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Reduction of Load Capacity of Screw Fixings into a Timber Soffit During and After Fire

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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

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], sprinkler 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 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 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

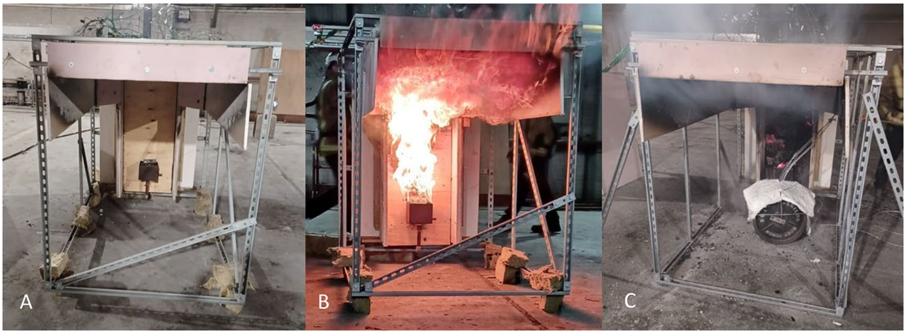

Fig. 1 The fire test rig. **A** Pre-fire, **B** During testing, and **C** Post-fire

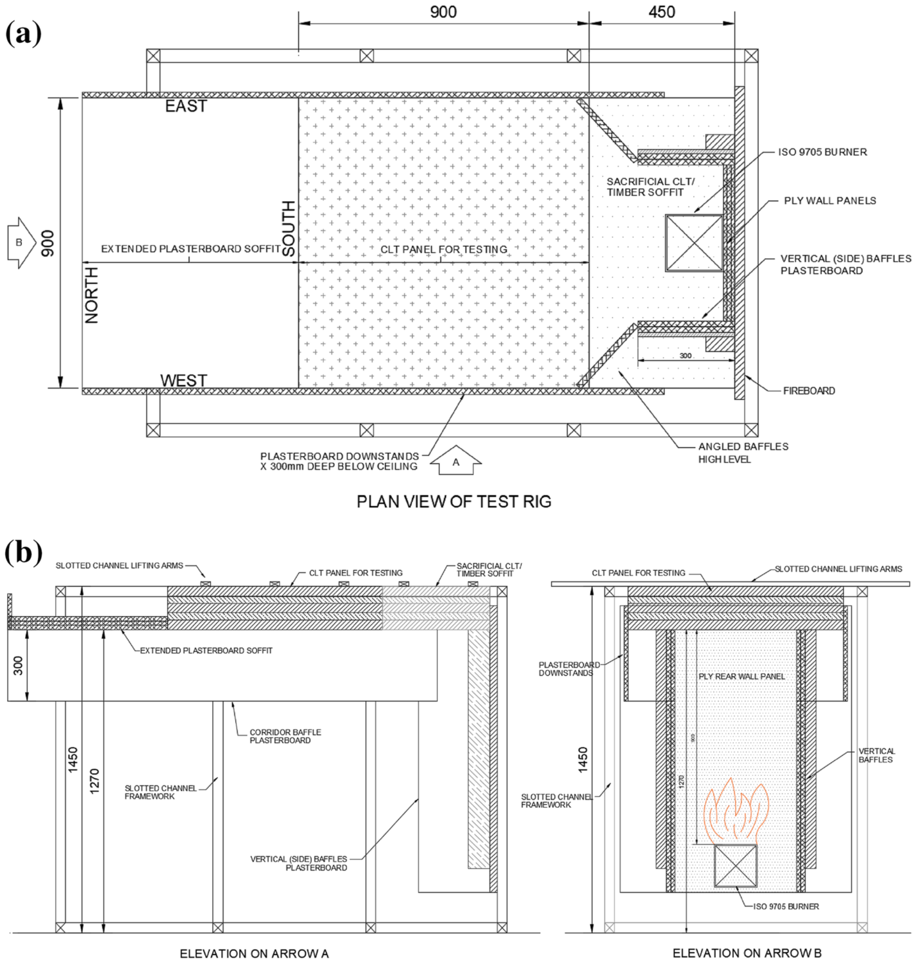

Fig. 2 Design of the bespoke test rig. Plan view and elevation on arrow '**A**' and '**B**.'

