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Fire Behaviour of Gaps in Cross Laminated Timber Panel-to-Panel Connections

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Abstract
Mass timber construction results in small gaps at abutting members due to construction tolerances and varying moisture conditions, among other reasons. These intersections, typically at connections, may have detrimental impacts on the fire performance of a structure causing loss of fire integrity earlier in the fire and thereby enabling the spread of fire. However, there has been a lack of testing to explore the effects of these gaps on the fire behaviour of mass timber, particularly at cross laminated timber (CLT) panel-to-panel connections. To investigate the fire behaviour of CLT with gaps at the panel-to-panel connections, twenty-five unprotected, unloaded CLT panels with gaps (3 and 6 mm) were tested. Panels were exposed to the standard fire (ASTM E119) for one hour. Temperature and char depths were measured to explore the influence of connection geometry and gap size. The results were compared to current design guidance provided in the Fire Design Specification (FDS) for Wood Construction. The results of the analysis demonstrated that the horizontal and vertical charring between abutting members in the panel-to-panel connections was overestimated by the FDS in every specimen tested. During the cooling phase, char continued to develop in the connection gaps when unrestricted airflow was enabled. Connection geometry, gap size, and the restriction of airflow had the greatest impact on temperature rise and char development within the connection gap.

Keywords: Fire Tests, Mass Timber, Connections, Gaps

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1 Introduction

Mass timber construction practices result in faster erection times, carbon sequestration, and aesthetic benefits [1]. Specifically, cross laminated timber (CLT) can expedite floor construction due to its panelised nature. The panelised nature of CLT requires that there are splice connections between the panels to maintain load path for gravity demands and enable the CLT deck to act as the structural diaphragm for lateral demands [2]. However, due to construction tolerances and the natural creep of wood products, small gaps between CLT panels often occur. While mass timber connections require tolerance gaps for constructability (typically 1–3 mm) [3], gap sizes up to 0–10 mm can reasonably be expected during erection due to fabrication tolerances and due to the expansion and shrinkage of timber throughout the construction process [4].

These small gaps can potentially have detrimental impacts on the fire performance of a mass timber building. When there is unrestricted airflow through these gaps, the potential for fire integrity failure can be expedited, enabling fire spread vertically throughout the building, and loss of compartmentation. Therefore, these gaps can have a detrimental effect on the fire safety within mass timber buildings. To avoid this type of failure, current codes and standards [5, 6] require the installation of additional fire protection measures, such as intumescent sealants, caulk, or insulative material within the gap. However, the incorporation of these protective measures adds time and cost to construction.

There is a lack of experimental validation of the current guidance for codes and standards [6, 7] and a need to better understand heat transfer and the pyrolysis process within these gaps. This paper provides a summary of an experimental investigation of CLT panel-to-panel connections with gaps and varying connection details.

2 Background

2.1 Design Guidelines for Abutting Members

Current code and specification guidance provides prescriptive char depths at intersections and joints exposed to fire demands. Specifically, the International Building Code (IBC) [5] requires sealant or adhesive at abutting edges and intersections in mass timber elements of building Types IV-A, IV-B, and IV-C construction. Whereas the 2024 Fire Design Specification (FDS) for Wood Construction [6] provides a bit more nuance regarding when to use sealants or adhesives at abutting edges, specific to the gap size and air flow potential through the gap. FDS provides three conditions for char penetration at timber member intersections (Fig. 1). When the exposed surface is protected by an approved fire-resistant joint system [6], vertical char penetration into the gap is assumed to be equal to the one-dimensional char depth (a_{char}). For gaps less than or equal to 1/8 inch (3 mm), vertical char depth penetration is equal to two times the one-dimensional char depth (a_{char}), assuming that air flow through the gap is negligible (Fig. 1a). When airflow cannot be neglected or the gap exceeds 3 mm, the full depth of the abutting edge is assumed to be a fully exposed surface during fire (Fig. 1b).

