[212] The Building (Higher-Risk Buildings Procedures) (England) Regulations 2023, No. 909. (2023). The Building (Higher-Risk Buildings Procedures) (England) Regulations 2023. Retrieved from https://www.legislation.gov.uk/uksi/2023/909/contents

[213] The Fire and Rescue Services (Northern Ireland) Order 2006, No. 1254 (N.I. 9). (2006). Retrieved from https://www.legislation.gov.uk/nisi/2006/1254/contents

[214] Rebuilding of London Act 1666, c. 8 (Cha. 2). (1666). Rebuilding of London Act 1666. Retrieved from https://www.legislation.gov.uk/aep/Cha2/18-19/8/contents/enacted

[215] UK Government. (1938). Fire Brigades Act 1938: 1 & 2 Geo. 6 c. 72. Retrieved from https://www.legislation.gov.uk/ukpga/Geo6/1-2/72/enacted.

[216] Fires Prevention (Metropolis) Act 1774, c. 78 (14 Geo. 3). (1774). Fires Prevention (Metropolis) Act 1774. Retrieved from https://www.legislation.gov.uk/apgb/Geo3/14/78/contents

[217] Manual of safety for theatres. (1934). University of California Libraries. Retrieved from https://babel.hathitrust.org/cgi/pt?id=uc1.$b811086&seq=1

[218] Factories Act 1937, c. 67 (1 Edw. 8 & 1 Geo. 6). (1937). Factories Act 1937. Retrieved from https://www.legislation.gov.uk/ukpga/Edw8and1Geo6/1/67/contents/enacted

[219] United Kingdom. (1947). Fire Services Act 1947: 10 & 11 Geo. 6 c. 41. Retrieved from https://www.legislation.gov.uk/ukpga/Geo6/10-11/41/contents.

[220] United Kingdom. (1965). The Building Regulations 1965: Statutory Instrument 1965 No. 1373. Retrieved from https://www.legislation.gov.uk/uksi/1965/1373/made.

[221] United Kingdom. (1971). Fire Precautions Act 1971: Chapter 40. Retrieved from https://www.legislation.gov.uk/ukpga/1971/40/enacted.

[222] United Kingdom. (2022). Building Safety Act 2022: Chapter 30. Retrieved from https://www.legislation.gov.uk/ukpga/2022/30/contents

[223] Department for Levelling Up, Housing & Communities. (2022). PAS 9980:2022 – Technical guidance for applicants of building safety funding. Retrieved from https://www.gov.uk/government/publications/building-safety-fund-guidance-for-new-applications-2022/annex-a-technical-guidance-for-applicants-of-building-safety-funding-applying-for-funding-via-pas-99802022.

[224] United Kingdom. (2012). Building (Repeal of Provisions of Local Acts) Regulations 2012: Statutory Instrument 2012 No. 3124. Retrieved from https://www.legislation.gov.uk/uksi/2012/3124/made

[225] United Kingdom. (1939). London Building Acts (Amendment) Act 1939: Chapter 97. Retrieved from https://www.legislation.gov.uk/ukla/1939/97/contents/enacted

[226] The Building (Scotland) Regulations 2004, SSI 2004/406. (2004). Legislation.gov.uk. https://www.legislation.gov.uk/ssi/2004/406/contents

[227] Building Regulations (Northern Ireland) 2012, SR 2012/192. (2012). Legislation.gov.uk. https://www.legislation.gov.uk/nisr/2012/192/contents/made

[228] Scottish Government. (2025). Building standards technical handbook January 2025: domestic buildings. https://www.gov.scot/publications/building-standards-technical-handbook-january-2025-domestic/

[229] Scottish Government. (2025). Building standards technical handbook January 2025: non-domestic buildings. https://www.gov.scot/publications/building-standards-technical-handbook-january-2025-non-domestic/

[230] Welsh Government. (2025). Approved Document B: Fire safety – Volume 1: Dwelling houses; Volume 2: Buildings other than dwelling houses. https://www.gov.wales/approved-document-b-fire-safety

[231] Department of Finance (Northern Ireland). (n.d.). Technical Booklet E: Fire safety. Building Control Northern Ireland. https://www.buildingcontrol-ni.com/regulations/technical-booklets

[232] Fire (Scotland) Act 2005, asp 5. (2005). Legislation.gov.uk. https://www.legislation.gov.uk/asp/2005/5/contents

[233] Fire Safety (Scotland) Regulations 2006, SSI 2006/456. (2006). Legislation.gov.uk. https://www.legislation.gov.uk/ssi/2006/456/contents

[234] Scottish Government. (n.d.). Non-domestic fire safety: Guidance on carrying out a fire safety risk assessment for people responsible for non-domestic premises and houses of multiple occupation (HMO). https://www.gov.scot/policies/fire-and-rescue/non-domestic-fire-safety/

[235] Welsh Government. (2022). Fire Safety Act 2021: Guidance on the roles and duties of those responsible for fire safety in buildings. Retrieved from https://www.gov.wales/fire-safety-act-2021-html

[236] UK Government. (2006). The Fire and Rescue Services (Northern Ireland) Order 2006 (Statutory Instrument No. 1254 (N.I. 9)). Retrieved from https://www.legislation.gov.uk/nisi/2006/1254/contents

[237] UK Government. (2009). The Welsh Ministers (Transfer of Functions) (No. 2) Order 2009 (Statutory Instrument No. 3019). Retrieved from https://www.legislation.gov.uk/uksi/2009/3019/contents

[238] UK Government. (1990). The Planning and Building Regulations (Amendment) (Northern Ireland) Order 1990 (Statutory Instrument No. 1510 (N.I. 14)). Retrieved from https://www.legislation.gov.uk/nisi/1990/1510/contents

[239] Northern Ireland Assembly. (2009). Building Regulations (Amendment) Act (Northern Ireland) 2009 (Chapter 4). Retrieved from https://www.legislation.gov.uk/nia/2009/4/contents

[240] The Building (Inner London) Regulations 1985, SI 1985/1936. (1985). Retrieved from https://www.legislation.gov.uk/uksi/1985/1936/contents/made

[241] The Fire Precautions (Sub-surface Railway Stations) Regulations 1989, SI 1989/1401. (1989). Retrieved from https://www.legislation.gov.uk/uksi/1989/1401/contents/made

[242] Defence Infrastructure Organisation. (2017). Defence Infrastructure Fire Standards. Ministry of Defence. Retrieved from https://assets.publishing.service.gov.uk/media/5a82ccc5ed915d74e6237b30/Defence_InfrastructureFire_Standards-Nov-17.pdf

[243] HM Prison and Probation Service. (2022). Fire safety in prison establishments: PSI 11/2015. Ministry of Justice. Retrieved July 29, 2025, from https://assets.publishing.service.gov.uk/media/6243119ce90e075f1088f5c1/ps-11-fire-safety-march-2022.pdf

[244] NHS England. (2015). Health Technical Memorandum 05-02: Firecode – Guidance in support of functional provisions (Fire safety in the design of healthcare premises). Crown copyright. Retrieved from https://www.england.nhs.uk/wp-content/uploads/2021/05/HTM_05-02_2015.pdf

[245] Building Bulletin 100: design for fire safety in schools Retrieved from https://www.gov.uk/government/publications/building-bulletin-100-design-for-fire-safety-in-schools

[246] The Building (Amendment) Regulations 2018, SI 2018/1230. (2018). Retrieved from https://www.legislation.gov.uk/uksi/2018/1230/made

[247] British Standards Institution. (n.d.). BS 8414: Fire performance of external cladding systems. Retrieved from https://landingpage.bsigroup.com/LandingPage/Series?UPI=BS%208414

[248] British Standards Institution. (n.d.). The changing status of the BS 476 standard series: A summary. Retrieved from https://knowledge.bsigroup.com/articles/the-changing-status-of-the-bs-476-standard-series-a-summary

[249] British Standards Institution. (n.d.). Fire classification of construction products and building elements: Classification using data from reaction to fire tests (EN 13501-1). Retrieved from https://knowledge.bsigroup.com/products/fire-classification-of-construction-products-and-building-elements-classification-using-data-from-reaction-to-fire-tests

[250] Domestic Fire Safety (Wales) Measure 2011, nawm 3. (2011). Retrieved from https://www.legislation.gov.uk/mwa/2011/3/contents

[251] British Standards Institution. (2022). BS 8644-1:2022 Digital management of fire safety information: Design, construction, handover, asset management and emergency response – Code of practice. Retrieved from https://www.en-standard.eu/bs-8644-1-2022-digital-management-of-fire-safety-information-design-construction-handover-asset-management-and-emergency-response-code-of-practice/

[252] Rackauskaite, E., Kotsovinos, P., & Barber, D. (2021). Design fires for open-plan buildings with exposed mass-timber ceiling [Letter to the editor]. Fire Technology, 57(2), 487–495. https://doi.org/10.1007/s10694-020-01047-0

[253] Kotsovinos, P., Christensen, E. G., Glew, A., O'Loughlin, E., Mitchell, H., Amin, R., Robert, F., Heidari, M., Barber, D., Rein, G., & Schulz, J. (2023). Impact of partial encapsulation on the fire dynamics of an open-plan compartment with exposed timber ceiling and columns: CodeRed #04. Fire and Materials, 1–30. https://doi.org/10.1002/fam.3112

[254] Hopkin, C., & Spearpoint, M. (2019). Evaluation of sprinkler actuation times in FDS and B-RISK. Institution of Fire Engineers, https://www.researchgate.net/publication/333001790_Evaluation_of_sprinkler_actuation_times_in_FDS_and_B-RISK

[255] British Standards Institution. (1999). BS EN 12259-1:1999 Fixed firefighting systems. Components for sprinkler and water spray systems. Sprinklers. https://doi.org/10.3403/02677656

[256] Poreh, M., & Garrad, G. (2000). A study of wall and corner fire plumes. *Fire Safety Journal*, 34(1), 89-98. https://doi.org/10.1016/S0379-7112(99)00040-5

[257] International Organization for Standardization. (2016). ISO 9705-1:2016 Reaction to fire tests — Room corner test for wall and ceiling lining products — Part 1: Test method for a small room configuration. ISO. https://www.iso.org/standard/59895.html

[258] BRE Global Ltd. (2014). LPS 1181 Part 1: Issue 1.2 Series of fire growth tests for LPCB approval listing of construction product systems. BRE Global Ltd. https://storage.redbooklive.com/media/assets/LPS_1181part1_ce58c62a08.pdf [storage.re...oklive.com]

[259] Beck, J, V. (1962) Thermocouple Temperature Disturbances in Low Conductivity Materials. *Journal of Heat Transfer*. 84(2), 124-131. https://doi.org/10.1115/1.3684310

[260] Pope, I., Hidalgo, J, P., Torero, J, L. (2021) A correction method for thermal disturbances induced by thermocouples in a low-conductivity charring material, *Fire Safety Journal*, Volume 120, 103077, ISSN 0379-7112, https://doi.org/10.1016/j.firesaf.2020.103077

[261] Terrei, L., Acem, Z., Marchetti, V., Lardet, P., Boulet, P. (2021) In-depth wood temperature measurement using embedded thin wire thermocouples in cone calorimeter tests. *International Journal of Thermal Sciences*, Volume 162, 106686, ISSN 1290 0729, https://doi.org/10.1016/j.ijthermalsci.2020.106686

[262] Brandon, D., Sjöström, J., & Kahl, F. (2021). Post-fire rehabilitation of CLT (RISE Report 2021:67). RISE Research Institutes of Sweden. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1627124

[263] Gernay, T., Zehfuß, J., Brunkhorst, S., Robert, F., Bamonte, P., McNamee, R., Mohaine, S., & Franssen, J.-M. (2022). Experimental investigation of structural failure during the cooling phase of a fire: Timber columns. Fire and Materials, 1–16. https://doi.org/10.1002/fam.3110

[264] Khelifa, M., Thi, V, D., Oudjène, M., Khennane, A., Ganaoui, M, E., Rogaume, Y. (2024) Modelling the Response of Timber Beams Under Fire, International Journal of Civil Engineering. 22:1537–1549 https://doi.org/10.1007/s40999-024-00973-2

[265] Shi, L., & Chew, M. Y. L. (2021). A review of thermal properties of timber and char at elevated temperatures. Indoor and Built Environment, 32(1), 9–24. https://doi.org/10.1177/1420326X211035557

Regulatory Requirements for England (Health & Life Safety only)

Building Safety Act 2022

Amends the Building Regulations 2010, the Building Act 1984, the RR(FS)O 2005 and the DPA 1972.

Buildings under construction

Building Act 1984

Section 1 - the power to make building regulations through the Secretary of State of the responsible ministry.

Section 6 - delegates the power to the Secretary of State to publish statutory guidance in the form of Approved Documents.

Amended under the BSA 2022 for higher risk buildings

England and Wales - Building Regulations 2010

Regulation 8 - 'the purpose of securing reasonable standards of health and life safety for persons in or about buildings'.

Regulation 7 - materials & workmanship amended 2018 and 2022 to address external walls on relevant buildings.

Competence Standards in Design & Construction

BS 8670-1 - 2024 Competence frameworks for building safety - Part 1 - Core Criteria - COP

PAS 8671 - 2022 Framework for Competence of Individual Principal Designers - Specification

PAS 8672 - 2022 Framework for Competence of Individual Principal Contractors - Specification

Route 1 to compliance

Higher risk buildings of any construction

Route 2 to compliance

Uncommon building situations or 'Non Standard' Construction that are not higher risk buildings.

Route 3 to compliance

For Common Building Situations or 'Standard' Construction that are not higher risk buildings

Manual to the Building Regulations and Building Safety Regulator Draft Operational standards rules

Reduces the scope of the statutory guidance excluding:
* Difficult ground conditions
* Buildings with unusual occupancies or high levels of complexity
* Very large or very tall buildings
* Large timber buildings
* Some buildings that incorporate modern construction methods

Building Safety Regulator Strategic Plan

The Building Safety Regulator will oversee and monitor the performance of all Building Control Bodies in England and the competence of professionals delivering building control functions

Building Safety Regulator

Building Control Authority (BCA) for higher risk buildings

Gateways 1 & 2

The BSR refers to specialist alternatives

Fire Engineering Solutions

* BS 9999
* BS 9991
* BS 7974

Sector Guidance

* HTM - Healthcare
* BB100 - Education

Approved Documents

(Non-mandatory statutory guidance)
For common building situations through Local Authority. Building Control (LABC) or the Approved Inspectors
The ADs refer to specialist alternatives

Gateway 3

Key Building Information (KBI) provided digitally as the Golden Thread using BS 8644-1:2022 to the Accountable Person under the BSA 2022 at Gateway 3, before handover.

The Building (Higher-Risk Buildings Procedures) (England) Regulations 2023) Re-introduces an enhanced Regulation 38, handover of information on completion.

Building Regulation 38

Mandatory Fire Safety Information provided to the Responsible Person under the RR(FS)O 2005 at handover.

Mandatory fire safety information required through The Building Regulations 2010, which had a precursor in Regulation 16B of the Building Regulations 2000. Introduced through The Building and Approved Inspectors (Amendment) (No. 2) Regulations 2006.

Key:

- UK Law (mandatory)
- Guidance (non-mandatory)
- Reccomendations for suppression systems identified in legislation or guidance

Completed buildings in occupation

Competence Standards in Housing Management

PAS 8673 - 2022 Competence Requirements for the Management of Safety in Residential Buildings - Specification

BS 8670-1 - 2024 Competence frameworks for building safety - Part 1 - Core Criteria - COP

The Regulatory Reform (Fire Safety) Order 2005

Creates the duty of the 'responsible person' and the requirement for Fire Risk Assessments (FRA).

Fire Safety Act 2021

Clarifies the scope of the RR(FS)O 2005 to the premises and the requirements for the structure, external walls and front doors of domestic premises for common areas.

Fire Risk Assessment

PAS 79-1 - Buildings other than housing
PAS 79-2 - Housing - Withdrawn
BS 9792:2025 - Fire risk assessment. Housing. Code of practice
BS 8674 - 2025 Framework for Competence of Individual Fire Risk Assessors - Code of Practice

PAS 9980:2022 Fire risk appraisal of external wall construction and cladding of existing blocks of flats - Code of practice

PAS 9980 is permissive of timber construction in the external wall(s) unlike Building Regulation 7(2).

For existing blocks of flats.

High Court Building Liability Order

Section 130 of the BSA 2022 may be initiated by the F&RS enforcing an improvement alteration, or prohibition notice.

The Defective Premises Act 1972

Claims for defects in buildings by the building owner as a consequence of FRA under the RR(FS)O 2005 as amended by BSA 2022.

Section 38 Civil liability of the Building Act 1984

Despite its mention in the Building Safety Act 2022, Section 38 Civil liability has still not been activated by the Secretary of State.

Regulatory Requirements for Wales, Scotland, and Northern Ireland (Not considered for this project research)

Building Act 1984 (Section 1 - the power to make building regulations through the Secretary of State of the responsible ministry. Section 6 - delegates the power to the Secretary of State to publish statutory guidance in the form of Approved Documents. Amended under the BSA 2022 for higher risk buildings)	England and Wales - Building Regulations 2010 (Regulation 8 - 'the purpose of securing reasonable standards of health and life safety for persons in or about buildings'. Regulation 7 - materials & workmanship amended 2018 and 2022 to address external walls on relevant buildings.)	Wales Approved Documents
Building (Scotland) Act 2003	Scotland - Building (Scotland) Regulations 2004	Scotland Technical Handbooks
Building Regulations (Northern Ireland) Order 1979	Northern Ireland - Building Regulations (Northern Ireland) 2012	Northern Ireland Technical Booklets

Figure 5-1 : requirements showing where fire sprinklers are covered within guidance

University of Lancashire

'Development of fire sprinkler system design for buildings with exposed timber surfaces' – Appendices

Dale Kinnersley

(G21040246)

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'Investigation of sprinkler wetting patterns for fire protection of exposed timber'.

Appendix A – LPC Technical Bulletin

Sprinkler protection to buildings featuring exposed timber structure and surfaces - Insurance requirements

TB238.1 INTRODUCTION

This Technical Bulletin provides insurers requirements for the sprinkler protection of mass timber constructed buildings which typically can include a combination of commercial and residential occupancies.

Sprinkler protection designed and installed in accordance with this Technical Bulletin will provide a minimum level of 'Property Protection,' which is recognised by building insurers. It will also help ensure tenable conditions are achieved during a fire, both for the safe evacuation of occupants of the building and for safe conditions for the Fire & Rescue Service personnel to attend and conduct their search and rescue operations and achieve fire control/extinguishment.

The main objective of this Technical Bulletin is to provide the user with guideline requirements for sprinkler protection of exposed timber construction which has been researched and tested including sprinkler head selection, spacing and fixing requirements. This Technical Bulletin is not intended to give detailed requirements and recommendations on all aspects of mass timber construction. For more comprehensive guidance, it is strongly recommended that the fire insurer be consulted at appropriate stages in the planning and construction of a sprinkler system as outlined in TB205 and recommendation incorporated from the Mass Timber Insurance Playbook.

TB238.2 GENERAL

A sprinkler system for mass timber buildings consists of a water supply, installation alarm control valve sets, system piping, zone valves, flow switches, and sprinkler heads located in accordance with the requirements of this Technical Bulletin. The water supplies for these properties will comply with configurations outlined in TB233 and will typically consist of independent water storage tank(s), associated sprinkler pump(s) and dedicated installation alarm control valve set(s) for commercial classifications.

The water supplies shall be sized to satisfy the design criteria in the most demanding area of hazard classification, generally in accordance with the current *LPC Rules for automatic sprinkler installations, incorporating BS EN 12845*, except where amended within this Technical Bulletin.

The provision of a sprinkler system multi- occupancies does not diminish the requirements for structural fire resistance, escape routes, fire alarms and safe housekeeping practices.

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TB238.3 DEFINITIONS

TB238.3.1 **Fire resistant compartment** – enclosed volume capable of maintaining its fire integrity for a minimum specified time as detailed in TB206.

TB238.3.2 **Multi-Occupancy** – Mixture of different hazard classifications within one building.

TB238.3.3 **Sprinkler** – nozzle with a thermally sensitive sealing device which opens to discharge water for firefighting in commercial occupancies.

TB238.3.4 **Stop valve** – a manually operated valve for controlling the flow of water into installation pipework.

TB238.3.5 **Water motor alarm** – a device for detecting the flow of water into an installation and sounding an alarm.

For all other sprinkler system definitions, refer to BS EN 12845 clause 3.

TB238.4 CONSULTATION

Where a sprinkler system or an extension or alteration to a sprinkler system is being considered for new or existing buildings it is essential that as a minimum the following shall be consulted at an early stage:

a) The fire authority
b) The water authority
c) The fire insurer (as additionally detailed in LPC Technical Bulletin TB205)

During the construction/development of a building, insurance companies may change from construction phase to completion phase. It should be established through the property owner which insurance company will have ultimate authority at practical completion when considering the sprinkler provisions for the building.

TB238.5 COMPONENTS

TB238.5.1 **Suitable Components**

TB238.5.1.1 ***Approved Products***

The following products shall be used:

a) Commercial sprinkler heads in accordance with TB207
b) Alarm valve
c) Flow switches and indicators
d) Fire-pumps
e) Water storage tanks
f) Pipework & fittings shall comply with the appropriate standards of TB227.

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All sprinkler system components shall comply with the requirements of LPC Technical Bulletin TB201.

Commentary and Recommendations on TB238.5.1.1
Details of approved sprinkler products are given in LPC Technical Bulletin TB201. LPCB 'REDBOOKLIVE' website provides examples of approved products and services. All other products should be in accordance with appropriate British Standards and/or other nationally recognised standards such as F.M. and U.L.

TB238.6 DESIGN CONSIDERATIONS

TB238.6.1 Extent of sprinkler protection

TB238.6.1.1 Sprinkler protection shall be provided in all parts of the building as detailed in LPC Technical Bulletin TB206. Permitted and necessary exceptions are not considered where the full construction of the building utilises combustible materials, for example, construction of the primary structure (framework) and secondary structure (floors, walls and ceiling) are timber. Where hybridisation is used in the construction of the building, permitted and necessary exceptions may be permitted subject to consultation and written agreement with all interested parties as detailed in TB202.5, at planning stage prior to any design or installation works being carried out.

TB238.6.2 Installation type

TB238.6.2.1 Timber and hybrid buildings

Installation type shall be in accordance with BS EN 12845 clause 11 and shall be either:

a) Wet pipe installation; or
b) Pre-Action type A installation for areas susceptible to freezing such as IT suite comms rooms.

TB238.6.3 Water supplies

Water supplies shall be sized to satisfy the design criteria in the most demanding area of hazard classification, generally in accordance with the current LPC Rules for automatic sprinkler installations, incorporating BS EN 12845, except as amended by TB238.10.

(Where sprinkler systems are required by building control, TB233 may be applied with respects to life-safety water supply configuration).

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TB238.6.4 Pipework

TB238.6.4.1 Pipe sizing

Pipe sizes shall be determined using the methods identified in Technical Bulletin TB231 clause TB231.2.

Pipework downstream of the sprinkler installation shall be sized in accordance with the requirements of BS EN 12845 clause 13 or, for High Rise Systems, BS EN 12845 Annex E, as clarified/updated by TB229.3.24.

TB238.6.4.2 Frost protection

Wet-pipe installations shall only be used where there is no danger of the water in the pipes freezing. Parts of the installation which may be subject to freezing may be protected by electrical trace heating or use of a subsidiary dry-pipe or alternate extension.

TB238.6.4.3 Drainage

Sprinkler pipework shall be installed in accordance with the requirements of BS EN 12845 clause 17.1.8. Main zone and installation drain valves shall be positioned in a readily accessible location and provided with hard piping to a permanent drain. This is to ensure inadvertent operation or accidental damage resulting in unwanted water discharge from the sprinkler system can be quickly isolated and drained to prevent water damage to the timber structure.

TB238.7 OCCUPANCIES AND FIRE HAZARD CLASSIFICATIONS

All occupancies within the building shall be sprinkler protected in accordance with the design criteria given for the relevant hazard classification detailed in BS EN 12845 and be a minimum of OH3.

Where there are car parks within a mixed occupancy building, these shall be sprinkler protected to meet the requirements of TB229 Table 7a which requires a design density of 12.5mm/min over an assumed fire area of 260m^2.

Commentary and Recommendations on TB238.7
Due to the increased fire risk associated with car parks, a 'wet' type sprinkler system is preferred. A pre-action type B installation is acceptable using a suitable fire detection system to BS 5839-6. When considering detection, linear heat detection may be more beneficial for these types of occupancies.

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TB238.8 DESIGN CRITERIA

TB238.8.1 Sprinkler spacing and selection

TB238.8.1.1 Sprinkler spacing

Sprinkler spacing shall be as detailed in BS EN 12845 clause 12 and be a maximum of 9m^2. Sidewall sprinklers are not permitted to be used. Staggered spacing shall be in accordance with BS EN 12845 clause 12.2 and Figure 8.

The location of sprinkler heads shall be as follows:

a) Minimum distance between sprinklers – 2.0 m
b) Maximum distance between sprinklers – 3.0 m
c) Minimum distance from timber soffit – 0.075 m
d) Maximum distance from timber soffit – 0.2 m
e) Maximum distance from walls – 1.5 m
f) Minimum distance from walls – 0.2 m
g) Maximum distance from windows – 1.5 m
h) Location around obstructions to be in accordance with TB229 and BS EN 12845 clause 12.4.6 to 12.4.11 inclusive.

TB238.8.1.2 Void sprinkler protection

Sprinkler protection to voids shall be as detailed in TB221, clause TB221.3.2 (c) and Figure TB221.F1.

Commentary and Recommendations on TB238.8.1.2
Voids in buildings pose a particular fire hazard in that they allow rapid and severe spread of fire around buildings. Fire spread through this means is a common feature of disproportionate fire losses. The likelihood of their contribution to an event is greatly exacerbated when voids are of combustible construction materials and/or contain combustible contents even in apparently modest amounts. Voids have the potential to hide and transfer fire through a building, be it flaming or smouldering combustion. The fire protection of combustible voids is certainly essential but the use of sprinklers to do this can be hindered by depth preventing spray pattern development. TB221.3.2 c) outlines configurations that are commonly acceptable and by omission, unacceptable configurations where sprinkler protection to the LPC Rules for Automatic Sprinkler Installations is specified.

Server rooms and IT hubs should be sprinkler protected. Alternatively, they may be properly segregated and protected by a gaseous extinguishing system complying with the requirements of LPS 1230 (with design concentration suitable for protecting a cable risk) or equivalent. For anything other than full sprinkler protection of such spaces, written consent from the fire insurers and relevant authorities shall be obtained.

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TB238.8.1.3 Sprinkler head selection

Following extensive testing for the correct selection of sprinkler head type for the specific protection of exposed timber surfaces, Conventional type sprinkler heads shall be used which provide multi-directional spray characteristics to allow wetting of the exposed combustible surfaces (floors, walls and ceilings) as shown in Figure TB238.F1 and TB238.F2.

Commentary and Recommendations on TB238.8.1.2
Studies (see references) have shown that modern Spray Sprinkler Pendant (SSP) and Spray Sprinkler Upright (SSU) sprinklers discharge 100% of the water downwards to the moveable fuel load located at the floor. The combustible nature of the timber structure has increased the Heat Release Rate (HRR), surface spread of flame and duration of fire necessitating the sprinkler system to achieve more. The use of Conventional sprinklers (CUP) has been proven to provide wetting to surfaces without compromising sprinkler design density at floor level.

Sprinkler heads shall be 'LPCB' approved or equivalent and selected from TB207.

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Figure TB238.F1 Conventional spray discharge pattern (floor and ceiling wetting).

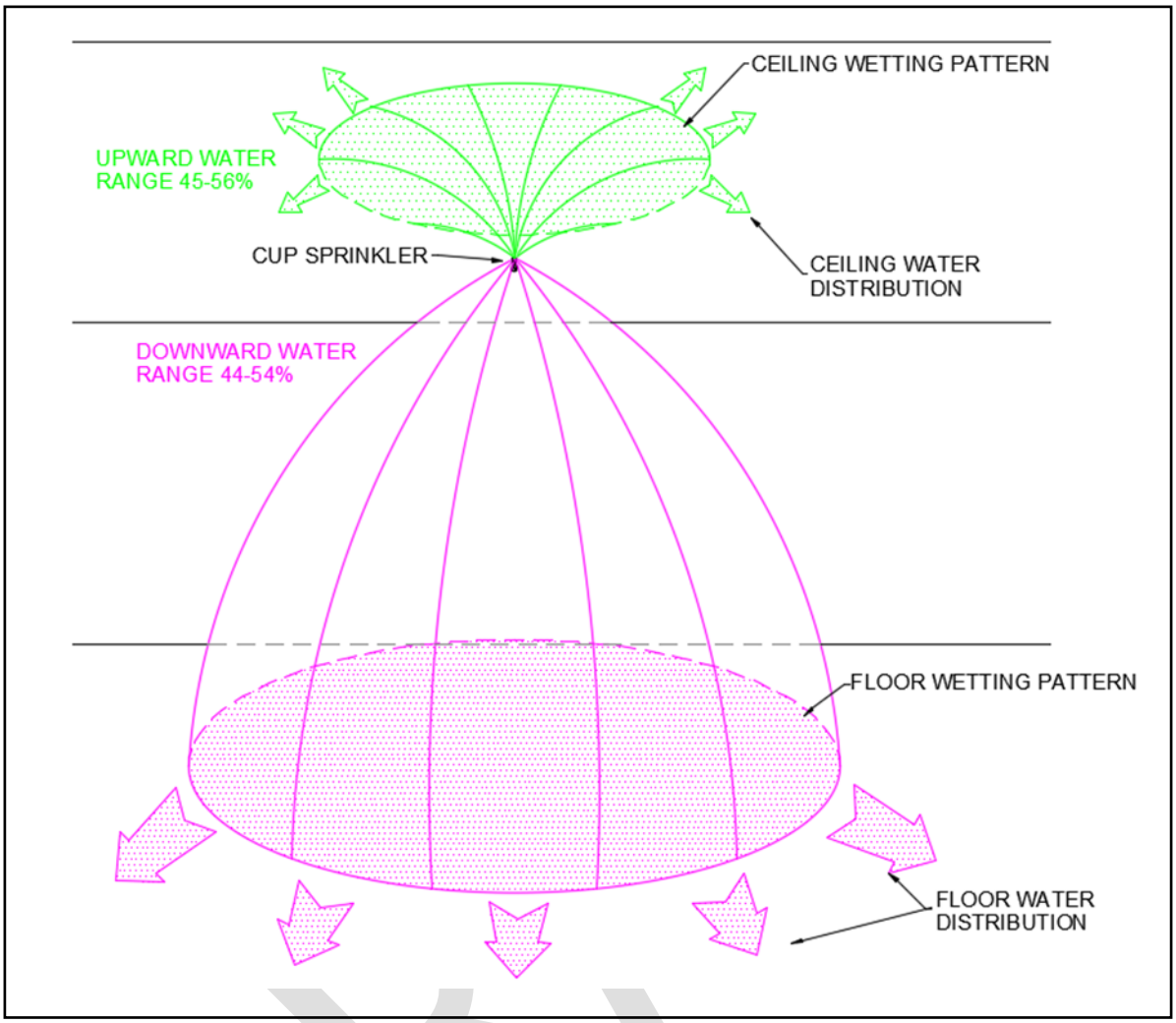
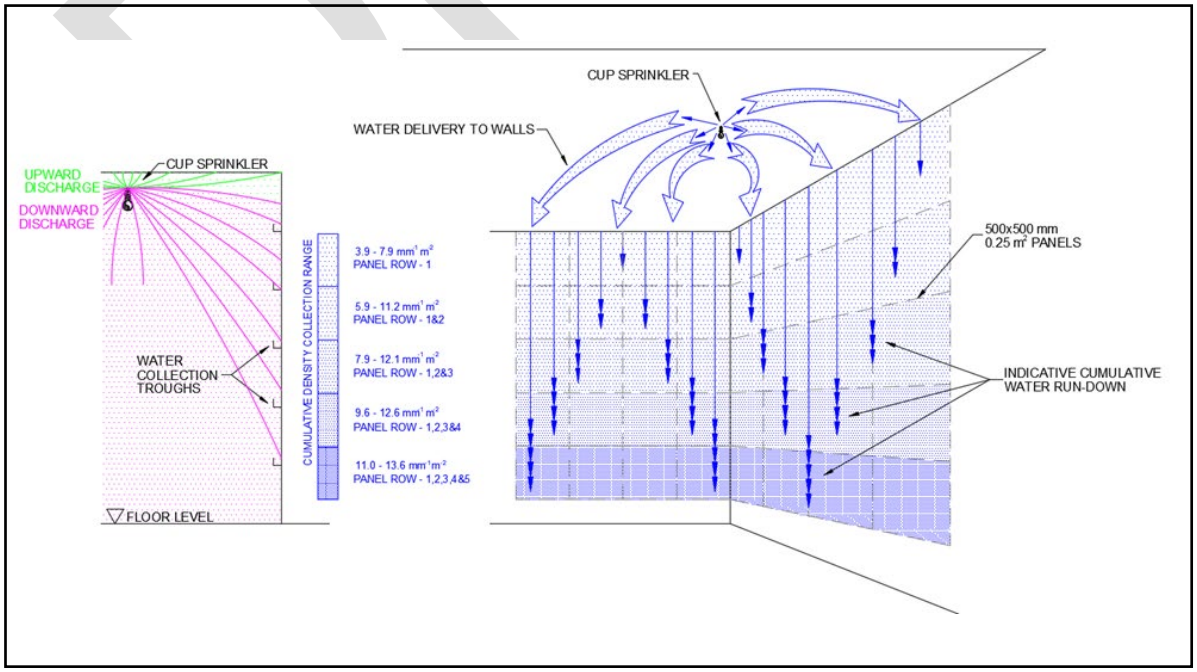


Figure TB238.F2 Conventional spray discharge pattern (wall wetting).



TB238.8.2 Zoning

The sprinkler system shall be zoned in accordance with the requirements of Annex D, and /or Annex F. Additionally, each floor within the building shall be controlled by a separate zone valve arrangement to limit the area of sprinkler protection which needs to be isolated during alteration works or maintenance operations and to enable the location of any sprinkler activation due to fire to be identified.

All zone control arrangements and facilities shall be securely located for access by authorised personnel only. All fire activation alarms shall automatically be transmitted to either a remote manned central monitoring station or direct to the fire & rescue service to ensure the earliest possible response time by the fire & rescue service to a fire incident.

Commentary and Recommendations on TB238.8.2
The provisions for the security of all valves shall be considered and located in a manner where malicious damage or isolation can be removed. Where accidental operation of the sprinkler system has occurred, access to the isolation valve should be available to site security, contingent on the building management system in place.

TB238.8.3 Installations

Sprinkler installations shall be as detailed in TB202.9.3 and conform to BS EN 12845 clause 11.

TB238.9 SPRINKLER PIPE SUPPORTS AND FIXINGS INTO TIMBER

TB238.9.1 Sprinkler pipe supports

Wherever possible sprinkler pipe shall be supported from non-combustible building, structural or permanent plant elements which shall be capable of supporting the additional load of the water-filled pipework and shall not impair the performance of the sprinklers under fire conditions. (where combustible building elements are used for support, extra protection is provided by the appropriate requirements of TB238.8.1).

Support systems for sprinkler pipework shall not be used to support any other objects except where a primary support system is employed which has been specifically designed for the suspension of multi-service loads including the sprinkler pipes. Sprinkler supports shall completely surround the pipe and shall not be welded to the pipe or fittings.

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Where sprinkler pipework rests on a support it shall be secured in position to accommodate any movement of the sprinkler pipework when the sprinkler system operates.

When selecting suitable pipework supports consideration shall be given to thermal movement of pipework, relative movement between elements of the structure to which pipes are attached, reaction to sudden filling of the pipework, uniformity of supporting effort, potential damage caused by movement of plant or machinery and maintenance of installation integrity under fire conditions.

Typical sprinkler pipework supports for general structure attachment can be found in TB229.3.22 and BS EN 12845 clause 17.2.

TB238.9.2 Fixings into timber

PHASE 1 TESTING - COMPLETE

PHASE 2 TESTING – IN PROGRESS

CHAPTER TO BE CONCLUDED FOLLOWING COMPLETION OF PHASE 2 TESTING

TB238.10 WATER SUPPLIES

TB238.10.1 Choice of water supply

Sprinkler system water shall meet the requirements of:

a) at least one superior single water supply as detailed in BS EN 12845 clause 9.6.2, or
b) comply with the requirements of Approved Document B as detailed in LPC Technical Bulletin TB233

based on the more onerous duty/capacity required to satisfy the design criteria of the sprinkler system in the commercial & industrial areas of the premises or, the residential & domestic areas of the premises, whichever is the greater.

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TB238.10.2 Tanks

Where a water storage tank is used, it shall be one of the following:

a) A single full capacity tank,
b) Two half capacity tanks; or
c) For car park hazards, a single full capacity tank which may be reduced where the infill rate from the water authority's supply main is sufficient to make up the shortfall within the operating period defined in BS EN 12845, clause 8.1.1. for High Hazard.

The water storage shall have a system design capacity of not less than that required to support 60 minutes' duration. Where car parks are present, 90 minutes' water supply shall be provided.

Water storage arrangements shall be agreed with the authority having jurisdiction and the fire insurer at the planning stage.

Commentary and Recommendations on TB238.10.2
Concrete tanks designed and constructed in accordance with BS EN 1992-3, with rigid roofs of concrete, metal or glass fibre reinforced plastic may also be considered suitable.

All sprinkler tanks should comply with water byelaws.

TB238.10.3 Automatic sprinkler pumps

Where the sprinkler pumps draw from two water storage tanks, arrangements shall be such that any pump is able to draw water from either tank. It shall be possible to isolate either tank for maintenance whilst retaining supply to both pumps from the other tank. The siting and housing of the sprinkler pumps shall meet the requirements of Technical Bulletin TB210, clause TB210.3.

Sprinkler Pumps, arrangements, power supplies and related equipment shall comply with the requirements of LPC Technical Bulletin TB210. They shall be installed to comply with the positive suction head conditions specified in TB210.6.2.2 only.

TB238.10.4 Fire and rescue service inlets

Appropriately sized and housed fire and rescue service breeching inlets shall be provided to comply with the requirements of LPC Technical Bulletin TB232.3.5.

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TB238.11 REFERENCES

- BS EN 1992-3: Eurocode 2. Design of concrete structures. Liquid retaining and containment structures.
- LPC Rules for automatic sprinkler installations 2105 incorporating BS EN 12845.
- BS EN 12845:2015+A1:2019 incorporating corrigenda December 2015 and January 2016. Fixed firefighting systems – Automatic sprinkler systems – Design, installation, and maintenance.
- Mass Timber Insurance Playbook
- Scientific research paper - Investigation of sprinkler wetting patterns for fire protection of exposed timber
- Scientific research paper - Reduction of load capacity of screw fixings into a timber soffit during and after fire.

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Appendix B – Supplementary sprinkler material (Chapter 6)

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Methodology for converting raw data into graphical representation for Floor Density Distribution Plot Data.

Floor Density Distribution Plot Data

Floor Density Plot – Test Number : 01 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 02 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 03 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number: 04 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 05 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 06 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 07 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 08 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 09 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 10 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 11 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 12 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 13 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 14 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 15 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 16 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 17 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 17 (Isometric 3D and Plan 2D)
Floor Density Plot – Test Number : 01 (Isometric 3D and Plan 2D – 4 x head array)
Floor Density Plot – Test Number : 02 (Isometric 3D Unclipped)
Floor Density Plot – Test Number : 04 (Isometric 3D Unclipped)
Floor Density Plot – Test Number : 06 (Isometric 3D Unclipped)
Floor Density Plot – Test Number : 08 (Isometric 3D Unclipped)
Floor Density Plot – Test Number : 09 (Isometric 3D Unclipped)
Floor Density Plot – Test Number : 10 (Isometric 3D Unclipped)
Floor Density Plot – Test Number : 11 (Isometric 3D Unclipped)
Floor Density Plot – Test Number : 14 (Isometric 3D Unclipped)
Floor Density Plot – Test Number : 15 (Isometric 3D Unclipped)
Floor Density Plot – Test Number : 16 (Isometric 3D Unclipped)
Floor Density Plot – Test Number : 17 (Isometric 3D Unclipped)

Wall Wetting Distribution Plot Data

Wall Wetting Test Number : W01 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W02 (Individual Density Plot and Cumulative Density Plot)

Wall Wetting Test Number : W03 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W04 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W05 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W06 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W07 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W08 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W09 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W10 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W11 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W12 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W13 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W14 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W15 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W16 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W17 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W18 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W19 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W20 (Individual Density Plot and Cumulative Density Plot)
Wall Wetting Test Number : W21 (Individual Density Plot and Cumulative Density Plot)

Ceiling Wetting Distribution Data

Water Distribution Spray Pattern Test Number : 01 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 02 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 03 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 04 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 05 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 06 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 07 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 08 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 09 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 10 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 11 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 12 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 13 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 14 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 15 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 16 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 17 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : 18 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : W03 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : W04 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : W12 (Photograph and Visual Representation)

Water Distribution Spray Pattern Test Number : W14 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : W20 (Photograph and Visual Representation)
Water Distribution Spray Pattern Test Number : W21 (Photograph and Visual Representation)

Methodology for converting raw data into graphical representation for Floor Density Distribution Plot Data.

Stage 1:

108 identical buckets were used to capture water distribution in specific locations below the sprinkler. Water captured in each bucket (geographically located below the sprinkler) was weighed and recorded. On completion of data entry into Excel, a 180^0 representation of water distribution weight was produced for individual bucket locations, shown in Figure 1.

Bucket No.	Weight
1	0.02
2	0.19
3	0.8
4	1.32
5	1.03
6	1.76
7	9.01
8	4.07
9	5.58
10	8.31
11	1.73
12	1.12
13	1.22
14	1.41
15	0.83
16	0.18
17	0.05

Pipe

Sprinkler

1	0.02	17	0.05	33	0.03	49	0.01										
2	0.19	18	0.48	34	0.32	50	0.14	65	1.13								
3	0.8	19	1.16	35	0.93	51	0.66	66	0.57	79	0.01						
4	1.32	20	1.38	36	2.13	52	2.53	67	0.69	80	0.08	91	0.02				
5	1.03	21	1.15	37	1.67	53	2.3	68	0.76	81	0.31	92	0.1	101	0.01		
6	1.76	22	1.36	38	1.18	54	1.36	69	0.86	82	0.46	93	0.12	102	0.0001		
7	9.01	23	1.56	39	1.13	55	0.98	70	0.86	83	0.17	94	0.02	103	0.0001		
8	4.07	24	3.32	40	1.55	56	0.98	71	1.63	84	0.29	95	0.08	104	0.0001		
9	5.58	25	1.56	41	1.52	57	1.24	72	0.98	85	0.23	96	0.03	105	0.0001		
10	8.31	26	1.62	42	1.18	58	1.39	73	0.3	86	0.11	97	0	106	0		
11	1.73	27	1.19	43	1.06	59	1.16	74	0.07	87	0.14	98	0.005	107	0		
12	1.12	28	1.1	44	1.31	60	2.05	75	0.01	88	0.46	99	0.02	108	0		
13	1.22	29	1.36	45	1.75	61	2.2	76	0.08	89	0.45	100	0.0001				
14	1.41	30	1.38	46	1.13	62	1.24	77	0.31	90	0.12						
15	0.83	31	0.92	47	0.28	63	0.33	78	0.46								
16	0.18	32	0.29	48	0.04	64	0.02										

Figure 1: Shows data input of individual buckets (Columns 1 &2, buckets 1-17) and 180^0 representation of individual water distribution weights (all buckets).

Stage 2:

From individual bucket weights, a full 360^0 representation of the water distribution was produced, applying X, Y and Z coordinates in the spreadsheet and mirroring data collected (assuming symmetry), along the black vertical line in Figure 2.

	X	Y	Z
1	0.25	3.75	0.02
2	0.25	3.25	0.19
3	0.25	2.75	0.8
4	0.25	2.25	1.32
5	0.25	1.75	1.03
6	0.25	1.25	1.76
7	0.25	0.75	9.01
8	0.25	0.25	4.07
9	0.25	-0.25	5.58
10	0.25	-0.75	8.31
11	0.25	-1.25	1.73
12	0.25	-1.75	1.12
13	0.25	-2.25	1.22
14	0.25	-2.75	1.41
15	0.25	-3.25	0.83
16	0.25	-3.75	0.18
17	0.75	3.75	0.05
18	0.75	3.25	0.48
19	0.75	2.75	1.16

Y \ X	-3.75	-3.25	-2.75	-2.25	-1.75	-1.25	-0.75	-0.25	0.25	0.75	1.25	1.75	2.25	2.75	3.25	3.75
3.75	0	0	0	0	0.01	0.03	0.05	0.02	0.02	0.05	0.03	0.01	0	0	0	0
3.25	0	0	0	1.13	0.14	0.32	0.48	0.19	0.19	0.48	0.32	0.14	1.13	0	0	0
2.75	0	0	0.01	0.57	0.66	0.93	1.16	0.80	0.80	1.16	0.93	0.66	0.57	0.01	0	0
2.25	0	0.02	0.08	0.69	2.53	2.13	1.38	1.32	1.32	1.38	2.13	2.53	0.69	0.08	0.02	0
1.75	0.01	0.10	0.31	0.76	2.30	1.67	1.15	1.03	1.03	1.15	1.67	2.30	0.76	0.31	0.10	0.01
1.25	0.00	0.12	0.46	0.86	1.36	1.18	1.36	1.76	1.76	1.36	1.18	1.36	0.86	0.46	0.12	0.00
0.75	0.00	0.02	0.17	0.86	0.98	1.13	1.56	9.01	9.01	1.56	1.13	0.98	0.86	0.17	0.02	0.00
0.25	0.00	0.08	0.29	1.63	0.98	1.55	3.32	4.07	4.07	3.32	1.55	0.98	1.63	0.29	0.08	0.00
-0.25	0.00	0.03	0.23	0.98	1.24	1.52	1.56	5.58	5.58	1.56	1.52	1.24	0.98	0.23	0.03	0.00
-0.75	0.00	0.00	0.11	0.30	1.39	1.18	1.62	8.31	8.31	1.62	1.18	1.39	0.30	0.11	0.00	0.00
-1.25	0.00	0.01	0.14	0.07	1.16	1.06	1.19	1.73	1.73	1.19	1.06	1.16	0.07	0.14	0.01	0.00
-1.75	0.00	0.02	0.46	0.01	2.05	1.31	1.10	1.12	1.12	1.10	1.31	2.05	0.01	0.46	0.02	0.00
-2.25	0	0.00	0.45	0.08	2.20	1.75	1.36	1.22	1.22	1.36	1.75	2.20	0.08	0.45	0.00	0
-2.75	0	0	0.12	0.31	1.24	1.13	1.38	1.41	1.41	1.38	1.13	1.24	0.31	0.12	0	0
-3.25	0	0	0	0.46	0.33	0.28	0.92	0.83	0.83	0.92	0.28	0.33	0.46	0	0	0
-3.75	0	0	0	0	0.02	0.04	0.29	0.18	0.18	0.29	0.04	0.02	0	0	0	0

Pipe

Details in terms of collected weights of water (kg)

Blue numbers are just mirror image copies of values on the RHS

Figure 2: Full 360^0 representation of the water distribution weights for 216 buckets (108 buckets mirrored).

Stage 3:

To establish actual density delivered, weight of water was divided by duration of each test and then by the area of the bucket opening, which provided a density in mm min^{-1} m^{-2}. Figure 3 shows the calculation within the spreadsheet.

Calculations for mm/min/m2													
Diameter =			0.315	m		(of bucket + half the lip width)							
Area =			0.078	m2									
Collection time =			15	min									
				sec									
		=	15.00	min									

Figure 3: Calculation parameters for conversion of weight to density for each individual bucket.

Stage 4:

On conversion of weight to density within the spreadsheet, an independent 360^0 representation of density was produced, shown in Figure 4.

	Calcualated water distribution rate (mm/min/m2) in each collection area															
	-3.75	-3.25	-2.75	-2.25	-1.75	-1.25	-0.75	-0.25	0.25	0.75	1.25	1.75	2.25	2.75	3.25	3.75
3.75	0	0	0	0	0.01	0.03	0.04	0.02	0.02	0.04	0.03	0.01	0	0	0	0
3.25	0	0	0	0.97	0.12	0.27	0.41	0.16	0.16	0.41	0.27	0.12	0.97	0	0	0
2.75	0	0	0.01	0.49	0.56	0.80	0.99	0.68	0.68	0.99	0.80	0.56	0.49	0.01	0	0
2.25	0	0.02	0.07	0.59	2.16	1.82	1.18	1.13	1.13	1.18	1.82	2.16	0.59	0.07	0.02	0
1.75	0.01	0.09	0.27	0.65	1.97	1.43	0.98	0.88	0.88	0.98	1.43	1.97	0.65	0.27	0.09	0.01
1.25	0.00	0.10	0.39	0.74	1.16	1.01	1.16	1.51	1.51	1.16	1.01	1.16	0.74	0.39	0.10	0.00
0.75	0.00	0.02	0.15	0.74	0.84	0.97	1.33	7.71	7.71	1.33	0.97	0.84	0.74	0.15	0.02	0.00
0.25	0.00	0.07	0.25	1.39	0.84	1.33	2.84	3.48	3.48	2.84	1.33	0.84	1.39	0.25	0.07	0.00
-0.25	0.00	0.03	0.20	0.84	1.06	1.30	1.33	4.77	4.77	1.33	1.30	1.06	0.84	0.20	0.03	0.00
-0.75	0.00	0.00	0.09	0.26	1.19	1.01	1.39	7.11	7.11	1.39	1.01	1.19	0.26	0.09	0.00	0.00
-1.25	0.00	0.00	0.12	0.06	0.99	0.91	1.02	1.48	1.48	1.02	0.91	0.99	0.06	0.12	0.00	0.00
-1.75	0.00	0.02	0.39	0.01	1.75	1.12	0.94	0.96	0.96	0.94	1.12	1.75	0.01	0.39	0.02	0.00
-2.25	0	0.00	0.38	0.07	1.88	1.50	1.16	1.04	1.04	1.16	1.50	1.88	0.07	0.38	0.00	0
-2.75	0	0	0.10	0.27	1.06	0.97	1.18	1.21	1.21	1.18	0.97	1.06	0.27	0.10	0	0
-3.25	0	0	0	0.39	0.28	0.24	0.79	0.71	0.71	0.79	0.24	0.28	0.39	0	0	0
-3.75	0	0	0	0	0.02	0.03	0.25	0.15	0.15	0.25	0.03	0.02	0	0	0	0

Pipe

Figure 4: Full 360^0 representation of density collection for individual geographical locations for 216 buckets.

Using Microsoft spreadsheet graph representation, a plan plot of water density was produced, shown in Figure 5.

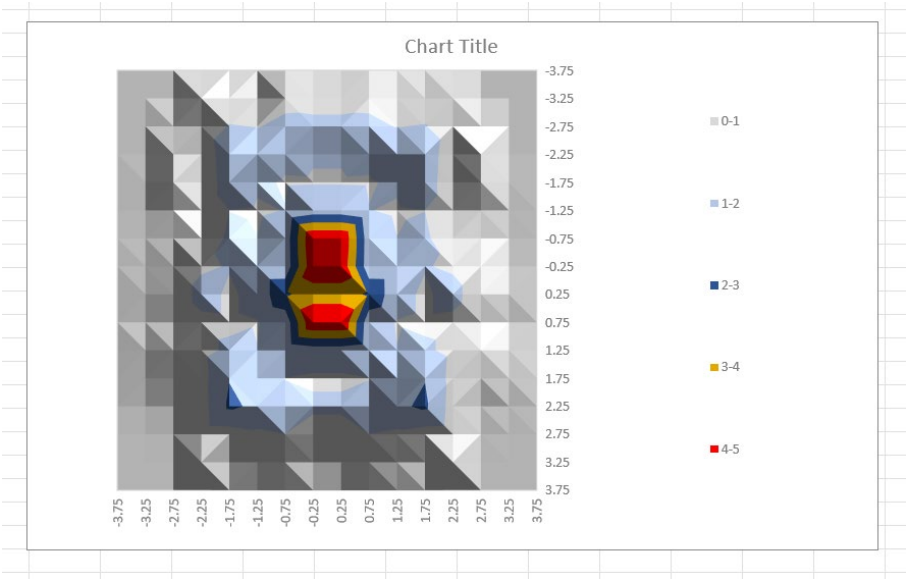


Figure 5: Microsoft Excel graphical representation of actual density delivered at floor level.

Stage 5

Using 'Microcal Origin', data from the spreadsheet was incorporated into the software based on an 8 x 16 grid. The grid was mirrored to provide a plotable matrix on 16 x 16 grid shown in Figure 6. The grid was then expanded by interpolation by a factor of 4 to give a matrix of 64 x 64 to improve presentation shown in Figure 7.

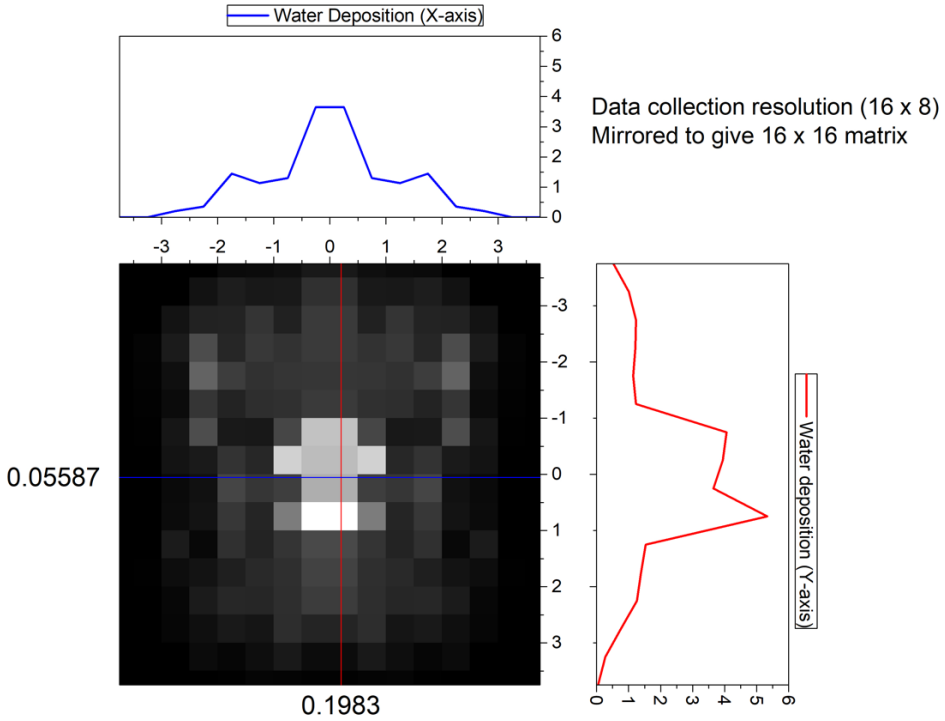


Figure 6: Shows graphical representation on a 16 x 16 grid.

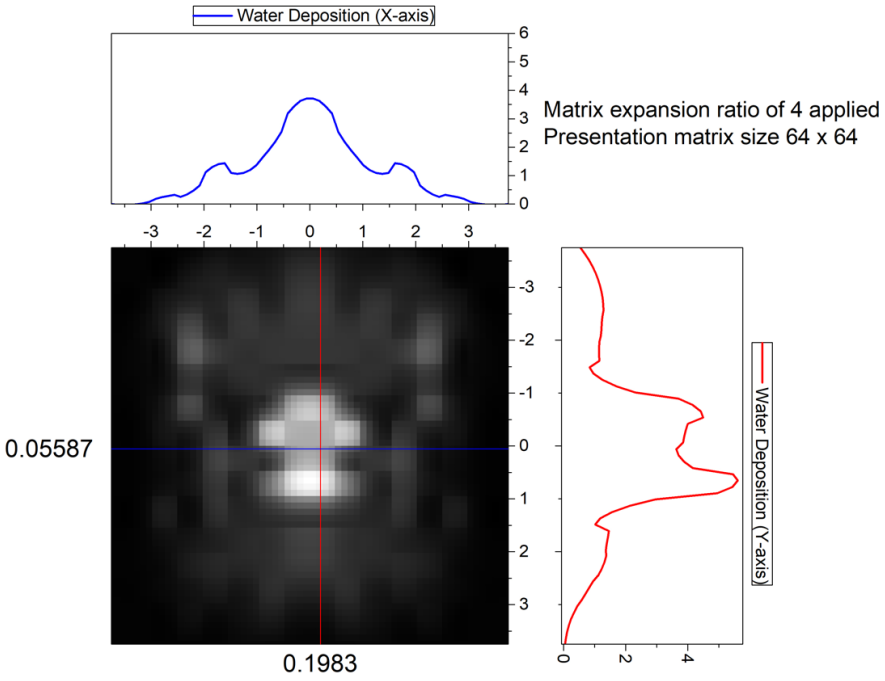


Figure 7: Shows graphical representation on a 64 x 64 grid.

Using the 64 x 64 grid, software parameters / presentation was adjusted to provide colour contour plots, shown in Figure 8 and colour plan plots at a density height of 6 mm, shown in Figure 9.

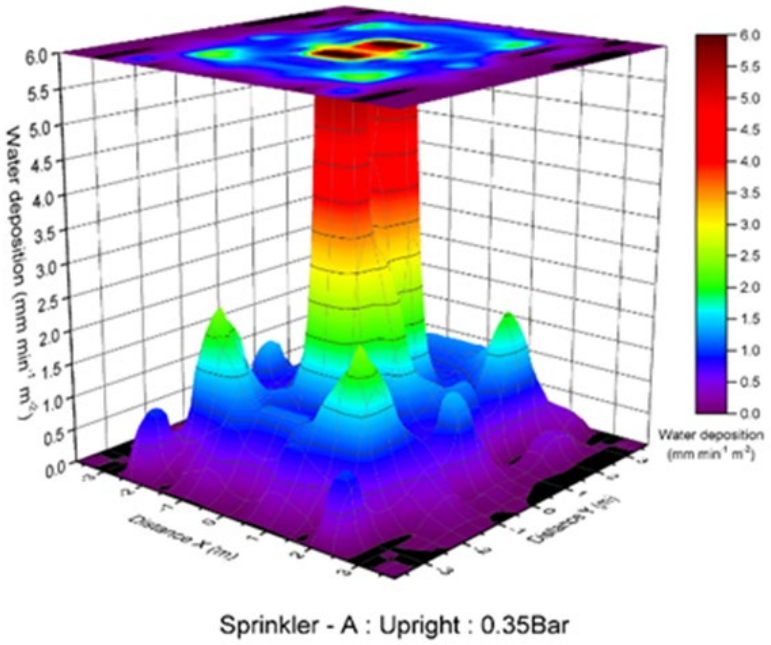


Figure 8: Isometric contour plot of density from Sprinkler A.

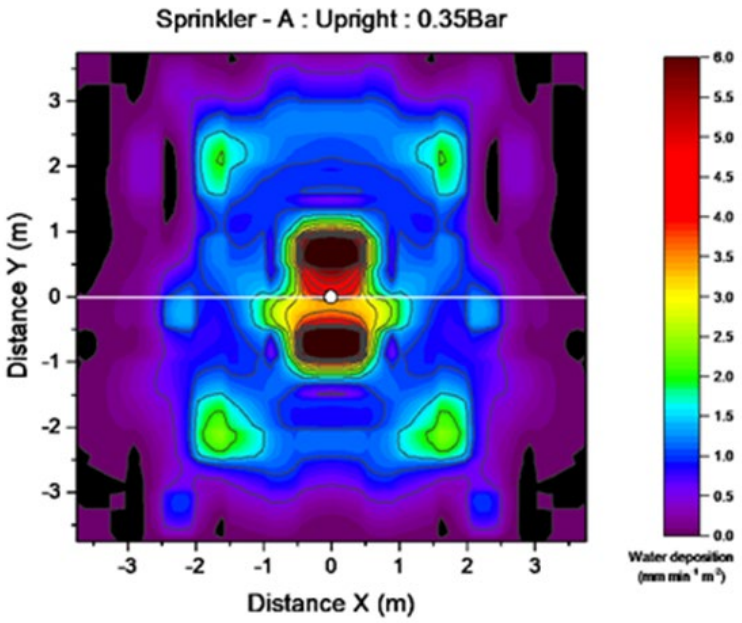
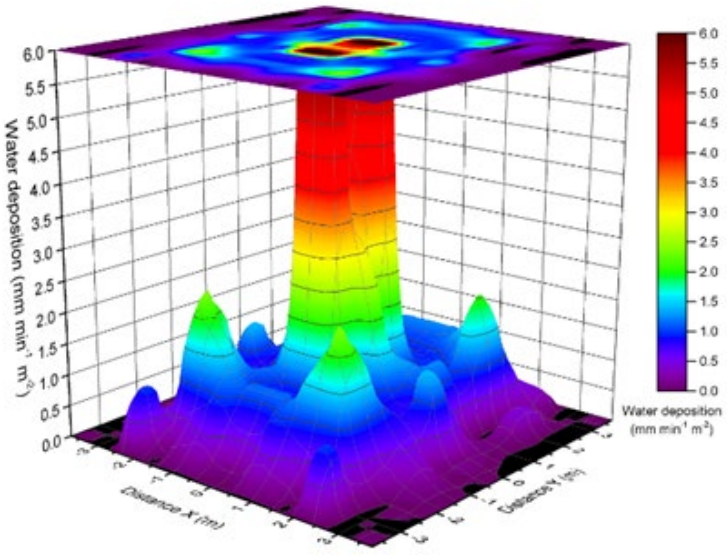


Figure 9: Plan plot of density captured from Sprinkler A at 6 mm depth.

For all sprinklers tested, Excel raw data was used within Microcal Origin to produce density plots as shown in the paper and supplementary material.

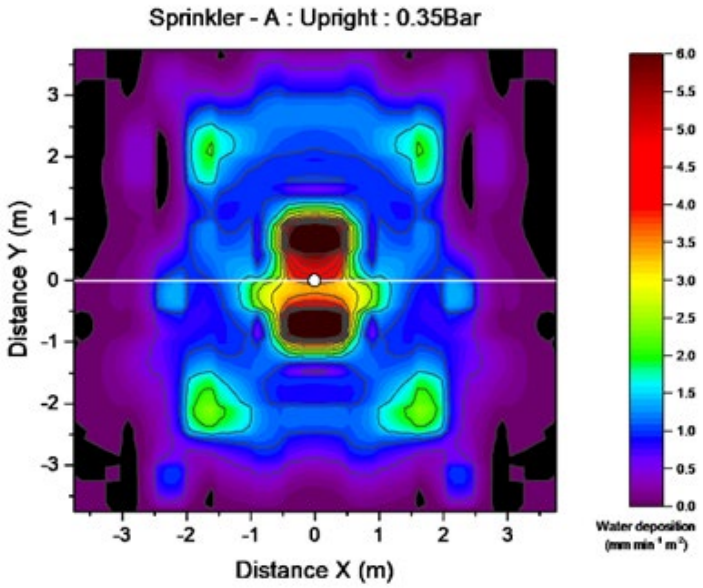
Floor Density Plot - Test Number : 01	
Date of Fire Test	17th October 2023
Time of Fire Test	15:46
Duration of Fire Test	15 Minutes, 00 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	0.35 bar (0.35 bar average achieved)

Isometric 3D Visual:



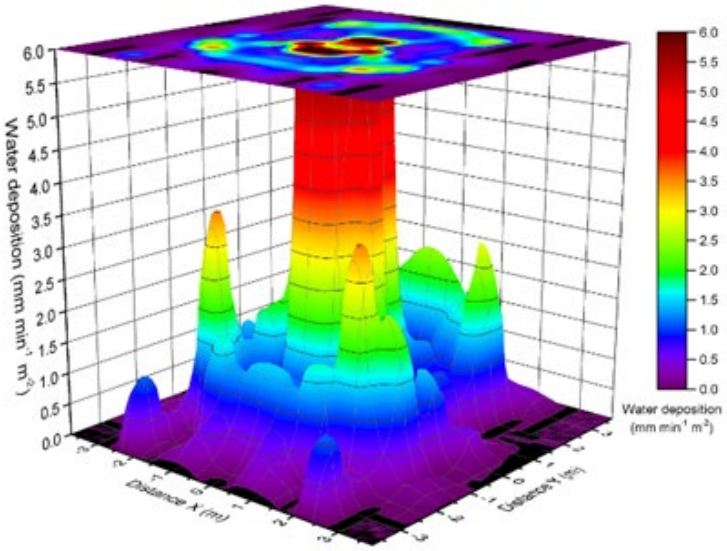
Sprinkler - A : Upright : 0.35Bar

Plan 2D Visual:



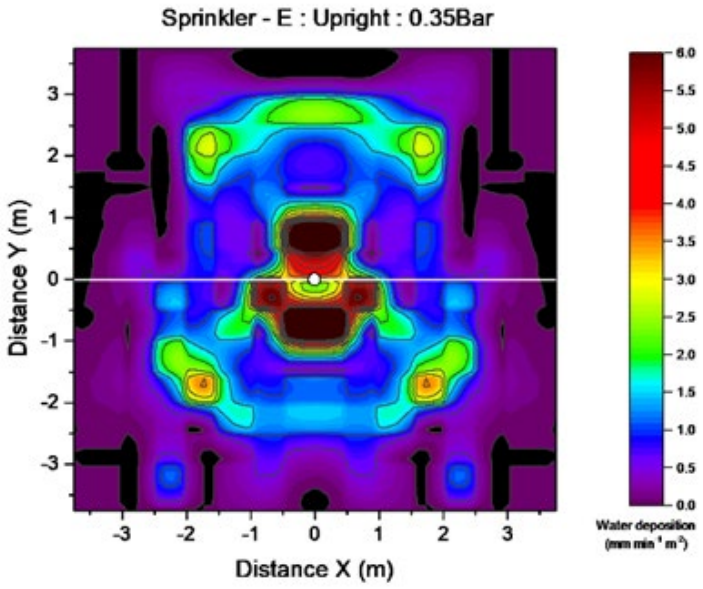
Floor Density Plot – Test Number : 02	
Date of Fire Test	18th October 2023
Time of Fire Test	09:44
Duration of Fire Test	13 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler E
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Isometric 3D Visual:



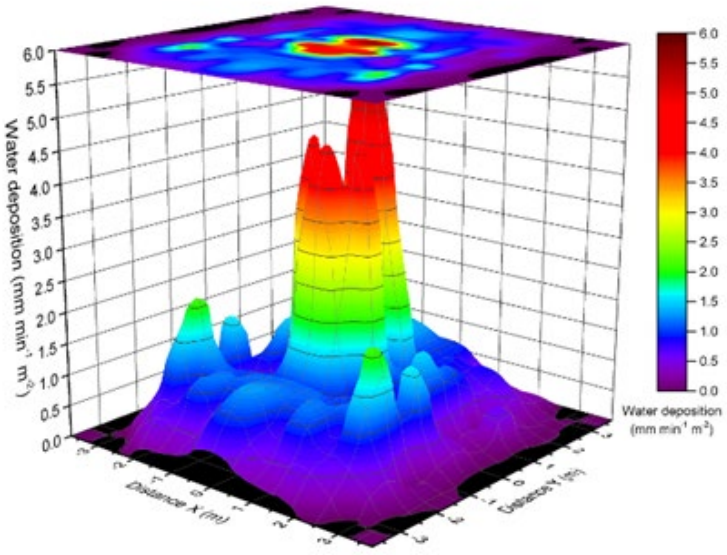
Sprinkler - E : Upright : 0.35Bar

Plan 2D Visual:



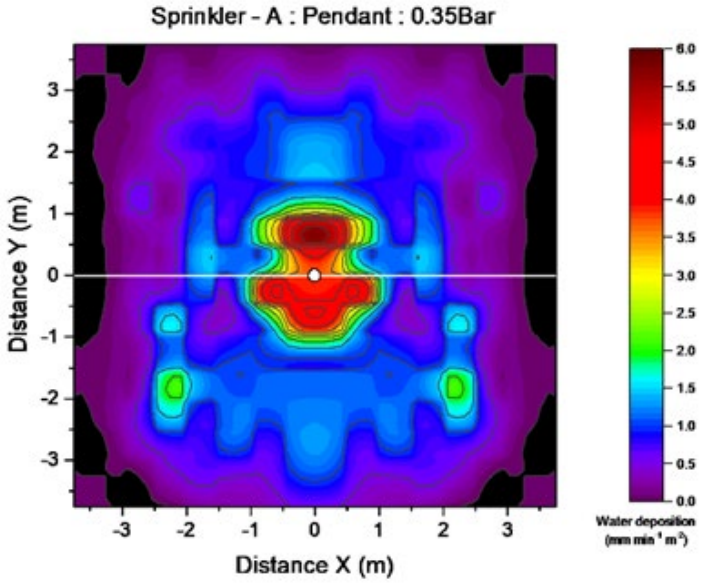
Floor Density Plot - Test Number : 03	
Date of Fire Test	18th October 2023
Time of Fire Test	12:16
Duration of Fire Test	19 Minutes, 00 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	175 mm
Sprinkler Head Pressure	0.35 bar (0.33 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:



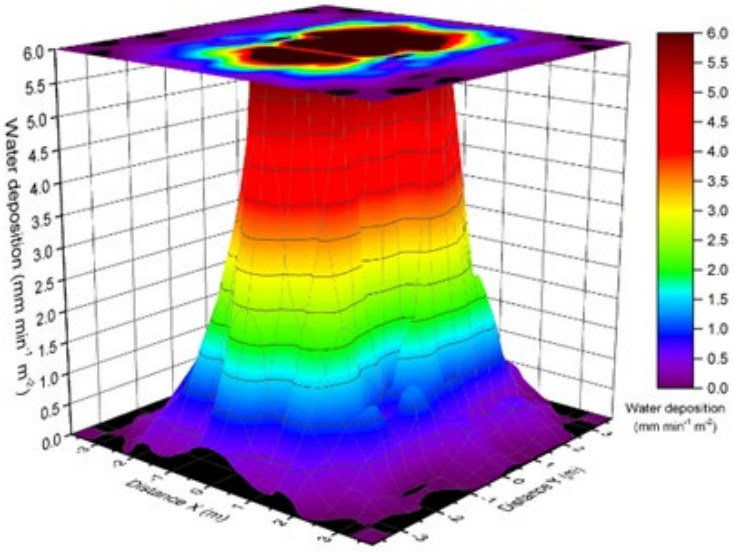
Sprinkler - A : Pendant : 0.35Bar

Plan 2D Visual:



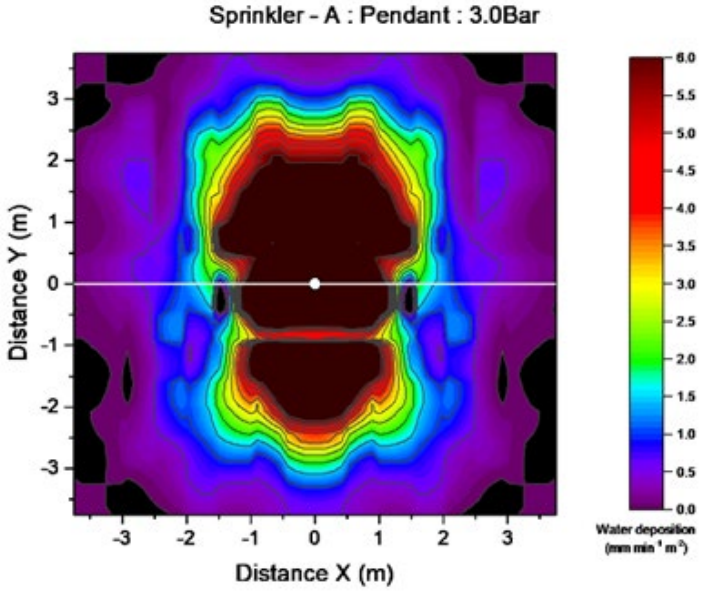
Floor Density Plot - Test Number : 04	
Date of Fire Test	18th October 2023
Time of Fire Test	14:45
Duration of Fire Test	05 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	175 mm
Sprinkler Head Pressure	3.00 bar (3.02 bar average achieved)

Isometric 3D Visual:



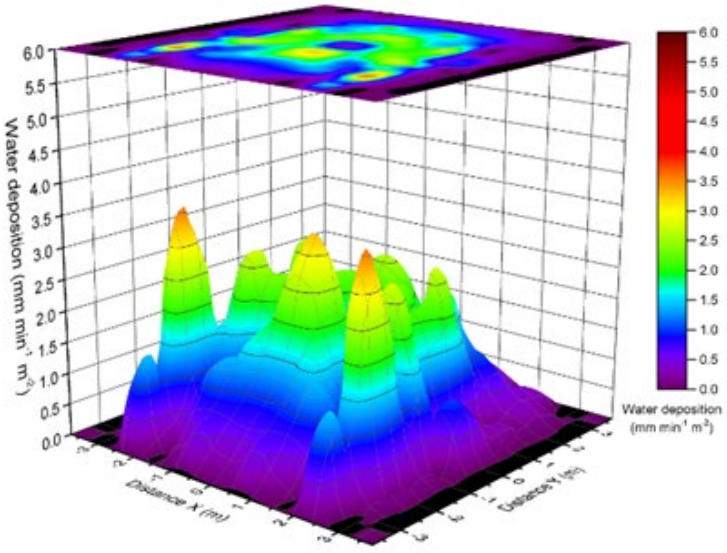
Sprinkler - A : Pendant : 3.0Bar

Plan 2D Visual:



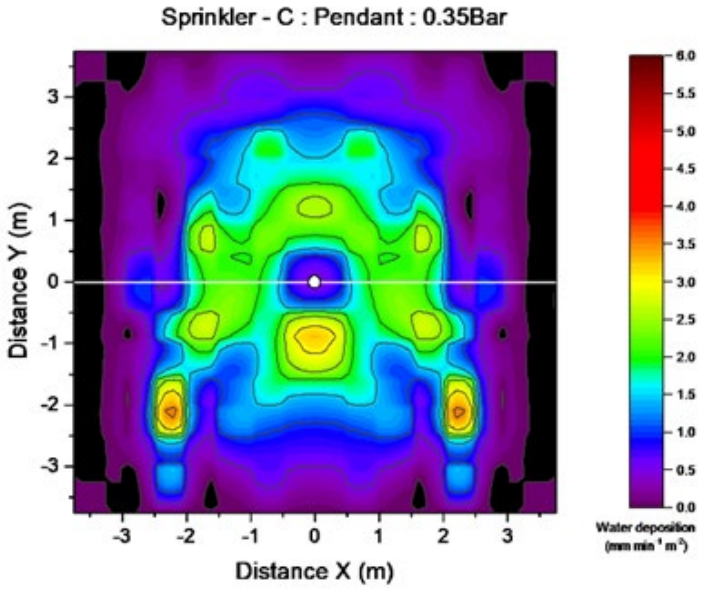
Floor Density Plot - Test Number : 05	
Date of Fire Test	2nd November 2023
Time of Fire Test	10:12
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Isometric 3D Visual:



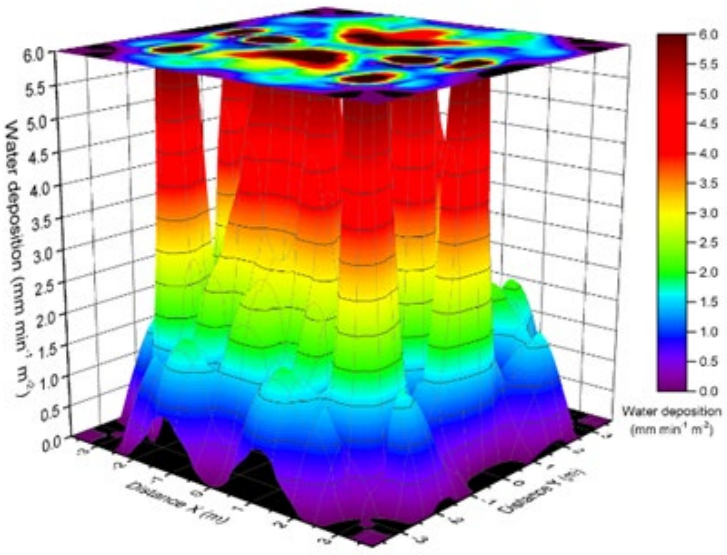
Sprinkler - C : Pendant : 0.35Bar

Plan 2D Visual:



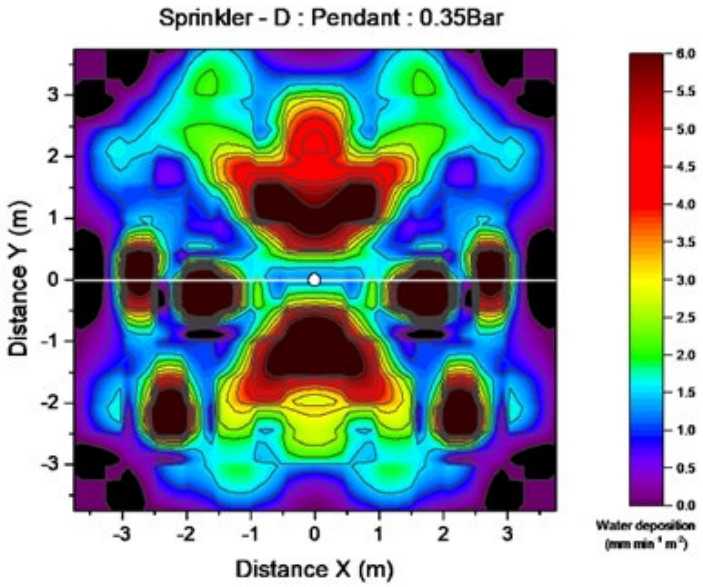
Floor Density Plot - Test Number : 06	
Date of Fire Test	2nd November 2023
Time of Fire Test	12:36
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler D
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Isometric 3D Visual:



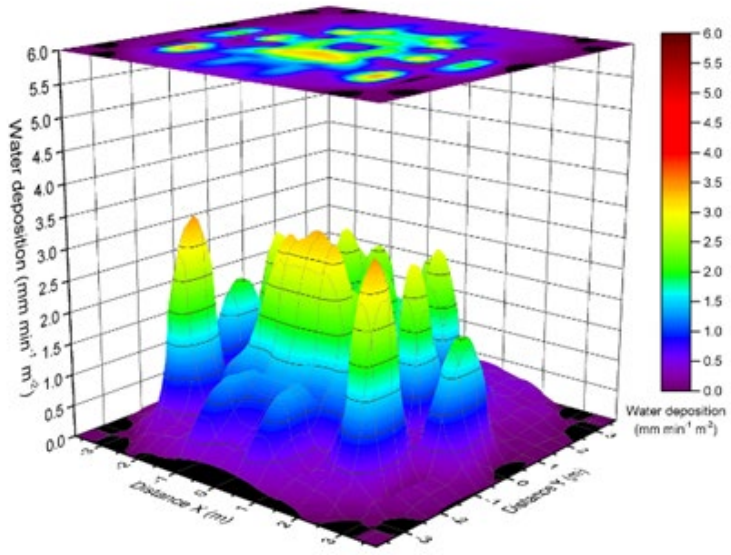
Sprinkler - D : Pendant : 0.35Bar

Plan 2D Visual:

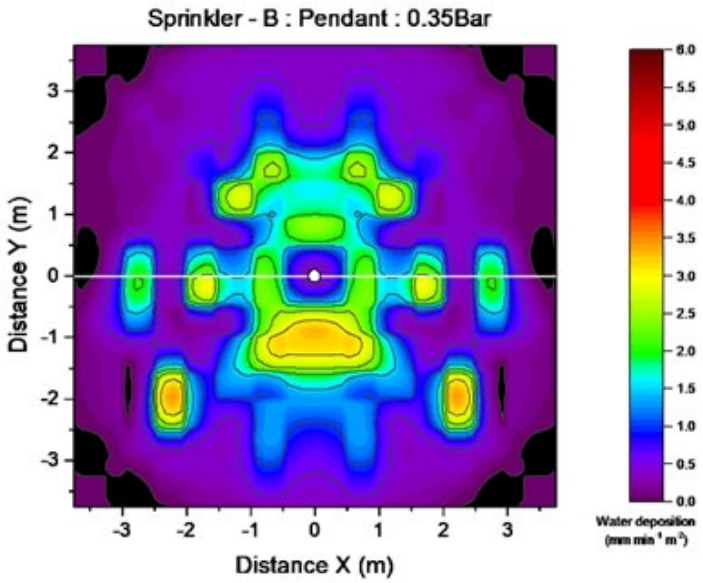


Water Distribution Spray Pattern Test Number : 07	
Date of Fire Test	2nd November 2023
Time of Fire Test	14:49
Duration of Fire Test	15 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Isometric 3D Visual:

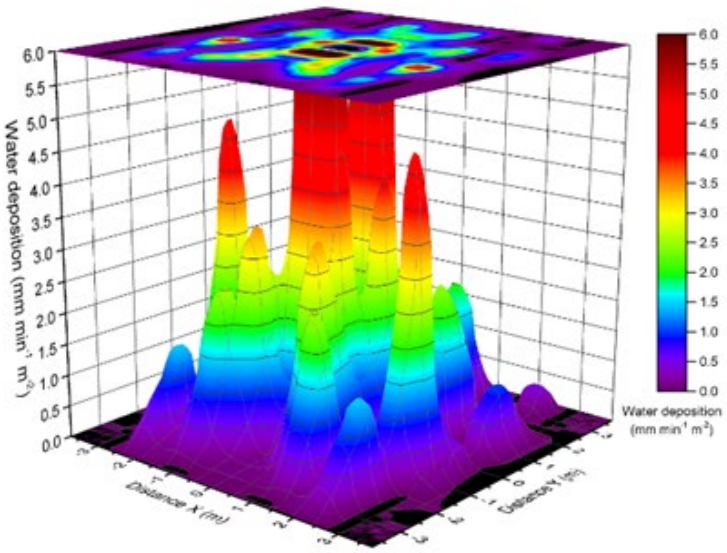


Plan 2D Visual:



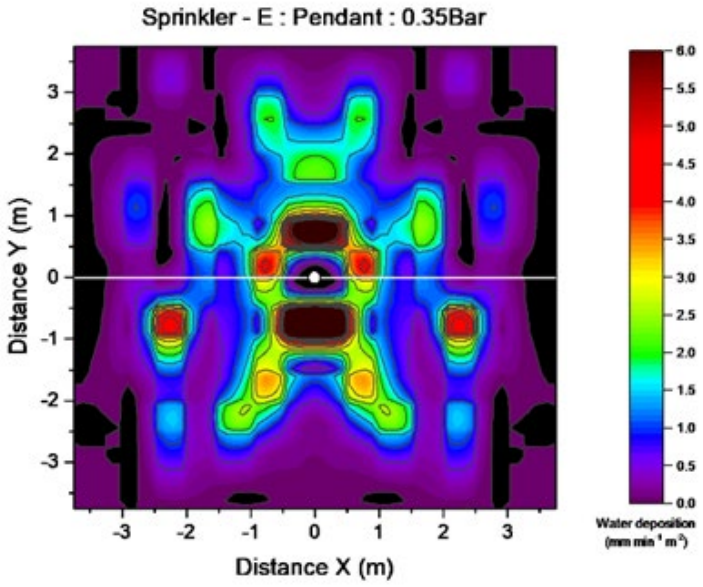
Floor Density Plot - Test Number : 08	
Date of Fire Test	6th November 2023
Time of Fire Test	09:20
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler E
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Isometric 3D Visual:



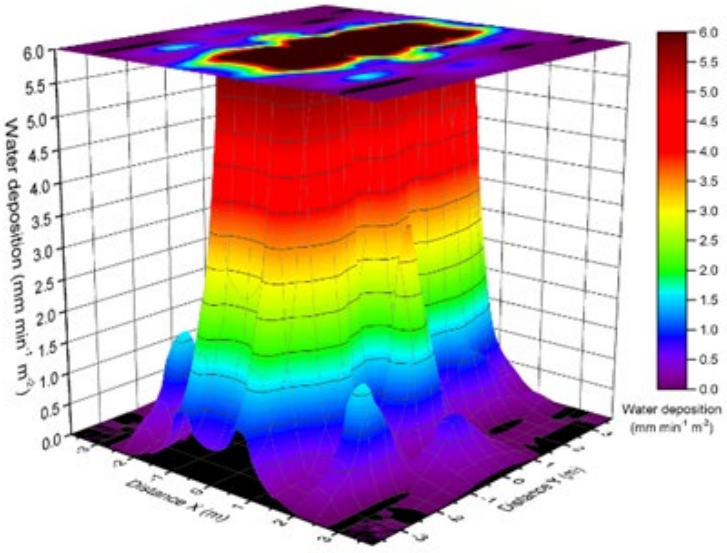
Sprinkler - E : Pendant : 0.35Bar

Plan 2D Visual:



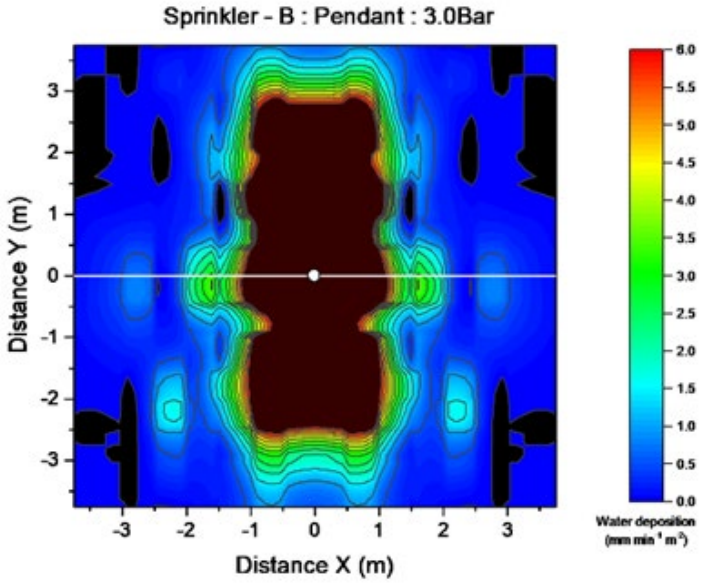
Floor Density Plot - Test Number : 09	
Date of Fire Test	6th November 2023
Time of Fire Test	11:44
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Head Pressure	3.00 bar (3.11 bar average achieved)

Isometric 3D Visual:



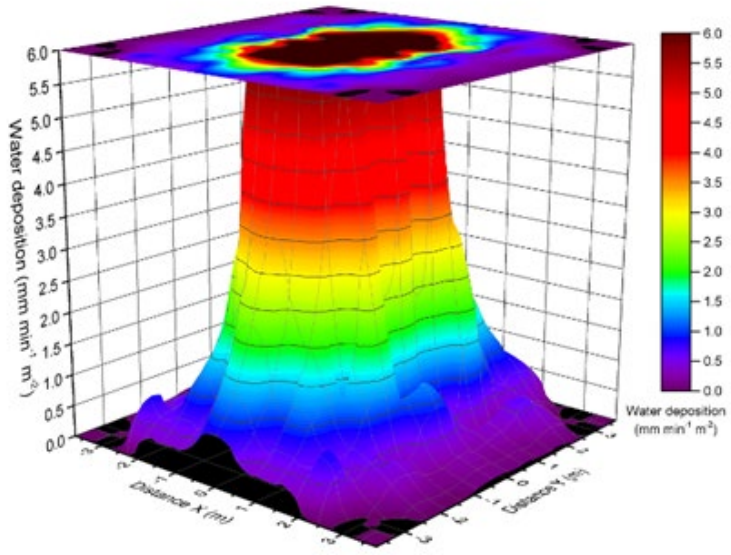
Sprinkler - B : Pendant : 3.0Bar

Plan 2D Visual:



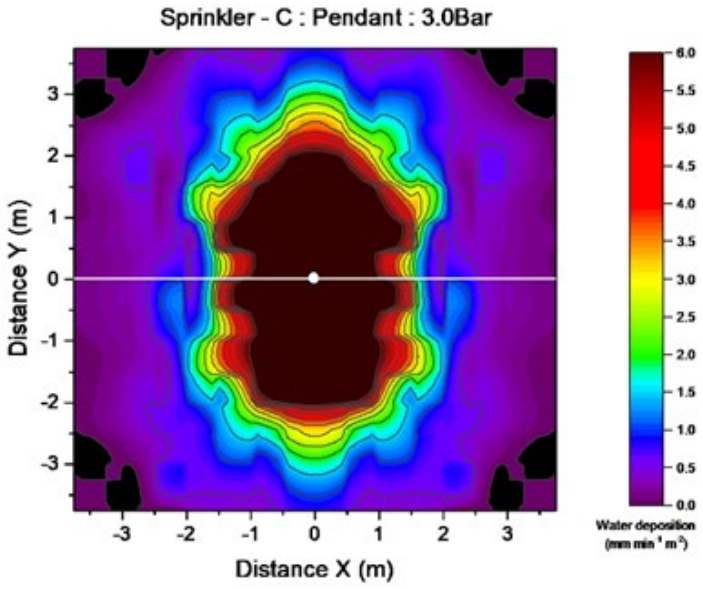
Floor Density Plot - Test Number : 10	
Date of Fire Test	6th November 2023
Time of Fire Test	14:07
Duration of Fire Test	11 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Head Pressure	3.00 bar (3.10 bar average achieved)

Isometric 3D Visual:



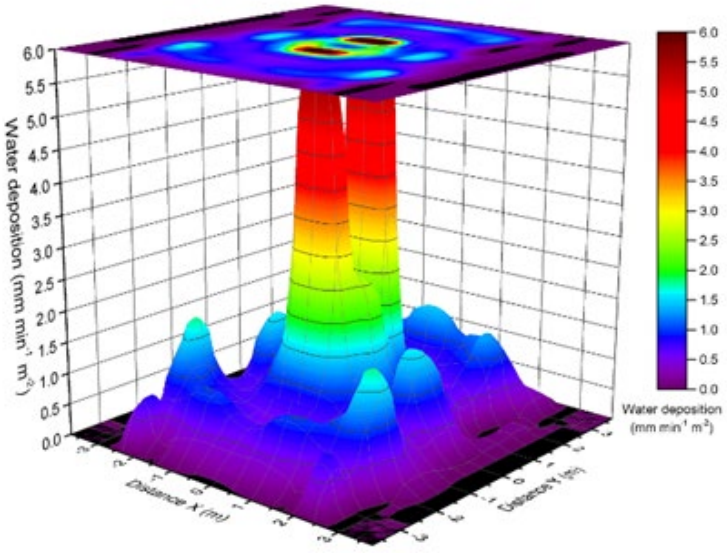
Sprinkler - C : Pendant : 3.0Bar

Plan 2D Visual:



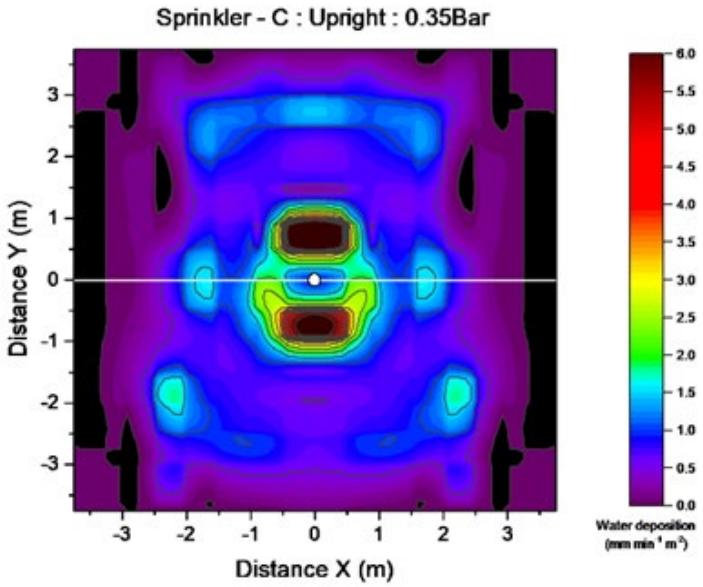
Floor Density Plot - Test Number : 11	
Date of Fire Test	7th November 2023
Time of Fire Test	09:07
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	0.35 bar (0.34 bar average achieved)

Isometric 3D Visual:



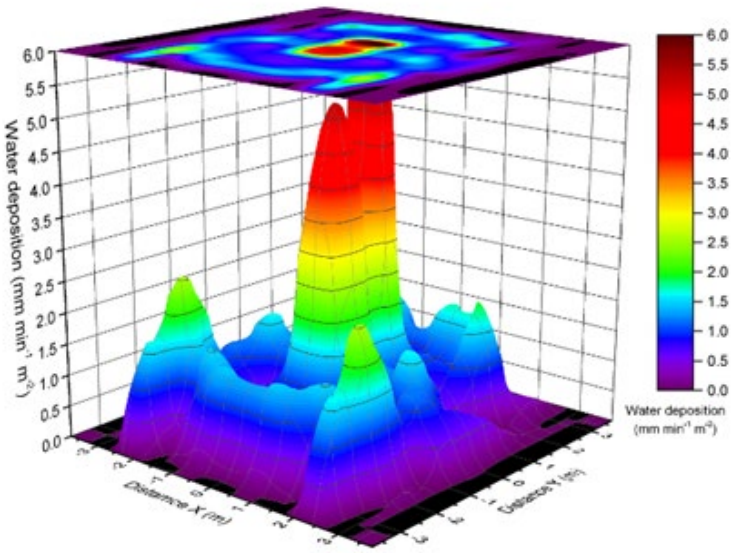
Sprinkler - C : Upright : 0.35Bar

Plan 2D Visual:



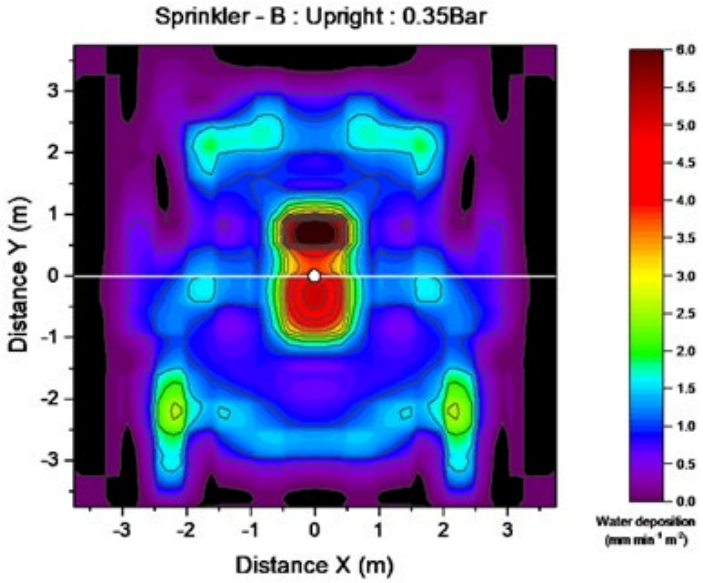
Floor Density Plot - Test Number : 12	
Date of Fire Test	7th November 2023
Time of Fire Test	14:45
Duration of Fire Test	15 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Isometric 3D Visual:



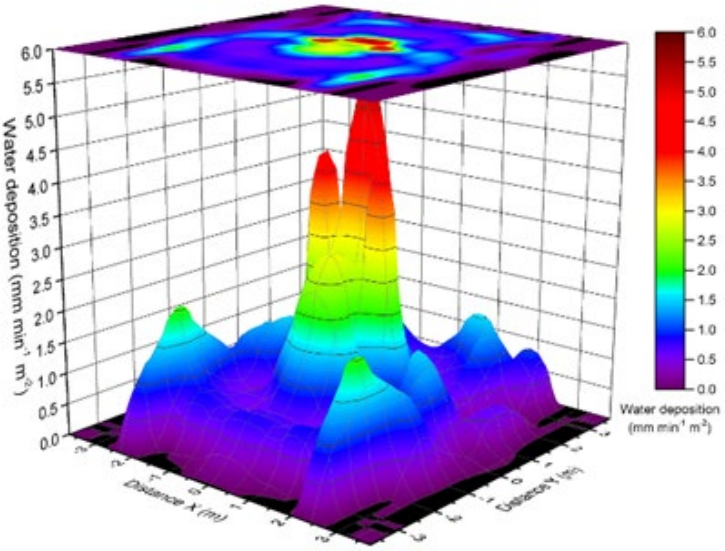
Sprinkler - B : Upright : 0.35Bar

Plan 2D Visual:



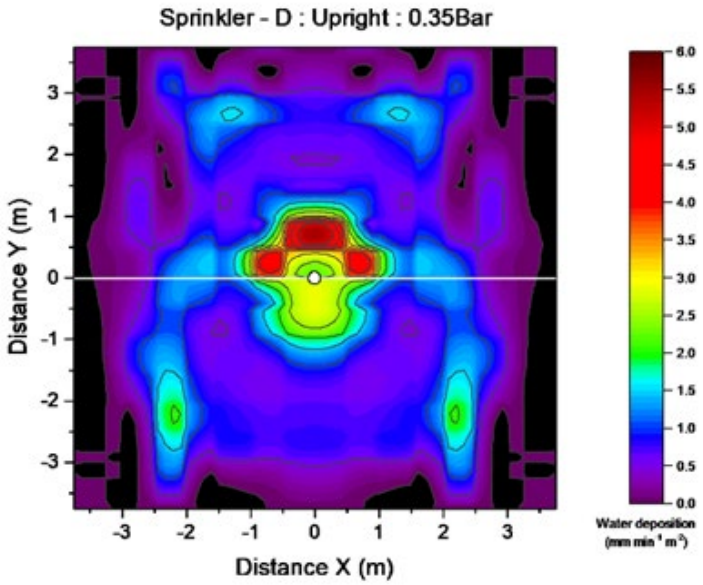
Floor Density Plot - Test Number : 13	
Date of Fire Test	8th November 2023
Time of Fire Test	09:43
Duration of Fire Test	15 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler D
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	0.35 bar (0.34 bar average achieved)

Isometric 3D Visual:



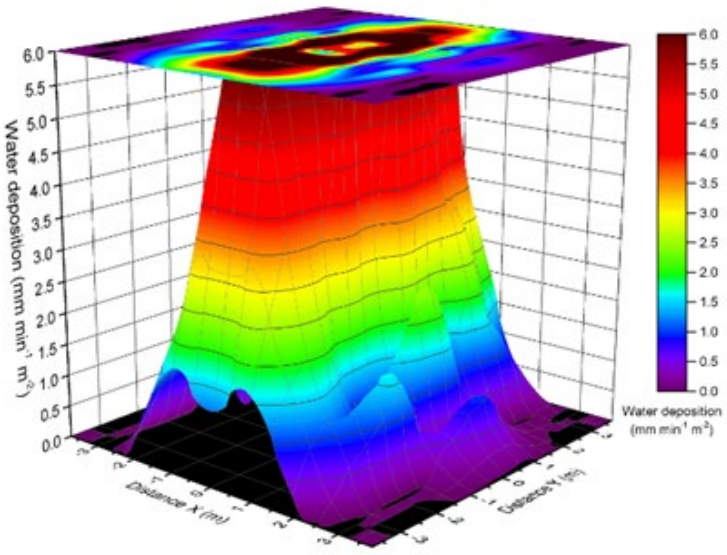
Sprinkler - D : Upright : 0.35Bar

Plan 2D Visual:



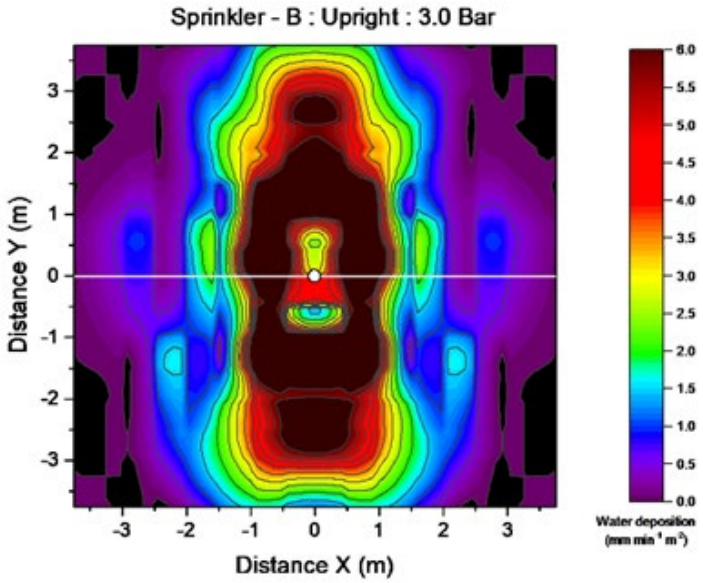
Floor Density Plot - Test Number : 14	
Date of Fire Test	8th November 2023
Time of Fire Test	14:07
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.00 bar (3.12 bar average achieved)

Isometric 3D Visual:



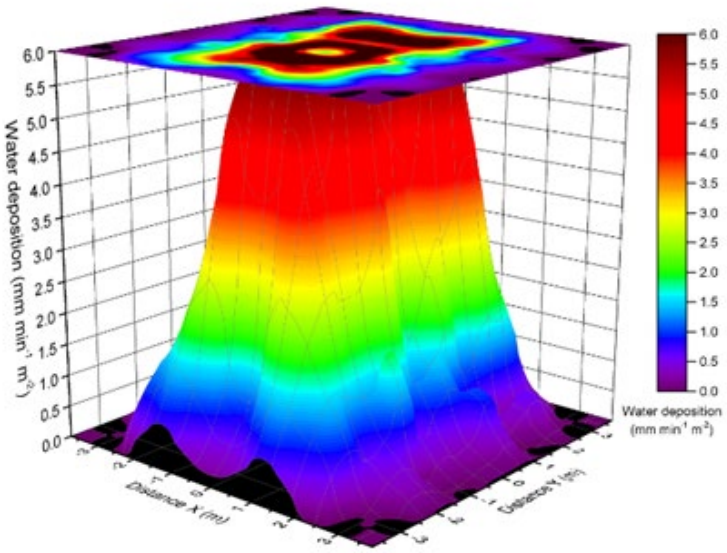
Sprinkler - B : Upright : 3.0 Bar

Plan 2D Visual:



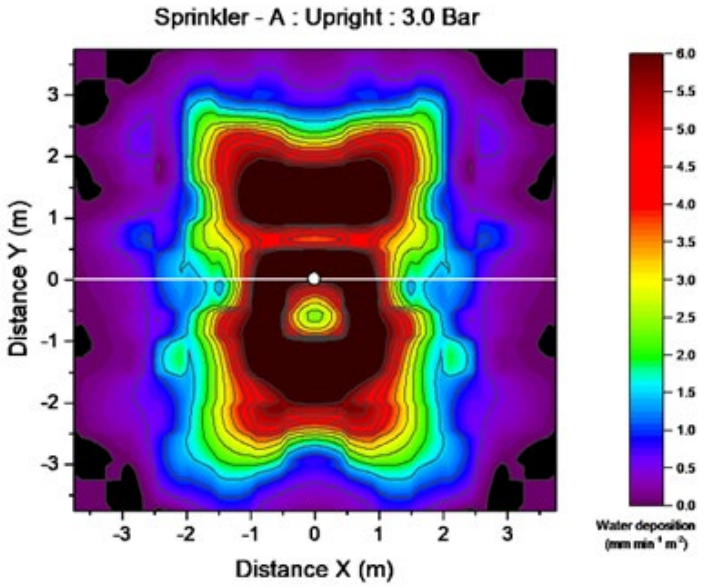
Floor Density Plot - Test Number : 15	
Date of Fire Test	9th November 2023
Time of Fire Test	09:14
Duration of Fire Test	08 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.00 bar (3.03 bar average achieved)

Isometric 3D Visual:



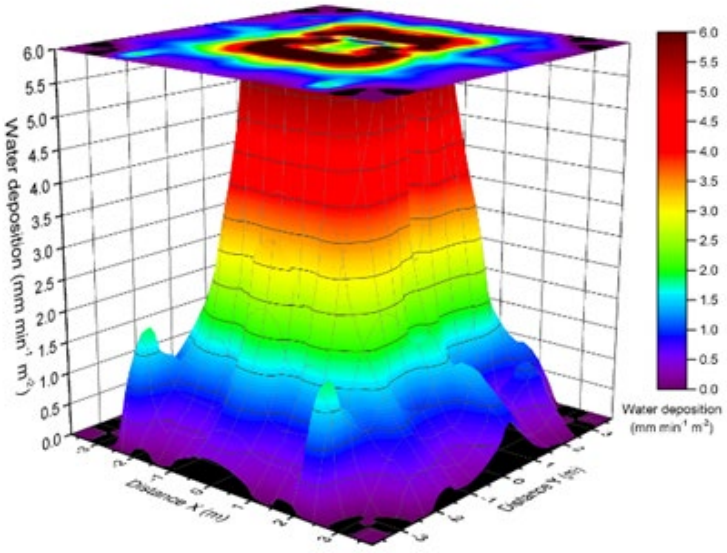
Sprinkler - A : Upright : 3.0 Bar

Plan 2D Visual:



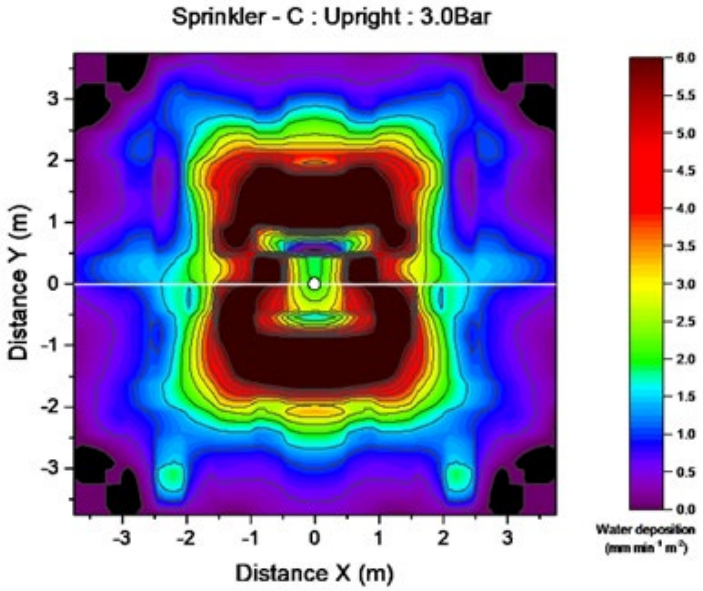
Floor Density Plot - Test Number : 16	
Date of Fire Test	9th November 2023
Time of Fire Test	11:40
Duration of Fire Test	07 Minutes, 03 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.00 bar (3.11 bar average achieved)

Isometric 3D Visual:



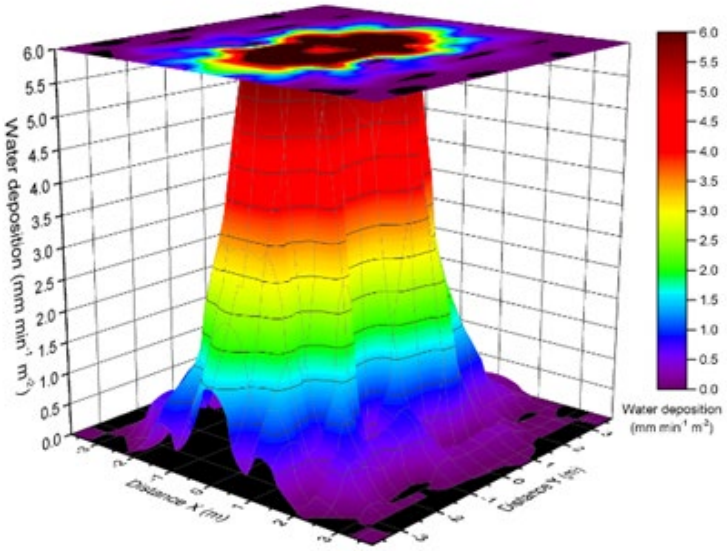
Sprinkler - C : Upright : 3.0Bar

Plan 2D Visual:



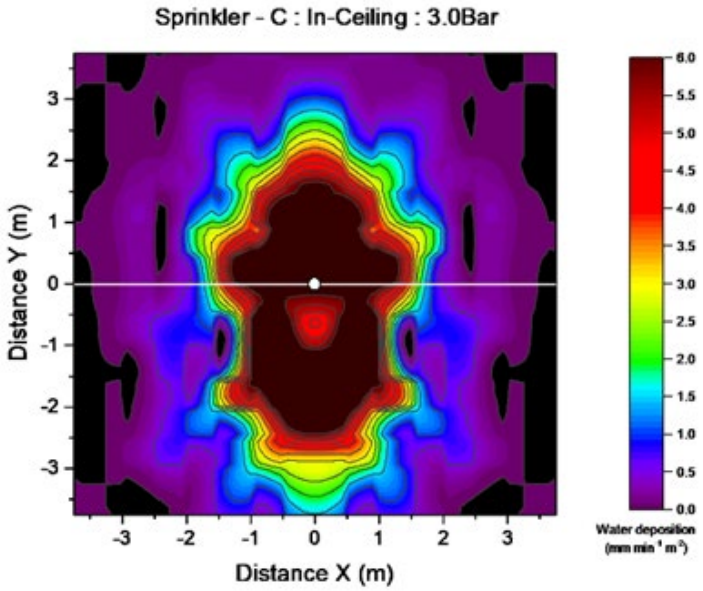
Floor Density Plot - Test Number : 17	
Date of Fire Test	28th November 2023
Time of Fire Test	12:56
Duration of Fire Test	08 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant within ceiling
Location of Deflector Below Ceiling	45 mm
Sprinkler Head Pressure	3.00 bar (2.85 bar average achieved)

Isometric 3D Visual:



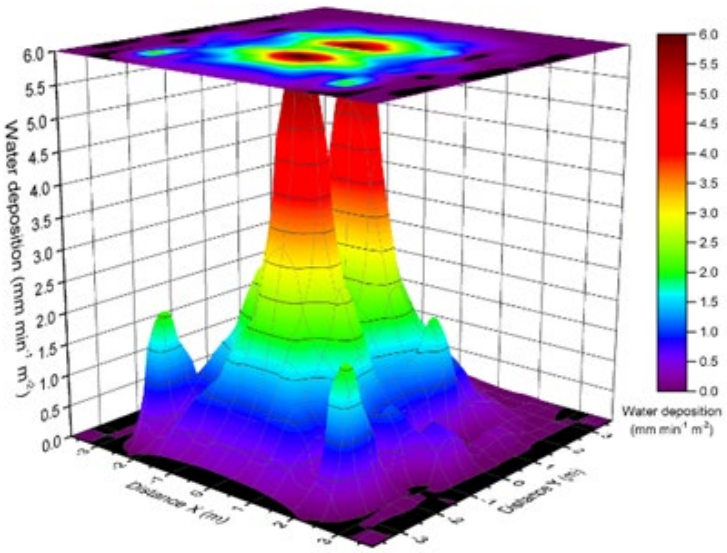
Sprinkler - C : In-Ceiling : 3.0Bar

Plan 2D Visual:



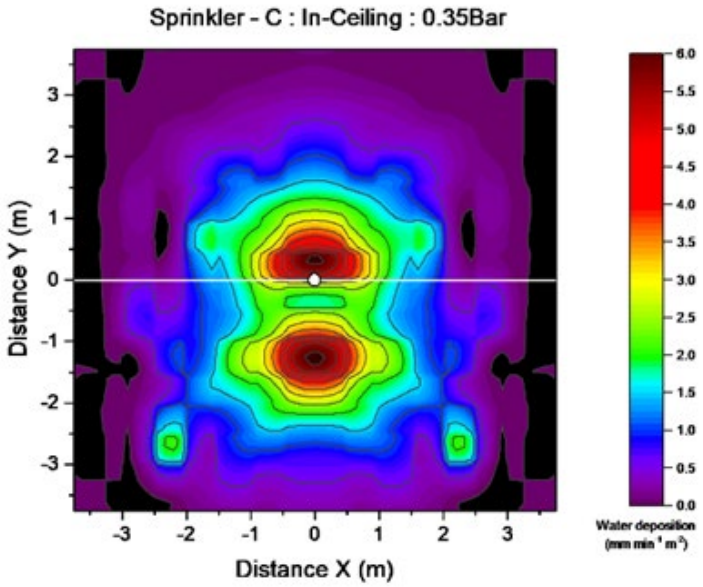
Floor Density Plot - Test Number : 18	
Date of Fire Test	29th November 2023
Time of Fire Test	09:35
Duration of Fire Test	15 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant within ceiling
Location of Deflector Below Ceiling	45 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Isometric 3D Visual:



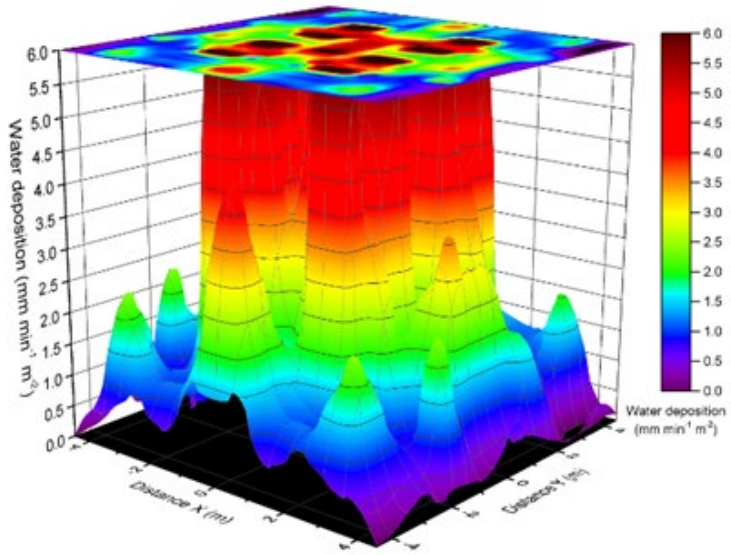
Sprinkler - C : In-Ceiling : 0.35Bar

Plan 2D Visual:



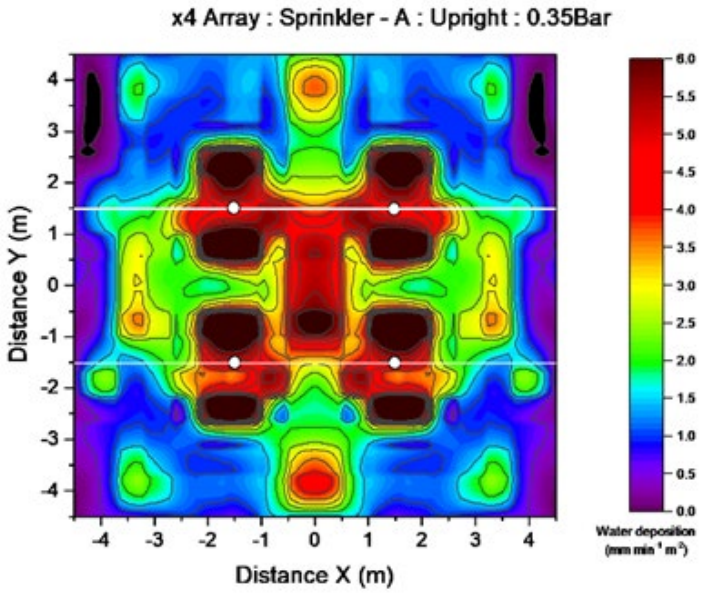
Floor Density Plot - Test Number : 01	
Date of Fire Test	17th October 2023
Time of Fire Test	15:46
Duration of Fire Test	15 Minutes, 00 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	0.35 bar (0.35 bar average achieved)

Isometric 3D Visual of 4 head layout:



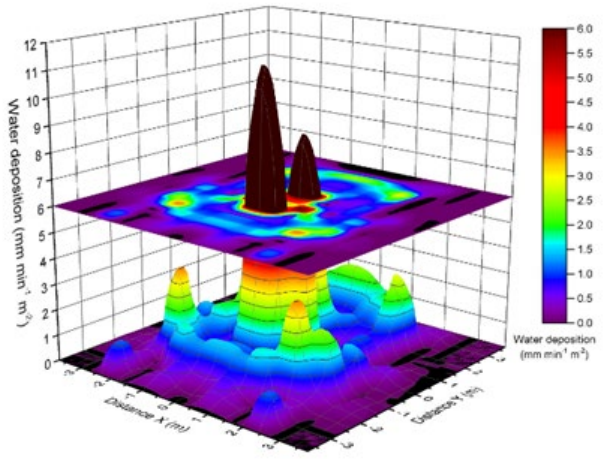
x4 Array : Sprinkler - A : Upright : 0.35Bar

Plan 2D Visual of 4 head layout:



Floor Density Plot - Test Number : 02	
Date of Fire Test	18th October 2023
Time of Fire Test	09:44
Duration of Fire Test	13 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler E
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

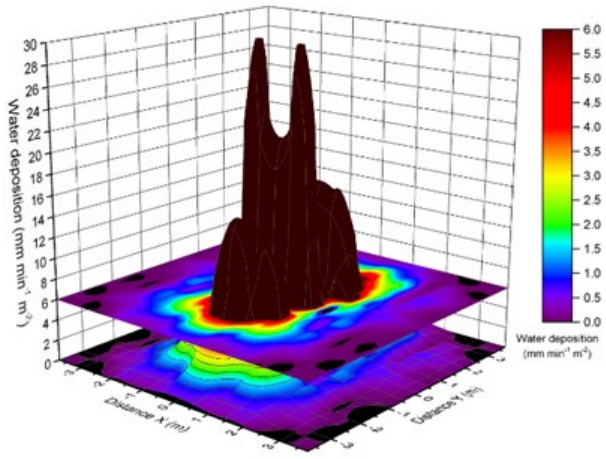
Isometric 3D Visual Unclipped:



Sprinkler - E : Upright : 0.35Bar

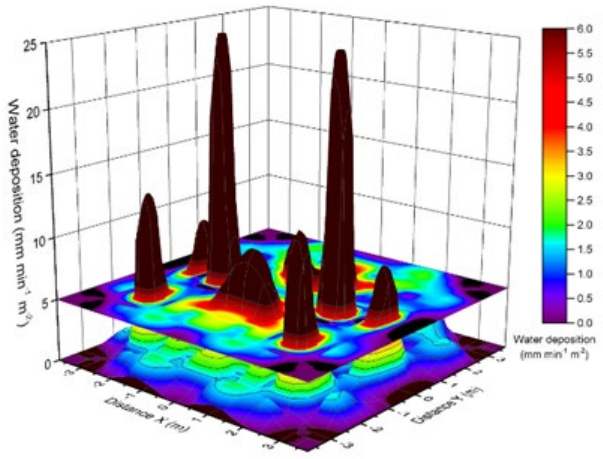
Floor Density Plot - Test Number : 04	
Date of Fire Test	18th October 2023
Time of Fire Test	14:45
Duration of Fire Test	05 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	175 mm
Sprinkler Head Pressure	3.00 bar (3.02 bar average achieved)

Isometric 3D Visual Unclipped:



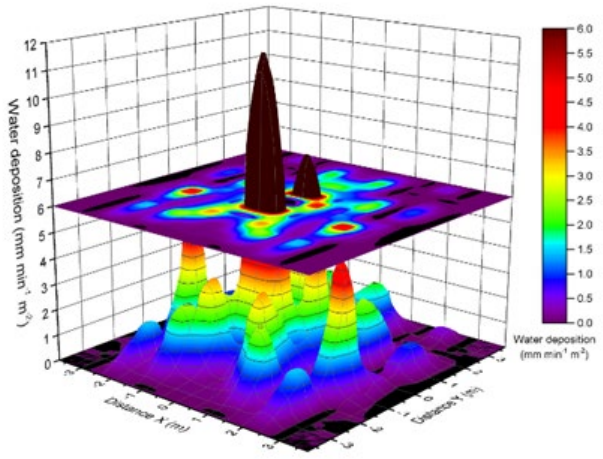
Sprinkler - A : Pendant : 3.0Bar

Floor Density Plot - Test Number : 06	
Date of Fire Test	2nd November 2023
Time of Fire Test	12:36
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler D
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)
Isometric 3D Visual Unclipped:	



Sprinkler - D : Pendant : 0.35Bar

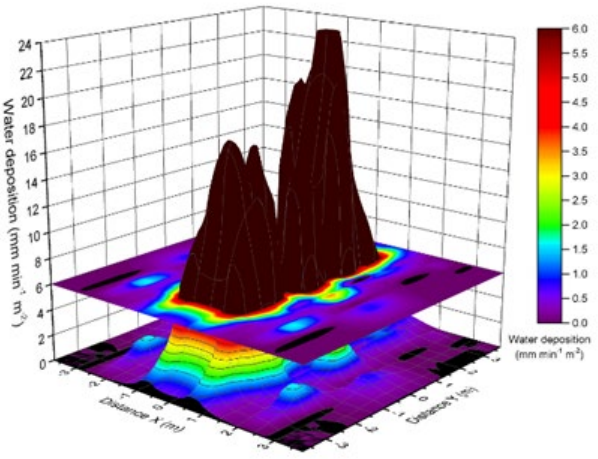
Floor Density Plot - Test Number : 08	
Date of Fire Test	6th November 2023
Time of Fire Test	09:20
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler E
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)
Isometric 3D Visual Unclipped:	



Sprinkler - E : Pendant : 0.35Bar

Floor Density Plot - Test Number : 09	
Date of Fire Test	6th November 2023
Time of Fire Test	11:44
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Head Pressure	3.00 bar (3.11 bar average achieved)

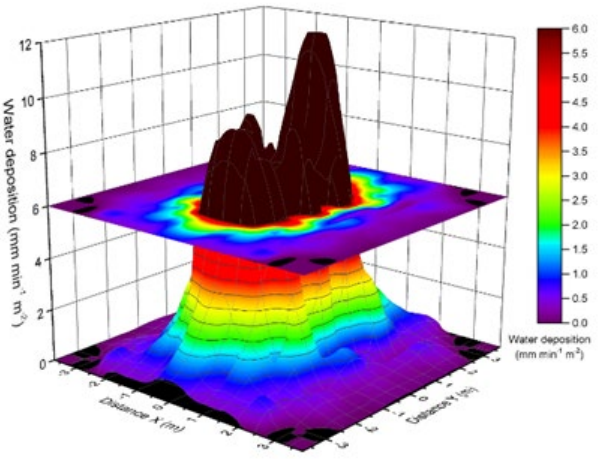
Isometric 3D Visual Unclipped:



Sprinkler - B : Pendant : 3.0Bar

Floor Density Plot - Test Number : 10	
Date of Fire Test	6th November 2023
Time of Fire Test	14:07
Duration of Fire Test	11 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Head Pressure	3.00 bar (3.10 bar average achieved)

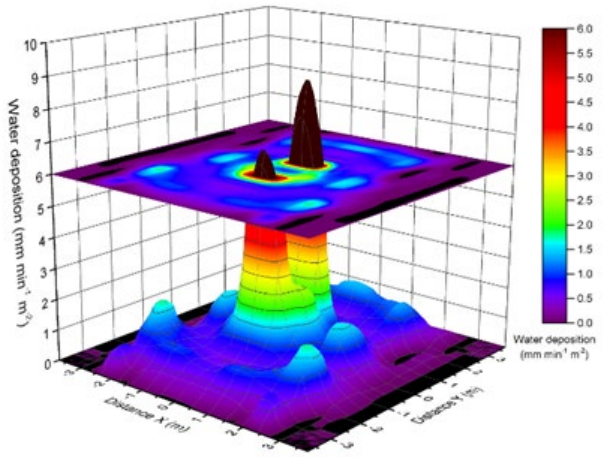
Isometric 3D Visual Unclipped:



Sprinkler - C : Pendant : 3.0Bar

Floor Density Plot - Test Number : 11	
Date of Fire Test	7th November 2023
Time of Fire Test	09:07
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	0.35 bar (0.34 bar average achieved)

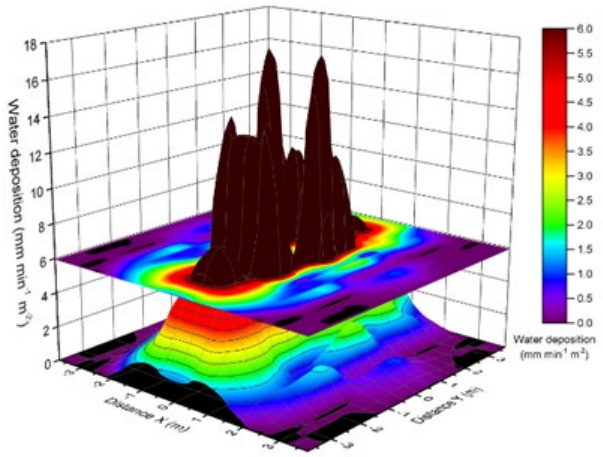
Isometric 3D Visual Unclipped:



Sprinkler - C : Upright : 0.35Bar

Floor Density Plot - Test Number : 14	
Date of Fire Test	8th November 2023
Time of Fire Test	14:07
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.00 bar (3.12 bar average achieved)

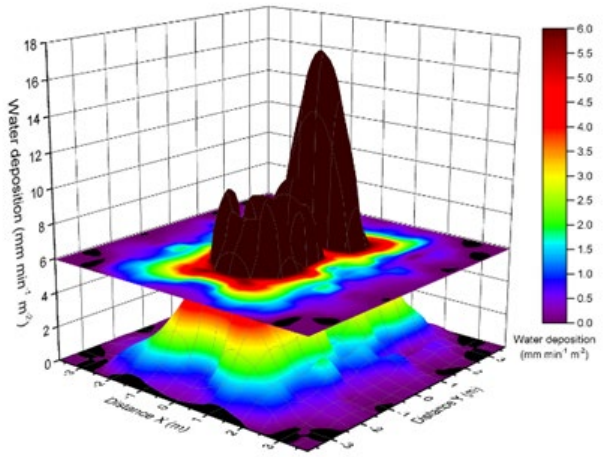
Isometric 3D Visual Unclipped:



Sprinkler - B : Upright : 3.0 Bar

Floor Density Plot - Test Number : 15	
Date of Fire Test	9th November 2023
Time of Fire Test	09:14
Duration of Fire Test	08 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.00 bar (3.03 bar average achieved)

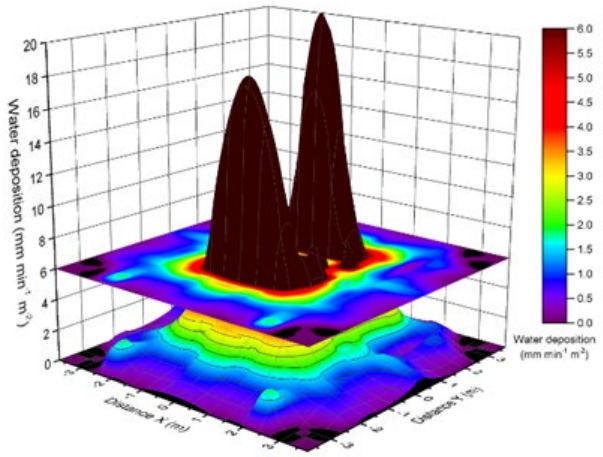
Isometric 3D Visual Unclipped:



Sprinkler - A : Upright : 3.0 Bar

Floor Density Plot - Test Number : 16	
Date of Fire Test	9th November 2023
Time of Fire Test	11:40
Duration of Fire Test	07 Minutes, 03 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.00 bar (3.11 bar average achieved)

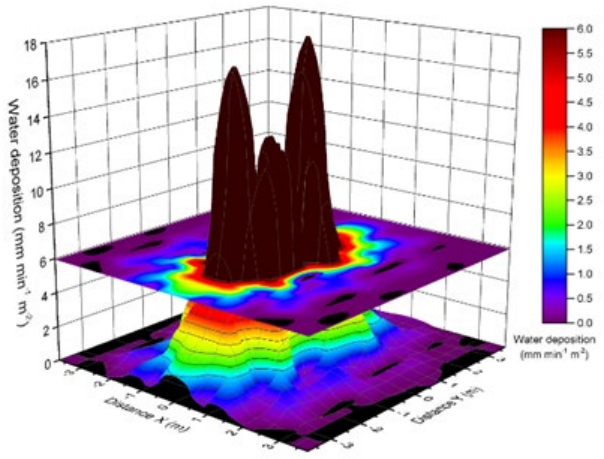
Isometric 3D Visual Unclipped:



Sprinkler - C : Upright : 3.0Bar

Floor Density Plot - Test Number : 17	
Date of Fire Test	28th November 2023
Time of Fire Test	12:56
Duration of Fire Test	08 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant within ceiling
Location of Deflector Below Ceiling	45 mm
Sprinkler Head Pressure	3.00 bar (2.85 bar average achieved)

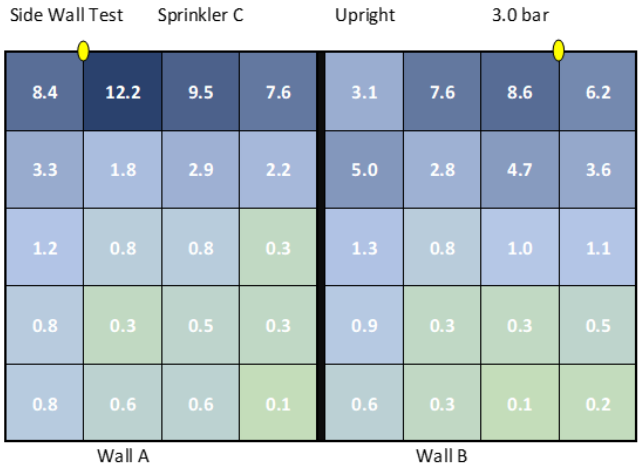
Isometric 3D Visual Unclipped:



Sprinkler - C : In-Ceiling : 3.0Bar

Wall Wetting Test Number : W01	
Date of Fire Test	13th November 2023
Time of Fire Test	11:18
Duration of Fire Test	05 Minutes, 03 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	3.0 bar (3.13 bar average achieved)

Individual Density Plot:

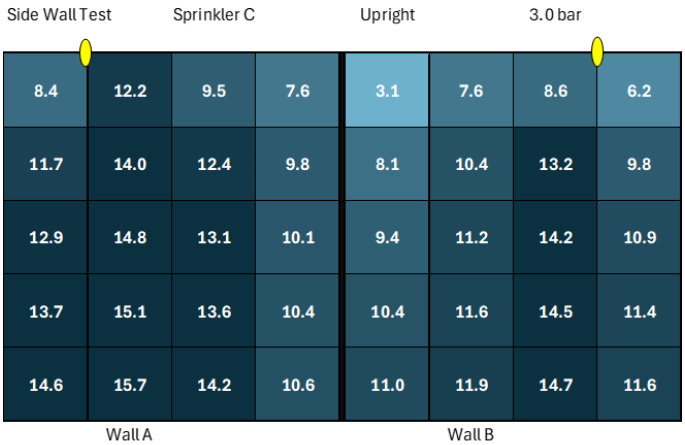


Vertical Level	mm min^{-1} per row	
	Wall A	Wall B
Row 5	9.4	6.4
Row 4	2.5	4.0
Row 3	0.8	1.1
Row 2	0.5	0.5
Row 1	0.5	0.3

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	2.9	3.1	2.8	2.1	2.2	2.4	2.9	2.3

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	2.8	2.5

Cumulative Density Plot:

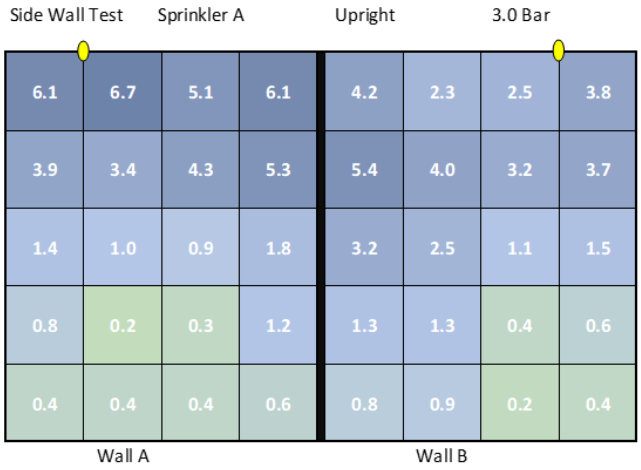


Vertical Level	mm min^{-1} per row	
	Wall A	Wall B
Row 5	9.4	6.4
Row 4	12.0	10.4
Row 3	12.7	11.4
Row 2	13.2	12.0
Row 1	13.8	12.3

% wall wetting from sprinkler	Wall A	Wall B
	53%	47%

Wall Wetting Test Number : W02	
Date of Fire Test	13th November 2023
Time of Fire Test	12:35
Duration of Fire Test	07 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	3.0 bar (2.99 bar average achieved)

Individual Density Plot:

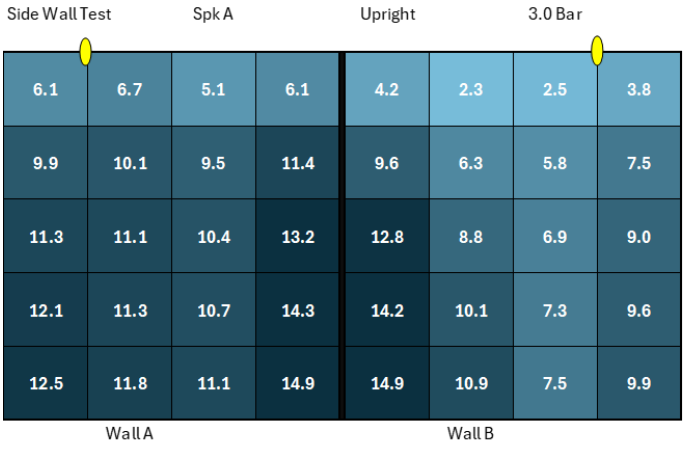


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	6.0	3.2
Row 4	4.2	4.1
Row 3	1.3	2.1
Row 2	0.6	0.9
Row 1	0.5	0.6

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	2.5	2.4	2.2	3.0	3.0	2.2	1.5	2.0

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	2.5	2.2

Cumulative Density Plot:

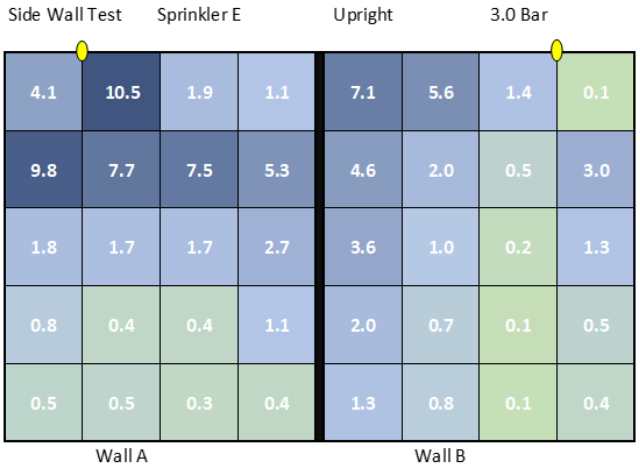


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	6.0	3.2
Row 4	10.2	7.3
Row 3	11.5	9.4
Row 2	12.1	10.3
Row 1	12.6	10.8

% Wall wetting from sprinkler	Wall A	Wall B
	54%	46%

Wall Wetting Test Number : W03	
Date of Fire Test	13th November 2023
Time of Fire Test	14:14
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler E
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	3.0 bar (2.98 bar average achieved)

Individual Density Plot:

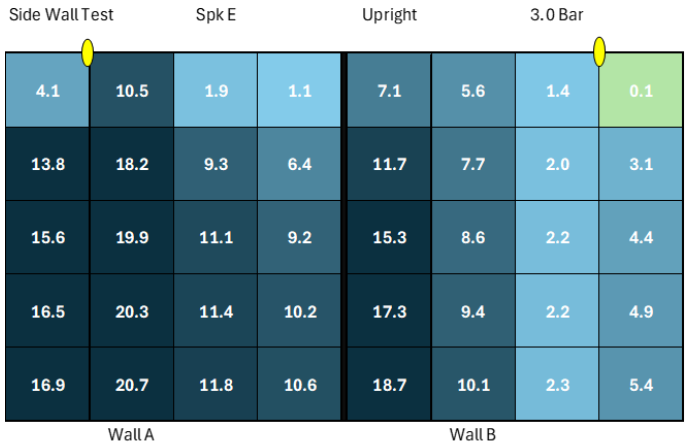


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	4.4	3.6
Row 4	7.6	2.5
Row 3	2.0	1.5
Row 2	0.7	0.8
Row 1	0.4	0.7

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	3.4	4.1	2.4	2.1	3.7	2.0	0.5	1.1

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	3.0	1.8

Cumulative Density Plot:

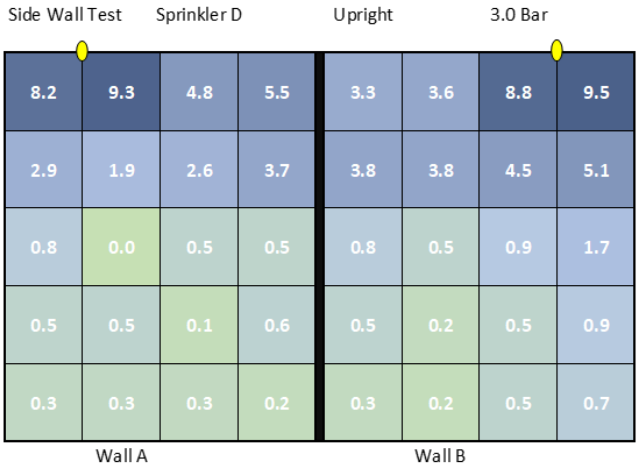


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	4.4	3.6
Row 4	12.0	6.1
Row 3	13.9	7.6
Row 2	14.6	8.5
Row 1	15.0	9.1

% Wall wetting from sprinkler	Wall A	Wall B
	62%	38%

Wall Wetting Test Number : W04	
Date of Fire Test	13th November 2023
Time of Fire Test	15:18
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler D
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	3.0 bar (3.05 bar average achieved)

Individual Density Plot:

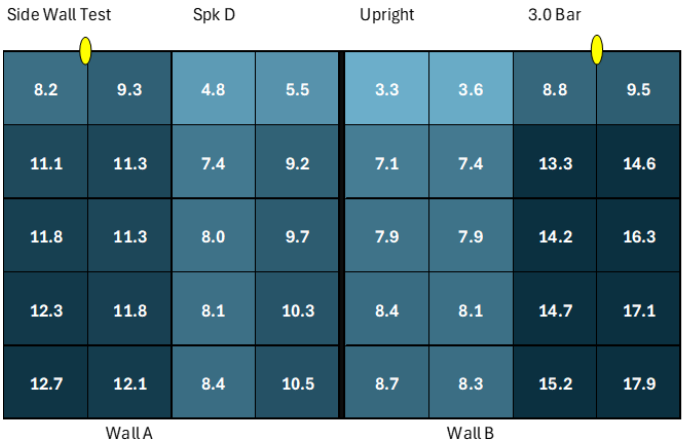


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	6.9	6.3
Row 4	2.8	4.3
Row 3	0.4	1.0
Row 2	0.4	0.5
Row 1	0.3	0.4

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	2.5	2.4	1.7	2.1	1.7	1.7	3.0	3.6

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	2.2	2.5

Cumulative Density Plot:

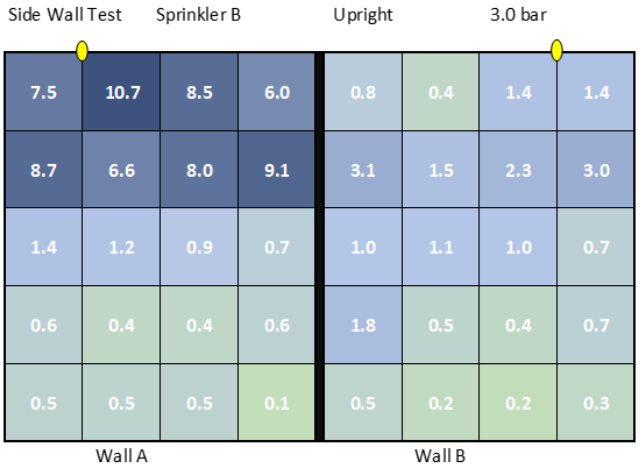


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	6.9	6.3
Row 4	9.7	10.6
Row 3	10.2	11.6
Row 2	10.6	12.1
Row 1	10.9	12.5

% Wall wetting from sprinkler	Wall A	Wall B
	47%	53%

Wall Wetting Test Number : W05	
Date of Fire Test	13th November 2023
Time of Fire Test	16:18
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	3.0 bar (3.09 bar average achieved)

Individual Density Plot:

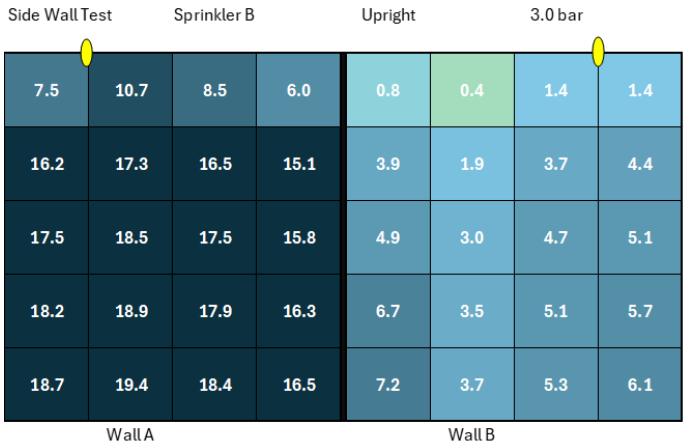


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	8.2	1.0
Row 4	8.1	2.5
Row 3	1.1	0.9
Row 2	0.5	0.8
Row 1	0.4	0.3

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	3.7	3.9	3.7	3.3	1.4	0.7	1.1	1.2

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	3.7	1.1

Cumulative Density Plot:

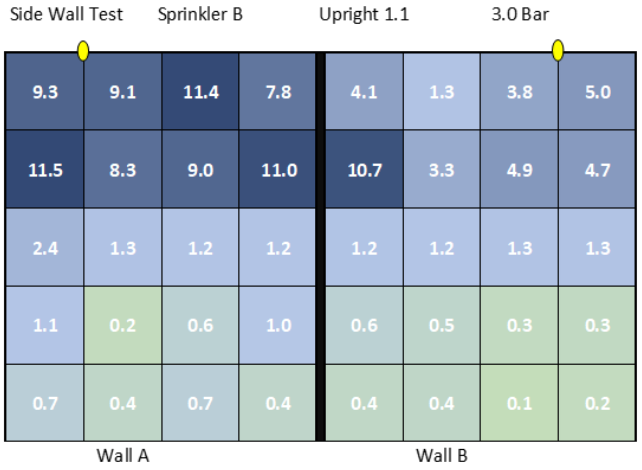


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	8.2	1.0
Row 4	16.3	3.5
Row 3	17.3	4.4
Row 2	17.8	5.3
Row 1	18.3	5.6

% wall wetting from sprinkler	Wall A	Wall B
	77%	23%

Wall Wetting Test Number : W06	
Date of Fire Test	14th November 2023
Time of Fire Test	09:29
Duration of Fire Test	05 Minutes, 03 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	3.0 bar (3.10 bar average achieved)

Individual Density Plot:

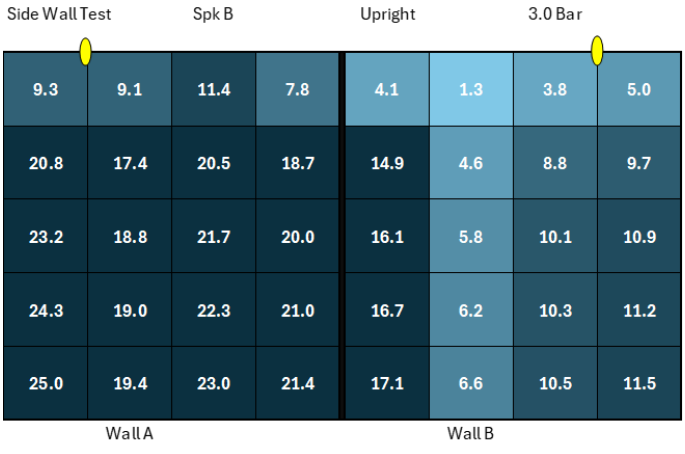


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	9.4	3.6
Row 4	10.0	5.9
Row 3	1.6	1.2
Row 2	0.7	0.4
Row 1	0.6	0.3

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	5.0	3.9	4.6	4.3	3.4	1.3	2.1	2.3

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	4.4	2.3

Cumulative Density Plot:

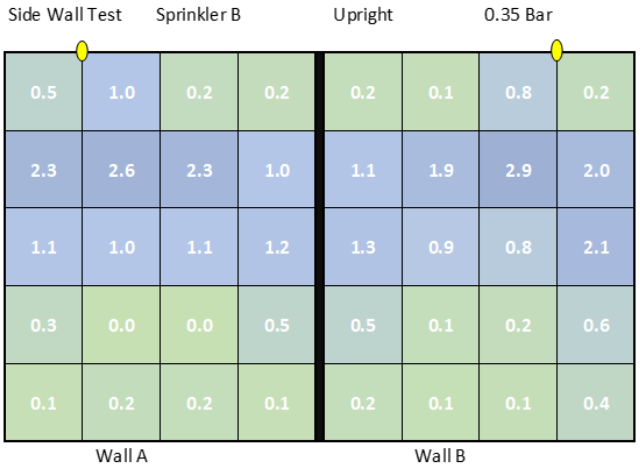


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	9.4	3.6
Row 4	19.4	9.5
Row 3	20.9	10.7
Row 2	21.6	11.1
Row 1	22.2	11.4

% Wall wetting from sprinkler	Wall A	Wall B
	66%	34%

Wall Wetting Test Number : W07	
Date of Fire Test	14th November 2023
Time of Fire Test	12:23
Duration of Fire Test	10 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	0.35 bar (0.34 bar average achieved)

Individual Density Plot:

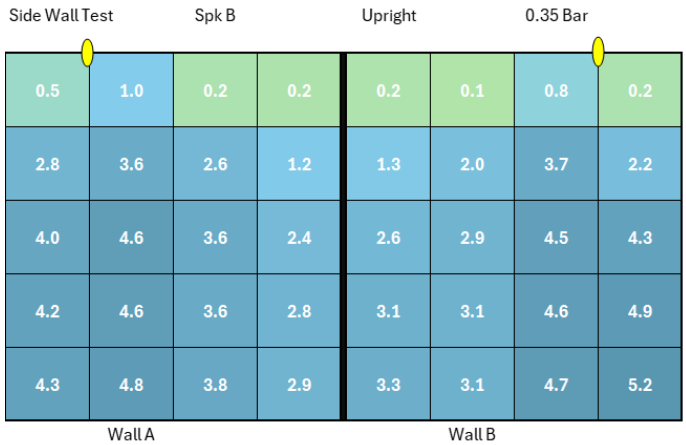


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	0.5	0.3
Row 4	2.1	2.0
Row 3	1.1	1.3
Row 2	0.2	0.3
Row 1	0.1	0.2

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	0.9	1.0	0.8	0.6	0.7	0.6	0.9	1.0

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	0.8	0.8

Cumulative Density Plot:

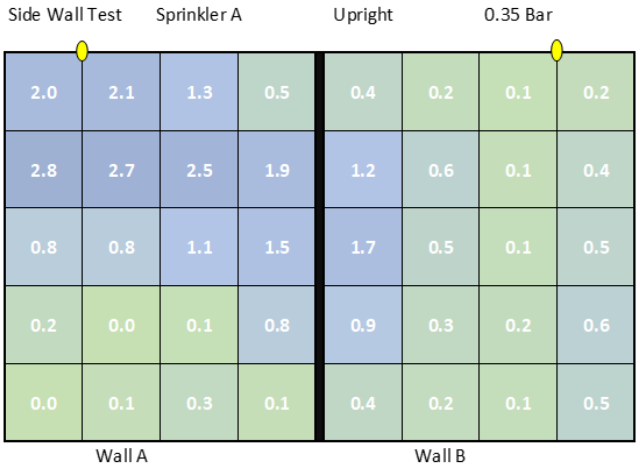


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	0.5	0.3
Row 4	2.5	2.3
Row 3	3.6	3.6
Row 2	3.8	3.9
Row 1	3.9	4.1

% Wall wetting from sprinkler	Wall A	Wall B
	49%	51%

Wall Wetting Test Number : W08	
Date of Fire Test	14th November 2023
Time of Fire Test	15:08
Duration of Fire Test	10 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	0.35 bar (0.35 bar average achieved)

Individual Density Plot:

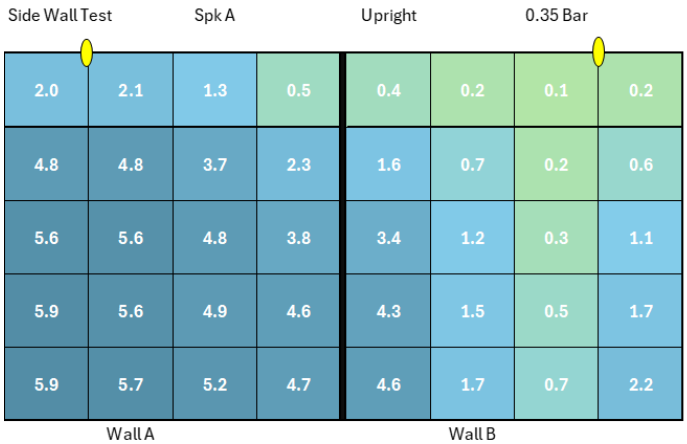


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	1.4	0.2
Row 4	2.5	0.6
Row 3	1.0	0.7
Row 2	0.3	0.5
Row 1	0.1	0.3

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	1.2	1.1	1.0	0.9	0.9	0.3	0.1	0.4

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	1.1	0.5

Cumulative Density Plot:

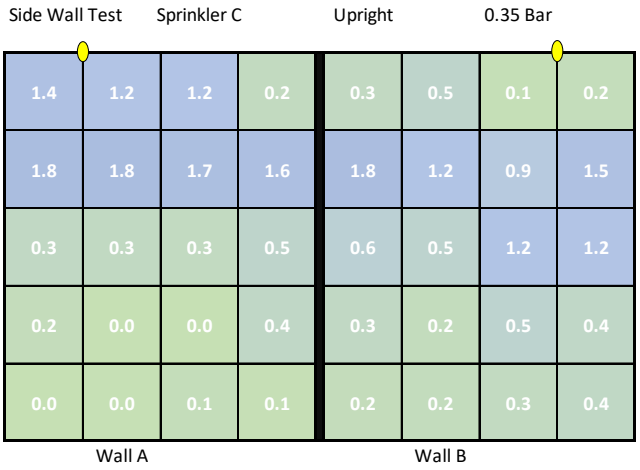


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	1.4	0.2
Row 4	3.9	0.8
Row 3	5.0	1.5
Row 2	5.2	2.0
Row 1	5.4	2.3

% Wall wetting from sprinkler	Wall A	Wall B
	70%	30%

Wall Wetting Test Number : W09	
Date of Fire Test	14th November 2023
Time of Fire Test	15:54
Duration of Fire Test	10 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	0.35 bar (0.35 bar average achieved)

Individual Density Plot:

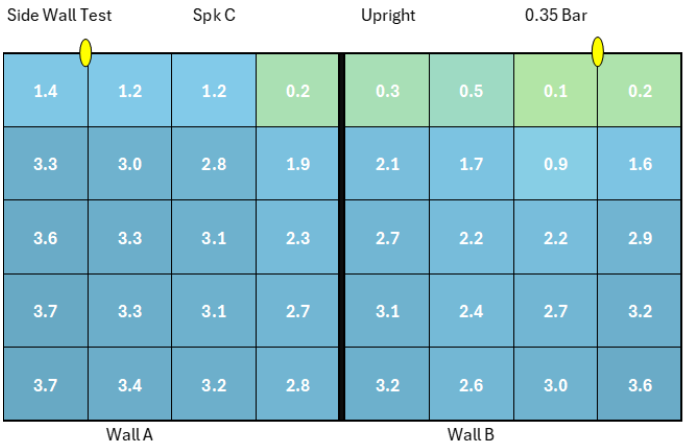


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	1.0	0.2
Row 4	1.7	1.3
Row 3	0.3	0.9
Row 2	0.1	0.4
Row 1	0.1	0.2

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	0.7	0.7	0.6	0.6	0.6	0.5	0.6	0.7

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	0.7	0.6

Cumulative Density Plot:

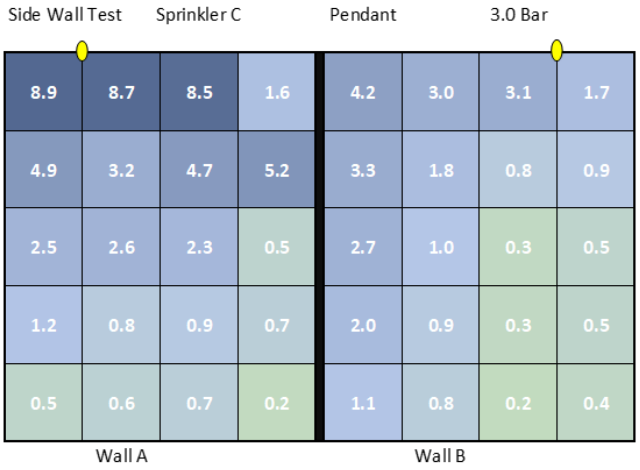


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	1.0	0.2
Row 4	2.8	1.6
Row 3	3.1	2.5
Row 2	3.2	2.9
Row 1	3.3	3.1

% Wall wetting from sprinkler	Wall A	Wall B
	51%	49%

Wall Wetting Test Number : W10	
Date of Fire Test	15th November 2023
Time of Fire Test	08:43
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Test Head Pressure	3.0 bar (3.12 bar average achieved)

Individual Density Plot:

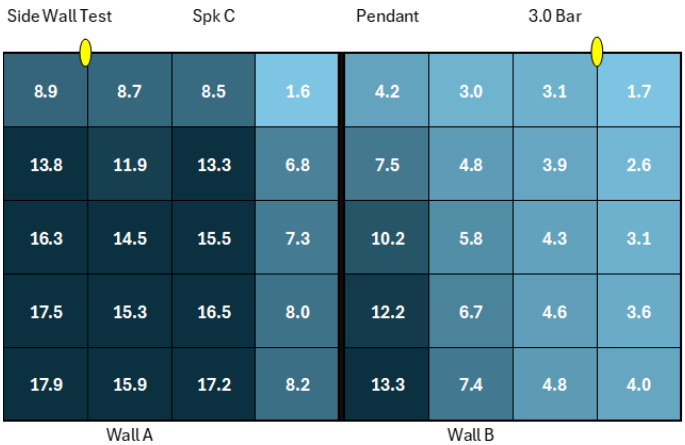


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	6.9	3.0
Row 4	4.5	1.7
Row 3	2.0	1.1
Row 2	0.9	0.9
Row 1	0.5	0.6

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	3.6	3.2	3.4	1.6	2.7	1.5	1.0	0.8

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	3.0	1.5

Cumulative Density Plot:

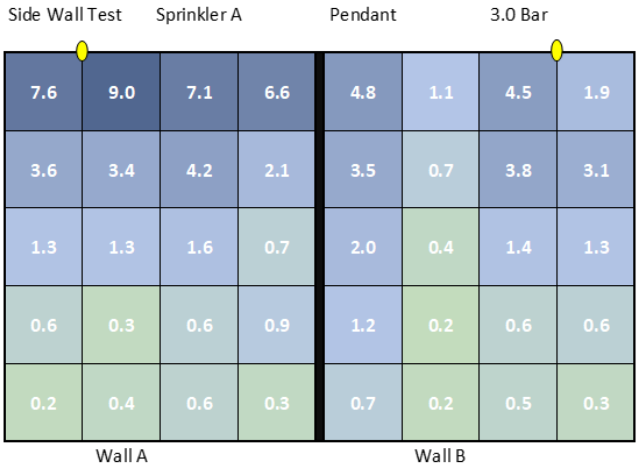


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	6.9	3.0
Row 4	11.4	4.7
Row 3	13.4	5.8
Row 2	14.3	6.8
Row 1	14.8	7.4

% Wall wetting from sprinkler	Wall A	Wall B
	67%	33%

Wall Wetting Test Number : W11	
Date of Fire Test	15th November 2023
Time of Fire Test	09:32
Duration of Fire Test	06 Minutes, 002 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	175 mm
Sprinkler Test Head Pressure	3.0 bar (3.00 bar average achieved)

Individual Density Plot:

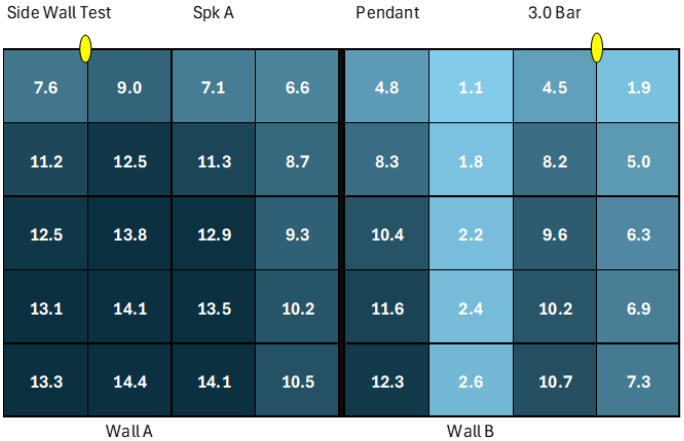


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	7.6	3.1
Row 4	3.3	2.8
Row 3	1.2	1.3
Row 2	0.6	0.7
Row 1	0.4	0.4

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	2.7	2.9	2.8	2.1	2.5	0.5	2.1	1.5

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	2.6	1.6

Cumulative Density Plot:

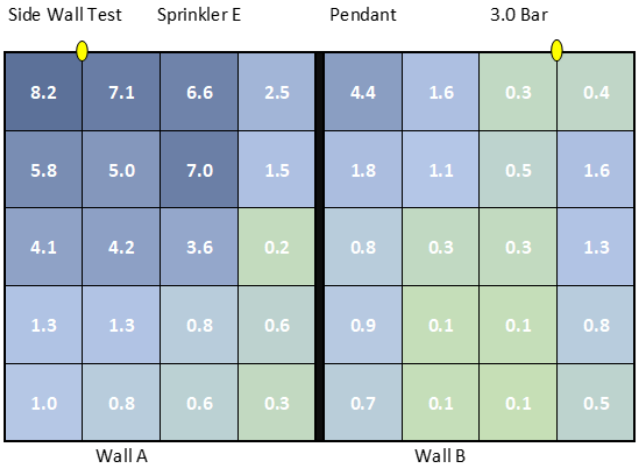


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	7.6	3.1
Row 4	10.9	5.8
Row 3	12.1	7.1
Row 2	12.7	7.8
Row 1	13.1	8.2

% Wall wetting from sprinkler	Wall A	Wall B
	61%	39%

Wall Wetting Test Number : W12	
Date of Fire Test	15th November 2023
Time of Fire Test	10:43
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler E
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Test Head Pressure	3.0 bar (3.02 bar average achieved)

Individual Density Plot:

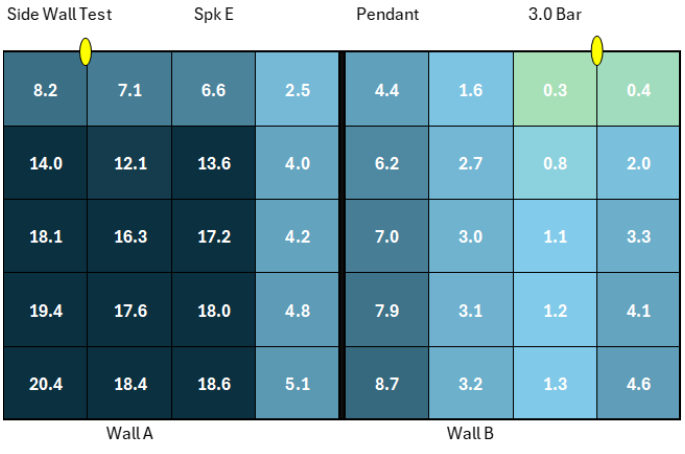


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	6.1	1.7
Row 4	4.8	1.2
Row 3	3.0	0.7
Row 2	1.0	0.5
Row 1	0.7	0.4

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	4.1	3.7	3.7	1.0	1.7	0.6	0.3	0.9

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	3.1	0.9

Cumulative Density Plot:

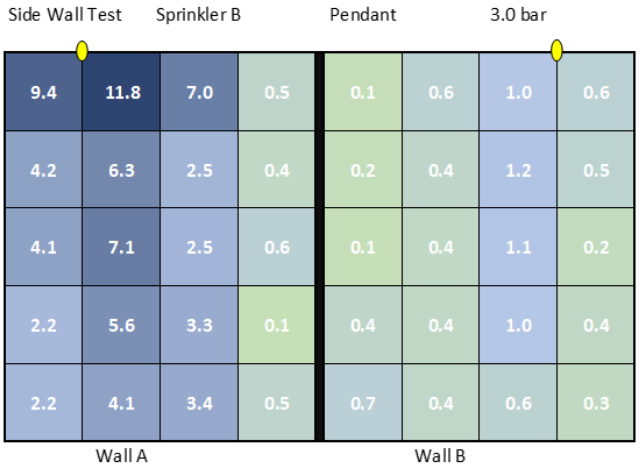


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	6.1	1.7
Row 4	10.9	2.9
Row 3	14.0	3.6
Row 2	15.0	4.1
Row 1	15.6	4.4

% Wall wetting from sprinkler	Wall A	Wall B
	78%	22%

Wall Wetting Test Number : W13	
Date of Fire Test	15th November 2023
Time of Fire Test	11:27
Duration of Fire Test	06 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Test Head Pressure	3.0 bar (3.10 bar average achieved)

Individual Density Plot:

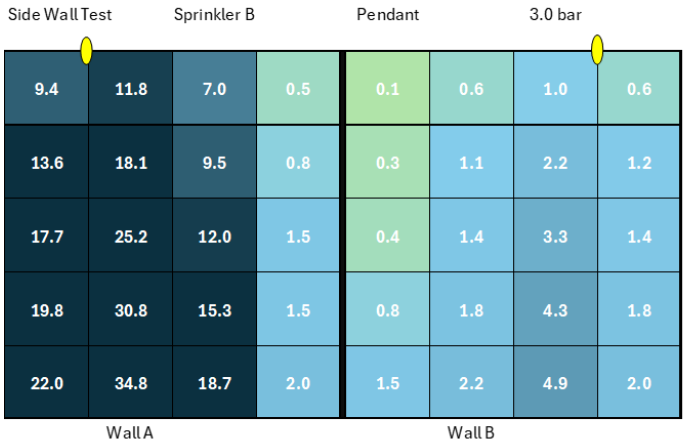


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	7.2	0.6
Row 4	3.3	0.6
Row 3	3.6	0.5
Row 2	2.8	0.5
Row 1	2.5	0.5

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	4.4	7.0	3.7	0.4	0.3	0.4	1.0	0.4

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	3.9	0.5

Cumulative Density Plot:

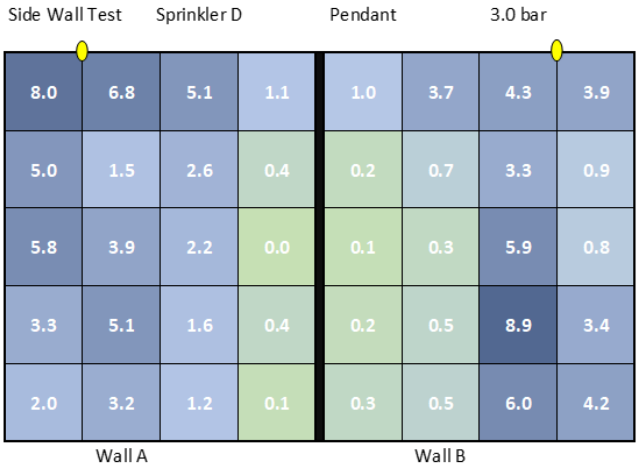


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	7.2	0.6
Row 4	10.5	1.2
Row 3	14.1	1.6
Row 2	16.9	2.2
Row 1	19.4	2.6

% wall wetting from sprinkler	Wall A	Wall B
	88%	12%

Wall Wetting Test Number : W14	
Date of Fire Test	15th November 2023
Time of Fire Test	12:07
Duration of Fire Test	05 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler D
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Test Head Pressure	3.0 bar (3.05 bar average achieved)

Individual Density Plot:

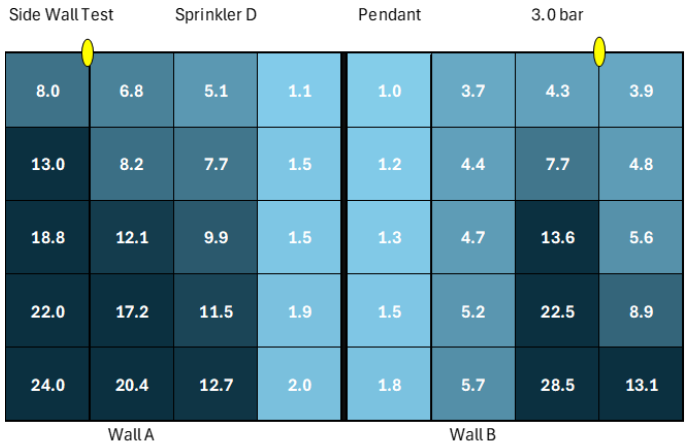


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	5.2	3.2
Row 4	2.4	1.3
Row 3	3.0	1.8
Row 2	2.6	3.2
Row 1	1.6	2.8

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	4.8	4.1	2.5	0.4	0.4	1.1	5.7	2.6

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	3.0	2.5

Cumulative Density Plot:

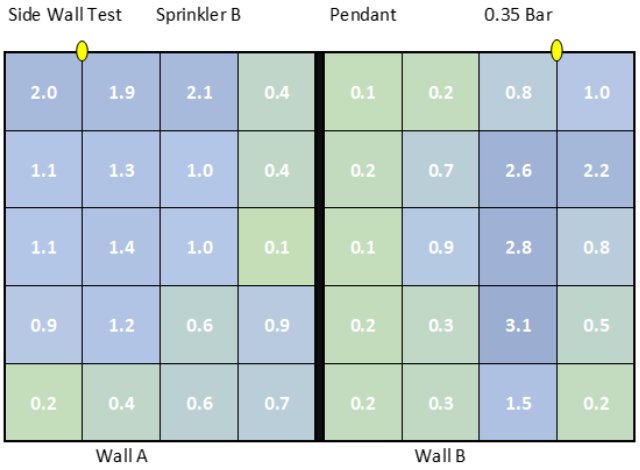


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	5.2	3.2
Row 4	7.6	4.5
Row 3	10.6	6.3
Row 2	13.2	9.5
Row 1	14.8	12.3

% wall wetting from sprinkler	Wall A	Wall B
	55%	45%

Wall Wetting Test Number : W15	
Date of Fire Test	15th November 2023
Time of Fire Test	13:46
Duration of Fire Test	10 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Test Head Pressure	0.35 bar (0.34 bar average achieved)

Individual Density Plot:

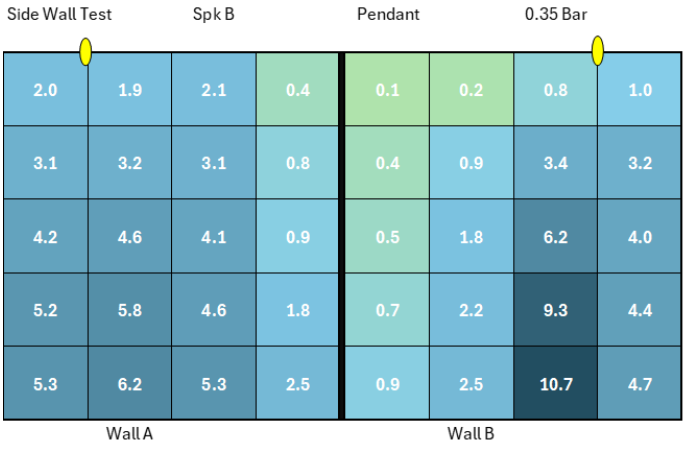


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	1.6	0.5
Row 4	1.0	1.4
Row 3	0.9	1.2
Row 2	0.9	1.0
Row 1	0.5	0.5

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	1.1	1.2	1.1	0.5	0.2	0.5	2.1	0.9

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	1.0	0.9

Cumulative Density Plot:

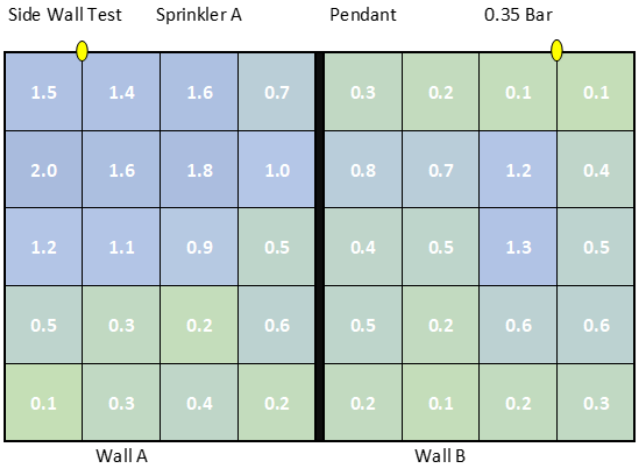


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	1.6	0.5
Row 4	2.6	2.0
Row 3	3.4	3.1
Row 2	4.3	4.1
Row 1	4.8	4.7

% Wall wetting from sprinkler	Wall A	Wall B
	51%	49%

Wall Wetting Test Number : W16	
Date of Fire Test	15th November 2023
Time of Fire Test	14:22
Duration of Fire Test	10 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	175 mm
Sprinkler Test Head Pressure	0.35 bar (0.34 bar average achieved)

Individual Density Plot:

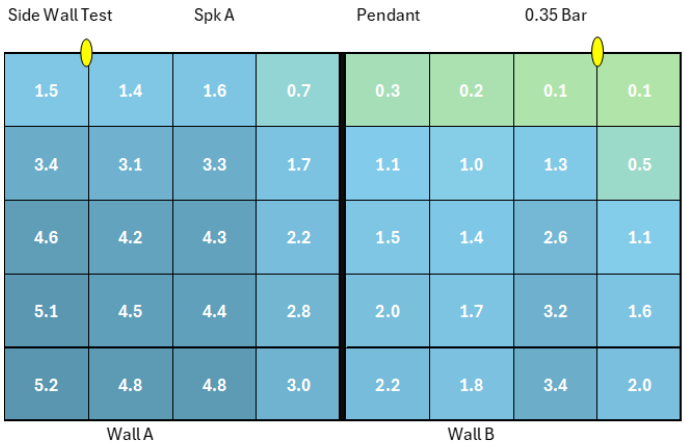


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	1.3	0.2
Row 4	1.6	0.8
Row 3	0.9	0.7
Row 2	0.4	0.5
Row 1	0.2	0.2

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	1.0	1.0	1.0	0.6	0.4	0.4	0.7	0.4

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	0.9	0.5

Cumulative Density Plot:

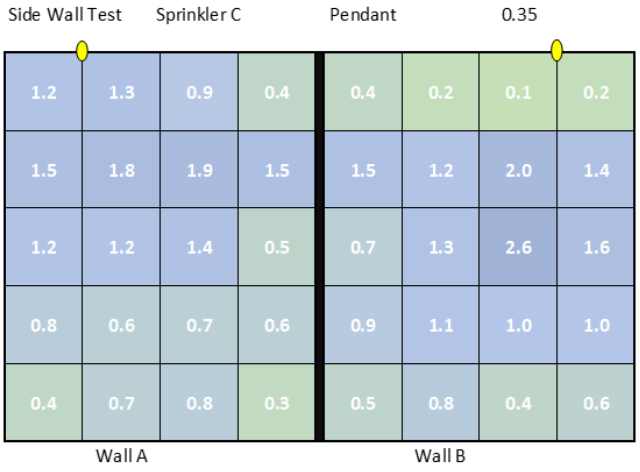


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	1.3	0.2
Row 4	2.9	1.0
Row 3	3.8	1.6
Row 2	4.2	2.1
Row 1	4.4	2.3

% Wall wetting from sprinkler	Wall A	Wall B
	65%	35%

Wall Wetting Test Number : W17	
Date of Fire Test	15th November 2023
Time of Fire Test	15:02
Duration of Fire Test	10 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Test Head Pressure	0.35 bar (0.36 bar average achieved)

Individual Density Plot:

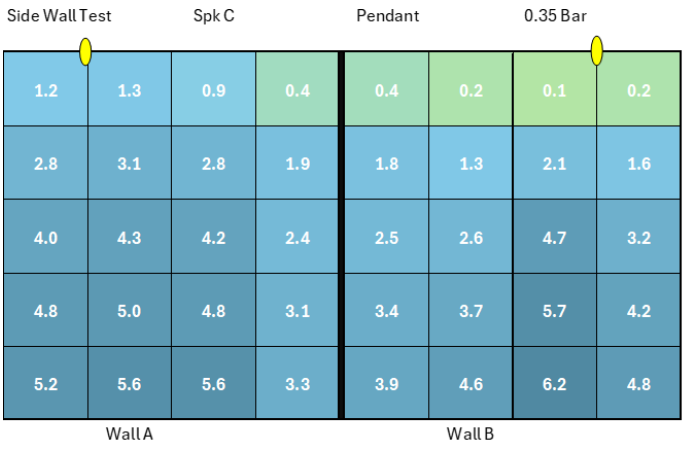


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	1.0	0.2
Row 4	1.7	1.5
Row 3	1.1	1.6
Row 2	0.7	1.0
Row 1	0.5	0.6

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	1.0	1.1	1.1	0.7	0.8	0.9	1.2	1.0

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	1.0	1.0

Cumulative Density Plot:

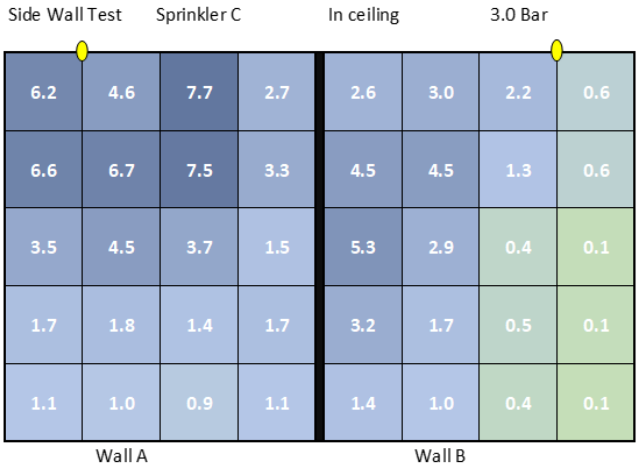


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	1.0	0.2
Row 4	2.7	1.7
Row 3	3.7	3.3
Row 2	4.4	4.3
Row 1	4.9	4.9

% Wall wetting from sprinkler	Wall A	Wall B
	50%	50%

Wall Wetting Test Number : W18	
Date of Fire Test	27th November 2023
Time of Fire Test	15:01
Duration of Fire Test	07 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant in ceiling
Location of Deflector Below Ceiling	45 mm
Sprinkler Test Head Pressure	3.0 bar (2.85 bar average achieved)

Individual Density Plot:

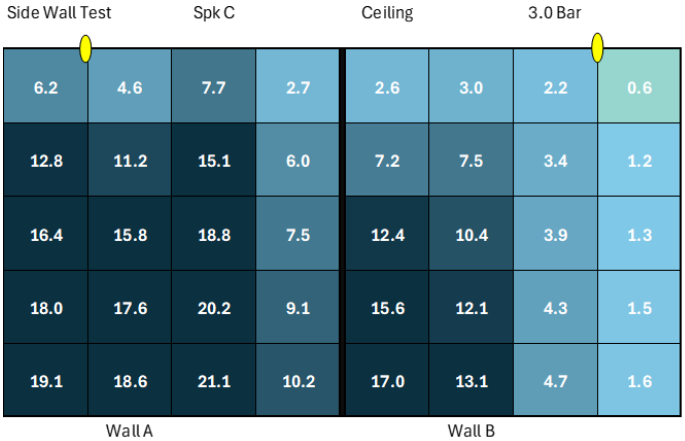


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	5.3	2.1
Row 4	6.0	2.7
Row 3	3.3	2.2
Row 2	1.6	1.4
Row 1	1.0	0.7

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	3.8	3.7	4.2	2.0	3.4	2.6	0.9	0.3

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	3.4	1.8

Cumulative Density Plot:

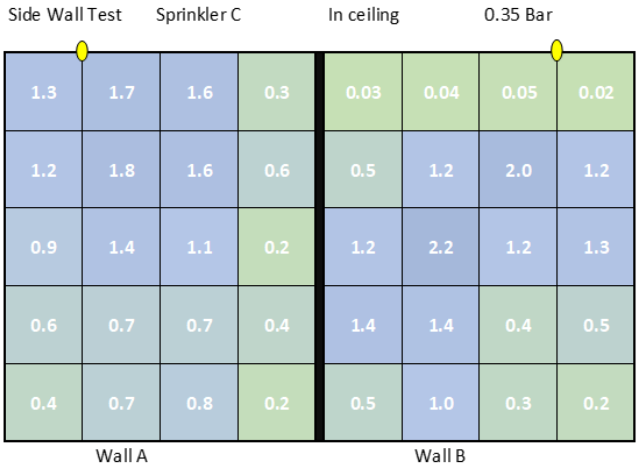


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	5.3	2.1
Row 4	11.3	4.8
Row 3	14.6	7.0
Row 2	16.2	8.4
Row 1	17.2	9.1

% Wall wetting from sprinkler	Wall A	Wall B
	65%	35%

Wall Wetting Test Number : W19	
Date of Fire Test	27th November 2023
Time of Fire Test	15:55
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant in ceiling
Location of Deflector Below Ceiling	45 mm
Sprinkler Test Head Pressure	0.35 bar (0.37 bar average achieved)

Individual Density Plot:

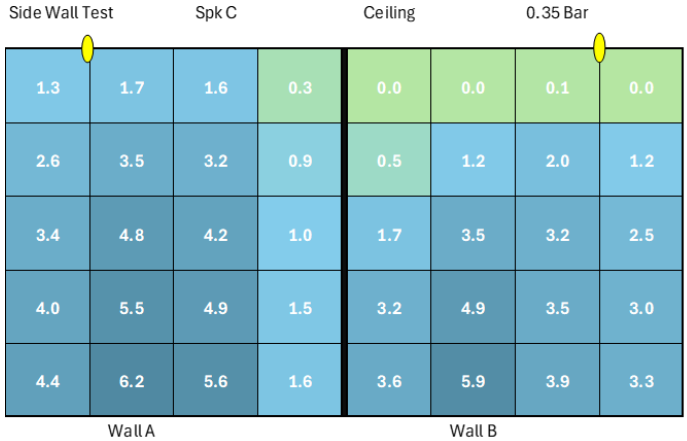


Vertical Level	mm min⁻¹ per row Wall A	Wall B
Row 5	1.2	0.04
Row 4	1.3	1.2
Row 3	0.9	1.5
Row 2	0.6	0.9
Row 1	0.5	0.5

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min⁻¹ per column	0.9	1.2	1.1	0.3	0.7	1.2	0.8	0.7

Mean water density per wall (mm min⁻¹)	Wall A	Wall B
	0.9	0.8

Cumulative Density Plot:

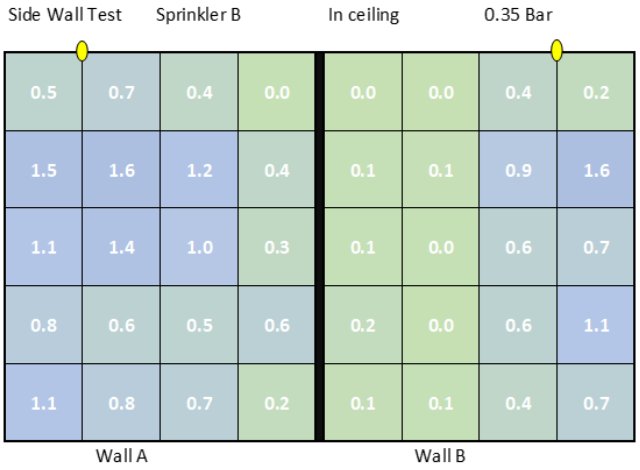


Vertical Level	mm min⁻¹ per row Wall A	Wall B
Row 5	1.2	0.0
Row 4	2.5	1.2
Row 3	3.4	2.7
Row 2	4.0	3.7
Row 1	4.5	4.2

% Wall wetting from sprinkler	Wall A	Wall B
	52%	48%

Wall Wetting Test Number : W20	
Date of Fire Test	28th November 2023
Time of Fire Test	09:24
Duration of Fire Test	15 Minutes, 03 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant in ceiling
Location of Deflector Below Ceiling	45 mm
Sprinkler Test Head Pressure	0.35 bar (0.35 bar average achieved)

Individual Density Plot:

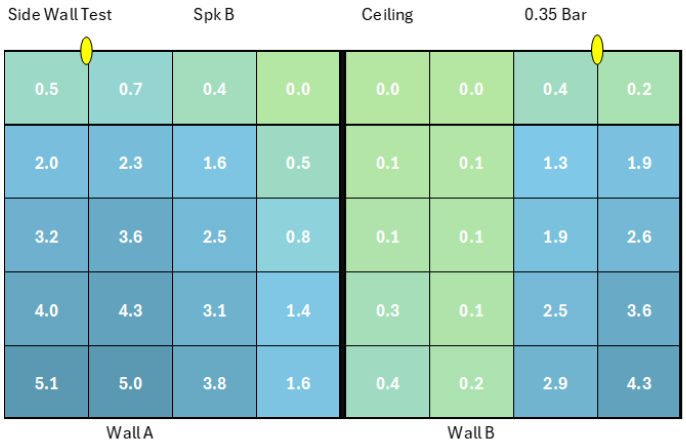


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	0.4	0.2
Row 4	1.2	0.7
Row 3	0.9	0.3
Row 2	0.6	0.5
Row 1	0.7	0.3

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	1.0	1.0	0.8	0.3	0.1	0.0	0.6	0.9

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	0.8	0.4

Cumulative Density Plot:

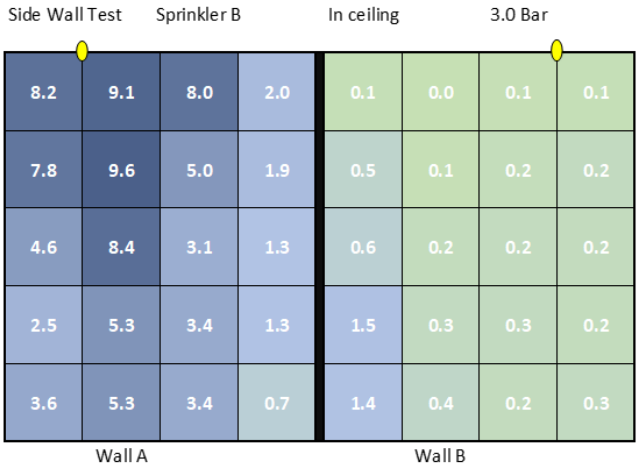


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	0.4	0.2
Row 4	1.6	0.8
Row 3	2.5	1.2
Row 2	3.2	1.6
Row 1	3.9	2.0

% Wall wetting from sprinkler	Wall A	Wall B
	66%	34%

Wall Wetting Test Number : W21	
Date of Fire Test	28th November 2023
Time of Fire Test	10:40
Duration of Fire Test	06 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant in ceiling
Location of Deflector Below Ceiling	45 mm
Sprinkler Test Head Pressure	3.0 bar (2.80 bar average achieved)

Individual Density Plot:

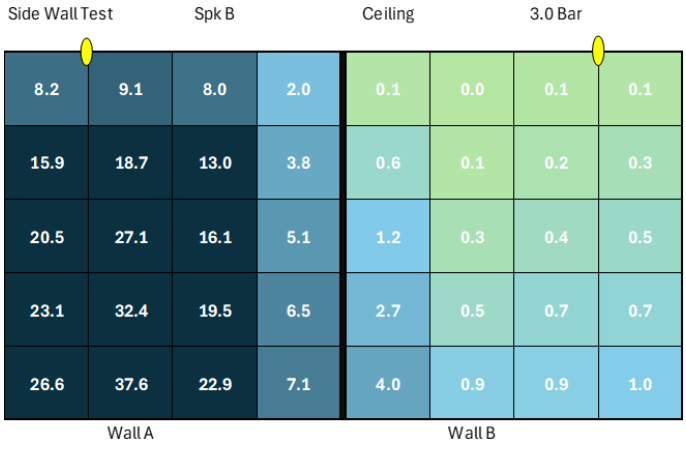


	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	6.8	0.1
Row 4	6.0	0.2
Row 3	4.3	0.3
Row 2	3.1	0.5
Row 1	3.2	0.6

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm min^{-1} per column	5.3	7.5	4.6	1.4	0.8	0.2	0.2	0.2

Mean water density per wall (mm min^{-1})	Wall A	Wall B
	4.7	0.3

Cumulative Density Plot:



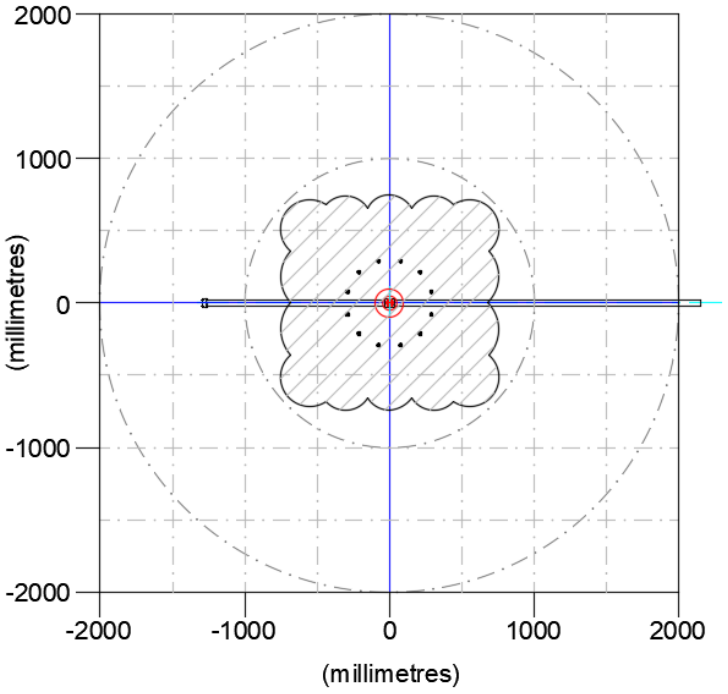
	mm min^{-1} per row	
Vertical Level	Wall A	Wall B
Row 5	6.8	0.1
Row 4	12.9	0.3
Row 3	17.2	0.6
Row 2	20.4	1.1
Row 1	23.6	1.7

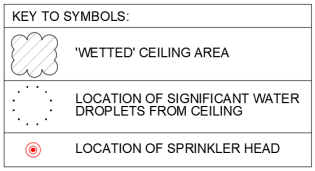
% Wall wetting from sprinkler	Wall A	Wall B
	93%	7%

Water Distribution Spray Pattern Test Number : 01	
Date of Fire Test	17th October 2023
Time of Fire Test	15:46
Duration of Fire Test	15 Minutes, 00 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Test Head Pressure	0.35 bar (0.35 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:

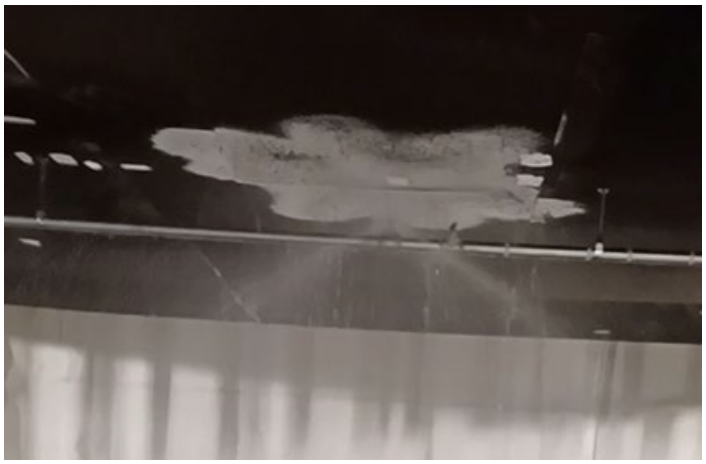




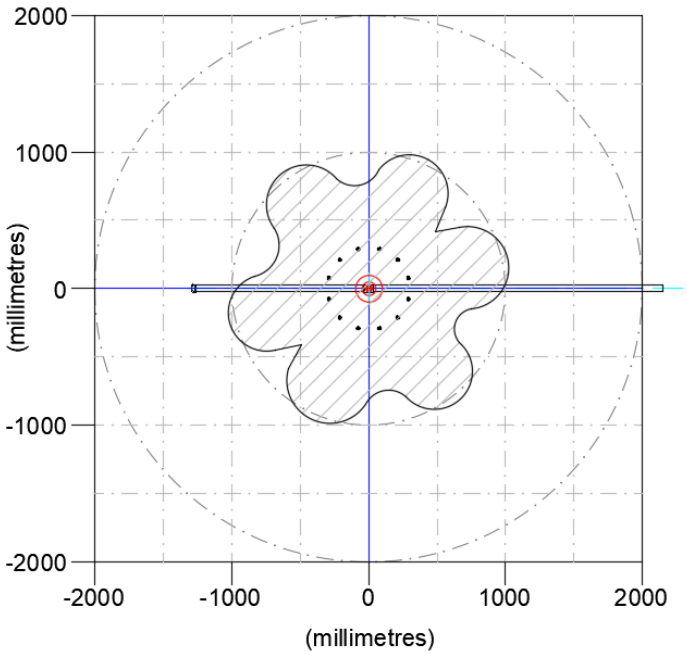
Ceiling area 'wetted' = 2 m^2

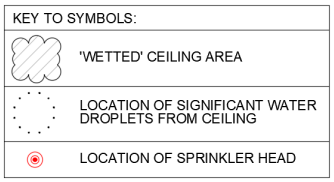
Water Distribution Spray Pattern Test Number : 02	
Date of Fire Test	18th October 2023
Time of Fire Test	09:44
Duration of Fire Test	13 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler E
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:



Representation of Ceiling 'Wetting' Pattern:

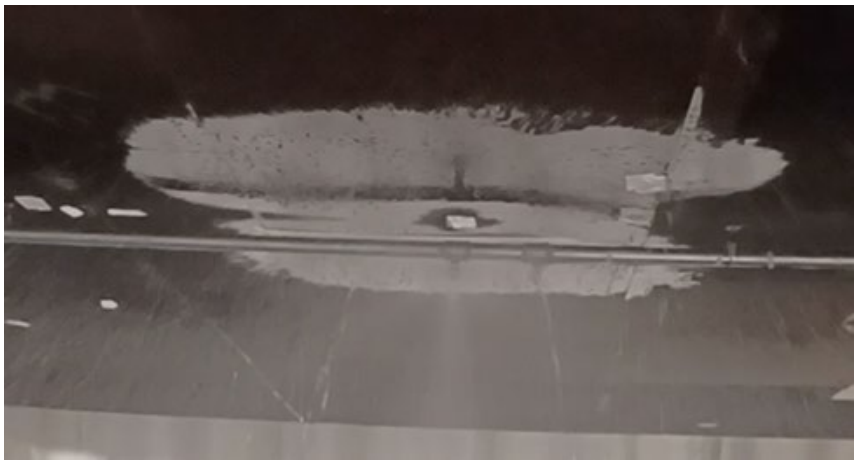




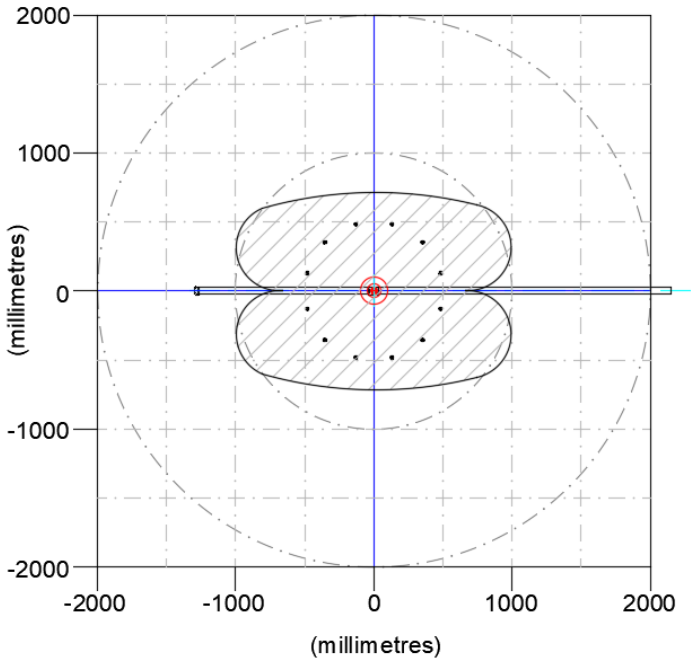
Ceiling area 'wetted' = 3 m^2

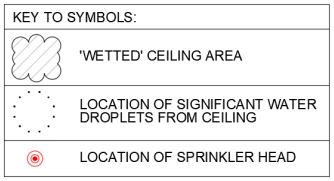
Water Distribution Spray Pattern Test Number : 03	
Date of Fire Test	18th October 2023
Time of Fire Test	12:16
Duration of Fire Test	19 Minutes, 00 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	175 mm
Sprinkler Head Pressure	0.35 bar (0.33 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:



Representation of Ceiling 'Wetting' Pattern:



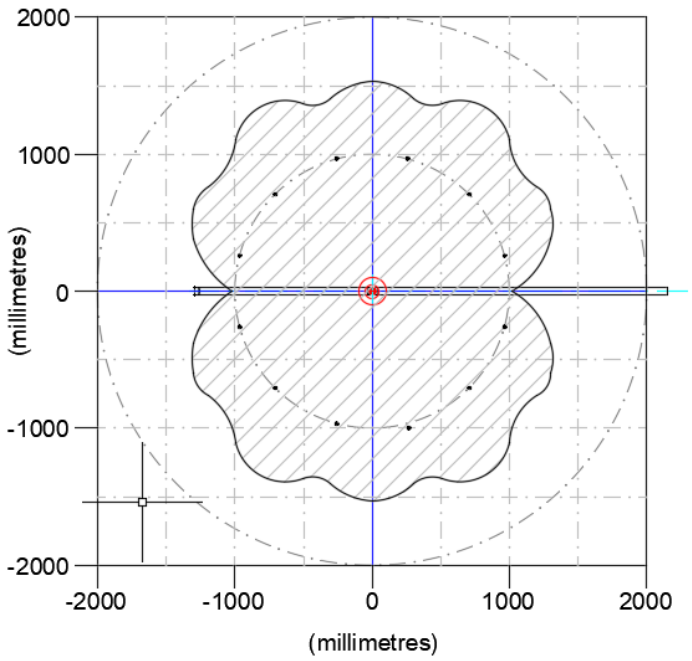


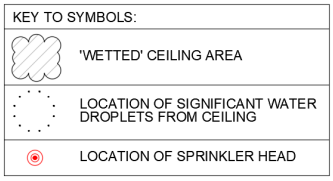
Ceiling area 'wetted' = 3 m^2

Water Distribution Spray Pattern Test Number : 04	
Date of Fire Test	18th October 2023
Time of Fire Test	14:45
Duration of Fire Test	05 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	175 mm
Sprinkler Head Pressure	3.00 bar (3.02 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:

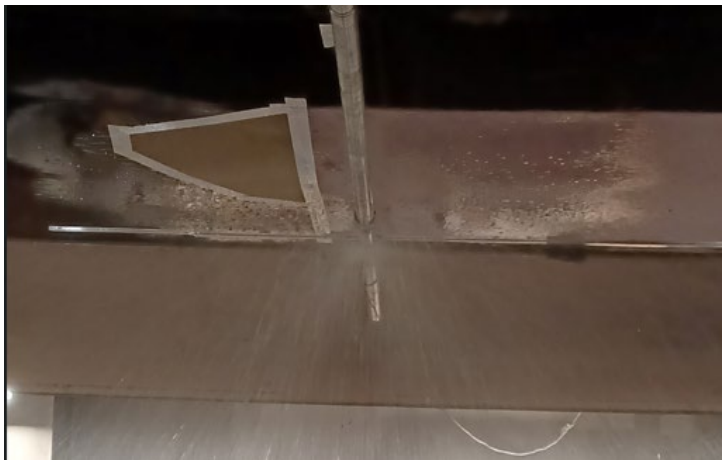




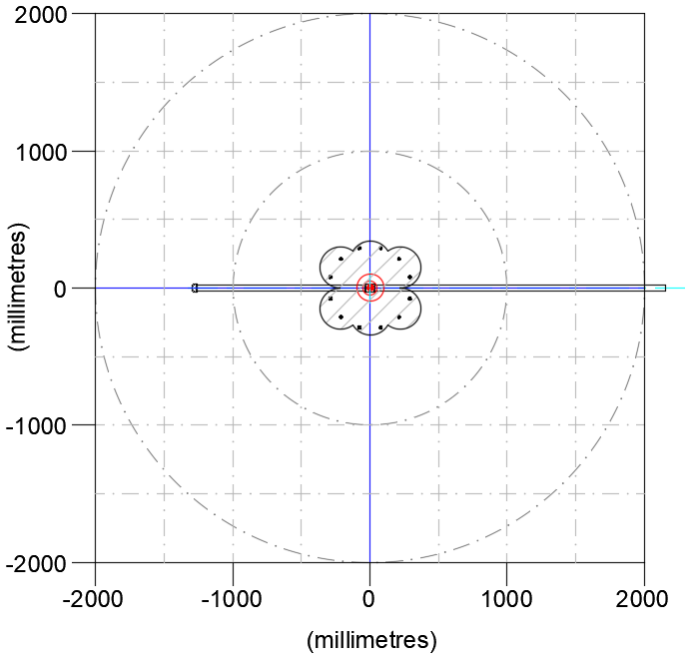
Ceiling area 'wetted' = 6 m^2

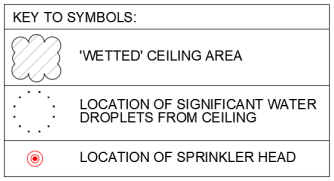
Water Distribution Spray Pattern Test Number : 05	
Date of Fire Test	2nd November 2023
Time of Fire Test	10:12
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:



Representation of Ceiling 'Wetting' Pattern:



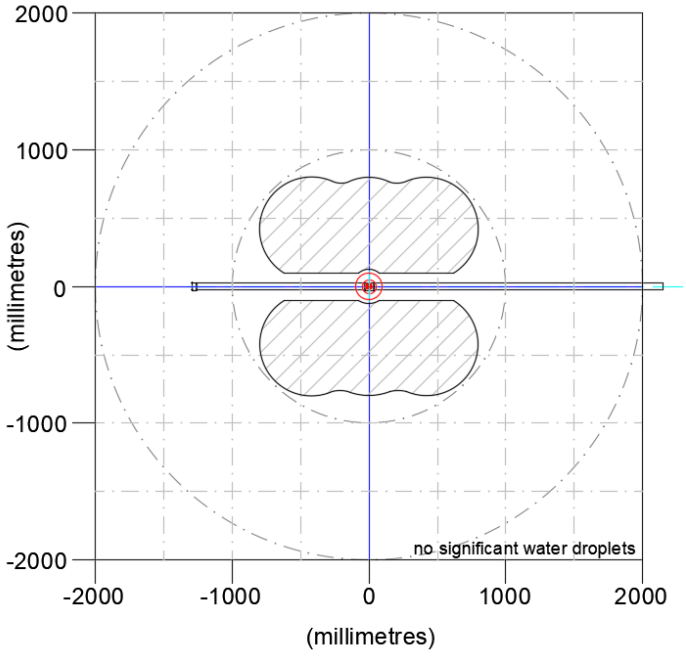


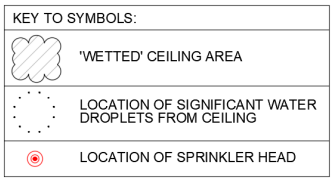
Ceiling area 'wetted' = <1 m^2

Water Distribution Spray Pattern Test Number : 06	
Date of Fire Test	2nd November 2023
Time of Fire Test	12:36
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler D
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:

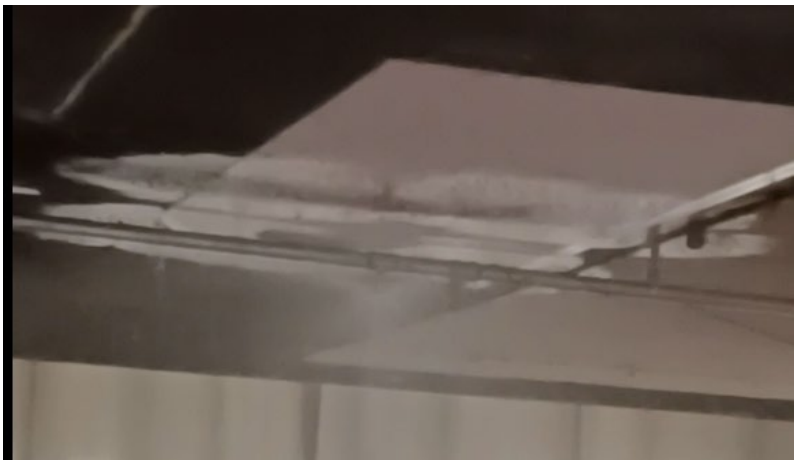




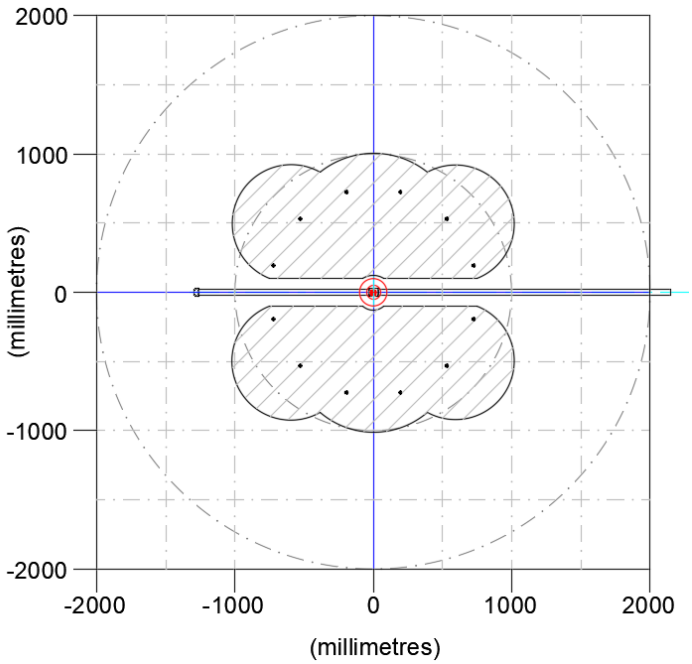
Ceiling area 'wetted' = 2 m^2

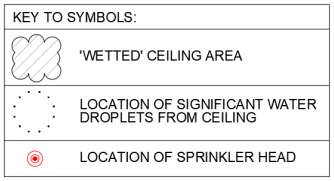
Water Distribution Spray Pattern Test Number : 07	
Date of Fire Test	2nd November 2023
Time of Fire Test	14:49
Duration of Fire Test	15 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:



Representation of Ceiling 'Wetting' Pattern:



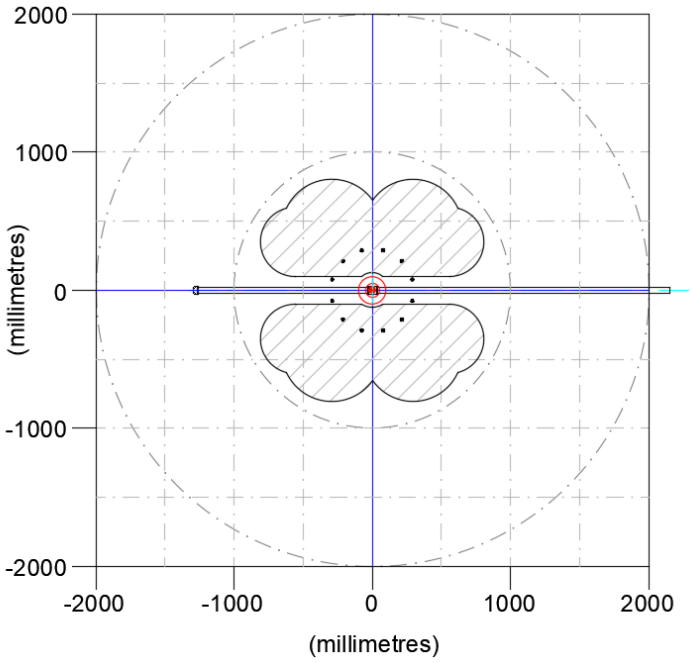


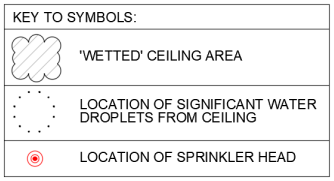
Ceiling area 'wetted' = 3 m^2

Water Distribution Spray Pattern Test Number : 08	
Date of Fire Test	6th November 2023
Time of Fire Test	09:20
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler E
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



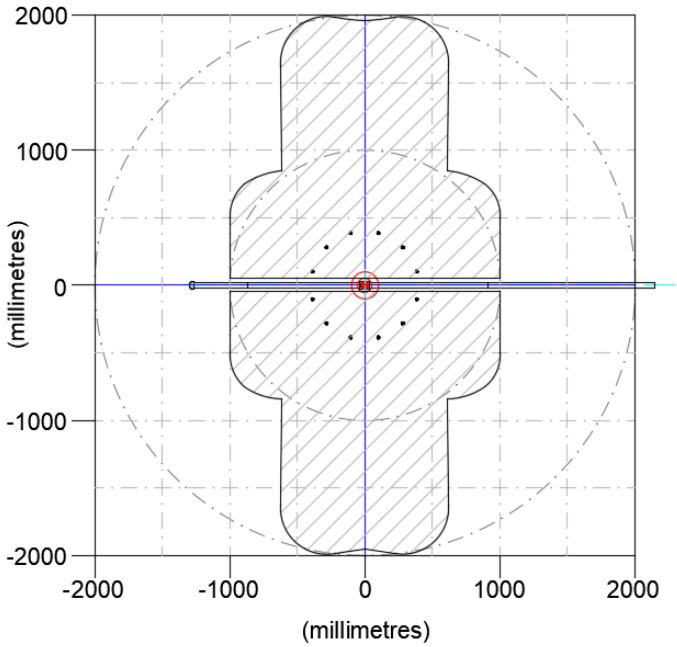


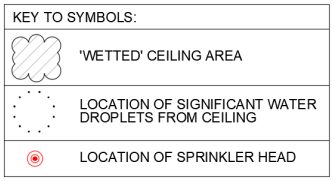
Ceiling area 'wetted' = 2 m^2

Water Distribution Spray Pattern Test Number : 09	
Date of Fire Test	6th November 2023
Time of Fire Test	11:44
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Head Pressure	3.00 bar (3.11 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



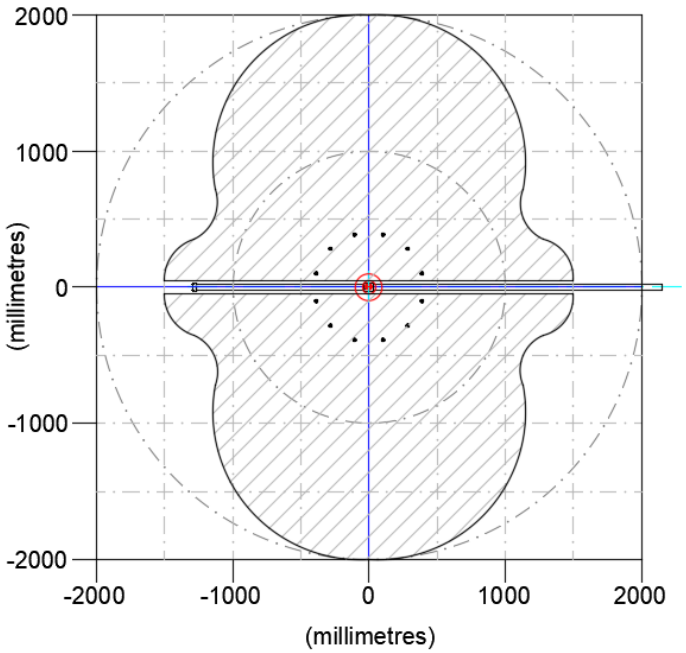


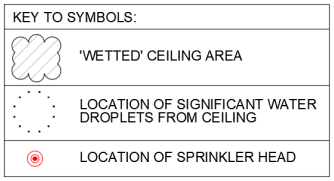
Ceiling area 'wetted' = 5 m^2

Water Distribution Spray Pattern Test Number : 10	
Date of Fire Test	6th November 2023
Time of Fire Test	14:07
Duration of Fire Test	11 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	170 mm
Sprinkler Head Pressure	3.00 bar (3.10 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



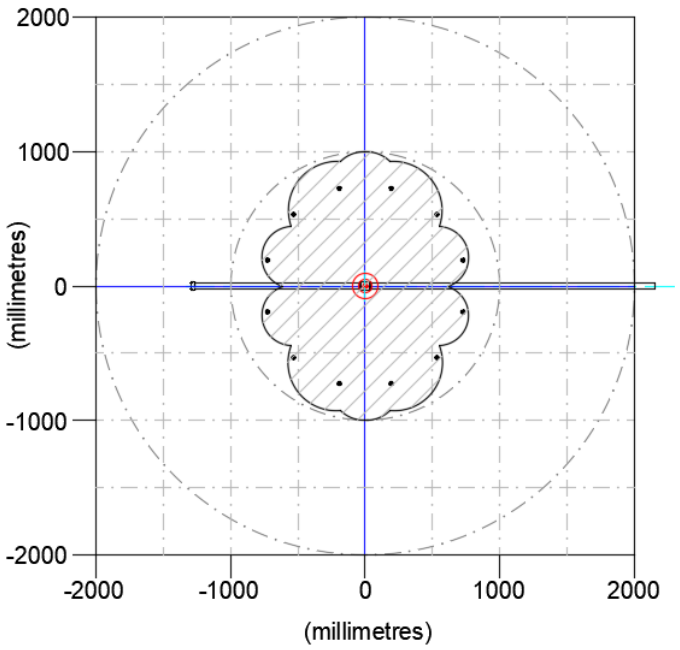


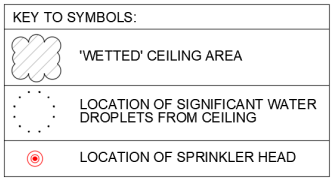
Ceiling area 'wetted' = 8 m^2

Water Distribution Spray Pattern Test Number : 11	
Date of Fire Test	7th November 2023
Time of Fire Test	09:07
Duration of Fire Test	13 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	0.35 bar (0.34 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



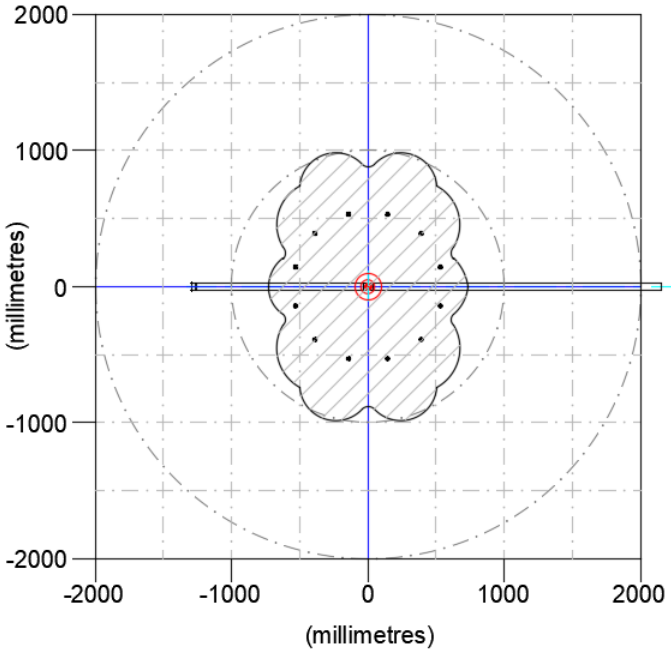


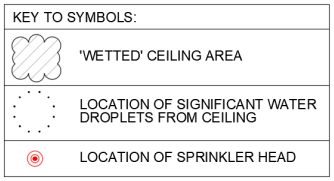
Ceiling area 'wetted' = 2 m^2

Water Distribution Spray Pattern Test Number : 12	
Date of Fire Test	7th November 2023
Time of Fire Test	14:45
Duration of Fire Test	15 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



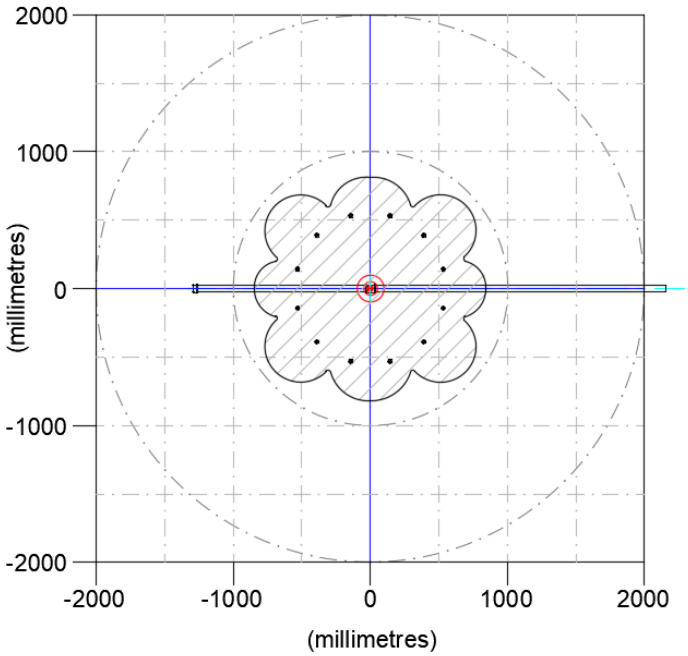


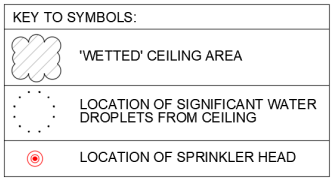
Ceiling area 'wetted' = 2 m^2

Water Distribution Spray Pattern Test Number : 13	
Date of Fire Test	8th November 2023
Time of Fire Test	09:43
Duration of Fire Test	15 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler D
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	0.35 bar (0.34 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



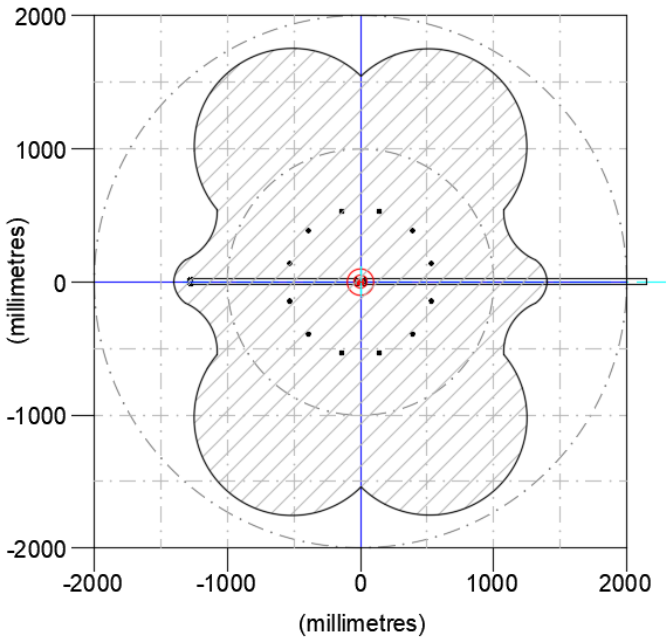


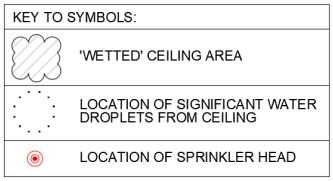
Ceiling area 'wetted' = 2 m^2

Water Distribution Spray Pattern Test Number : 14	
Date of Fire Test	8th November 2023
Time of Fire Test	14:07
Duration of Fire Test	06 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.00 bar (3.12 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



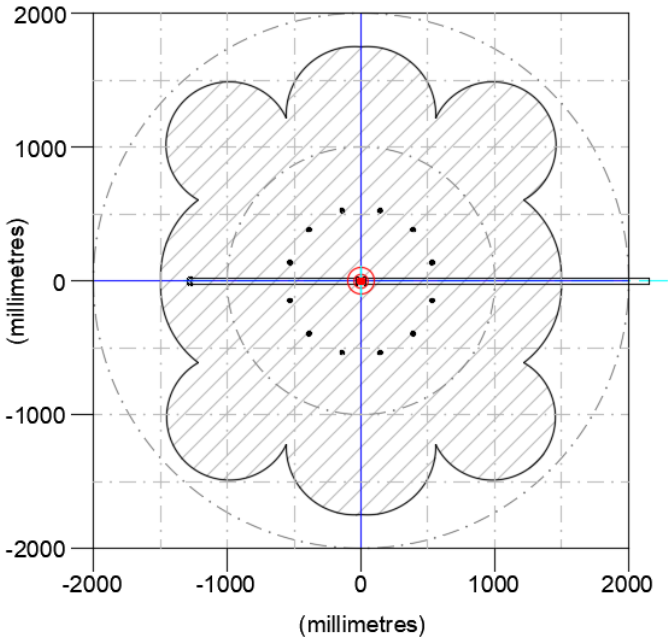


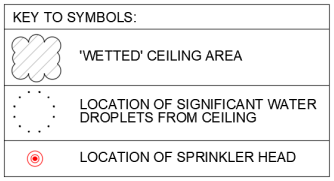
Ceiling area 'wetted' = 8 m^2

Water Distribution Spray Pattern Test Number : 15	
Date of Fire Test	9th November 2023
Time of Fire Test	09:14
Duration of Fire Test	08 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler A
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.00 bar (3.03 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



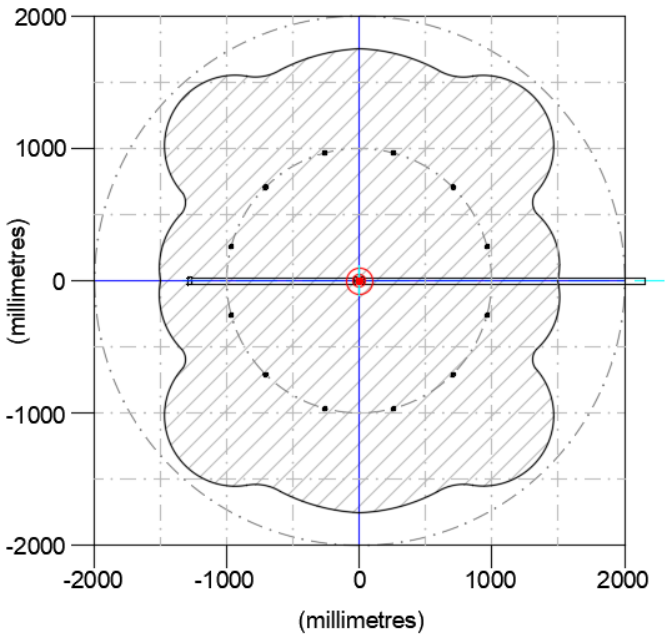


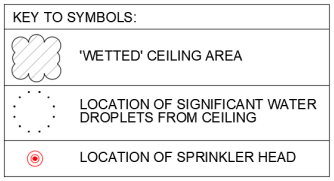
Ceiling area 'wetted' = 9 m^2

Water Distribution Spray Pattern Test Number : 16	
Date of Fire Test	9th November 2023
Time of Fire Test	11:40
Duration of Fire Test	07 Minutes, 03 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.00 bar (3.11 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



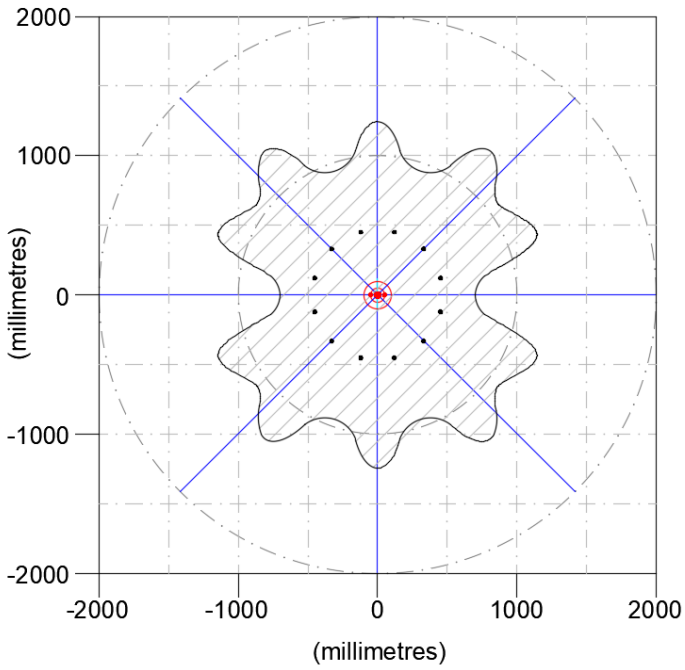


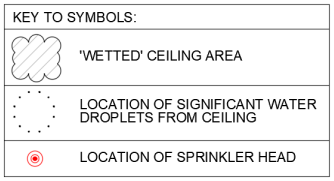
Ceiling area 'wetted' = 9 m^2

Water Distribution Spray Pattern Test Number : 17	
Date of Fire Test	28th November 2023
Time of Fire Test	12:56
Duration of Fire Test	08 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant within ceiling
Location of Deflector Below Ceiling	45 mm
Sprinkler Head Pressure	3.00 bar (2.85 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



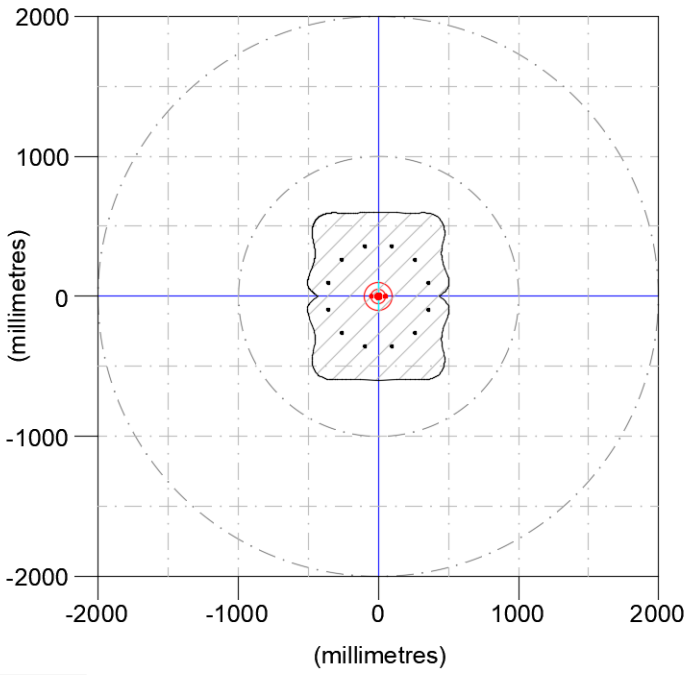


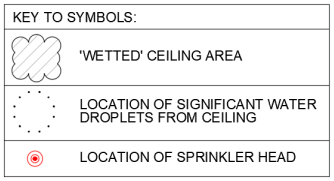
Ceiling area 'wetted' = 4 m^2

Water Distribution Spray Pattern Test Number : 18	
Date of Fire Test	29th November 2023
Time of Fire Test	09:35
Duration of Fire Test	15 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant within ceiling
Location of Deflector Below Ceiling	45 mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:

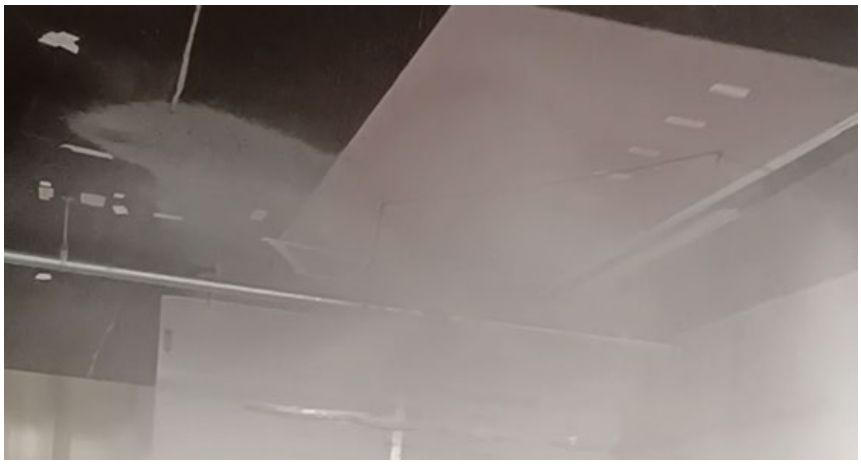




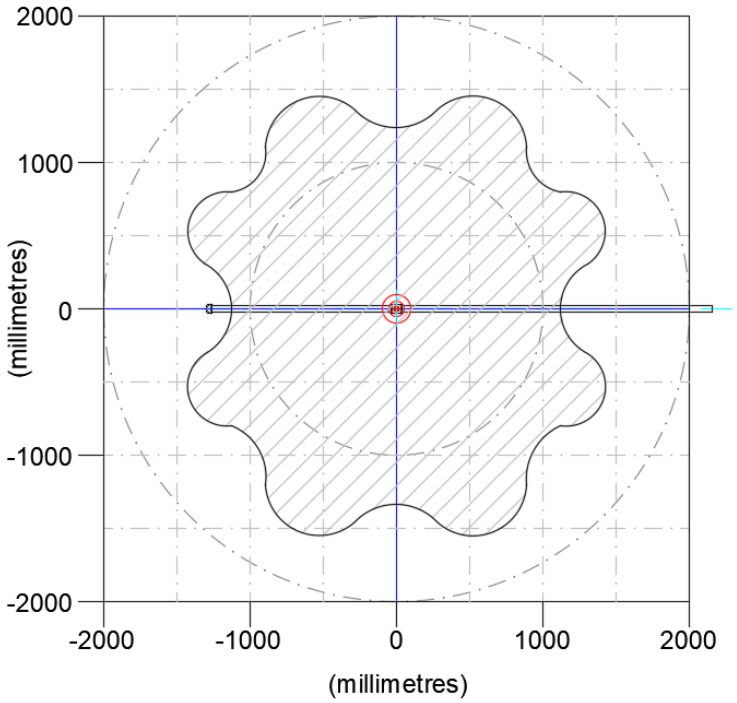
Ceiling area 'wetted' = 1 m^2

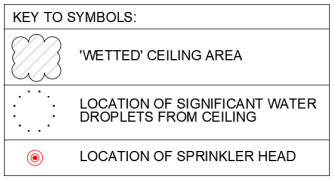
Water Distribution Spray Pattern Test Number : W03	
Date of Fire Test	13th November 2023
Time of Fire Test	14:12
Duration of Fire Test	6 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler E
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.0 bar (2.98 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:



Representation of Ceiling 'Wetting' Pattern:



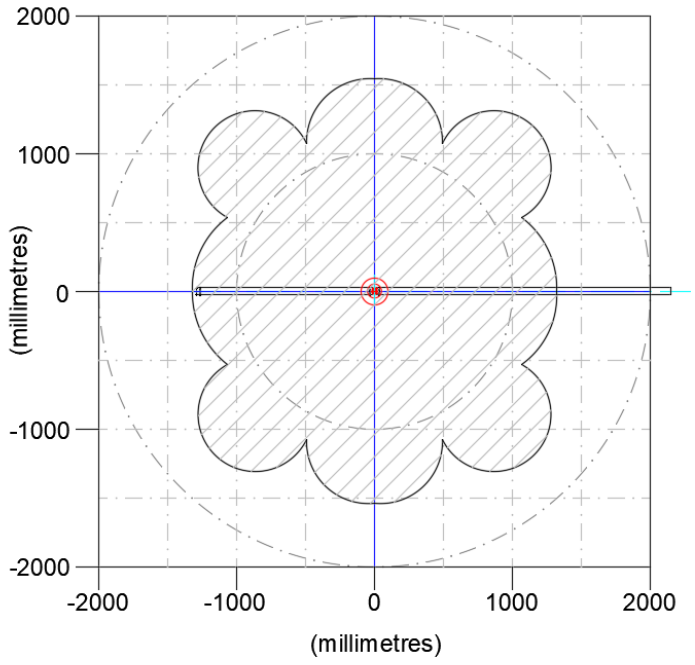


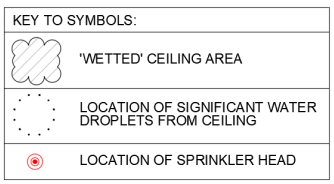
Ceiling area 'wetted' = 6 m^2

Water Distribution Spray Pattern Test Number : W04	
Date of Fire Test	13th November 2023
Time of Fire Test	15:16
Duration of Fire Test	6 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler D
Sprinkler Head Orientation	Upright
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.0 bar (3.05 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



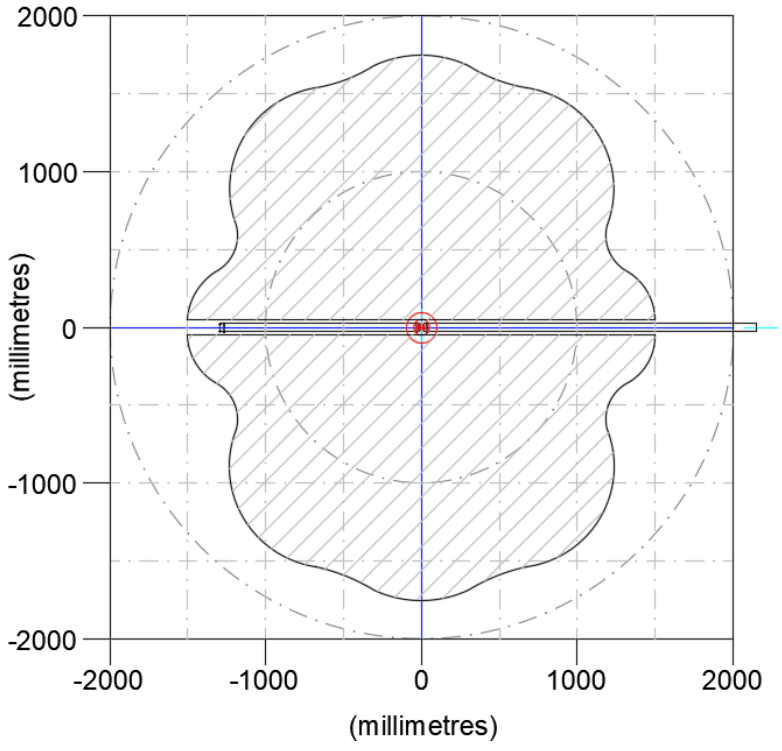


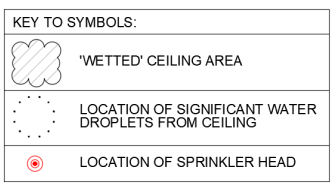
Ceiling area 'wetted' = 7 m^2

Water Distribution Spray Pattern Test Number : W12	
Date of Fire Test	15th November 2023
Time of Fire Test	10:42
Duration of Fire Test	6 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler E
Sprinkler Head Orientation	Pendant within ceiling
Location of Deflector Below Ceiling	150 mm
Sprinkler Head Pressure	3.0 bar (3.02 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



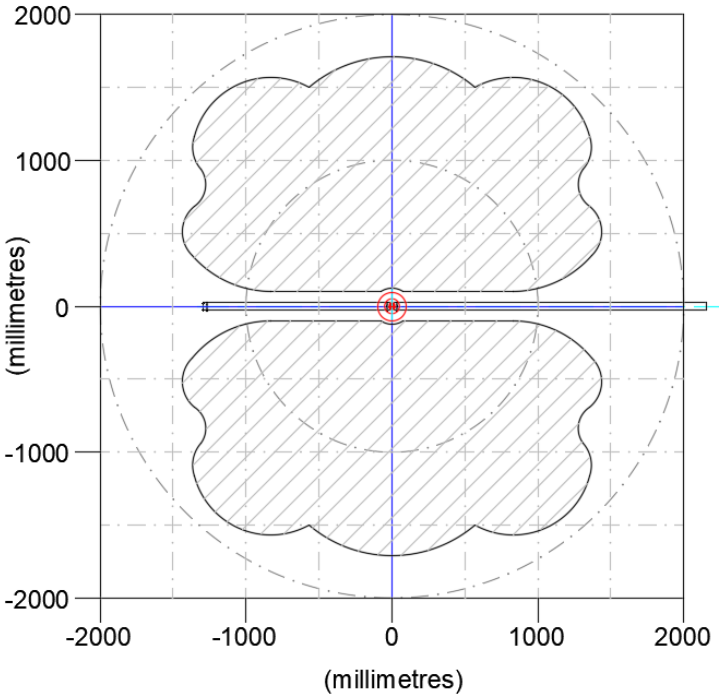


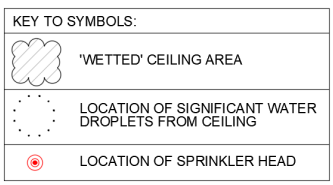
Ceiling area 'wetted' = 8 m^2

Water Distribution Spray Pattern Test Number : W14	
Date of Fire Test	15th November 2023
Time of Fire Test	12:06
Duration of Fire Test	5 Minutes, 02 Seconds
Sprinkler Head Reference	Sprinkler C
Sprinkler Head Orientation	Pendant
Location of Deflector Below Ceiling	180 mm
Sprinkler Head Pressure	3.0 bar (3.05 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:

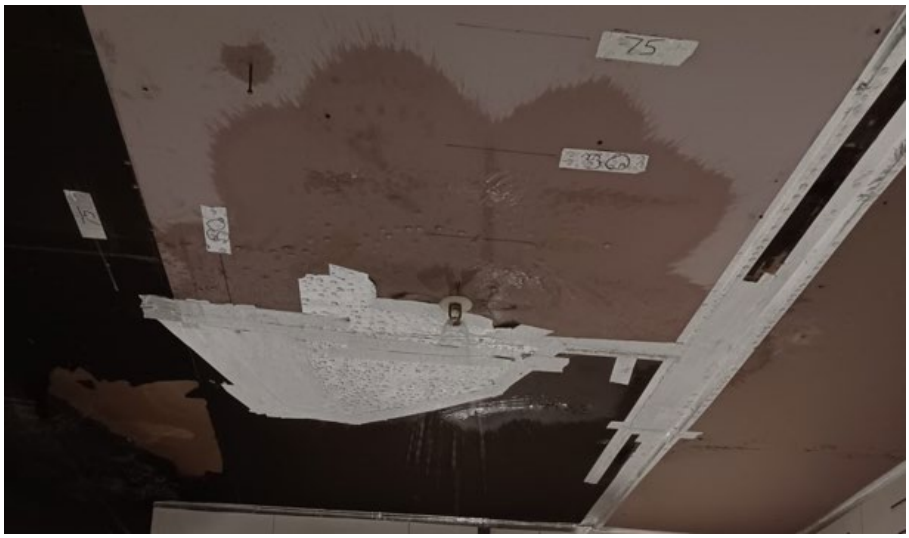




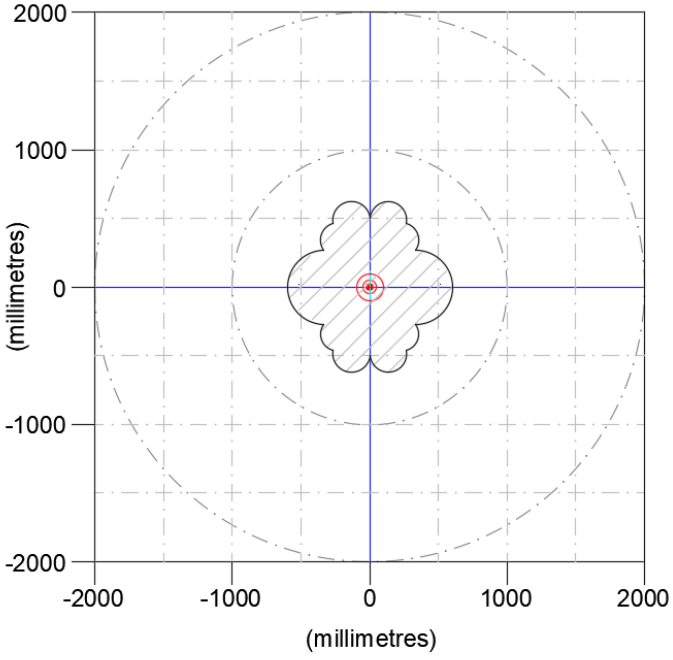
Ceiling area 'wetted' = 8 m^2

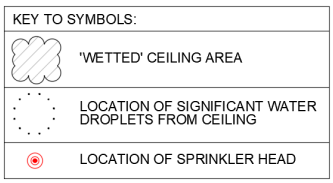
Water Distribution Spray Pattern Test Number : W20	
Date of Fire Test	28th November 2023
Time of Fire Test	09:23
Duration of Fire Test	15 Minutes, 03 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant within ceiling
Location of Deflector Below Ceiling	45mm
Sprinkler Head Pressure	0.35 bar (0.35 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:



Representation of Ceiling 'Wetting' Pattern:



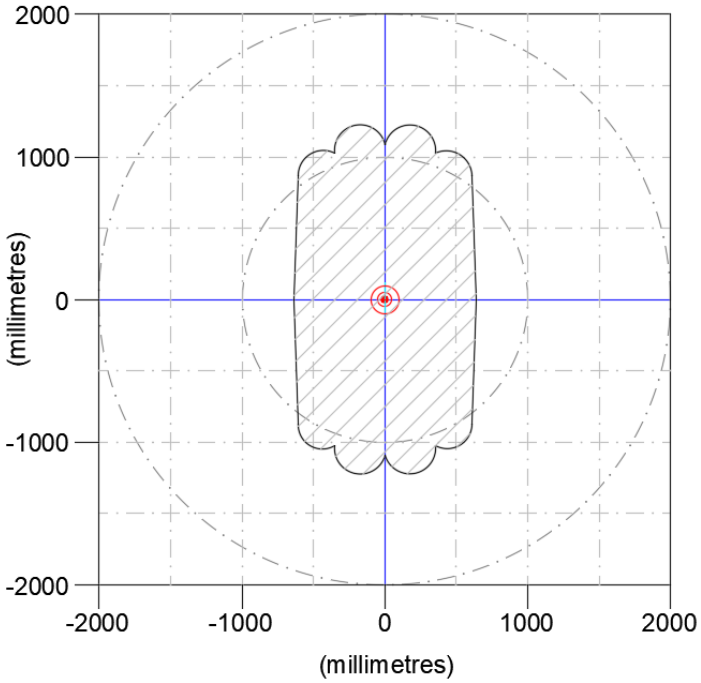


Ceiling area 'wetted' = 1 m^2

Water Distribution Spray Pattern Test Number : W21	
Date of Fire Test	28th November 2023
Time of Fire Test	10:39
Duration of Fire Test	6 Minutes, 01 Seconds
Sprinkler Head Reference	Sprinkler B
Sprinkler Head Orientation	Pendant within ceiling
Location of Deflector Below Ceiling	45mm
Sprinkler Head Pressure	3.0 bar (2.8 bar average achieved)

Photograph Showing Ceiling 'Wetting' Pattern:

Representation of Ceiling 'Wetting' Pattern:



KEY TO SYMBOLS:	
	'WETTED' CEILING AREA
	LOCATION OF SIGNIFICANT WATER DROPLETS FROM CEILING
	LOCATION OF SPRINKLER HEAD

Ceiling area 'wetted' = 3 m^2

Appendix C – Supplementary fixings material (Chapter 7)

Contents Page:

Ambient pull-out test tables:

Table AT1 : M10 & M12 Coachscrews

Table AT2 : M10 & M12 Coachscrews

Table AT3 : Stud-bolts & Rod-hangers

Table AT4 : M10 & M12 Coachscrews

Table AT5 : M10 & M12 Coachscrews

Fire pull-out tests:

Table FT1 : M10 & M12 Coachscrews

Table FT2 : M10 & M12 Coachscrews

Table FT3 : M10 & M12 Coachscrews

Table FT4 : M10 & M12 Coachscrews

Table FT5 : M10 & M12 Coachscrews

Table FT6 : M8 Coachscrews, Stud-bolts & Rod-hangers

Table FT7 : M8, M10 & M12 Coachscrews, with bracket components

Table FT8 : M10 & M12 Coachscrews

Fire Test 1 – 30 minutes HB S panel (05.12.2023)

Figure 1 : FT1 Gas burner plume temperature and heat output.

Figure 2 : FT1 Gas temperatures 15 mm below sample.

Figure 3 : FT1 Screw shank temperature profiles below sample.

Figure 4 : FT1 Screw temperature profiles inside the sample (Mid-point and screw tips).

Figure 5 : FT1 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 6 : FT1 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 7 : FT1 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 8 : FT1 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

Figure 9 : FT1 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 10 : FT1 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

Figure 11 : FT1 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 2 – 30 minutes HB X panel (07.12.2023)

Figure 12 : FT2 Gas burner plume temperature and heat output.

Figure 13 : FT2 Gas temperatures 15 mm below sample.

Figure 14 : FT2 Screw shank temperature profiles below sample.

Figure 15 : FT2 Screw temperature profiles inside the sample (Mid-point and screw tips).

Figure 16 : FT2 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 17 : FT2 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 18 : FT2 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 19 : FT2 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

Figure 20 : FT2 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 21 : FT2 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

Figure 22 : FT2 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 3 – 30 minutes HB S panel (20.12.2023)

Figure 23 : FT1 Gas burner plume temperature and heat output.

Figure 24 : FT3 Gas temperatures 15 mm below sample.

Figure 25 : FT3 Screw shank temperature profiles below sample.

Figure 26 : FT3 Screw temperature profiles inside the sample (Mid-point and screw tips).

Figure 27 : FT3 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 28 : FT3 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 29 : FT3 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 30 : FT3 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

Figure 31 : FT3 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 32 : FT3 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

Figure 33 : FT3 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 4 – 60 minutes HB X panel (03.01.2024)

Figure 34 : FT4 Gas burner plume temperature and heat output.

Figure 35 : FT4 Gas temperatures 15 mm below sample.

Figure 36 : FT4 Screw shank temperature profiles below sample.

Figure 37 : FT4 Screw temperature profiles inside the sample (Mid-point and screw tips).

Figure 38 : FT4 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 39 : FT4 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 40 : FT4 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 41 : FT4 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

Figure 42 : FT4 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 43 : FT4 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

Figure 44 : FT4 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 5 – 60 minutes HB S panel (05.01.2024)

Figure 45 : FT5 Gas burner plume temperature and heat output.

Figure 46 : FT5 Gas temperatures 15 mm below sample.

Figure 47 : FT5 Screw shank temperature profiles below sample.

Figure 48 : FT5 Screw temperature profiles inside the sample (Mid-point and screw tips).

Figure 49 : FT5 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 50 : FT5 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 51 : FT5 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 52 : FT5 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

Figure 53 : FT5 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 54 : FT5 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

Figure 55 : FT5 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 6 – 30 minutes HB S panel (08.01.2024)

Figure 56 : FT6 Gas burner plume temperature and heat output.

Figure 57 : FT6 Gas temperatures 15 mm below sample.

Figure 58 : FT6 Screw shank temperature profiles below sample.

Figure 59 : FT6 Screw temperature profiles inside the sample (Mid-point and screw tips).

Figure 60 : FT6 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 61 : FT6 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

Figure 62 : FT6 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 63 : FT6 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

Figure 64 : FT6 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 7 – 30 minutes HB S panel (10.01.2024)

Figure 65 : FT7 Gas burner plume temperature and heat output.

Figure 66 : FT7 Gas temperatures 15 mm below sample.

Figure 67 : FT7 Slotted channel bracket screw temperature profiles below sample.

Figure 68 : FT7 Slotted channel bracket screw temperature profiles below sample.

Figure 69 : FT7 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 70 : FT7 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

Figure 71 : FT7 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 72 : FT7 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

Figure 73 : FT7 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 8 – 60 minutes HB X panel (15.01.2024)

Figure 74 : FT8 Gas burner plume temperature and heat output.

Figure 75 : FT8 Gas temperatures 15 mm below sample.

Figure 76 : FT8 Screw shank temperature profiles below sample.

Figure 77 : FT8 Screw temperature profiles inside the sample (Mid-point and screw tips).

Figure 78 : FT8 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 79 : FT8 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

Figure 80 : FT8 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 81 : FT8 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

Figure 82 : FT8 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

Figure 83 : FT8 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

Figure 84 : FT8 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Thermocouple Locations:

Figure 85 : Locations of thermocouples below each fire test sample.

Figure 86 : Locations of thermocouples adjacent to fixings for each fire test sample.

Figure 87 : Locations of thermocouples from above to mid-ply, glue line, and bolt tips for each fire test sample.

Table TC01 : Location table of each thermocouple for fire tests.

Table AT1 : M10 & M12 Coachscrews

AT1 (CLT panel 13) 30.11.2023 - HB S					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M10 x 120 mm, 110 mm Embedment (A)	20.6	20.9	15.8	19.1	2.33
Fixing Type 2 M10 x 100 mm, 90 mm Embedment (B)	19.4	16.9	14.8	17.0	1.88
Fixing Type 3 M12 x 100 mm, 90 mm Embedment (C)	18.5	22.2	18.1	19.6	1.84
Fixing Type 4 M12 x 120 mm, 110 mm Embedment (D)	28.5	24.6	22.3	25.1	2.55

Table AT2 : M10 & M12 Coachscrews

AT2 (CLT panel 3) 30.11.2023 - HB X					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M10 x 120 mm, 110 mm Embedment (A)	15	16.9	16.3	16.1	0.79
Fixing Type 2 M10 x 100 mm, 90 mm Embedment (B)	13.5	13.3	14.8	13.9	0.66
Fixing Type 3 M12 x 100 mm, 90 mm Embedment (C)	14.9	16.4	16.9	16.1	0.84
Fixing Type 4 M12 x 120 mm, 110 mm Embedment (D)	20.9	26.8	23.4	23.7	2.41

Table AT3 : Stud-bolts & Rod-hangers

AT3 (CLT panel 9) 01.12.2023 - HB S					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M12 Studbolt long, 60 mm Embedment	11.2	10.7	10.3	10.7	0.36
Fixing Type 2 M10 Studbolt long, 60 mm Embedment	15.7	14.8	13.3	14.6	0.98
Fixing Type 3 M10 studbolt short, 60 mm Embedment	10.9	10.1	8.7	9.9	0.9
Fixing Type 4 M10 rodhanger, 60 mm Embedment	10.5	10.5	8.3	9.8	1.03

Table AT4 : M10 & M12 Coachscrews

AT4 (CLT panel 4) 08.12.2023 - HB X					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M10 x 100 mm, 50 mm Embedment	7.4	9.8	9.1	8.8	1
Fixing Type 2 M12 x 100 mm, 50 mm Embedment	9.4	8	9.2	8.9	0.61
Fixing Type 3 M10 x 100 mm, 70 mm Embedment	12.3	17.6	13	14.3	2.35
Fixing Type 4 M12 x 100 mm, 70 mm Embedment	13.6	14.3	14.2	14.0	0.3

Table AT5 : M10 & M12 Coachscrews

AT5 (CLT panel 15) 08.12.2023 - HB S					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M10 x 100 mm, 50 mm Embedment	9.4	7.1	7.7	8.1	0.97
Fixing Type 2 M12 x 100 mm, 50 mm Embedment	8.7	9.1	9.7	9.2	0.41
Fixing Type 3 M10 x 100 mm, 70 mm Embedment	11.5	12.9	11.6	12.0	0.63
Fixing Type 4 M12 x 100 mm, 70 mm Embedment	16.5	15.5	16.2	16.1	0.41

Fire pull-out tests:

Table FT1 : M10 & M12 Coachscrews

FT1 (CLT panel 14) 05.12.2023 - HB S - 30 Minutes					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M10 x 120 mm, 110 mm Embedment (A)	12.5	9.5	9.1	10.4	1.51
Fixing Type 2 M10 x 100 mm, 90 mm Embedment (B)	5.9	5.7	7.4	6.3	0.76
Fixing Type 3 M12 x 100 mm, 90 mm Embedment (C)	4.7	2.6	1.7	3.0	1.26
Fixing Type 4 M12 x 120 mm, 110 mm Embedment (D)	14.9	8.7	7.2	10.3	3.33

Table FT2 : M10 & M12 Coachscrews

FT2 (CLT panel 5) 07.12.2023 - HB X - 30 Minutes					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M10 x 120 mm, 110 mm Embedment (A)	11.9	11.8	11	11.6	0.4
Fixing Type 2 M10 x 100 mm, 90 mm Embedment (B)	7.7	6.5	5.4	6.5	0.93
Fixing Type 3 M12 x 100 mm, 90 mm Embedment (C)	5.2	2.3	1.1	2.9	1.72
Fixing Type 4 M12 x 120 mm, 110 mm Embedment (D)	11.2	8.7	7.5	9.1	1.54

Table FT3 : M10 & M12 Coachscrews

FT3 (CLT panel 16) 20.12.2023 - HB S - 30 Minutes					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M10 x 120 mm, 110 mm Embedment (A)	15.2	12.5	13.3	13.7	1.13
Fixing Type 2 M10 x 100 mm, 90 mm Embedment (B)	9.6	7.5	6.8	8.0	1.18
Fixing Type 3 M12 x 100 mm, 90 mm Embedment (C)	7.1	0 (Weighted)	1.8	4.45 (Fixing rows 1 & 3)	2.65
Fixing Type 4 M12 x 120 mm, 110 mm Embedment (D)	16.7	12.5	11.2	13.5	2.34
Fixing Type 5 M10 x 120 mm, 50 mm Embedment	0.1	x	N/A	0.1	
Fixing Type 6 M10 x 100 mm, 50 mm Embedment	x	x	N/A		
Fixing Type 7 M12 x 100 mm, 50 mm Embedment	x	x	N/A		
Fixing Type 8 M12 x 120 mm, 50 mm Embedment	x	x	N/A		
x - Represents a value less than 0.1kN (fixing pulled out by hand - no detectable pull-out force was measured post-fire					

Table FT4 : M10 & M12 Coachscrews

FT4 CLT (panel 6) 03.01.2024 - HB X - 60 Minutes					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M10 x 120 mm, 110 mm Embedment (A)	13.9	9.9	8.4	10.7	2.32
Fixing Type 2 M10 x 100 mm, 90 mm Embedment (B)	5.5	4.9	2.8	4.4	1.15
Fixing Type 3 M12 x 100 mm, 90 mm Embedment (C)	1.8	0 (Weighted)	0.5	1.2 (Fixing rows 1 & 3)	0.65
Fixing Type 4 M12 x 120 mm, 110 mm Embedment (D)	10.1	7.4	8.5	8.7	1.1

Table FT5 : M10 & M12 Coachscrews

FT5 (CLT panel 17) 05.01.2024 - HB S - 60 Minutes					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M10 x 120 mm, 110 mm Embedment (A)	10	7.9	9.5	9.1	0.89
Fixing Type 2 M10 x 100 mm, 90 mm Embedment (B)	8	3 (Weighted)	2.8	5.4 (Fixing rows 1 & 3)	2.6
Fixing Type 3 M12 x 100 mm, 90 mm Embedment (C)	3	2.2	0.3	1.8	1.13
Fixing Type 4 M12 x 120 mm, 110 mm Embedment (D)	8.3	2.8	1.5	4.2	2.94
Fixing Type 5 M8 x 100 mm, 90 mm Embedment	4.4	14.6	4	7.7	4.9

Table FT6 : M8 Coachscrews, Stud-bolts & Rod-hangers

FT6 (CLT panel 18) 08.01.2024 - HB S -30 Minutes					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M12 Studbolt long, 60 mm Embedment	0.1	x	x	0.1	0.04
Fixing Type 2 M10 Studbolt long, 60 mm Embedment	1.8	0.2	0.1	0.7	0.77
Fixing Type 3 M10 studbolt short, 60 mm Embedment	0.2	0.1	x	0.2	0.05
Fixing Type 4 M10 rodhanger, 60 mm Embedment	4.4	2	1.1	2.5	1.39
Fixing Type 5 M8 x 100 mm, 90 mm Embedment	9.4	8.1	9.1	8.9	0.55
Fixing Type 6 M8 x 100 mm, 90 mm Embedment	6.4	6.5	6	6.3	0.21

Table FT7 : M8, M10 & M12 Coachscrews, with bracket components

FT7 (CLT Panel 20) 10.01.2024 - HB S - 30 Minutes			
Bracket Reference	Load (kN)	Bracket Reference	Load (kN)
A M8 x 100 mm 2 x fixings at 95 mm embedment	14.5	L M12 x 120 mm 2 x fixings at 74 mm embedment	0.8
B M10 x 100 mm 2 x fixings at 95 mm embedment	18.1	M M8 x 100 mm 2 x fixings at 95 mm embedment	17.2
C M10 x 120 mm 2 x fixings at 115 mm embedment	25+	N M10 X 120 mm 2 x fixings at 74 mm embedment	3.6
D M10 x 120 mm 2 x fixings at 115 mm embedment	24.8	P M12 x 120 mm 1 x fixing at 74 mm embedment	1
E M10 x 120 mm 2 x fixings at 115 mm embedment	25+	Q M8 X 100 mm 1 x fixing at 95 mm embedment	10
F M8 x 100 mm 2 x fixings at 95 mm embedment	16.8	R M10 x 120 mm 1 x fixings at 74 mm embedment	4.2
G M12 x 100 mm 2x fixings at 95 mm embedment	10.9	S M12 x 120 mm 1 x fixing at 74 mm embedment	3.1
H M12 x 120 mm 2 x fixings at 115 mm embedment	25	T M8 x 100 mm 1 x fixing at 95 mm embedment	12.5
J M12 X 120 mm 2 x fixings at 115 mm embedment	22.2	U M10 X 120 mm 1 x fixing at 74 mm embedment	6.2
K M12 x 120 mm 2 x fixings at 115 mm embedment	18.1		
+ Represents a value greater than 25.0kN (Tester maximum load of 25kN - No pull-out force could be measured post-fire test). Full bracket assemblies			

Table FT8 : M10 & M12 Coachscrews

FT8 (CLT panel 8) 15.01.2024 - HB X - 60 Minutes					
Fixing Reference	Fixing Row 1 (kN)	Fixing Row 2 (kN)	Fixing Row 3 (kN)	Mean Load (kN)	SD
Fixing Type 1 M10 x 120 mm, 110 mm Embedment (A)	11.5	8.8	10.6	10.3	1.12
Fixing Type 2 M10 x 100 mm, 90 mm Embedment (B)	5.6	1.4 (Weighted)	3.1	4.4 (Fixing rows 1 & 3)	1.25
Fixing Type 3 M12 x 100 mm, 90 mm Embedment (C)	1.4	0.5	0.4	0.8	0.44
Fixing Type 4 M12 x 120 mm, 110 mm Embedment (D)	6.5	4.3	3.3	4.7	1.33

Fire Test 1 – 30 minutes HB S panel (05.12.2023)

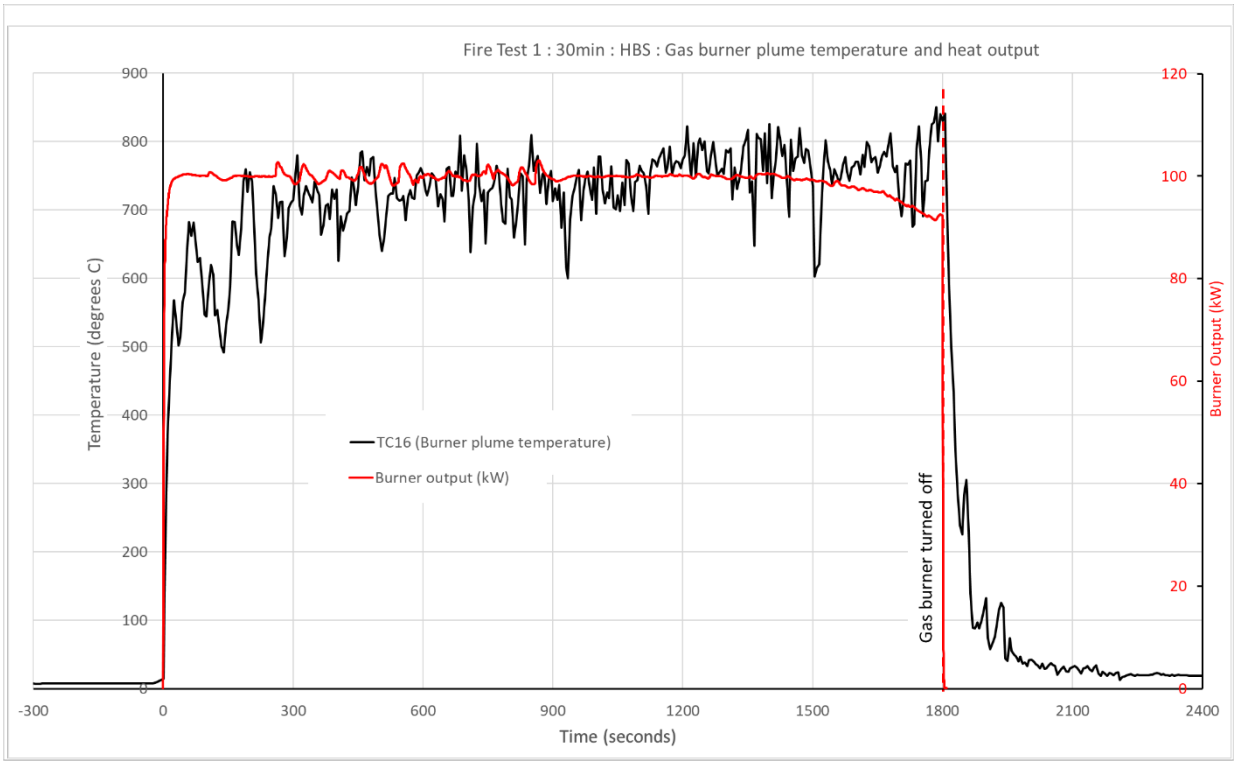


Figure 1 : FT1 Gas burner plume temperature and heat output.

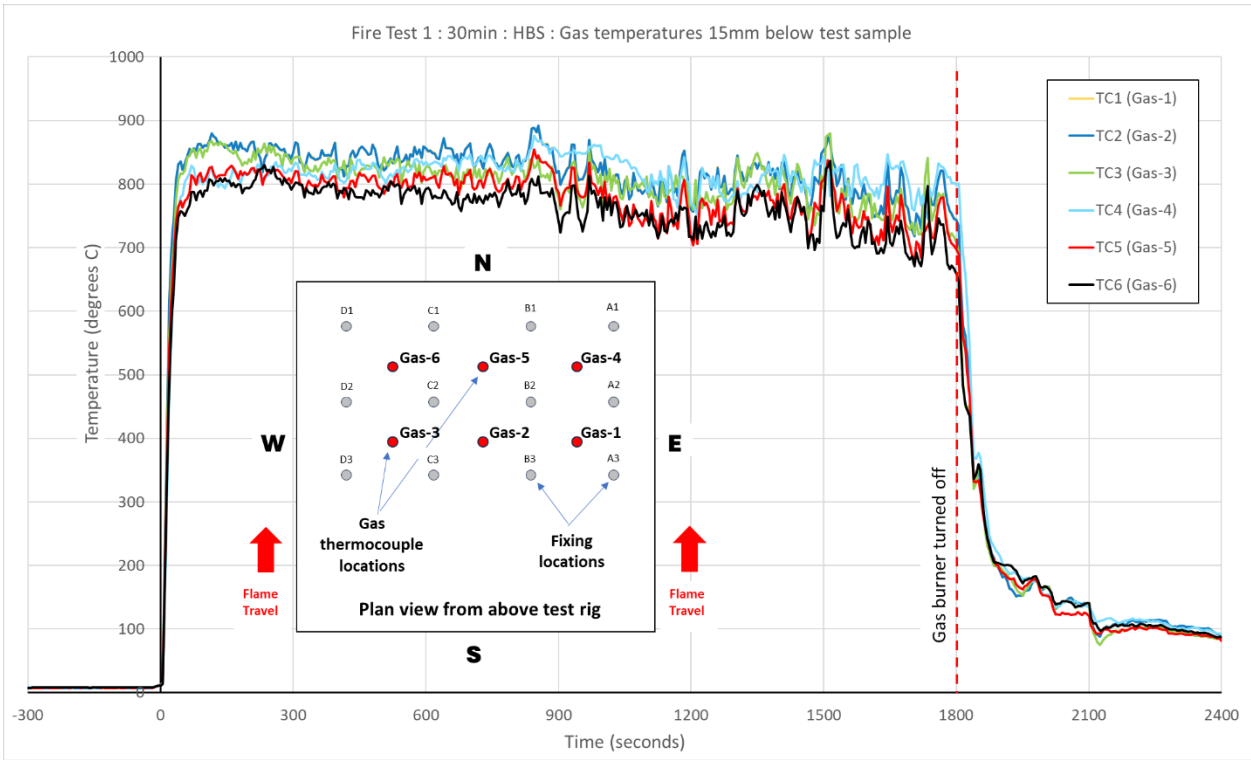


Figure 2 : FT1 Gas temperatures 15 mm below sample.

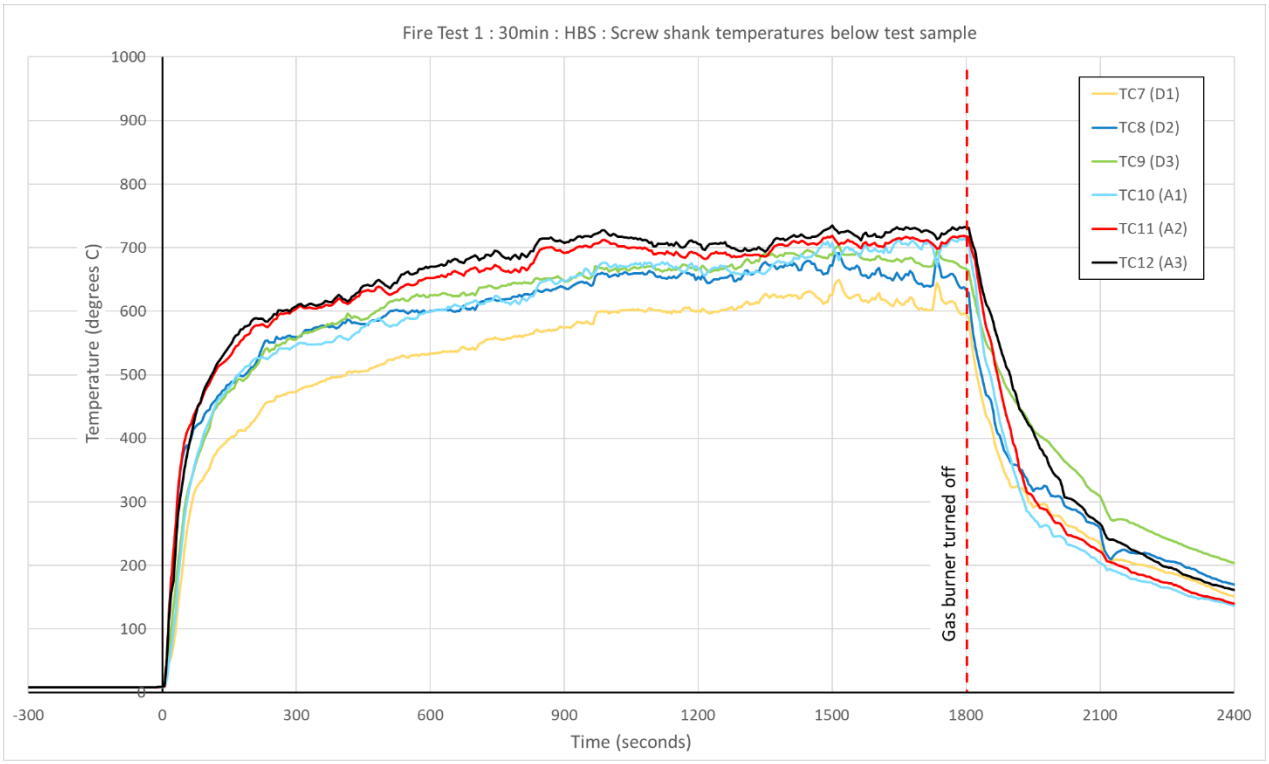


Figure 3 : FT1 Screw shank temperature profiles below sample.

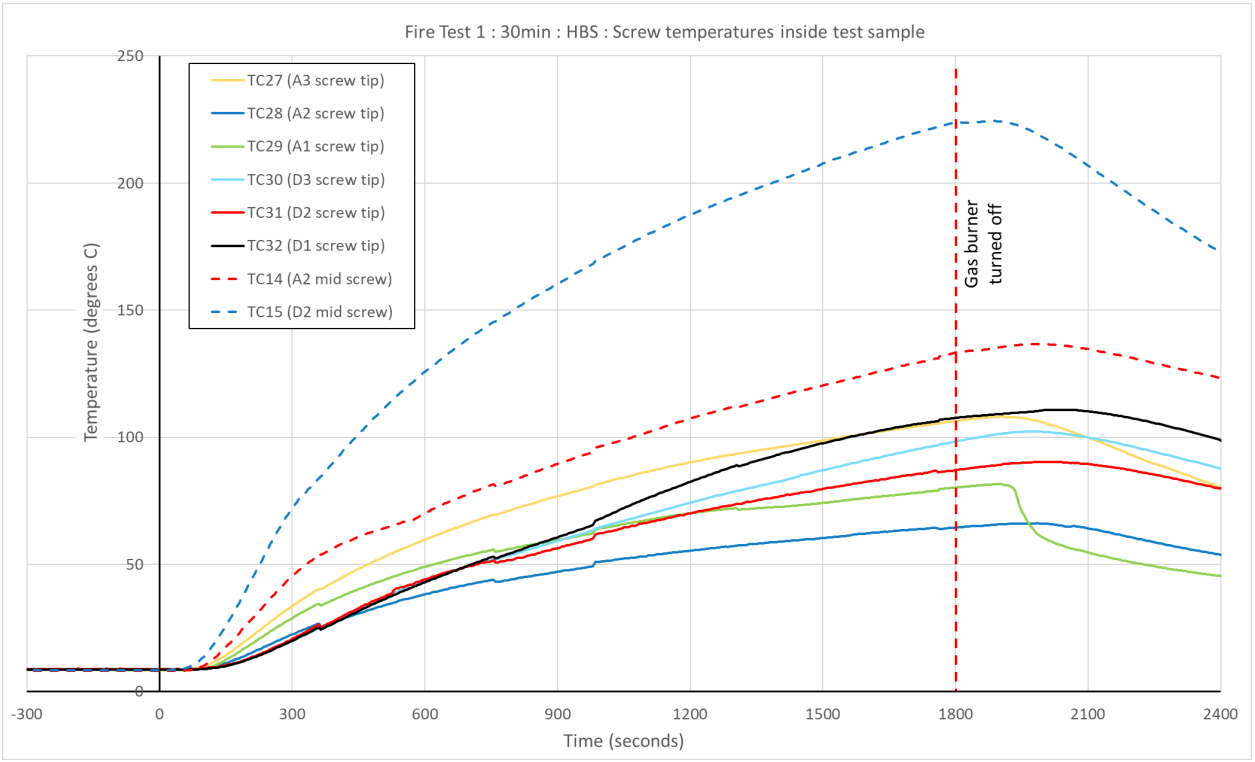


Figure 4 : FT1 Screw temperature profiles inside the sample (Mid-point and screw tips).