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.

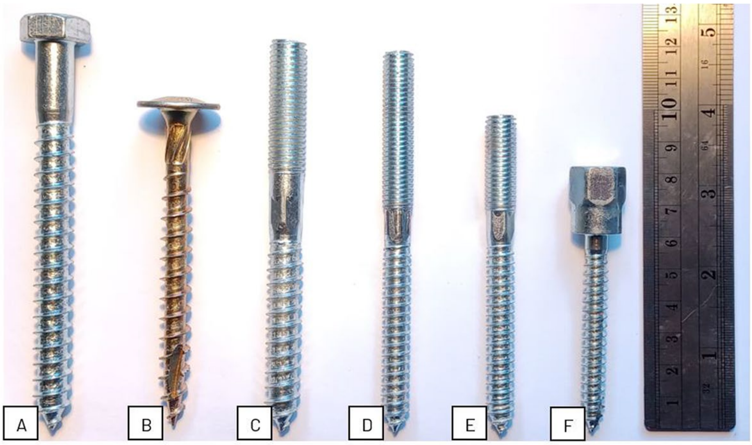

Fig. 3 Screw fixings tested **A**—M12 coach screw, **B** – M10 (M8) coach screw, **C** – M12 stud screw, **D** – M10 stud screw (long), **E** – M10 stud screw (short) and **F** – M10 rod hanger (M6 thread) supplied by Midfix

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

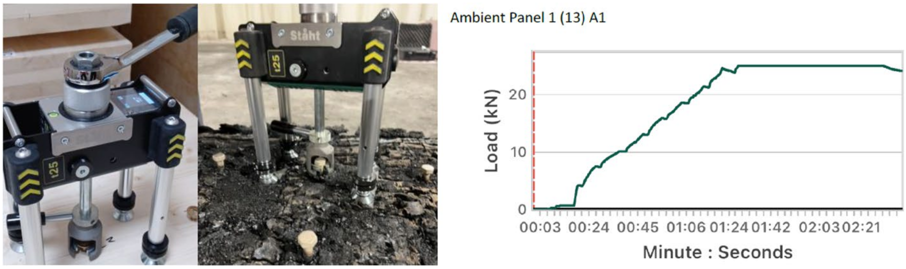

Fig. 4 Staht t25 digital pull tester device at ambient and post-fire testing with individual result print-out

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.