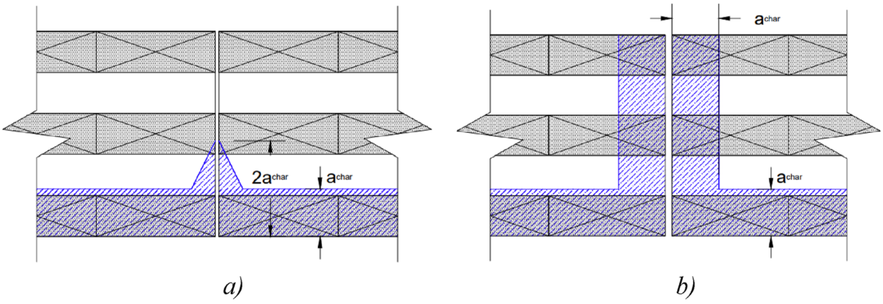

Fig. 1 FDS char penetration assumptions: **a** Gap ≤ 3 mm, **b** Gap > 3 mm

2.2 Current Knowledge

There is limited research on the temperatures and char rates within gaps in connections during a fire exposure. However, this research has demonstrated consistent results under standard fire exposure [8, 9]. Specifically, connections with gaps that are 3 mm or less typically have charring rates that are commensurate with the specification-prescribed charring rates [10–14]. As the size of the unprotected (i.e., no fire sealant) gaps increased beyond 3 mm, temperatures within the gap also increased when the gaps were unprotected. When the gaps were protected, the impact of the sealants on lowering temperatures in the gaps increased as the gap size exceeded 3 mm [13, 15]. However, in connections where airflow was restricted, even just slightly by a piece of plywood [13], the temperatures on the unexposed surface of the connections remained under 100 °C [13] for gaps less than 4 mm and under 180 °C with sealant for gaps up to 20 mm [15]. Increases in charring within gaps of 6 mm or greater were observed along with temperature rise, and reduction in fire resistance ratings [14, 16]. While none of these research investigations compared the char rates and depths to those prescribed within FDS [6], Plessis et al. concluded that the prescriptive char models and temperatures from the upcoming prEN1995-1-2:2025 for predicting temperatures within gaps were nonconservative [11]. However, comparing these results with the prescriptive gap charring assumptions given in FDS [6], the temperatures were less than expected in all cases for gaps up to 10 mm.

While these conclusions provide insight into the temperature rises within the gaps and the effect of sealants, these conclusions focus on the heating portion of the fire curve only, leaving large research gaps on the effect of gaps within mass timber connections during the decay phase of the fire. Standard fire exposure [8, 9] represents a post-flashover, fully developed heating phase [17]. However, temperatures in charred timber continue to rise during the decay phase of a fire, with a thermal wave extending from the char layer into the uncharred timber [18]. This temperature rise and continued pyrolysis can lead to structural failure [19, 20]. Additionally, flaming combustion in timber can persist even after fire exposure ends and will continue to persist in the presence of oxygen until self-extinction [21]. Smouldering is the slow, lower temperature, and flameless combustion of solid fuels [22]. Driven by oxygen supply and rate of heat transfer, smouldering combustion can maintain temperatures of up to 450 to 700 °C with the possibility of reignition [23]. Gaps in connections may provide a path for airflow through smouldering cavities following fire exposure, enabling additional pyrolysis and char oxidation [24]. While this behaviour has not been studied extensively, it was demonstrated to occur within glulam beam-to-column connections during the decay phase of a fire [25]. Reignition of the mass timber occurred in the edge gap between the connections and CLT deck. Small gaps were observed to accelerate the rate of smouldering and expedite the transition to reignition after fire exposure ended [25]. The standard fire fails to account for a cooling or decay phase of the fire and therefore, prescriptive fire design, developed through standard fire testing does not account for the additional degradation of timber assemblies due to the cooling phase behaviours.