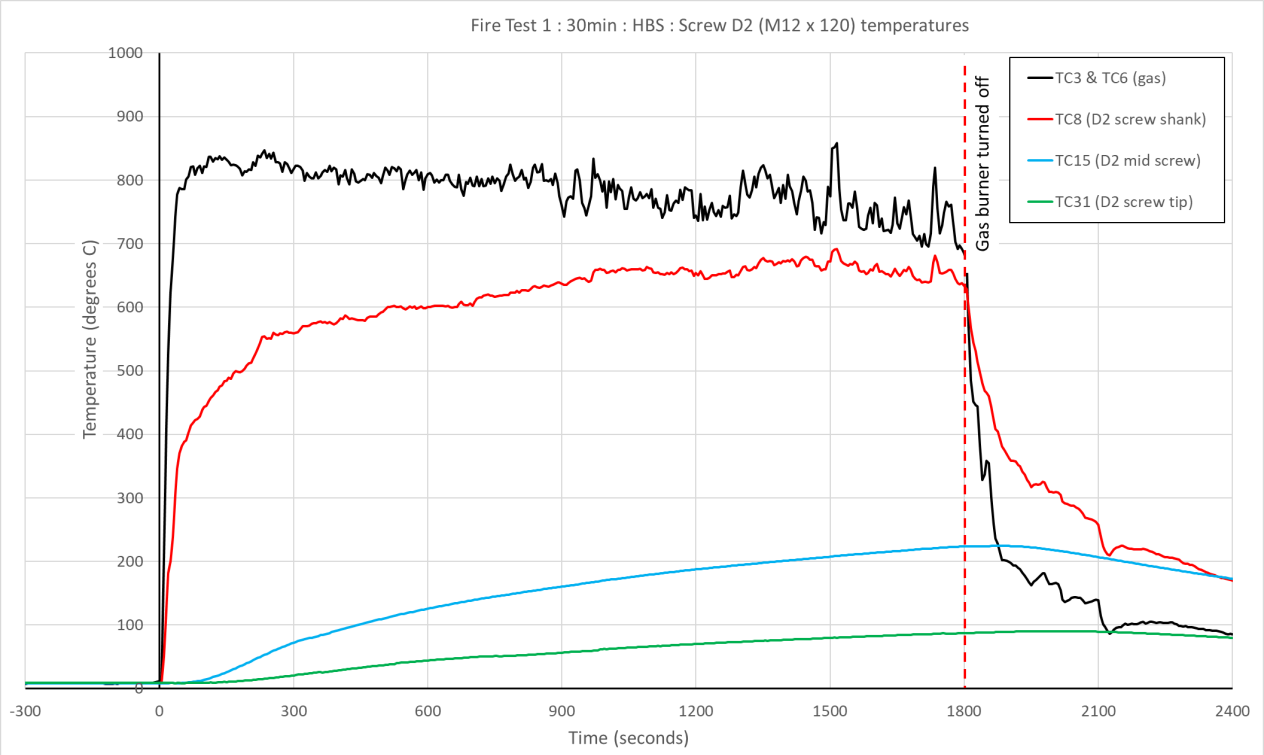


Figure 5 : FT1 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

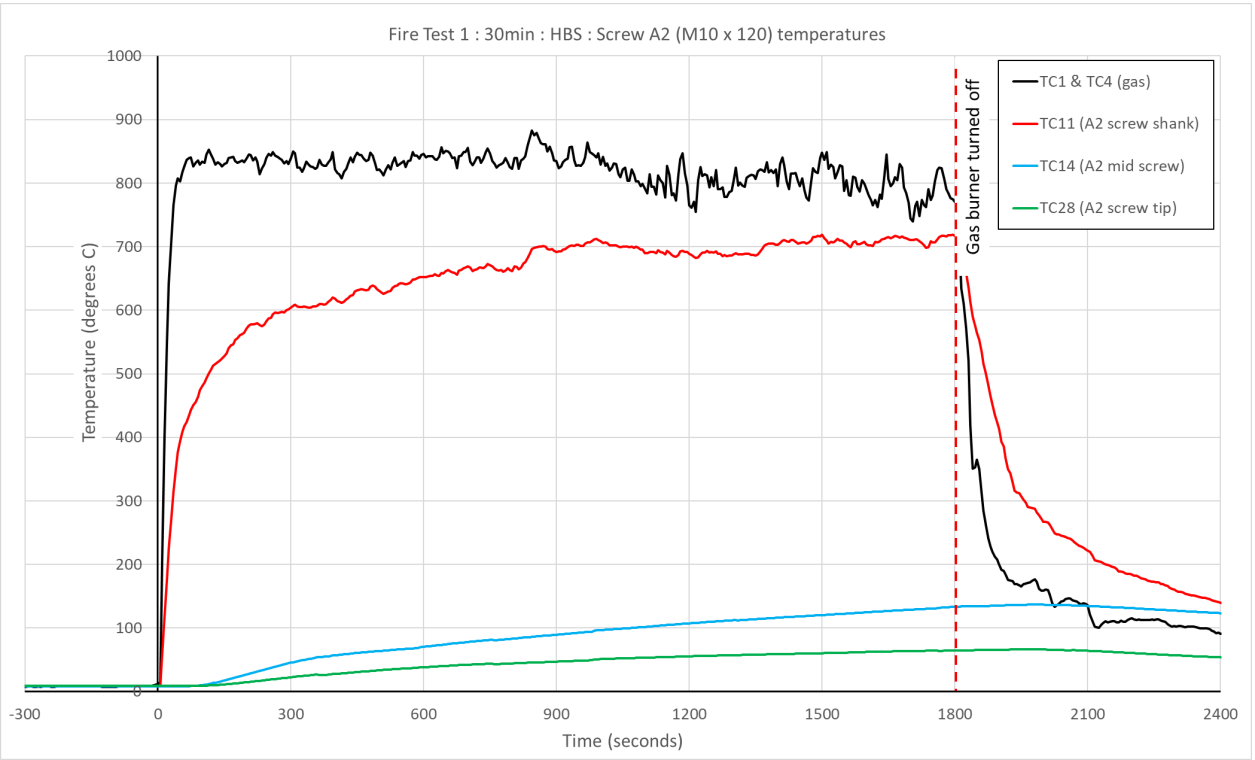


Figure 6 : FT1 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

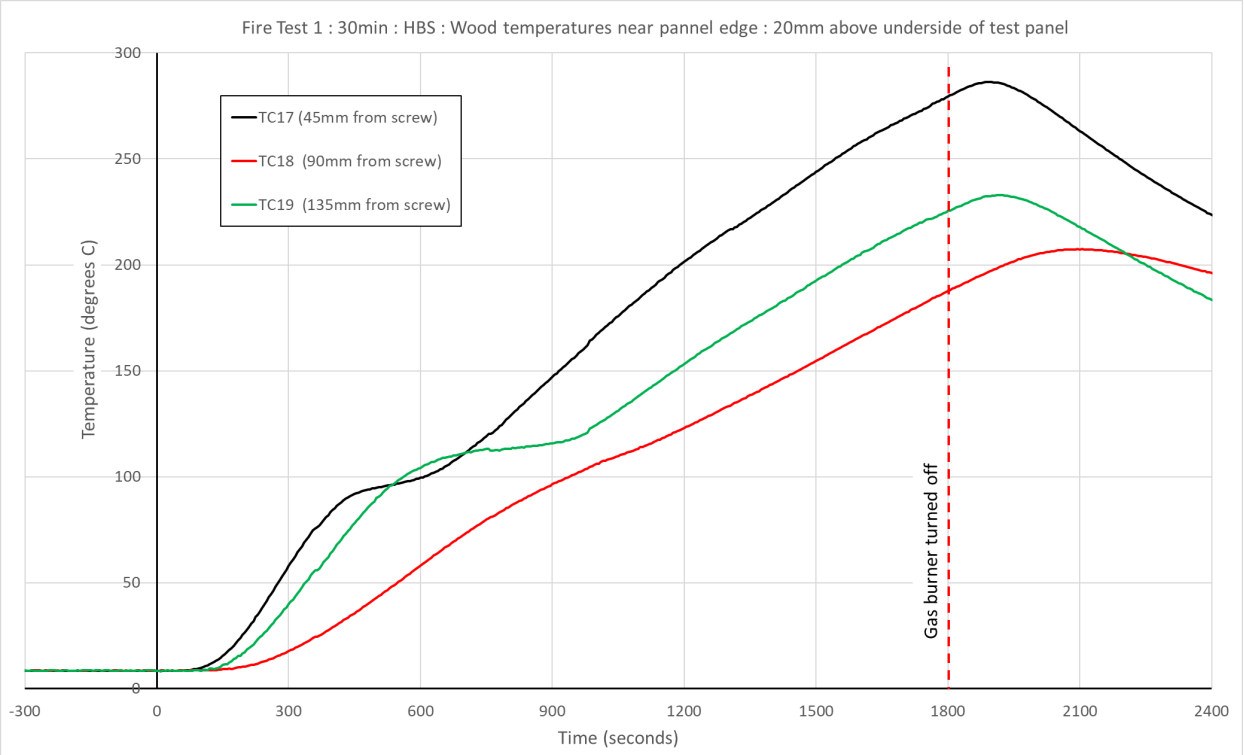


Figure 7 : FT1 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

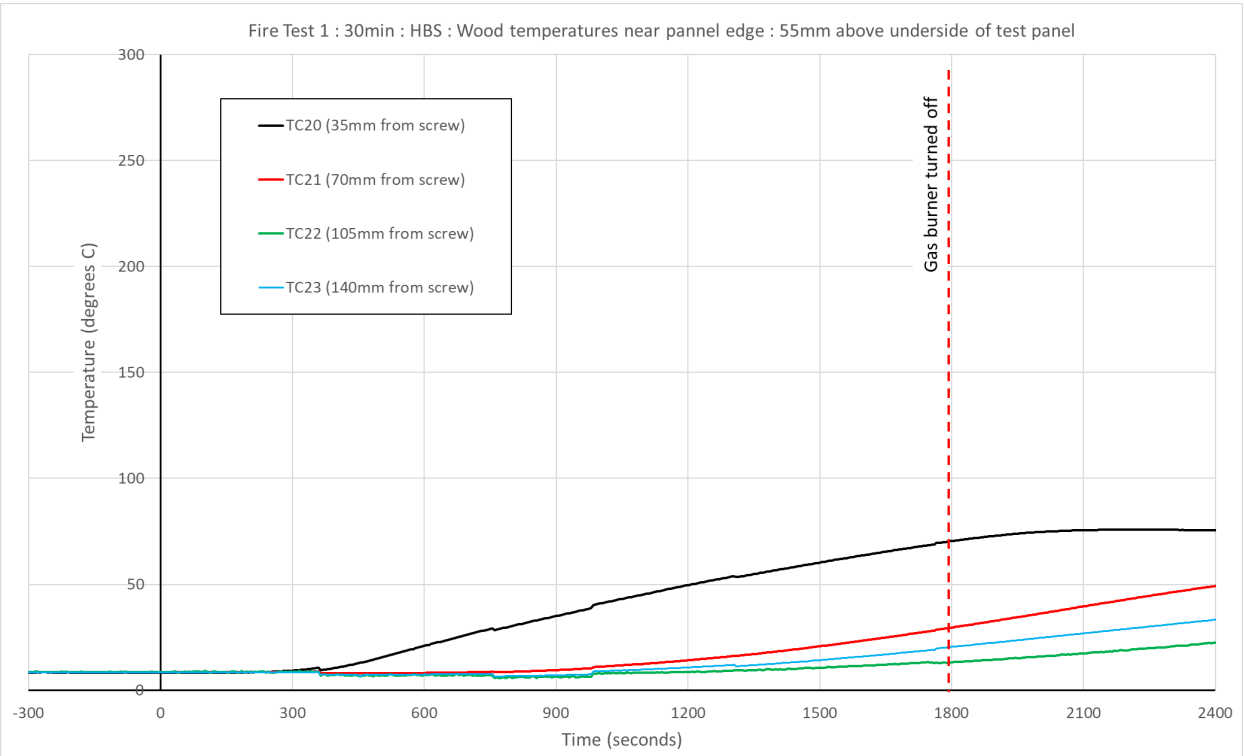


Figure 8 : FT1 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

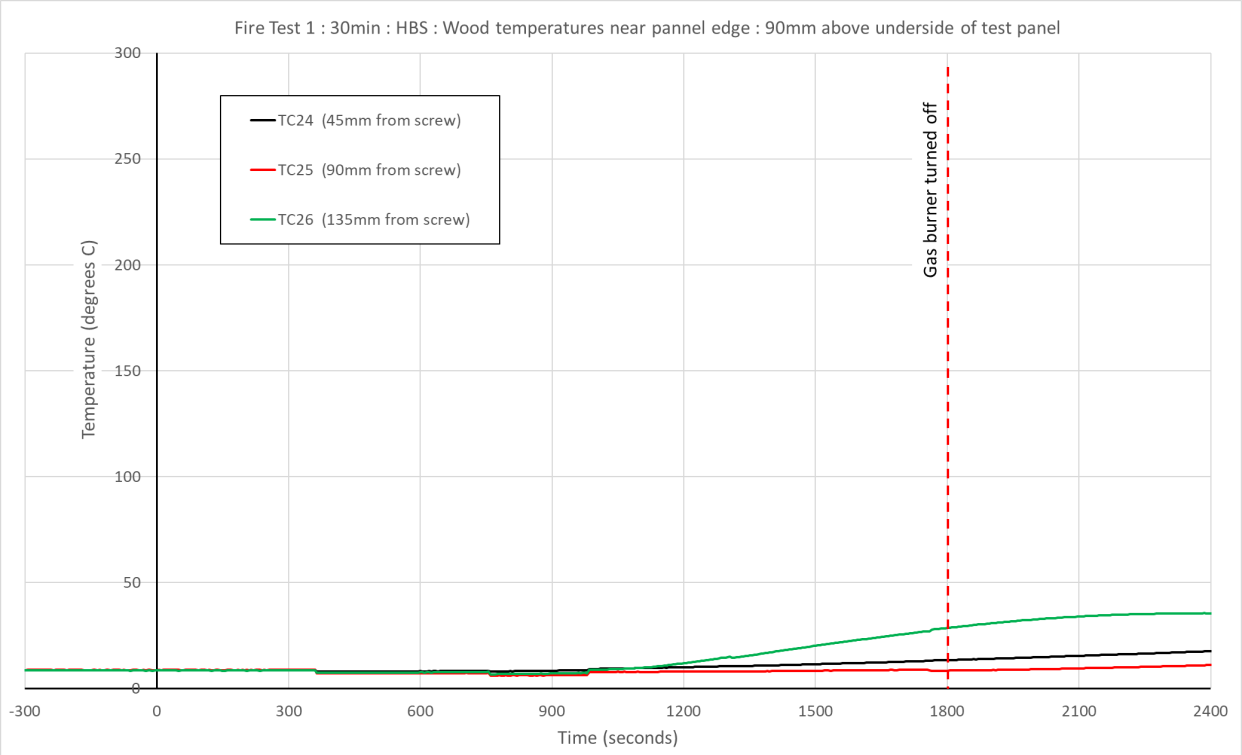


Figure 9 : FT1 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

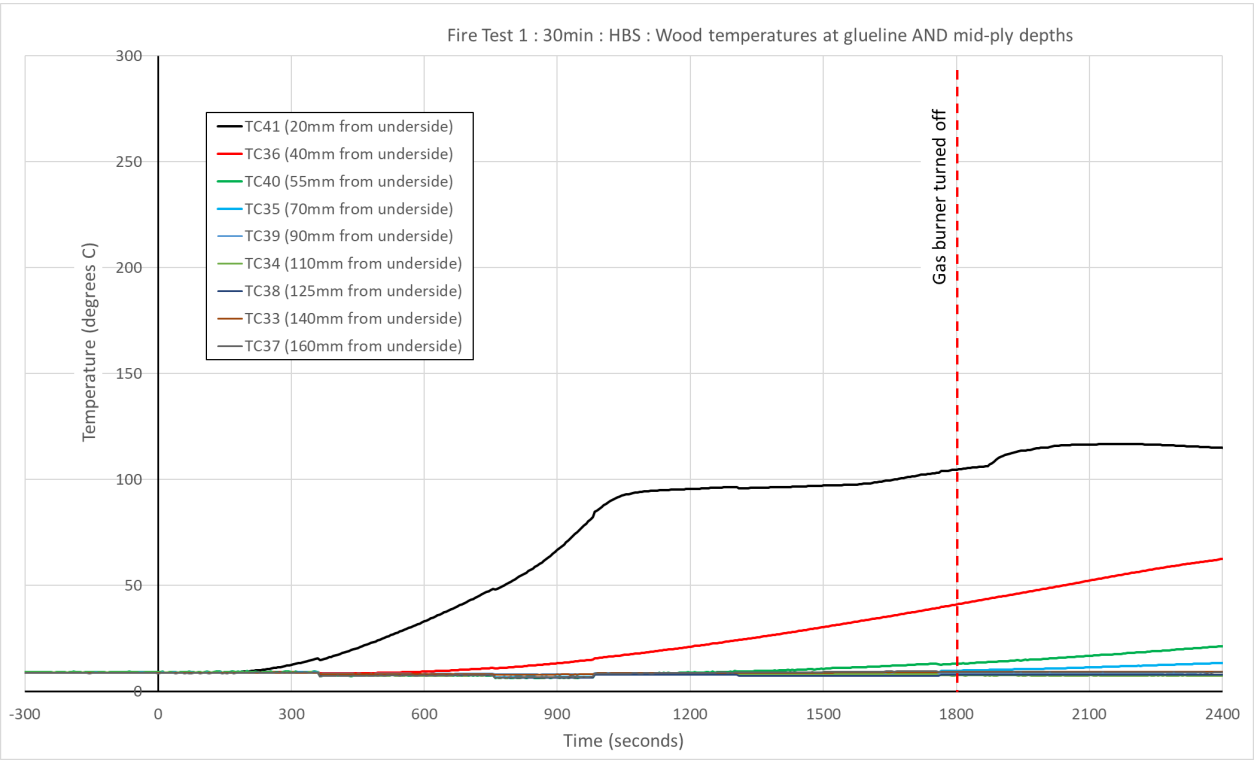


Figure 10 : FT1 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

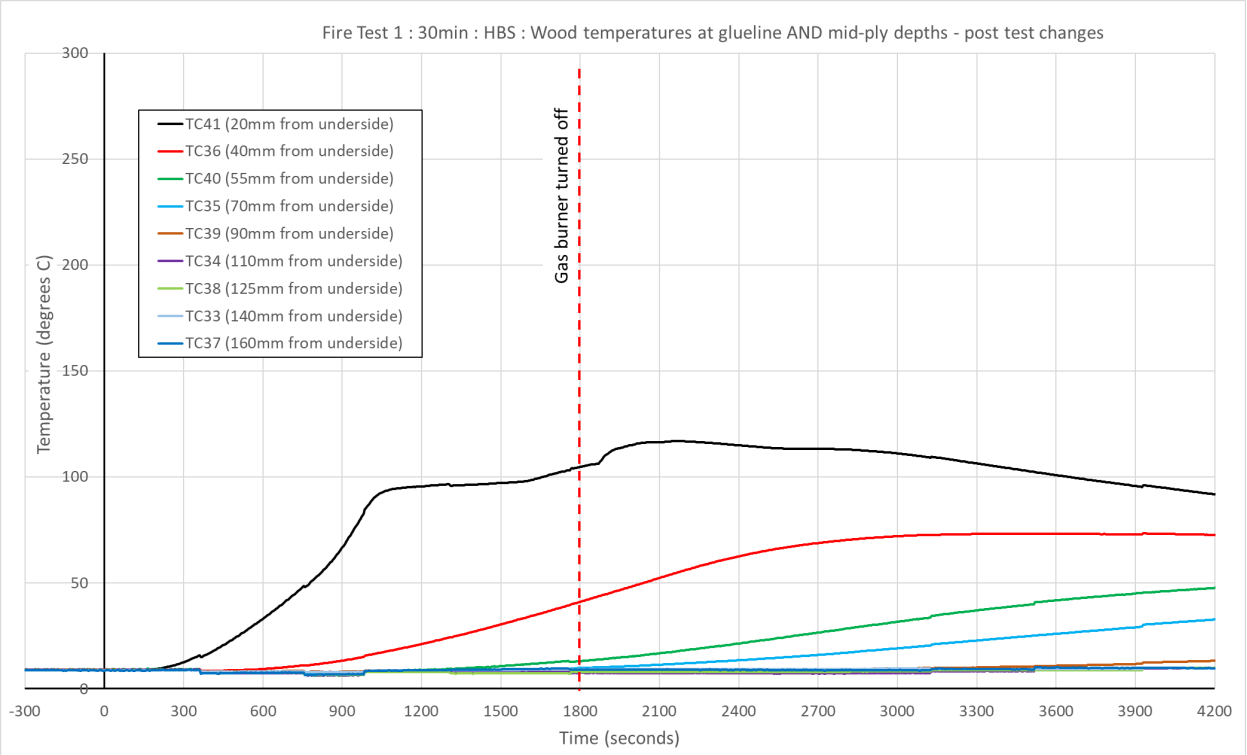


Figure 11 : FT1 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 2 – 30 minutes HB X panel (07.12.2023)

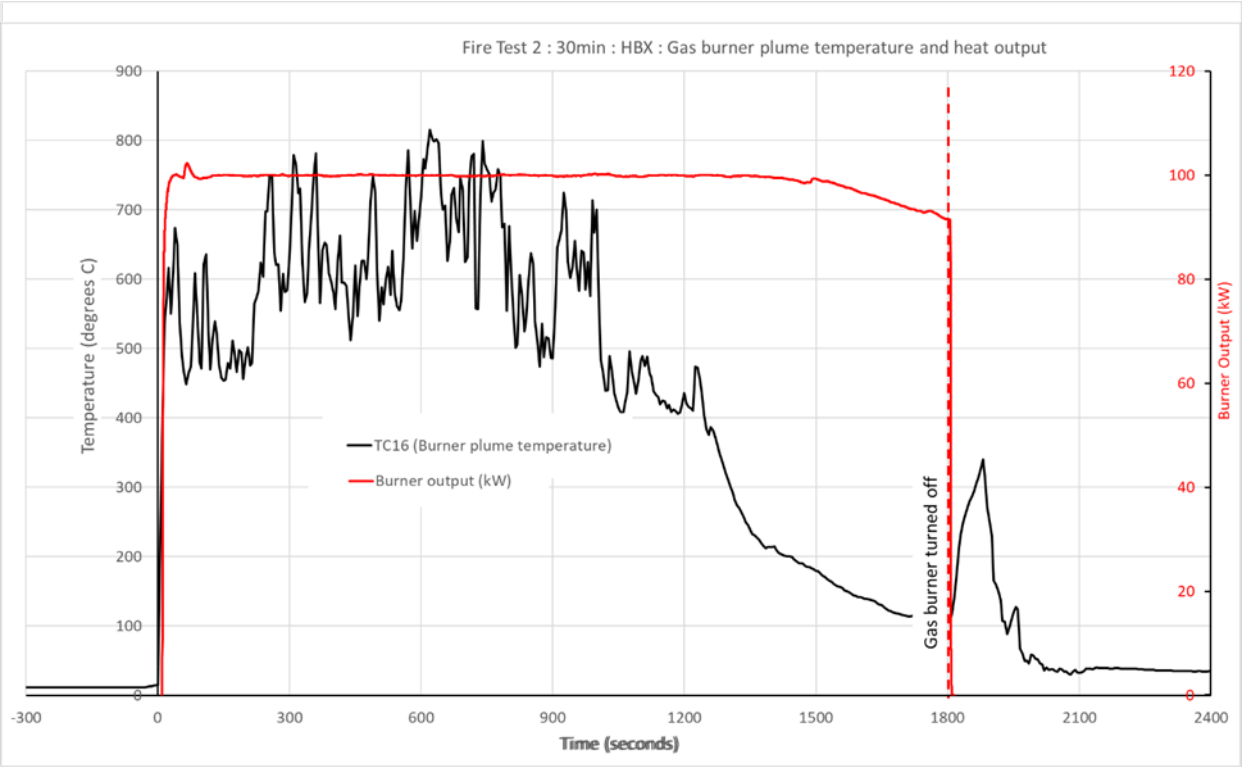


Figure 12 : FT2 Gas burner plume temperature and heat output.

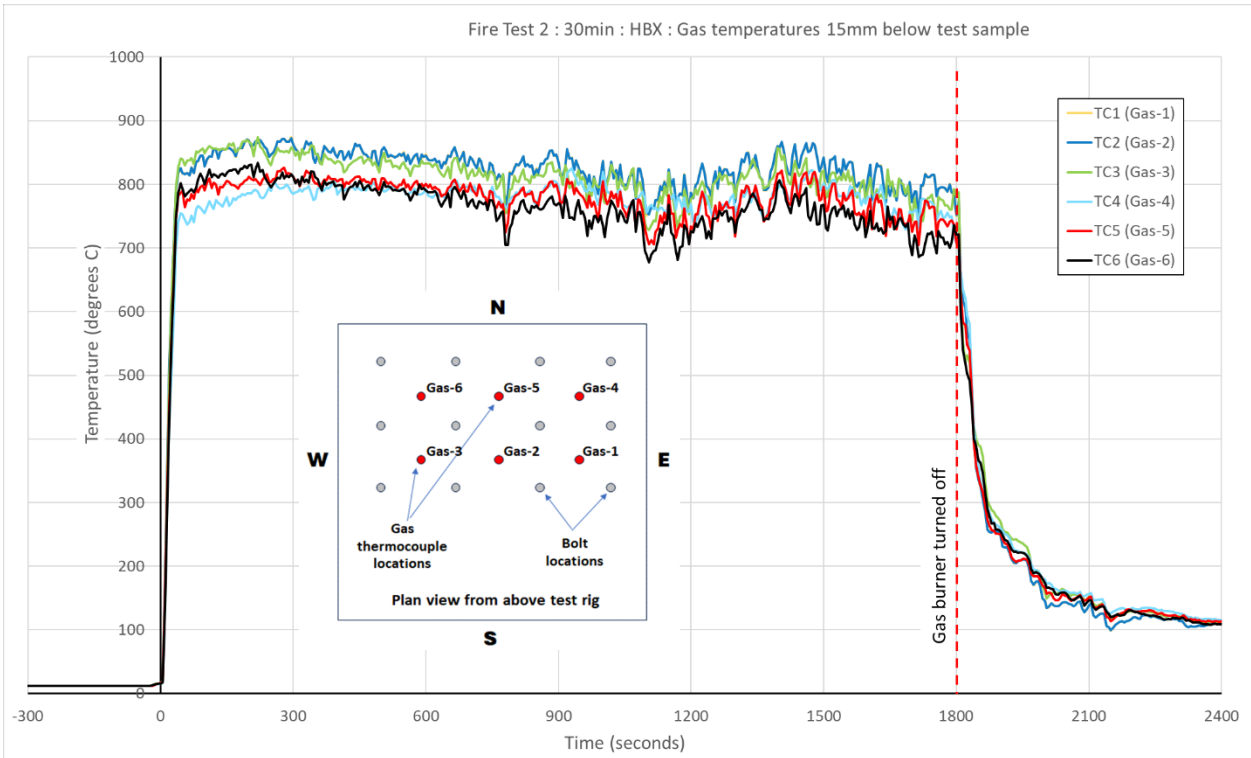


Figure 13 : FT2 Gas temperatures 15 mm below sample.

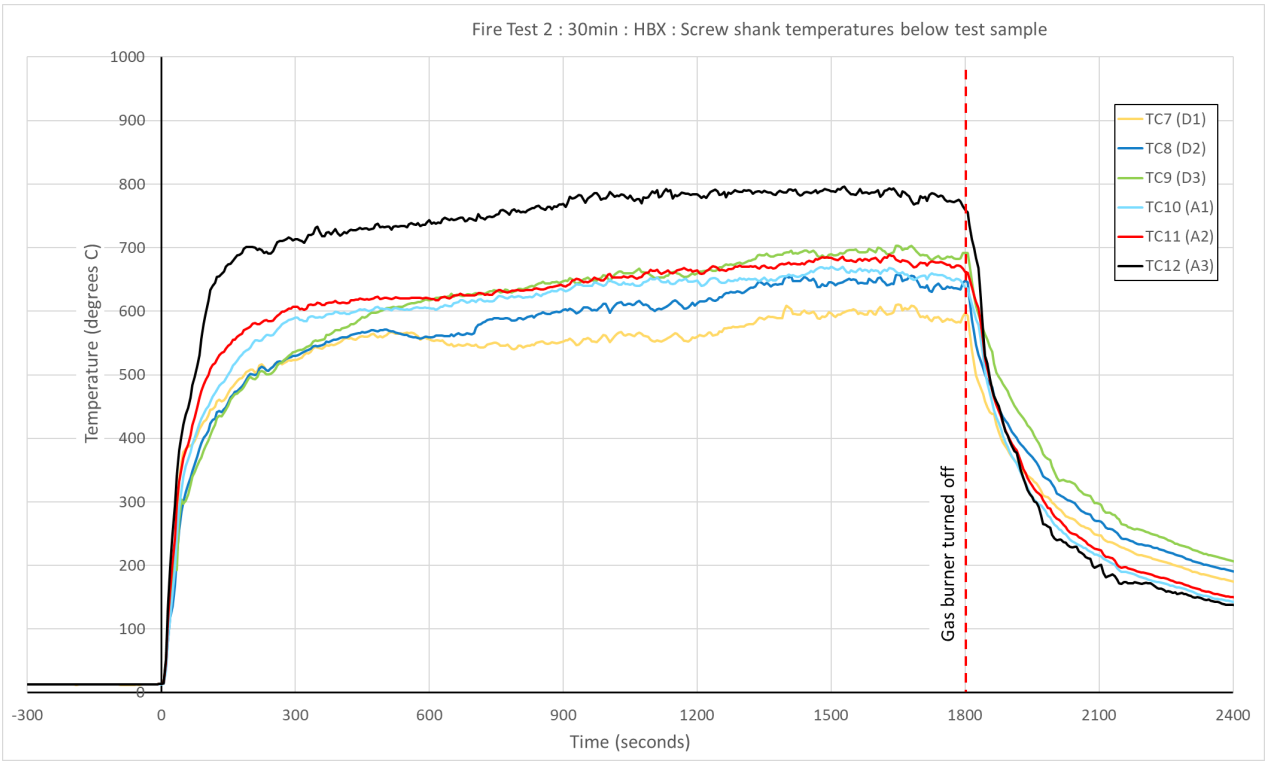


Figure 14 : FT2 Screw shank temperature profiles below sample.

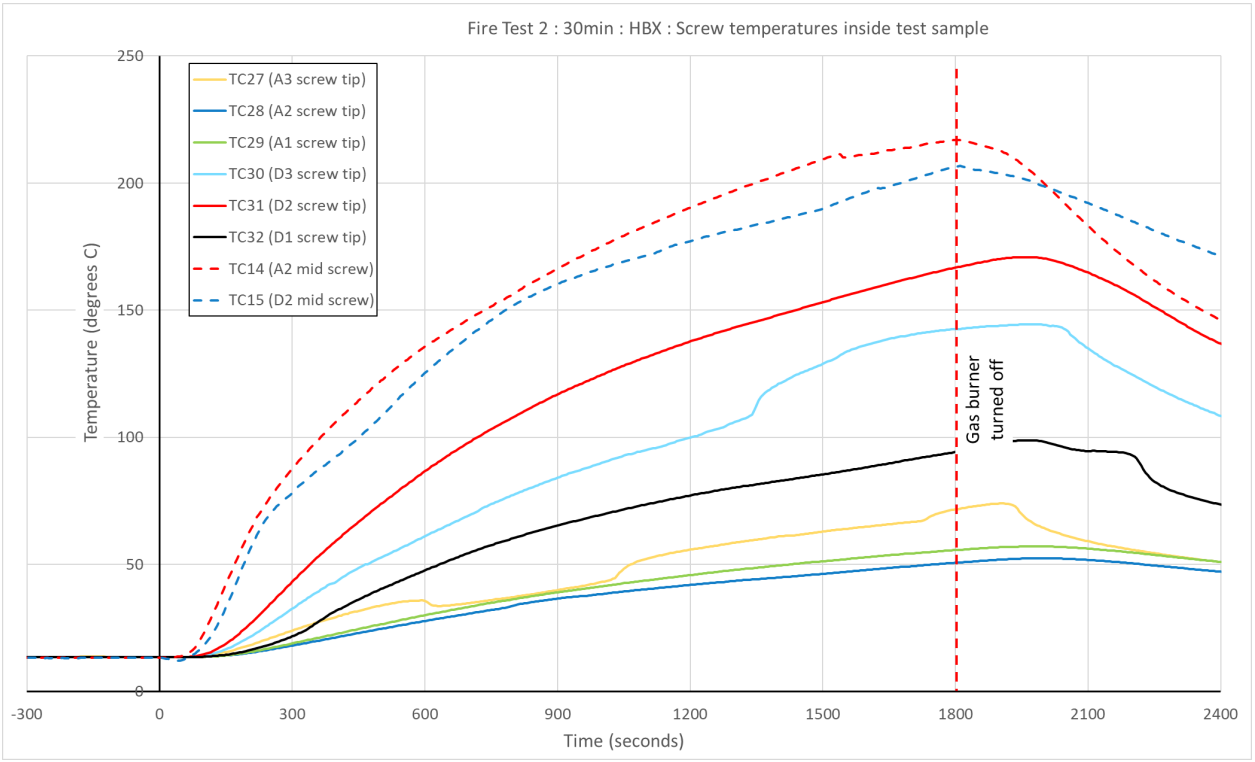


Figure 15 : FT2 Screw temperature profiles inside the sample (Mid-point and screw tips).

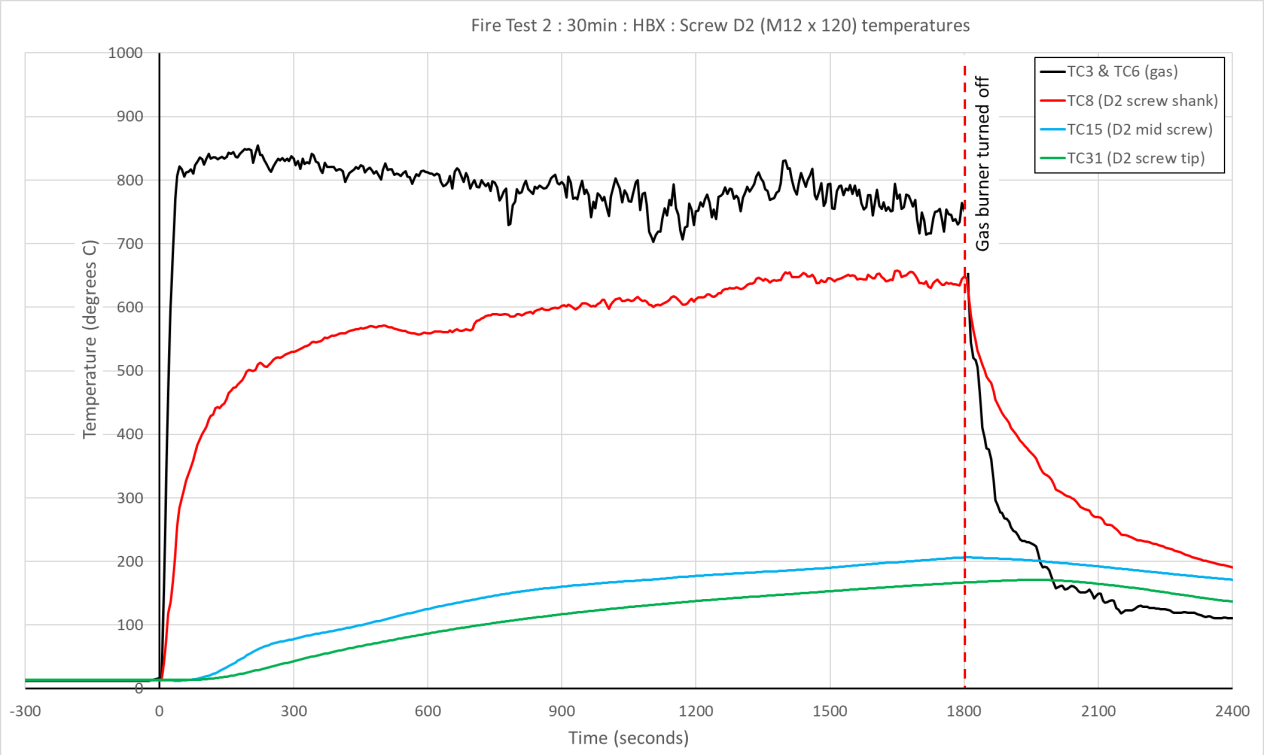


Figure 16 : FT2 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

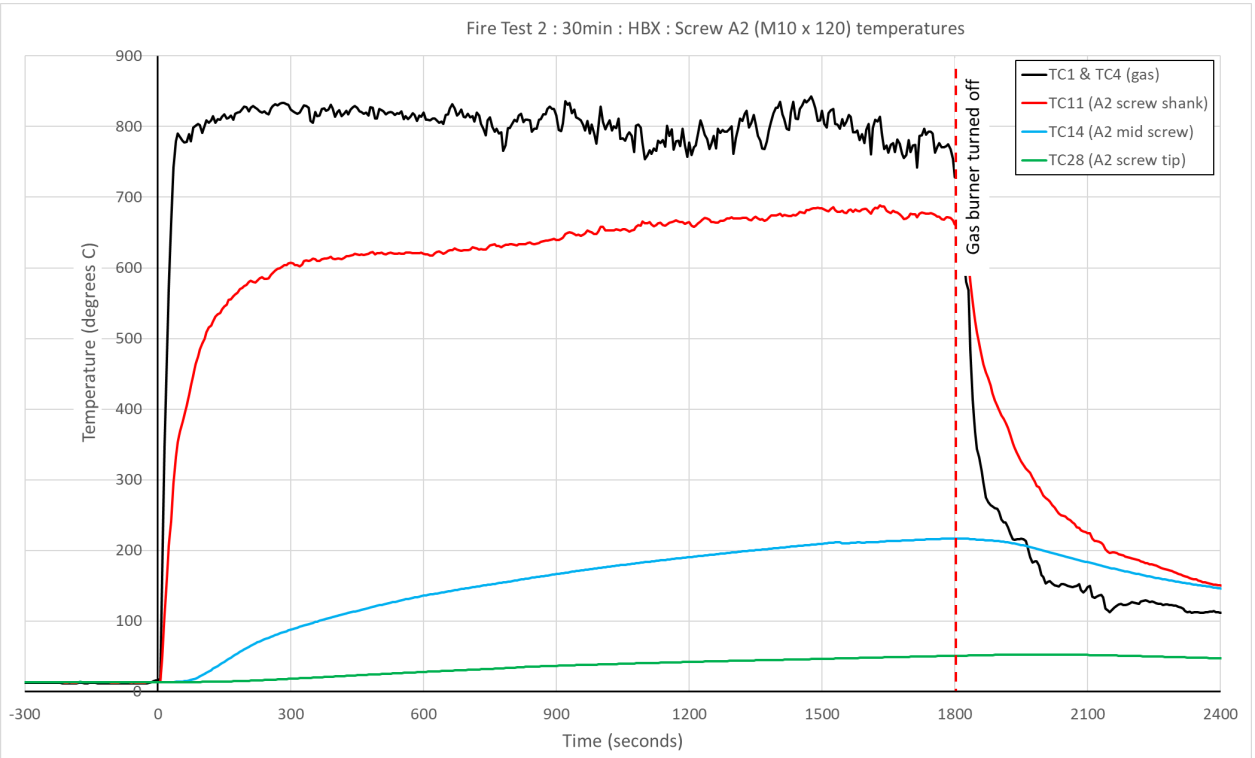


Figure 17 : FT2 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

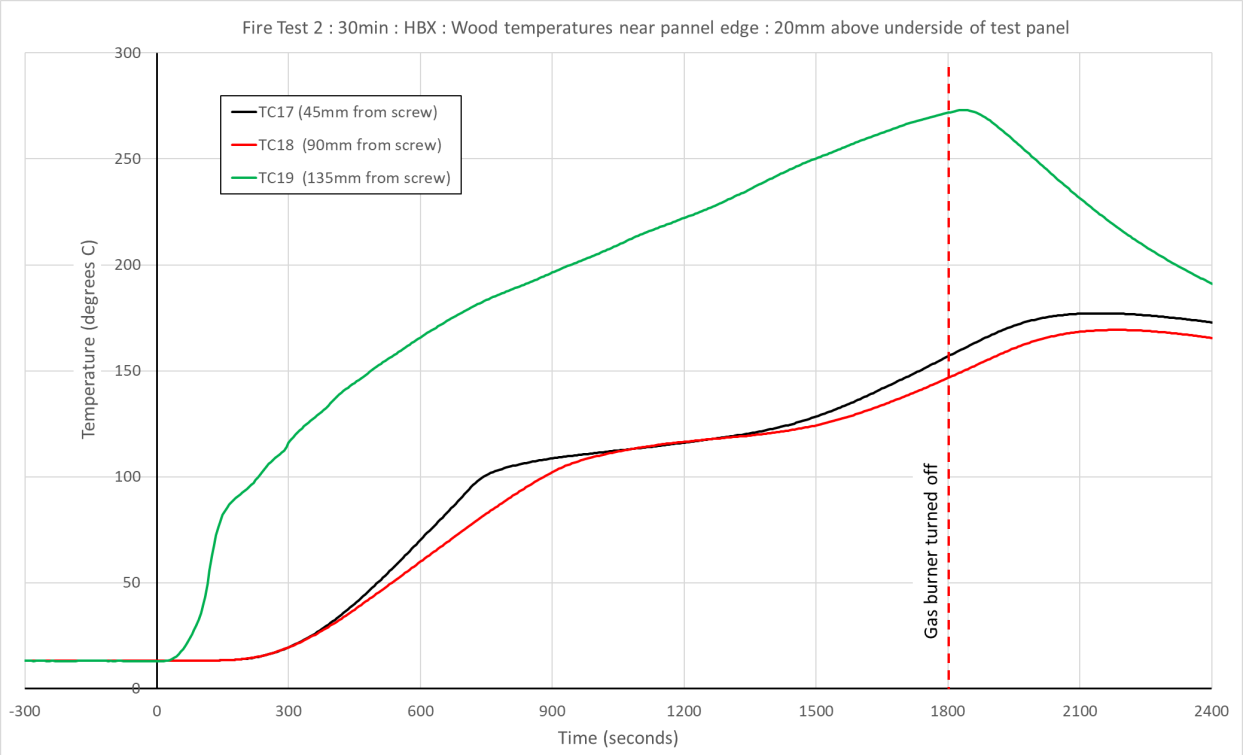


Figure 18 : FT2 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

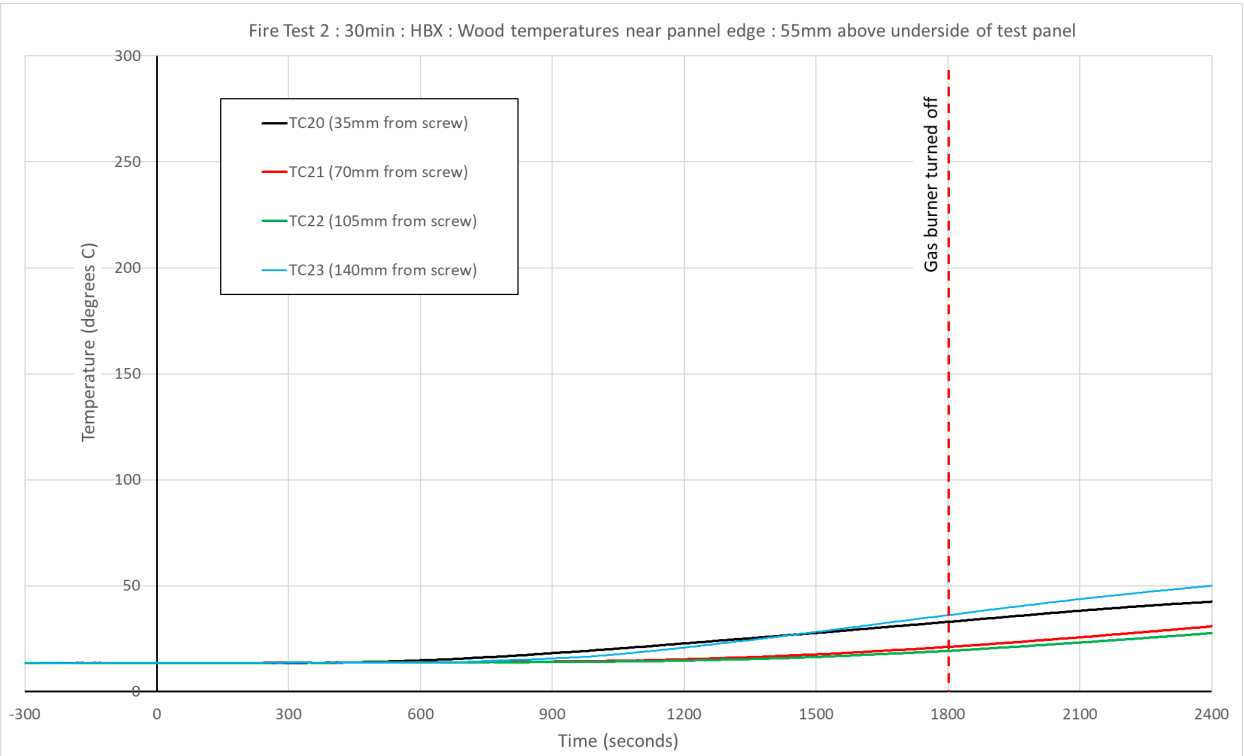


Figure 19 : FT2 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

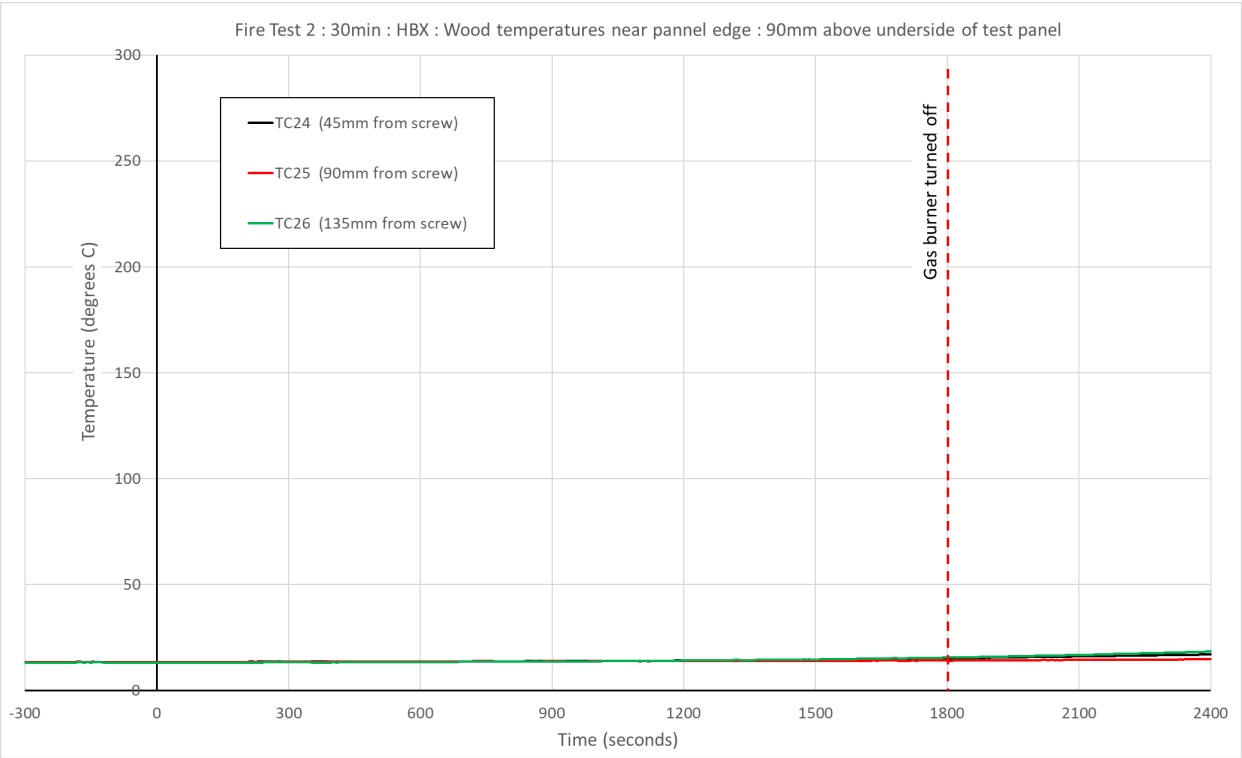


Figure 20 : FT2 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

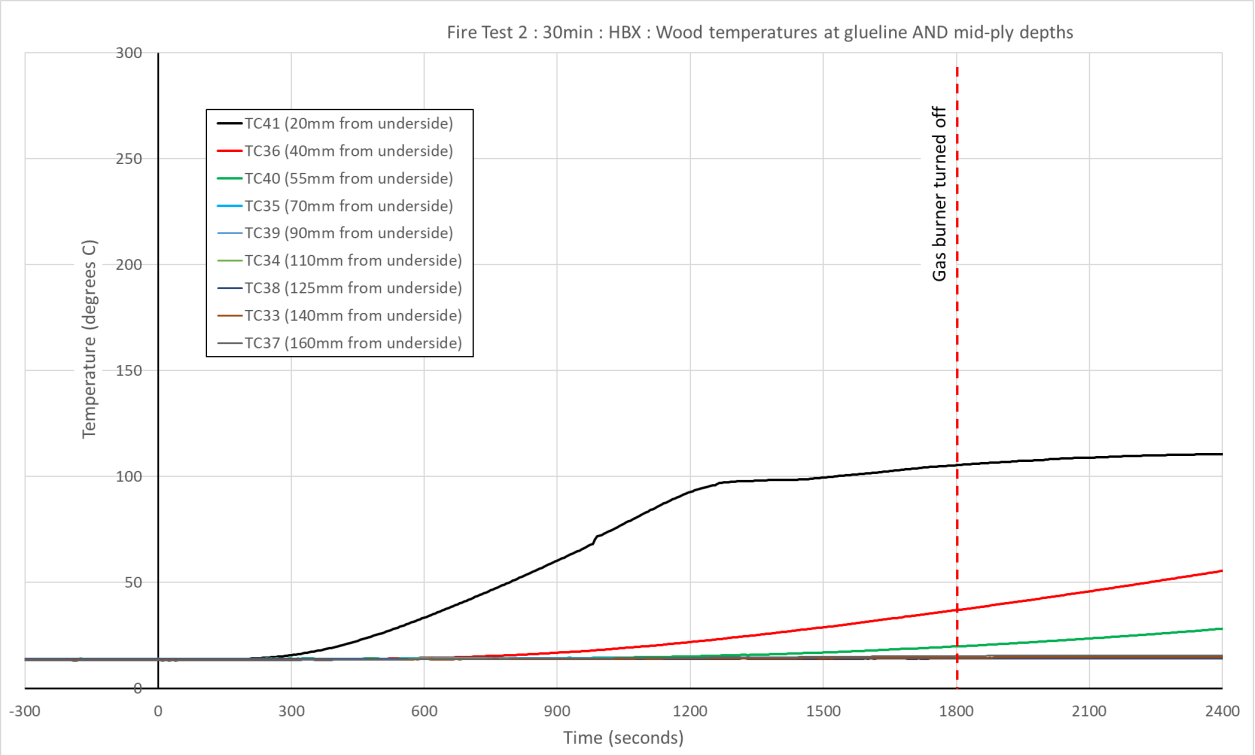


Figure 21 : FT2 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

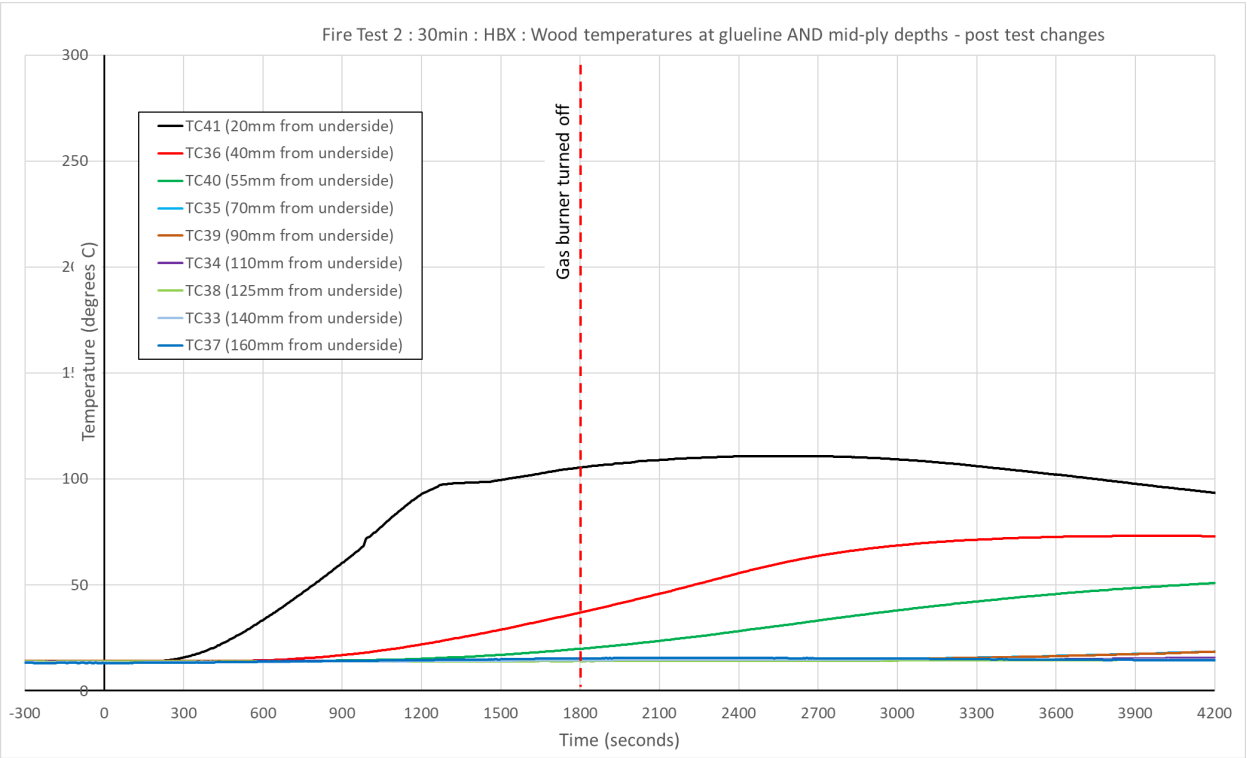


Figure 22 : FT2 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 3 – 30 minutes HB S panel (20.12.2023)

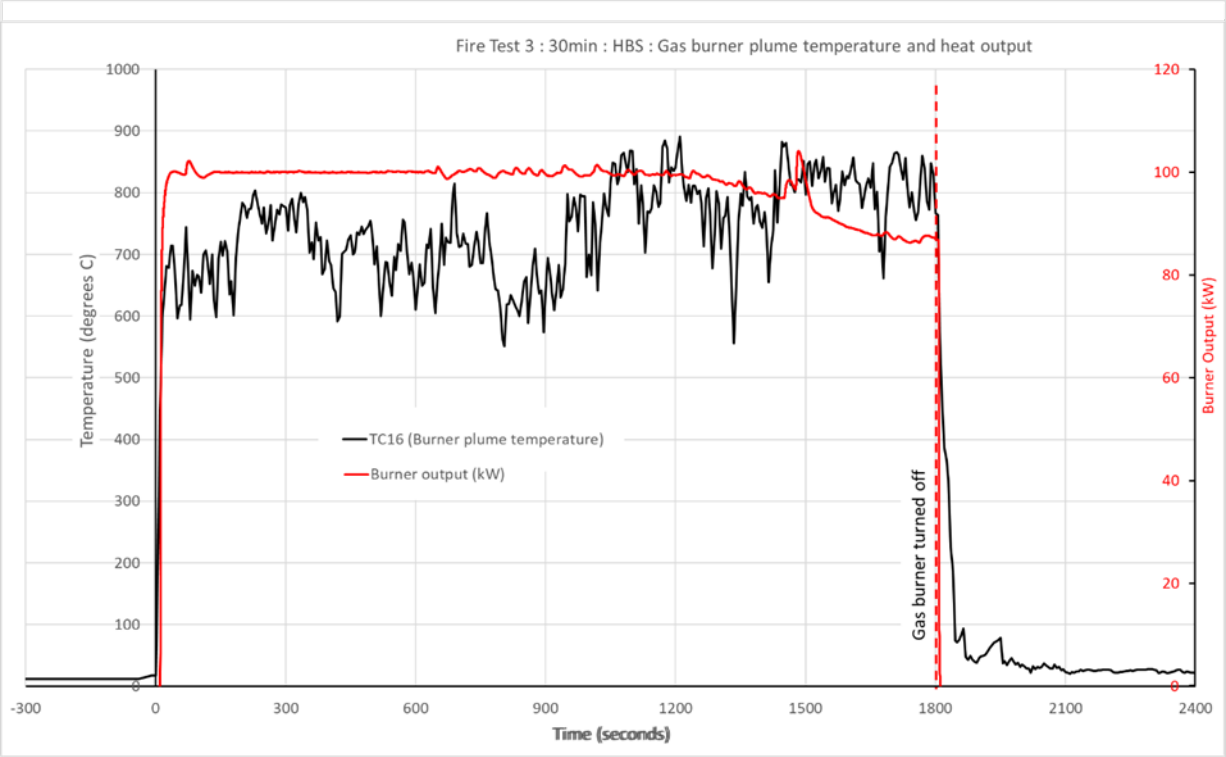


Figure 23 : FT1 Gas burner plume temperature and heat output.

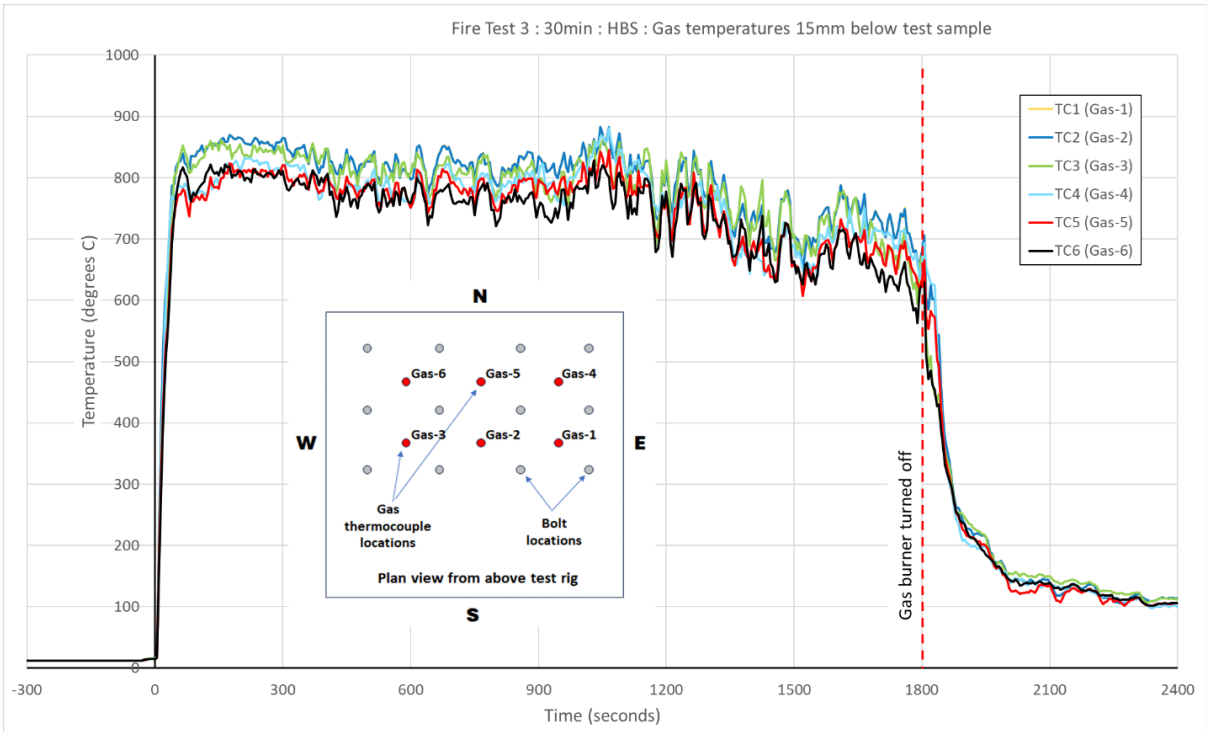


Figure 24 : FT3 Gas temperatures 15 mm below sample.

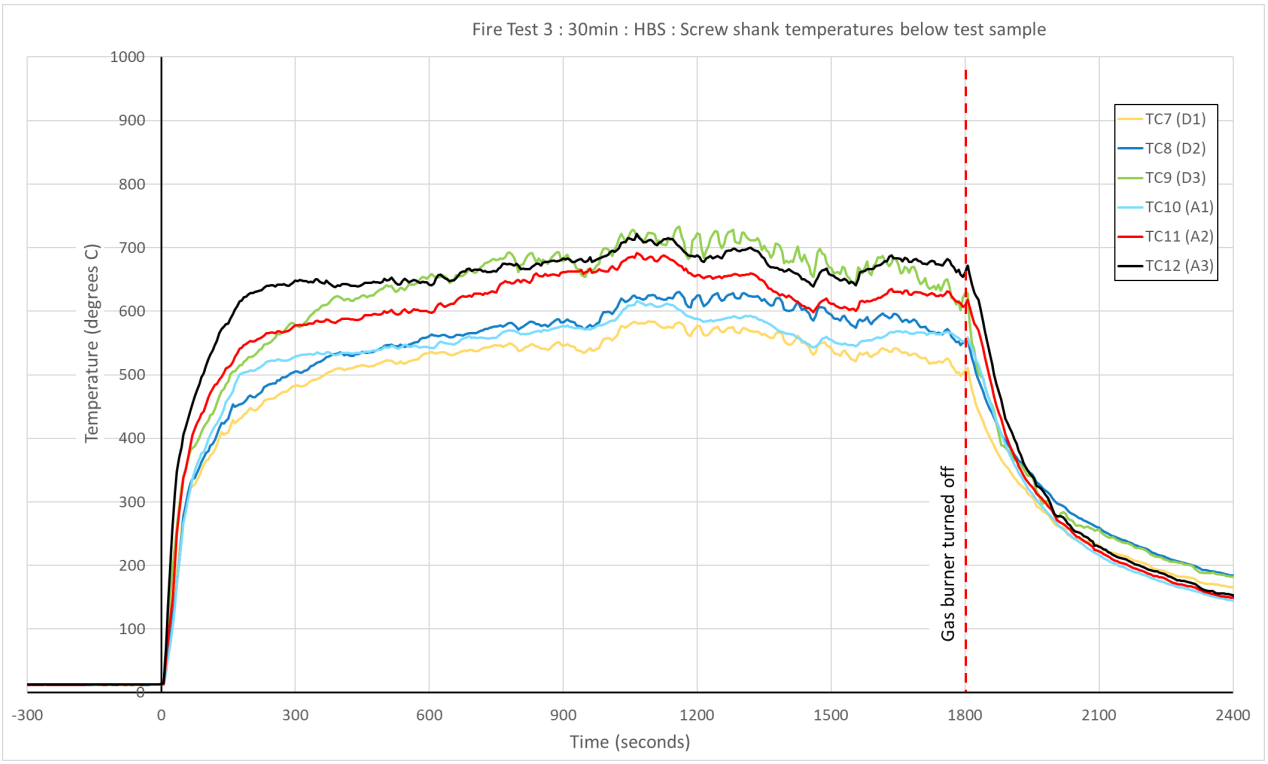


Figure 25 : FT3 Screw shank temperature profiles below sample.

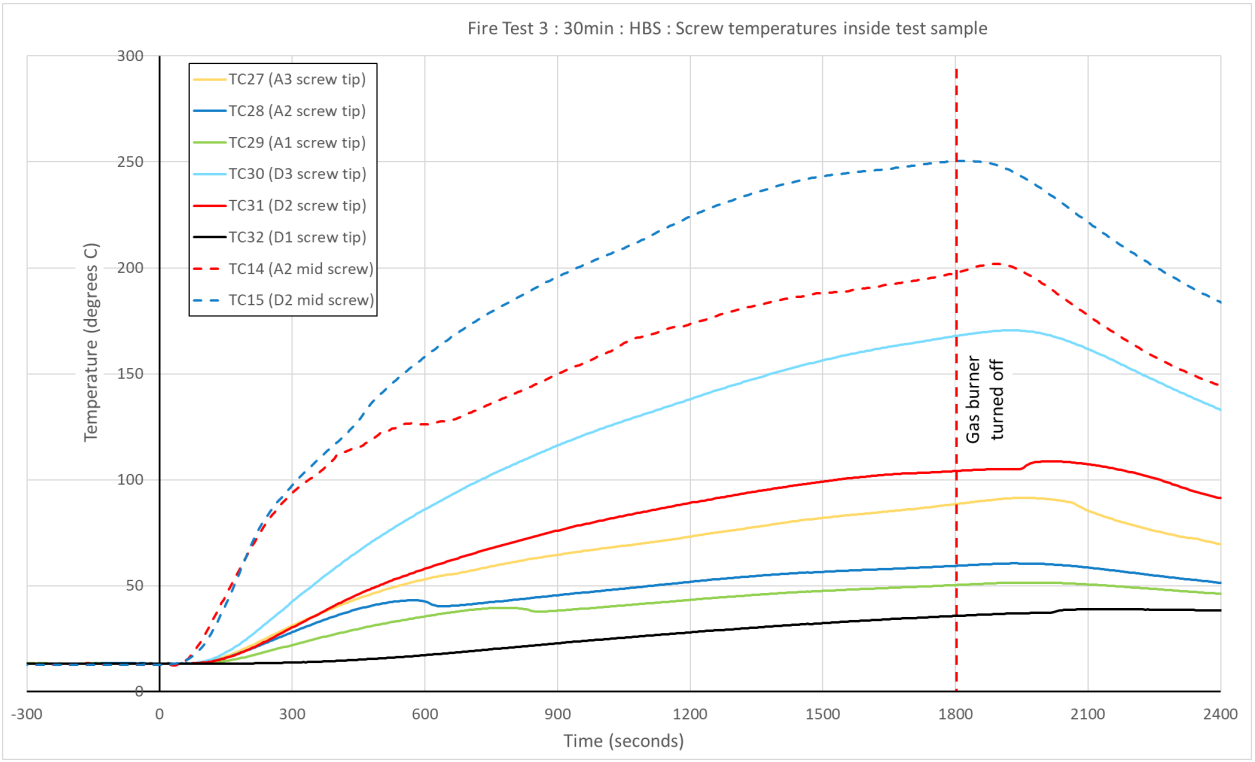


Figure 26 : FT3 Screw temperature profiles inside the sample (Mid-point and screw tips).

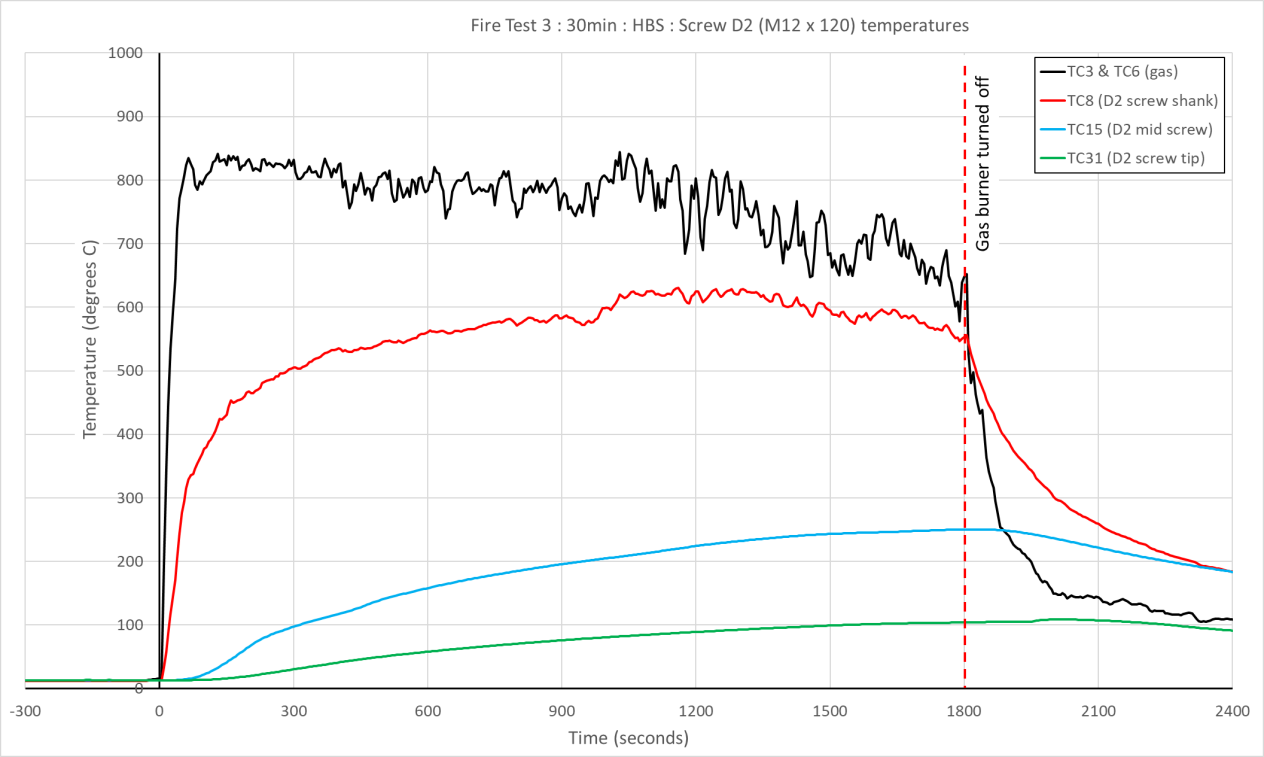


Figure 27 : FT3 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

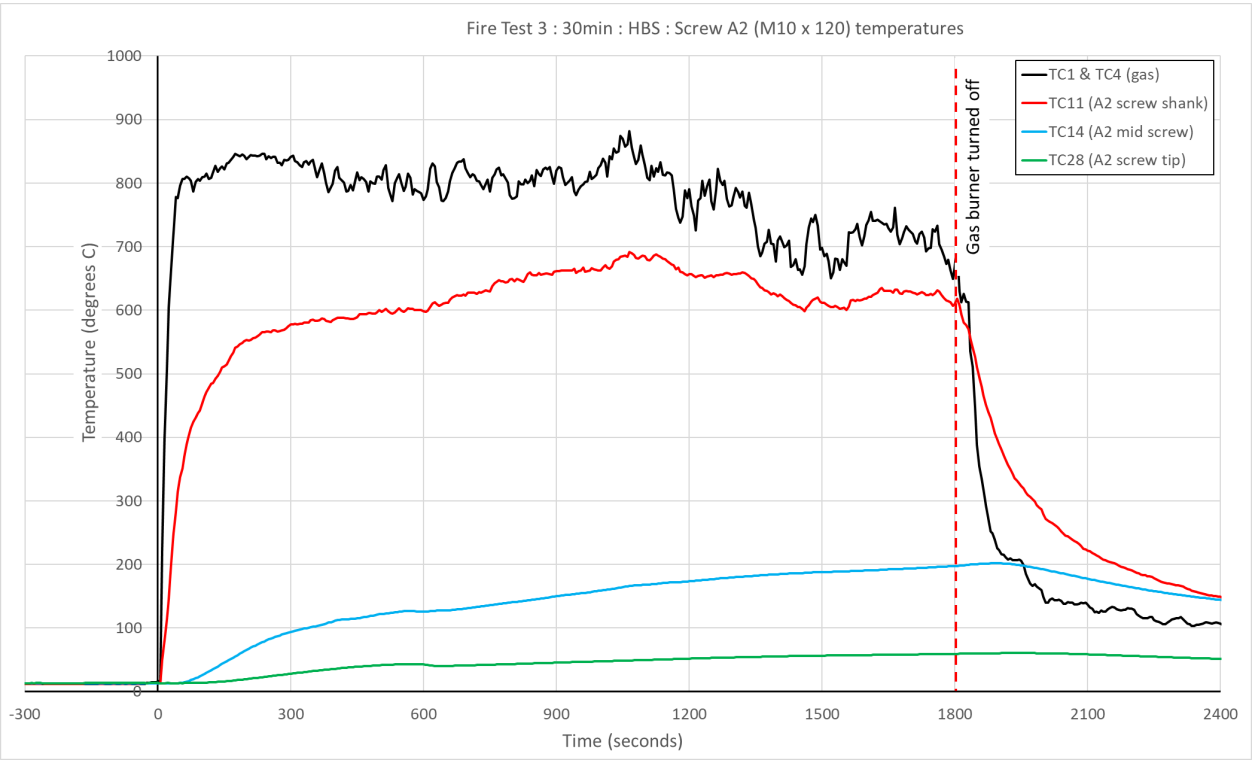


Figure 28 : FT3 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

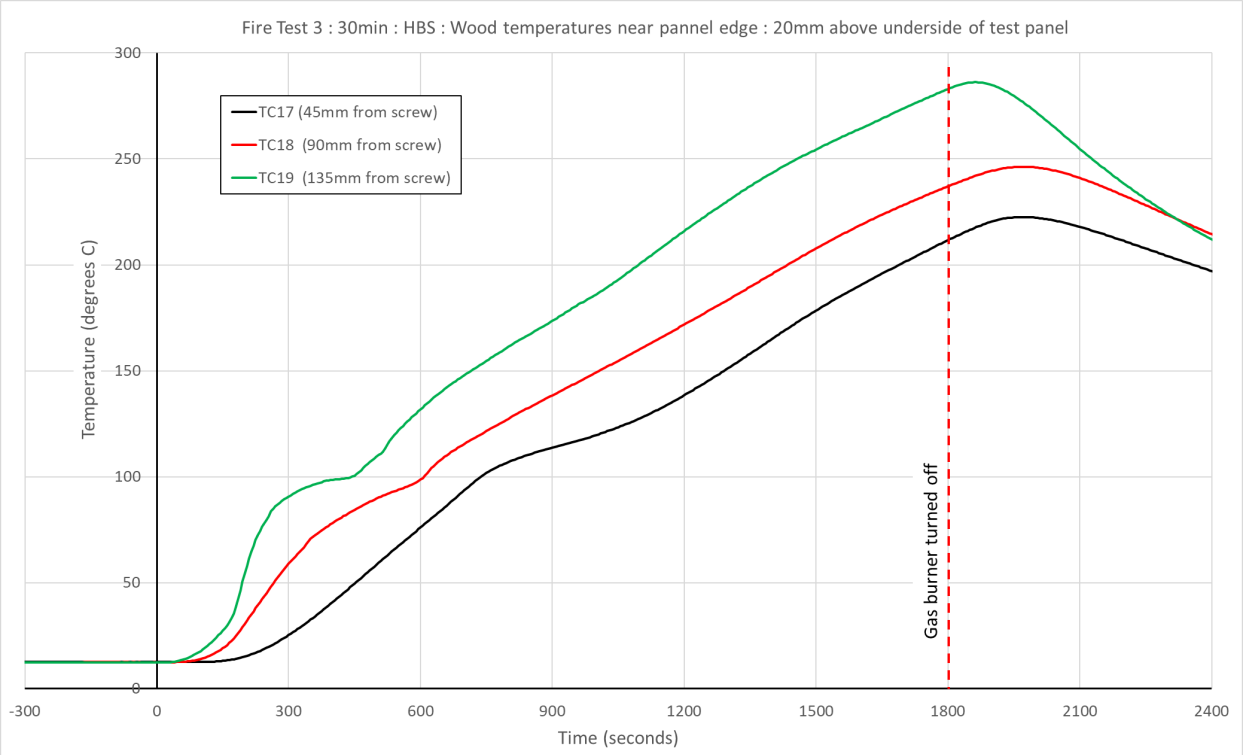


Figure 29 : FT3 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

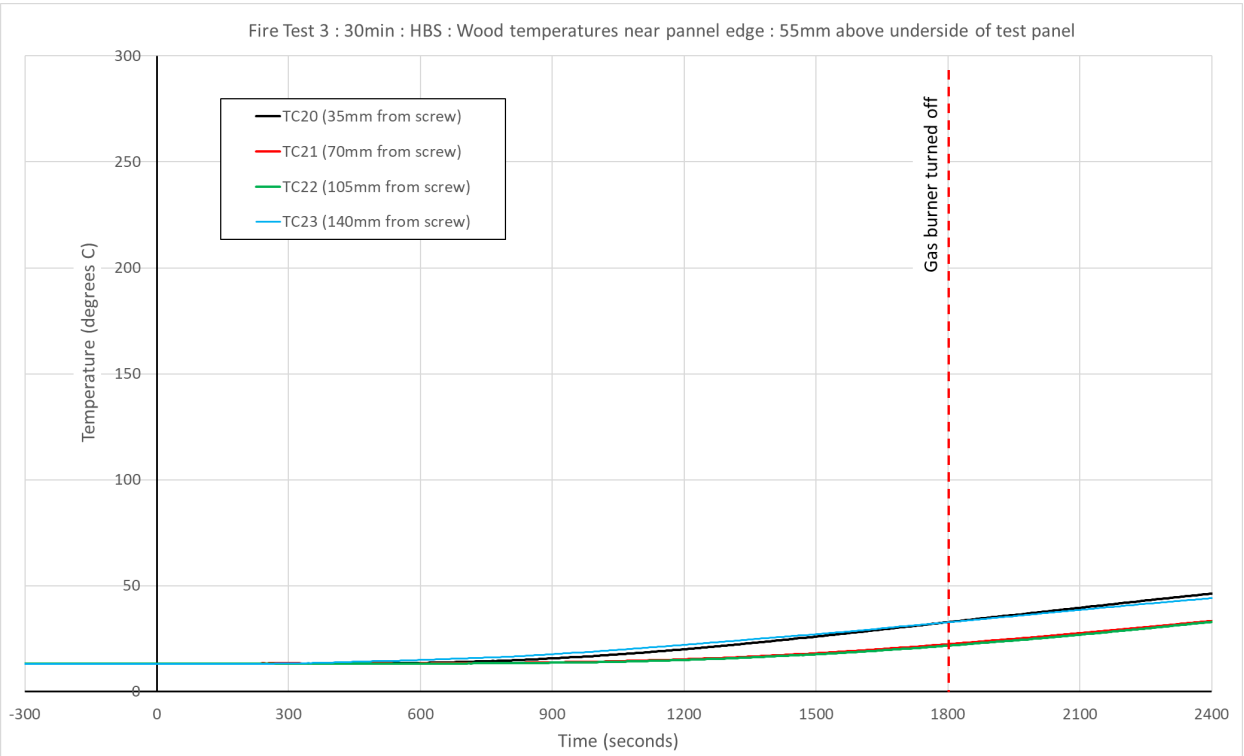


Figure 30 : FT3 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

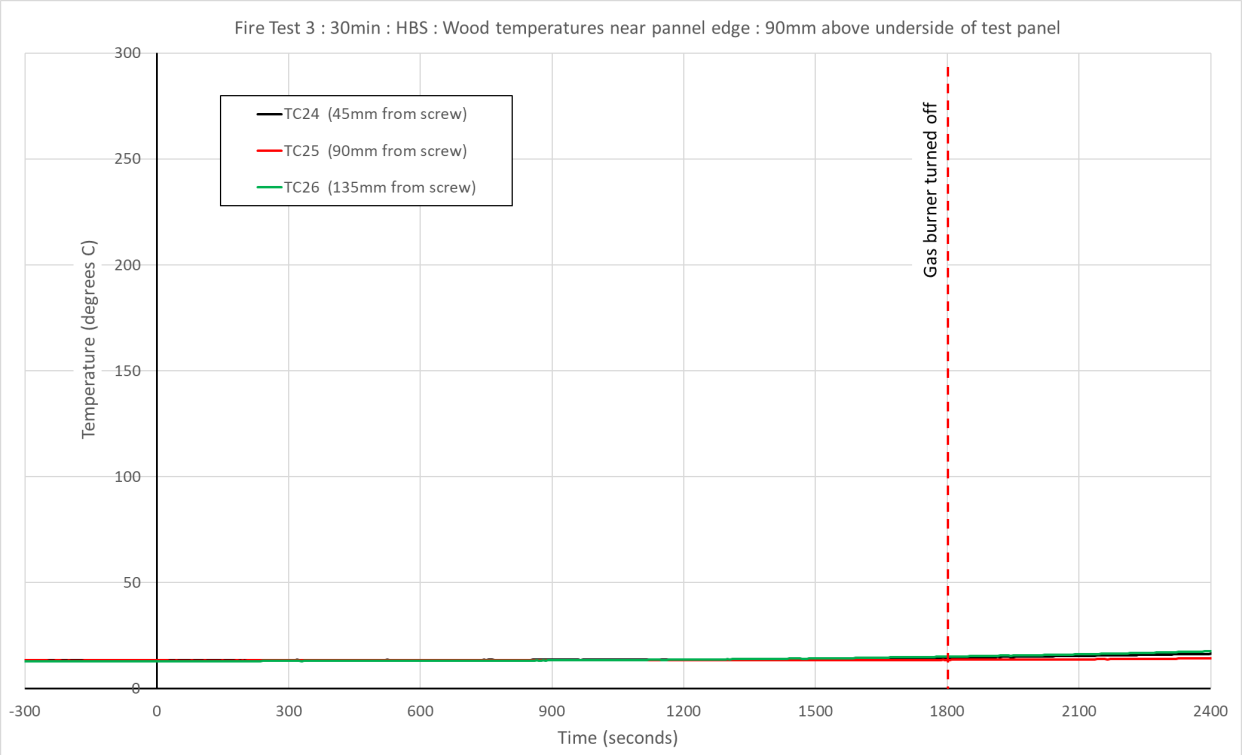


Figure 31 : FT3 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

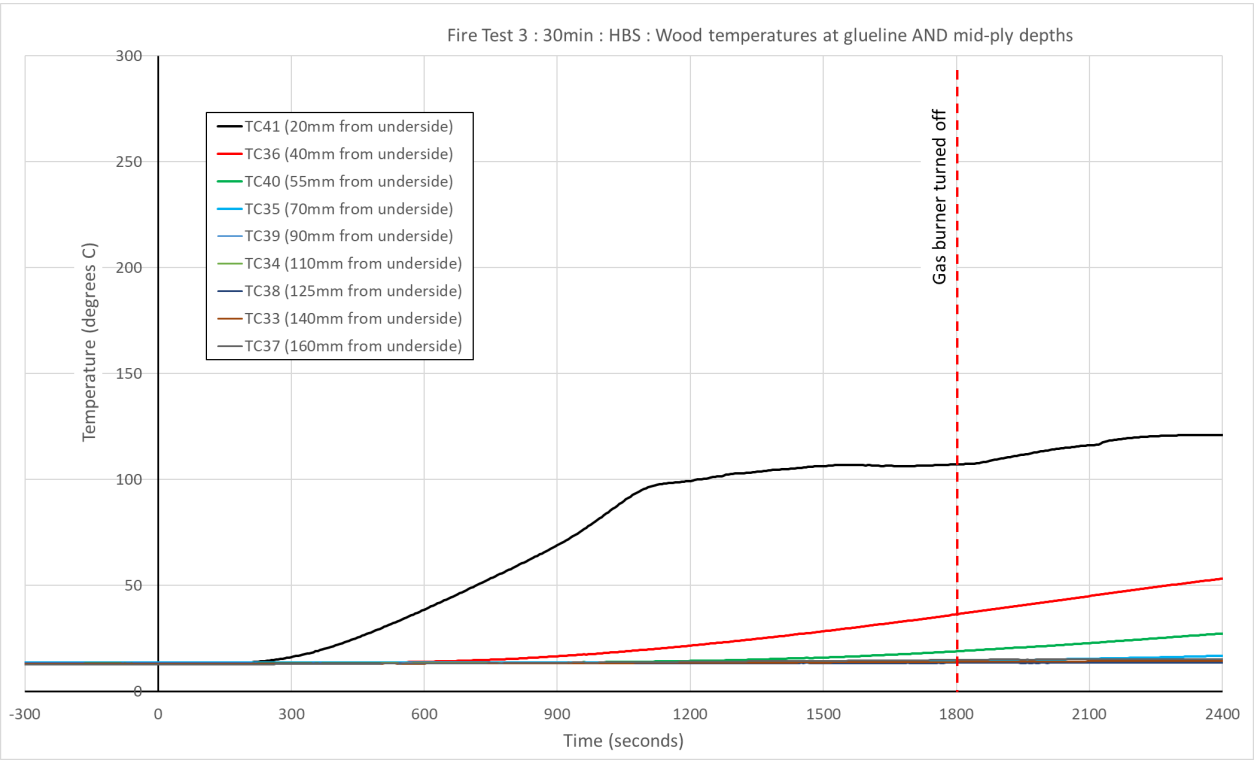


Figure 32 : FT3 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

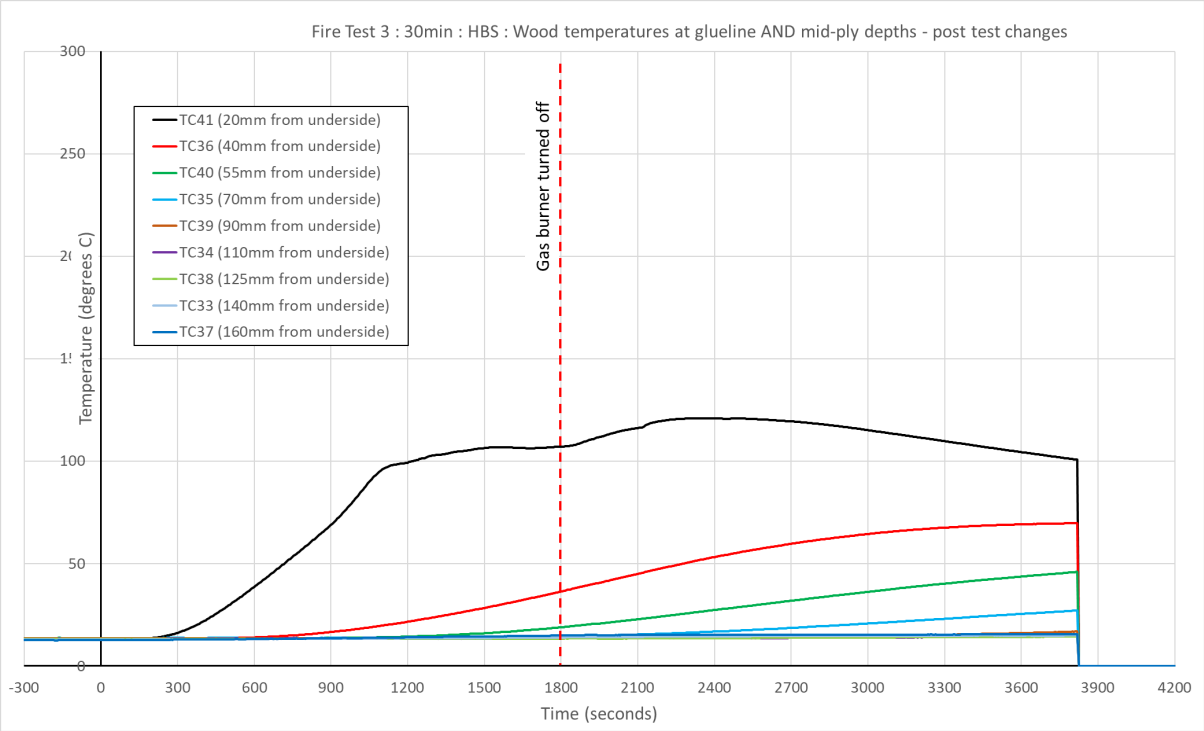


Figure 33 : FT3 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 4 – 60 minutes HB X panel (03.01.2024)

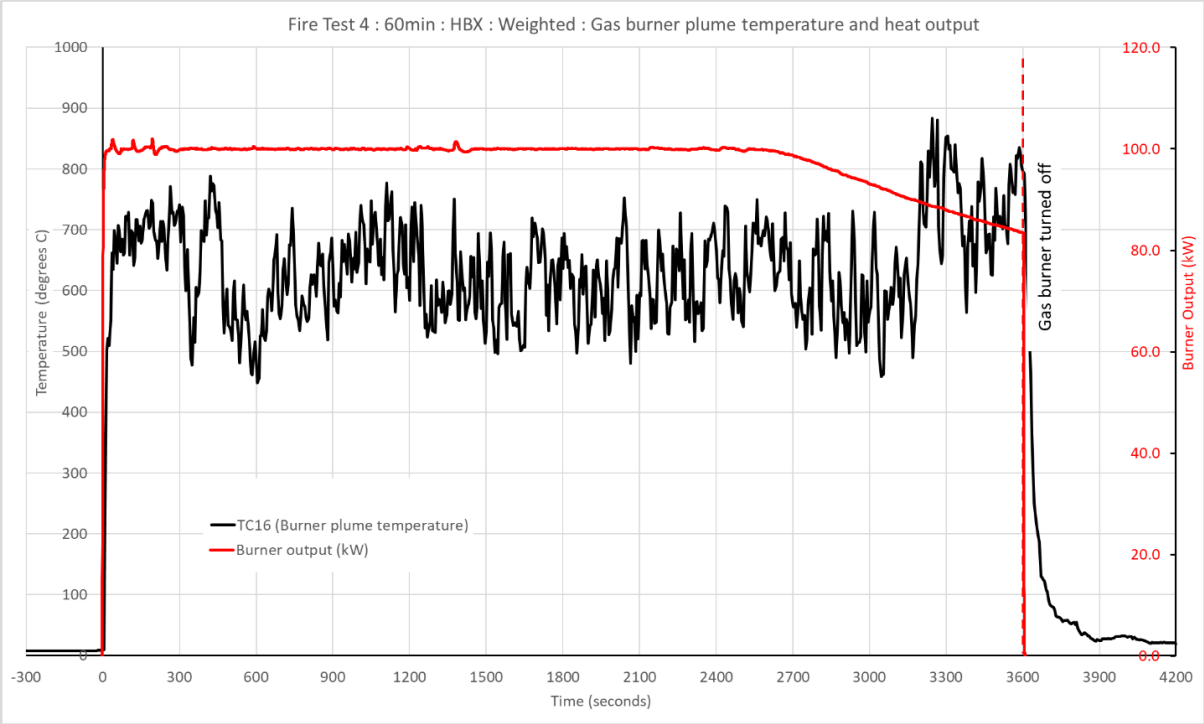


Figure 34 : FT4 Gas burner plume temperature and heat output.

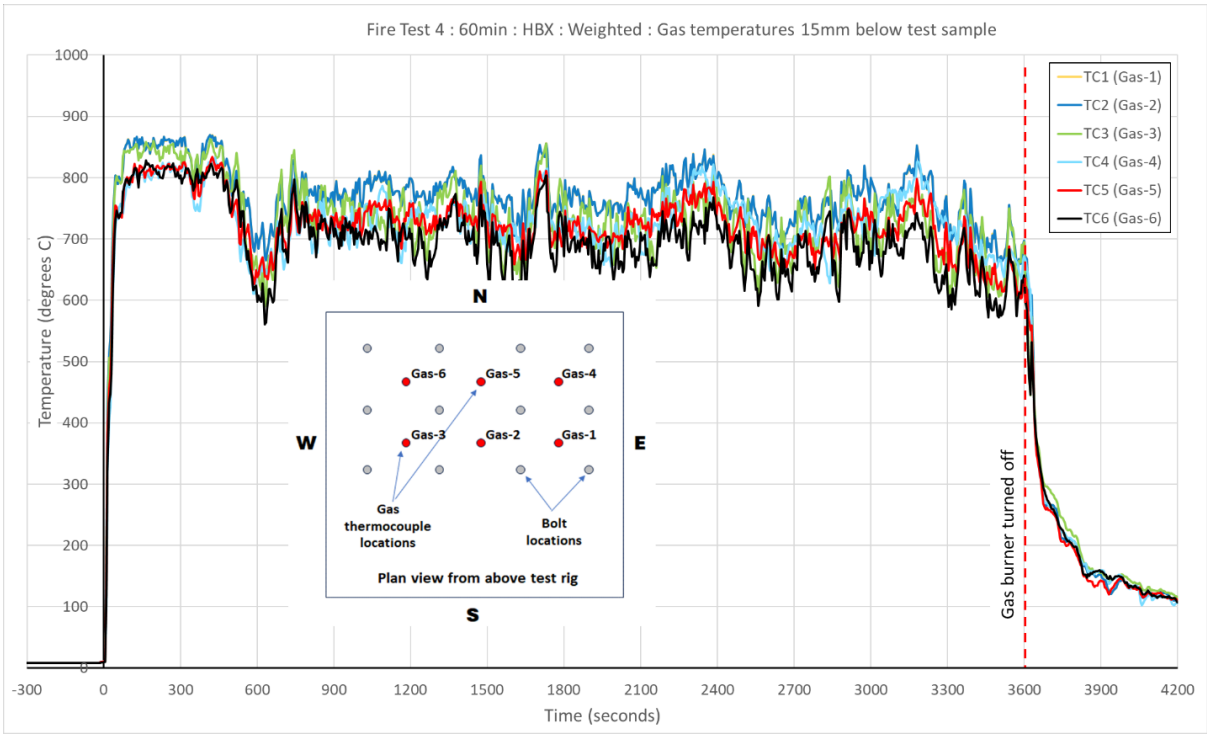


Figure 35 : FT4 Gas temperatures 15 mm below sample.

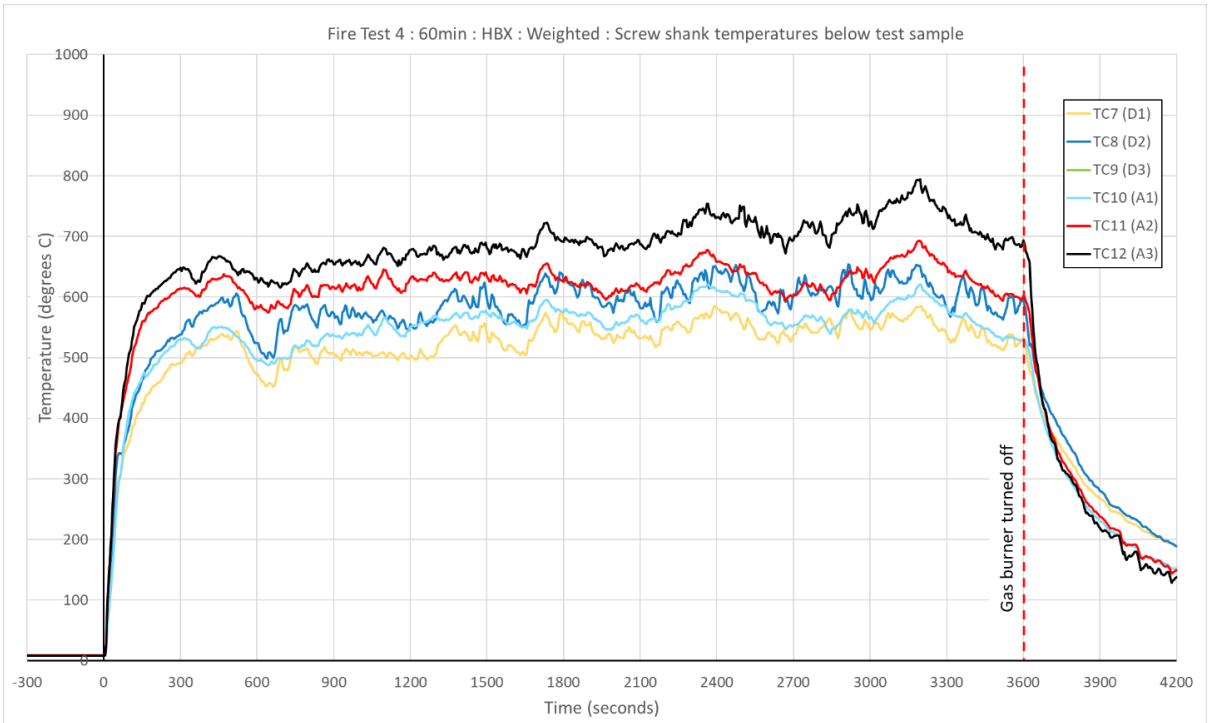


Figure 36 : FT4 Screw shank temperature profiles below sample.

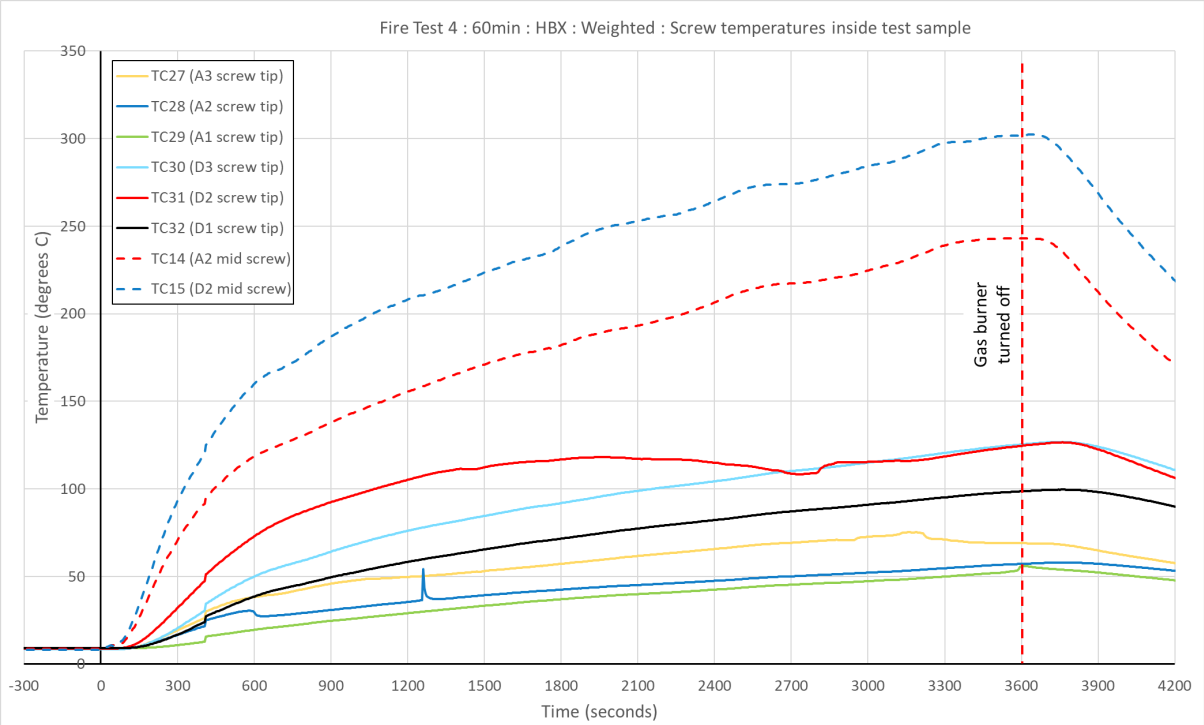


Figure 37 : FT4 Screw temperature profiles inside the sample (Mid-point and screw tips).