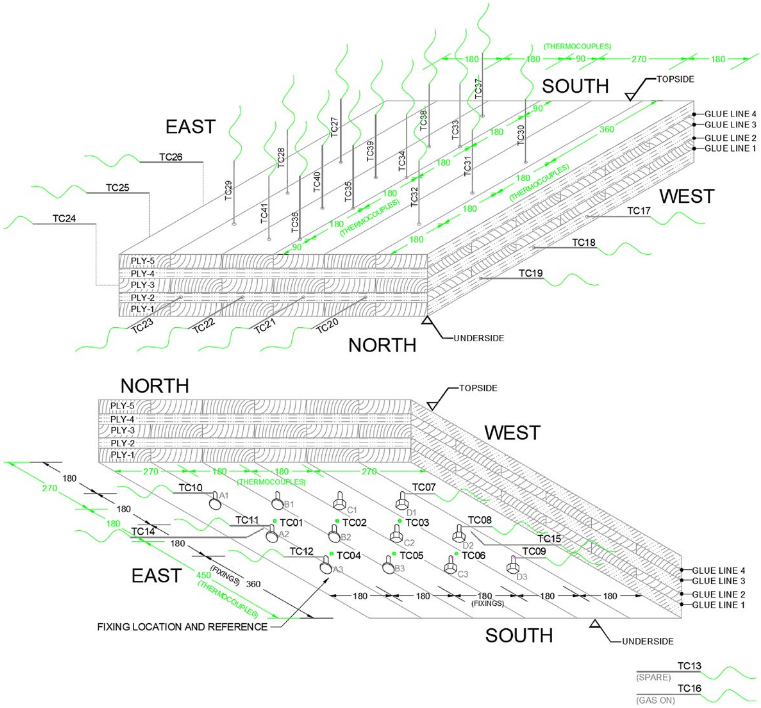

Fig. 5 Locations of thermocouples, Top: Internal locations. Bottom: Exposed/below the CLT panel. The depth of the thermocouples is detailed in Table 3

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 (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

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

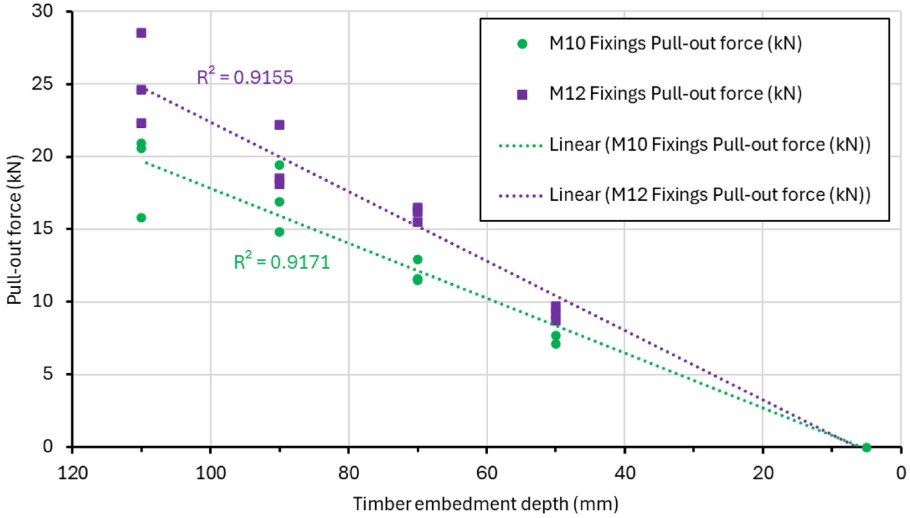

Fig. 6 Pull-out force versus embedment depth for HB S adhesive, ambient conditions

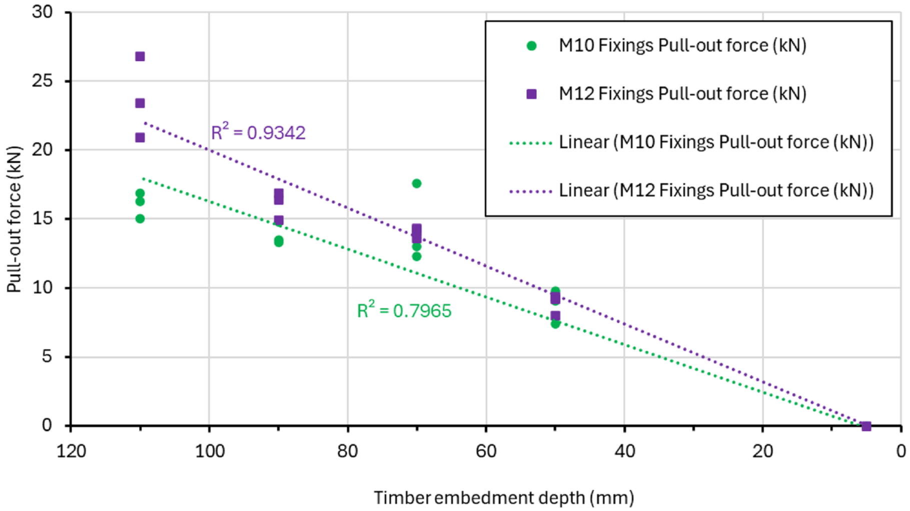

Fig. 7 Pull-out force versus embedment depth for HB X adhesive, ambient conditions