Despite the data that already exists, there is a lack of repeatable fire experiments on CLT panel-to-panel connections with gaps that examine charring both horizontally and vertically within varying gap size across all viable connection types in heating and cooling. This type of data would be able to validate the prescribed charring models within FDS as well as the upcoming prEN1995-1-2:2025. Data from such experiments would provide not just the char depth measurements, but also temperature distributions within the gaps during both the heating and cooling phase that could inform engineers on safe design practices during all phases of a fire when conducting performance-based fire design.

3 Research Objectives

To fill the gaps in knowledge identified by the authors, a series of furnace tests were performed on four types of CLT panel-to-panel connections with triplicates of each specimen. The gap sizes tested included no gap, 3, and 6 mm gaps to develop a comprehensive data set that could be used to develop a prescribed char model for CLT panel-to-panel connections with gaps and to further understand the thermal penetration into the CLT during both the heating and cooling phases. The specific research objectives were to (1) investigate the influence of connection type and gap size on horizontal and vertical charring in CLT panel-to-panel connections following 1-h fire exposure, (2) analyze the effects of smouldering combustion in the cooling phase of fire exposure on the thermal wave into the CLT, and (3) compare measured and calculated char depths to code prescribed char depths for abutting members.

4 Methodology

4.1 Materials and Specimens

Twenty-five specimens were constructed of 5 ply (175 mm) V2 Spruce Pine Fir CLT panels with 35 mm laminations of equal thickness, manufactured by Kalesnikoff. Each specimen was 1016 × 1219 mm (Fig. 2). The CLT was produced according to ANSI/APA PRG320 with a phenol resorcinol formaldehyde (PRF) adhesive [26]. Four different panel-to-panel connections were tested: a butt joint, half lap, plywood single surface spline, and steel single surface spline. To analyse the impact of gap size on each connection, six connections were constructed for each connection type with three specimens having a gap size of 3 mm and three specimens having a gap size of 6 mm. A control butt joint specimen was prepared with a tight fit between panels to benchmark fire behaviours with no gap. In all cases, no fire pro-