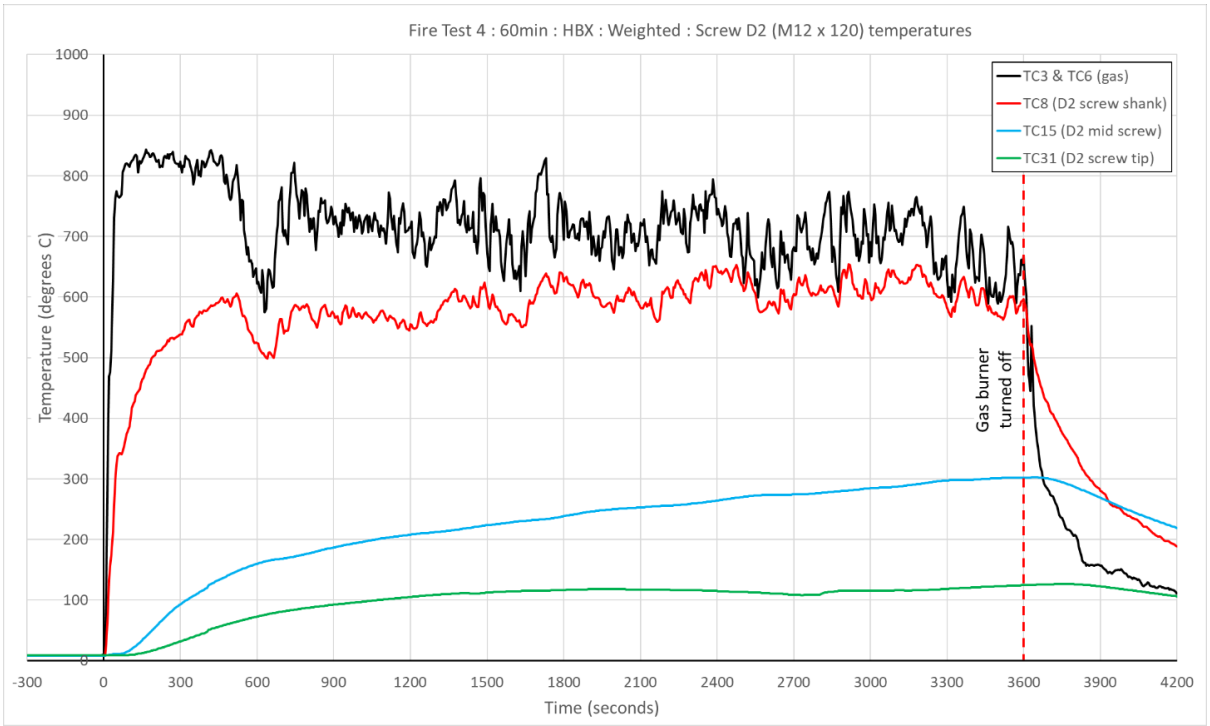


Figure 38 : FT4 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

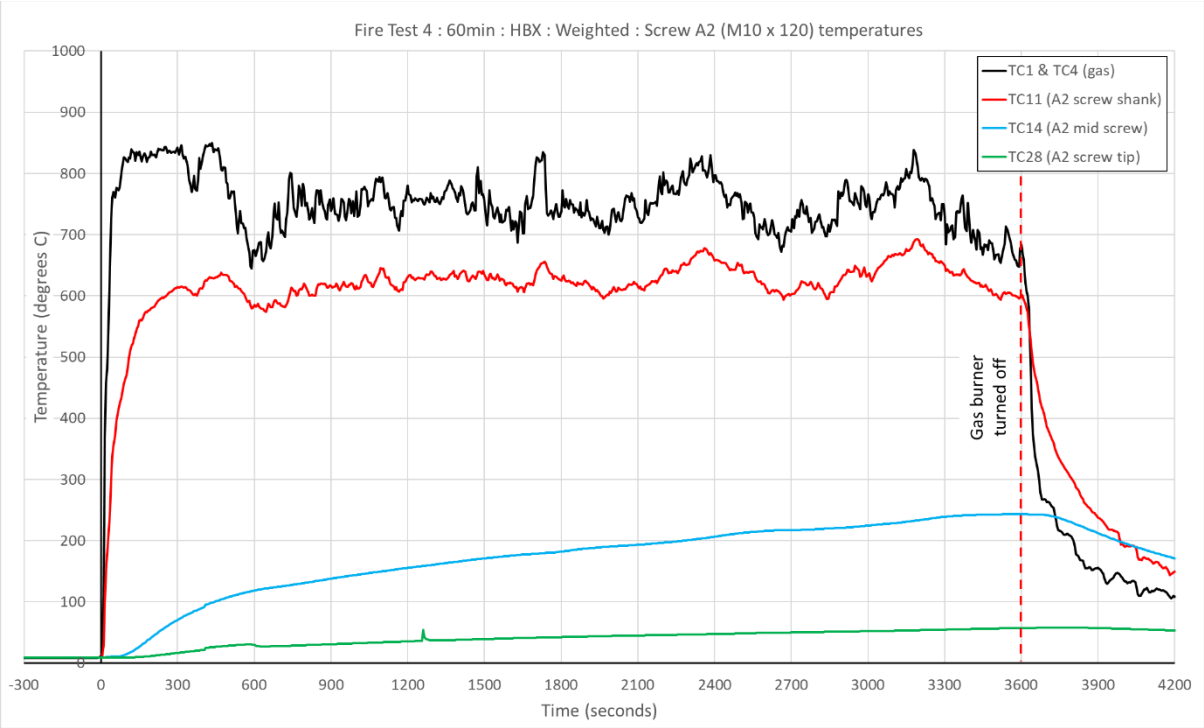


Figure 39 : FT4 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

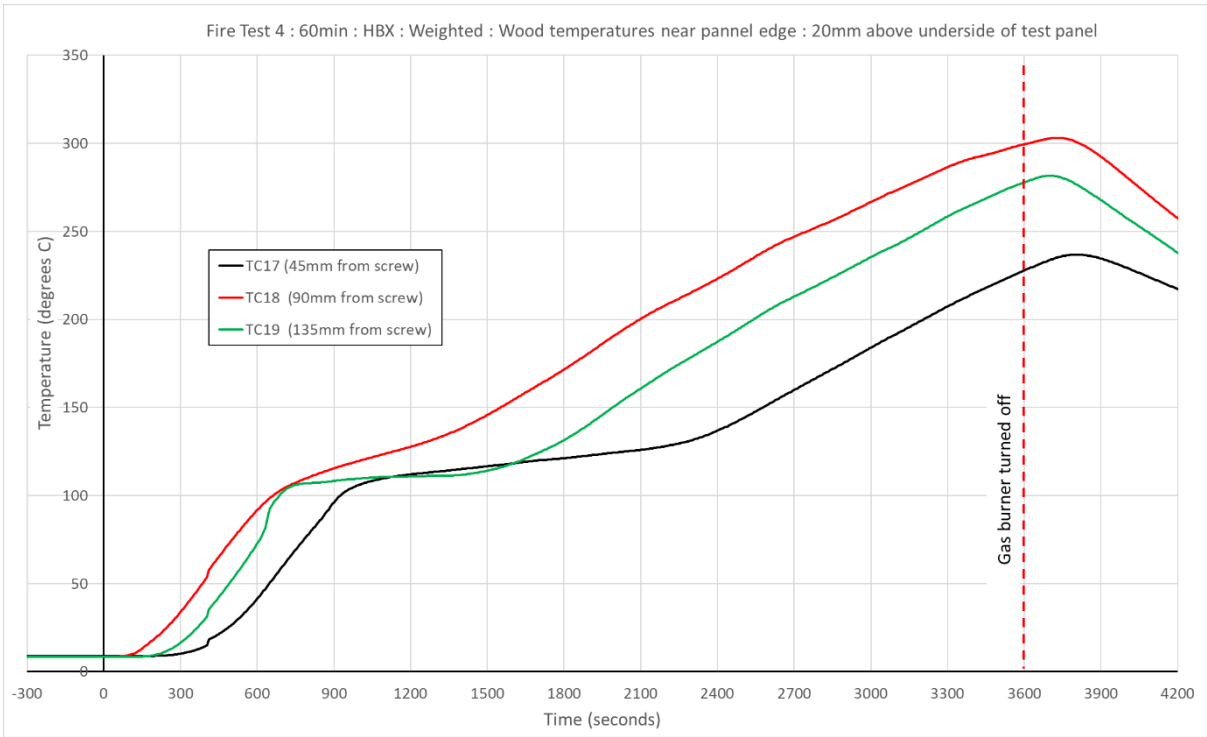


Figure 40 : FT4 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

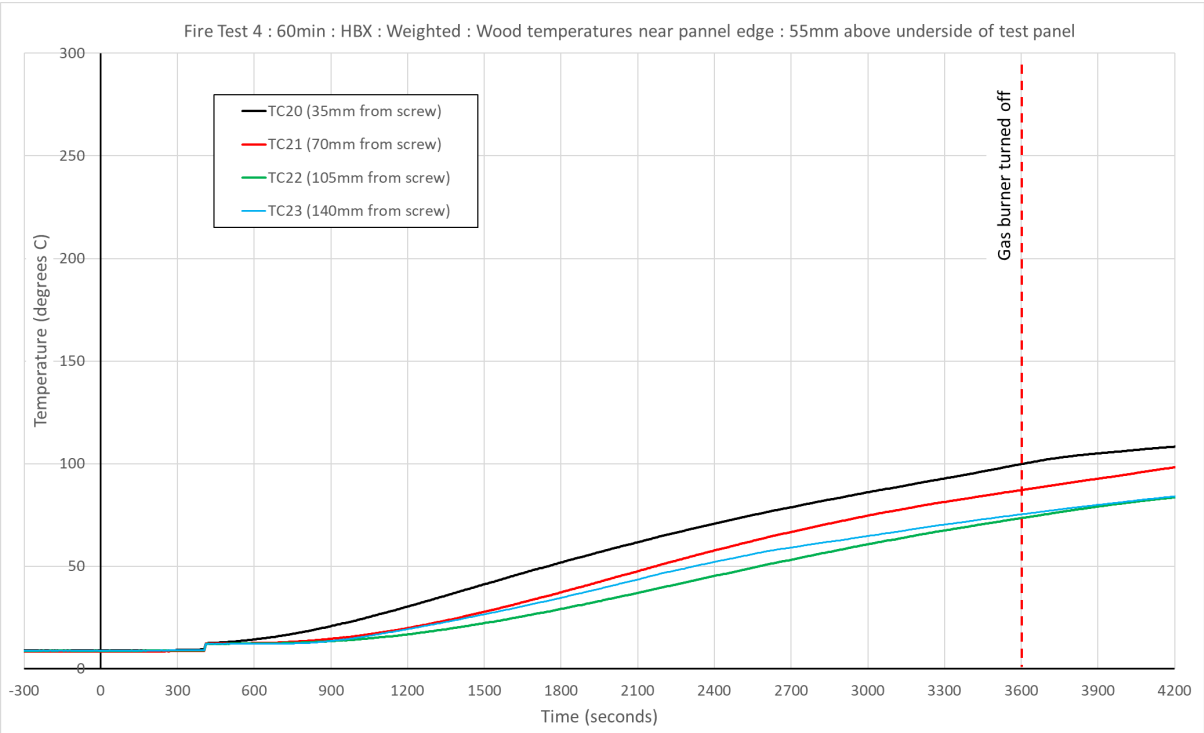


Figure 41 : FT4 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

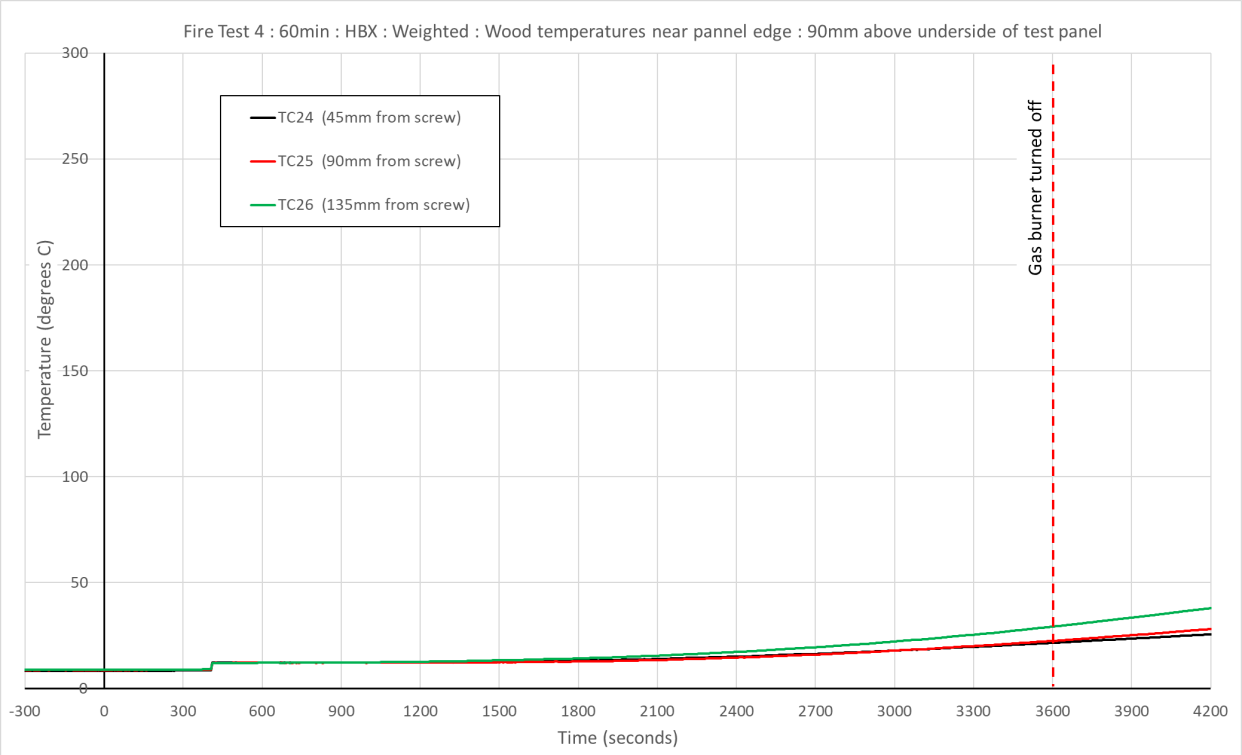


Figure 42 : FT4 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

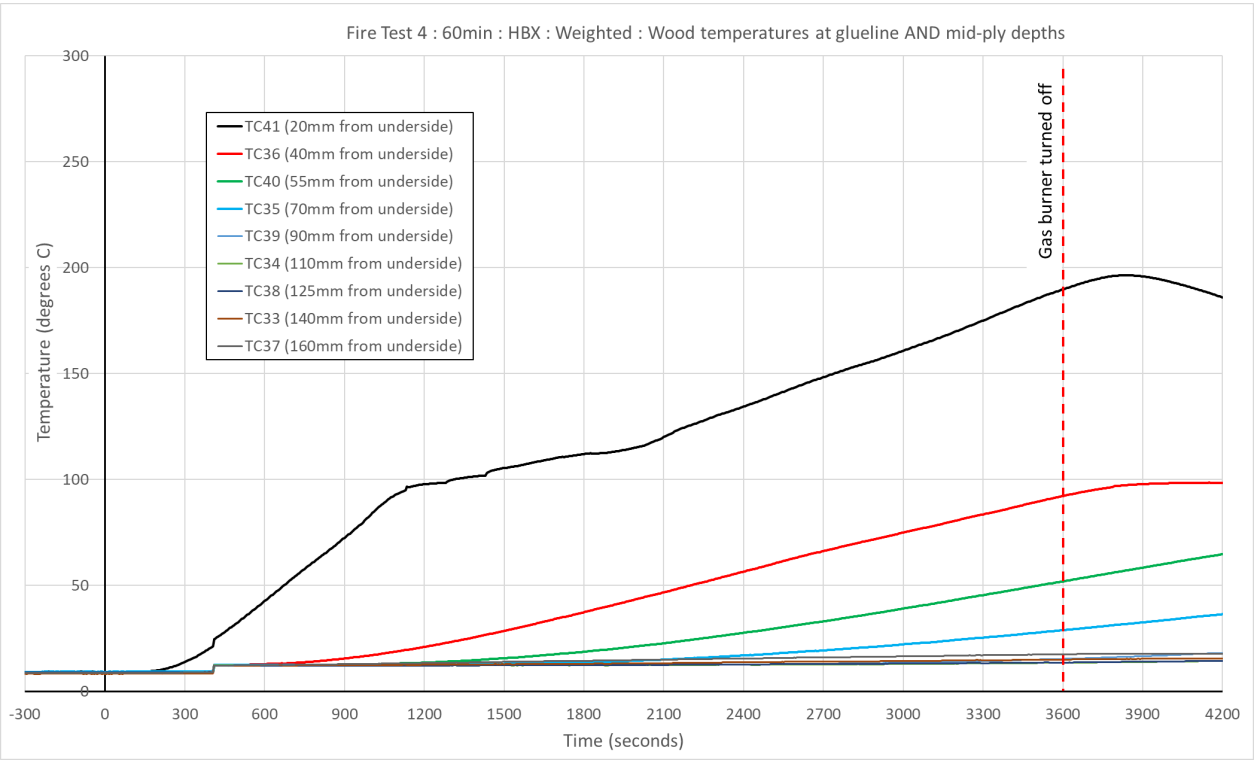


Figure 43 : FT4 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

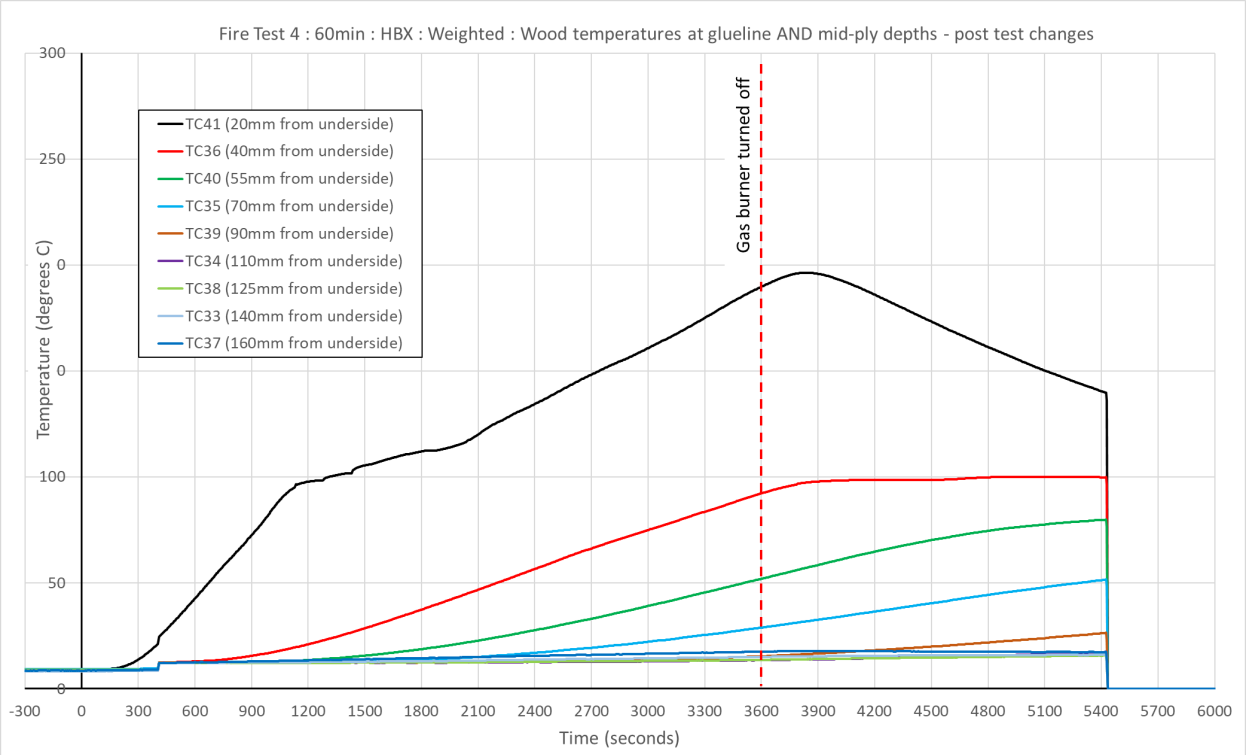


Figure 44 : FT4 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 5 – 60 minutes HB S panel (05.01.2024)

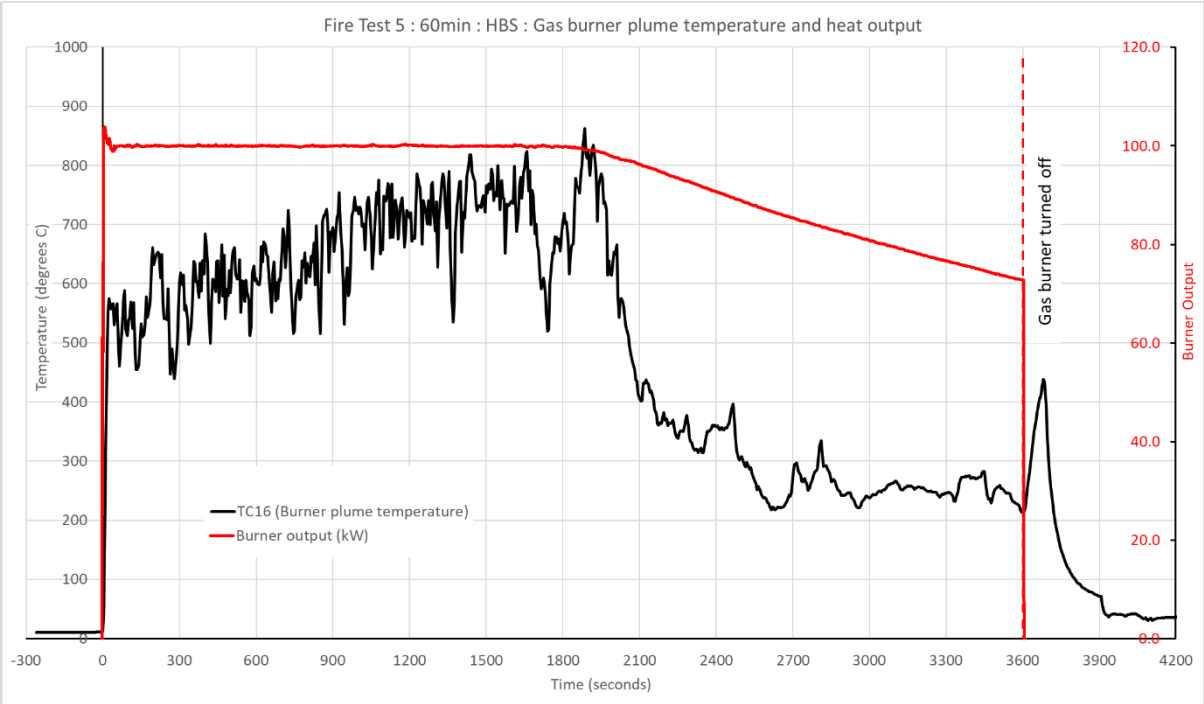


Figure 45 : FT5 Gas burner plume temperature and heat output.

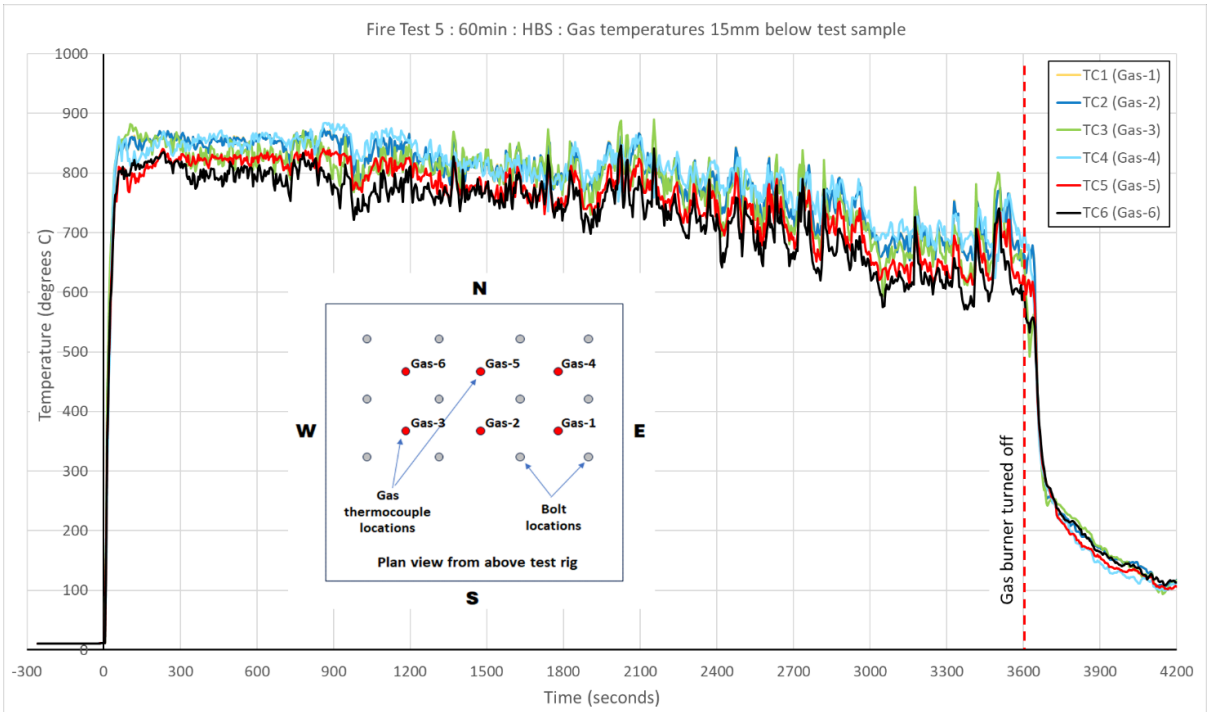


Figure 46 : FT5 Gas temperatures 15 mm below sample.

The gradual drop-off in burner output probably accounts (at least partially) for the slow drop in gas temperatures below the sample. The apparently large drop in burner plume temperature is unsubstantiated, as the effect on flame size/temperature should not have been significant. Video footage shows some material from the back wall partially blocked/deflected the flame as it reduced in intensity.

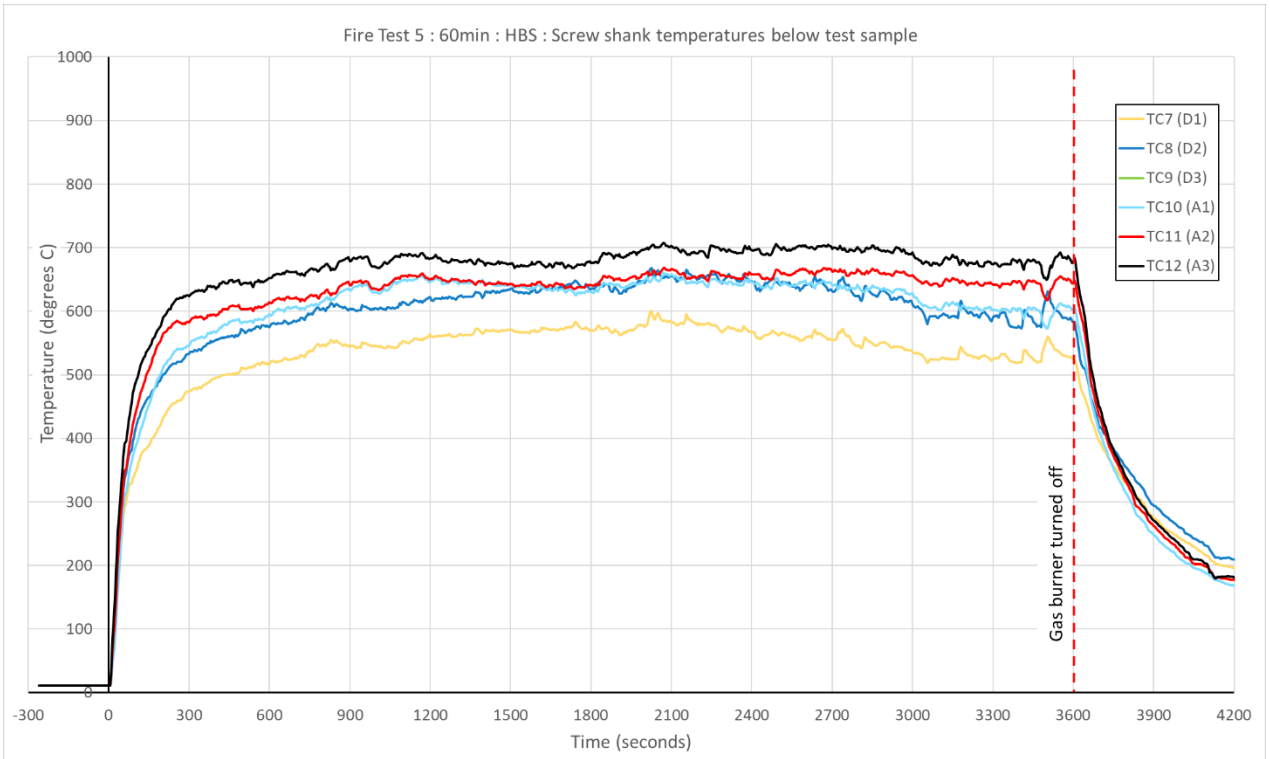


Figure 47 : FT5 Screw shank temperature profiles below sample.

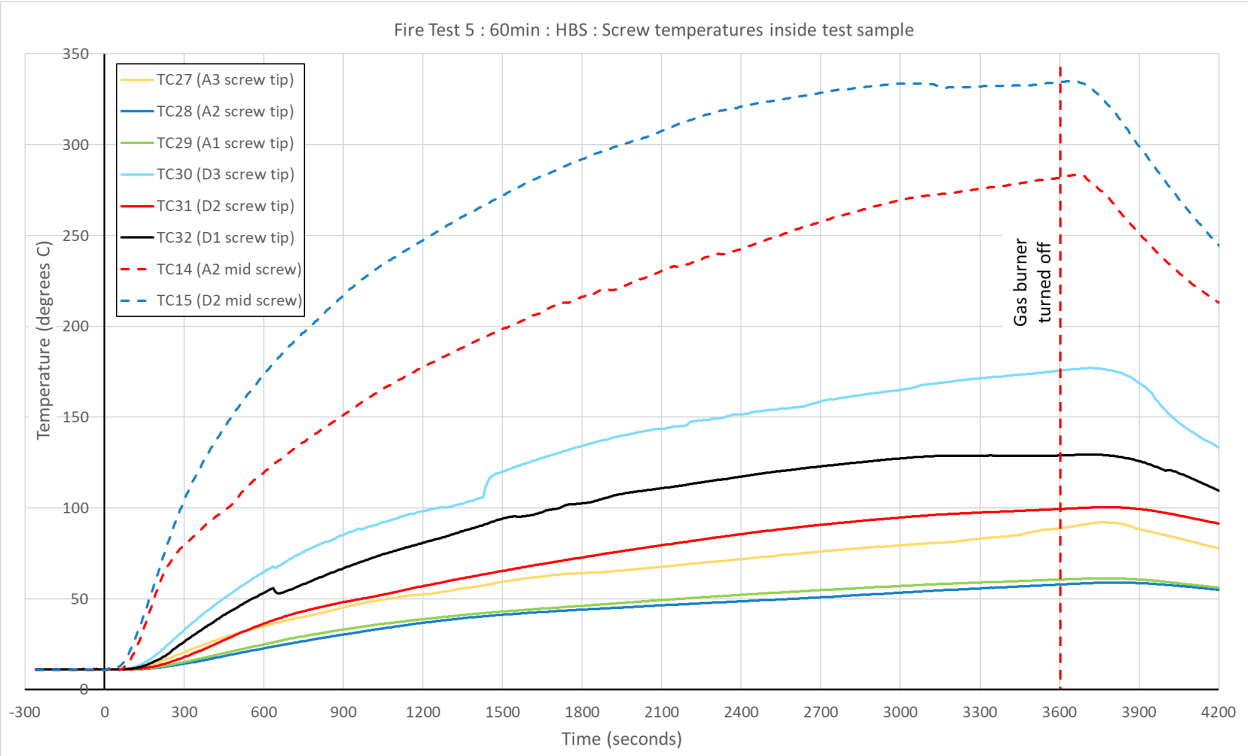


Figure 48 : FT5 Screw temperature profiles inside the sample (Mid-point and screw tips).

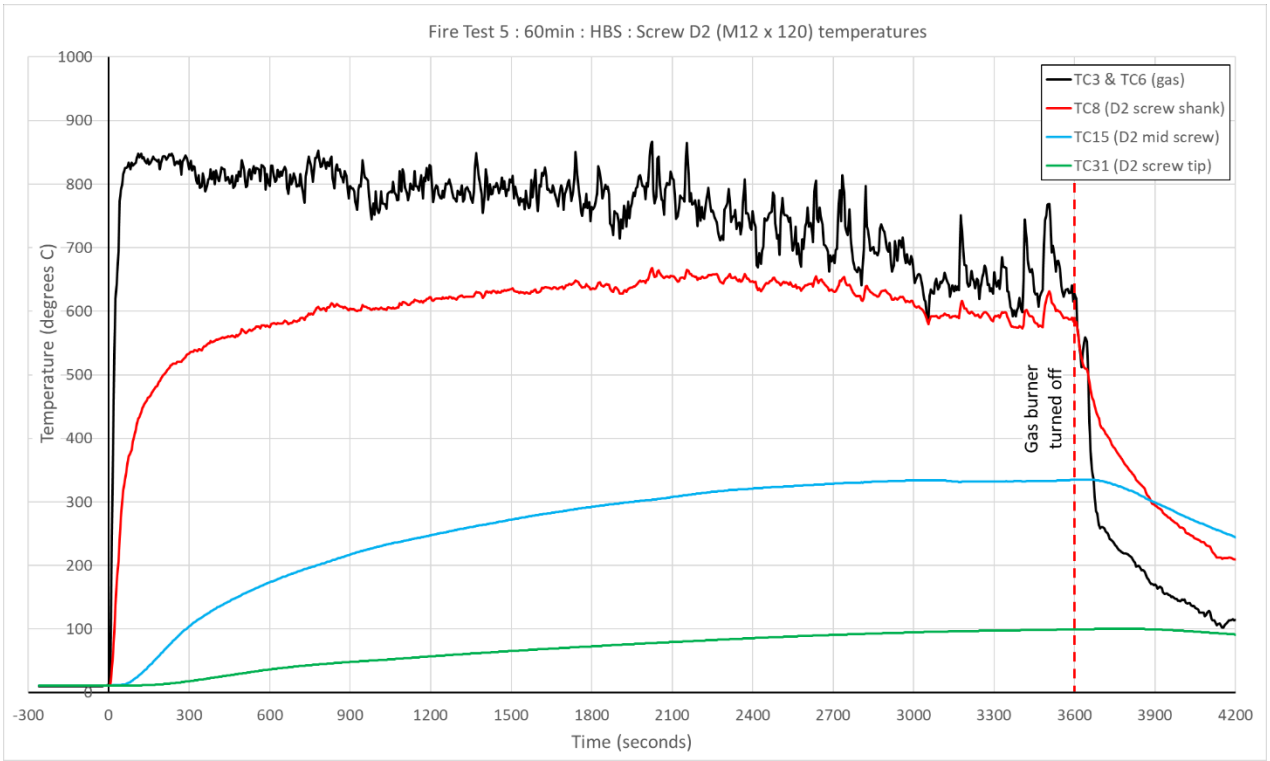


Figure 49 : FT5 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

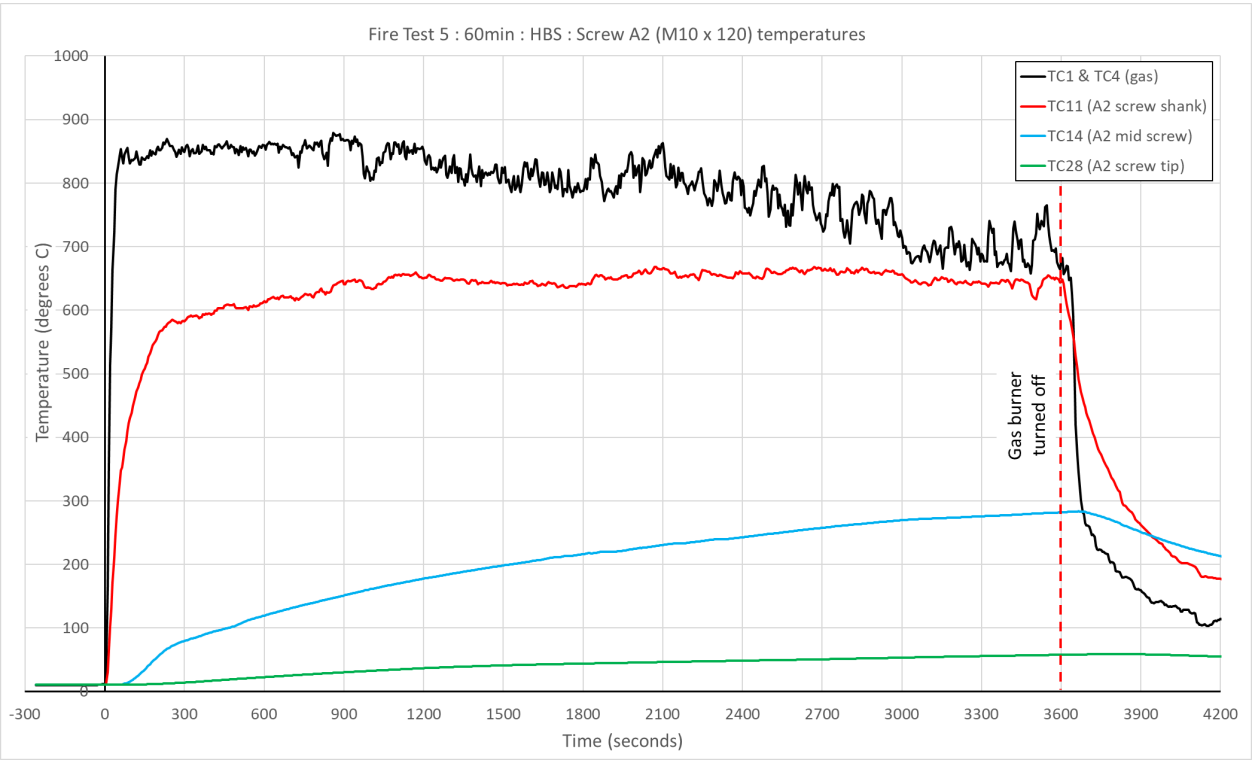


Figure 50 : FT5 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

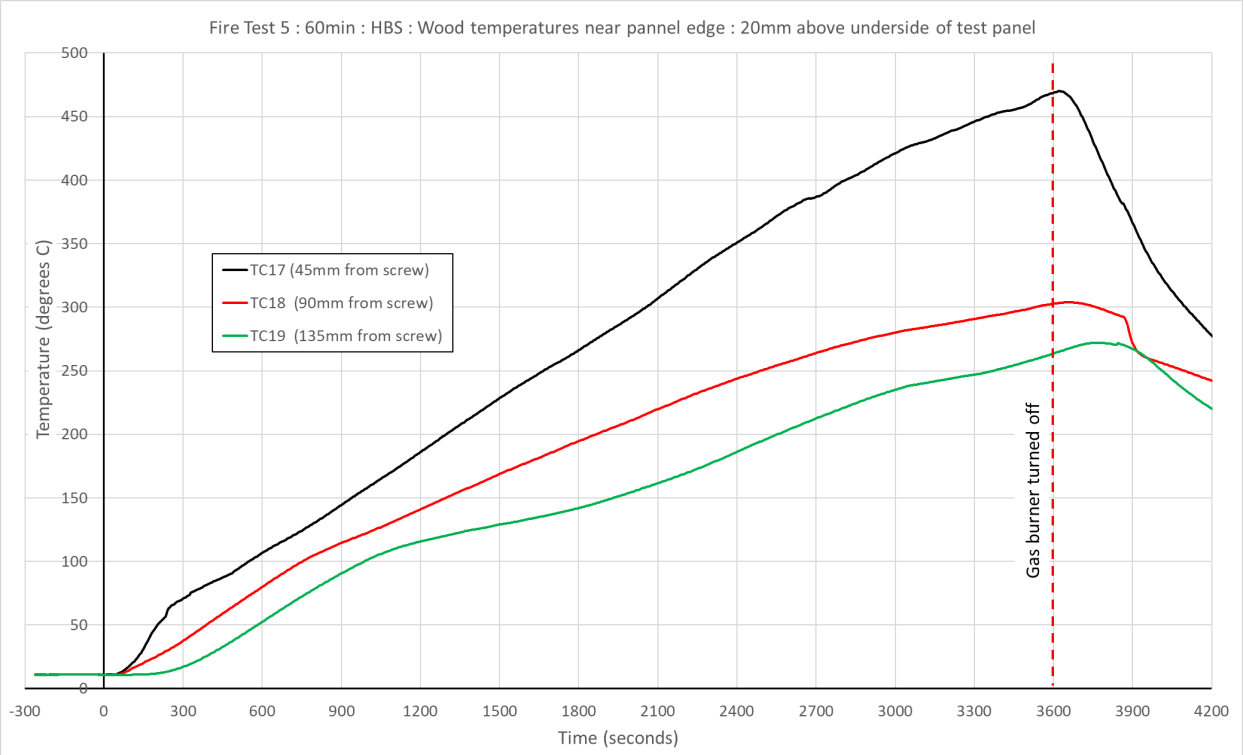


Figure 51 : FT5 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

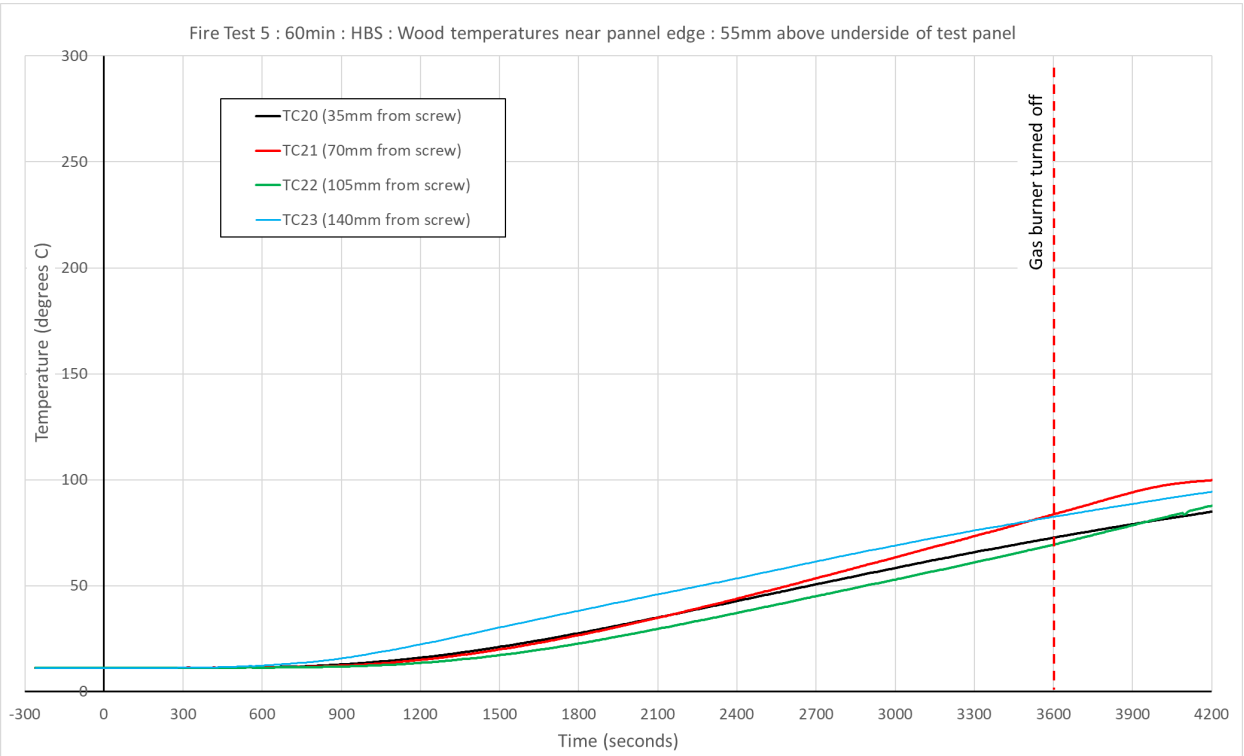


Figure 52 : FT5 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

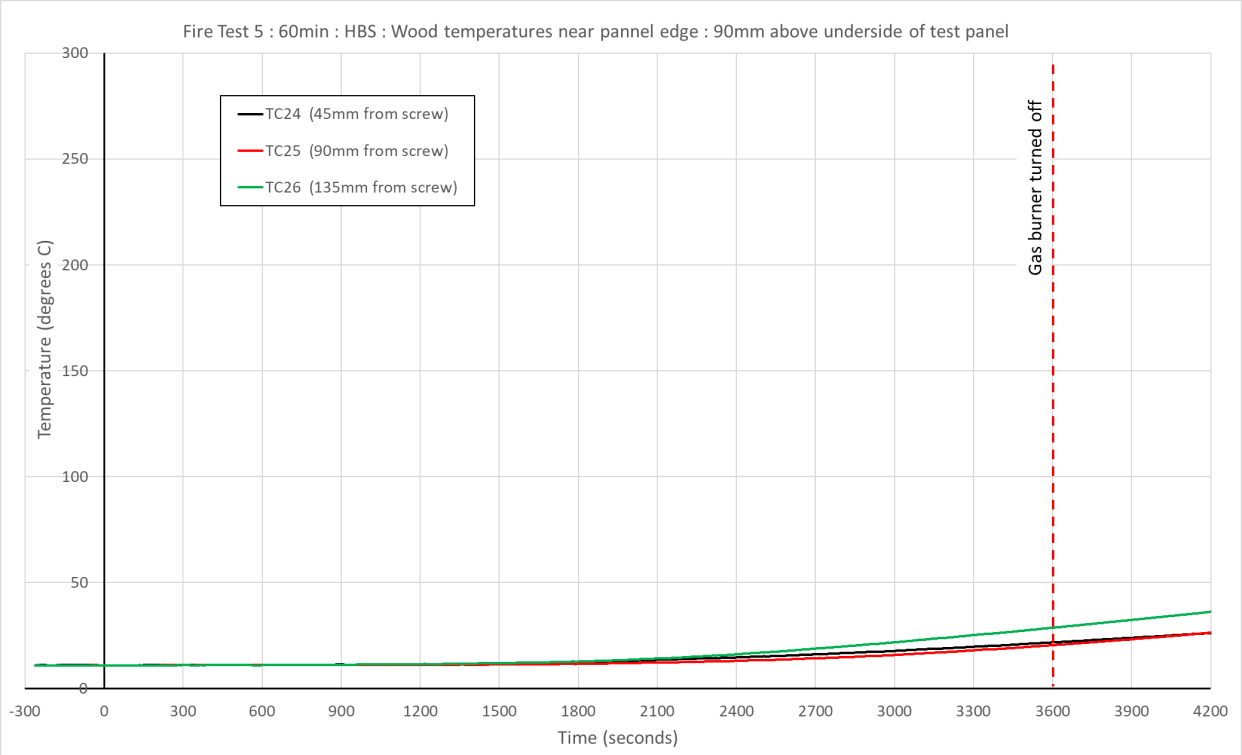


Figure 53 : FT5 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

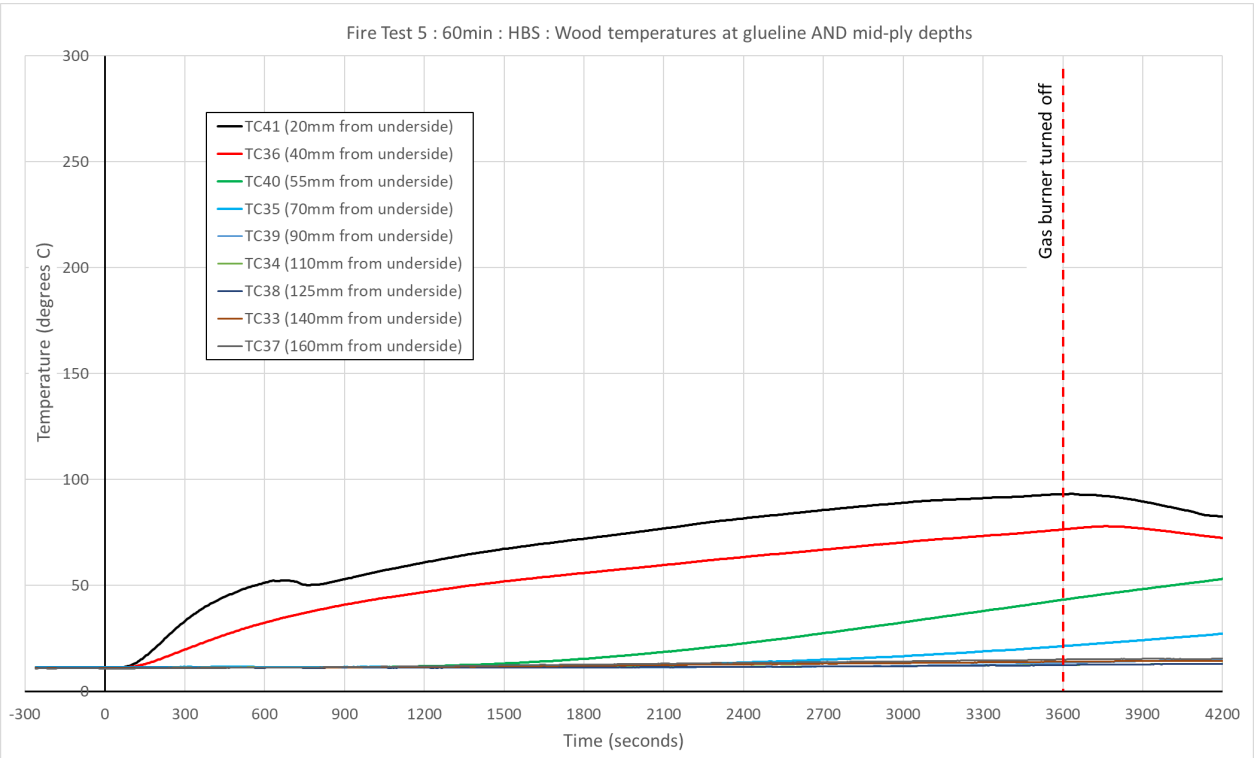


Figure 54 : FT5 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

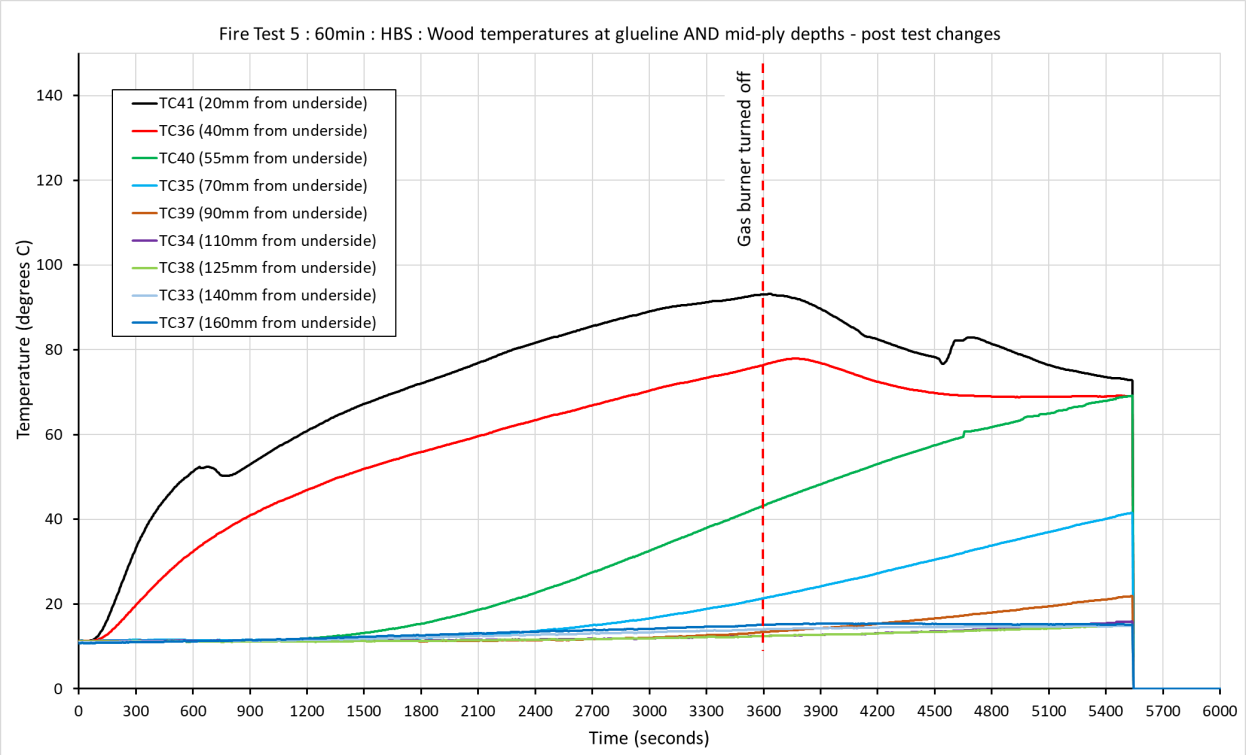


Figure 55 : FT5 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 6 – 30 minutes HB S panel (08.01.2024)

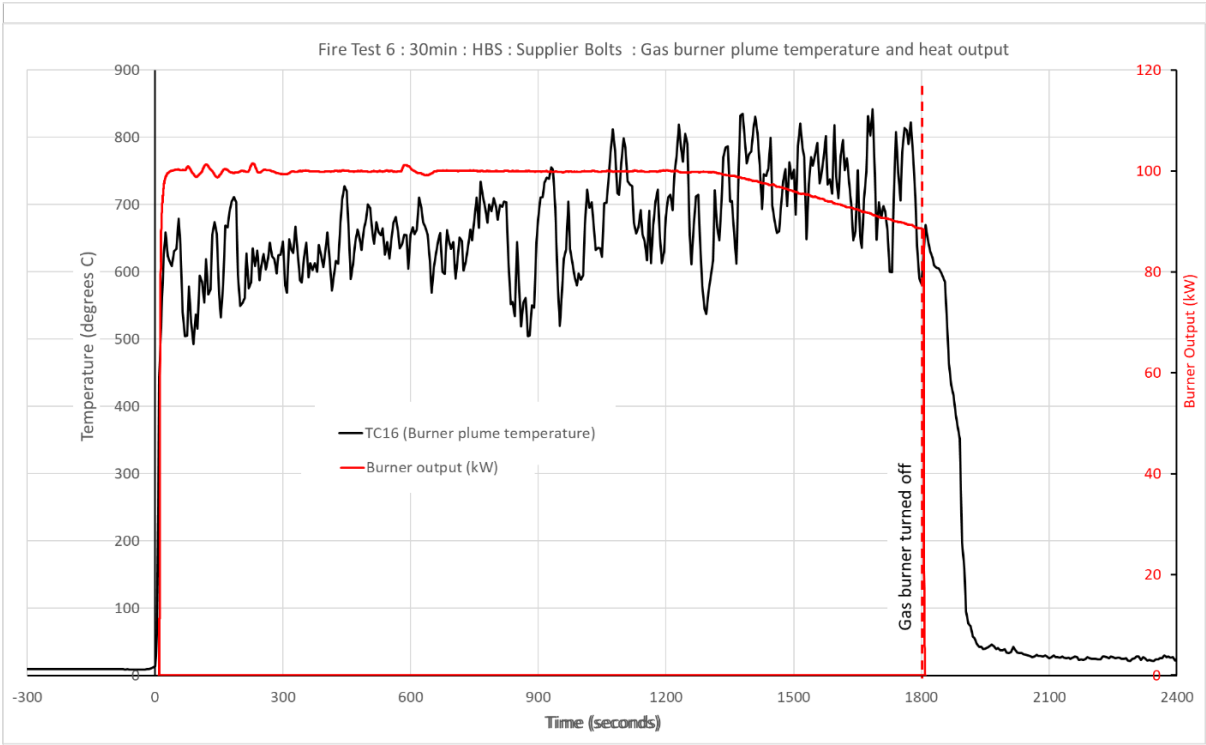


Figure 56 : FT6 Gas burner plume temperature and heat output.

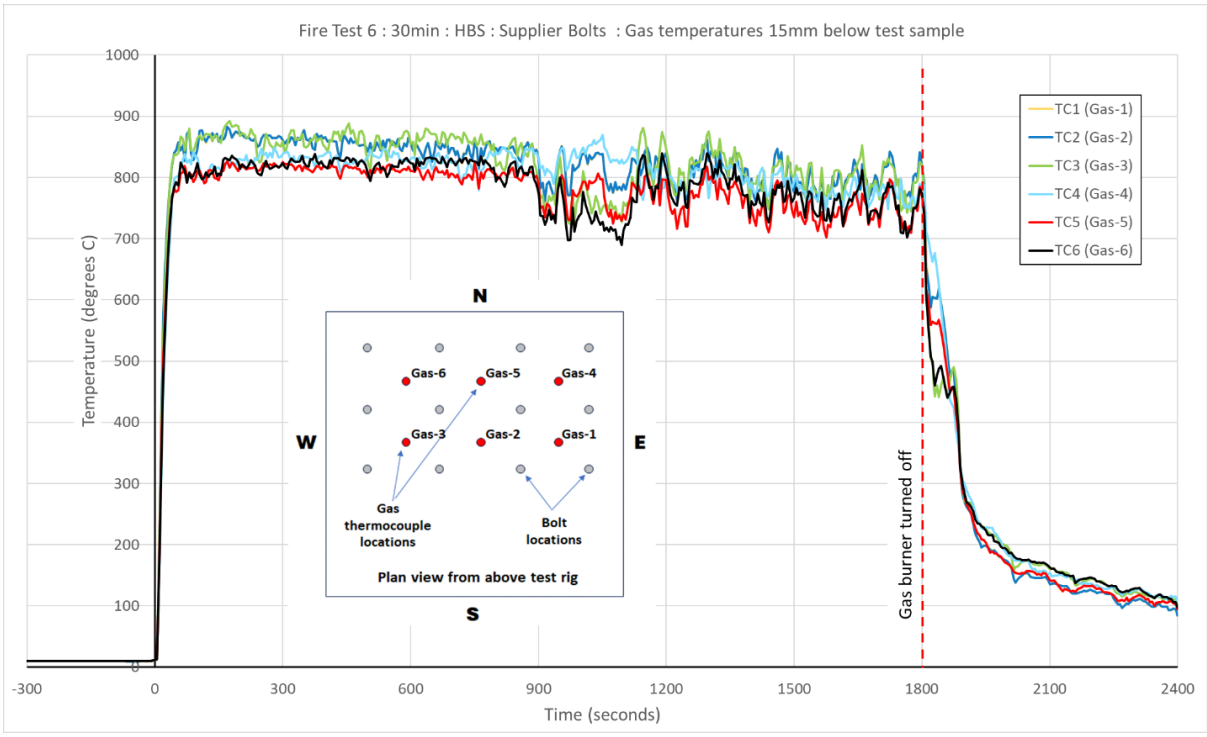


Figure 57 : FT6 Gas temperatures 15 mm below sample.

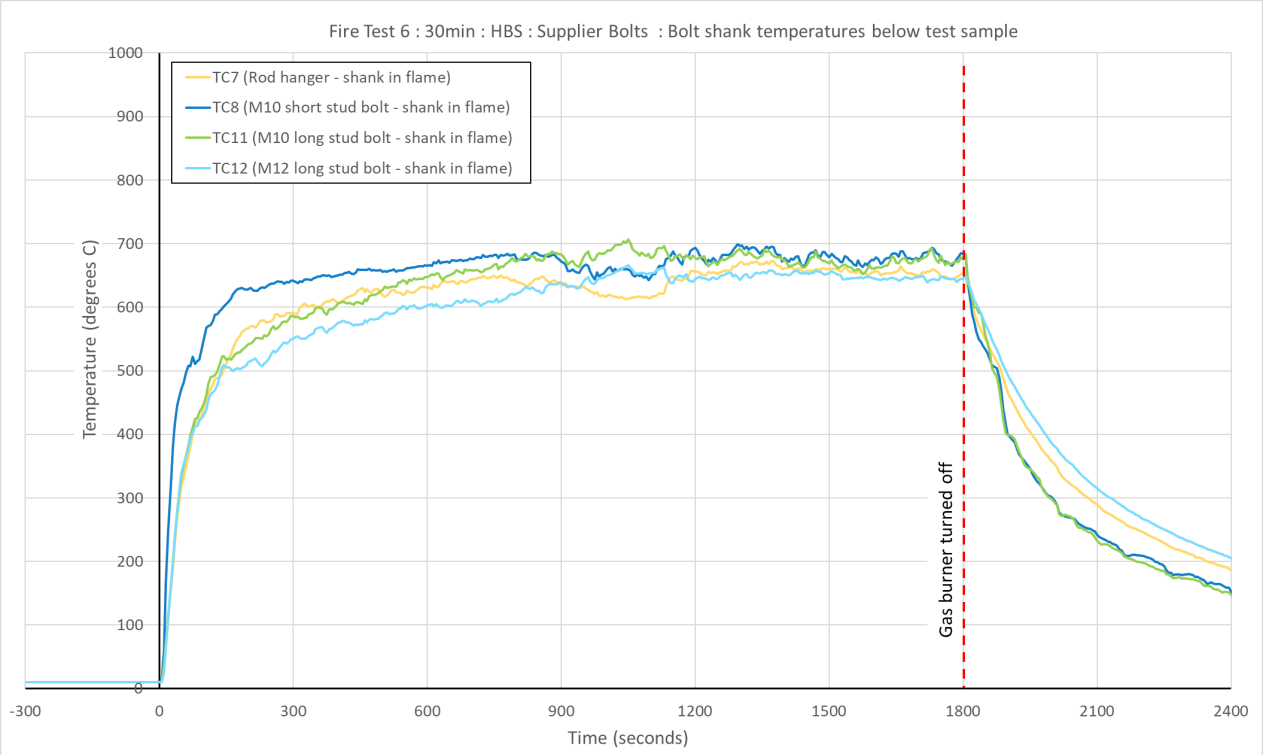


Figure 58 : FT6 Screw shank temperature profiles below sample.

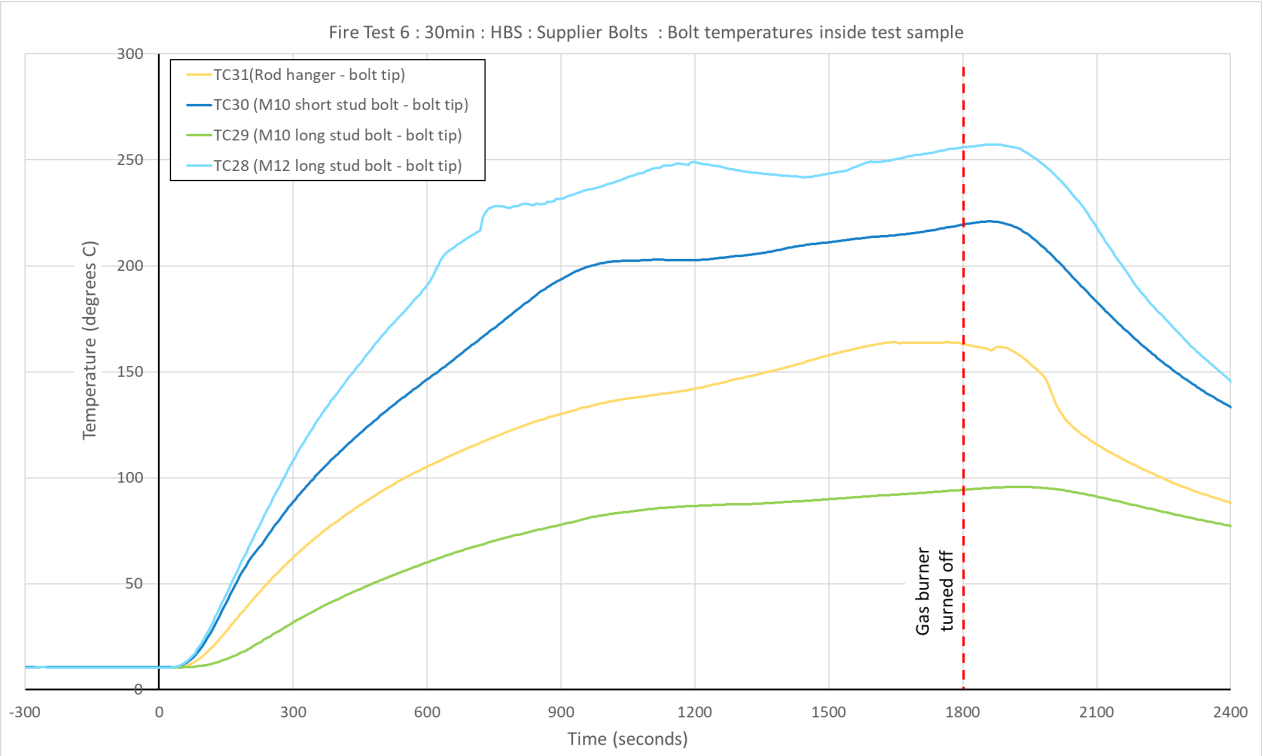


Figure 59 : FT6 Screw temperature profiles inside the sample (Mid-point and screw tips).

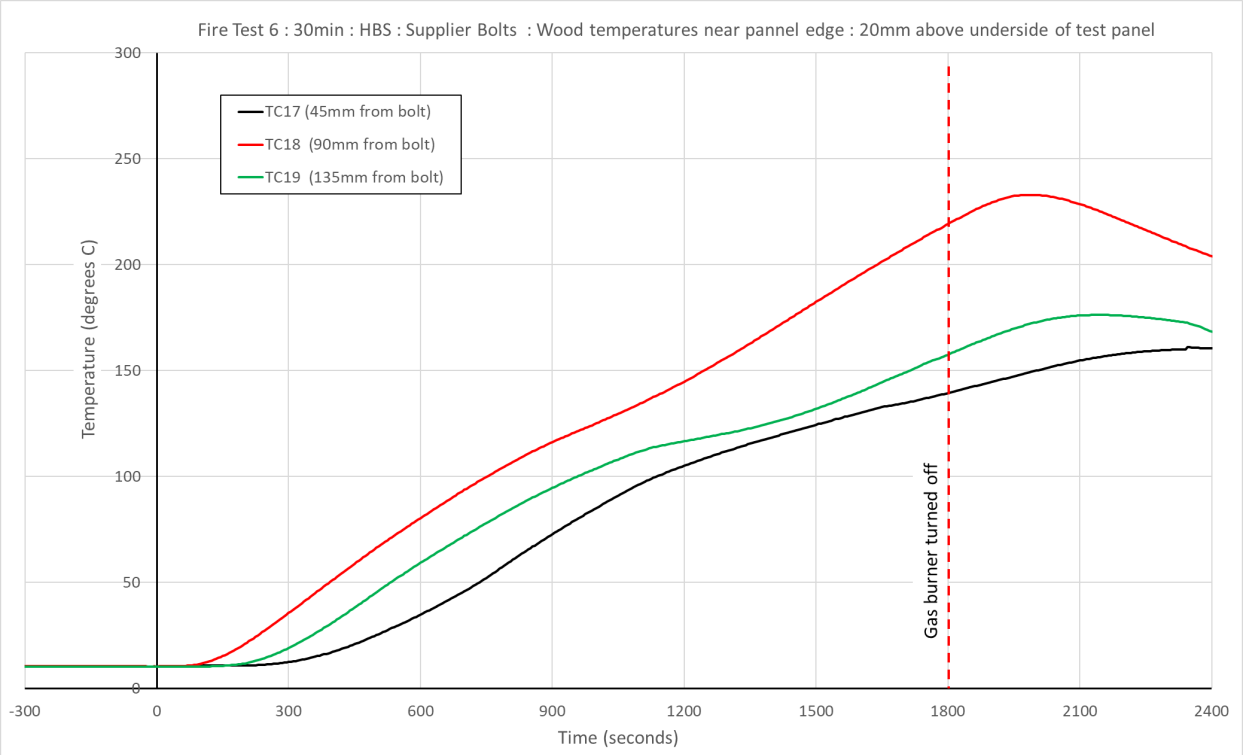


Figure 60 : FT6 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

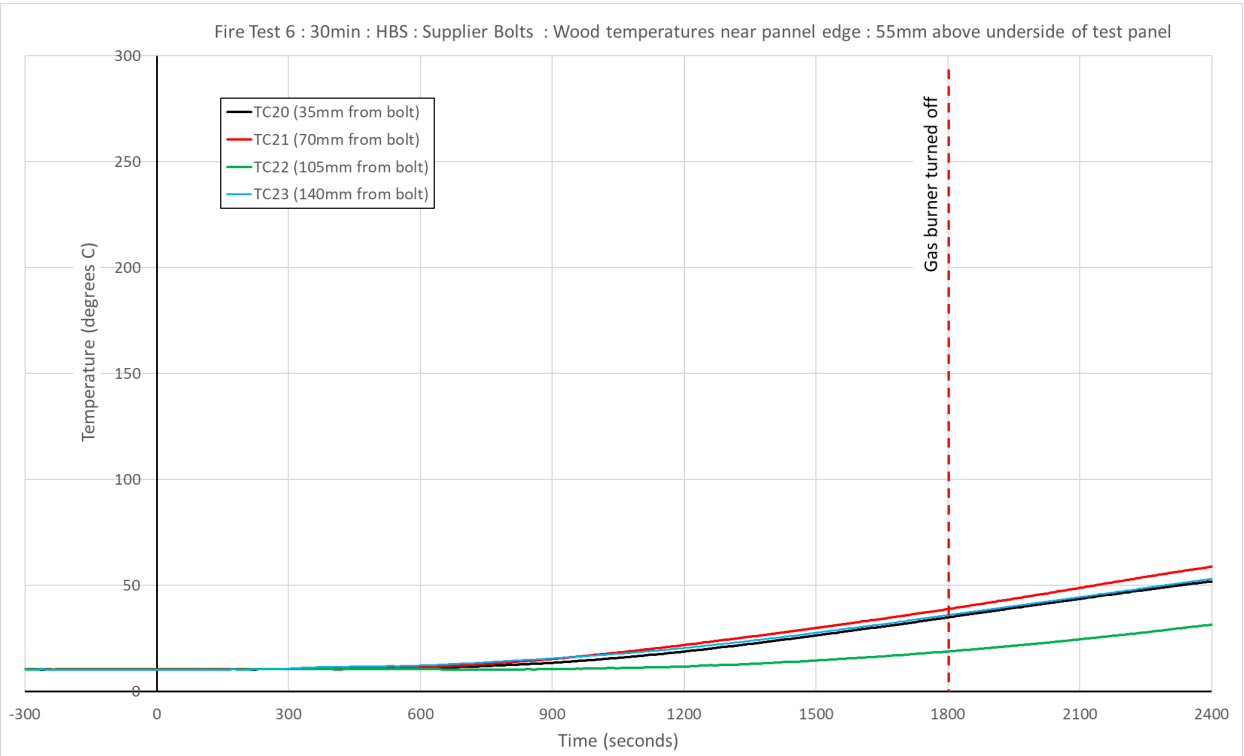


Figure 61 : FT6 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

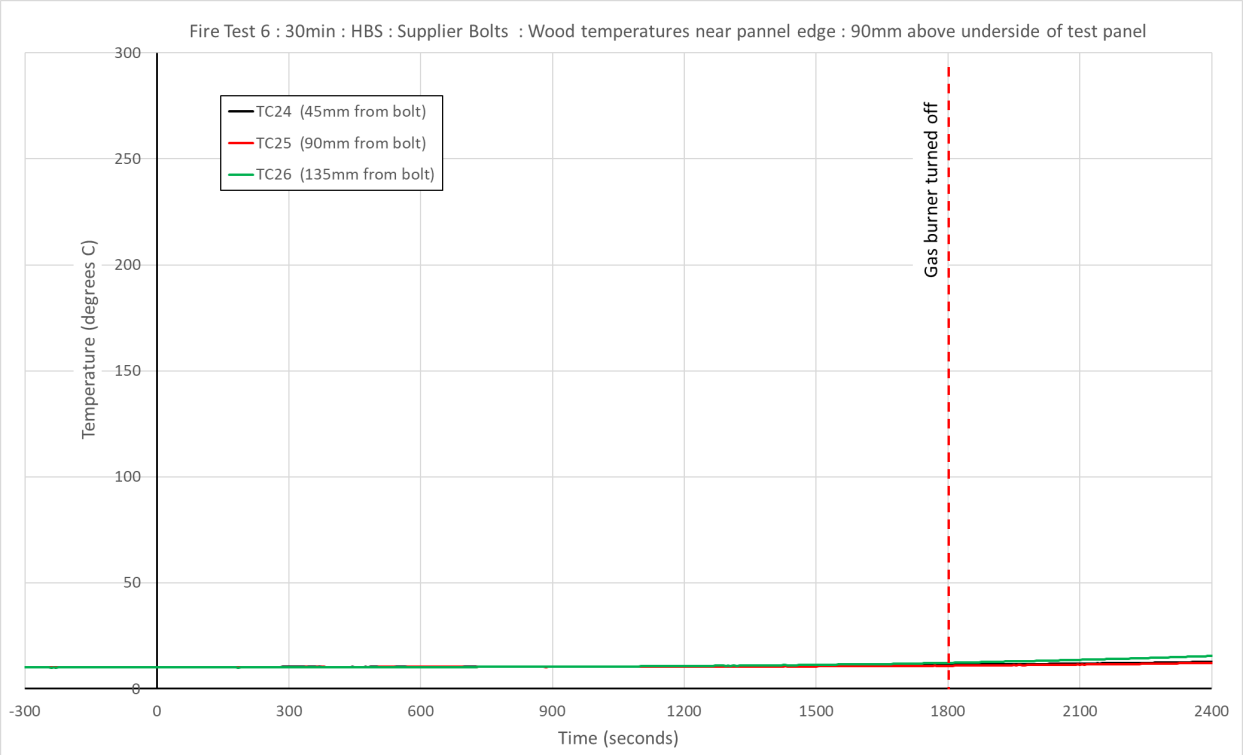


Figure 62 : FT6 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

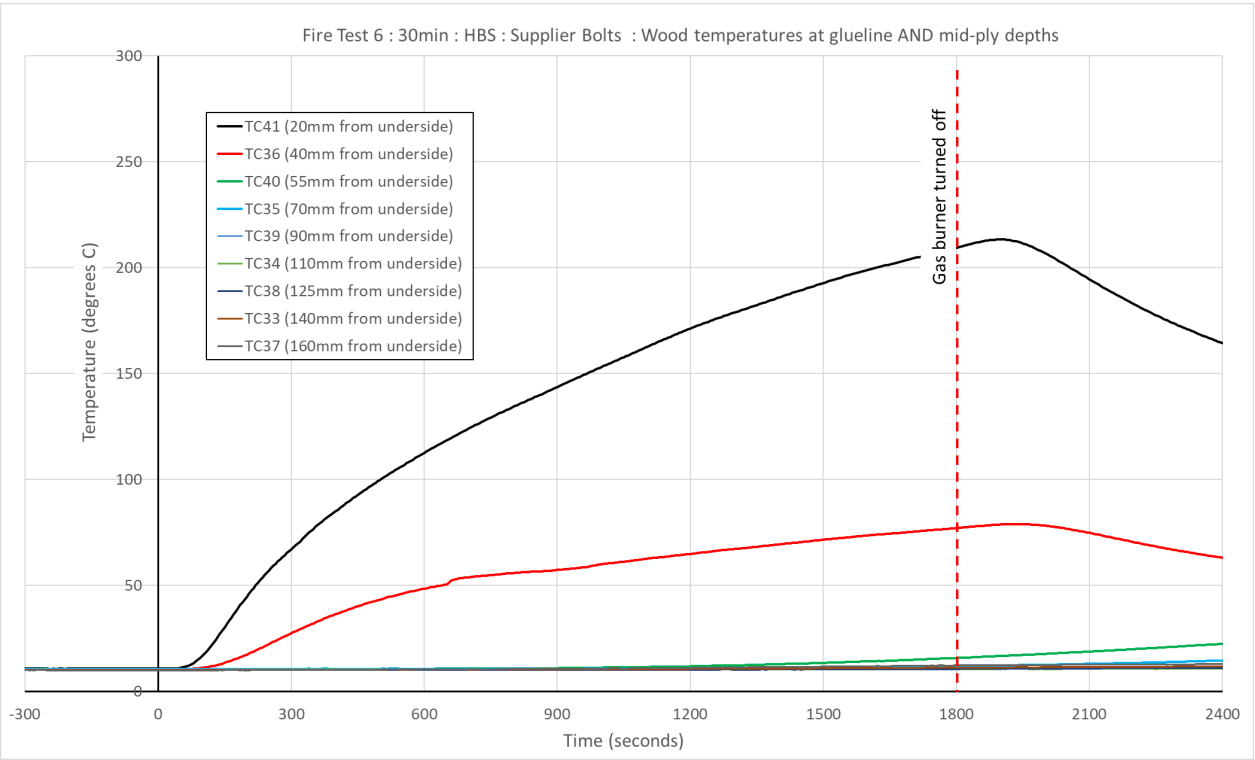


Figure 63 : FT6 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

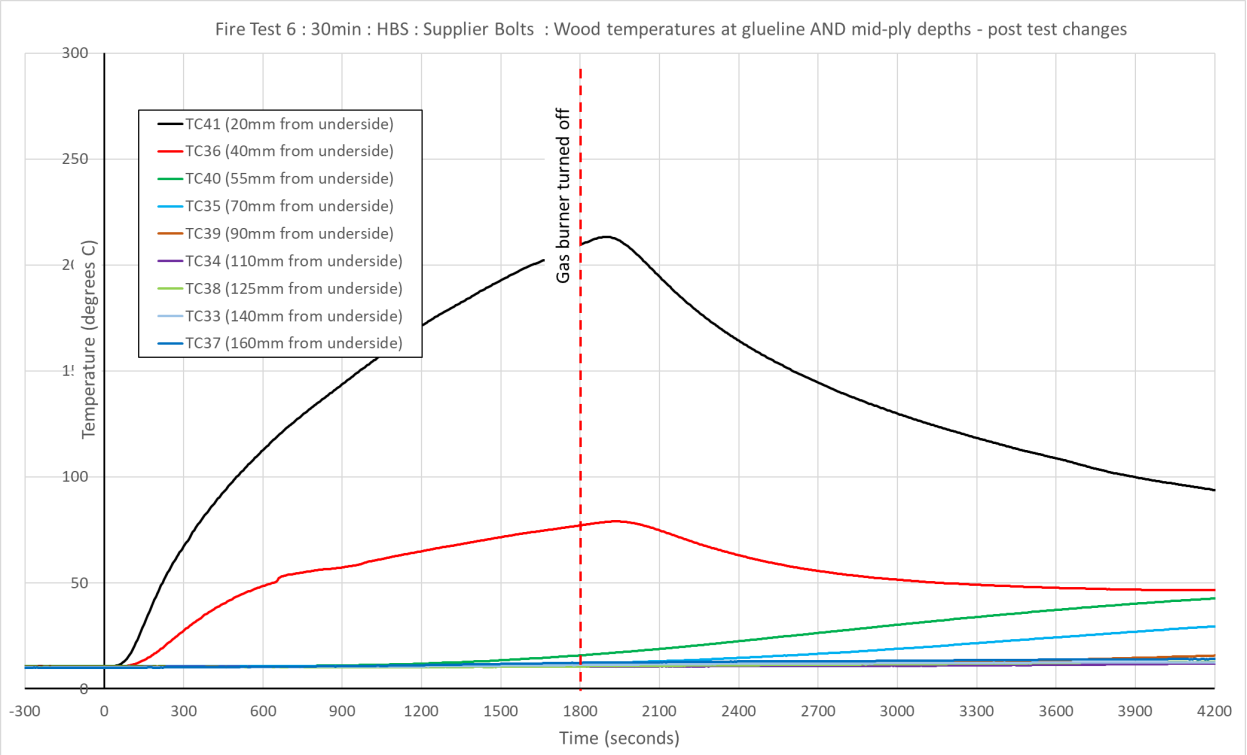


Figure 64 : FT6 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 7 – 30 minutes HB S panel (10.01.2024)

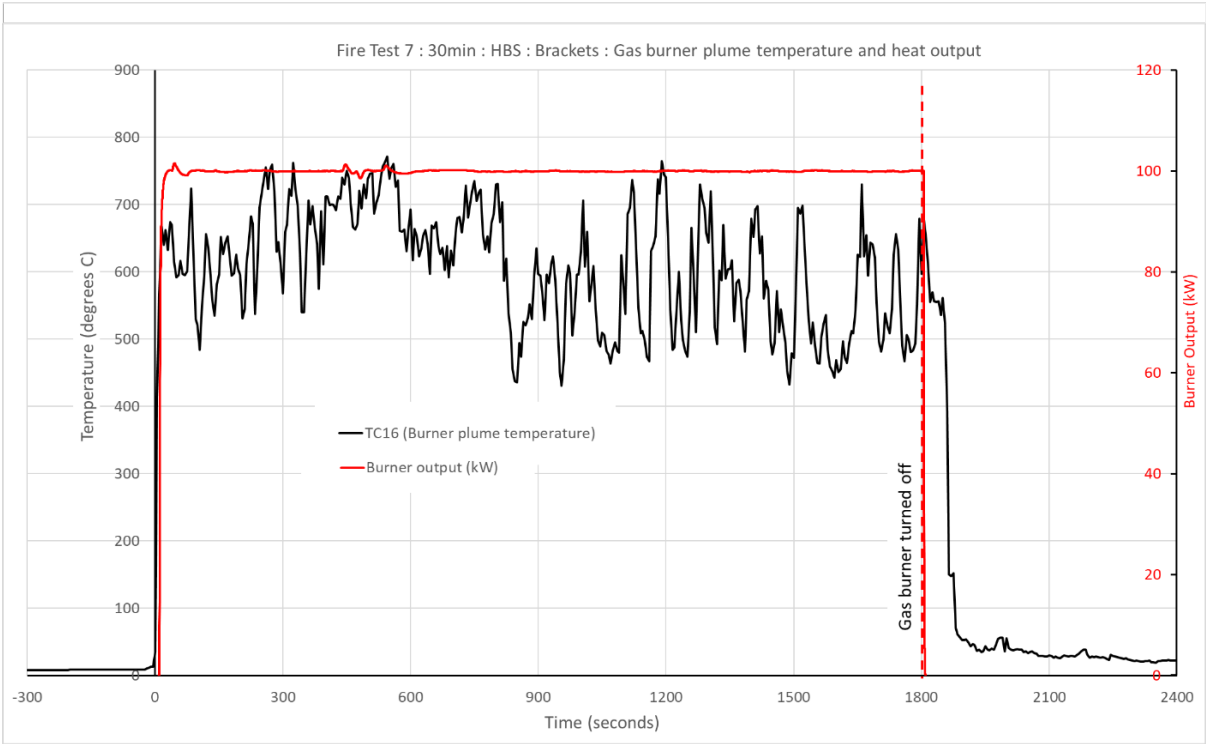


Figure 65 : FT7 Gas burner plume temperature and heat output.

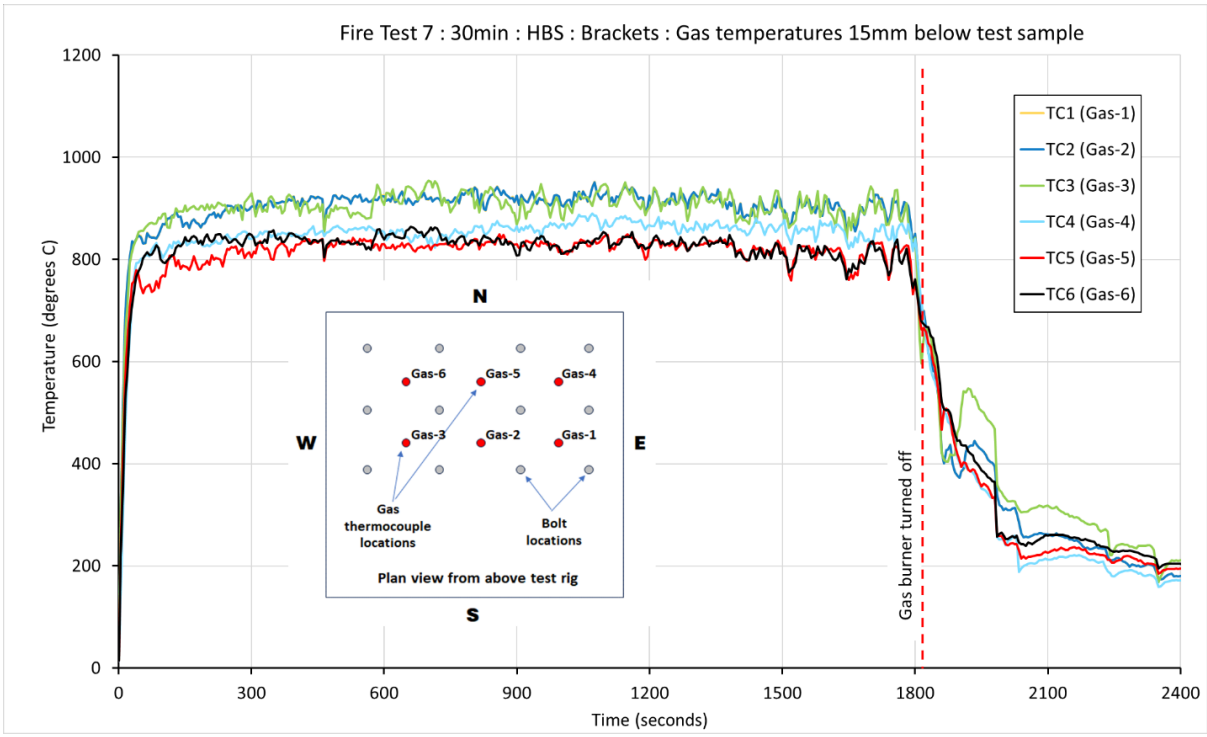


Figure 66 : FT7 Gas temperatures 15 mm below sample.

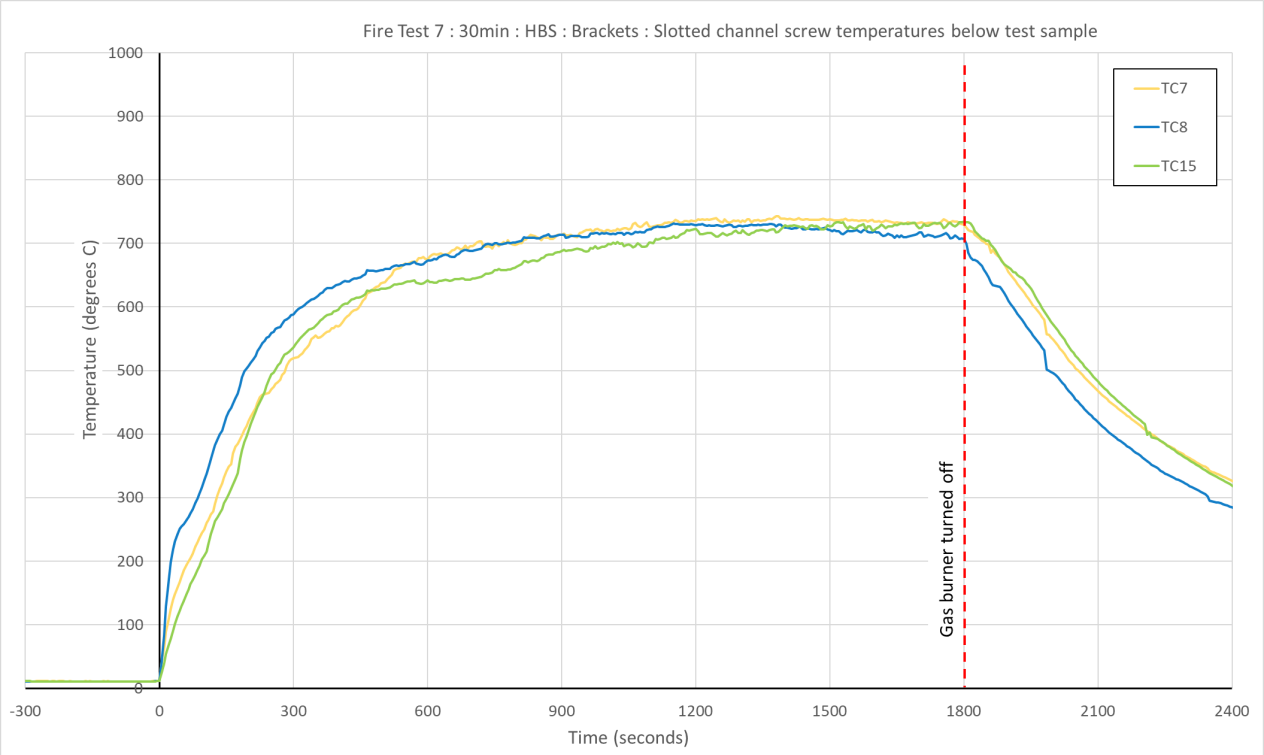


Figure 67 : FT7 Slotted channel bracket screw temperature profiles below sample.

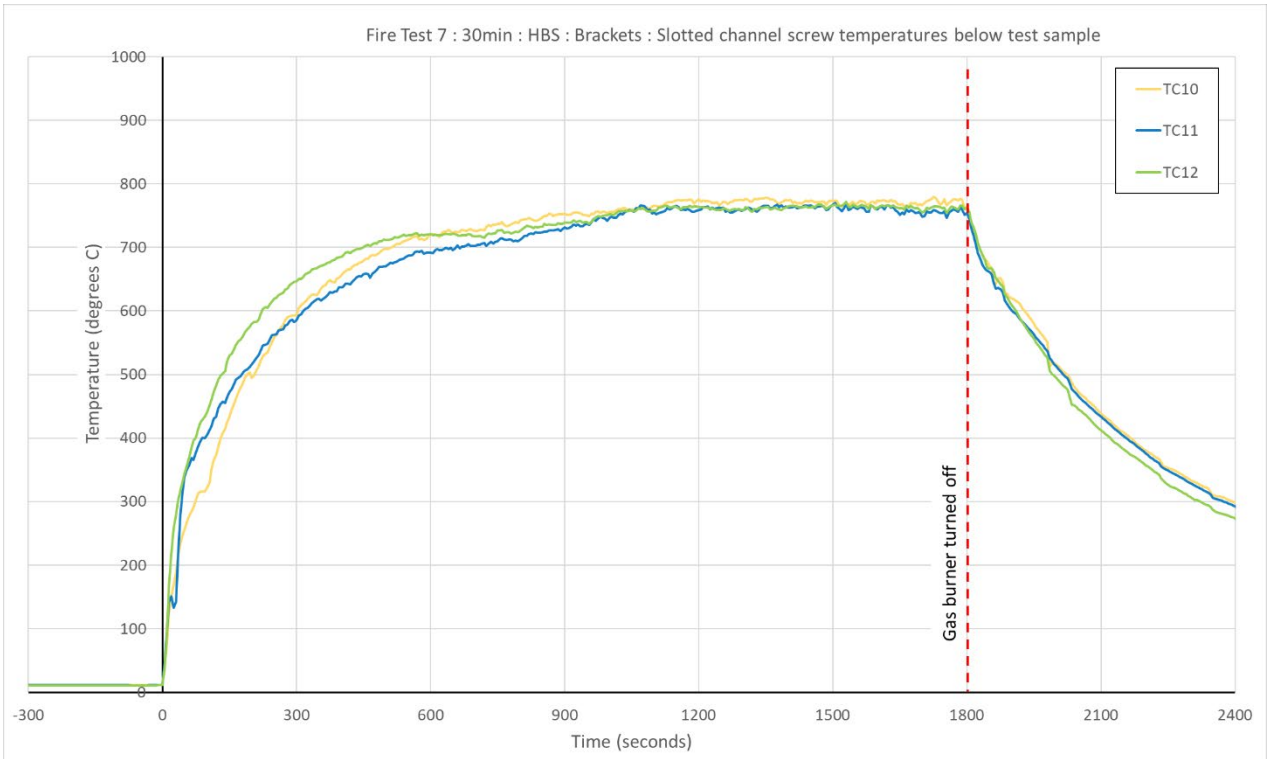


Figure 68 : FT7 Slotted channel bracket screw temperature profiles below sample.