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

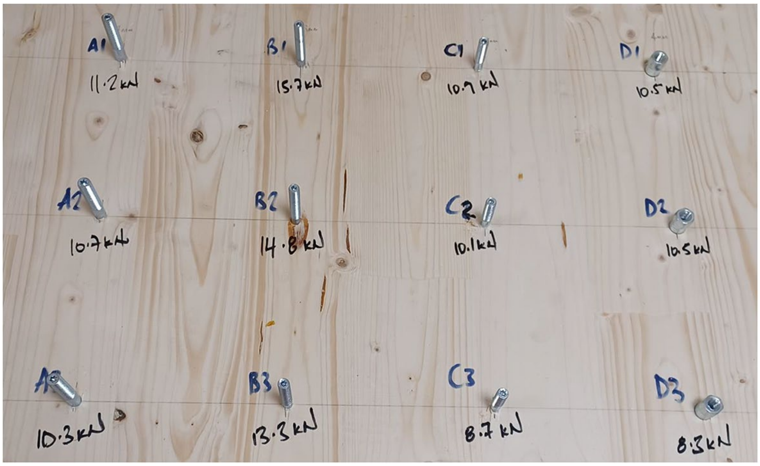

Fig. 8 Standard Industrial-type screw fixings for M&E services (ambient conditions) (A1-3 M12 stud screw, B1-3 M10 stud screw-long, C1-3 M10 stud screw-short, and D1-3 M10 rod hanger)

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

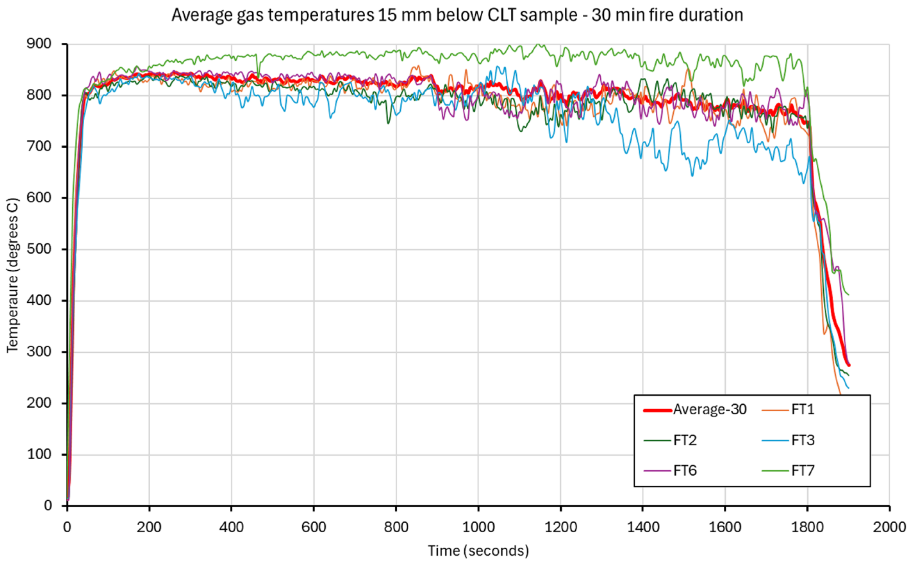

Fig. 9 Average gas temperatures measured 15 mm below the underside of the CLT sample for 30 min, tests (FT1, 2, 3, 6 and 7)