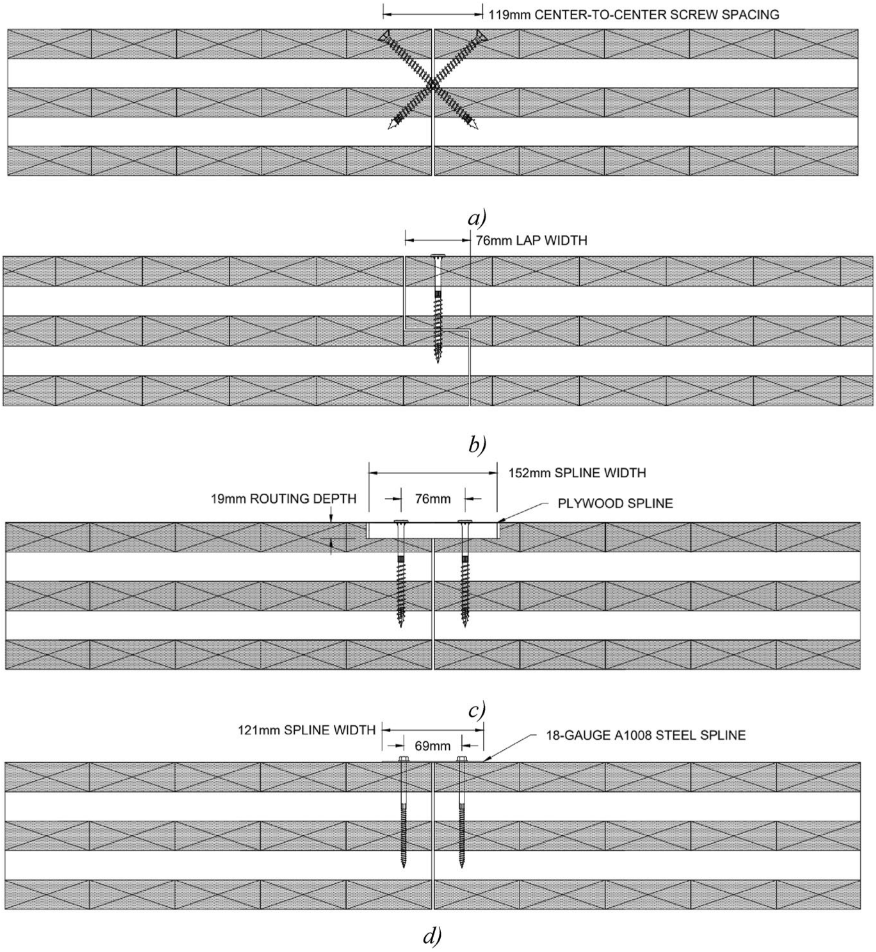

Fig. 2 Connection dimensions **a** Butt joint, **b** Half lap, **c** Plywood spline, **d** Steel spline

tection was installed within the connection gap or on the unexposed surface. No mechanical loading was applied during testing.

All connections used self-tapping screws with spacings adhering to the minimum requirements established in the National Design Specification for Wood Construction [27]. A summary of fastener type, dimensions, and spacings is provided in Table 1. The butt joint connection was constructed using screws installed at 45° (Fig. 2a). The butt joint specimens with gaps were included as an extreme case, with no restriction of airflow through the connection gap. This connection is not permitted to be built as unprotected in panelised construction and this type of connection is not permitted in high seismic regions [2]. However, it can reflect conditions during construction. A 76 mm overlap at midspan of the specimens was used in the half lap connection (Fig. 2b). In the half lap connections, the connection gap is the horizontal distance between the CLT panels, while the horizontal lap was designed to remain tight in every test. The plywood spline connection used 18 × 152 mm plywood

Table 1 Fastener summary

Connection type	Screw type	Screw length (mm)	Screw diameter (mm)	End distance (mm)	Edge distance (mm)	Screw spacing (mm)	Row spacing (mm)
butt joint (b)	Simpson SDCF27614	159	10	152	57	152 (STG)	114
Half lap (HL)	Simpson SDWS27500SS	127	7	152	38	152	–
Plywood spline (PS)	Simpson SDWS27500SS	127	7	152	38	152	76
Steel spline (SS)	Simpson SDS25500	127	6	152	35	152	70

sheathing situated in routing along the top surface measuring 19 × 158 mm (Fig. 2c). The steel spline connection used a 121 mm, 18-gauge A1008 steel strap spline fastened on the top surface (Fig. 2d). Every connection spanned the full 1219 mm depth of the specimens, representing a continuous panel-to-panel connection. The half lap, plywood spline, and steel spline connections were assumed to prevent airflow through the gap [6]. Before testing, specimens were conditioned in an environmental chamber with a relative humidity of 50% and temperature of 21 °C. Moisture content was recorded using a pin-type moisture meter prior to each test with an average for all specimens of 12.5 ± 0.5%.

4.2 Instrumentation

Thermocouples were made from 30-gauge, Type K glass insulated thermocouple wire (Evolution Sensors, K1X-FGXX) and installed in each specimen to collect temperature data throughout the experiments. Thermocouples were installed in groups parallel to the CLT laminations and charring isotherms [28]. Three groupings of thermocouples were installed along the 1219 mm depth of the connection. These groups (A, B, and C), were located 361, 610, and 857 mm from the panel edge and provided data replication as well as avoidance of unintended influence of behaviour at the panel edges. All holes drilled to place thermocouples were filled with fire caulk and data was recorded at 5 s intervals for all tests. Figure 3 provides all thermocouple locations used in each connection type. For simplicity, thermocouples shown are overlayed on the same section (squares from ‘A’ section, circles from ‘B’ section, triangles from ‘C’).