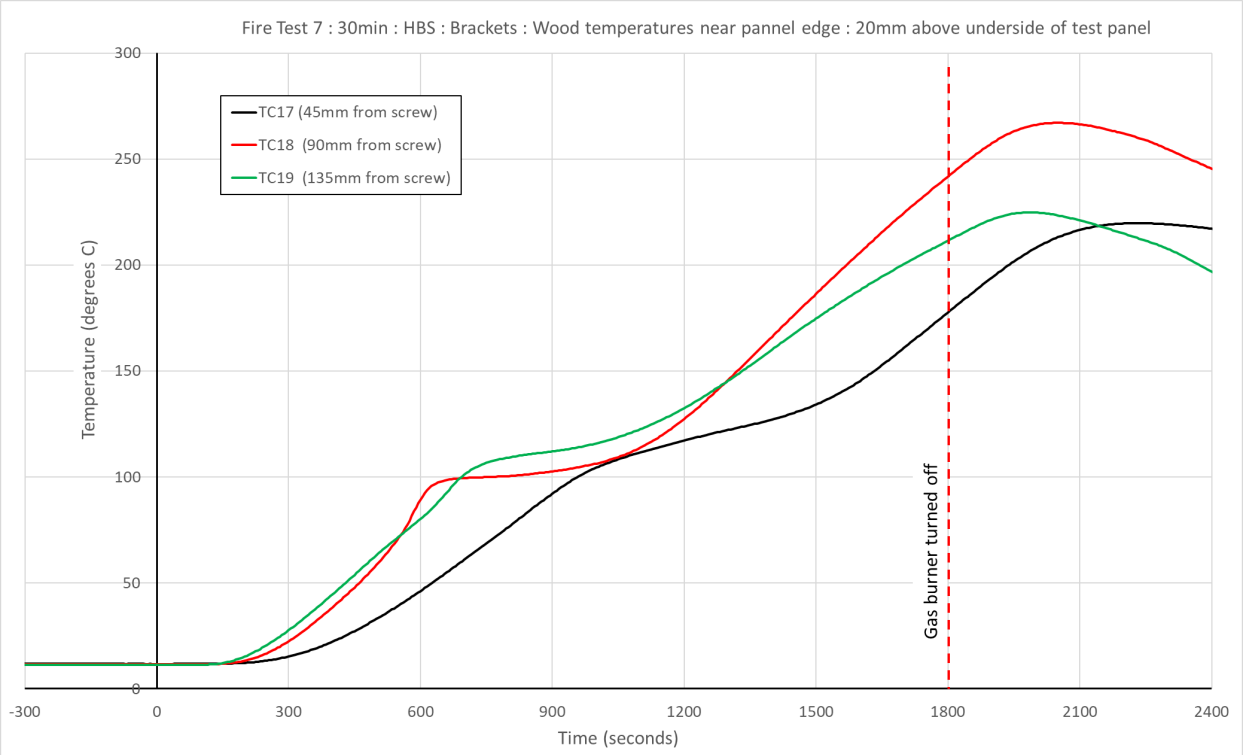


Figure 69 : FT7 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

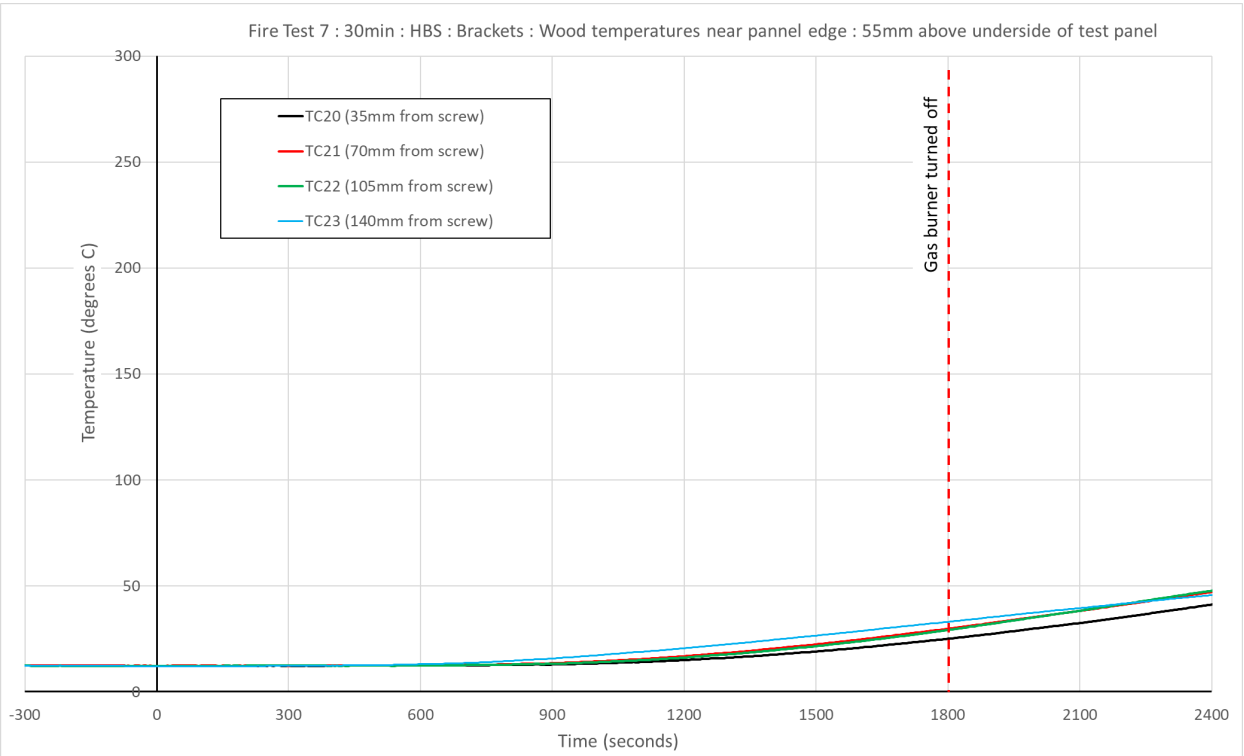


Figure 70 : FT7 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

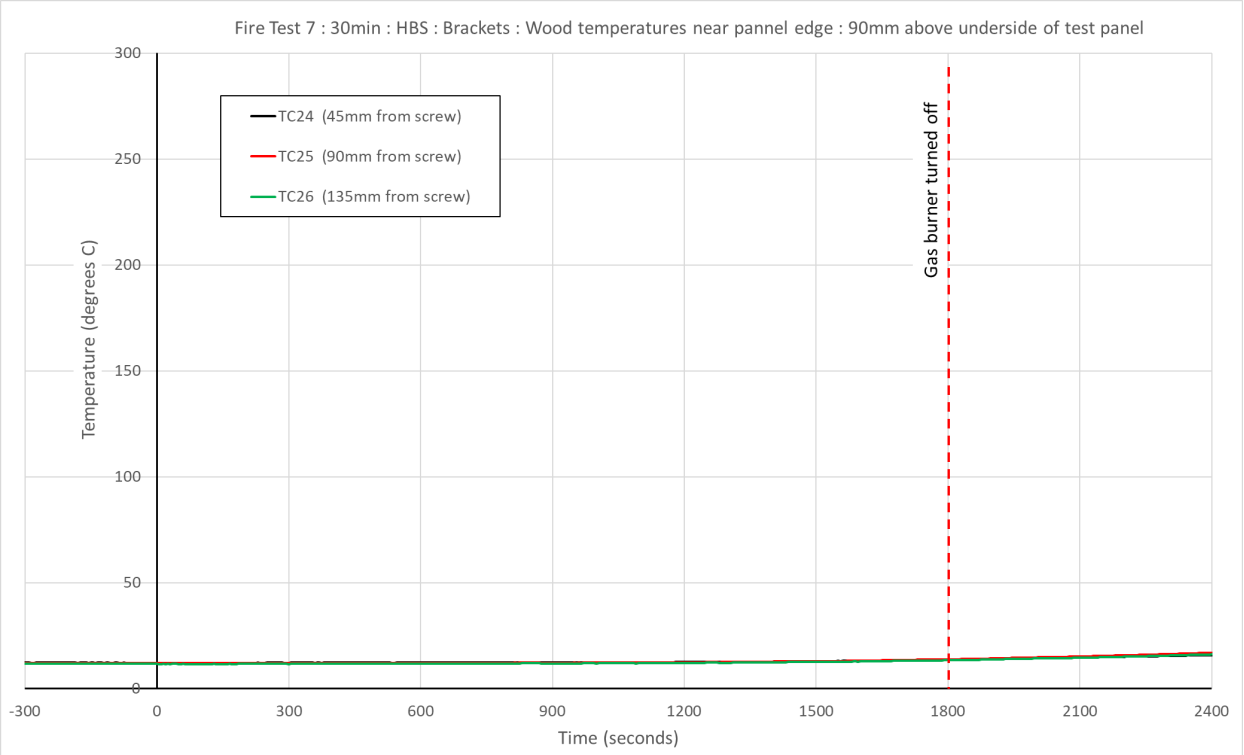


Figure 71 : FT7 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

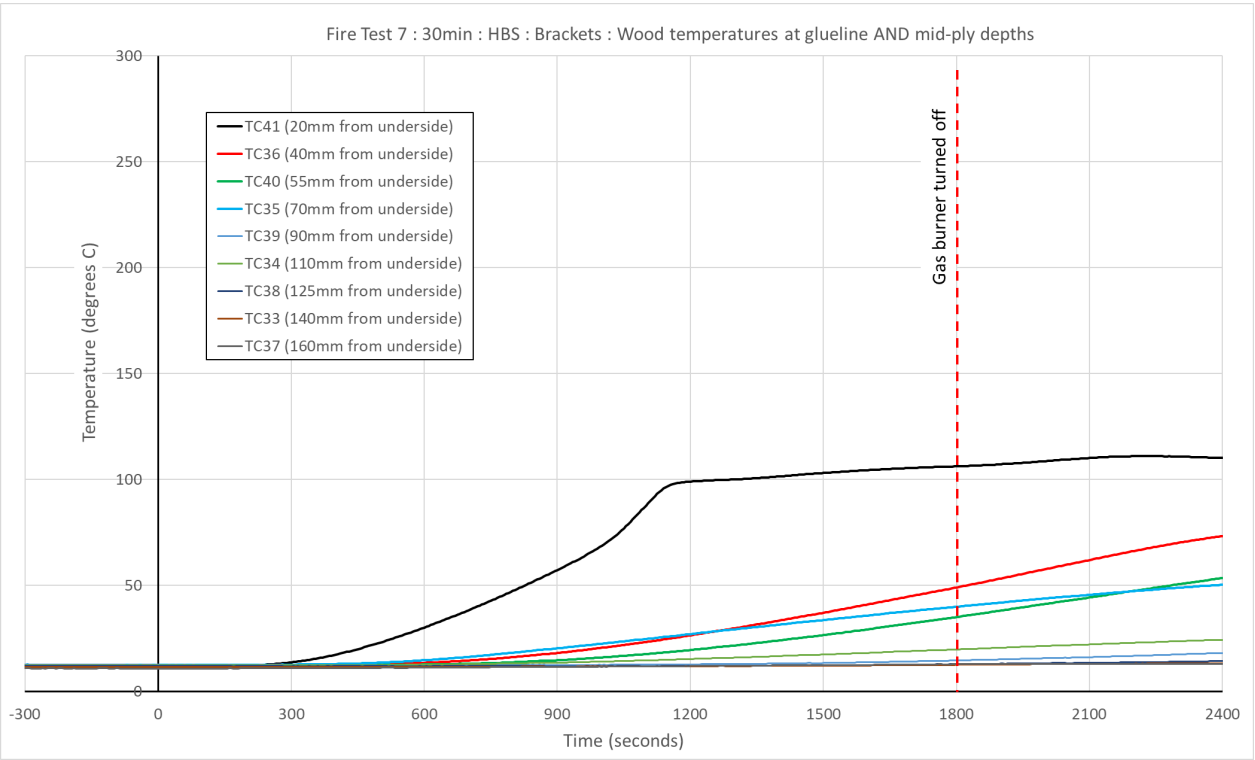


Figure 72 : FT7 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

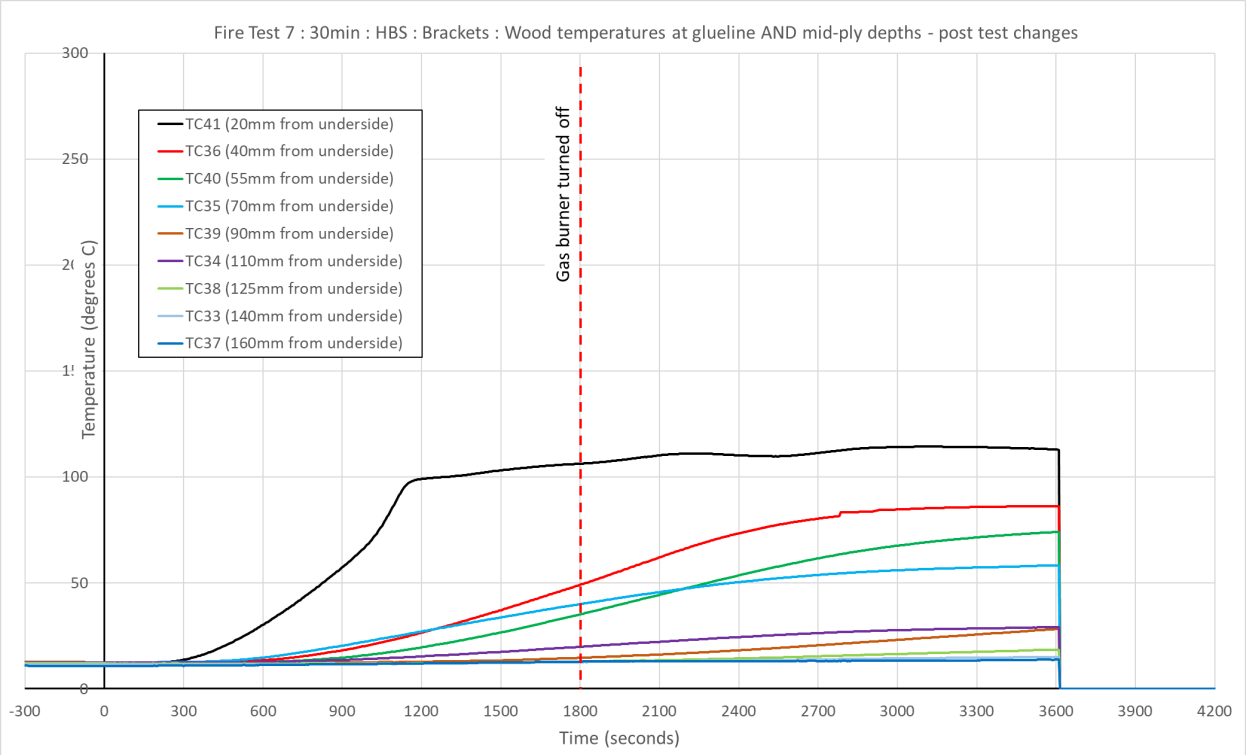


Figure 73 : FT7 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Fire Test 8 – 60 minutes HB X panel (15.01.2024)

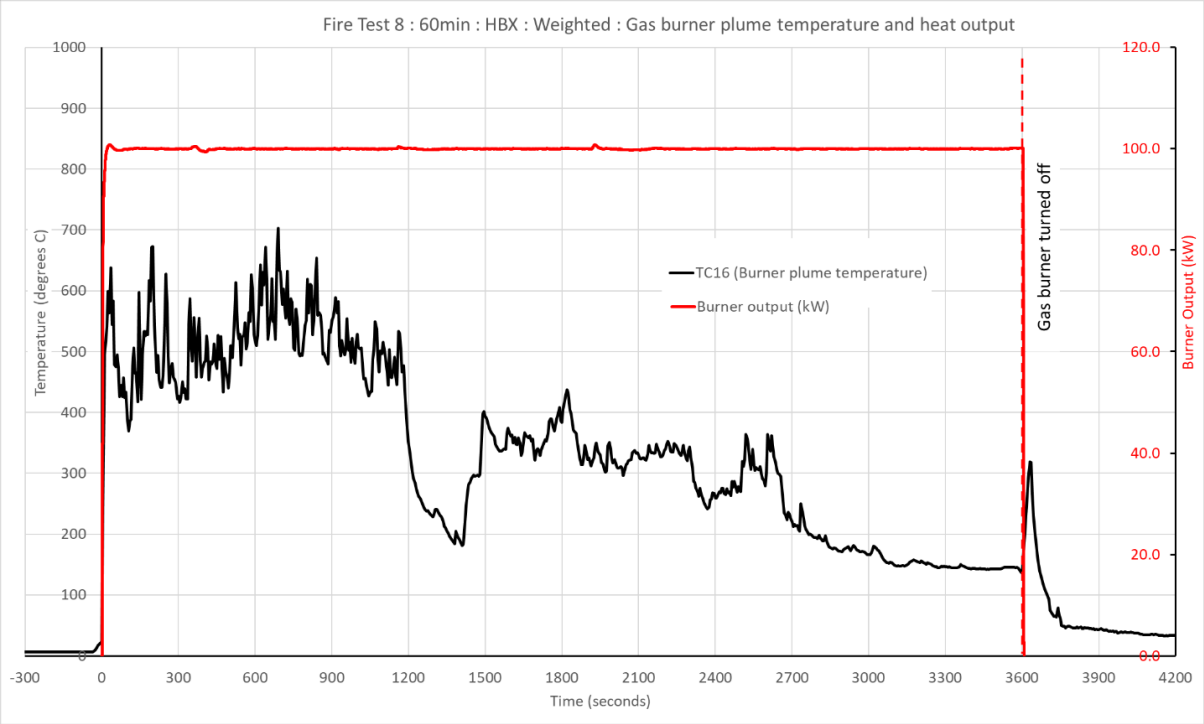


Figure 74 : FT8 Gas burner plume temperature and heat output.

Gas burner plume thermocouple – faulty during this test.

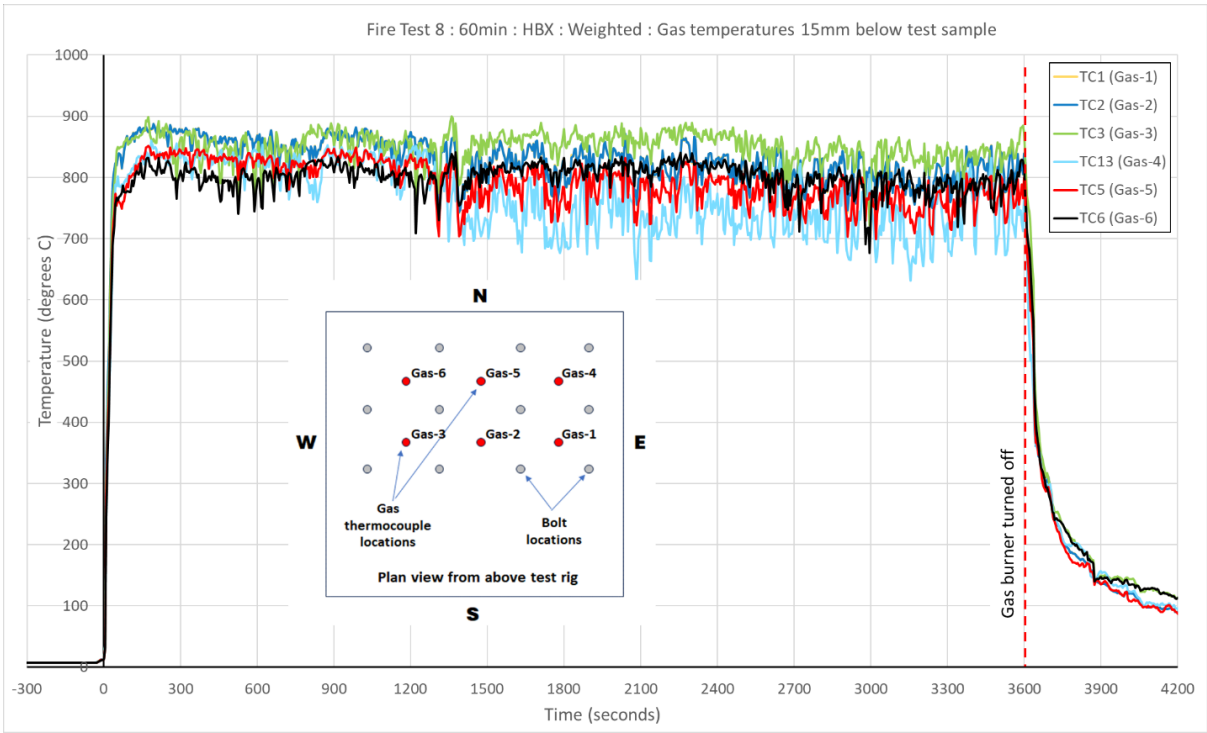


Figure 75 : FT8 Gas temperatures 15 mm below sample.

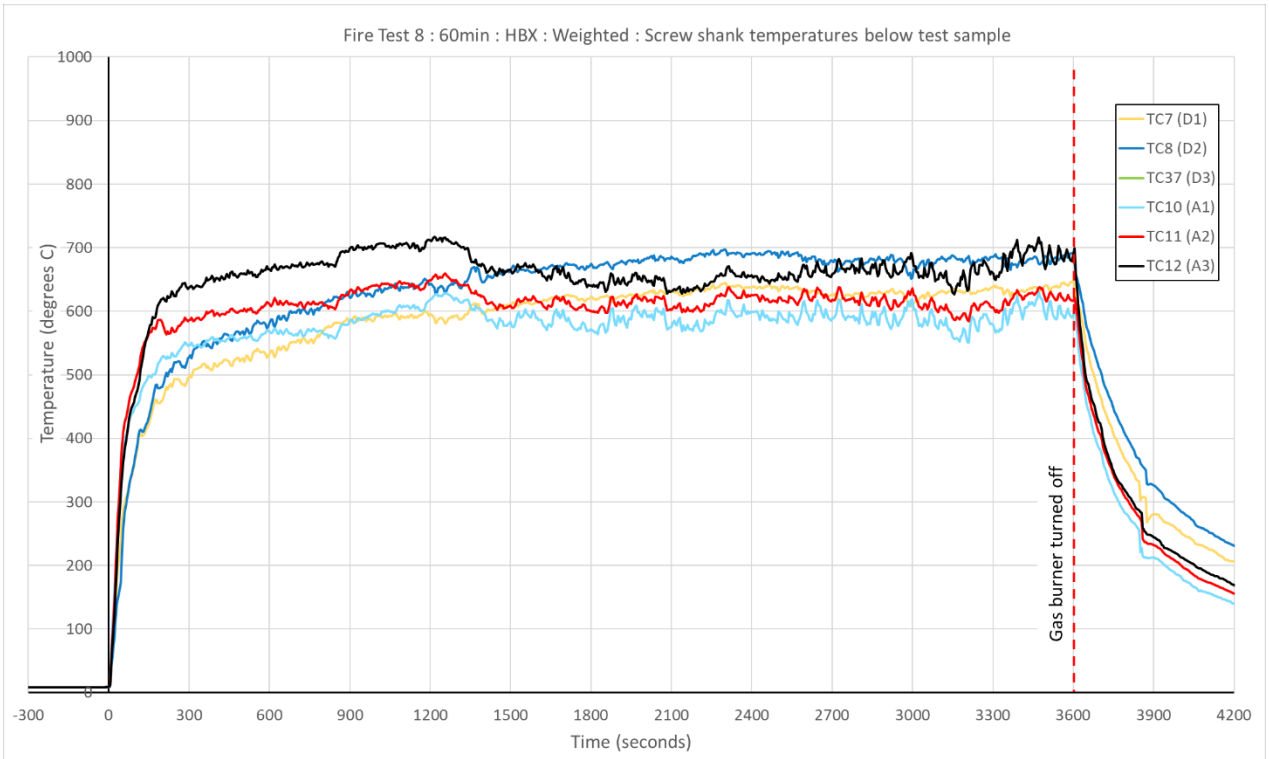


Figure 76 : FT8 Screw shank temperature profiles below sample.

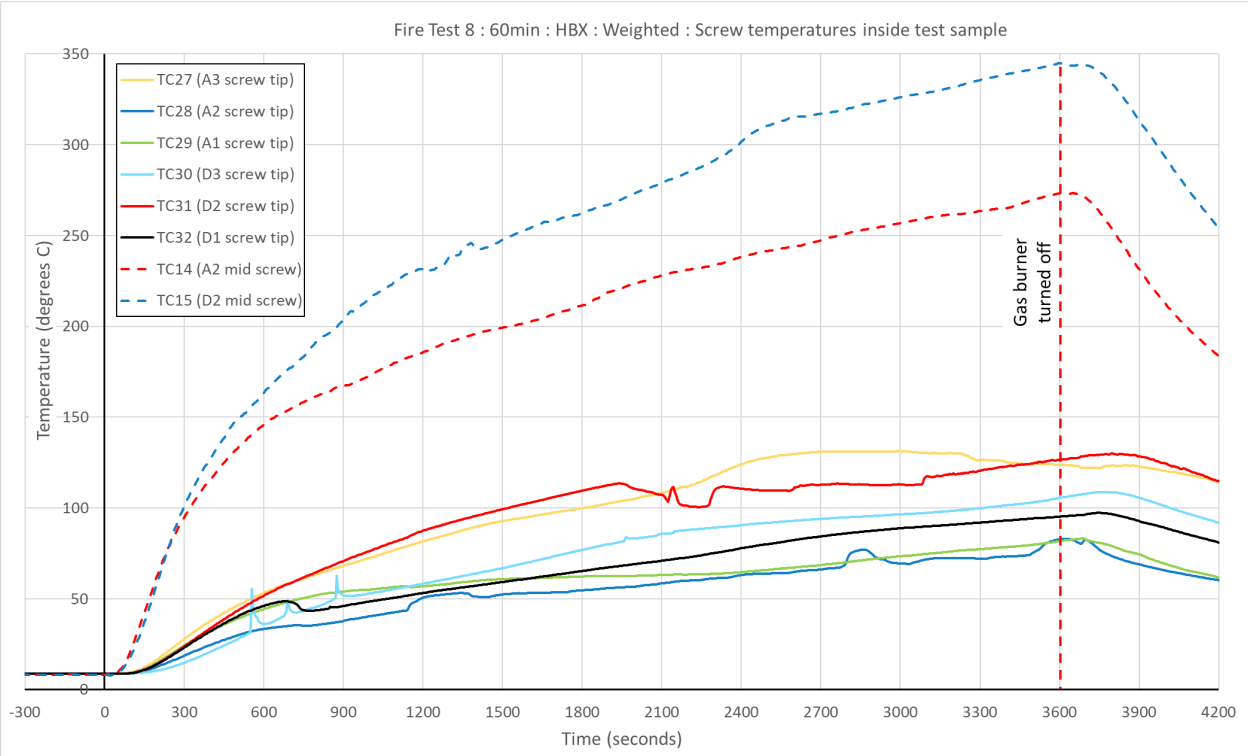


Figure 77 : FT8 Screw temperature profiles inside the sample (Mid-point and screw tips).

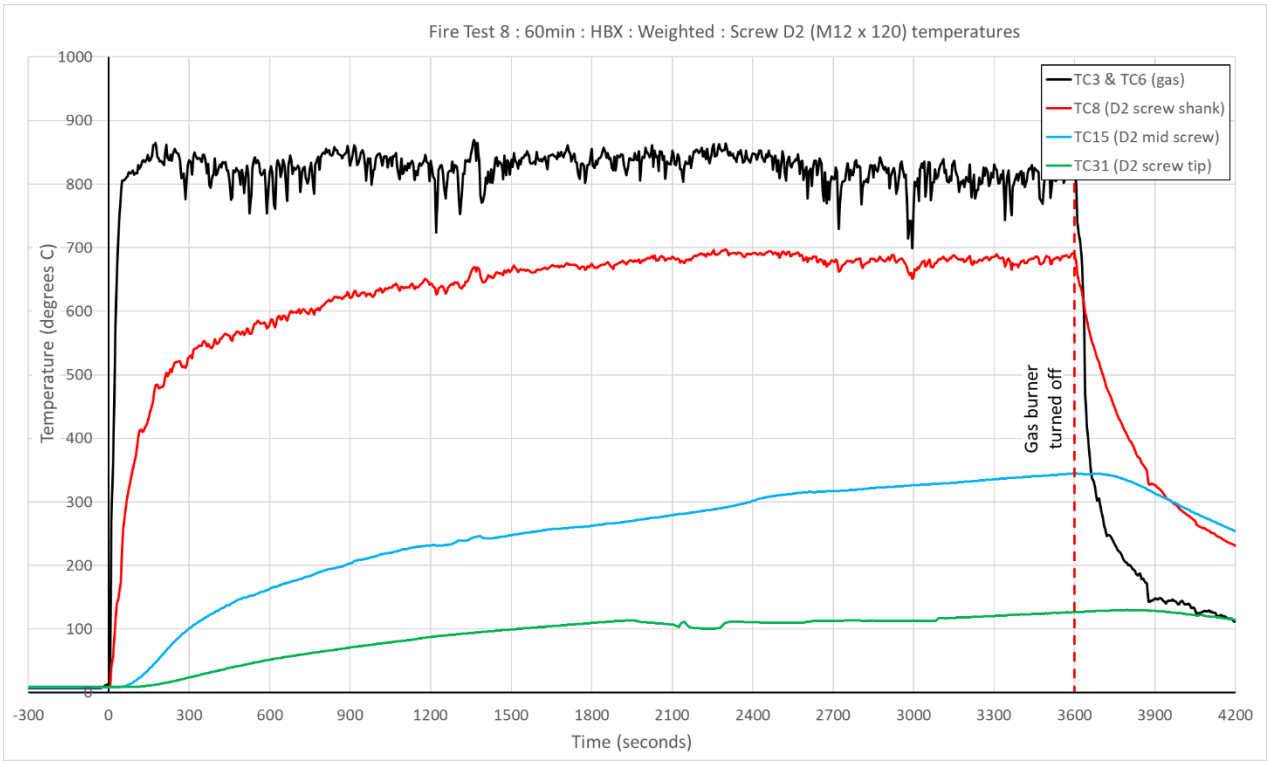


Figure 78 : FT8 Fixing type 4 (screw D2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

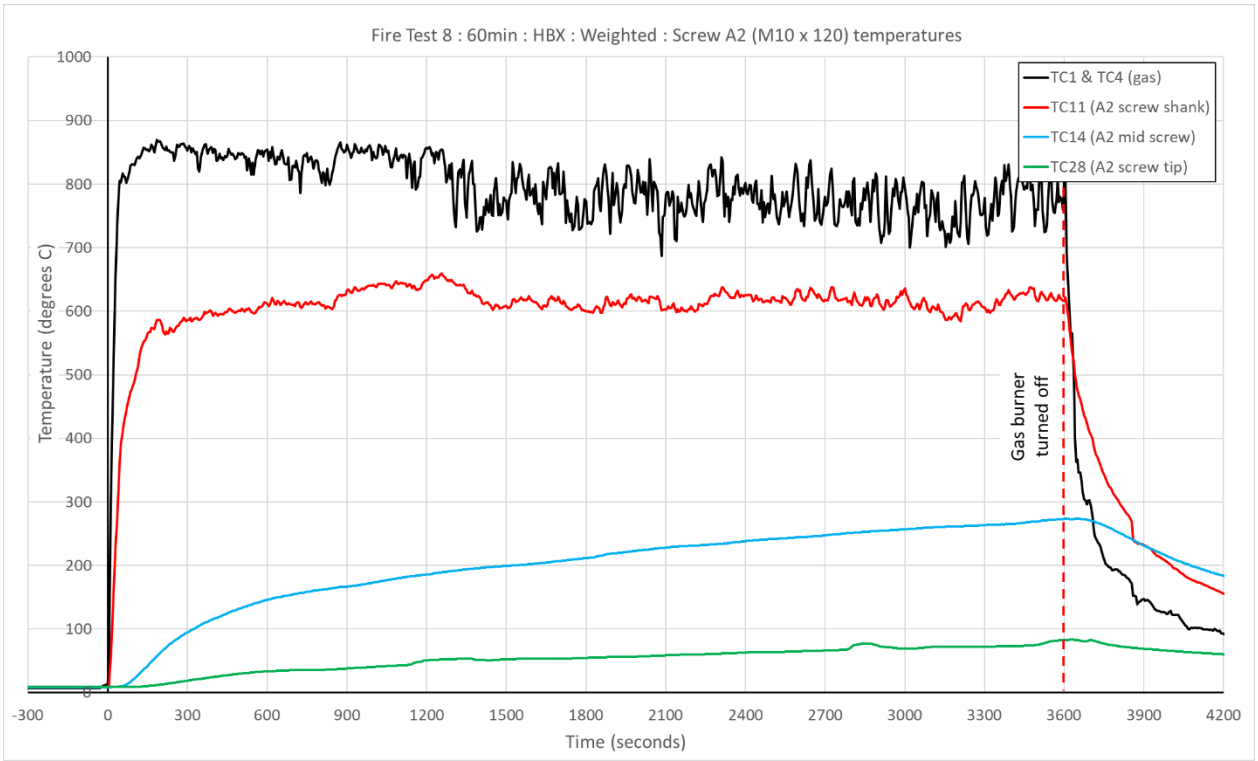


Figure 79 : FT8 Fixing type 1 (screw A2, shank, mid-point, and screw tip) and adjacent ceiling gas temperature profiles.

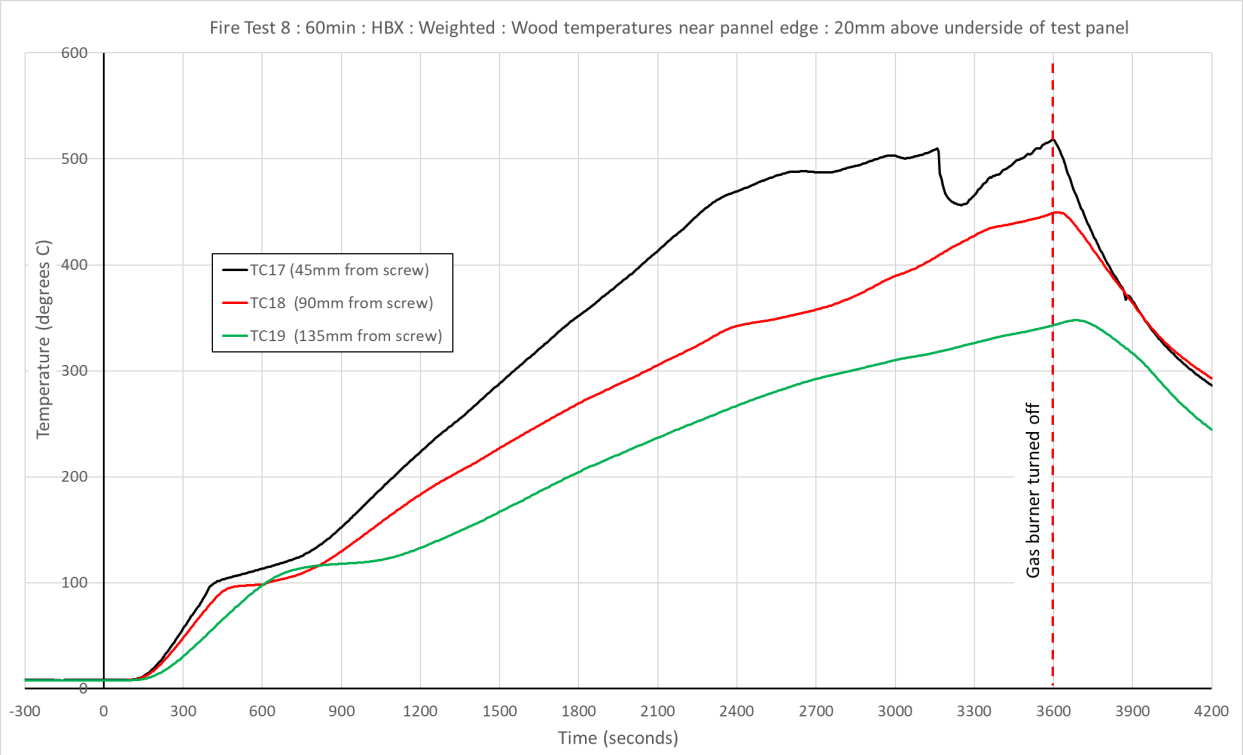


Figure 80 : FT8 Temperature profiles at 20 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

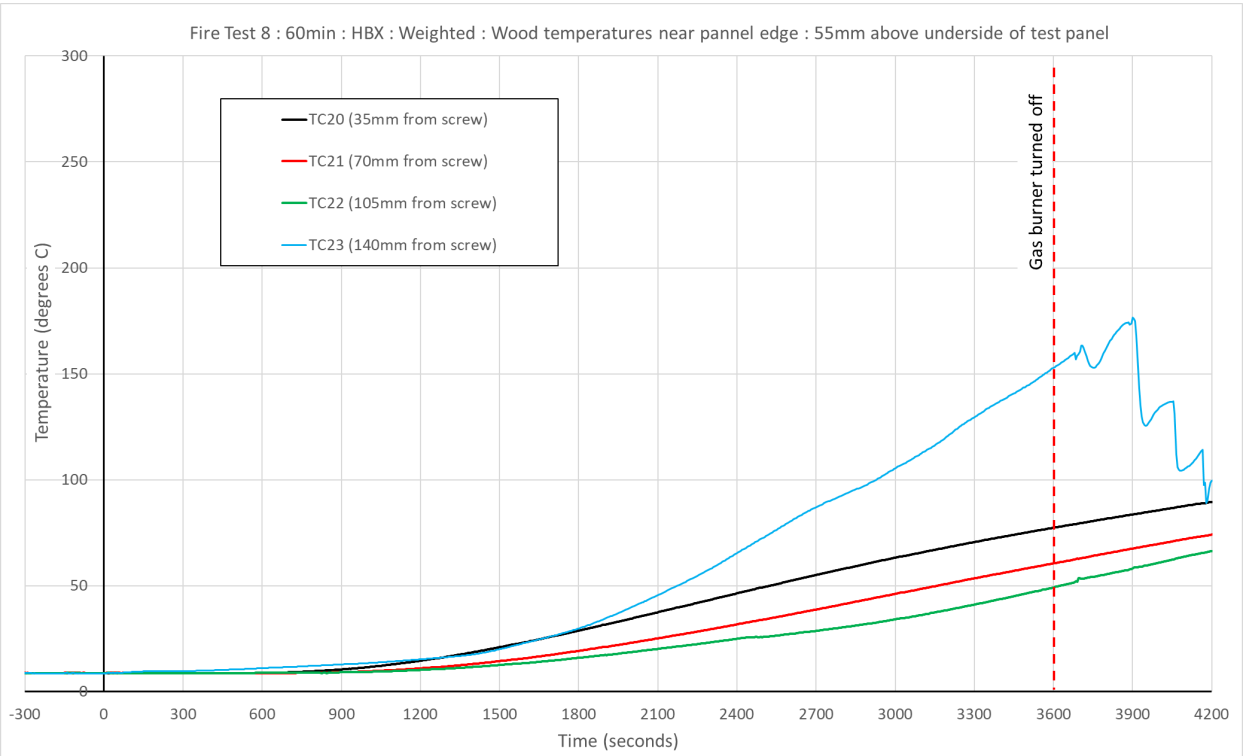


Figure 81 : FT8 Temperature profiles at 55 mm above the sample (fire side) at four distances (35, 70, 105 and 140 mm) from the nearest adjacent screw.

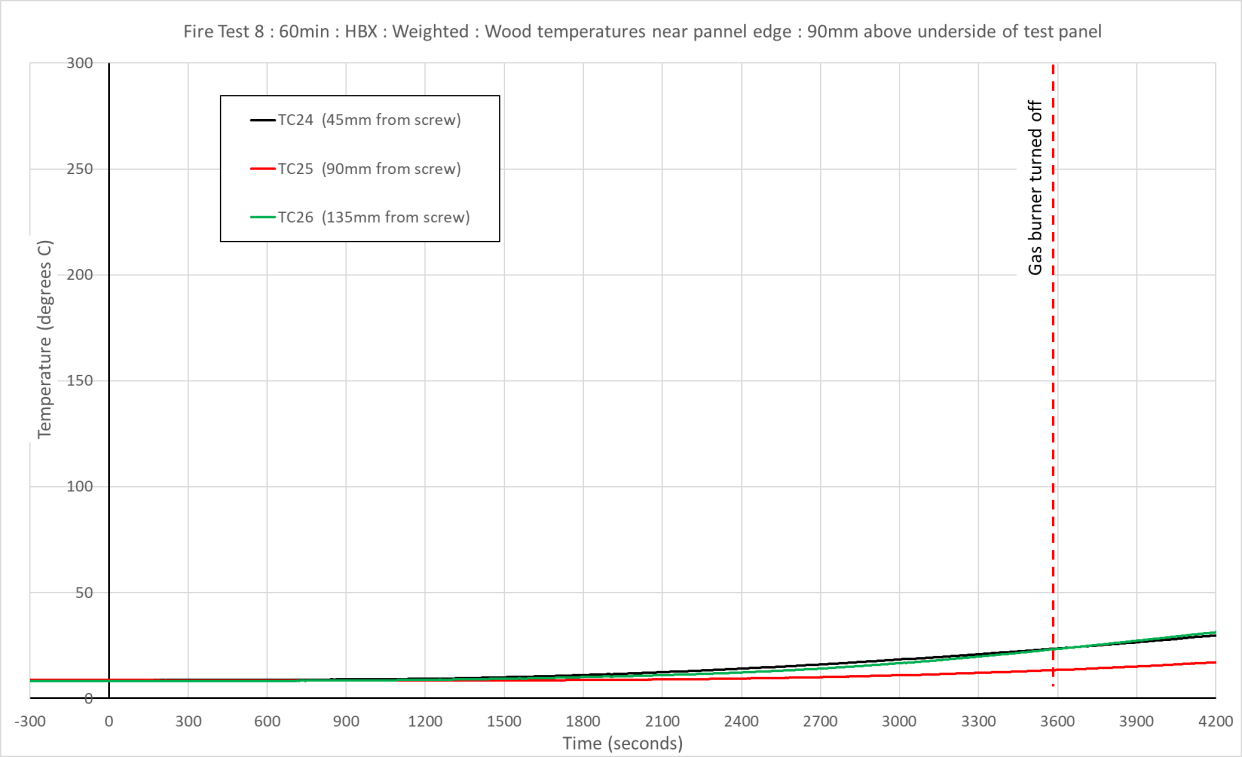


Figure 82 : FT8 Temperature profiles at 90 mm above the sample (fire side) at three distances (45, 90 and 135 mm) from the nearest adjacent screw.

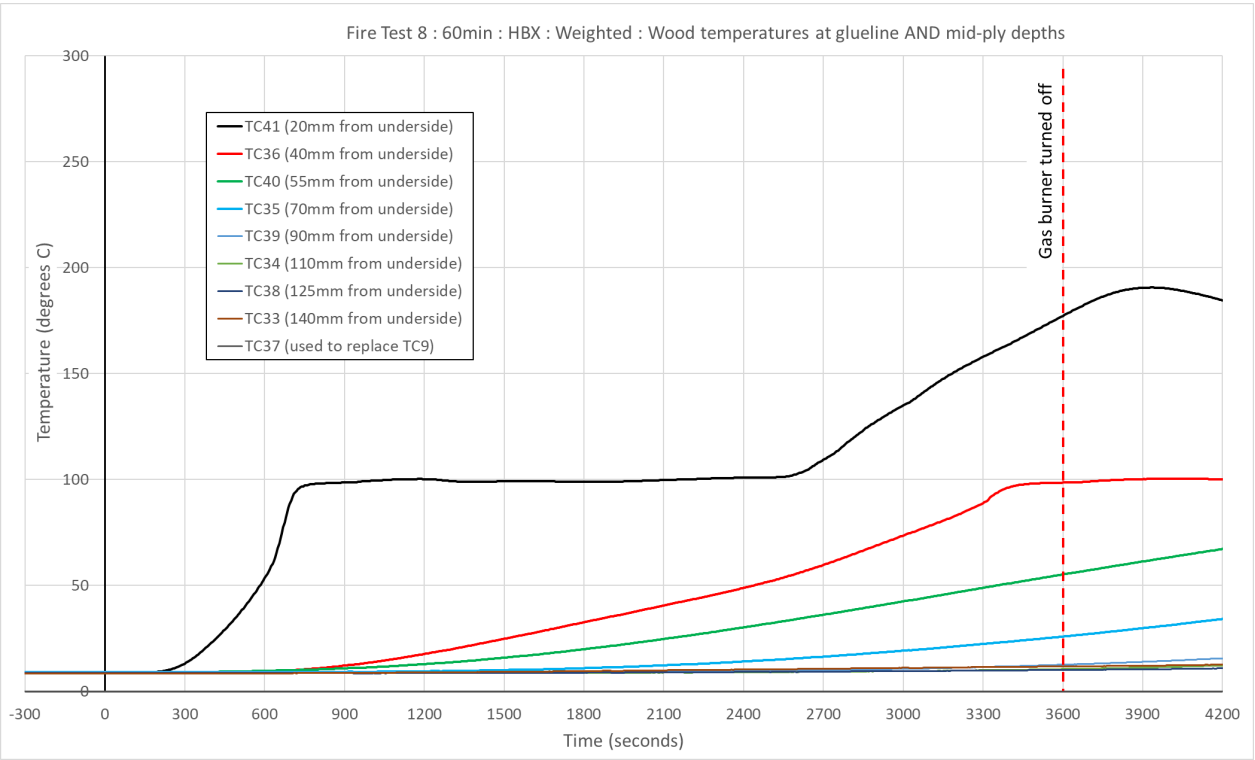


Figure 83 : FT8 Temperature profiles measured at each glueline and at the mid-point of each individual ply: test duration.

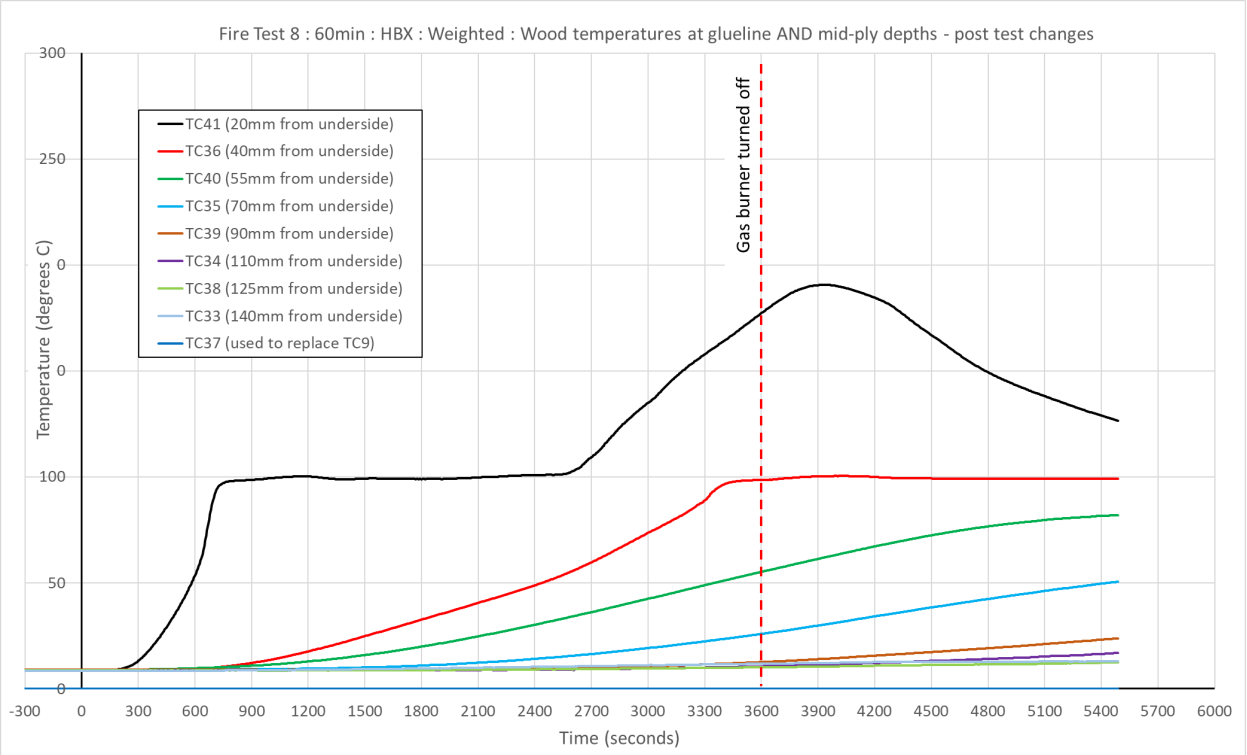


Figure 84 : FT8 Temperature profiles measured at each glueline and at the mid-point of each individual ply: post-test duration.

Thermocouple Locations:

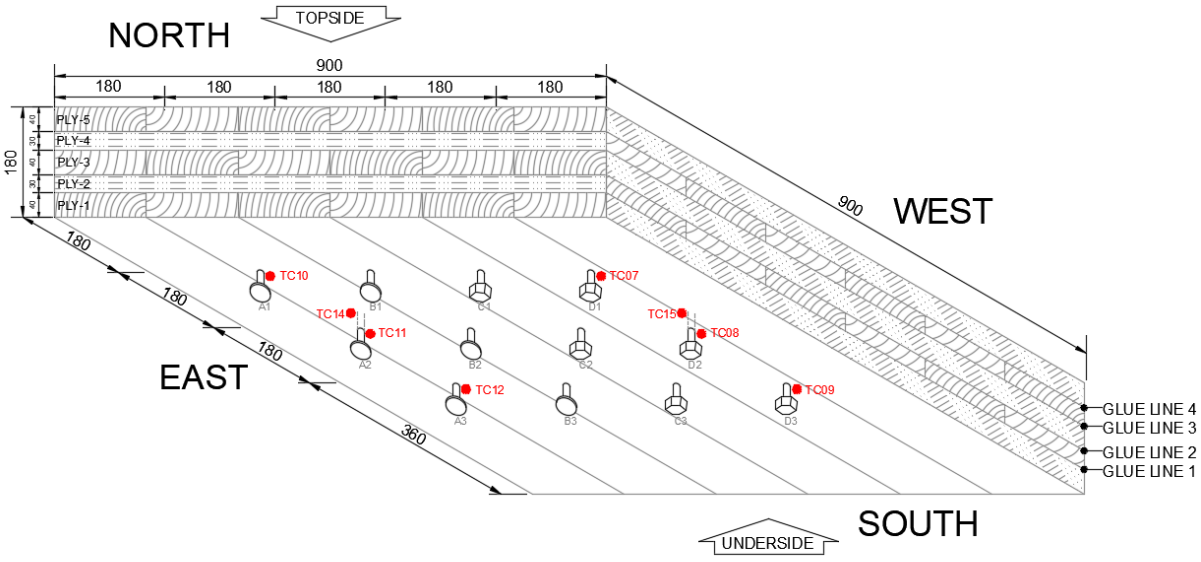


Figure 85 : Locations of thermocouples below each fire test sample.

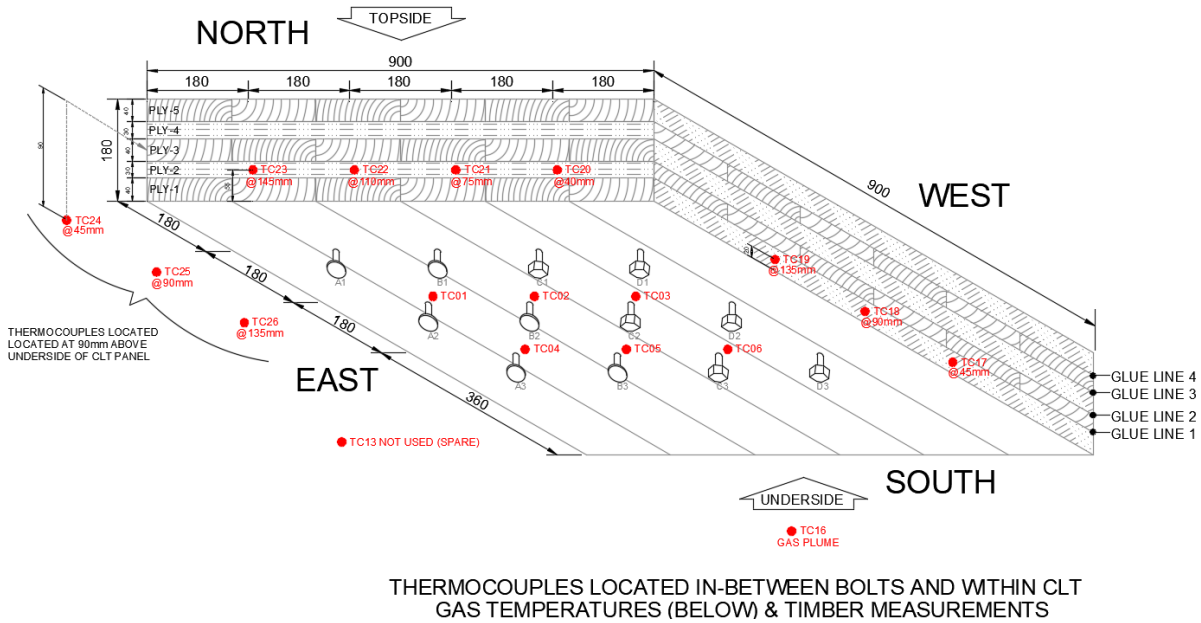
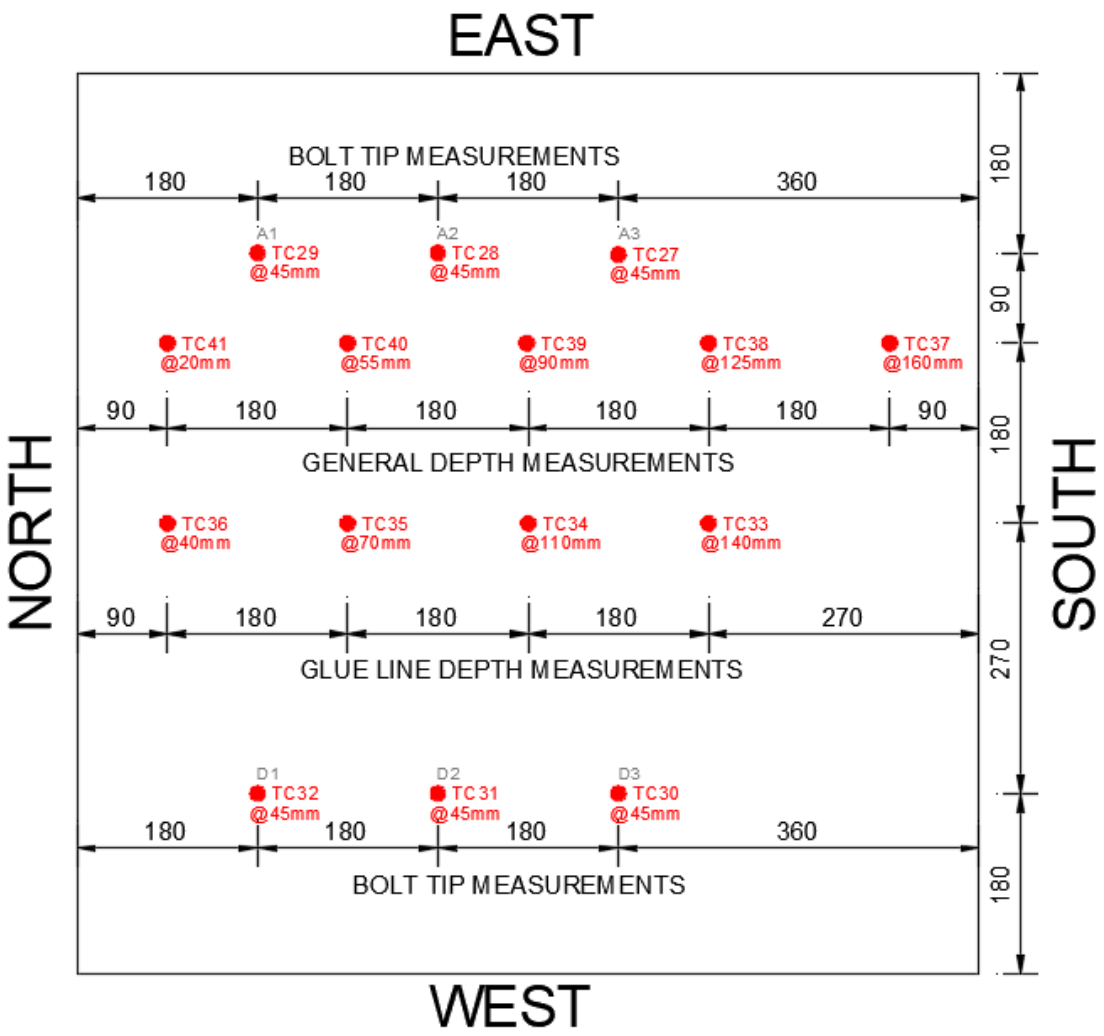


Figure 86 : Locations of thermocouples adjacent to fixings for each fire test sample.



PLAN VIEW OF THERMOCOUPLES MEASURING BOLT TIP, GLUE LINE AND GENERAL DEPTHS. (DEPTHS INDICATED FROM UNDERSIDE OF CLT)

Figure 87 : Locations of thermocouples from above to mid-ply, glue line, and bolt tips for each fire test sample.

Table TC01 : Location table of each thermocouple for fire tests.

Thermocouple Number	Measuring	Location: above / below CLT Soffit	Comments
TC01	Gas Temperature	Below CLT soffit	Located at 10mm below CLT soffit / within flame
TC02	Gas Temperature	Below CLT soffit	Located at 10mm below CLT soffit / within flame
TC03	Gas Temperature	Below CLT soffit	Located at 10mm below CLT soffit / within flame
TC04	Gas Temperature	Below CLT soffit	Located at 10mm below CLT soffit / within flame
TC05	Gas Temperature	Below CLT soffit	Located at 10mm below CLT soffit / within flame
TC06	Gas Temperature	Below CLT soffit	Located at 10mm below CLT soffit / within flame
TC07	Bolt D1 (M12x120mm)	Below CLT soffit	Located at soffit in bolt shank
TC08	Bolt D2 (M12x120mm)	Below CLT soffit	Located at soffit in bolt shank
TC09	Bolt D3 (M12x120mm)	Below CLT soffit	Located at soffit in bolt shank
TC10	Bolt A1 (M10x120mm)	Below CLT soffit	Located at soffit in bolt shank
TC11	Bolt A2 (M10x120mm)	Below CLT soffit	Located at soffit in bolt shank
TC12	Bolt A3 (M10x120mm)	Below CLT soffit	Located at soffit in bolt shank
TC13	Spare	Spare	Spare
TC14	Bolt A2 (M10x120mm)	Above CLT soffit	Located at the midpoint of the bolt (50mm from surface)
TC15	Bolt D2 (M12x120mm)	Above CLT soffit	Located at the midpoint of the bolt (50mm from surface)
TC16	Gas Plume	Below CLT soffit	Located at 200mm above ISO 9705 Burner (in flame)
TC17	General wood (Ply-3)	Above CLT soffit	Located at 90mm above CLT and 45mm in from West Face
TC18	General wood (Ply-3)	Above CLT soffit	Located at 90mm above CLT and 90mm in from West Face
TC19	General wood (Ply-3)	Above CLT soffit	Located at 135mm above CLT and 45mm in from West Face
TC20	General wood (Ply-2)	Above CLT soffit	Located at 55mm above CLT and 40mm in from North Face
TC21	General wood (Ply-2)	Above CLT soffit	Located at 55mm above CLT and 75mm in from North Face
TC22	General wood (Ply-2)	Above CLT soffit	Located at 55mm above CLT and 110mm in from North Face
TC23	General wood (Ply-2)	Above CLT soffit	Located at 55mm above CLT and 145mm in from North Face
TC24	General wood (Ply-1)	Above CLT soffit	Located at 20mm above CLT and 45mm in from East Face
TC25	General wood (Ply-1)	Above CLT soffit	Located at 20mm above CLT and 90mm in from East Face
TC26	General wood (Ply-1)	Above CLT soffit	Located at 20mm above CLT and 135mm in from East Face
TC27	Bolt A3 (M10x120mm)	Above CLT soffit	Located at the bolt tip and fed from above
TC28	Bolt A2 (M10x120mm)	Above CLT soffit	Located at the bolt tip and fed from above
TC29	Bolt A1 (M10x120mm)	Above CLT soffit	Located at the bolt tip and fed from above
TC30	Bolt D3 (M12x120mm)	Above CLT soffit	Located at the bolt tip and fed from above
TC31	Bolt D2 (M12x120mm)	Above CLT soffit	Located at the bolt tip and fed from above
TC32	Bolt D1 (M12x120mm)	Above CLT soffit	Located at the bolt tip and fed from above
TC33	Glue Line 1	Above CLT soffit	Located at the glue line 40mm from underside of CLT soffit
TC34	Glue Line 2	Above CLT soffit	Located at the glue line 70mm from underside of CLT soffit
TC35	Glue Line 3	Above CLT soffit	Located at the glue line 110mm from underside of CLT soffit
TC36	Glue Line 4	Above CLT soffit	Located at the glue line 140mm from underside of CLT soffit
TC37	General wood (Ply-5)	Above CLT soffit	Located in general timber 160mm from underside of CLT soffit
TC38	General wood (Ply-4)	Above CLT soffit	Located in general timber 125mm from underside of CLT soffit
TC39	General wood (Ply-3)	Above CLT soffit	Located in general timber 90mm from underside of CLT soffit
TC40	General wood (Ply-2)	Above CLT soffit	Located in general timber 55mm from underside of CLT soffit
TC41	General wood (Ply-1)	Above CLT soffit	Located in general timber 20mm from underside of CLT soffit

Appendix D – Scientific paper 1 :
'Reduction of load capacity of screw fixings into a timber soffit during and after fire'.

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Reduction of Load Capacity of Screw Fixings into a Timber Soffit During and After Fire

Dale Kinnersley[1,2] · **T. Richard Hull**[2] · **James L. D. Glockling**[2] · **Stuart Campbell**[1]

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Abstract
The load capacity of screw fixings supporting building services, such as sprinklers in Cross Laminated Timber (CLT) ceilings was tested before, during and after exposure to fire, to investigate the risk of detachment. The pull-out strength of screw fixing in ambient conditions, during and post-fire were investigated in relation to pull-out strength versus embedment depth. The relationships between pull-out strength have been reported as functions of screw fixing embedment depth, screw dimensions, and char formation. In the experimental study, samples of standard industrial CLT were tested with two distinct types of adhesives with typical construction industry screw fixings used for the suspension of Mechanical and Electrical (M&E) services. A purpose built fire-test rig was designed to expose screw fixings embedded into CLT to a fire in a ceiling mounted configuration. A series of eight fires were conducted, and the pull-out strength of each screw fixing was assessed during or after the fire. The reduction of load capacity can be conceptualised into two factors: The charring across the whole timber surface which was deeper close to the fixings leaving a fragile char which could be scraped off; and the weakening of the timber along the length of the screw thread, resulting from the higher thermal conductivity of the screw fixing. Both these effects increased as a function of the shank width of the screw. The outcome of this study is to inform guidance on the ability of screw fixings to support M&E services beneath timber ceilings in the event of fire.

Keywords CLT (Cross Laminated Timber) · Charring · Pull-out force · Embedment · Sprinkler · M&E screw fixing

1 Introduction

Engineered timber is gaining popularity in construction due to its availability in various forms, sustainability credentials, strength for primary structure, and visual appearance of structural components and exposed internal surfaces [1–5]. Timber is replacing materials such as steel and concrete which are non-combustible and have well understood structural fire performance. The increased use of timber in the UK has been driven by government

Extended author information available on the last page of the article

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in their vision for addressing climate change [6]. It is also seen as conferring enhanced sustainability to a building and the businesses that might operate from it, and so internal surfaces are likely to be exposed to create the aesthetic visual qualities demanded by modern construction. Where combustible surfaces are exposed, sprinklers have been shown to be effective provided the sprinkler system is appropriate for the risk and has been serviced and maintained correctly. Activation in the early stages of fire will provide control and cooling from the sprinklers to adjacent surfaces limiting fire spread [7–10].

It is acknowledged that timber has two mechanisms for burning: flaming combustion of the volatiles released through pyrolysis; and surface oxidation of char, often resulting in glowing combustion at the surface [7]. In some fires, the build-up of char will be sufficient to suppress flaming combustion. The temporary or permanent extinction of flaming without external intervention is sometimes described as auto-extinguishment [12–21]. Details related to heat flux conditions for auto-extinguishment differ amongst the research and variances in air flow velocities are seen to be a contributing factor.

Little guidance for fixing fire sprinkler and M&E services directly to the underside of timber ceilings is provided within standards. European sprinkler standards only cover fixing into concrete [22], industry guidance provides best practice for concrete, but does not cover timber [23], and British standards only consider concrete [24]. Sprinkler and M&E services are suspended using mechanical assemblies fixed to the underside of the structure. For concrete this is achieved using anchors (also known as expansion fixings) that connect to vertically threaded drop rods. Clamps are used for steel beams that also connect to drop rods where the services will be fixed using approved components, such as mild steel loop bands for pipework.

Recently, a 100 mm water pipe collapsed from a fixing failure which resulted in a fatality [25] and historically, the deaths of firefighters have been attributed to entanglement in cables and structures that fell from the ceiling during fire (Shirley Towers) [26], and requirements have been tightened to ensure this is not repeated (IEE Wiring Regulations) [27]. In addition to the obvious life-safety benefit of fire suppression, sprinklers are likely to enhance the ability of ceiling mounted systems to remain in place through the cooling effects of the sprinkler water.

Suppression systems are fitted into many different types of construction to support life-safety and for property and business protection [22, 28–33]. However, installation guidance has been developed around building types which do not include fixing directly to combustible structures.

Structural load capacity, bracket assemblies, and individual fixings need to be considered, not just for sprinkler systems, but for all services supported from timber ceilings.

This research looks at common industry screw fixings and loading capacities under ambient, fire, and post-fire conditions to provide information enabling considered decisions to be made for screw fixing into timber. It is very much needed, as lack of knowledge increases the risks that substantial loads may fall in the event of fire which might impede evacuation and response actions, allow fire spread across passive boundaries through broken ductwork, and increase consequential damage as fluid and gas bearing pipes incur mechanical damage.

Much is already known about fire in timber structures. Knowledge of timber fuel contributions with increased Heat Release Rate (HRR) [11, 34, 35], auto or self-extinguishment [12–21], surface spread and travelling fires [36], compartment fire dynamics [37–43], sprin-

kler protection [44–54] watermist suppression [55, 56] in CLT compartments, and structural capacity of timber in fire [57] have been investigated.

Most fixings used to secure M&E services to timber ceilings are of the metal screw type. The ability of the screw fixing to hold load is determined at the contact surface between the threads and wood into which it is embedded [58–68]. Metals are good conductors of heat and in fire screw fixings can transmit heat within, heating the timber and eventually turning timber to char and weakening the contact surfaces that assure its retaining capability. When a screw fixing is used to secure other metal framings in place, such as channel, brackets, or hanger rod this can increase the rate of heat uptake by the screw fixing, by substantially increasing the area for heat collection and conduction. For mounting services below a timber ceiling, larger diameter screw fixings are currently used to support larger loads as opposed to using more numerous or longer fixings.

Delamination of timber boards and char formation (mass loss) are known contributors to timber failure and structural loss during fire [15]. Delamination can occur in the area local to direct fire exposure from glue-line integrity failure and movement of the CLT boards. Screw fixing selection should therefore consider ply layer thickness and numbers in the determination of suitable embedment depths.

The aim of the study was to investigate key relationships between screw fixing diameter and embedment depth into exposed CLT for suspension of sprinkler systems and M&E services in ambient, fire and post-fire conditions. This was accomplished by load capacity testing during and after repeatable, and controllable fire testing. Test results captured data on pull-out forces, embedment depths, ply depths, and local temperatures. Knowledge gained from this study will provide information for improved guidance on screw fixing directly to timber, including CLT surfaces.

2 Potential Contributing Mechanisms of Timber Strength Loss

Wood is known to lose strength under the action of heat which can impact its ability to both support weight (loads in compression and tension), or hold in place devices attached by frictional fit, such as screws. Depending upon the temperatures reached some of these may result in reversible or irreversible loss of strength. The key mechanisms are:

- Water evaporation
- Thermal degradation of the polymer components of wood
- Char formation

Wood contains ‘free’ water in cell lumens (transit routes), and ‘bound’ water in the cell walls. When heated to 100 °C, free water can boil resulting in internal vapour pressure. Up to 150 °C bound water vaporises causing cell-wall shrinkage and the formation of microcracks; defects which act to reduce the wood’s capacity to carry load.

The incremental loss of strength due to polymer degradation is as follows:

- Between 200 °C and 300 °C hemicellulose, the flexible supporting mesh between plant fibres, loses rigidity.
- On further heating (300 °C to 400 °C) the main load-bearing polymer cellulose degrades

- Between 250 °C and 500 °C lignin, the 'glue' that binds together all fibres, softens and chars.

Char formation usually occurs between 300 °C and 400 °C during which time volatile gases escape leaving a smaller brittle carbonaceous char that cannot support compressive loads effectively. The loss of material during this process also contributes to overall loss of strength.

Table 1 below shows approximate retained bending strength for a dry softwood (e.g., pine) under standard test conditions. Exact values will vary by species, moisture content, and loading mode.

An additional consideration specific to cross laminated timber is the role played by the composite layers and the type of glue used to bond them together. Some glue types soften and melt under the action of heat (thermoplastic), and some decompose and char (thermoset). Both can be used for CLT assembly. A fixing into CLT could conceivably fail due to the premature loss of strength of the glue holding the lamina in place into which it is fixed, or the wood itself weakening.

3 Methods and Materials

3.1 Development and Design of Bespoke Test Rig

A medium-scale test rig was developed incorporating CLT test panels with a wall to ceiling interface which subjected the panels to a 100 kW fire from the burner as shown in Fig. 1. The scale of the test rig allowed for exposure of an area measuring 0.81 m^2 of ceiling in which to insert multiple test screw fixings. The primary heat source was a 170 × 170 × 170 mm gravel bed gas burner (as specified in ISO 9705 [69]), fuelled with propane gas via a Bronkhorst mass flow controller at a constant 100 kW. This was placed in contact with a vertical backing wall comprising sheets of 18 mm plywood which were gradually consumed during testing. This, together with a sacrificial section of CLT directly above the burner, helped ensure that the test samples of CLT were fully exposed to flames throughout the tests.

See Fig. 1 shows the test rig which measured 2050 mm (L) × 1200 mm (W) × 1450 mm (H) overall. To ensure flames were channelled up the rear wall to the underside of the ceiling, and minimise the influence of draughts within the laboratory, the burner was framed with vertical plasterboard baffles. Full design of the test rig is shown in Fig. 2.

Table 1 Typical temperature to strength relationship for dry softwoods

Temperature (°C)	Retained Bending Strength (%)	Dominant Polymer Change
20 (room temp)	100	none
100	90–95	moisture loss
150	75–85	hemicellulose softening
200	50–70	hemicellulose degradation starts
250	30–50	rapid cellulose weakening
300	10–20	cellulose pyrolysis
>350	<5	residual char, negligible strength

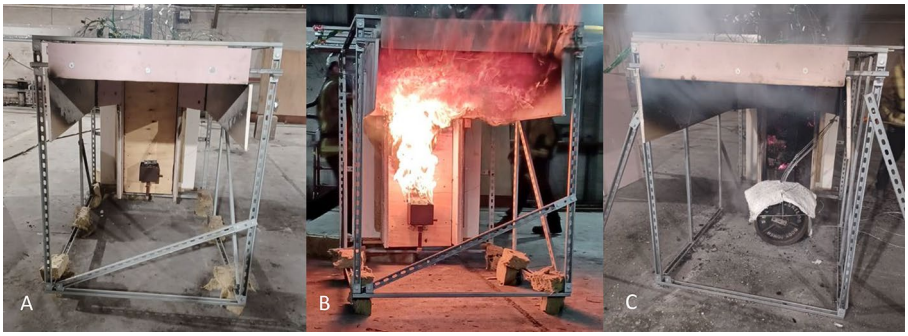

Fig. 1 The fire test rig. **A** Pre-fire, **B** During testing, and **C** Post-fire

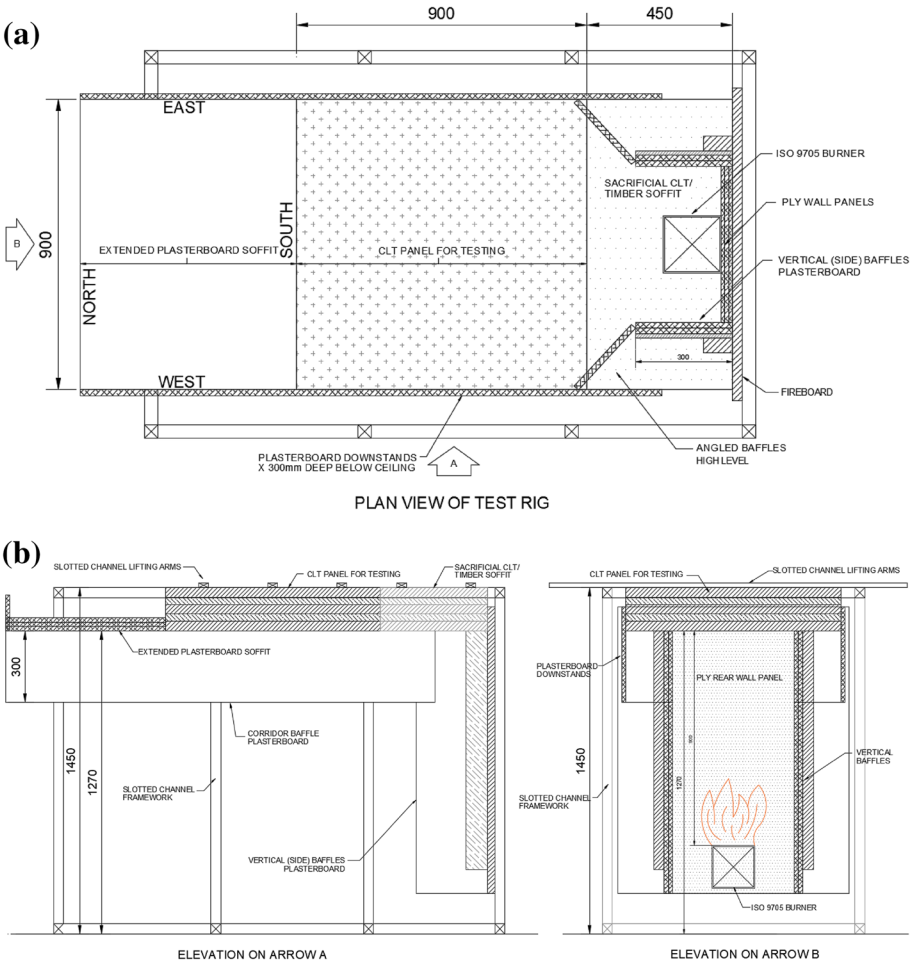

Fig. 2 Design of the bespoke test rig. Plan view and elevation on arrow '**A**' and '**B**.'

Type 'K' thermocouples were used to measure temperatures below and within the CLT sample. Thermocouples were connected to a DataTaker data logger which in turn was connected to a PC for data recording.

3.2 Test Samples

3.2.1 Cross Laminated Timber (CLT)

The CLT test panels were 900 mm × 900 mm × 180 mm thick, 5-ply (consisting of layers 40, 30, 40, 30, 40 mm thick), replicating a typical floor/ceiling composition. The CLT was made from European spruce having a density ρ of 385 kg / m^3 and was commercially available in Industrial Visual Quality (IVI) suitable for visually exposed applications. Panels were supplied with two different adhesive types consisting of standard Polyurethane (PU) adhesive, code HB S, and a heat-resistant modified-PU adhesive, code HB X which retains surface bonding at higher temperatures.

All panels including those for the ambient (baseline) tests were conditioned for a minimum of 4 weeks prior to testing in an enclosure controlled to 23 (±2) °C and 50 (±5)% relative humidity. Moisture content was measured and recorded in numerous locations on each panel and on the plywood rear wall before each test to ensure a common starting point for repeatability. Measurement of moisture content will be used as a cross reference to appreciate potential differences in results.

3.2.2 Fixings

Supporting sprinkler systems and M&E services into timber is not considered within current British or European standards [22 & 24]. BS EN 1995–1-1 (Eurocode 5) [70] allows for the ambient load carrying capacities to be evaluated through calculation but does not provide guidance on individual fixing requirements. Using European Test Approvals (ETAs) will provide fire test data on individual fixings tested in fire conditions. Fixings selected reflect the requirements of BS EN 12845:2015+A1:2019 [22] for sprinkler systems suspended from concrete. Table 40 in BS EN 12845 identifies minimum cross section area of fixing based on minimum load capacity, reflecting different pipe diameters/loads. The minimum length of fixing is also specified for concrete.

Using Table 40 [22], 10 mm (M10) and 12 mm (M12) diameter screw fixings were selected based upon a minimum load capacity of 500 kg at 20 °C. This will support pipework up to 150 mm diameter. Screw fixings chosen for testing were M10 and M12 coach screws at 100 mm and 120 mm long respectively, shown in Fig. 3 (A and B). Embedment depths were chosen to allow for maximum penetration into the CLT with 100 mm screw fixings embedded at 90 mm and 120 mm screw fixings embedded at 110 mm (into 3-ply layers) [58]. Smaller embedment depths were evaluated using M10 and M12 screw fixings at 70 mm and 50 mm (into 2-ply layers), respectively.

Standard hanger-type industrial screw fixings, known as stud screws and rod hangers (M10 and M12), shown in Fig. 3 (C, D, E and F) were evaluated at their full embedment depth of 60 mm and smaller 8 mm (M8) coach screws in the same configuration as Fig. 3 (B) at 100 mm long embedded to 90 mm.

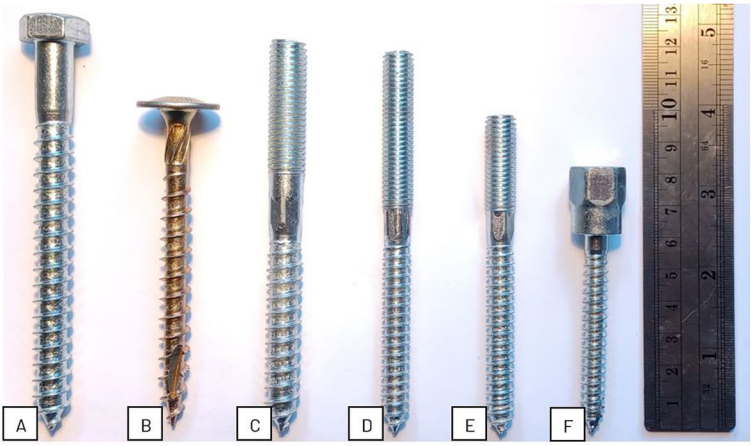

Fig. 3 Screw fixings tested **A**—M12 coach screw, **B** – M10 (M8) coach screw, **C** – M12 stud screw, **D** – M10 stud screw (long), **E** – M10 stud screw (short) and **F** – M10 rod hanger (M6 thread) supplied by Midfix

Screw fixings A, C, D, E and F are carbon steel with zinc coating to a thickness of 5 µm. Screw fixing B is hardened carbon steel, finished in zinc plating with a yellow chromate passivation to a thickness of 5 µm. It is acknowledged that there are a multitude of different screw types for use in timber that have different shank to thread ratios, including pitch angle and tip shapes.

The ability of a screw fixing to withstand an extractive force is dependent on the contact area of the thread with the wood, the amount of compression it exerts on the surrounding wood on insertion, and insertion angle in relation to the extraction force direction. Screw fixing engagement is also affected by the pilot hole (diameter and depth), shank diameter, thread diameter and pitch, all of which are variables which were investigated. M8 screw fixings were not piloted as advised by the fixing's supplier. Pilot details for coach screw fixings were as follows:

- M10 screw fixings (Fig. 3 B); 5.5 mm pilot hole – drilled full screw depth, 6.5 mm screw shank, 9.9 mm screw thread and 6.0 mm thread pitch.
- M12 screw fixings (Fig. 3 A); 7.0 mm pilot hole – drilled full screw depth, 8.8 mm screw shank, 11.7 mm screw thread and 5.0 mm thread pitch.

3.3 Measurements

3.3.1 Pull-out Force Testing in Ambient Conditions

With screw fixings inserted into the samples, pull-out forces were recorded for all CLT panels. Figure 4 shows load testing conducted using the Staht t25 digital pull tester to BS 8539 [24].

Table 2 below shows the tests performed at both ambient and post-fire condition for each combination of glue type fire exposure duration and fixing types. 13 tests in total were

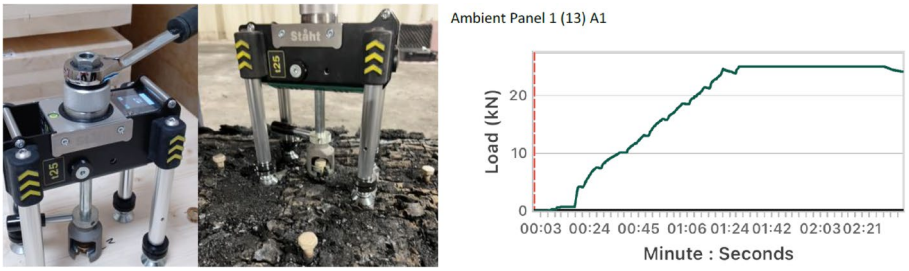

Fig. 4 Staht t25 digital pull tester device at ambient and post-fire testing with individual result print-out

Table 2 Experimental tests undertaken at both ambient and post-fire conditions

Test Reference	Test Condition (Ambient / Fire / Post-fire)	Glue Type (HBS / HBX)	Fire Test Duration (min)	Fixings Tested
AT1	Ambient	HBS	N/A	M10 & M12 Coachscrews
AT2	Ambient	HBX	N/A	M10 & M12 Coachscrews
AT3	Ambient	HBS	N/A	Stud-bolts & Rod-hangers
AT4	Ambient	HBX	N/A	M10 & M12 Coachscrews
AT5	Ambient	HBS	N/A	M10 & M12 Coachscrews
FT1	Post-fire	HBS	30	M10 & M12 Coachscrews
FT2	Post-fire	HBX	30	M10 & M12 Coachscrews
FT3	Fire / Post-fire	HBS	30	M10 & M12 Coachscrews
FT6	Post-fire	HBS	30	M8 Coachscrews, Stud-bolts & Rod-hangers
FT7	Post-fire	HBS	30	M8, M10 & M12 Coachscrews, with bracket components
FT4	Fire / Post-fire	HBX	60	M10 & M12 Coachscrews
FT5	Fire / Post-fire	HBS	60	M8 ,M10 & M12 Coachscrews
FT8	Fire / Post-fire	HBX	60	M10 & M12 Coachscrews

conducted, 5 ambient tests and 8 fire tests in order to allow pull-out force testing to be evaluated.

3.3.2 Fire Conditions

Eight panels were fire tested incorporating screw fixings, and 41 mineral insulated type 'K' thermocouples, 1.5 mm dia × 300 mm long, were installed in locations below and within the CLT panel as shown in Fig. 5 and Table 3. Thermocouples were installed parallel and perpendicular to the exposed heated surface to record ceiling gas, screw (tip, mid-point, head), glue line and general ply temperatures. It is acknowledged that thermocouple output can be impacted through installation positions and orientations [71–73]. With the exception of gas measuring thermocouples, all other thermocouples were installed on the non-fire side to reduce errors associated with conduction along the metal sheathing. To ensure thermocouples were touching the fixings at the mid-point and the tip, a jig was used for drilling accuracy until the drill tip contacted the embedded fixing. The thermocouple was then fully inserted, and contact was confirmed by metal-on-metal sound. The thermocouple was then retracted and insertion depth compared through measurement against drilling depth as a secondary check. Durations for fire testing were 30 and 60 min.

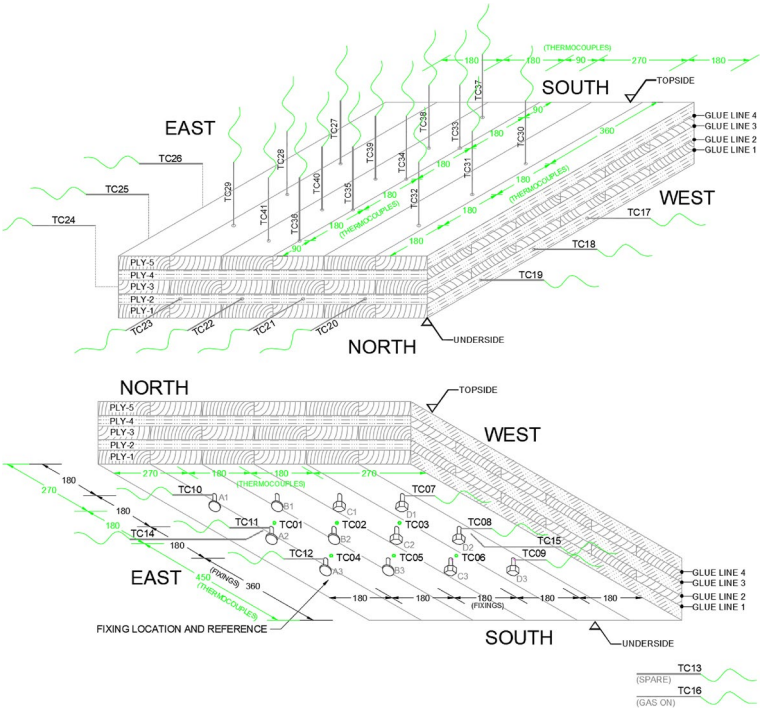

Fig. 5 Locations of thermocouples, Top: Internal locations. Bottom: Exposed/below the CLT panel. The depth of the thermocouples is detailed in Table 3

Of the 13 tests conducted, five used high temperature adhesive (HB X), and four tests FT3, FT4, FT5 and FT8, incorporated weighted testing of coach screws to a value of 150 kg. Tests FT3 and FT4 used M12 × 100 mm coach screws, and tests FT5 and FT8, M10 × 100 mm coach screws as detailed in Table 2.

A weight of mass 150 kg (1.471 kN) was selected for testing. This load represents a 150 mm diameter steel pipe 3.2 m long filled with water, commonly used in the sprinkler industry utilising a single bracket, meeting the requirements of BS EN 12845 [18].

Typical M&E service loads would also include ductwork, cable trays, conduit, filter units, sewerage pipework and potentially assemblies supported from the structure with different load requirements but were not specifically investigated in the current work.

3.3.3 Post-fire Conditions

Post-fire test measurements included pull-out force and char depths. Pull-out forces were measured once the sample had been allowed to cool for 60 min and took around 30 min to complete. Following pull-out testing, char was removed, and surface char depths were measured local to the screw fixings and in areas between the screw fixings.

Table 3 Location of thermocouples

Thermocouple Number	Insertion Top/Side/Below	Distance from exposed surface (mm)	Location Glueline/Mid-ply	Screw location Head/Midpoint/Tip	Comments
TC01	Below	15	N/A	N/A	Gas temperature measurements
TC02	Below	15	N/A	N/A	Gas temperature measurements
TC03	Below	15	N/A	N/A	Gas temperature measurements
TC04	Below	15	N/A	N/A	Gas temperature measurements
TC05	Below	15	N/A	N/A	Gas temperature measurements
TC06	Below	15	N/A	N/A	Gas temperature measurements
TC07	Below	N/A	N/A	Head	Fixing D1 (M12 x 120)
TC08	Below	N/A	N/A	Head	Fixing D2 (M12 x 120)
TC09	Below	N/A	N/A	Head	Fixing D3 (M12 x 120)
TC10	Below	N/A	N/A	Head	Fixing A1 (M10 x 120)
TC11	Below	N/A	N/A	Head	Fixing A2 (M10 x 120)
TC12	Below	N/A	N/A	Head	Fixing A3 (M10 x 120)
TC13	Spare	Spare	Spare	Spare	Spare
TC14	Below	N/A	N/A	Midpoint	Fixing A2 (M10 x 120)
TC15	Below	N/A	N/A	Midpoint	Fixing D2 (M12 x 120)
TC16	Side	N/A	N/A	N/A	Gas burner on measurement
TC17	Side	20	Mid-ply	N/A	Tip at 135 mm from Fixing D3
TC18	Side	20	Mid-ply	N/A	Tip at 90 mm from Fixing D2
TC19	Side	20	Mid-ply	N/A	Tip at 45 mm from Fixing D1
TC20	Side	55	Mid-ply	N/A	Tip at 140 mm from Fixing D1
TC21	Side	55	Mid-ply	N/A	Tip at 105 mm from Fixing C1
TC22	Side	55	Mid-ply	N/A	Tip at 70 mm from Fixing B1
TC23	Side	55	Mid-ply	N/A	Tip at 35 mm from Fixing A1
TC24	Side	90	Mid-ply	N/A	Tip at 135 mm From Fixing A1
TC25	Side	90	Mid-ply	N/A	Tip at 90 mm From Fixing A2
TC26	Side	90	Mid-ply	N/A	Tip at 45 mm From Fixing D3
TC27	Top	N/A	N/A	Tip	Fixing A3 (M10x120)
TC28	Top	N/A	N/A	Tip	Fixing A2 (M10 x 120)
TC29	Top	N/A	N/A	Tip	Fixing A1 (M10 x 120)
TC30	Top	N/A	N/A	Tip	Fixing D3 (M12 x 120)
TC31	Top	N/A	N/A	Tip	Fixing D2 (M12 x 120)
TC32	Top	N/A	N/A	Tip	Fixing D1 (M12 x 120)
TC33	Top	140	Glueline	N/A	General measurement from exposed surface
TC34	Top	110	Glueline	N/A	General measurement from exposed surface
TC35	Top	70	Glueline	N/A	General measurement from exposed surface
TC36	Top	40	Glueline	N/A	General measurement from exposed surface
TC37	Top	160	Mid-ply	N/A	General measurement from exposed surface
TC38	Top	125	Mid-ply	N/A	General measurement from exposed surface
TC39	Top	90	Mid-ply	N/A	General measurement from exposed surface
TC40	Top	55	Mid-ply	N/A	General measurement from exposed surface
TC41	Top	20	Mid-ply	N/A	General measurement from exposed surface

4 Results and Discussion

4.1 Benchmark Ambient Pull-out Test Results

4.1.1 Coach Screws

To provide baseline pull-out-force measurements, four tests were initially conducted using pristine (non-fire tested) examples of both the HB S and HB X panels. For each panel, three of each screw fixing type (M10 × 100 mm, M10 × 120 mm, M12 × 100 mm and M12 × 120 mm) were embedded and then pull-out force determined at penetration depths of 50 mm, 70 mm, 90 mm and 110 mm. All screw fixings were equidistantly spaced and positioned so as not to lie along the joint of two wood segments.

Pull-out forces measured as a function of embedment depth are shown in Figs. 6 and 7. These illustrate the positive linear relationship between pull out force and embedment depth for the two panel types and two coach screw diameters. The increased pull-out resistance of the M12 coach screw relative to M10 coach screws is also evident for embedment depths

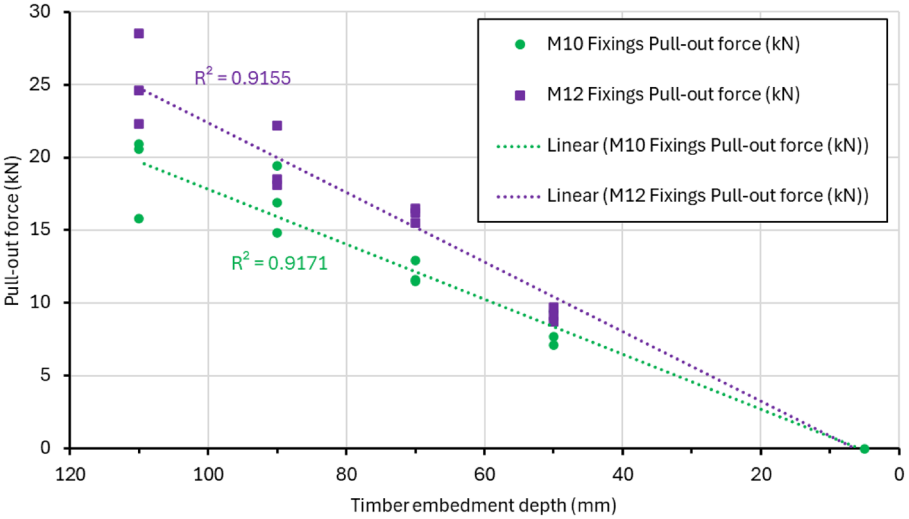

Fig. 6 Pull-out force versus embedment depth for HB S adhesive, ambient conditions

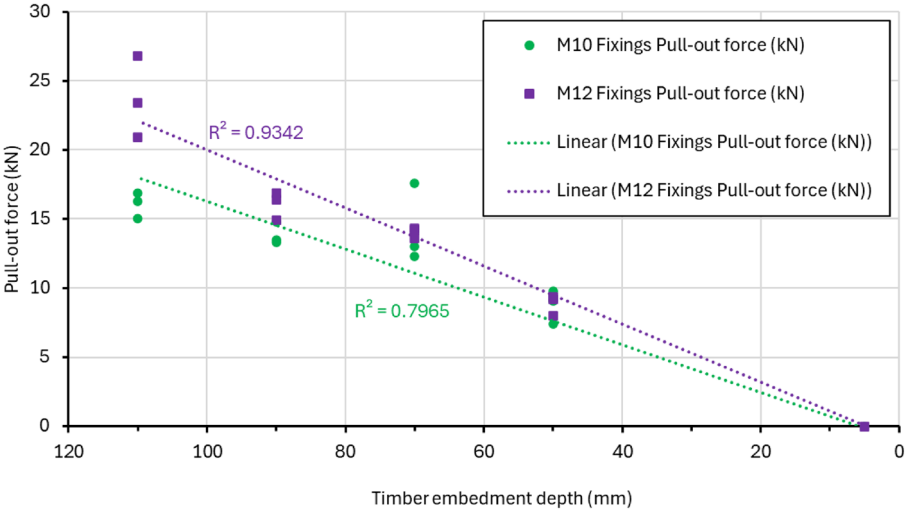

Fig. 7 Pull-out force versus embedment depth for HB X adhesive, ambient conditions

greater than 50 mm. It is apparent that there is very little difference in results between the two different adhesives shown in the graphs.

It is assumed that the observed variability in pull out force at each depth is attributed to intrinsic variations in the physical properties of the wood (density, resin content, moisture content, structural inhomogeneity) and the panel's construction (multiple wood lengths glued into multiple layers). Sub-surface knots may also have been a factor.

Results confirm that prior to fire exposure the capacities of the coach screws are capable of supporting the specified water filled sprinkler pipework (i.e. 4.9 kN (500 kg) at 20 °C (ambient) conditions detailed in Table 40 of BS EN 12845 [22].)

The linear line of best fit has been extended to reach an embedment depth of 5 mm with zero load capacity as it is confirmed that at this embedment depth the fixing holds its own weight.

4.1.2 Stud Screws and Rod Hangars

Stud screws and rod hangers were assessed at their maximum embedment depth of 60 mm with holes pre-drilled as advised by the supplier (see Table 2, Fig. 3 (C-F) and Fig. 8). These screw fixing types are currently supplied for suspension of M&E services in timber construction. Figure 8 shows the pull-out force results for each stud screw and rod hanger at ambient temperature. References/naming convention (A1 to D3) shown in Fig. 8 relate to location on the test panel not the fixing types detailed in Fig. 3.

Results show load capacities at both ambient (baseline) and post-fire in Table 4. Most notable from the results are:

- The loss of strength from ambient to post-fire in the stud screws, with M12 screws losing 100% load capacity and all others greatly reduced.
- The variation that can exist in pull out force between screw fixing of identical diameter and embedment depth.

4.2 Fire Challenge Assessment & Charring

Ideally the fire challenge tests would mimic the conditions in a fully developed fire in a full-scale compartment. Gas temperatures alone cannot describe the heat transfer into the CLT surfaces. Full-scale testing of CLT compartments and the potential for a different fuel source (propane) would provide a different thermal contribution from the fuel and re-radiation from

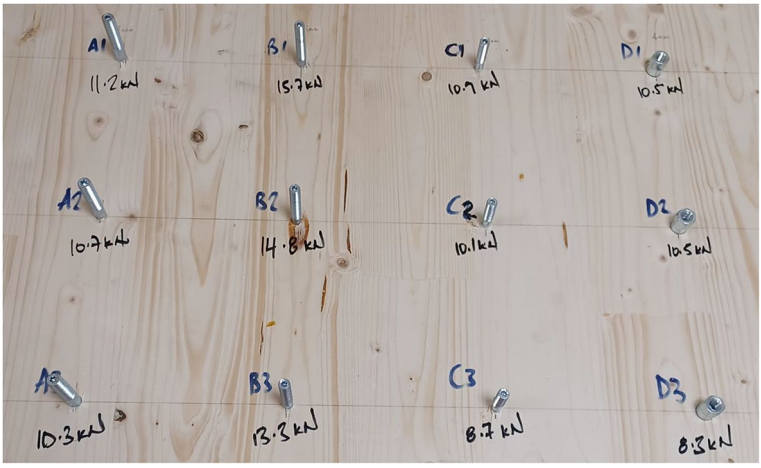

Fig. 8 Standard Industrial-type screw fixings for M&E services (ambient conditions) (A1-3 M12 stud screw, B1-3 M10 stud screw-long, C1-3 M10 stud screw-short, and D1-3 M10 rod hanger)

Table 4 Average pull-out results for standard industrial stud screw and rod hanger fixings (showing uncertainty expressed as a ± 1 Standard Deviation (SD) showing the amount of variation in the measured results from the mean value)

Fixing type	Initial embedment depth (mm)	Mean ambient pull-out force (kN) ± 1 SD	Post-fire embedment depth (mm)	Mean post-fire pull-out force (kN) ± 1 SD
M12 Stud bolt	60	10.7 ± 0.5	39	< 0.1
M10 Studbolt-long	60	14.6 ± 1.2	43	0.7 ± 0.6
M10 studbolt-short	60	9.9 ± 1.1	39	0.1 ± 0.1
M10 Rod hanger	60	9.8 ± 1.6	43	2.5 ± 1.7

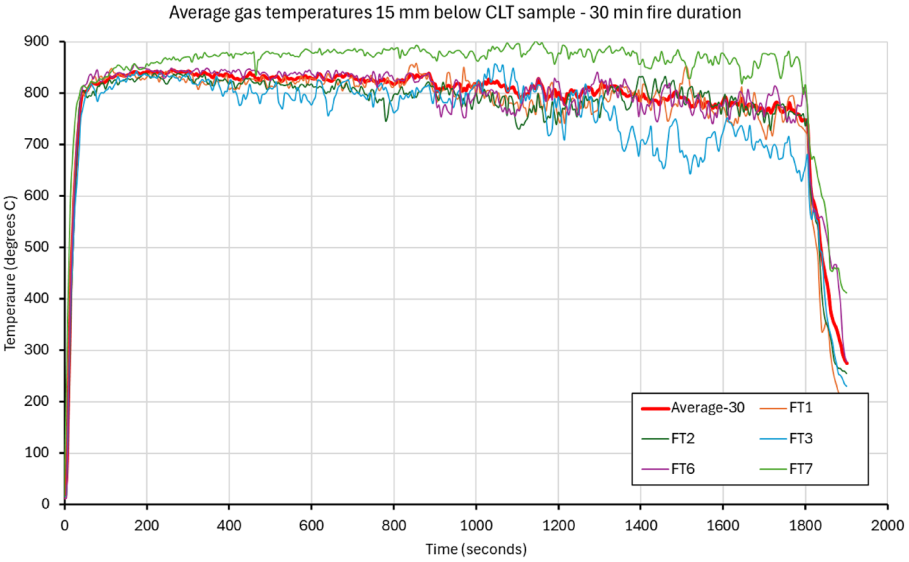

Fig. 9 Average gas temperatures measured 15 mm below the underside of the CLT sample for 30 min, tests (FT1, 2, 3, 6 and 7)

adjacent surfaces. However, combining gas temperature data with the resulting char rates could give some indication of how the rig approximates to reported full-scale referenced tests.