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

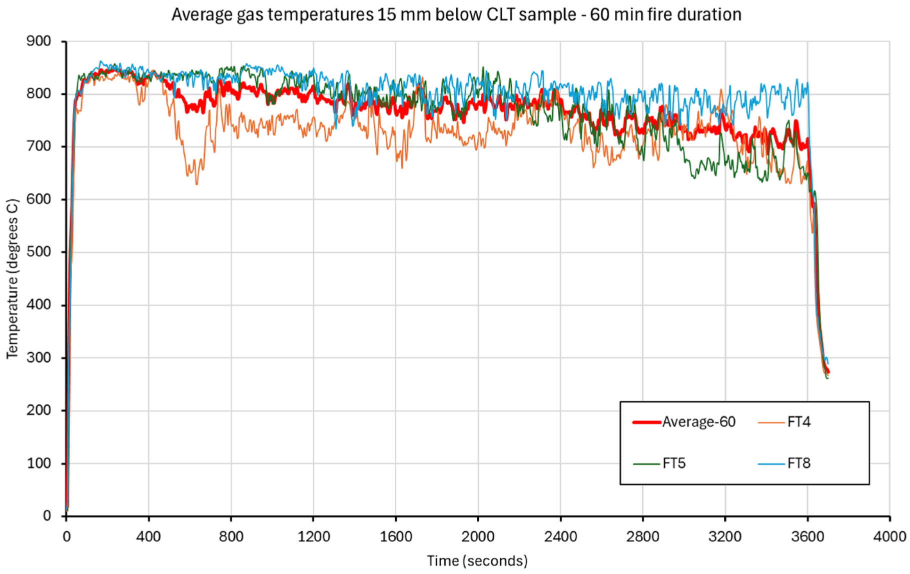

Fig. 10 Average gas temperatures measured 15 mm below the underside of the CLT sample for 60 min, tests (FT4, 5 and 8)

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

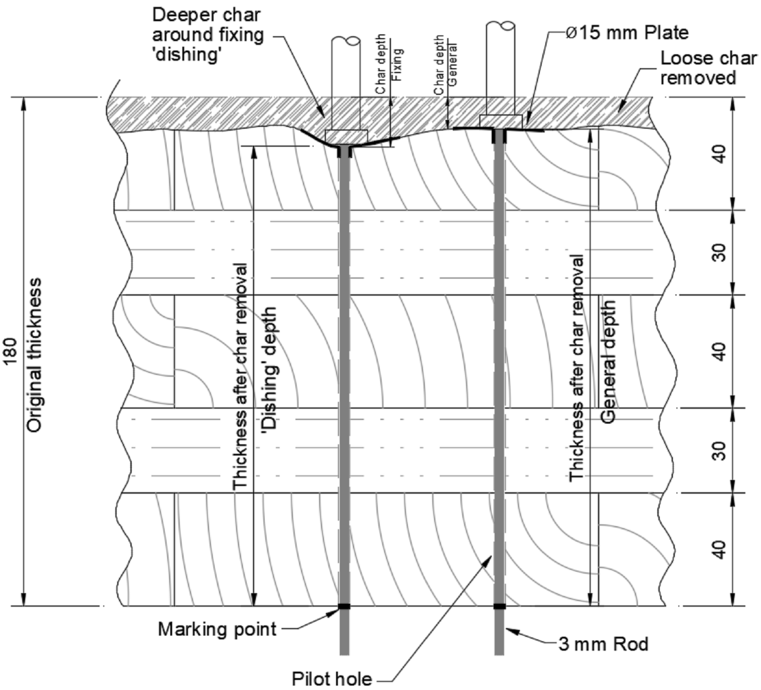

Fig. 12 Shows how the char depths were measured with a 3 mm diameter rod pushed through pilot holes to the 15 mm diameter plate with marking point