4.2.1 Gas Temperatures

Gas/flame temperatures were measured 15 mm below the wood sample around the screw fixings shown in Fig. 5, (TC01 – TC06 inclusive). Temperature results for fire tests were all very similar. Figures 9 and 10 show average temperature data consistent with a fully developed compartment fire (i.e. > 600 °C). Temperatures were approximately consistent for 30 min for tests FT1, FT2, FT3, FT6 & FT7 and 60 min for tests FT4, FT5 & FT8. Gas temperatures were observed to be around 100 °C greater closer to the burner at TC04, 05 & 06, than those further from it at TC01, 02 & 03. This resulted in lower pull-out forces for

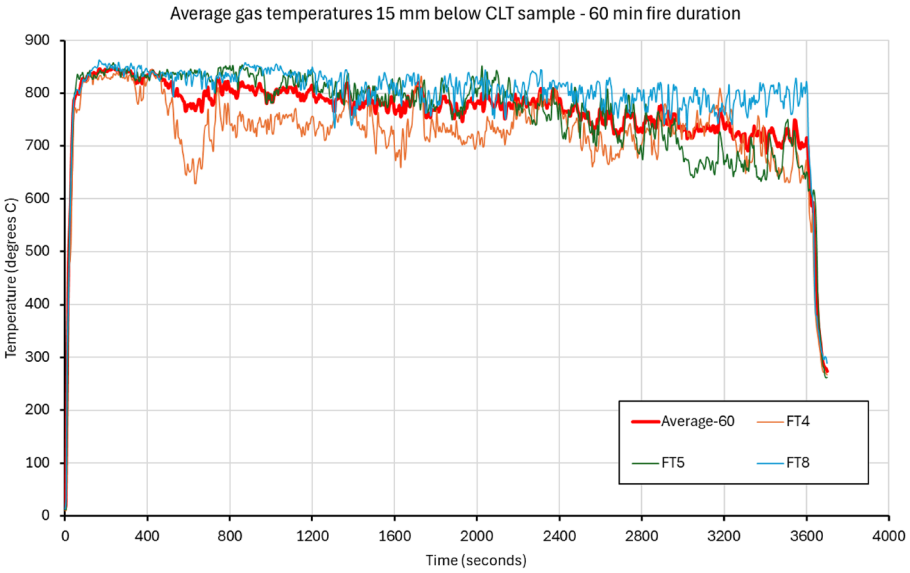

Fig. 10 Average gas temperatures measured 15 mm below the underside of the CLT sample for 60 min, tests (FT4, 5 and 8)

the screw fixings located closer to the burner. For example, in FT1, three M10 × 120 mm screw fixings experienced pull-out forces of 9.1, 9.5 and 12.5 kN with locations 360, 540 and 720 mm from the S edge (see Fig. 5) moving away from the burner. These results are presented as an average value of 10.4 kN ± 1.5 Standard Deviation (SD).

It can be seen from Fig. 9 that the temperature for FT3 is lower than other 30 min fire tests. This was caused by frost developing on the cylinder affecting gas flow through the mass flow controller, causing a drop in output temperature (< 100 kW) from the burner at ~ 700 s. FT7 shows a higher temperature output which resulted from warming the cylinder during the test, providing a very steady burner output of 100 kW.

Test FT4 shows a lower than average gas temperature for the 60 min duration and a drop off at ~ 500–700 s. Burner output remained constant at 100 kW for 45 min until a drop off due to frost build up on the cylinders. The drop off at ~ 500 s could potentially be due to early char formation slowing contribution from the wood, but this is not proven in these experiments.

4.2.2 Char Formation

Char depths were measured following pull-out tests. Each sample had char carefully scraped away as shown in Fig. 11, using a wallpaper scraper and hand brush. To determine embedment depth on the resulting uneven surface, pilot holes were drilled through the full depth of the sample and measurements were taken of the remaining timber depth to provide char depth measurements shown in Fig. 18, not dissimilar to the procedure used by Brandon et al. [77].

Measuring consisted of using a 3 mm diameter rod pushed through the pilot hole to a small flat circular plate ~ 15 mm diameter that sat on the face of the charred surface. The

Fig. 11 CLT panel with the char removed around the screw fixings (left) and pilot drill holes for remaining slab thickness measurements (right)

depth of insertion from the opposite face from the fire was marked on the rod then measured and recorded with digital callipers. Where screw fixings were removed from the sample, the circular plate was inserted into the depth of the 'dishing' and the same measuring principal applied. Figure 12 shows the details for char measurements taken.

Figures 13 and 14 show loss of structural material (char) from the surface of the sample. They also show the 'dishing' effect at the surface and blackening internally where screw fixings were installed. The extent of charring with depth is difficult to define, but internal temperatures measured (Table 7 and Fig. 18) confirm discolouring and charring, as described by Drysdale [76]. However, reduced pull-out results indicate that less unburnt timber is present around the M12 screws than M10.

Table 5 (general) and Table 6 (at fixings) show loss of material due to char formation on the surface, which are slightly less than measurements recorded at the ceiling by Hadden et al. [13].

Figure 15 shows a close-up of the charring effect of heat conduction through the screw fixings, with greater charring at the M12 coach screws than the M10 coach screws, which was observed across all fire tests. The M10 coach screw shows partial charring through the screw embedment and rupture of the wood fibres towards the location of the tip.

Post-fire test results confirm that the larger diameter of the screw fixing, the greater the loss of char local to its insertion area.

Whilst Tables 5 and 6 reference a typical charring rate between 0.6–0.7 mm/min, it is acknowledged that charring rates are higher in the initial stages of a fire and reduce as the char layer forms. It is confirmed that charring rates differ between wood species and fire exposure, where charring rate increases with heat flux [78].

4.2.3 Fire Challenge Conclusions

Mean gas temperatures of ~ 800 °C show the fire to be significant, but the average charring rate at locations remote from the screw fittings of 0.32 mm/min is less than that measured during full-scale tests conducted by Haddon [13] of 0.6 mm/min at the ceiling. This would suggest that the fire conditions in this study are less severe than for a typical well-developed

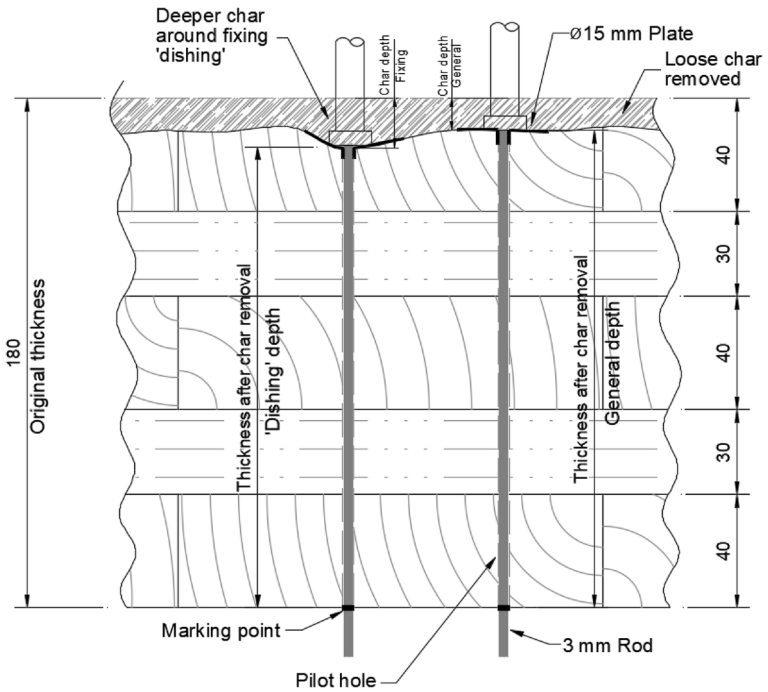

Fig. 12 Shows how the char depths were measured with a 3 mm diameter rod pushed through pilot holes to the 15 mm diameter plate with marking point

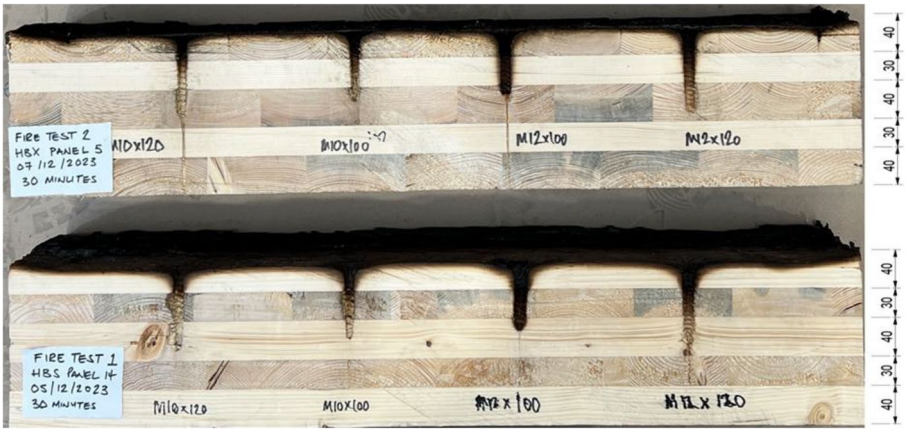

Fig. 13 Cross section of tests FT1 and FT2 showing loss of material at the surface of the CLT panel and the 'dishing' effect localised around the screw fixings after 30 min fire exposure

Fig. 14 Cross section of tests FT4 and FT5 showing loss of material at the surface of the CLT panel and the 'dishing' effect localised around the screw fixings after 60 min fire exposure

Table 5 Average loss of structural material measured in locations between screw fixings for both adhesive types after the fire

Location of measurement (Figure 11)	Average loss (mm) ± 1 SD at 30 min	Average loss (%) from sample (180 mm) at 30 min	Equivalent charring rate mm/min	Average loss (mm) ± 1 SD at 60 min	Average loss (%) from sample (180 mm) at 60 min	Equivalent charring rate mm/min
Location 01 (general area)	11 ± 1.2	6	0.37	18 ± 0.8	10	0.3
Location 02 (general area)	14 ± 1.6	8	0.47	20 ± 2.4	11	0.33
Location 03 (general area)	11 ± 0.9	6	0.37	18 ± 1.2	10	0.3
Location 04 (general area)	12 ± 1.4	7	0.4	20 ± 2.6	11	0.33
Location 05 (general area)	9 ± 1.2	5	0.3	21 ± 2.4	12	0.35
Location 06 (general area)	11 ± 1.6	6	0.37	20 ± 0.5	11	0.33
Note: 0.6 -0.7 mm/min is typical of the literature mass loss rates for timber [72 & 78]						

Table 6 Average loss of structural material measured at screw fixing positions for both adhesive types after the fire

Fixing reference and embedment depth (Figure 11)	Average loss at fixing (mm) ± 1 SD at 30 min	Average loss (%) from sample (180 mm) at 30 min	Equivalent charring rate mm/min	Average loss at fixing (mm) ± 1 SD at 60 min	Average loss (%) from sample (180 mm) at 60 min	Equivalent charring rate mm/min
A1 M10 x 120 mm (110 mm Embedment)	15 ± 1.7	8	0.5	24 ± 1.9	13	0.4
A2 M10 x 120 mm (110 mm Embedment)	17 ± 1.7	9	0.57	27 ± 1.6	15	0.45
A3 M10 x 120 mm (110 mm Embedment)	17 ± 3.3	9	0.57	30 ± 2.11	17	0.5
B1 M10 x 100 mm (90 mm Embedment)	15 ± 1.6	8	0.5	23 ± 0.9	13	0.38
B2 M10 x 100 mm (90 mm Embedment)	16 ± 0.5	9	0.53	29 ± 1.7	16	0.48
B3 M10 x 100 mm (90 mm Embedment)	17 ± 1.2	9	0.57	30 ± 1.2	17	0.5
C1 M12 x 100 mm (90 mm Embedment)	16 ± 2.6	9	0.53	29 ± 3.6	16	0.48
C2 M12 x 100 mm (90 mm Embedment)	19 ± 2.6	11	0.63	27 ± 3.6	15	0.45
C3 M12 x 100 mm (90 mm Embedment)	20 ± 2.4	11	0.67	32 ± 1.6	18	0.53
D1 M12 x 120 mm (110 mm Embedment)	16 ± 1.4	9	0.53	28 ± 1.6	16	0.47
D2 M12 x 120 mm (110 mm Embedment)	19 ± 1.7	11	0.63	32 ± 3.1	18	0.53
D3 M12 x 120 mm (110 mm Embedment)	18 ± 0.7	10	0.6	29 ± 7.3	16	0.48
Note: 0.6 -0.7 mm/min is typical of the literature mass loss rates for timber [72& 78]						

fire. This may be due to the design of the test rig and the lack of oxygen (needed for char oxidation) at the timber surface. This deviation needs to be considered as a significant factor in the overall conclusions drawn from this study.

Fig. 15 Enlarged view of internal charring through heat conduction at the coach screws

4.3 CLT and Fixing Temperatures

4.3.1 CLT Temperatures

Measurements within the sample show an increase in temperature in all 5-ply layers. After cut-off of the burner gas supply, internal temperatures continued to rise slowly which may contribute to further loss of load capacity post-fire extinguishment. This can be seen in Fig. 16 for measurements at 20 mm above the exposed CLT and is consistent with findings by Gernay et al. [50] with general locations of thermocouples shown in Fig. 17. It is also noticeable for tests FT1, 2, 3, 4, 7 and 8 that temperature remains at a constant 100 °C for a period of time, until the moisture is driven off, before temperature starts to increase. Tests FT5 and FT6 show inconsistent results which could be due to the inconsistencies in CLT moisture condition at the time of the test.

In all but one fire test, no fragments of char were seen to fall off the test panels. Fire test 8 had small fragments of ~ 10 mm depth of char, fall from a very small area of the panel < 10%. In test FT4 (a 60 min test), delamination at the glue line in a sacrificial HB S specimen (directly above the burner and not part of the test sample) was observed.

4.3.2 Screw Fixing Temperatures

Tests FT1, 2, 3, 4, 5 and FT8 utilised coach screws shown in Fig. 11. A consistent temperature rise from exposed screw head shank to the embedded screw tip was observed as shown in Table 7 and Fig. 18.

Measured temperatures at the screw head shank, mid-point and tip for coach screws (M10 and M12) for tests FT1, 2, 3, 4, 5 and 8 are shown in Table 7 and Fig. 18 at 30- and 60-min fire durations. At 30 min, screw head shank temperatures ranged from 554—717 °C, mid-point ranged from 133 – 292 °C, and tip ranged from 42—167 °C, with an average gas tem-

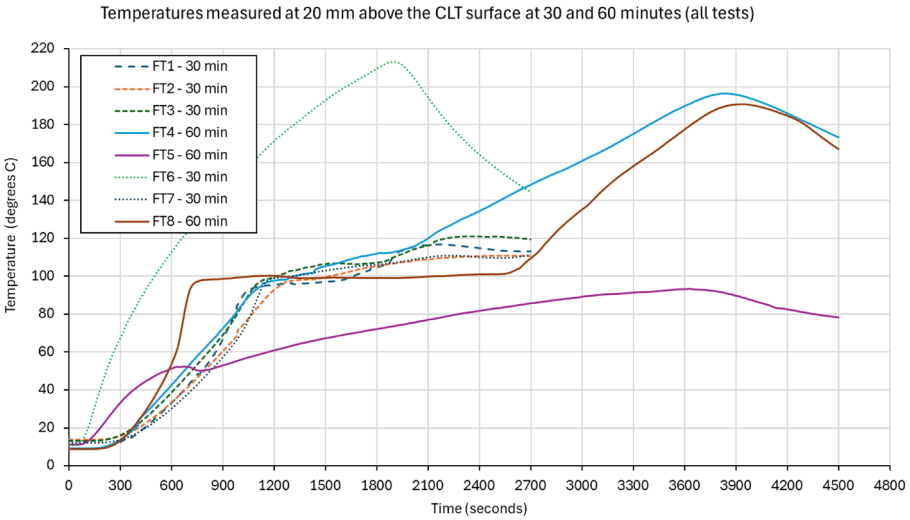

Fig. 16 Measurements of temperature within the CLT test sample at 20 mm above the exposed CLT surface at 30 and 60 min

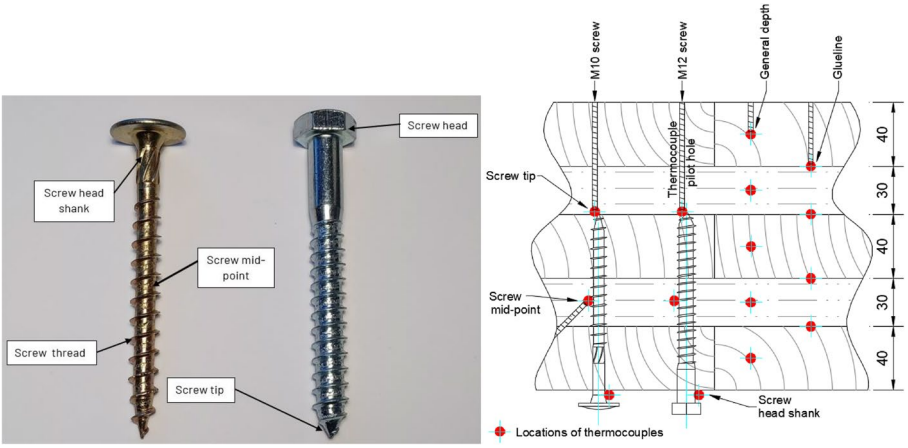

Fig. 17 Shows coach screws under test (left) and locations for thermocouples at different screw fixing locations, general ply depths and glue line (right)

perature ranging from 658—811 °C. At 60 min, screw head shank temperatures ranged from 583—690 °C, mid-point ranged from 243 – 345 °C, and tip ranged from 57—127 °C, with an average gas temperature ranging from 651—823 °C. In stark contrast to the lower thermal conductivity of timber, much higher temperatures were reached adjacent to the screws which would account for the degradation of the load capacity of the timber as detailed by Khelifa et al. [74]. The mid-point screw temperatures at a depth of 55 mm, are observed to be much greater than for the timber at the same time and depth shown in Table 7 and Fig. 18. Measurements within the timber confirm larger diameter M12 screws consistently result in higher temperatures than M10.

Table 7 Average gas temperatures, wood temperatures at 55 mm above the exposed CLT sample and fixing temperatures in three locations at 30 and 60 min

Test Reference/Measurement location	FT1 M10 / M12	FT2 M10 / M12	FT3 M10 / M12	FT4 M10 / M12	FT5 M10 / M12	FT8 M10 / M12
Average gas temperature @ 30 min (ºC)	725	736	658	718	773	811
Wood temperature, 55 mm depth @ 30 min (ºC)	13	20	19	19	15	20
Fixing head/shank temperature @ 30 min (ºC)	717 / 633	662 / 649	610 / 554	625 / 626	641 / 635	600 / 675
Fixing mid-point (55 mm) temperature @ 30 min (ºC)	133 / 224	217 / 206	197 / 250	182 / 238	216 / 292	212 / 262
Fixing tip temperature @ 30 min (ºC)	65 / 87	51 / 167	59 / 104	42 / 117	44 / 73	55 / 110
Average gas temperature @ 60 min (ºC)	X	X	X	673	651	823
Wood temperature, 55 mm depth @ 60 min (ºC)	X	X	X	52	43	55
Fixing head/shank temperature @ 60 min (ºC)	X	X	X	602 / 596	644 / 583	616 / 690
Fixing mid-point (55 mm) temperature @ 60 min (ºC)	X	X	X	243 / 302	282 / 335	273 / 345
Fixing tip temperature @ 60 min (ºC)	X	X	X	57 / 125	58 / 99	83 / 127

Note: X represents no data recorded post 30 min for fire tests FT1, FT2 and FT3

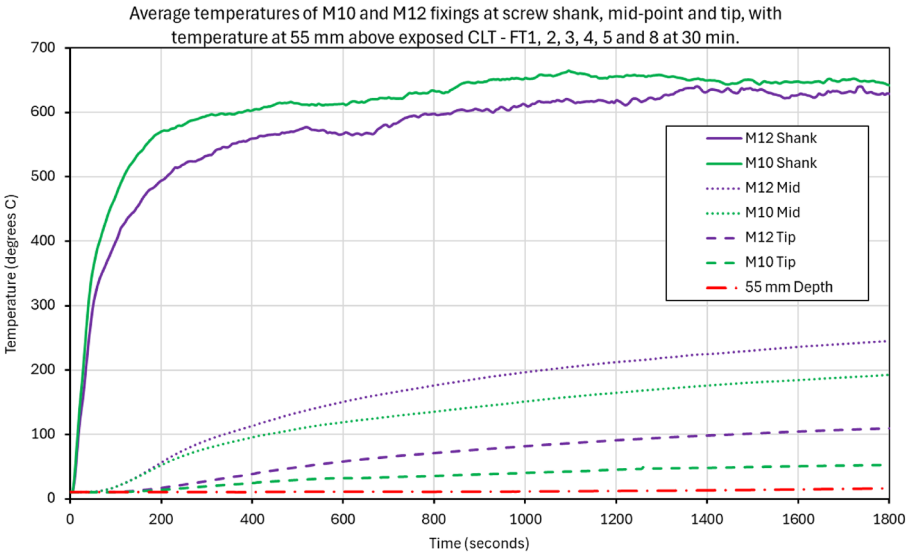

Fig. 18 Average screw fixing temperatures recorded as a function of depth at the CLT (screw shank), at the mid-point (internal) the screw tip (internal) and at 55 mm above the exposed CLT at 30 min

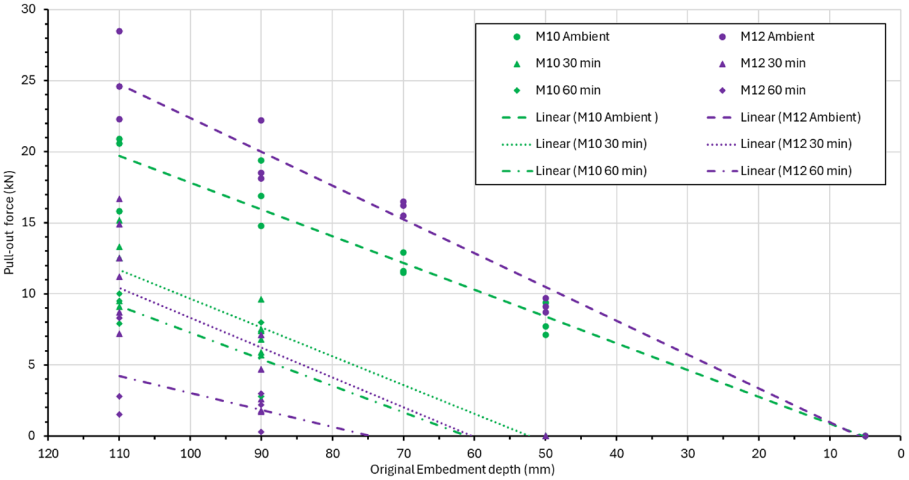

Fig. 19 Pull-out force versus embedment depth for HB S adhesive, ambient conditions, 30 and 60 min fire exposure

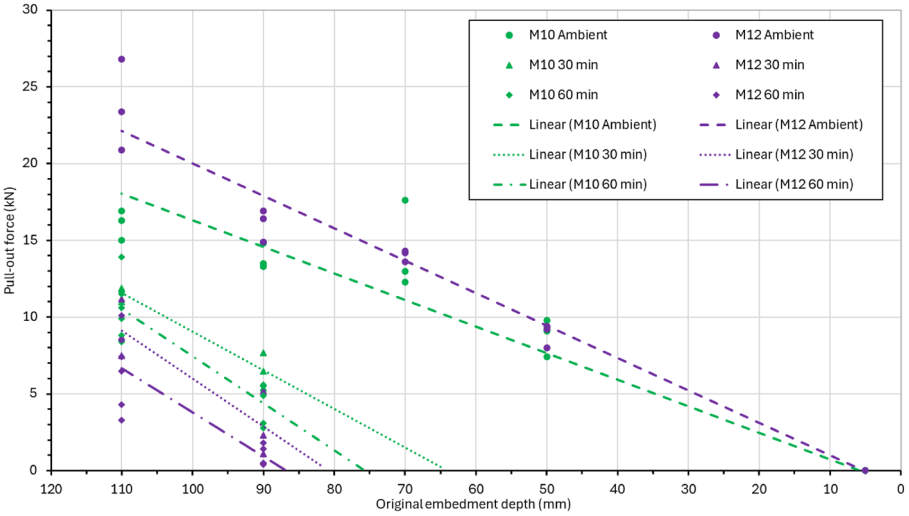

Fig. 20 Pull-out force versus embedment depth for HB X adhesive, ambient conditions, 30 and 60 min fire exposure

4.4 Fire Pull-out Test Results

4.4.1 Pull-out Forces – Coach Screws

Figures 19 and 20 show pull-out force versus embedment depths for each CLT adhesive type at ambient, 30 min and 60 min fire exposure. Embedment depth scatter shown in the graphs for post-fire test results derive from actual embedment depths where char has been

removed. For example, after the fire actual embedment depth of 73 – 77 mm was found for pre-fire embedment depth of 90 mm.

Comparison of the two graphs (Fig. 19 and 20) show a similar relationship in loss of load versus embedment depth. Above 50 mm embedment and at ambient conditions, M12 screw fixings having a greater load capacity than M10. However, post-fire results indicate the opposite, M10 screw fixings retain a greater load than M12. This result might seem counter intuitive but is believed to result from greater heat transfer into the CLT through the wider screws resulting in higher temperatures at the interface between the thread and the timber leading to charring and loss of strength. The steeper slope of the post-fire tests shows the increased beneficial influence of embedment depth on the load capacity.

Figure 21 shows pull-out forces versus embedment depths for coach screws, measured across all tests (benchmark ambient, and post-fire) irrespective of CLT adhesive type.

Table 40 of BS EN 12845 requires a load capacity of 500 kg (4.9 kN) at ~ 20 °C, benchmark ambient loads suggest this is achievable with M10 screw fixings at an embedment depth of ~ 31 mm and M12 at ~ 25 mm (indicated in Fig. 21) assuming linear extrapolation. At ambient conditions with a minimum of 2-ply embedment ~ 70 mm, load capacity for M10 and M12 fixings is just over twice the requirement of BS EN 12845.

Where screw fixings were tested at ambient conditions, load capacity exceeds the minimum specification. However, during and after fire there is significant reduction in load capacity when compared to ambient load measurements. This is due to the increase in timber temperature and char formation which leads to loss of material at the surface and loss

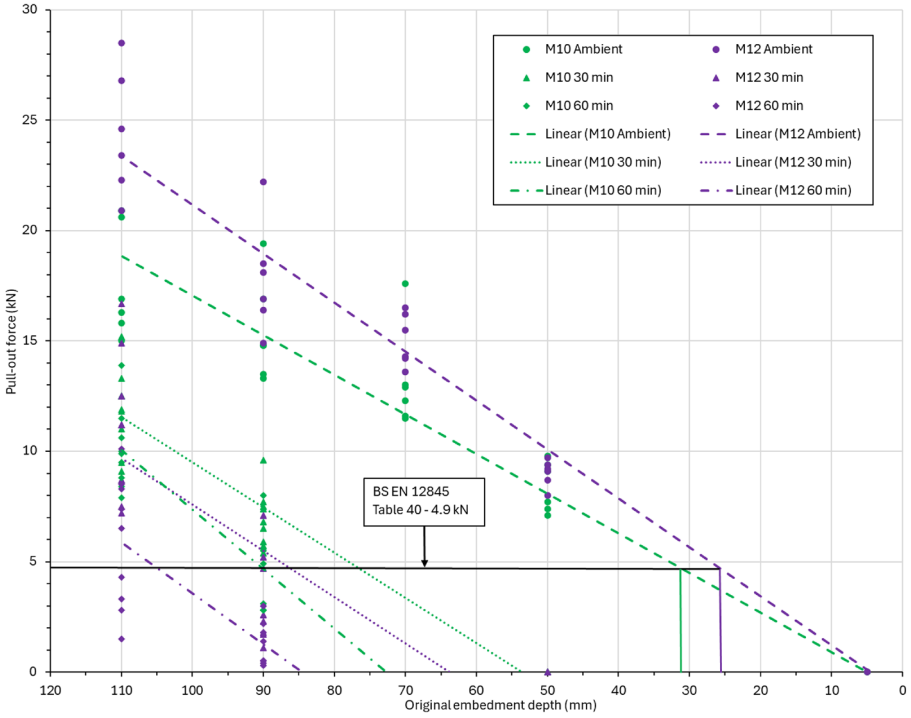

Fig. 21 Pull-out force versus embedment depth, all results, ambient conditions, 30 and 60 min fire exposure

of strength of the timber [74] and around the screw fixing. Without load, the screw fixing remains in place. However, char at these contact interfaces will increase in thermal conductivity as temperature rises [75] leading to increased heat conduction through the screw.

Four fire tests were conducted with screw fixings statically loaded replicating common sprinkler service loads. Results from these tests are discussed further in Sect. 4.4.2.

4.4.2 Statically Loaded, During Fire Tests

With screw fixings loaded, char formation at the contact point through the screw thread will be under compression, pulling the screw fixing in the direction of the force and leaving a small char void above the thread and compressing the char layer below, shown in Fig. 22. Contact surfaces between the wood and screw thread are reduced. Once the char extends to the outer circumference of the screw thread, the effective embedment depth is reduced to a point where detachment occurs.

This is evident in the two statically loaded tests (FT3 & FT4) which recorded catastrophic failure of the screw fixing at ~ 20 min (full pull-out). In the other two loaded tests (FT5 & FT8) the cable failed at ~ 10 min and ~ 19 min respectively, with the screw fixing remaining in place. However, pull-out forces of the loaded screw fixings were significantly reduced. The average capacity of the same unloaded screw fixings in tests FT5 & FT8, were recorded at 5.4 kN and 4.4 kN, indicating a significant loss from ambient test results. Loaded fixings were recorded at 3.0 kN and 1.4 kN respectively, representing a 56% and 47% loss from unloaded screws due to load.

At temperatures above 200–250 °C, and through prolonged heating at lower temperatures ~ > 120 °C, wood discolours and chars, described by Drysdale [76]. Screw fixings A2 (M10 × 120 mm) and D2 (M12 × 120 mm) shown in Fig. 5 and Fig. 11, included thermocouples located at the screw head shank, mid-point, and tip. Temperatures were recorded in

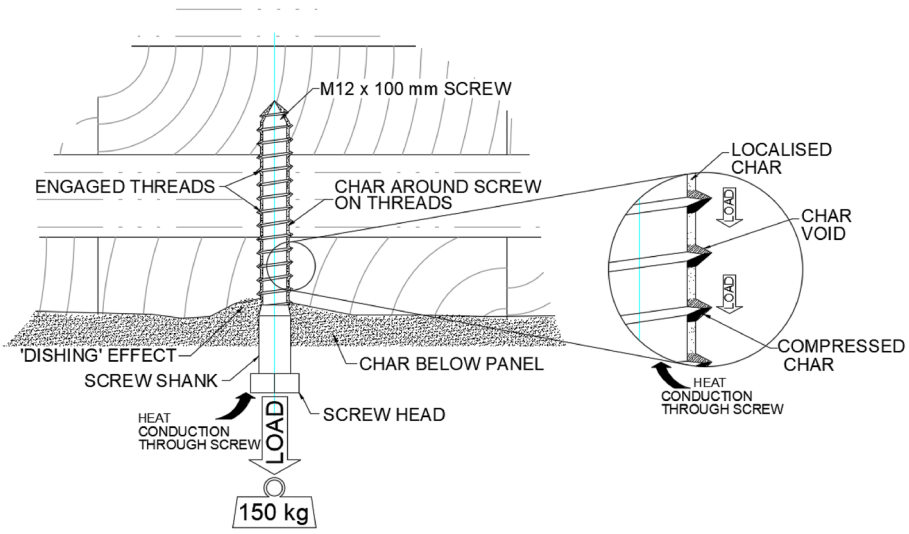

Fig. 22 Shows a coach screw under load, heat conduction through the fixing leading to char formation at the contact point between screw thread and timber

Table 8 Capacity of M10 and M12 (coach screws) post-fire at various embedment depths

Fixing Type	Embedment depth (mm)	Ambient mean pull-out force (kN) ± 1 SD	30 min fire exposure mean pull-out force (kN) ± 1 SD	60 min fire exposure mean pull-out force (kN) ± 1 SD
M10 coach screw (A2)	110	17.6 ± 2.3	11.9 ± 1.8	10.1 ± 1.7
	90	15.5 ± 2.1	6.9 ± 1.2	4.7 ± 1.8
	70	13.2 ± 2.1	–	–
	50	8.4 ± 1.1	0[#]	–
M12 coach screw (D2)	110	24.4 ± 2.6	11.0 ± 3.1	5.9 ± 2.8
	90	17.8 ± 2.3	3.3 ± 2.0	1.3 ± 0.9
	70	15.1 ± 1.1	–	–
	50	9.0 ± 0.6	0[#]	–

Note: 70 mm embedment depth and 50 mm embedment for 60 min was not fire tested

0[#] Based on recorded pull-out force of 0

fire tests FT1, FT2, FT3, FT6 and FT7 at 30 min. The results have been averaged showing uncertainty expressed as a standard deviation for each screw fixing type.

Using ambient baseline results, the remaining capacity for the coach screws once cooled is shown in Table 8. This highlights the severity of the load capacity reduction for M12 screw fixings. This has significant implications for the M&E industries fixing into timber.

M8 × 100 mm screw fixings were assessed after 30 and 60 min fire exposure. Screw fixings were embedded to a depth of 90 mm. After fire testing, pull-out forces after 30 and 60 min were measured as 7.6 kN and 7.7 kN, respectively. For comparison, both M10 and M12 screw fixings embedded at 90 mm, M10 measured (averaged) at 6.9 kN and 4.7 kN respectively, with M12 screw fixings measuring (averaged) 3.3 kN and 1.3 kN, respectively. The smaller diameter of the M8 screw fixings will conduct less heat which has been shown to reduce the loss of load capacity.

5 Conclusions

This study aimed to characterise the load bearing capacity of screw fixings of the type used to secure M&E to timber ceilings under fire conditions. The potential consequence of early failure of these fittings include entanglement, crush, and electrocution risks to evacuees and attending fire services; enhanced fire spread through fire compartment boundaries via broken and dislodged vent ducts; and increased consequential damage and impairment of systems (including fire sprinklers) from mechanical damage to fallen fluid filled pipes (liquid and gas).

Under ambient conditions screw fittings into timber were shown to comfortably exceed the load bearing requirements for typical M&E suspension applications and larger diameter screws were also shown to support greater loads.

When tested under fire conditions two factors can be considered to contribute to the loss, the complete loss of material near the surface due to char oxidation, and the weakening of the internal timber around the screw thread by charring. This results from the metal of the screw fixing conducting heat from the attached brackets into the timber and around the thread promoting char formation, coupled with the propensity of timber to weaken under the action of heat.

This study also shows that the timber is weaker during the fire than after it has cooled, although the data to support this observation is limited.

The results show that screws with the same overall width and embedment depth, but narrower shanks and wider threads have greater retention capacity in timber exposed to fire. In addition the wider shank of the M12 screws conducted more heat to the 'vulnerable volume' of wood between the shank and the outside of the thread than the narrower M8 or M10 screws causing more charring and greater loss of load capacity. This effect was most noticeable for screws with the greatest overall width/shank ratio (for example comparing the left and right hand screws in Fig. 17).

The complete loss of strength of screw fixings under loaded fire conditions was both very rapid and structurally significant indicating that the aforementioned concerns highlighted relating to the potential consequences of failure are both justified, highly plausible, and in need of a further detailed investigation, and a solution.

In spite of the very significant load bearing changes observed under the set fire conditions, analysis of char rates indicate that more onerous conditions are likely at in fires involving mass timber construction. Compounded by the likelihood that the screw fixing will additionally be attached to greater amounts of heat-collecting metalwork that will also be in the flame zone, it should be assumed that loss of strength will occur sooner in real fires. It is also noted that post-fire, on cooling there is an improvement in load bearing capacity of the timber substrate, indicating that it is essential to have more detailed information on the performance of fixings in the loaded fire condition.

This study was limited to considering screw fixings being installed in traditional arrangements i.e. perpendicular to the surface and concentrated on screw fixing diameters specified to the installation of fire sprinkler systems as described in European sprinkler standard BS EN 12845 [18].

The inclusion of a suitably designed and fully functional sprinkler system in a building's design, means the potential for fire spread will be reduced, gas temperatures will be lower, and the impact upon the load-bearing capacity of the screw fixings holding the sprinkler system itself, and other M&E services will be greatly reduced. Without a sprinkler system, M&E services are vulnerable to complete and rapid failure that will result in premature detachment of suspended services– it is clear that for this situation new approaches to fixings are required, properly supported by standards and test protocols, to ensure this risk is annulled.

6 Future Work

Whilst this study was originally undertaken to gain knowledge on how fixing methods for fire sprinkler systems might need adaption for the mass timber situation, it has highlighted more serious implications for M&E in general. To ensure building safety under fire conditions and to support evacuation of occupants and response by the attending fire service, better understanding of the load bearing capacity of timber in fire is needed. There are also implications for the level of consequential damage the building might incur through fire spread and damage to other ceiling supported systems.

Potential solutions may include the development of new types of fixings, or the use of current screw fixings in a different way where the load is out of plane to the fixing insertion. The development of appropriate test standards and specification requirements are also required in response to these new building methods.

Based on the loss of load capacity described, it is expected that decisive action will be taken to prevent detachment of services and the foreseeable potential implications for escapee or firefighter entanglement, similar to that which occurred at Shirley Towers. In that instance it was the fixings that had a vulnerability to fire, not the substrate into which they were embedded, so whilst the outcomes could be the same, the necessary solutions will be different. This work provides stakeholders with information necessary to develop a new standard or guidance document for fixing M&E services into timber based upon the findings within this paper, which is urgently required.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

1. Structural Timber Association - Structural timber buildings - fire safety in use guidance - Volume 6 - Mass timber structures; Building Regulation compliance B3(1) - STA fire safety research and guidance project - Version v1.1 October 2020
2. Hopkin D, Spearpoint M (2020) Compliance road-map for the structural fire safety design of mass timber buildings in England. SFPE Europe Q4:2020
3. Hopkin D, Gorska C, Spearpoint MJ, Fu I, Krenn H, Sleik T, Stapf G (2021) Experimental characterisation of the fire behaviour of CLT ceiling elements from different leading suppliers. Appl Structl Fire Eng 2021:10–11. https://doi.org/10.14264/5010564
4. Hopkin D, W˛egrzy´nski W, Spearpoint M, Fu I, Krenn H, Sleik T, Gorska C, Stapf G (2022) Large-scale enclosure fire experiments adopting CLT slabs with different types of polyurethane adhesives: genesis and preliminary findings. Fire 2022(5):39. https://doi.org/10.3390/fire5020039
5. Ronquillo G, Hopkin D, Spearpoint M (2021) Review of large-scale fire tests on cross-laminated timber. J Fire Sci. https://doi.org/10.1177/07349041211034460
6. HM Government Policy Paper – Net Zero Strategy: Build Back Greener (October 2021) [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf
7. Östman, B, A-L. (2013). Fire Safety in timber buildings [Paper presentation]. Seminário Casas de Maderia.
8. Östman, B., Mikkola, E., Stein, R., Frangi, A., König, J., Dhima, D., Hakkarainen, T., & Bregulla, J. (2010). Fire safety in timber buildings: technical guideline for Europe. SP Report No. 2010:19

9. Zelinka, S, L., Hasburgh, L., Bourne, K., Tucholski, D., & Ouellette, J. (2018). Compartment fire testing of a two-story mass timber building. https://doi.org/10.13140/RG.2.2.26223.33447
10. Mitchell H, Kotsovinos P, Richter F, Thomson D, Barber D, Rein G (2023) Review of fire experiments in mass timber compartments: current understanding, limitations, and research gaps. Fire Mater 47(4):415–432. https://doi.org/10.1002/fam.3121
11. Babrauskas V (2023) Comments on "The curious case of the second/end peak in the heat release rate of wood: a cone calorimeter investigation," by Sanned et al. Fire Mater 47(5):733–734. https://doi.org/10.1002/fam.3143
12. BS EN ISO 13943:2017 – Fire safety – Vocabulary
13. Hadden R, M. Bartlett A, I. Hidalgo J, P. Santamaria S, Wiesner F, Bisby L, A. Deeny S, Lane B (2017) Effects of exposed cross laminated timber on compartment fire dynamics. Fire Saf J 91:480–489. https://doi.org/10.1016/j.firesaf.2017.03.074
14. Bartlett AI, Hadden RM, Hidalgo JP, Santamaria S, Wiesner F, Bisby LA, Deeny S, Lane B (2017) Auto-extinction of engineered timber: application to compartment fires with exposed timber surfaces. Fire Safety J 91:407–413. https://doi.org/10.1016/j.firesaf.2017.03.050
15. Emberley R, Inghelbrecht A, Yu Z, Torero J L (2017) Self-extinction of timber. Proc Combust Inst 36(2):3055–3062. https://doi.org/10.1016/j.proci.2016.07.077
16. Emberley R, Do T, Yim J, Torero J L (2017) Critical heat flux and mass loss rate for extinction of flaming combustion of timber. Fire Saf J 91:252–258. https://doi.org/10.1016/j.firesaf.2017.03.008
17. Morrisset, D. Law, A. Emberley, R. (2019). "Effects of thickness on the self-extinction of timber." IFireSS - Conference - 3rd International fire safety symposium. https://www.researchgate.net/publication/334898704_Effects_of_Thickness_on_the_Self-extinction_of_Timber
18. Crielaard R, Kuilen J-W, Terwel K, Ravenshorst G, Steenbakkers P (2019) Self-extinguishment of cross-laminated timber. Fire Saf J 105:244–260. https://doi.org/10.1016/j.firesaf.2019.01.008
19. Cuevas J, Torero JL, Maluk C (2021) Flame extinction and burning behaviour of timber under varied oxygen concentrations. Fire Safety J 120:103087. https://doi.org/10.1016/j.firesaf.2020.103087
20. Nothard S, Lange D, Hidalgo J P, Gupta V, McLaggan MS, Wiesner F, Torero JL (2022) Factors influencing the fire dynamics in open-plan compartments with an exposed timber ceiling. Fire Saf J. https://doi.org/10.1016/j.firesaf.2022.103564
21. Xu H, Pope I, Gupta V, Cadena J, Carrascal J, Lange D, McLaggan M S, Mendez J, Osorio A, Solarte A, Soriguer D, Torero J L, Wiesner F, Zaben A, Hidalgo J P (2022) Large-scale compartment fires to develop a self-extinction design framework for mass timber Part 1": literature review and methodology. Fire Saf J. https://doi.org/10.1016/j.firesaf.2022.103523
22. BS EN 12845:2015+A1:2019 Incorporating corrigenda December 2015 and January 2016 - Fixed firefighting systems - Automatic sprinkler systems - Design, installation and maintenance.
23. Building Engineering Services Association - Guide to Good Practice for: Supports and Fixings – TR 50 – V1 April 2021 [Online]. Available: https://www.thebesa.com/knowledge/shop/products/tr50-guide-to-good-practice-for-supports-and-fixings/
24. BS 8539:2012+A1:2021 - Code of practice for the selection and installation of post-installed anchors in concrete and masonry
25. CROSS Safety Report; 13 December 2024 - Collapse of a suspended 100mm water pipe due to fixing failure. Report ID: 1350 [online]. Available: https://www.cross-safety.org/uk/safety-information/cross-safety-report/collapse-suspended-100mm-water-pipe-due-fixing-1350
26. Shropshire and Wrekin Fire and Rescue Authority; 24 April 2013 - Coroner's Rule 43, Letter Shirley Towers, Hampshire [online]. Available: www.shropshirefire.gov.uk/sites/default/files/11-coroners-rule-43-letter.pdf
27. BS 7671:2018+A3:2024 – SET Requirements for Electrical Installations. IET Wiring Regulations
28. BS EN 16925:2018 - Fixed firefighting systems - Automatic residential sprinkler systems - Design, installation, and maintenance
29. BS 8458:2015 - Fixed fire protection systems – Residential and domestic watermist systems – Code of practice for design and installation
30. BS 8489–1:2016 - Fixed fire protection systems – Industrial and commercial watermist systems - Part 1: Code of practice for design and installation
31. BS EN 14972–1:2020 - Fixed firefighting systems - Water mist systems - Part 1: Design, installation, inspection, and maintenance
32. LPC Rules for Automatic Sprinkler Installations 2015 Incorporating BS EN 12845
33. BS 9251:2021 - Fire sprinkler systems for domestic and residential occupancies — Code of practice
34. Bateman, C. Bartlett, A. Rutkauskas, L. Hadden, R. (2018). "Effects of fuel load and exposed CLT surface configuration." World conference on timber engineering. Available:https://www.researchgate.net/publication/325319406_Effects_of_Fuel_Load_and_Exposed_CLT_Surface_Configuration_in_Reduced-Scale_Compartments

35. Bartlett A, McNamee I, Robert R, Bisby F, Bisby L, Bisby A (2020) Comparative energy analysis from fire resistance tests on combustible versus non-combustible slabs. Fire Mater 44:301–310. https://doi.org/10.1002/fam.2760
36. Rackauskaite E, Kotsovinos P, Barber D (2021) Letter to the editor: design fires for open-plan buildings with exposed mass-timber ceiling. Fire Technol 57:487–495. https://doi.org/10.1007/s10694-020-01047-0
37. Shuna N, Gernay T (2022) On the effect of exposed timber on the severity of structural fires in a compartment and required firefighting resources. Fire Technol 58:2691–2725. https://doi.org/10.1007/s10694-022-01254-x
38. Zelinka SL, Hasburgh LE, Bourne KJ, Tucholski DR, Ouellette JP, Kochkin V (2018) Compartment fire testing of a two-story mass timber building. Gen Tech Report Forest Prod Lab. https://doi.org/10.2737/FPL-GTR-247
39. Madden, J., Kriel, M., Wiesner, F., Wu, W., Hilditch, R., Ervine, A., Lange, D. (2024) Burning behaviour of a timber ceiling: a bench-scale investigation [Paper presentation]. 13th International conference on structures in fire. Coimbra, Portugal.
40. Xu H, Pope I, Gupta V, Cadena J, Carrascal J, Lange D, McLaggan M, McLaggan S, Mendez J, Osorio A, Solarte A, Soriguer D, Torero J, Torero L, Wiesner F, Zaben A, Hidalgo J, Hidalgo P (2022) Large-scale compartment fires to develop a self-extinction design framework for mass timber—Part 1: literature review and methodology. Fire Saf J 128:103523. https://doi.org/10.1016/j.firesaf.2022.103523
41. Emberley R, Gorska Putynska C, Bolanos A, Lucherini A, Solarte A, Soriguer D, Gutierrez Gonzalez M, Humphreys K, Hidalgo J, Hidalgo P, Maluk C, Law A, Torero J, Torero L (2017) escription of small and large-scale cross laminated timber fire tests. Fire Saf J 91:327–335. https://doi.org/10.1016/j.firesaf.2017.03.024
42. Bøe A, Bøe S, Friquin K, Friquin L, Brandon D, Steen-Hansen A, Ertesvåg I, Ertesvåg S (2023) Fire spread in a large compartment with exposed cross-laminated timber and open ventilation conditions: #FRIC-01 – exposed ceiling. Fire Saf J. https://doi.org/10.1016/j.firesaf.2023.103869
43. Brandon, D. Östman, B. (2016). "Fire Safety Challenges of Tall Wood Buildings. Phase 2: Task 1 - Literature Review". Report Number: FRPF-2016–22: Affiliation: NFPA. https://www.researchgate.net/publication/308417172_Fire_Safety_Challenges_of_Tall_Wood_Buildings_Phase_2_Task_1_-_Literature_Review
44. Östman B, Brandon D, Frantzich H (2017) Fire safety engineering in timber buildings. Fire Saf J 91:11–20. https://doi.org/10.1016/j.firesaf.2017.05.002
45. Frangi A, Fontana M (2005) Fire performance of timber structures under natural fire conditions. Fire Saf Sci 8:279–290. https://doi.org/10.3801/IAFSS.FSS.8-279
46. Khoat H, Khoat T, Kim J, Kim T, Quoc T, Quoc D, Kwark J, Kwark H, Ryou H, Ryou S (2020) A numerical analysis of the fire characteristics after sprinkler activation in the compartment fire. Energies 13(12):3099. https://doi.org/10.3390/en13123099
47. Barber D, Gerard R (2015) Summary of the fire protection foundation report - fire safety challenges of tall wood buildings. Fire Sci Rev. https://doi.org/10.1186/s40038-015-0009-3
48. Frangi A, Fontana M, Knobloch M (2008) Fire design concepts for tall timber buildings. Struct Eng Int 18(2):148–155. https://doi.org/10.2749/101686608784218716
49. Buchanan, A. Östman, B. Frangi, A. (2014) "White paper on fire resistance of timber structures" *NIST GCR 15–985*. https://doi.org/10.6028/NIST.GCR.15-985
50. Structural timber buildings - fire safety in use guidance - Volume 6 - Mass timber structures; Building Regulation compliance B3(1) - STA fire safety research and guidance project - Version v1.1 October 2020 (Structural Timber Association) [Online]. Available: https://www.structuraltimber.co.uk/timber-systems/research/timber-frame-fire-safety-in-use-guidance/
51. Timber-frame buildings and cavity fires: the burning question.(2022). [Online]. Available: https://www.insidehousing.co.uk/insight/insight/timber-frame-buildings-and-cavity-fires-the-burning-question-77981
52. Building, Design and Management - Fire in timber frame buildings – "A review of fire statistics from the UK and the USA" - BDM14 - First published 2011Version 01 By RISCAuthority and administered by *The Fire Protection Association*. [Online]. Available: https://www.thefpa.co.uk/resource-download/243
53. Hoehler, M, S., Su, J. Lafrance, P-S. Bundy, M, F. Kimball, A. Brandon, D. Östman, B. (2018) Fire safety challenges of tall wood buildings: large-scale cross-laminated timber compartment fire tests In: *SiF 2018– The 10th International Conference on Structures in FireFireSERT.* [Online]. Available: http://urn.kb.se/resolve?urn=urn:nbn:se:lnu:diva-77612
54. Sæter AB, Hox K, Mikalsen RF, Friquin KL (2024) Large-scale fire experiments in a cross-laminated timber compartment with an adjacent corridor – Partly and fully protected with a water sprinkler system. Fire Safety J. https://doi.org/10.1016/j.firesaf.2024.1042122

55. Arup – LND884 - Mass timber fire safety experiment (Code Red) Experiment one update and experiment two initial findings June 2021 [Online]. Available: https://www.arup.com/perspectives/large-compartment-fire-experiments-expanding-knowledge-of-building-safely-with-timber
56. Kotsovinos P, Rackauskaite E, Christensen E, Glew A, O'Loughlin E, Mitchell H, Amin R, Robert F, Heidari M, Barber D, Rein G, Schulz J (2022) "Fire dynamics inside a large and open-plan compartment with exposed timber ceiling and columns": CodeRed #01. Fire Mater. https://doi.org/10.1002/fam.3049
57. Gernay T, Zehfuß J, Brunkhorst S, Robert F, Bamonte P, McNamee R, Mohaine S, Franssen J (2022) Experimental investigation of structural failure during the cooling phase of a fire: timber columns. Fire Mater. https://doi.org/10.1002/fam.3110
58. Ringhofer A, Brandner R, Blaß H J (2018) Cross laminated timber (CLT): design approaches for dowel-type fasteners and connections. Eng Struct 171:849–861. https://doi.org/10.1016/j.engstruct.2018.05.032
59. Uibel T, Blaß HJ (2013) Joints with dowel type fasteners in CLT structures. Karlsruhe. https://doi.org/10.5445/IR/1000035507
60. Fischer E C, Bhandari S, Sinha A (2025) Fire testing of glue-laminated beam-to-column connections. J Struct Eng. https://doi.org/10.1061/JSENDH.STENG-13888
61. Saito, S., Kikuchi, T., Nakayama, Y. Totsuka, M., Hirashima, T. (2024) Embedment strength of dowelled connections of glulam timber at high temperatures. Paper presented at the conference on structures in fire. University of Coimbra, Portugal. 1359–1370. https://doi.org/10.30779/cmm_SIF24
62. Building Engineering Services Association (BESA) – TB58 Alternative systems for building services supports – Version 1 January 2024.
63. Khai TD, Young JG (2022) Withdrawal capacity and strength of self-tapping screws on cross-laminated timber. Structures 37:772–786. https://doi.org/10.1016/j.istruc.2022.01.033
64. Horne P, Abu A, Palermo A, Moss P (2023) Thermal response of timber connections in the cooling phase. Fire Mater 47:479–497. https://doi.org/10.1002/fam.3136
65. Abdoli F, Rashidi M, Rostampour-Haftkhani A, Layeghi M, Ebrahimi G (2022) Withdrawal performance of nails and screws in cross-laminated timber (CLT) made of poplar (*Populus alba*) and fir (*Abies alba*). Polymers 14:3129. https://doi.org/10.3390/polym14153129
66. Moraes PD, Rogaume Y, Bocquet JF, Triboulot P (2005) Influence of temperature on the embedding strength. Holz Roh Werkst 63:297–302. https://doi.org/10.1007/s00107-004-0568-9
67. Hoelz K, Dörner P, Hohlweg J, Matthiesen S (2022) Influence of thread parameters on the withdrawal capacity of wood screws to optimize the thread geometry. Eur J Wood Wood Prod 80:529–540. https://doi.org/10.1007/s00107-022-01792-9
68. Peng L, Hadjisophocleus G, Mehaffey J, Mohammad M (2011) Predicting the fire resistance of wood–steel–wood timber connections. Fire Technol 47:1101–1119. https://doi.org/10.1007/s10694-009-0118-4
69. BS 476–33:1993, ISO 9705:1993 Fire tests on building materials and structures — Part 33: Full-scale room test for surface products.
70. BS EN 1995–1–1:2004 Eurocode 5: Design of timber structures - Part 1–1: General - Common rules and rules for buildings
71. Beck JV (1962) Thermocouple temperature disturbances in low conductivity materials. J Heat Transf 84(2):124–131. https://doi.org/10.1115/1.3684310
72. Pope I, Hidalgo JP, Torero JL (2021) A correction method for thermal disturbances induced by thermocouples in a low-conductivity charring material. Fire Saf J 120:103077. https://doi.org/10.1016/j.firesaf.2020.103077
73. Terrei L, Acem Z, Marchetti V, Lardet P, Boulet P (2021) In-depth wood temperature measurement using embedded thin wire thermocouples in cone calorimeter tests. Int J Therm Sci 162:106686. https://doi.org/10.1016/j.ijthermalsci.2020.106686
74. Khelifa M, Thi VD, Oudjène M, Khennane A, Ganaoui ME, Rogaume Y (2024) Modelling the response of timber beams under fire. Int J Civ Eng 22:1537–1549. https://doi.org/10.1007/s40999-024-00973-2
75. Shi L, Chew MYL (2021) A review of thermal properties of timber and char at elevated temperatures. Indoor Built Environ 32(I):9–24
76. Drysdale D (1999) An introduction to fire dynamics. Wiley, Hoboken
77. Brandon, D., Sjöström, J., Kahl, F. (2021). Post-fire rehabilitation of CLT. [online]. Available: https://www.diva-portal.org/smash/get/diva2:1627124/FULLTEXT01.pdf
78. Xu Q, Chen L, Harries K, Zhang F, Liu Q, Feng J (2015) Combustion and charring properties of five common constructional wood species from cone calorimeter tests. Constr Build Mater 96:416–427. https://doi.org/10.1016/j.conbuildmat.2015.08.062

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Authors and Affiliations

Dale Kinnersley[1,2] · T. Richard Hull[2] · James L. D. Glockling[2] · Stuart Campbell[1]

✉ Dale Kinnersley
dkinnersley@thefpa.co.uk

T. Richard Hull
TRHull1@lancashire.ac.uk

James L. D. Glockling
Jim@glockling.co.uk

Stuart Campbell
stuart.c.campbell@outlook.com

[1] Fire Protection Association, London Road, Moreton in Marsh, Gloucestershire GL56 0RH, UK

[2] Centre for Fire and Hazard Science, University of Lancashire, Preston PR1 2HE, UK

Appendix E – Scientific paper 2 :
'Investigation of sprinkler wetting patterns for fire protection of exposed timber'.

Accepted by Fire Technology 27th May 2026

Investigation of sprinkler wetting patterns for fire protection of exposed timber

Dale Kinnersley[ab]*, T. Richard Hull[b], James L. D. Glockling[b], Stuart Campbell[a]
[a] Fire Protection Association, London Road, Moreton in Marsh, Gloucestershire GL56 0RH, UK, dkinnersley@thefpa.co.uk, stuart.c.campbell@outlook.com
[b] Centre for Fire and Hazard Science, University of Central Lancashire, Preston PR1 2HE, UK, TRHull1@uclan.ac.uk, Jim@glockling.co.uk

Highlights

- Contemporary sprinklers do not directly discharge water on exposed timber wall and ceilings. Some sprinklers are specifically designed to discharge water simultaneously on exposed timber ceilings and contents from the fire.
- Appropriate sprinkler head spacing is critical to ensure adequate wall and ceiling surface coverage of combustible surfaces.

Abstract

In this experimental study, a range of sprinkler head types were tested to evaluate the wetting potential of exposed timber ceilings and walls in addition to providing water to the room's contents. Water distribution tests were conducted using standard single sprinklers at high and low pressures with different mounting orientations. Water capture below the sprinklers allowed the assessment of actual delivered density against requirements. A specifically designed test rig was used to evaluate water delivery rates to walls, and ceiling wetting patterns were captured photographically and through measurement for later analysis.

The aim of this study is to provide evidence and data to inform organisations/standards bodies of potential changes that can optimise sprinkler systems for the protection of mass timber buildings with exposed internal combustible timber surfaces. The results presented demonstrate that, through careful consideration of sprinkler head type and positioning, improved surface wetting of ceilings and walls can be achieved without compromising water delivery to the contents/fuel load. It is estimated that minor changes to system design can greatly improve system performance for mass timber construction at minimal cost.
This work is presented with a view to support the adaption of current UK sprinkler standards to this new protection scenario.

Keywords: CLT (Cross Laminated Timber); Mass Timber; BS EN 12845; LPC Rules; Sprinkler; Density

1. Introduction

Timber is gaining popularity in construction, not only for its aesthetic appearance, but also to enhance sustainability metrics. Timber is being used in the primary structure and secondary finishes as exposed surfaces in interior compartments [1–7]. The biggest driver for the increase in the use of timber in the UK is the government [8], helping their vision to tackle climate change by reducing CO_2 emissions in UK construction. However, the substitution of steel and concrete for timber brings with it new challenges for fire protection.

Timber is a combustible material that will need to be protected against fire. This can be achieved with fire retardants [9], encapsulation using plasterboard, or with the installation of an active fire suppression system. Fire retardants increase costs and may need to be reapplied at specified intervals, which may be difficult in existing buildings. Encapsulation is another

consideration; however, this removes the visual aesthetics of the raw material and has been seen to fall away during a fire through inadequate fixings and general failure. Encapsulation also has the potential to allow and hide smouldering combustion [10].

Sprinkler statistics [11-13] confirm that the effectiveness of sprinklers to control fires and halt fire spread is over 96%, and with proper design, inspection, and maintenance this can improve to 99%. Studies show that from 2017–2021, deaths were reduced by 90% when sprinklers were present, and firefighter injuries per fire were 35% lower. Where sprinklers were present, fires were contained to the room of origin or object in 94% of fires reported, and sprinklers operated in 92% of fires recorded and were 97% effective in controlling the fire. However, there is concern that this track record will be impacted if the same protocols are used in buildings with combustible walls and ceilings.

As fire safety and sustainability goals converge, fire sprinkler systems are increasingly seen as a carbon-conscious investment in resilient, low-impact timber building designs. That said, adaptation of the design of fire sprinkler systems is required to ensure that both contents and any exposed timber surfaces are appropriately protected. The additional fuel load and propensity for timber to smoulder and later re-ignite, means an optimised response from the fire sprinkler system is required to ensure containment and prevent spread to inaccessible seams and voids. A published study is described later in this introduction in which a sprinkler system in an exposed timber corridor was unable to control a fire starting in an adjoining unsprinklered bedroom. This was due to the sprinklers' inability to deliver water to the ceiling's surface and is presented as evidence of need for this approach. Specific protection of the ceiling is also critical to ensuring the integrity of Mechanical & Electrical (M&E) services that rely on them for structural support.

Fire protection of buildings with internal timber surfaces using sprinkler systems is not a new concept. In Victorian Britain, sprinkler systems, and the type of sprinkler head used, were designed to protect timber mill floors/ceilings. Sprinkler heads were designed to provide water upward to the ceiling and downward to the fuel load below. These sprinklers are known as 'Conventional' type. Manufacturers still produce these sprinklers today, also known as 'old-style conventional sprinklers.' However, due to changes in building methods and materials, modern sprinklers have been developed to provide 100% of the water discharge downward to cover the fuel load at floor level, based on the assumption that modern buildings have essentially limited or non-combustible walls and ceilings (this is accepted in current sprinkler installation rulesets described below).

There are a number of suppression standards that can be applied to different building types and occupancies in the UK today. The most commonly used standards are for sprinkler systems, which separately cover Commercial and Industrial [14, 15] and Residential and Domestic [16, 17] premises.

Standards used for sprinkler head testing vary, from commercial to residential. Table 1 provides general details of test standards and their specific requirements.

Table 1. Summary of sprinkler head test standards.

Standard	Container Size (WxDxH) (mm)	Ceiling height above container (mm)	Sprinkler Flow Rate (l/min)	Wall Wetting Distance from ceiling (mm)	Head Pressure (bar)	Test Duration (mins)	Permitted containers less than 50% (qty)	Sprinkler coverage (mm)	Discharge Downwards (%)
BS EN 12259-1 * [18]	H – 500	2700	61.3	N/A	0.59	Satisfactory average time	5	N/A	40-60
BS 9252 ** [19]	H – 300	2500	56.6	700	0.5	6	N/A	N/A	80-100
BS EN 12259-14 ** [20]	300x300, 500x500	2400	56.6	711	0.5	20/10	N/A	N/A	80-100
UL 199 * [21]	300 x 300 x 300	2300, 3050, 1200	57	N/A	0.5	10	5	3050	40-60
UL 1626 ** [22]	300 x 300 x 300	2440, 2080	57	710	0.5	20/10	N/A	N/A	80-100
FM 2000 *[23]	305 x 305	2300	57	N/A	0.5	10	5	3050	40-60
FM 2030 ** [24]	300 x 300	2400, 2030	57	711	0.5	20/10	N/A	N/A	80-100
LPS 1039 * [25]	H – 500	2700	60	N/A	0.59	N/A	5	N/A	40-60
* Indicates Commercial Standard ** Indicates Residential Standard									

Table 1 highlights differences between used standards. Sprinklers installed in the UK are typically approved to European and American standards and are subjected to numerous tests shown in the table.

The same distinction is applied to watermist standards [26–28]: however, watermist is not generally considered appropriate for property protection by UK insurers and is therefore not considered in this study[1]. There are also an extremely limited number of approved watermist nozzles available.

Sprinkler systems have been around for over two centuries, with the first known system being installed at Drury Lane Theatre, London, in 1812 [15]. They work through heat activation of the thermal sensing element located in the sprinkler head itself. In the event of fire, heat accumulating at the ceiling (where the sprinklers are located) activates the sprinklers when the temperature reaches a specified value. Sprinkler head(s) closest to the fire will activate, providing water to the fire below.

The amount of water discharged, based on the risk profile or occupancy hazard classification, is specified according to the standard adopted. Water discharge from sprinkler heads is measured as density of water (depth) in mm min^{-1} m^{-2} (~5–30 mm min^{-1} m^{-2}),[2] over an estimated fire area (confirmed by the hazard classification, usually between 72 and 300 m^2). Sprinklers are

[1] Watermist is perceived by some to be an alternative to sprinklers but is a relatively new form of suppression. The technology was developed for quite different environments derived from offshore needs, such as protecting engine bays in ships. Watermist is a more three-dimensional system than sprinklers, using heat absorption and oxygen displacement. It has more in common with gaseous fire protection systems in its mode of operation than with sprinkler systems.

[2] Within the sprinkler industry, density measurement is normally expressed as mm/min/m^2, which represents the depth of water in mm over an area of 1 m^2, for 1 min after activation.

located where the hottest gas layer would be expected at ceiling level (75–150 mm below the ceiling), to ensure early activation. Commercial/industrial sprinklers are spaced between 2 m (minimum) and 3.7/4 m (maximum) apart to cover an area of 9 to 12 m^2 per sprinkler depending on hazard classification. Each sprinkler is designed to discharge in a circular spray pattern, covering the fire area at floor level. The droplet size distribution for sprinkler systems is deliberately large (>1 mm), so droplets penetrate the fire plume to provide cooling and pre-wetting of the fuel load without cooling the ceiling gas layer (which would inhibit subsequent sprinkler heads from opening). Using sprinkler water to wet timber linings (walls, floors, and ceilings) will help to prevent flame spread within a compartment.

Sprinkler heads come in varied sizes having a range of 'K' factor constant coefficients that relate the orifice diameter, depth, and shape, to the operational pressure and output flow. Equation 1 shows the relationship between 'K' factor, pressure, and flow rate.

Equation 1:

$$K = Q/\sqrt{P}$$

where Q is the flow of water (L/min)

P is pressure (bar), and

K is the 'K' factor coefficient of the sprinkler head, which is directly proportional to Q and inversely proportional to the square root of the pressure.

Thermal sensitive elements in sprinkler heads differ in terms of type, and sensitivity and are chosen to suit the needs of the risk. They can take the form of a metal fusible link (soldered strut) or a thermal glass bulb containing a liquid that expands with heat to break the glass, as shown in Figure 1. In each case, once activated, the valve opens, allowing water to flow onto the sprinkler deflector to create the required spray pattern and coverage.

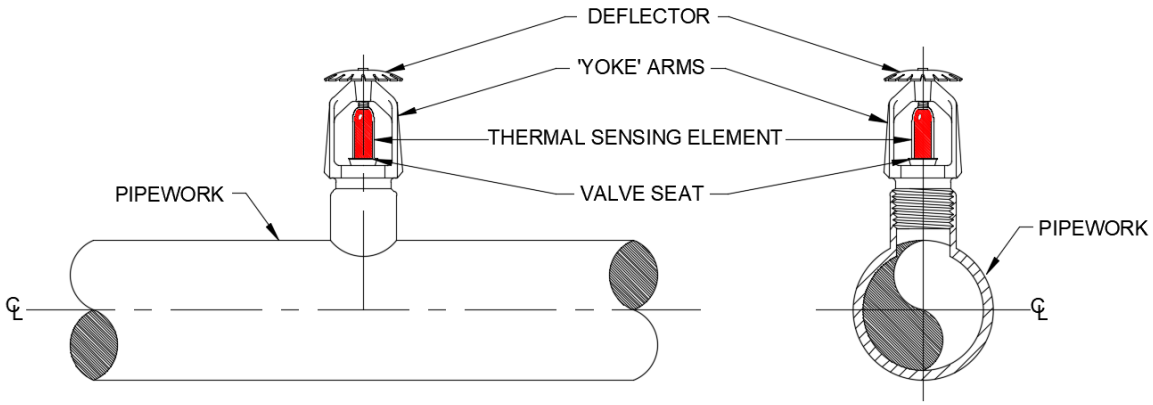


Figure 1. The main components of a sprinkler head with feed pipework (shown in the 'upright' mounting position).

Figure 1 shows a typical commercial sprinkler with glass bulb thermal sensing element connected onto a sprinkler range pipe through a welded socket, sized to match the sprinkler head (15 mm, K80 sprinkler).

In commercial sprinkler systems, sprinklers are spaced to ensure adequate floor coverage is achieved. Spray onto the walls and ceiling is not a consideration. However, there is a maximum spacing limitation of 1.5 m from external walls containing combustible material. Residential sprinkler standards allow for a greater area per sprinkler (~25 m^2) and at lower design densities (≥2.04 mm min^{-1} m^{-2}). Residential sprinklers are designed to provide an element of wall wetting 0.7 m below the ceiling, to cater for fires involving common household furnishings (curtains, cupboards, sofas, beds, etc.) that are located on the perimeter of rooms, but they are not required to wet the ceiling. Residential sprinkler systems are not specifically considered further in this study.

Knowledge of sprinkler head spray patterns has led this study to focus on Conventional sprinklers due to their ability to provide both an upward and a downward spray pattern, irrespective of whether the sprinkler is installed in a downward (pendant) or upward (upright) position.

Active suppression systems are installed in many types of building to support both life-safety and property/business resilience aims. Exposed timber surfaces, including walls, floors, and ceilings (in addition to the fuel load of the contents), present higher fire potential and increased Heat Release Rate (HRR), as observed by Bateman et al. [29]. Timber contributes to the fuel load of a fire, leading to longer and more severe fires, as studied by Hadden et al. [30]. In some instances, due to delamination of Cross Laminated Timber (CLT) slabs, secondary flashover occurs when the first lamella falls from the panel at the outermost glue line, exposing fresh timber to the fire.

Bartlett et al. [31] conducted small-scale tests on specimen CLT within a furnace to analyse the additional contribution and energy absorption. The small-scale testing led to six larger full-scale tests on a compartment that contained an exposed CLT slab at the ceiling with varying sizes of external openings leading to different oxygen and ventilation concentrations in each test. Due to the differences in openings, results from the tests varied. However, the tests confirmed that compartments with exposed timber linings contribute to a higher energy release than a standard compartment fuel load without the addition of timber linings. In addition to flaming combustion of exposed timber linings, smouldering combustion [10] in hidden voids [32] may mean that a fire could be unextinguishable by conventional means (fixed or intervention): this was witnessed by Building Research Establishment (BRE) in their TF2000 study [33]. Rein [10] confirms that smouldering combustion is the most persistent type of combustion phenomenon, it can be initiated with weaker ignition sources and is more difficult to suppress, with the potential transition from smouldering to flaming being a significant threat.

Research into the fire safety of timber construction has been conducted over the past decades, and much is already known. Self- or auto-extinguishment[3] [34–41] can only be considered in the decay phase of a fire when the moveable fuel load has been consumed and flaming combustion of the compartment turns to smouldering combustion. Fire tests in timber compartments [42–46] confirm this transitional change of combustion.

[3] A confusing term used that, rather than describing 'extinguishment,' actually refers to the end of 'flaming' combustion, where slower smouldering leads to the frequently observed phenomena of subsequent reignition and further flaming combustion.

Sprinklers have been tested in timber compartments [47–51], and recently watermist has been evaluated [52–53] showing successful suppression. The installation of a fire suppression system that activates in the early stages of a fire, to satisfy property protection requirements, should ensure that severe fire events never become unmanageable, and that a fire will not be allowed to persist long enough to 'burrow' or gain access to hidden voids.

Saeter Boe et al. [54] conducted fire testing simulating a fire in a student bedsit with an adjacent corridor, both with exposed CLT walls and ceilings, with sprinklers to EN 12845:2015 [11] using 15 mm sprinklers with a 'K' factor of 80 at a minimum pressure of 0.35 bar. Two experiments were conducted where the fire was started in the bedsit. In Experiment 1 all sprinklers were active; in Experiment 2 only corridor sprinklers were active. In Experiment 1, sprinklers activated after 2 minutes and controlled the fire until manual extinguishment. In Experiment 2, flashover of the room occurred at 5 minutes, with temperatures of 1,000°C recorded and rapid fire spread on the CLT wall and ceiling. Sprinklers in the corridor activated after 3–4 minutes, but these did not change the outcome. During the fire, pressure in the sprinkler heads was increased to 2.0 bar, with no effect on the fire. This demonstrates that a fire in an unsprinklered location, or with obstructed or isolated sprinklers, can cause the protection system to be significantly and rapidly overwhelmed within a timber-lined compartment and may point to the need for direct surface wetting. The test also demonstrated that the assurance of complete 'extinguishment' in timber structures requires manual follow-on intervention by the fire service.

The failure (overrunning) of the corridor sprinkler system was considered to derive from large flames from the bedsit entering the corridor and an inability of the system to prevent the involvement of the corridor CLT. In the corridor, large parts of the CLT walls remained standing post-fire, due to cooling from the colder air and water from the closest sprinkler (surface wetting). However, with no water application to the upper walls and ceiling provided by the Spray type sprinklers (100% water downward, detailed in section 2 and shown in the figure), damage was significantly greater as the system failed to stop the production of combustible gases that fed the existing flames and contributed to the uncontrolled fire spread along the corridor. The results indicate that appropriately selected sprinkler heads capable of wetting exposed surfaces should prevent CLT involvement and supress fire development and spread. When full sprinkler coverage is provided throughout all compartments, fire spread could be significantly slowed or halted within timber buildings.

With the objective of this investigation being to investigate water delivery from old-style sprinklers within timber enclosures, the discreet phases were as follows:

1. To investigate the suitability of commercially available sprinkler head designs.
2. To assess density of discharge (depth of water) from sprinklers at floor level, as detailed in current standards, appropriate to the risk occupancy classification of the building.
3. To assess wall wetting from adjacent sprinklers up to ceiling level in order to reduce surface spread of flame up compartment boundaries (walls).
4. To assess ceiling wetting from sprinklers, which could potentially contribute to slowing or halting surface spread of flame at ceiling level.

Each investigation, and its corresponding results are discussed in sections 2 to 5, respectively below.

2. Investigation into sprinkler system design

This study investigated the potential to adapt commercial sprinkler system design requirements for buildings that are considered non-combustible or of limited combustibility, to be suitable for mass timber CLT buildings with exposed timber surfaces. The shift to using increased quantities of timber and other low-carbon combustible materials, has underlined the importance of active fire protection for mass timber buildings, irrespective of height, but what is a suitable system?

For this study, sprinklers were considered as they have more stringent design standards than other suppression systems, alongside third-party certification, product approvals, guidance, history, interchangeable components, and they are not limited to specific contractors or manufacturers.

Sprinklers act on a fire directly by removing heat, and they also pre-wet surrounding fuel, reducing its ignitability and thereby limit the rate of flame spread. However, sprinkler heads differ in design, and their spray characteristics have changed over the decades. The following types of sprinkler heads were investigated, and their typical spray patterns are shown in Figure 2.

- Conventional (Upright and Pendant) sprinkler (CUP): The CUP sprinkler has a spherical water distribution directed towards the ground and the ceiling over a definite protection area. A conventional sprinkler discharges ~40% upward and 60% downward. The upward moving water typically but not consistently, strikes the ceiling and then drips downward, adding to the water below.

- Spray Sprinkler Pendant (SSP) sprinkler: This has a paraboloid water distribution directed towards the ground over a definite protection area. An SSP discharges 80–100% of the total water flow downward. SSP sprinklers give the specified distribution by having the jet of water directed downward against the deflector.

- Spray Sprinkler Upright (SSU) sprinkler: This has a paraboloid water distribution directed towards the ground over a definite protection area. An SSU also discharges 80–100% of the total water downward. SSU sprinklers give the specified distribution by having the jet of water directed upward against the deflector (as shown in Figure 1).

Sprinkler system constraints were reviewed to see what changes were needed to head type selection and spacing arrangements to improve water distribution to assist in protection of exposed combustible surfaces.
The study investigated water spray patterns, sprinkler size ('K' factor coefficients), distribution above and below the sprinkler deflector, and the potential for wall and ceiling wetting, in addition to providing the specified water density at floor level based on the associated hazard and risk of occupancy for common types of commercial buildings.

In the UK, water to sprinkler systems is generally supplied by centrifugal-type pumps as flow and pressure from town's mains are limited. Pumps are specified so they deliver water at not less than 0.35 bar to the most hydraulically remote sprinkler head when the maximum number of heads are operating, as specified in BS EN 12845:2015 [14] for Ordinary Hazard

classifications. The number of sprinklers operating within a specified fire area (known as the assumed area of operation) differs based on system classification ranging from 6 to 18 sprinklers (72 – 216 m^2). The 0.35 bar delivery pressure limit represents the failure point of the system, but inbuilt safety factors ensure this point is seldom reached and the fire will be managed by fewer sprinklers operating a higher pressure as defined by the pump's pressure/flow curve. To this end, in addition to testing at 0.35 bar, the sprinklers were also evaluated at 3.0 bar, representing a conservative pressure characteristic of the initial sprinkler head activation.

Entec UK Limited, for the UK Department for Communities and Local Government, reported that sprinklers control or extinguish fires in 99% of activations, with most incidents contained by four or fewer heads [55]. BAFSA data similarly shows that about 60% of commercial fires are controlled by four sprinklers [56]. UK design practice assumes a failure pressure of 0.35 bar for systems operating 18+ sprinklers, though actual pressures vary with system capacity and closed-valve pressure. Single-sprinklers was tested at 3.0 bar, which may be exceeded in practice. This study therefore adopts 3.0 bar as a conservative operating pressure in an Ordinary Hazard system.

3. Preliminary sprinkler dispersal patterns, 'K' factor and vertical distribution investigation

3.1 Methodology

3.1.1 Sprinkler dispersal patterns

An evaluation of different sprinkler head types to determine spray characteristics was conducted. Common sprinkler types were SSU (upright (upward)), SSP (pendant (downward)) and CUP (upright/pendant (ratio 40:60)), shown in Figure 2. Testing used 15 mm sprinklers with a 'K' factor of 80 at a delivery pressure of 0.35 bar, representing minimum head pressure of the system, and 3.0 bar, representing a single sprinkler head operating in the initial stages of a fire. Sprinklers were visually screen-tested to identify which heads provided a good proportion of upward spray.

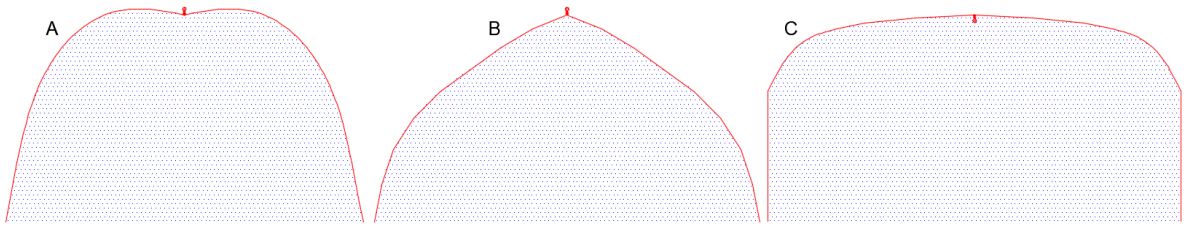


Figure 2. 2-dimensional representation of sprinkler distribution patterns. A: A CUP sprinkler discharging a proportion of water upward to the ceiling and downward to the floor. B: An SSP sprinkler discharging 100% water downward to the floor. C: An SSU sprinkler discharging 100% water downward to the floor.

Based on visual testing which complemented Figure 2, Conventional sprinkler head (CUP) types were selected for these specific tests as they provided an upward and downward spray characteristic, confirmed by manufacturers' data sheets. Sprinklers were obtained from five manufacturers with the same characteristics (CUP 15 mm, K80), referenced in this study as manufacturer A (Rapidrop), B (Reliable), C (Tyco), D (Victaulic) & E (Viking). These sprinklers have been shown to perform for the specific spray pattern/test for which they were originally produced. Sprinklers tested have the following approvals:

- A (Rapidrop) LPCB and VdS

- B(Reliable) LPCB and VdS
- C (Tyco) LPCB, VdS, UL and C-UL
- D (Victaulic) LPCB, VdS and C-UL
- E (Viking) LPCB and C-UL

3.1.2 'K' factor testing

The accuracy of 'K' factors was measured, as it is known that 'K' factors can vary from specified values. This provided an essential baseline so that accurate flow rates could be obtained during distribution testing through water pressure monitoring at the sprinkler head.

Manufacturers' data provided with the sprinkler samples confirm that the 'K' factor for each was 80. Testing to BS EN 12259-1:1999 [57] was used to obtain actual 'K' factors for each sprinkler.

Testing consisted of a water pump, pipework, sprinkler(s), pressure transducer, and water container. Volume of water collected, test duration and accurate pressure readings at the sprinkler allowed 'K' factors to be established using Equation 1. Results showed variations in 'K' factors from all manufacturers and are reported in section 3.2.

3.1.3 Vertical distribution (above and below) water collection

Manufacturers' data states that 40% of water delivered to a CUP sprinkler is distributed upward and 60% downward. To evaluate accurate above and below water distribution, a simplified test set-up based on BS EN 12259-1:1999 [57] Annex D.3 test rig was used, shown in Figures 3 and 4. This used the same components as the 'K' factor tests, with the addition of the above/below water deflector plate.

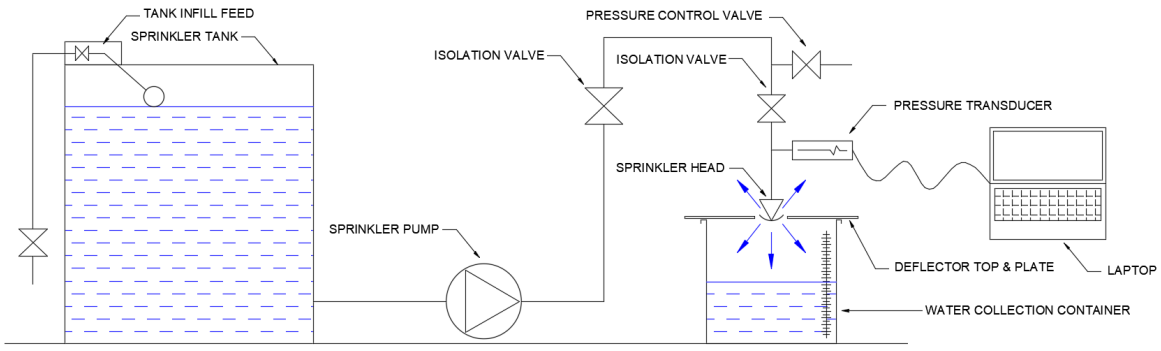


Figure 3. Schematic of the test set-up arrangement for sprinkler water collection below the deflector.

Using sprinkler head pressure and actual 'K' factors, the flow rate through each of the sprinklers was established through calculation (Equation 1). To evaluate above and below water distribution, measurements were taken from water collected in the container below the sprinkler over a period of time. This allowed water flow calculated below the sprinkler deflector to be deducted from the total flow of water being delivered through the sprinkler head, allowing the above/below ratio to be calculated. Tests were conducted at a range of different pressures over a range of time periods. Results for above and below water distribution are presented in section 3.2.

Figure 4. Simplified test set-up for recording below water distribution capture from sprinklers. A: The test set-up. B: Water capture below the sprinkler.

Figures 3 and 4 show the modified version of BS EN 12259-1:1999 Annex D3 set up. The board on top of the container was fitted with a thin metal plate ~2 mm thick which contained a hole that was ~1 mm larger than the sprinkler deflector shown in Figure 4A. The sprinkler deflector was located at the same level as the top of the plate to allow water to be collected in the container below the deflector. The water delivered above the container flowed away and was not collected.

3.2 Preliminary investigation sprinkler results

3.2.1 'K' factor testing

Testing was conducted with CUP sprinklers from five manufacturers. Data sheets confirmed a minimum 'K' factor coefficient of 80. Testing was undertaken as described in section 3.1.2 and, using Equation 1, results for accurate 'K' factors were obtained, confirmed in Table 2.

Table 2. 'K' factor test results.

Manufacturer reference	Specified 'K' factor (L min^{-1} $bar^{-1/2}$)	Measured 'K' factor (L min^{-1} $bar^{-1/2}$)	Tolerance value
Sprinkler A	80	85.45	+ 5.45
Sprinkler B	80	82.52	+2.25
Sprinkler C	80	80.27	+0.27
Sprinkler D	80	84.22	+4.22
Sprinkler E	80	84.41	+4.41
Note: In BS EN 12259-1:1990, Table 3's error range is 80 ± 4			

Table 2 shows variance between all manufacturers (sprinklers A to E). All sprinklers had slightly higher 'K' values, which would result in higher sprinkler flow rates. Two sprinklers fell within tolerance requirements of BS EN 12259-1:1990; three sprinklers fell outside tolerance values. At a consistent pressure provided to sprinklers assessed, those measured with a higher 'K' factor would provide higher flow rates. For example, at a pressure of 1 bar, Sprinkler A would provide a flow rate of 85.45 L/min, Sprinkler C would provide a flow rate of 80.27 L/min.

3.2.2 Vertical distribution testing (above and below)

Water distribution tests for above and below the sprinkler deflector were undertaken generally in accordance with BS EN 12259-1:1999 Annex D.3 using a modified test rig as detailed in

section 3.1.3. with each sprinkler flowing at 4.0 bar pressure. Results shown in Table 3 demonstrate that a good proportion of upward spray was achieved from all sprinklers. Results show different distribution ratios from each sprinkler when considering manufacturers' data, where more water is distributed above the deflector, which will support ceiling wetting.

Table 3. Above and below water distribution results.

Manufacturer reference	Specified distribution (%)		Measured distribution (%)	
	Above	Below	Above	Below
Sprinkler A	40	60	56.1	43.9
Sprinkler B	40	60	52.8	47.2
Sprinkler C	40	60	52.1	47.9
Sprinkler D	40	60	45.2	53.8
Sprinkler E	40	60	54.5	45.5

Table 3 shows different distribution ratios from each sprinkler when considering manufacturers' data. Results show more water is distributed above the deflector, which will support ceiling wetting. The increase in upward distribution could be attributed to the modified test arrangement being vertical as opposed to horizontal as detailed in BS EN 12259-1:1999 Annex D3, and potentially the lack of ventilation within the container to remove the air volume from within when discharging water and entrained air is directed into the collection container.

3.3 Preliminary investigation sprinkler discussion

Three sprinkler types were initially assessed, to recognize spray characteristic patterns. Testing showed that upward (SSU) and downward (SSP) sprinklers discharged 100% water downward, consistent with the manufacturers' literature. Conventional sprinklers (CUP) demonstrated both upward and downward spray, which would benefit exposed combustible timber ceilings.

To establish a basis for sprinkler selection criteria and to evaluate sprinklers in different orientations, pressures, and locations, three criteria were considered, shown in Figure 5. The first criterion was wall wetting. A fire located adjacent to a combustible wall has been shown to be larger than a fire in the middle of a compartment [58] where the initial fuel package is equivalent. Potential surface spread of flame upward to the ceiling was deemed to be a significant threat. Therefore, wall wetting is an important fire protection requirement. The next criterion was involvement and surface spread of flames on the ceiling above sprinklers. The final criterion was water flow to floor level for general contents fuel loads, which current sprinkler rulesets consider by specifying a minimum design density of discharge below sprinklers, based on occupancy classification.

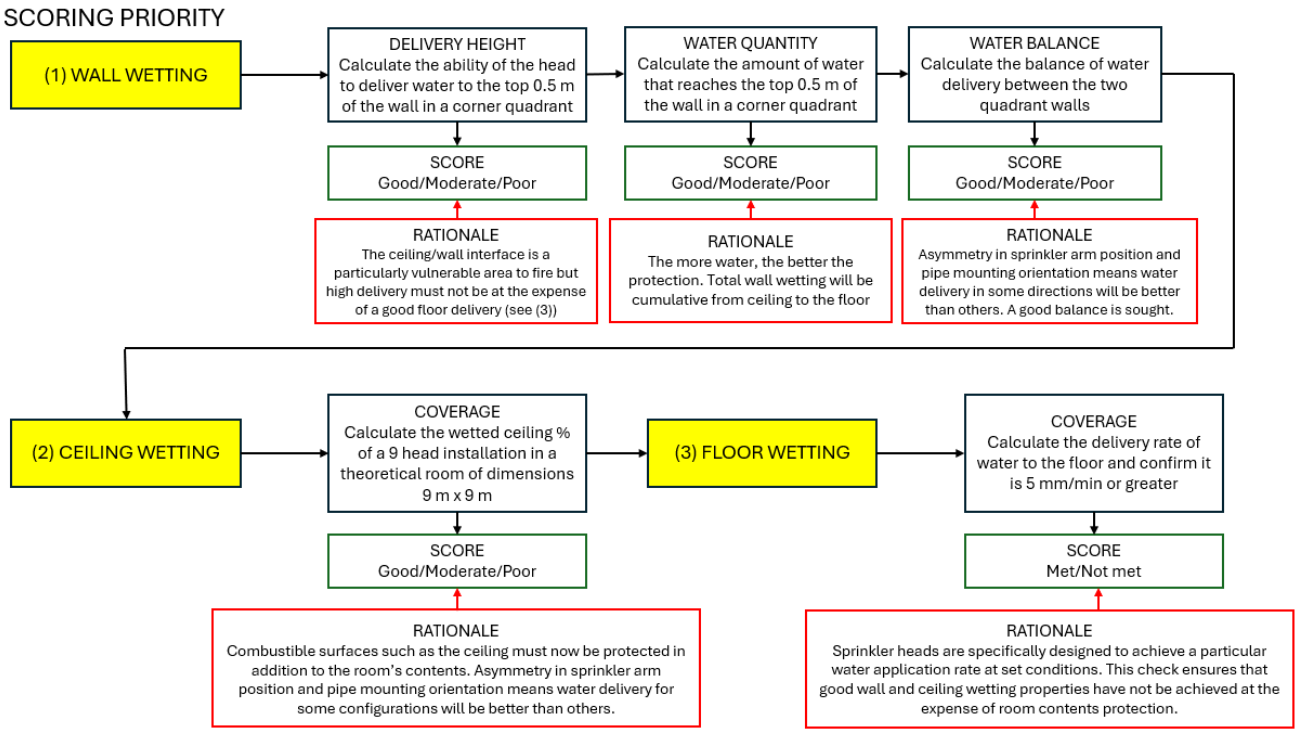


Figure 5. Flow chart for sprinkler head characterisation selection.

Thirty-nine individual water distribution tests were conducted to evaluate the performance of each sprinkler (A – E) against the criteria set out in Figure 5 and are summarised in Table 4. The complete set of data and results are summarised in the supplementary material.
As described in Section 1, automatic sprinkler systems are engineered to limit fire development through direct suppression and by pre-wetting adjacent combustible fuels to inhibit secondary ignition. Water remains the predominant suppression agent due to its favourable thermophysical properties, including a high latent heat of vaporisation and substantial specific heat capacity, which enable efficient absorption of thermal energy from the fire environment and attenuate heat transfer to nearby materials. Historically, conventional 'Victorian-era' sprinkler configurations have demonstrated enhanced wetting of exposed timber surfaces (ancestral mill floors and ceilings), contributing to reductions in incident heat flux and suppression of surface pyrolysis. This pre-wetting action delays ignition and decreases the rate of flame spread across timber substrates, thereby enhancing overall compartment fire resilience.

4. Ceiling and floor wetting

4.1 Methodology

A hybrid test was established to evaluate water distribution, capture water volume at floor level and measure ceiling surface wetting. It was decided to use elements of the different standards shown in Table 1 to optimise testing for this study.

The test set-up consisted of a tank, pump, pipework, fixings, pressure transducer, sprinkler(s) (CUP), water collection buckets, load cell and laptop for recording data, shown in Figure 6.

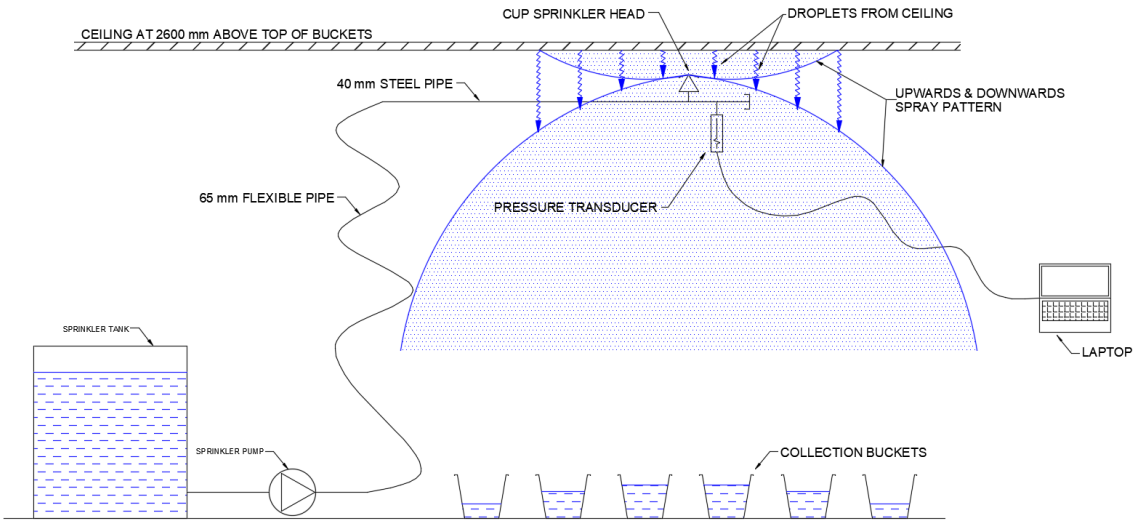


Figure 6. Schematic of water collection layout and major components.

The design layout for water collection is shown in Figure 7: 108 identical buckets were located at 500 mm centres on a semi-circle layout with a maximum radius of 4 000 mm to capture water. The CUP sprinkler head(s) were located between 150 and 180 mm below the ceiling. Location of sprinkler deflector below the ceiling is critical in terms of response time activation. Ideal locations for sprinkler thermal element (glass bulb) are 75–150 mm below the ceiling. Sprinklers were installed with the yoke arms running perpendicular to the sprinkler pipe. Using standard industry bracket material, allowed the sprinkler to be installed at 150 mm below the ceiling when tested in the upward position. However, due to physical bracketry size, when tested in the downward position, a range of 150–180 mm was achieved, depending on sprinkler head design. Table 1 summarizes the various sprinkler test standards, which specify ceiling heights ranging from 2030 mm to 3050 mm. For the present study, a ceiling height of 2600 mm above the tops of the buckets was selected, corresponding to the mean value of the surveyed standards. Based on these standards, it was assumed that this height provides sufficient clearance beneath the sprinkler to allow full development of the intended spray pattern. A ceiling height of 2600 mm is also representative of typical floor-to-ceiling heights in buildings without suspended ceilings, where mechanical and electrical services remain exposed. The experimental configuration further assumed the absence of any service-related obstructions to water discharge, ensuring that the resulting spray characteristics could be observed and recorded without interference.

To enable sprinkler wetting patterns to be quantified, the open area and the lip of a standard bucket was measured. Water droplets hitting the lip were predicted to have a 50% chance of entering the bucket. The area of the bucket, including half of the lip, was used as the area of capture for water discharge from the sprinkler(s).

Water collected in each of the 108 buckets was quantified gravimetrically and entered into Microsoft Excel according to each bucket's spatial position, producing a 180° distribution profile that was mirrored under the assumption of radial symmetry to obtain a full 360° representation. Application density (mm min^{-1} m^{-2}) was calculated by dividing the measured mass by test duration and bucket opening area, and a corresponding plan-view density map was generated. For enhanced visualisation, density data were imported into Microcal Origin, arranged on an 8 × 16 grid, and mirrored to form a 16 × 16 matrix. This matrix was then up-scaled to 64 × 64 using the software's grid-interpolation function, which estimates intermediate values

by fitting a smooth surface between measured points. The resulting high-resolution interpolated matrix enabled the production of detailed contour plots that more accurately depicted spatial density distribution. This procedure was applied uniformly across all sprinkler models evaluated, shown in section 4.2.2.

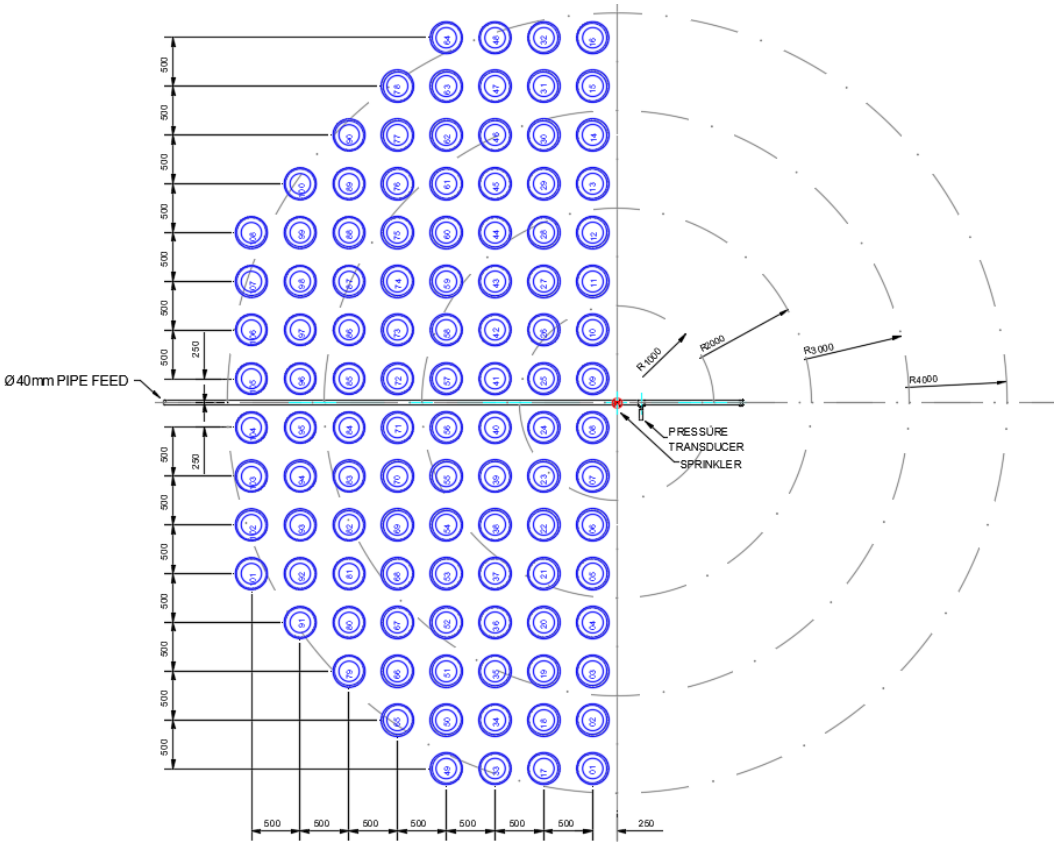


Figure 7. Test set-up for water distribution capture and ceiling wetting analysis from sprinklers. The blue concentric circles represent buckets.

The ceiling was marked up at 500 mm intervals, north–south and east–west from the centre point of the sprinkler, so that wetting patterns at ceiling post-test could be measured, photographed, and simulated. Figure 8 shows the test set-up with the buckets located below the ceiling, with pipework and sprinkler head above.

Given the optimum distance of sprinkler deflector below ceiling is 75–150 mm, testing at the lower level of 150/180 mm allowed space for the sprinkler to spray upward and develop a wetting pattern on the ceiling. This lower level would increase the activation time of the sprinkler slightly, but this would be offset by more efficient wetting of the timber ceiling.

Results for ceiling wetting were photographed, measured, and visually replicated in AutoCAD showing 'wetted' areas.

Figure 8. Water collection buckets in a semi-circular layout below the sprinkler.

Table 4 shows the summary of the varying tests undertaken with sprinklers located in an open area (tests 01-16), shown in Figures 6 and 7, and in a corner wall location prefixed with the letter W,(tests W01-W17) shown in Figures 17 and 18 where sprinklers were located at 1.5 m from each wall. For tests 17, 18, W18, W19, W20 and W21, sprinklers were selected based on best/worst performance and were tested where only the sprinkler head is exposed below the ceiling/soffit. Due to availability of the test laboratory, sprinkler performance was evaluated during testing and results obtained at lower pressures were used to select and rank sprinklers for testing at the higher pressure of 3.0 bar. Sprinklers A, B & C were chosen as best, average and worst performing. Sprinklers D and E were not tested at 3.0 bar as they fell in-between best/worst ranking at the lower pressure.

Table 4. Summary table of water distribution tests.

Test Reference	Sprinkler head manufacturer (A, B, C, D & E)	Target test pressure (bar)	Orientation tested (Downwards / Upwards / Ceiling)	Recorded Pressure (bar)
01	A	0.35	Upwards	0.35
02	E	0.35	Upwards	0.35
03	A	0.35	Downwards	0.33
04	A	3.0	Downwards	3.02
05	C	0.35	Downwards	0.35
06	D	0.35	Downwards	0.35
07	B	0.35	Downwards	0.35
08	E	0.35	Downwards	0.35
09	B	3.0	Downwards	3.11
10	C	3.0	Downwards	3.10
11	C	0.35	Upwards	0.34

12	B	0.35	Upwards	0.35
13	D	0.35	Upwards	0.34
14	B	3.0	Upwards	3.12
15	A	3.0	Upwards	3.03
16	C	3.0	Upwards	3.11
17	C	3.0	Ceiling	2.85
18	C	0.35	Ceiling	0.35
W01	C	3.0	Upwards	3.13
W02	A	3.0	Upwards	2.99
W03	E	3.0	Upwards	2.98
W04	D	3.0	Upwards	3.05
W05	B	3.0	Upwards	3.09
W06	B*	3.0	Upwards	3.10
W07	B	0.35	Upwards	0.34
W08	A	0.35	Upwards	0.35
W09	C	0.35	Upwards	0.35
W10	C	3.0	Downwards	3.12
W11	A	3.0	Downwards	3.00
W12	E	3.0	Downwards	3.02
W13	B	3.0	Downwards	3.10
W14	D	3.0	Downwards	3.05
W15	B	0.35	Downwards	0.34
W16	A	0.35	Downwards	0.34
W17	C	0.35	Downwards	0.36
W18	C	3.0	Ceiling	2.85
W19	C	0.35	Ceiling	0.37
W20	B	0.35	Ceiling	0.35
W21	B	3.0	Ceiling	2.80
Note: Test W06 (*) sprinkler was located at 1.5 x 1.1 m spacing				

Table 4 shows all water distribution testing undertaken for each sprinkler, in different orientations at different pressures. 'Ceiling' referenced within Table 4 refers to the sprinkler head being installed downwards (pendant) within a suspended ceiling configuration and with sprinkler pipework being located above the ceiling. This is a common installation method for compartments with suspended ceilings where the sprinkler deflector is located ~ 40-50 mm below the ceiling (depending on manufacturer).

4.1.1 Distribution criteria (ceiling and floor)

Ceiling wetting distribution is not a requirement in current sprinkler standards and was assessed purely on physical wetted area measured to the nearest m^2. The largest wetted area was considered best performing sprinkler and smallest measured area considered worst performing sprinkler for each orientation and pressure.

Sprinkler water distribution was evaluated at the floor using actual measured density. The largest area covered within the minimum design density of 5 mm min^{-1} m^{-2} was considered to have the best performance, the smallest area meeting the minimum design density was considered worst performance.

4.2 Ceiling and floor results

4.2.1 Ceiling wetting

Tests conducted at a system pressure of 3.0 bar confirmed that a substantial proportion of the ceiling surface received a continuous flow of water across it which manifested as a wetting pattern. The results are presented in diagrammatic form to illustrate the extent and distribution of the wetted ceiling area. For the purposes of this study, the wetted area was defined as the region of sustained water spray observed to contact and remain on the ceiling surface during testing.

Figures 9 and 10 summarise both measured and photographic records of the ceiling wetting patterns. These data were transferred into AutoCAD to provide a visual representation of surface wetting and to estimate the area of coverage produced by the sprinkler discharge. Observations showed that water spray from the sprinkler impinged on the ceiling and spread radially across the surface, forming a characteristic wetting pattern from which larger droplets detached and fell towards floor level.

Owing to the geometry of the sprinkler deflector, the remaining droplets were predominantly projected horizontally and downward in an umbrella-shaped spray distribution. This spray pattern governed water delivery to the floor, where measurements were collected to determine the actual application density achieved at floor level.

4.2.1.1 Pendant (downward) patterns

Results show sprinklers installed in the downward position produce slightly smaller wetted areas than sprinklers in the upward position. In downward orientation, it can clearly be seen how the pipework feeding the sprinkler (above the sprinkler head) impacts water distribution and coverage directly above, with a 'dry' area of ceiling. This is known in the sprinkler industry as *pipe shadowing* and would produce a larger 'dry' area with a larger-diameter sprinkler pipe.

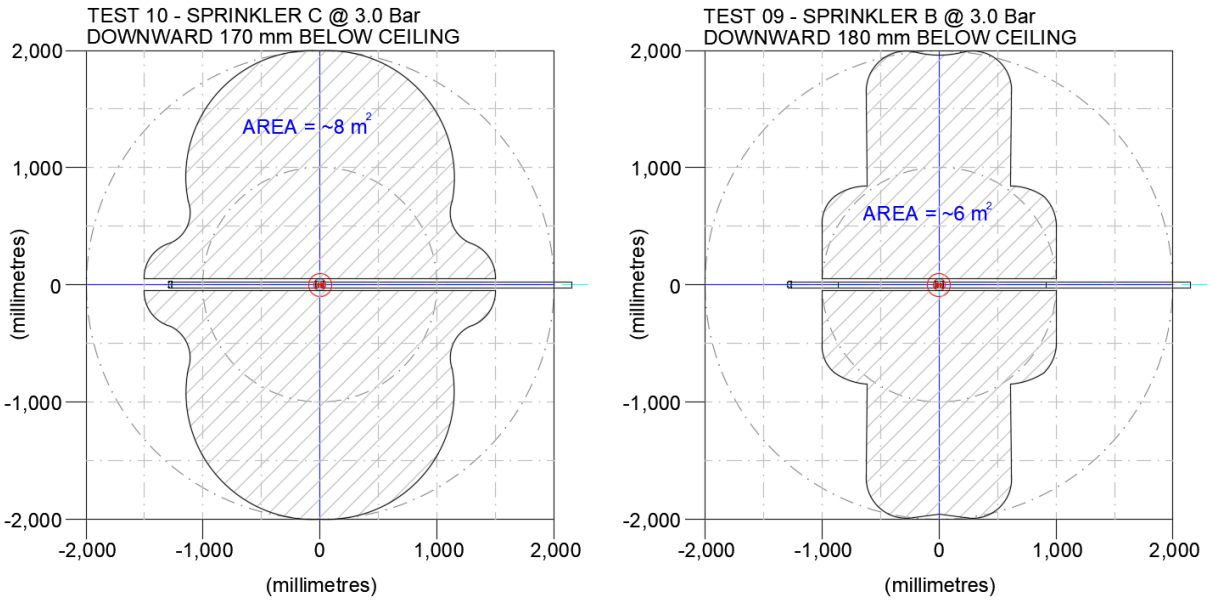


Figure 9. Representation of ceiling wetting patterns for sprinkler heads operating at 3.0 bar in the downward position. Left: Best ceiling wetting results from sprinkler C. Right: Worst ceiling wetting results from sprinkler B.

Figure 9 shows the ceiling pattern has an elongated shape, potentially due to the location of the sprinkler yoke arms causing an obstruction to the spray pattern. This complemented results from wall tests where better water distribution was achieved where the sprinkler yoke arms did not impact directional spray.

4.2.1.2 Upright (upward) patterns

Ceiling wetting patterns for sprinklers in the upward orientation are more circular than those in the downward orientation. Figure 10 shows the best and worst ceiling wetting patterns.

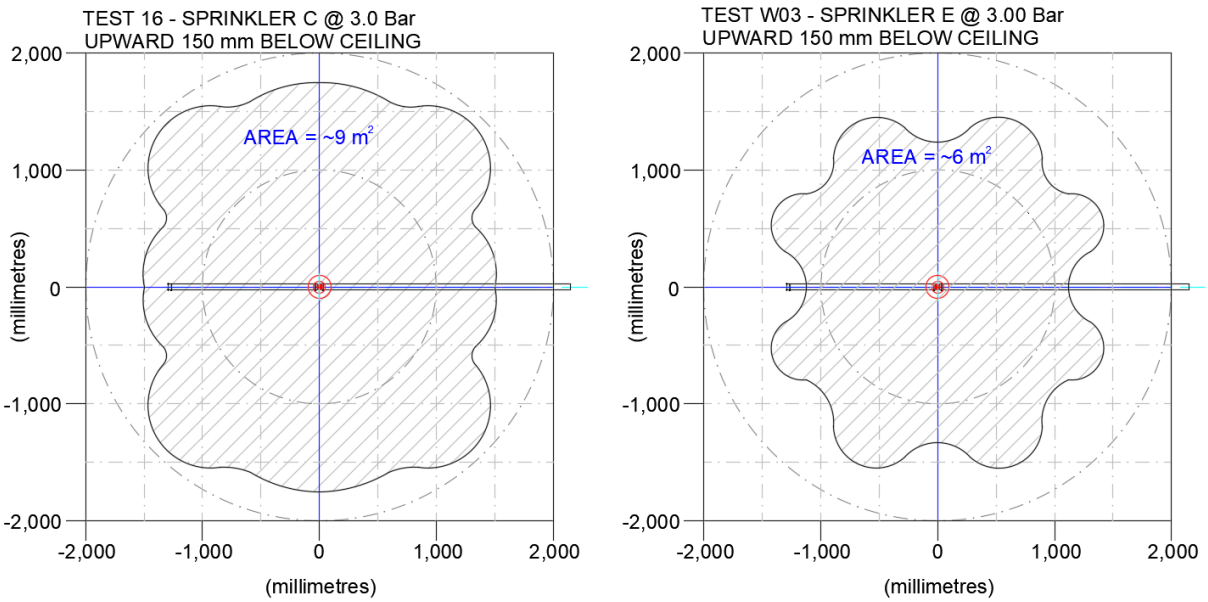


Figure 10. Representation of ceiling wetting patterns for sprinkler heads operating at 3.0 bar in the upward position. Left: Best ceiling wetting results from sprinkler C. Right: Worst ceiling wetting results from sprinkler E.

Figure 10 shows a more circular wetted ceiling area directly above the sprinkler head from the upward orientation of the sprinkler. When comparing both orientations, it is clear from the results that the surface area of wetted ceiling from sprinklers in the upward position would allow a more uniform spacing of sprinklers to cover ceiling area than those in the downward position which is simulated in Figure 23. For the full range of wetting patterns, see supplementary material.

4.2.2 Floor distribution

A requirement for all sprinklers, irrespective of type and orientation, is to provide water discharge to cover the floor where the contents fuel load will be present. A specified density of discharge from sprinklers is required to cover the contents and is based on occupancy classification. Current requirements for standard type commercial occupancies (Ordinary Hazard) require a design density of discharge of 5 mm min^{-1} m^{-2} over an assumed floor area varying from 6 to 18 sprinklers (72–216 m^2). Results at floor level shown in sections 4.2.2.1 and 5.2.2.2 have been capped at an adequately compliant density of 6 mm min^{-1} m^{-2}. These areas are shown in elevated black sections in Figure 11.

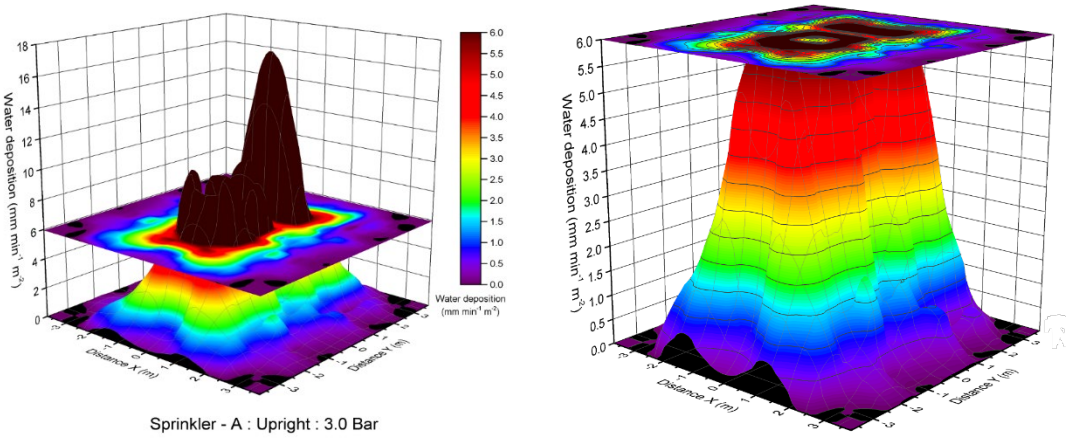


Figure 11. Delivery of water density at 3.0 bar in 3-D. Left: showing a density of discharge with higher densities 6-16 mm min^{-1} m^{-2} shown in black. Right: discharge results capped at 6 mm min^{-1} m^{-2}.

Figure 11 shows the actual density of water delivered from sprinkler A at a pressure of 3.0 bar. The peak recorded density is at ~16 mm min^{-1} m^{-2} over a small area. At ~5 mm min^{-1} m^{-2} (minimum requirement) the results show that the area adequately covered by the sprinkler is ~12 m^2 (3 x 4 m).

4.2.2.1 CUP in the Pendant (downward) position

Figures 12 and 13 show the best and worst results for actual density delivered at a pressure of 3.0 bar for sprinklers located in the downward orientation.

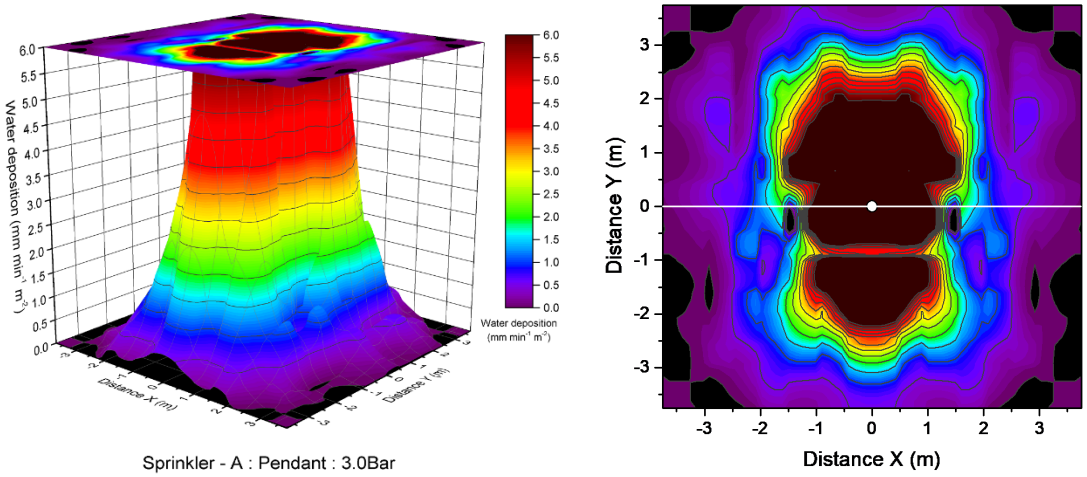


Figure 12. Best results of delivery of water density in downward orientation from sprinkler A at 3.0 bar in 3-D and 2-D.

Figure 12 demonstrates >6 mm min^{-1} m^{-2} density of discharge over an area of ~8 m^2 and an average density of 2.5–5.0 mm min^{-1} m^{-2} for the remaining area up to ~12 m^2. The red and black areas in the right-hand figure correspond to the area that complies with the standard for Ordinary Hazard.

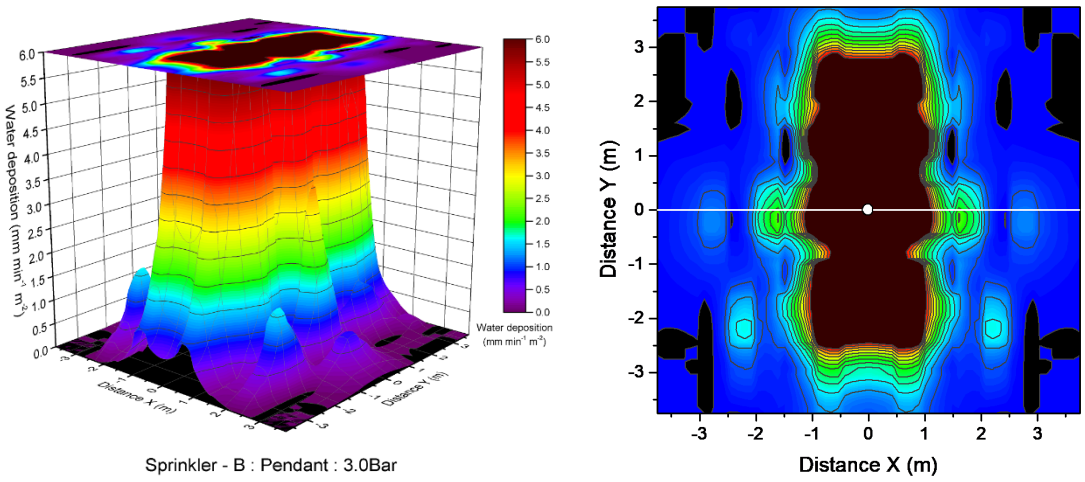


Figure 13. Worst results of delivery of water density in downward orientation from sprinkler B at 3.0 bar in 3-D and 2-D.

Figure 13 demonstrates >6 mm min^{-1} m^{-2} density of discharge over an area of ~7 m^2 and an average density of 1.0–3.0 mm min^{-1} m^{-2} for the remaining area up to ~12 m^2.

4.2.2.2 CUP in Upright (upward) position

Figures 14 and 15 show the best and worst results for actual density delivered at a pressure of 3.0 bar for sprinklers located in the upward orientation.

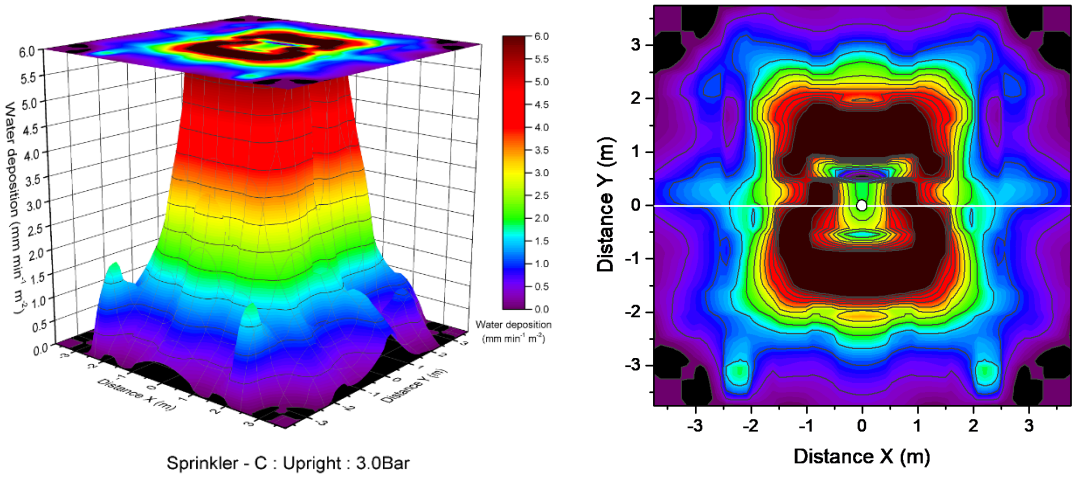


Figure 14. Best results of delivery of water density in upward orientation from sprinkler C at 3.0 bar in 3-D and 2-D.

Figure 14 demonstrates >6 mm min^{-1} m^{-2} density of discharge over an area of ~8 m^2 and an average density of 2.5–5.0 mm min^{-1} m^{-2} for the remaining area up to ~12 m^2.

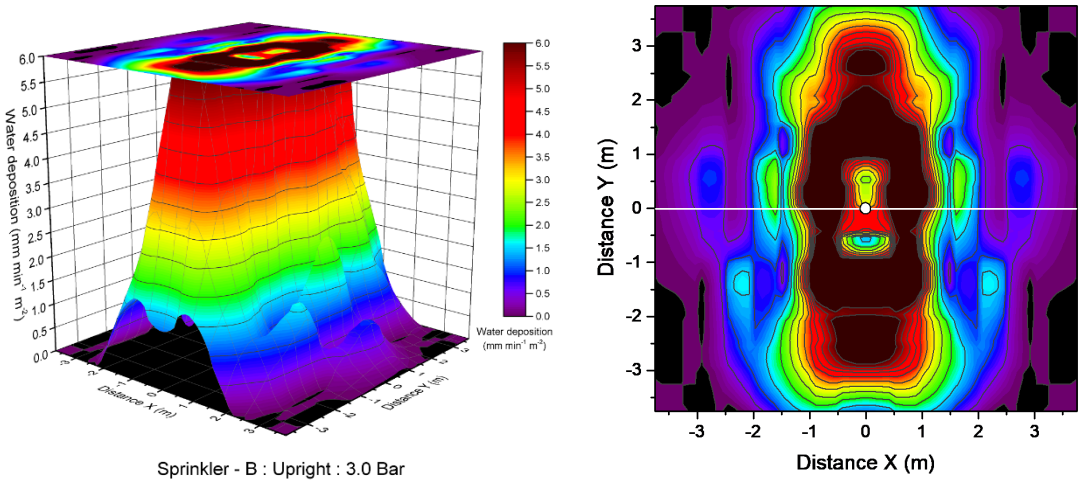


Figure 15. Worst results of delivery of water density in upward orientation from sprinkler B at 3.0 bar in 3-D and 2-D.

Figure 15 demonstrates >6 mm min^{-1} m^{-2} density of discharge over an area of ~6 m^2 and an average density of 1.0–5.0 mm min^{-1} m^{-2} for the remaining area up to ~12 m^2.

Results in both orientations show the actual delivered density of discharge for single sprinklers operating at 3.0 bar. It is difficult to confirm from a single head test if the appropriate density is achieved: however, results confirm that >6 mm min^{-1} m^{-2} is achieved directly below the sprinkler head in areas ≥6 m^2 and lower densities are confirmed for areas up to ~12 m^2. An overall density requirement of 5 mm min^{-1} m^{-2} can be considered achieved from these tests.

Figure 16 shows a simulation from a group of four sprinklers spaced at 3 m × 3 m, at a minimum pressure (0.35 bar).

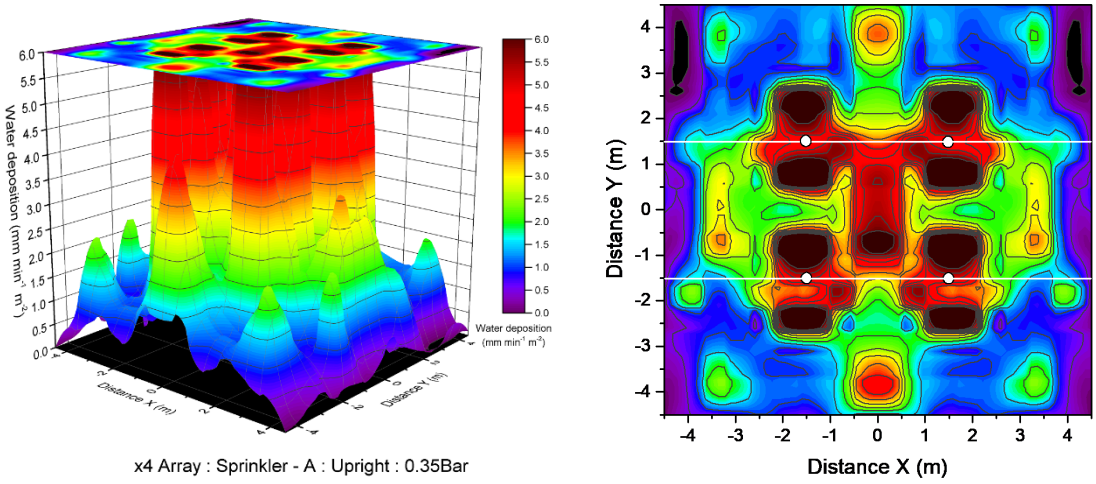


Figure 16. A simulated density of discharge from a group of four sprinklers in the upright orientation at a minimum pressure of 0.35 bar.

Figure 16 shows the density within the area of four sprinklers (9 m2) ranges from ~2.5 to >6 mm min^{-1} m^{-2}. The capture area shown can be assumed to be ~5 mm min^{-1} m^{-2} at 0.35 bar as an average mean collective. Smaller peaks of intensity shown in the figure are not artifacts of the software, they are the product of actual measurements. Results shown are for collected

densities at precise locations below the sprinkler, and do not consider full collective mean density at floor level.

4.3 Ceiling and floor wetting discussion

Subjective analysis has been conducted confirming ceiling wetting and floor density from sprinklers ranging from best to worst. Results for tests shown in Table 4 can be found in supplementary material.

The experimental programme was conducted under a simplified ceiling configuration, comprising a single ceiling height with no localised mechanical or electrical services or other ceiling-mounted obstructions, and employing single-sprinkler activation only. These conditions were intentionally selected to isolate intrinsic sprinkler discharge and plume interactions in a controlled environment. Consequently, the findings should be interpreted as comparative rather than directly representative of suppression performance in real compartments, where ceiling-mounted services, geometric complexity, and multi-sprinkler interactions are expected to significantly influence fire dynamics and sprinkler effectiveness.

Ceiling wetting results confirm that CUP sprinklers will provide an upward spray pattern to the ceiling. Results at minimum operating pressure of 0.35 bar, with sprinklers located ~150 mm below the ceiling show surface area of wetted ceiling is reduced. This is also evident from tests where the sprinkler was located within the ceiling irrespective of test pressure. At the higher pressure of 3.0 bar, with sprinklers located ~150 mm below the ceiling, wetting was optimised providing a larger wetted ceiling area.

To maximise the effectiveness of ceiling surface wetting, sprinkler layouts may be optimised through alternative spacing configurations aimed at limiting potential surface flame spread. Acceptable system performance is defined as achieving a wetted ceiling area and distribution that contributes to a measurable reduction in flame spread across combustible surfaces. A staggered sprinkler arrangement, consistent with the guidance provided in BS EN 12845:2015, clause 12.2, Table 20, and Figure 8, enables each sprinkler to be offset relative to adjacent units, producing a diamond-shaped pattern rather than a conventional square layout.

Staggered sprinkler spacing can enhance overlap of spray distributions at the ceiling, promoting sustained and more uniform wetting rather than isolated wetted areas beneath individual sprinklers. This configuration could reduce wide spacing gaps at combustible boundaries (<1.5 m), improving wetting at walls and corners that are otherwise vulnerable to early flame impingement and rapid surface flame spread.

Actual density delivered to the floor at a sprinkler head pressure of 0.35 bar shows that the minimum required density is achieved from all sprinklers in the upward position. However, in downward position, sprinklers B and C do not provide adequate density. At 0.35 bar all sprinklers show reduced floor area coverage at 5 mm min^{-1} m^{-2}. Sprinklers A, B and C were evaluated at 3.0 bar in both orientations and met minimum density requirements. Sprinklers D and E were not assessed at 3.0 bar. However, it could be assumed that as these fell within best/worst performance at 0.35 bar, they would provide minimum density requirements at 3.0 bar.

Initial considerations regarding sprinkler head selection indicate fundamental differences in spray characteristics between sprinkler types. Modern sprinkler heads are designed to deliver

water predominantly in a downward direction, whereas CUP sprinklers distribute water upwards, horizontally, and downwards, enhancing surface wetting in multiple orientations. While the precise coverage patterns of modern sprinklers were not evaluated in this study, both modern and CUP sprinklers are approved to relevant European and American standards, confirming that the minimum floor area coverage requirements prescribed by applicable standards are satisfied. The CUP sprinkler results demonstrate a smaller radius of higher water density concentrated directly beneath the sprinkler head, whereas modern sprinklers are likely to provide a more uniform water density over a larger radial floor area. Consequently, achieving equivalent fire suppression objectives with CUP sprinklers may require adjustment of sprinkler spacing to ensure adequate and consistent floor density coverage across the protected area.

Floor water distribution results at reduced sprinkler head spacing ~9 m^2 (based on 3m x 3m), at the minimum design pressure of 0.35 bar, show that the minimum design density requirement of 5 mm min^{-1} m^{-2} can be achieved.

In the early stages of fire with a single sprinkler operating, a higher pressure will provide a greater density of water directly over the fire area and simultaneously provide a larger ceiling wetting pattern.

5. Wall wetting

5.1 Methodology

The test set-up for wall wetting incorporated a corner wall scenario, using MDF panels and 100 × 50 mm structural timber batons shown in Figures 17 and 18. Walls were painted with a water-repellent paint and fitted with a lightweight metal L-shaped 90° angle. The angle was attached to the face of the wall and foil tape was used to seal and create a 5 mm × 5 mm trough.
The troughs were located at 500 mm intervals up the wall, and on the surface. Each 0.25 m^2 area of wall was numbered, with all water touching the surface being collected in the trough below (Figures 18a and 18b). The troughs were sloped feeding hoses through to the rear of the wall (Figures 18c and 18d). Hoses were glued and sealed into position and fed into corresponding numbered buckets for water capture from the respective section.
Sprinkler pipework and the arms of the sprinkler heads, known as the yokes, are known to contribute to shadowing of the sprinkler discharge spray pattern observed in ceiling wetting results. To prevent double shadowing, yoke arms were aligned with the sprinkler pipework which is the requirement for sprinkler head installation. Results shown in section 5.2 demonstrate the effect of shadowing.

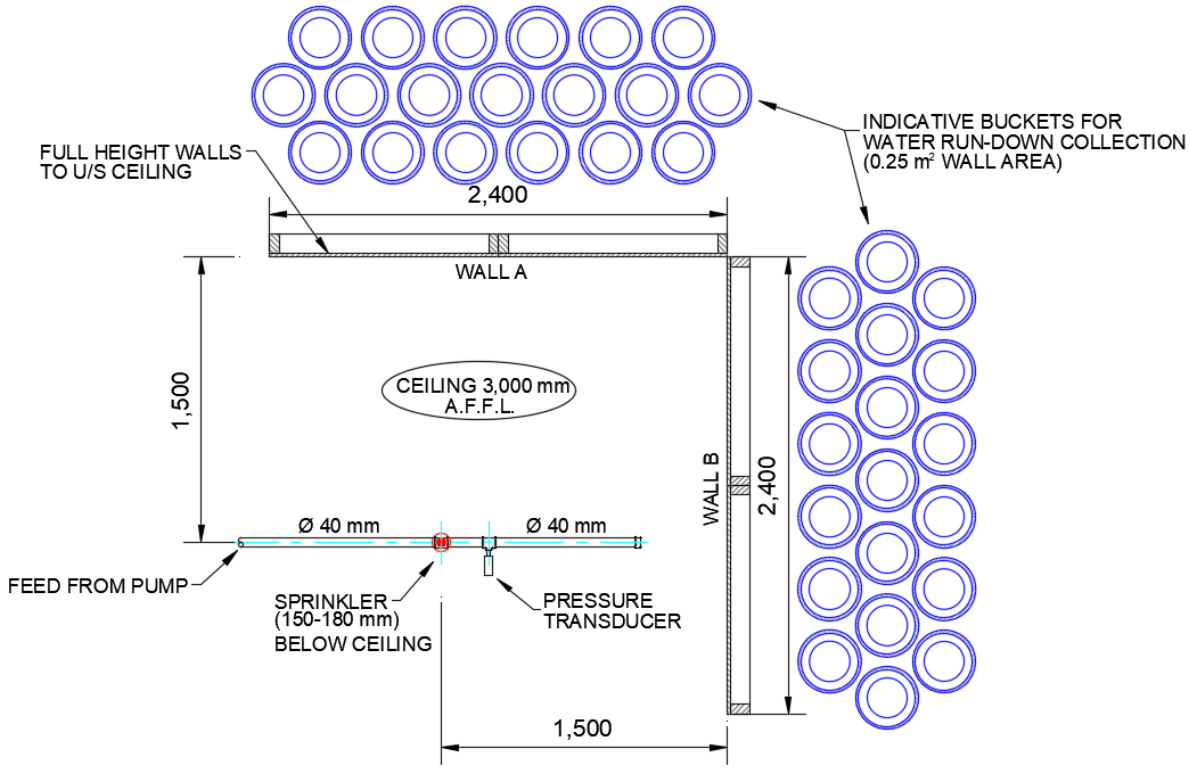


Figure 17. Design of water collection for water run-down. Hoses have not been shown for clarity.

The orientation of yoke arms running with the pipework ensures that spray from the sprinkler is not impeded by either. Running the yoke arms with the pipework allowed for unimpeded spray onto Wall A. Spray to Wall B would be interrupted by both the pipework and the yoke arms. The impact of the interference of water spray onto Wall B from the yoke arms is shown in section 5.2.

An acceptable level of performance from each sprinkler is considered to be the ability to provide sufficient water to the top 0.5 m section of the wall at the intersection of the ceiling, in addition to providing a similar distribution to both walls. This is not defined as a requirement in current standards for commercial sprinkler systems. Fire spread over the walls is likely to reach and involve the ceiling very quickly. The potential for sprinkler spray to reach the top 0.5 m section of the wall will provide wetting to both planes to assist in reducing the impact of surface spread of flame.

Figure 18. 18a: Corner wall set-up. 18b: 0.5 × 0.5 m (0.25 m^2) measured area. 18c: Water collection trough. 18d: Water collection buckets with clear tube feed pipes at the rear.

Water captured was weighed and converted into volume. The volume was divided by the area of each panel and test duration to provide a density in mm min^{-1} m^{-2}. Results are represented in graphical form in section 5.2.

5.1.1 Distribution criteria (walls)

Sprinklers were evaluated for wall wetting by using density of discharge to each 0.25 m^2 section of wall in mm min^{-1} m^{-2}, which is not a requirement in current commercial sprinkler standards. The sprinkler providing the most even proportional density and coverage to both walls was considered best performing sprinkler, and least even density with disproportionate coverage on both walls considered worst performing sprinkler.

5.2 Results

5.2.1 Area density collection

Twenty-one wall wetting tests were conducted using CUP sprinklers in downward and upward configurations at both 0.35 and 3.0 bar pressure. Measurement and capture of water to each 0.5 × 0.5 m (0.25 m^2) area was recorded and converted into actual density discharge per unit area of wall on each panel, to establish whether water reached the top wall area intersecting with the ceiling. Figures 19 and 20 show the results for both walls from the sprinkler located at 1.5 m from each wall, indicated as a yellow oval at the top of the wall.

Figures 19 and 20 show two sprinkler positions (upward and downward), delivering water at a pressure of 3.0 bar. Irrespective of orientation, wall wetting is achieved from all sprinklers, with significant differences between individual heads. However, adequate performance was observed for all sprinkler heads.

Actual densities are recorded per 0.25 m^2 panel (Figures 19 and 20). These figures show average density horizontally and vertically on Walls A and B. However, water run-down through cumulative density is a more important consideration. Colour shading is included to indicate actual density of water delivered to each individual panel. Light green/blue indicates a low delivery of water. The blue range indicates good water delivery, with darker shading delivering more water.

Side Wall Test Sprinkler C Upright 3.0 bar

8.4	12.2	9.5	7.6	3.1	7.6	8.6	6.2
3.3	1.8	2.9	2.2	5.0	2.8	4.7	3.6
1.2	0.8	0.8	0.3	1.3	0.8	1.0	1.1
0.8	0.3	0.5	0.3	0.9	0.3	0.3	0.5
0.8	0.6	0.6	0.1	0.6	0.3	0.1	0.2

Wall A Wall B

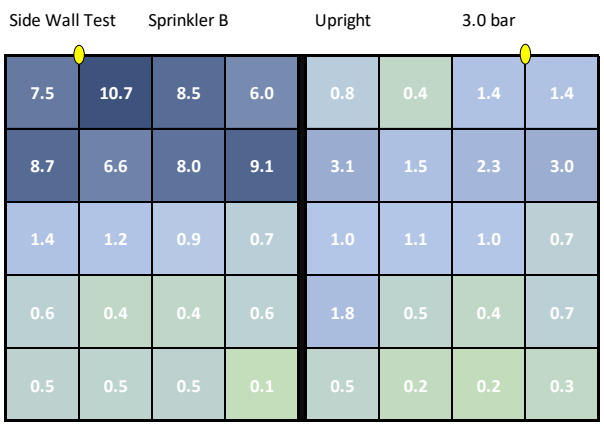
Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm/min per column	2.9	3.1	2.8	2.1	2.2	2.4	2.9	2.3

	mm/min per row	
Vertical Level	Wall A	Wall B
Row 5	9.4	6.4
Row 4	2.5	4.0
Row 3	0.8	1.1
Row 2	0.5	0.5
Row 1	0.5	0.3

Mean water density per wall (mm/min)	Wall A	Wall B
	2.8	2.5

Figure 19a. Measured densities from test W01, sprinkler C, for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling.

Figure 19a shows sprinkler density in near symmetry to both walls. Whilst there are slight differences in the density per 0.25 m^2 panel on walls A and B, the mean density per wall is very close. The effect of the yoke arm position can be clearly seen in the density recorded in the upper sections of the wall located closest to the sprinkler.



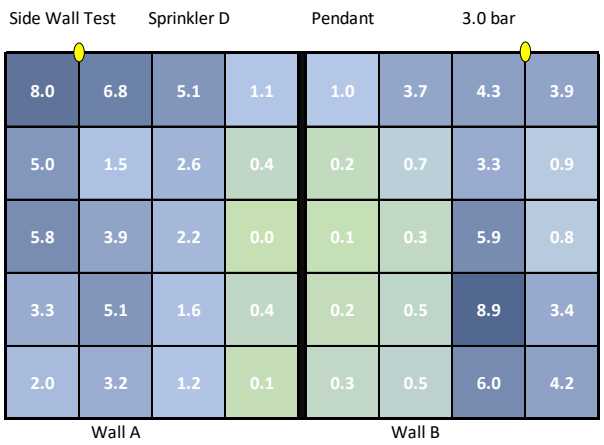
	mm/min per row	
Vertical Level	Wall A	Wall B
Row 5	8.2	1.0
Row 4	8.1	2.5
Row 3	1.1	0.9
Row 2	0.5	0.8
Row 1	0.4	0.3

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm/min per column	3.7	3.9	3.7	3.3	1.4	0.7	1.1	1.2

Mean water density per wall (mm/min)	Wall A	Wall B
	3.7	1.1

Figure 19b. Measured densities from test W05, sprinkler B, for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.

Figure 19b shows a disproportionate delivery of sprinkler density to each wall. Wall A is provided with greater density at the top two levels. Wall B follows a similar pattern in that more water is delivered to the top two section of wall, but at much lower densities.



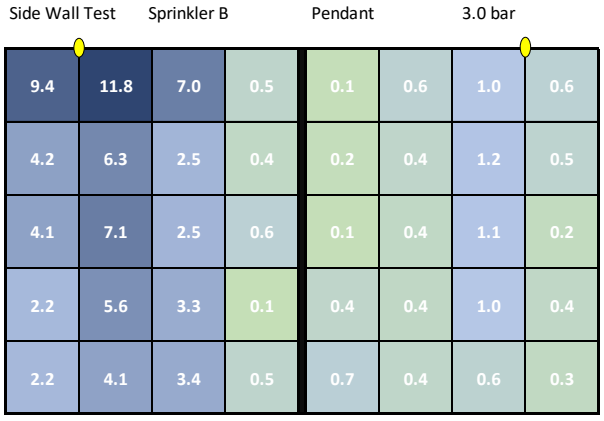
	mm/min per row	
Vertical Level	Wall A	Wall B
Row 5	5.2	3.2
Row 4	2.4	1.3
Row 3	3.0	1.8
Row 2	2.6	3.2
Row 1	1.6	2.8

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm/min per column	4.8	4.1	2.5	0.4	0.4	1.1	5.7	2.6

Mean water density per wall (mm/min)	Wall A	Wall B
	3.0	2.5

Figure 20a. Measured densities from test W14, sprinkler D, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling.

Figure 20a shows the closest sprinkler density on both walls for sprinklers in the downward orientation. The figure shows that the lowest density recorded is the intersection between wall A and B which is confirmed in the average density of both columns 1.



	mm/min per row	
Vertical Level	Wall A	Wall B
Row 5	7.2	0.6
Row 4	3.3	0.6
Row 3	3.6	0.5
Row 2	2.8	0.5
Row 1	2.5	0.5

Horizontal position	Col 4	Col 3	Col 2	Col 1	Col 1	Col 2	Col 3	Col 4
mm/min per column	4.4	7.0	3.7	0.4	0.3	0.4	1.0	0.4

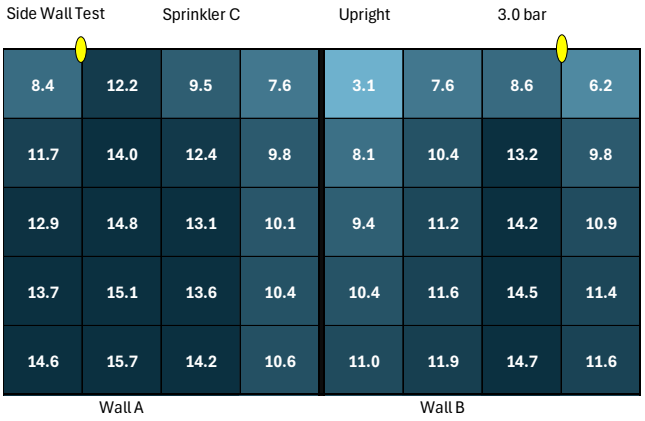
Mean water density per wall (mm/min)	Wall A	Wall B
	3.9	0.5

Figure 20b. Measured densities from test W13, sprinkler B, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.

Figure 20b shows a significant disproportionate delivery of sprinkler density to each wall. Wall A has a significant quantity of the water flow from the sprinkler with good density in columns 2, 3 and 4. Wall B has extremely low densities and the intersection of both walls has the lowest density recorded.

5.2.2 Cumulative density collection

Cumulative density reveals the beneficial effect of water run-down from the top of the wall, providing more than adequate wall wetting towards the floor. Figures 21 and 22 show cumulative recorded densities and water distribution proportions for each wall. Colour shading shows water delivery differences, with darker shading indicating greater water delivery.

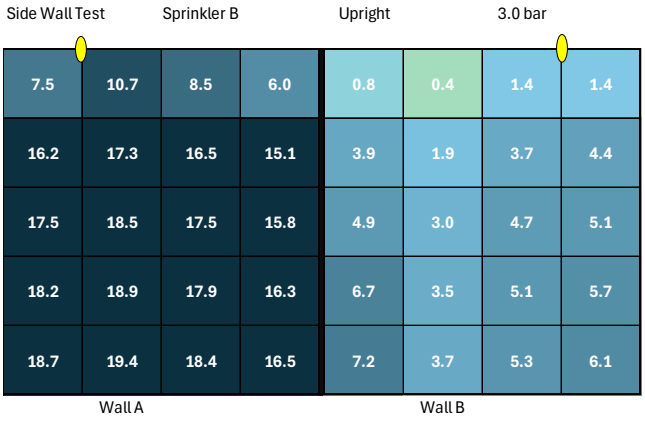


	mm/min per row	
Vertical Level	Wall A	Wall B
Row 5	9.4	6.4
Row 4	12.0	10.4
Row 3	12.7	11.4
Row 2	13.2	12.0
Row 1	13.8	12.3

% wall wetting from sprinkler	Wall A	Wall B
	53%	47%

Figure 21a. Cumulative densities from test W01, Sprinkler C, for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling.

Figure 21a shows the close ratio of water delivery to both walls confirming that sprinkler C in the upward position has good symmetry and water run down to floor level.

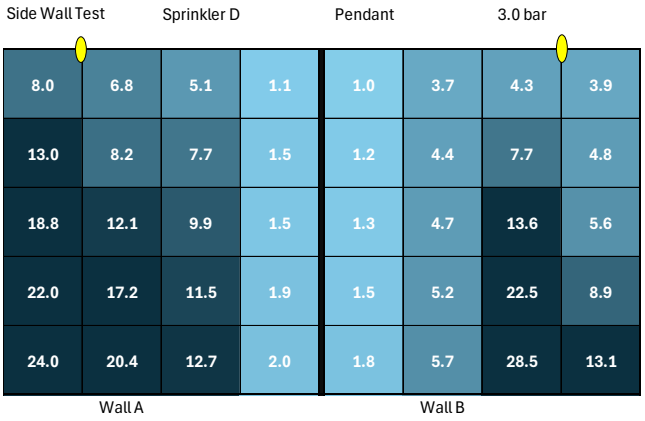


	mm/min per row	
Vertical Level	Wall A	Wall B
Row 5	8.2	1.0
Row 4	16.3	3.5
Row 3	17.3	4.4
Row 2	17.8	5.3
Row 1	18.3	5.6

% wall wetting from sprinkler	Wall A	Wall B
	77%	23%

Figure 21b. Cumulative densities from test W05, Sprinkler B for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.

Figure 21b shows the inferior performance of sprinkler B in the upward position providing less water delivery to wall B and poor water run down capability.

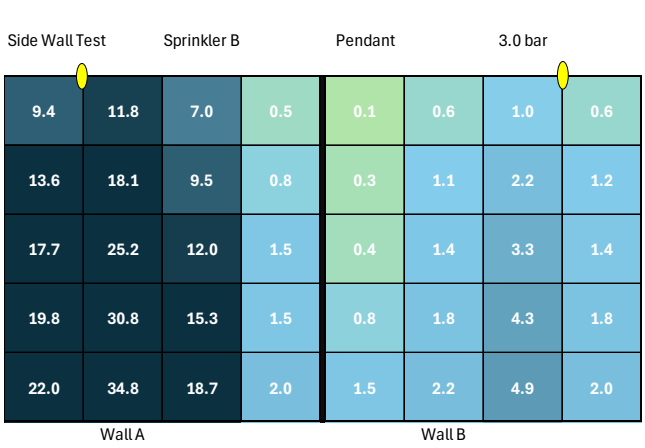


Vertical Level	mm/min per row Wall A	Wall B
Row 5	5.2	3.2
Row 4	7.6	4.5
Row 3	10.6	6.3
Row 2	13.2	9.5
Row 1	14.8	12.3

% wall wetting from sprinkler	Wall A	Wall B
	55%	45%

Figure 22a. Cumulative densities from test W14, Sprinkler D, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling.

Figure 22a shows the close ratio of water delivery from sprinkler D in the downward orientation. Results from the figure show that less water is delivered to the intersection of walls A and B.



Vertical Level	mm/min per row Wall A	Wall B
Row 5	7.2	0.6
Row 4	10.5	1.2
Row 3	14.1	1.6
Row 2	16.9	2.2
Row 1	19.4	2.6

% wall wetting from sprinkler	Wall A	Wall B
	88%	12%

Figure 22b. Cumulative densities from test W13, Sprinkler B, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.

Figure 22b confirms the worst results obtained showing disproportionate water delivery from the sprinkler head. The intersection of wall A and B suffer from poor water delivery in the downwards orientation.

5.3 Wall wetting discussion

The results indicate a difference in performance of sprinklers based on location of the yoke arms relative to the facing wall. Proportionate distribution irrespective of yoke arms is achievable in some sprinklers, but not others. Pipework shadowing is also a contributing factor in reduced distribution when sprinklers are installed in the pendant (downwards) position.

Water run-down has been shown in density (mm min^{-1} m^{-2}) for visual ease: however, this method of measurement is for depth of water at floor level over a specified area, which is captured in section 4.2.2. Irrespective of water measurement, it can be observed from Figures 19, 20, 21 and 22 that the top 0.5 m of the wall is wetted. However, results also show significant differences between sprinkler heads.

Experimental testing undertaken in this study demonstrates that, when sprinkler heads are arranged at 1.5 × 1.5 m spacing from corner sections and positioned 150–180 mm below the ceiling, the resulting discharge reliably reaches the ceiling–wall interface. The findings further show that water run-down from the upper wall surface produces sustained wetting, ensuring adequate distribution to lower interface regions. This wetting behaviour is expected to limit fire penetration into unsealed gaps or openings within the wall construction and thereby reduce the likelihood of smouldering.

6. Conclusions

This study demonstrates that sprinkler head spray characteristics play a critical role in achieving continuous protective water flow over the ceiling and walls. This is essential for protecting combustible surfaces, such as exposed timber buildings. While both modern and CUP sprinklers meet applicable European and American design standards, they exhibit different water distribution patterns. CUP sprinklers deliver water upward, horizontal, and downwards, whereas modern sprinklers provide a more uniform distribution across the floor area. As a result, sprinkler head spacing becomes a key design consideration when CUP sprinklers are used to ensure sufficient coverage. These findings reinforce the importance of sprinkler selection and layout in meeting fire performance objectives in fully sprinkler-protected timber compartments. Tests were conducted on sprinklers of the same type (CUP), size, temperature, and 'K' factor produced by five manufacturers.

'K' factor testing confirmed that minimum specifications were achieved. Results showed slightly higher 'K' factors, which would result in slightly greater water discharge from the sprinklers. However, this deviation is not likely to compromise the effectiveness of the system based on perceived fires.

Water distribution results above and below the sprinkler head show a closer ratio of water delivery than the manufacturers' specifications. Water distribution above the sprinkler deflector confirms slightly higher flows, which support ceiling wetting at distances of 150 – 180 mm below the ceiling.

There is no recognised standard for assessment of wall wetting from commercial sprinklers. Bespoke testing undertaken in this study confirms that wall wetting was achieved at lower and higher sprinkler head pressures. Performance and distribution ratios varied in the twenty-one tests performed. However, results from all tests confirmed that water was delivered to the top 0.5 m section of the wall at the intersection with the ceiling. The worst performing sprinkler provided minimal wetting in the corner wall (Figure 20b) where a fire could grow more quickly

up the walls. In this case closer spacing to the corner wall would allow more water flow from the sprinkler to be distributed onto the wall, improving cumulative water flow to the corner.

Ceiling wetting was achieved by all CUP sprinklers. Results varied between tests, from exceptionally good to extremely poor coverage, which represents worst-case scenarios. If the tests were conducted with a fire plume, it could be anticipated that the upward thrust of gas would help the water to spread further horizontally. Figure 23 shows a simulation of the extremity of the best and worst ceiling wetting in a compartment of 9 m × 9 m for standard sprinkler spacing at 3 m maximum.

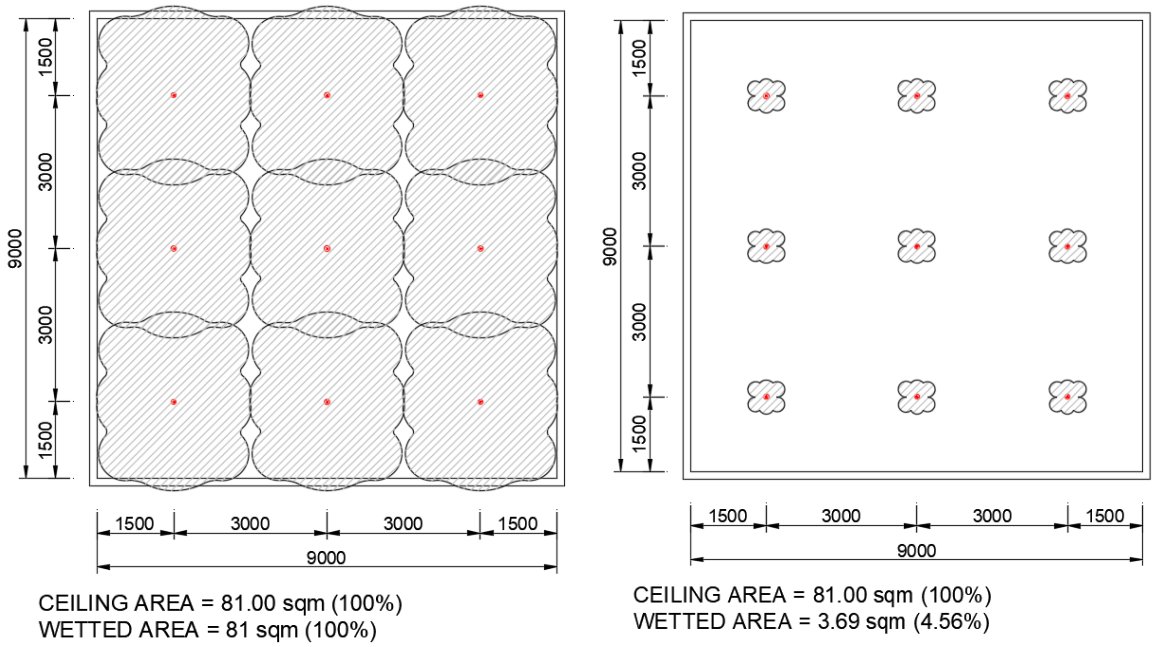


Figure 23. Extremities of ceiling wetting areas. Left: Sprinkler C in upright orientation at 3.0 bar. Right: Sprinkler C in pendant orientation at 0.35 bar.

Figure 23 shows the extreme limits of ceiling wetting results from testing. At a pressure of 3.0 bar, sprinkler C in an upward orientation demonstrates satisfactory ceiling coverage within a compartment. The same sprinkler head in a downward orientation at 0.35 bar exhibits wholly inadequate ceiling coverage. All other recorded sprinkler coverage tests fell between these two extremes and can be found in supplementary material.

To improve wetting coverage of the ceiling, sprinklers could be spaced in an irregular manner, known as staggered spacing in accordance with BS EN 12845:2015, to provide more of a continuous wetted ceiling line to prevent the surface spread of flame, but selection of the correct sprinkler in the optimum orientation would be required. Staggered spacing would allow sprinklers to be positioned so that each sprinkler is centrally offset from the adjacent sprinkler in more of a diamond shape than square. It is hoped that from this study manufacturers of sprinkler heads consider further development of CUP sprinklers to perform in a more optimal and desirable way in relation to upwards spray to improve surface wetting of the ceiling.

The final criterion was floor wetting/minimum density of discharge at floor level. Results at both tested pressures met the minimum specified densities for occupancy classifications considered within this study (offices, schools, hospitals, and general retail type outlets – classified as Ordinary Hazard occupancies).

Selection of the optimal performing sprinkler shall be evaluated against the three criteria set out in section 3.3.

Wall wetting (criteria 1): Good proportionate coverage to both walls with wetting to the top 0.5 m (wall/ceiling interface) irrespective of yoke arm and pipe shadowing is required to ensure this vulnerable area is wetted from the sprinkler head. Sprinkler head selection shall be taken based on tested results at 0.35 bar and 3.0 bar.

Ceiling wetting (criteria 2): Irrespective of sprinkler head orientation (upwards/downwards), the maximum potential water distribution pattern on the ceiling shall be used to select the most appropriate sprinkler. Using the wetting pattern, sprinklers shall be spaced to provide a barrier of wetting to the ceiling to slow or halt fire spread. Knowledge of or tested results showing wetting patterns at pressures of 0.35 bar and higher will confirm sprinkler head selection.

Floor wetting (criteria 3): Sprinklers shall be capable of providing minimum discharge density of 5 mm^{-1} min^{-2} over the required area as required for Ordinary Hazard classifications within BS EN 12845:2015.

The goal of this study was to establish whether commercially available sprinkler heads could adequately provide wetting to the surfaces of exposed timber. Modern sprinklers (SSP and SSU) demonstrated they have the ability to cover the floor and a percentage of the walls, but no upward spray can be achieved for the wetting of the ceiling, shown in Figure 2 when compared to CUP sprinklers. Testing aimed to assess whether a good distribution on ceilings, walls and contents could be achieved from sprinklers mounted in different orientations at two different pressures.

Experimental testing has demonstrated that appropriate selection of sprinkler head type, together with defined constraints on sprinkler spacing, can meet the requirements for achieving a continuous flow of water over combustible timber surfaces with the objective of delaying or preventing surface flame spread, while simultaneously maintaining the minimum required water application density to the contents fuel load at floor level, as illustrated in Figures 24 and 25.

It is recognised that surface wetting alone does not fully characterise key parameters such as water flux, film thickness, or wetting persistence, all of which influence ignition delay and suppression of timber pyrolysis. However, the continuous water discharge from adjacent operating sprinkler heads onto exposed surfaces may be considered functionally comparable to the pre-wetting of the movable fuel load at floor level. Pre-wetting, in terms of the fire tetrahedron, relates to the effective removal of fuel by rendering the ignitable and combustible components unignitable and non-combustible.

On this basis, the study demonstrates equivalent overall system performance in terms of fuel wetting and fire growth limitation. This pre-wetting of both fixed and movable fuel loads is expected to support occupant evacuation and contribute to improved conditions for firefighting operations undertaken by Fire and Rescue Services.

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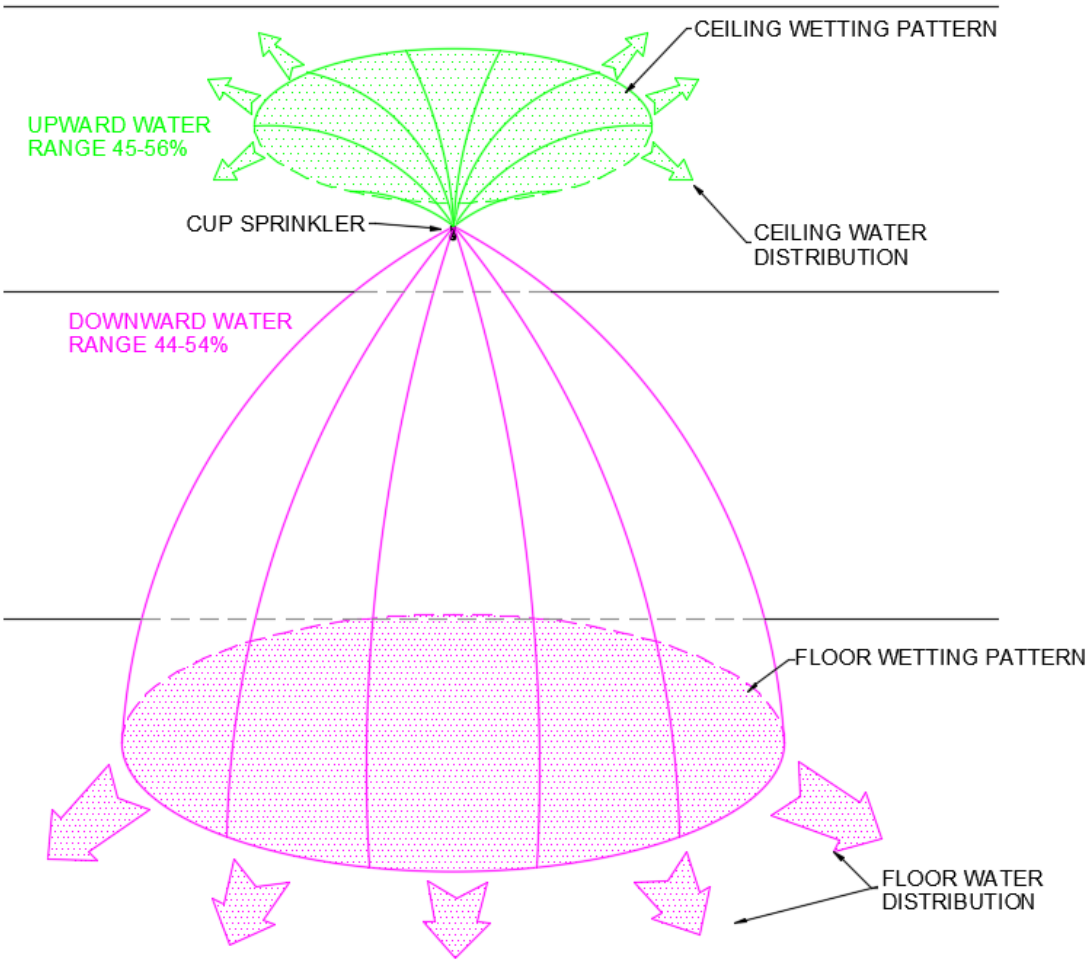

Figure 24. Simulated visual discharge characteristic of a CUP sprinkler, demonstrating ceiling and floor wetting achieved from a single sprinkler.

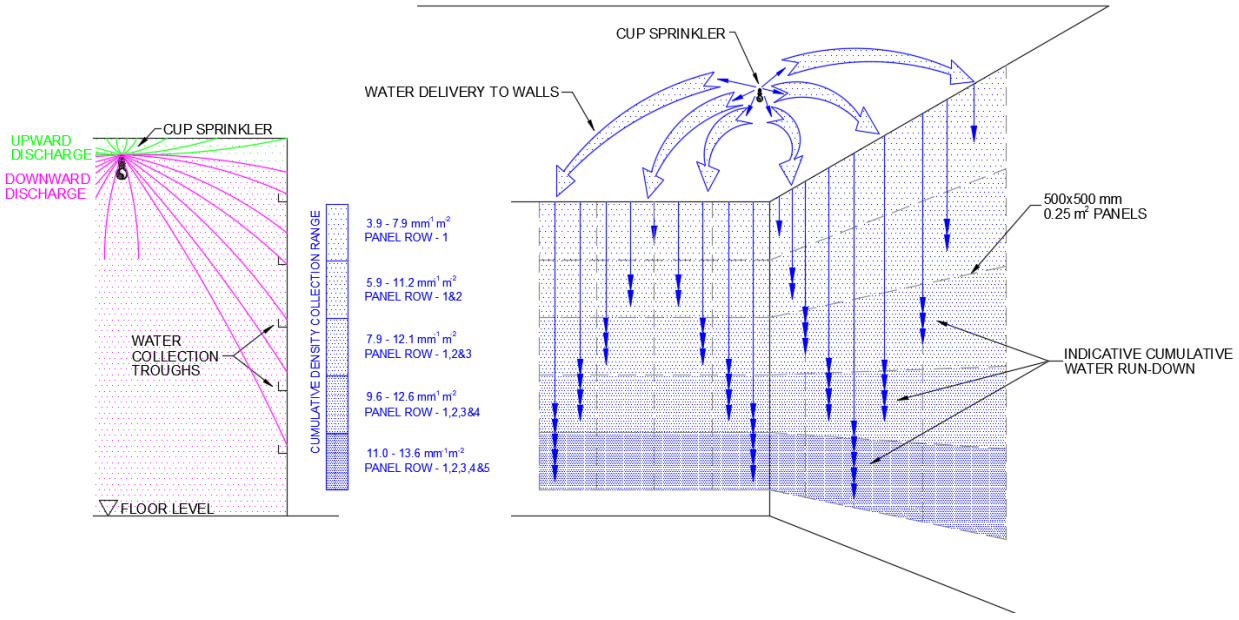

Figure 25. Simulated visual discharge characteristic of a CUP sprinkler, demonstrating wall wetting achieved from a single sprinkler.

It is acknowledged that experimental, theoretical, and CFD studies demonstrate that fire plumes and ceiling jets exert substantial influence on sprinkler water sprays by opposing droplet motion, reducing spray penetration, and altering droplet trajectories. Upward plume flows impede downward-moving droplets, while ceiling jets can deflect, entrain, cool, or redirect the spray, collectively modifying droplet momentum, dispersion, and evaporation. Gas jets and buoyant plumes can further distort the spray cone shape and path. Although sprinkler discharge cools and mixes with the ceiling jet, thereby affecting its velocity and temperature, the ceiling jet simultaneously modifies droplet behaviour in ways that can diminish suppression effectiveness if not considered in system design. These interactions confirm that plume and ceiling-jet gases can modify sprinkler discharge patterns and potentially lead to wetting distributions at the ceiling that differ from those observed in this experimental study.

Timber construction is different from traditional non-combustible or limited combustible construction. Fuel load, Heat Release Rate (HRR), surface spread of flame, and duration of fire in timber buildings is increased, requiring a different approach to active fire protection. Existing standards need to consider the location and spacing of sprinklers, and manufacturers could consider optimising sprinkler head spray patterns to ensure surface wetting and optimise their performance specific to timber buildings.

7. Potential changes to sprinkler design rules

Results of this study suggest that old style sprinklers are a viable technology to optimise sprinkler systems for the specific protection of buildings with exposed timber surfaces, as might be found in mass timber construction.

Rules for combustible walls, floors and ceilings must be modified. This study has shown that location to walls, location below ceiling, spacing of sprinklers, and selection of sprinkler type are crucial factors to allow wetting of combustible surfaces. Based on the data, the following modifications are deemed necessary.

Head selection should be Conventional type sprinklers, meeting requirements of BS EN 12259-1:1999. Spacing of sprinklers shall be a maximum of 3 m between sprinklers with a maximum spacing per sprinkler limited to 9 m^2. Spacing from any wall to be 1.5 m or at half the design spacing in accordance with BS EN 12845:2015+A1:2019. Location of sprinkler deflector below ceiling between 75 – 200 mm with sprinkler heads rated as quick response with an RTI of 50 or less as per LPC Rules Technical Bulletin TB207.

General requirements for sprinkler systems protecting mass timber buildings shall cover all areas of the building. Ceiling voids/concealed spaces not less than 300 mm shall be sprinkler protected[4]. Concealed voids less than 300 mm shall be compartmentalised by vertical cavity barriers enclosing areas of no more than 250 m^2. Fixing into the underside of timber ceilings/substrate as detailed by Kinnersley et al. [59]. Sprinkler pipework shall be steel with screwed or groove jointed connections and all pipework to be drained to a safe place detailed in the Mass Timber Insurance Playbook [60] and Insurer Requirements for Enhanced Escape of Water Protection and Safety in Building Plumbing and Water-Based Fire Suppression Systems [61].

[4] Flat spray type sprinklers might be considered for voids less than 800 mm but greater than 300 mm.

The impact of this study may require a slight increase in sprinkler head numbers, due to spacing limitations and the requirement to protect all areas of a building, but it is seen to be a balanced approach to fire protection of combustible buildings using active sprinkler protection and taking on board best engineering requirements for sprinkler protection.

With minor adaptions of existing sprinkler systems incurring minimal costs, the ability of a system to function for mass timber construction can be greatly increased.

Author contributions

D. Kinnersley: Data curation, formal analysis, investigation, methodology, project administration; writing
T. R. Hull: Conceptualisation, methodology, validation, and review
J. L. D. Glockling: Conceptualisation, methodology, validation, and review
S. C. Campbell: Data curation, investigation, conceptualisation, methodology, validation, and review

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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RISCAuthority, through the Fire Protection Association (FPA), provided the majority of equipment used for testing, as the primary author is an FPA employee. The FPA had no other involvement in the study design, collection, analysis, or interpretation of data. The FPA was not involved in the writing of the report, or in the decision to submit the article for publication.
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Data Availability

The data supporting this study are openly available in the Central Lancashire Online Knowledge (CLOK) at
https://clok.uclan.ac.uk/id/eprint/56883/1/Sprinkler%20Paper%20Supplementary%20Material.docx

Figure captions

Figure 1. The main components of a sprinkler head with feed pipework (shown in the 'upright' mounting position).
Figure 2. 2-dimensional representation of sprinkler distribution patterns. A: An SSU sprinkler discharging 100% water downward to the floor. B: An SSP sprinkler discharging 100% water downward to the floor. C: A CUP sprinkler discharging a proportion of water upward to the ceiling and downward to the floor.
Figure 3. Schematic of the test set-up arrangement for sprinkler water collection below the deflector.

Figure 4. Simplified test set-up for recording below water distribution capture from sprinklers. A: The test set-up. B: Water capture below the sprinkler.
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Figure 9. Representation of ceiling wetting patterns for sprinkler heads operating at 3.0 bar in the downward position. Left: Best ceiling wetting results from sprinkler C. Right: Worst ceiling wetting results from sprinkler B.
Figure 10. Representation of ceiling wetting patterns for sprinkler heads operating at 3.0 bar in the upward position. Left: Best ceiling wetting results from sprinkler C. Right: Worst ceiling wetting results from sprinkler E.
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Figure 14. Best results of delivery of water density in upward orientation from sprinkler C at 3.0 bar in 3-D and 2-D.
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Figure 20b. Measured densities from test W13, sprinkler B, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.
Figure 21a. Cumulative densities from test W01, Sprinkler C, for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling.
Figure 21b. Cumulative densities from test W05, Sprinkler B for CUP sprinklers installed in the upward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.

Figure 22a. Cumulative densities from test W14, Sprinkler D, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the best results for distribution and wall wetting at the ceiling.
Figure 22b. Cumulative densities from test W13, Sprinkler B, for CUP sprinklers installed in the downward position at 3.0 bar pressure, providing the worst results for distribution and wall wetting at the ceiling.
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Figure 24. Simulated visual discharge characteristic of a CUP sprinkler, demonstrating ceiling and floor wetting achieved from a single sprinkler.
Figure 25. Simulated visual discharge characteristic of a CUP sprinkler, demonstrating wall wetting achieved from a single sprinkler.

References

[1] Structural Timber Association (2020). *Structural timber buildings fire safety in use guidance. Volume 6 – mass timber structures.* Building Regulation compliance B3(1) (version 1.1).

[2] Frangi, A., Fontana, M., & Knobloch, M. (2008). Fire design concepts for tall timber buildings. *Structural Engineering International*, 18(2), 148-155. Https://doi.org/10.2749/101686608784218716

[3] Bartlett, A., Gajewski, K., Lineham, S., Thomson, D., Hadden, R., Bisby, L., & Butterworth, N. (2015). *Overcoming the Fire Barrier to Tall Timber Construction.* 3rd Infrastructure and Environment Scotland Conference. https://www.researchgate.net/publication/286937408_Overcoming_the_Fire_Barrier_to_Tall_Timber_Construction

[4] Hopkin, D., & Spearpoint, M. (2020). *Compliance Road-map for the Structural Fire Safety Design of Mass Timber Buildings in England.* SFPE Europe. https://www.sfpe.org/publications/periodicals/sfpeeuropedigital/sfpeeurope20/europeissue20feature5

[5] Hopkin, D., Gorska, C., Spearpoint, M., Fu, I., Krenn, H., Sleik, T., & Stapf, G. (2021). *Experimental Characterisation of the Fire Behaviour of CLT Ceiling Elements from Different Leading Suppliers.* Applications of Structural Fire Engineering conference, Ljubljana, Slovenia. 10.14264/5010564.

[6] Hopkin, D., Wegrzy´nski, W., Spearpoint, M., Fu, I., Krenn, H., Sleik, T., Gorska, C., & Stapf, G. (2022). Large-scale enclosure fire experiments adopting CLT slabs with different types of polyurethane adhesives: Genesis and preliminary findings. *Fire*, 5(2), 39. https://doi.org/10.3390/fire5020039

[7] Ronquillo, G., Hopkin, D., & Spearpoint, M. (2021). Review of large-scale fire tests on cross-laminated timber. *Journal of Fire Sciences*, 39(5). 10.1177/07349041211034460

[8] HM Government Policy Paper (2021). *Net Zero Strategy: Build Back Greener.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf

[9] Hansen-Bruhn, I., & Hull, T. R. (2023). Flammability and burning behaviour of fire protected timber. *Fire Safety Journal*, 140, 103918. https://doi.org/10.1016/j.firesaf.2023.103918

[10] Rein, G. (2016). *Smoldering Combustion. SFPE Handbook of Fire Protection Engineering* (5th ed., pp 581-603). Springer. http://link.springer.com/chapter/10.1007/978-1-4939-2565-0_19

[11] Richardson, J. K. (1985). The reliability of automatic sprinkler systems. National Research Council Canada, CBD-238. https://doi.org/10.4224/20330497

[12] Frank, K., Gravestock, N., Spearpoint, M., & Flieschmann, C. (2013). A review of sprinkler system effectiveness studies. Fire Science Reviews, 2(6). https://doi.org/10.1186/2193-0414-2-6

[13] McGree, T. (2024). US Experience with Sprinklers. NFPA Research. https://nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/us-experience-with-sprinklers?l=136

[14] BS EN 12845:2015 + A1:2019 Incorporating corrigenda December 2015 and January 2016. Fixed firefighting systems. Automatic sprinkler systems. Design, installation and maintenance. https://knowledge.bsigroup.com/products/fixed-firefighting-systems-automatic-sprinkler-systems-design-installation-and-maintenance-1

[15] LPC Rules for Automatic Sprinkler Installations 2015 Incorporating BS EN 12845 https://www.thefpa.co.uk/shop/lpc-sprinkler-rules-subscription/lpc-sprinkler-rules-with-bs-en-12845-digital-subscription

[16] British Standards Institute (2021). *BS 9251:2021 Fire sprinkler systems for domestic and residential occupancies. Code of practice.* https://knowledge.bsigroup.com/products/fire-sprinkler-systems-for-domestic-and-residential-occupancies-code-of-practice-1

[17] British Standards Institute (2020). *BS EN 16925:2018 Fixed firefighting systems. Automatic residential sprinkler systems. Design, installation and maintenance.* https://knowledge.bsigroup.com/products/fixed-firefighting-systems-automatic-residential-sprinkler-systems-design-installation-and-maintenance

[18] BS EN 12259-1:1999 Fixed firefighting systems. Components for sprinkler and water spray systems. Sprinklers https://doi.org/10.3403/02677656

[19] BS 9252:2011 Components for residential sprinkler systems. Specification and test methods for residential sprinklers https://knowledge.bsigroup.com/products/components-for-residential-sprinkler-systems-specification-and-test-methods-for-residential-sprinklers

[20] BS EN 12259-14:2020+A2:2024 Fixed firefighting systems. Components for sprinkler and water spray systems. Sprinklers for residential applications https://doi.org/10.3403/30488151

[21] UL 199 Automatic Sprinklers for Fire-Protection Service https://www.shopulstandards.com/ProductDetail.aspx?productId=UL199

[22] ULC 1626 Resdential Sprinklers for Fire Protection Service https://www.shopulstandards.com/ProductDetail.aspx?productId=ULC1626_1_0_20031101

[23] FM 2000:2024 Examination Standard for Automatic Sprinklers for Fire Protection https://shop.standards.ie/en-ie/standards/fm-2000-2024-511948_saig_fm_fm_3513223/

[24] FMAPPROVAL 2030 Residential Automatic Sprinklers for Fire Protection https://standards.globalspec.com/std/1189895/fmapproval-2030

[25] LPS 1039: Issue 5.2 Requirements and testing methods for automatic sprinklers https://storage.redbooklive.com/media/assets/LPS_1039_f7346bff83.pdf

[26] British Standards Institute (2021). *BS EN 14972-1:2020 Fixed firefighting systems. Water mist systems – Design, installation, inspection, and maintenance.* https://knowledge.bsigroup.com/products/fixed-firefighting-systems-water-mist-systems-design-installation-inspection-and-maintenance

[27] British Standards Institute (2016). *BS 8489-1:2016 - Fixed fire protection systems. Industrial and commercial watermist systems – Code of practice for design and installation.* https://knowledge.bsigroup.com/products/fixed-fire-protection-systems-industrial-and-commercial-watermist-systems-code-of-practice-for-design-and-installation-1

[28] British Standards Institute (2015). *BS 8458:2015 Fixed fire protection systems. Residential and domestic watermist systems. Code of practice for design and installation.* https://knowledge.bsigroup.com/products/fixed-fire-protection-systems-residential-and-domestic-watermist-systems-code-of-practice-for-design-and-installation-1

[29] Bateman, C., Bartlett, A., Rutkauskas, L., & Hadden, R. (2018). *Effects of Fuel Load and Exposed CLT Surface Configuration*. World Conference on Timber Engineering. https://www.researchgate.net/publication/325319406_Effects_of_Fuel_Load_and_Exposed_CLT_Surface_Configuration_in_Reduced-Scale_Compartments

[30] Hadden, R. M., Bartlett, A., Hidalgo, J. P., Santamaria, S., Wiesner, F., Bisby, L. A., Deeny, S., & Lane, B. (2017). Effects of exposed cross laminated timber on31ompartment fire dynamics. *Fire Safety Journal*, 91, 480-489. https://doi.org/10.1016/j.firesaf.2017.03.074

[31] Bartlett, A. I., McNamee, R., Robert, F., & Bisby, L. A. (2020). Comparative energy analysis from fire resistance tests on combustible versus non-combustible slabs. *Fire and Materials*, 44, 301-310. https://doi.org/10.1002/fam.2760

[32] Apps, P. (2022) *Timber-frame buildings and cavity fires: the burning question.* Inside Housing. https://www.insidehousing.co.uk/insight/insight/timber-frame-buildings-and-cavity-fires-the-burning-question-77981

[33] RISCAuthority and the Fire Protection Association (2011). *Building, Design and Management. Fire in timber frame buildings. A review of fire statistics from the UK and the USA*. BDM14, version 1. https://www.thefpa.co.uk/resource-download/243

[34] Bartlett, A. I., Hadden, R. M., Hidalgo, J. P., Santamaria, S., Wiesner, F., Bisby, L. A., Deeny, S., & Lane, B. (2017). Auto-extinction of engineered timber: Application to compartment fires with exposed timber surfaces. *Fire Safety Journal*, 91, 407-413. https://doi.org/10.1016/j.firesaf.2017.03.050

[35] Emberley, R., Inghelbrecht, A., Yu, Z., & Torero, J. L. (2017). Self-extinction of timber. *Proceedings of the Combustion Institute*, 36(2), 3055-3062. https://doi.org/10.1016/j.proci.2016.07.077

[36] Emberley, R., Do, T., Yim, J., & Torero, J. L. (2017). Critical heat flux and mass loss rate for extinction of flaming combustion of timber. *Fire Safety Journal*, 91, 252-258. https://doi.org/10.1016/j.firesaf.2017.03.008

[37] Morrisset, D., Law, A., & Emberley, R. (2019). *Effects of Thickness on the Self-extinction of Timber.* 3rd International Fire Safety Symposium (IFireSS 2019), Ottawa, Ontario. https://www.researchgate.net/publication/334898704_Effects_of_Thickness_on_the_Self-extinction_of_Timber

[38] Crielaard, R., Kuilen, J.-W., Terwel, K., Ravenshorst, G., & Steenbakkers, P. (2019). Self-extinguishment of cross-laminated timber. *Fire Safety Journal*, 105, 244-260. https://doi.org/10.1016/j.firesaf.2019.01.008

[39] Cuevas, J., Torero, J. L., & Maluk, C. (2021). Flame extinction and burning behaviour of timber under varied oxygen concentrations. *Fire Safety Journal*, 120, 130087. https://doi.org/10.1016/j.firesaf.2020.103087
[40] Nothard, S., Lange, D., Hidalgo, J. P., Gupta, V., McLaggan, M. S., Wiesner, F., & Torero, J. L. (2022). Factors influencing the fire dynamics in open-plan compartments with an exposed timber ceiling. *Fire Safety Journal*, 129, 103564. https://doi.org/10.1016/j.firesaf.2022.103564
[41] Xu, H., Pope, I., Gupta, V., Cadena, J., Carrascal, J., Lange, D., McLaggan, M. S., Mendez, J., Osorio, A., Solarte, A., Soriguer, D., Torero, J. L., Wiesner, F., Zaben, A., & Hidalgo, J. P. (2022). Large-scale compartment fires to develop a self-extinction design framework for mass timber. Part 1: Literature review and methodology. *Fire Safety Journal*, 128, 103523. https://doi.org/10.1016/j.firesaf.2022.103523
[42] Shuna, N., & Gernay, T. (2022). On the effect of exposed timber on the severity of structural fires in a compartment and required firefighting resources. *Fire Technology*, 58, 2691-2725. https://doi.org/10.1007/s10694-022-01254-x
[43] Zelinka, S. L., Hasburgh, L. E., Bourne, K. J., Tucholski, D. R., & Ouellette, J. P. (2018). *Compartment Fire Testing of a Two-story Mass Timber Building.* General Technical Report, Forest Products Laboratory. https://research.fs.usda.gov/treesearch/56588#
[44] Kincelova, K., Boton, C., Blanchet, P., & Dagenais, C. (2020). Fire safety in tall timber building: A BIM-based automated code-checking approach. *Buildings*, 10(7), 121. https://doi.org/10.3390/buildings10070121
[45] Brandon, D., & Östman, B. (2016). Fire Safety Challenges of Tall Wood Buildings. Phase 2: Task 1 – Literature Review. https://www.researchgate.net/publication/308417172_Fire_Safety_Challenges_of_Tall_Wood_Buildings_Phase_2_Task_1_-_Literature_Review
[46] Rackauskaite, E., Kotsovinos, P., & Barber, D. (2021). Letter to the editor: Design fires for open-plan buildings with exposed mass-timber ceiling. *Fire Technology*, 57, 487-495. https://doi.org/10.1007/s10694-020-01047-0
[47] Östman, B., Brandon, D., & Frantzich, H. (2017). Fire safety engineering in timber buildings. *Fire Safety Journal*, 91, 11-20. https://doi.org/10.1016/j.firesaf.2017.05.002
[48] Frangi, A., & Fontana, M. (2005). Fire performance of timber structures under natural fire conditions. *Fire Safety Science*, 8. 279-290. 10.3801/IAFSS.FSS.8-279.
[49] Khoat, H. T., Kim, J. T., Quoc, T. D., Kwark, J. H., & Ryou, H. S. (2020). A numerical analysis of the fire characteristics after sprinkler activation in the compartment fire. *Energies*, 13(12), 3099. https://doi.org/10.3390/en13123099
[50] Barber, D., & Gerard, R. (2015). Summary of the fire protection foundation report – fire safety challenges of tall wood buildings. *Fire Science Reviews*, 4(1). 10.1186/s40038-015-0009-3
[51] Hoehler, M. S., Su, J., Lafrance, P.-S., Bundy, M. F., Kimball, A., Brandon, D., Östman, B. (2018). *Fire Safety Challenges of Tall Wood Buildings: Large-scale Cross-laminated Timber Compartment Fire Tests*. SiF 2018 – The 10th International Conference on Structures in FireFireSERT, Ulster University, Belfast. http://urn.kb.se/resolve?urn=urn:nbn:se:lnu:diva-77612
[52] ARUP (2021). *Mass timber fire safety* (2021 Experimental series). https://www.arup.com/globalassets/downloads/insights/m/mass-timber-fire-safety-series-2021.pdf
[53] ARUP (2021). LND884 – Mass timber fire safety experiment (Code Red). Experiment 1: update and Experiment 2: initial findings. https://www.arup.com/globalassets/downloads/insights/m/mass-timber-fire-safety-

series-2021.pdf [46] Kotsovinos, P., Rackauskaite, E., Christensen, E., Glew, A., O'Loughlin, E., Mitchell, H., Amin, R., Robert, F., Heidari, M., Barber, D., Rein, G., & Schulz, J. (2022). Fire dynamics inside a large and open-plan compartment with exposed timber ceiling and columns. *Code Red #01. Fire and Materials*. 47. 10.1002/fam.3049

[54] Saeter Boe, A., Hox, K., Fjellgaard Mikalsen, R., & Friquin, K. L. (2024). Large-scale fire experiments in a cross-laminated timber compartment with an adjacent corridor-partly and fully sprinkler protected with a water sprinkler system. Fire Safety Journal, 148, 104212. https://doi.org/10.1016/j.firesaf.2024.104212

[55] Entec UK Limited. (2011). Effectiveness of sprinklers in housing, commercial, public and other buildings (Fire Research Report 27/2011). Department for Communities and Local Government. https://www.gov.uk/government/publications/effectiveness-of-sprinklers-in-buildings

[56] BAFSA. (n.d.). Sprinklers. https://www.bafsa.org.uk/sprinklers#e43

[57] British Standards Institute (1999). *BS EN 12259-1:1999 Fixed firefighting systems. Components for sprinkler and water spray systems – Sprinklers.* https://knowledge.bsigroup.com/products/fixed-firefighting-systems-components-for-sprinkler-and-water-spray-systems-sprinklers

[58] Poreh, M., & Garrad, G. (2000). A study of wall and corner fire plumes. *Fire Safety Journal*, 34(1), 89-98. https://doi.org/10.1016/S0379-7112(99)00040-5

[59] Kinnersley, D., Hull, T. R., Glockling, J. L. D., & Campbell, S. (2025) Reduction of load capacity of screw fixings into a timber soffit during and after fire. Under review.

[60] ASBP (2025). *Mass Timber Insurance Playbook*. https://asbp.org.uk/project/mass-timber-insurance-playbook

[61] RISCAuthority and the Fire Protection Association (2021). Insurer Augmented Approved Document G: Insurer Requirements for Enhanced Escape of Water Protection and Safety in Building Plumbing and Water-Based Fire Suppression Systems. Based on the Building Regulations 2010: Sanitation, hot water safety, water efficiency. https://www.thefpa.co.uk/resource-download/396