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-

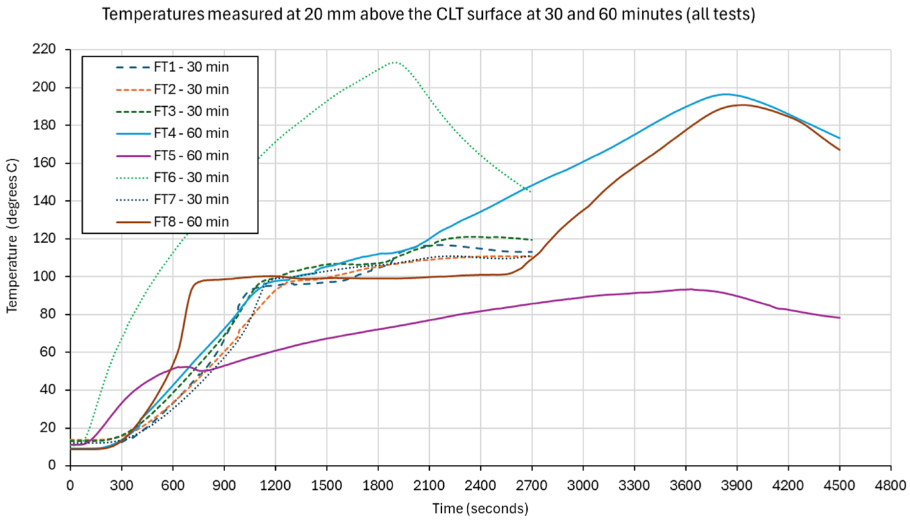

Fig. 16 Measurements of temperature within the CLT test sample at 20 mm above the exposed CLT surface at 30 and 60 min

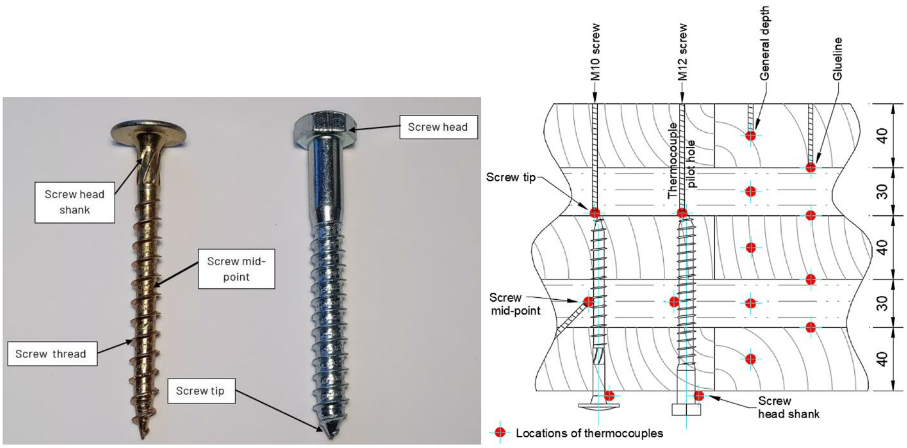

Fig. 17 Shows coach screws under test (left) and locations for thermocouples at different screw fixing locations, general ply depths and glue line (right)

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

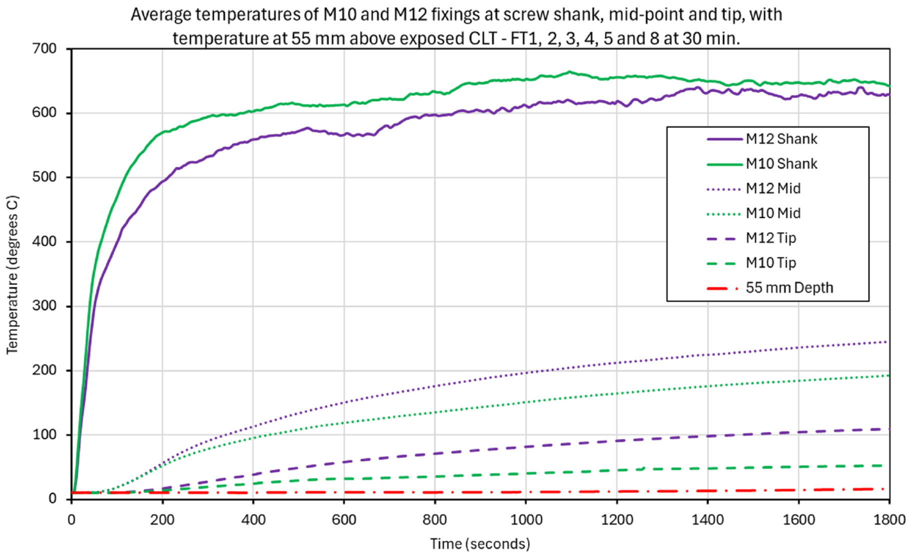

Fig. 18 Average screw fixing temperatures recorded as a function of depth at the CLT (screw shank), at the mid-point (internal) the screw tip (internal) and at 55 mm above the exposed CLT at 30 min

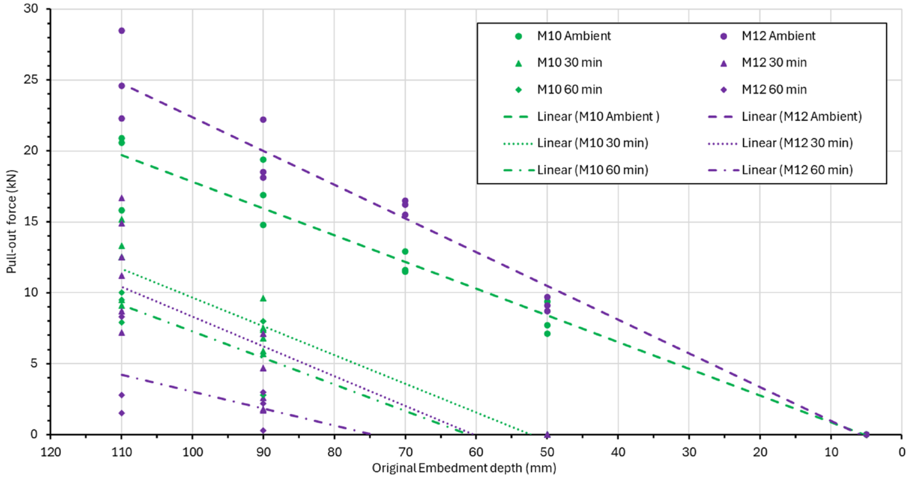

Fig. 19 Pull-out force versus embedment depth for HB S adhesive, ambient conditions, 30 and 60 min fire exposure

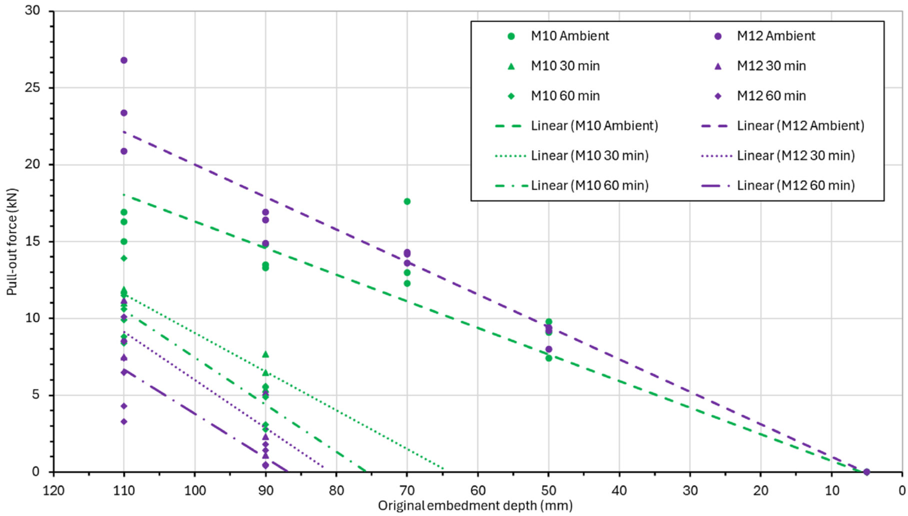

Fig. 20 Pull-out force versus embedment depth for HB X adhesive, ambient conditions, 30 and 60 min fire exposure

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

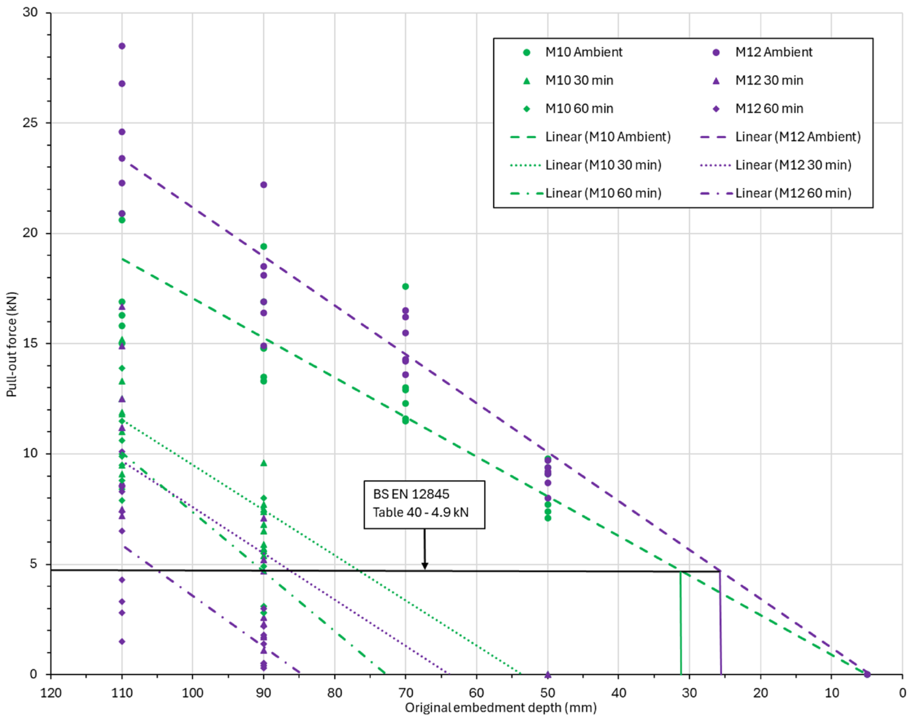

Fig. 21 Pull-out force versus embedment depth, all results, ambient conditions, 30 and 60 min fire exposure

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

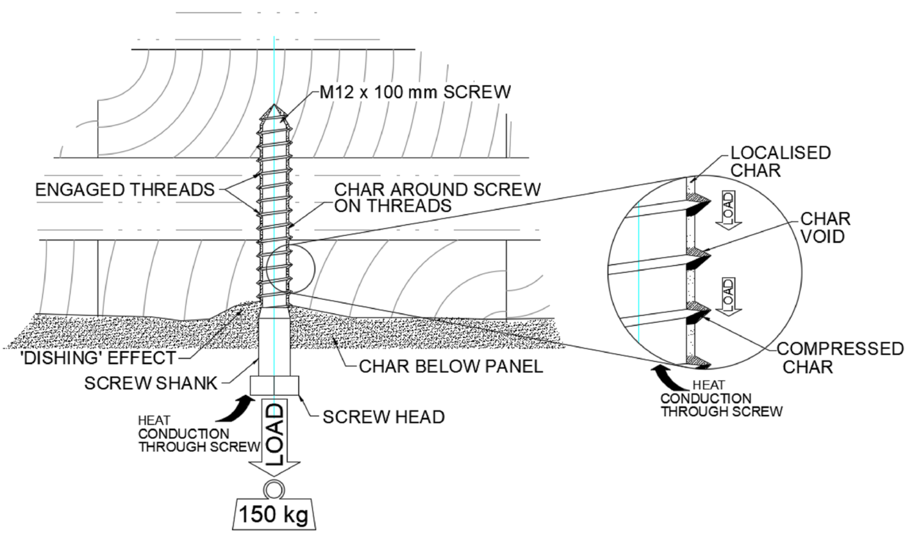

Fig. 22 Shows a coach screw under load, heat conduction through the fixing leading to char formation at the contact point between screw thread and timber

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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