4.3 Fire Exposure and Char Depth Calculations

Testing was completed at the USDA Forest Products Laboratory in Madison, Wisconsin with a medium-scale horizontal gas furnace (990 × 1829 mm). In all tests, specimens were exposed to the ASTM E119 standard fire for one hour [8]. Each test consisted of two specimens supported on a steel frame, and ceramic batting was fixed to the outside faces of all specimens to prevent influence on the adjacent connection or to prevent smoke escaping from the outside perimeter of the furnace. Additionally, plywood supports were added to the outside edges of each specimen at the connection gap to provide stability when lifting the specimens (Fig. 4). 1-h standard fire exposure was used to compare to previous literature and design standards and ensure that cooling phase behaviours could be observed at the connection gap. The specimens were unloaded during the exposure time and the failure criteria

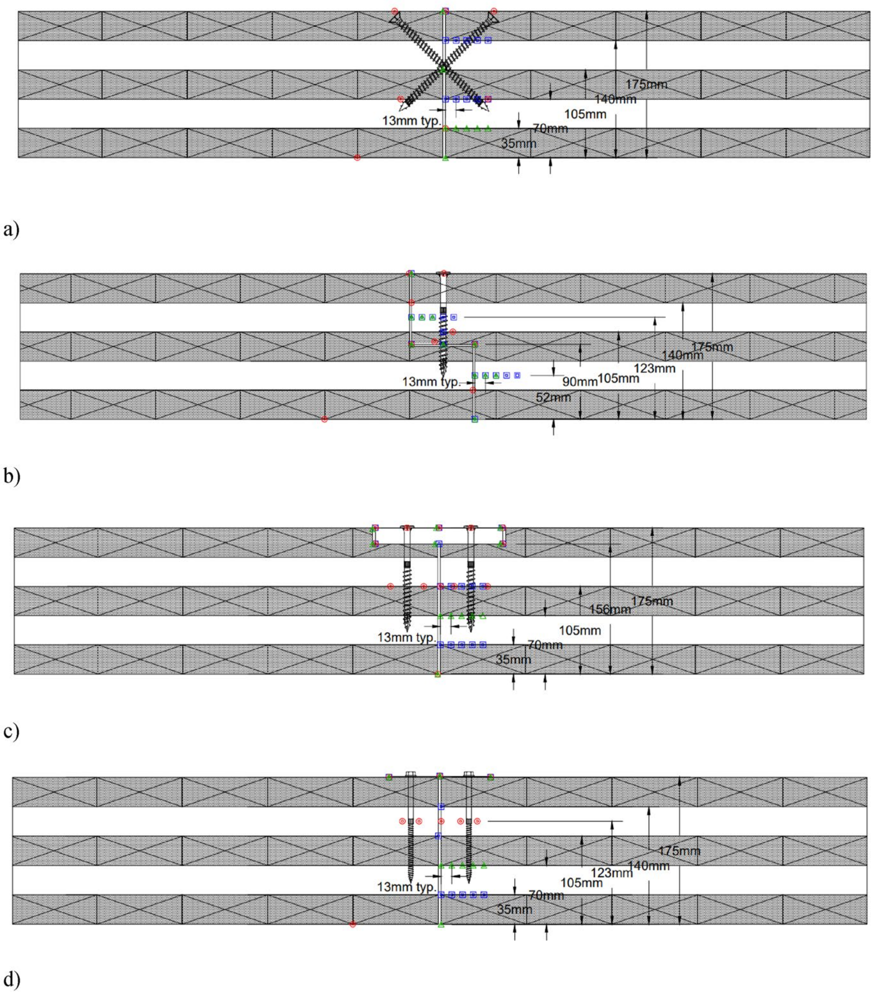

Fig. 3 Thermocouple locations: **a** butt joint, **b** half lap, **c** plywood spline, **d** steel spline. (squares indicate installation in 'A' section, circles from 'B' section, triangles from 'C')

established in ASTM E119 were not applied to this test series. Instead, failure was defined as the loss of structural integrity (i.e., collapse), which did not occur in any test.

At the end of the 1-h exposure, the frame was lifted off the furnace, and the samples were extinguished with water to preserve the char layer and prevent any additional charring. Two specimens of each connection type, one with a 3 mm and one with a 6 mm gap, were not extinguished and instead allowed to cool for an additional hour at the end of fire exposure while temperature data continued to be collected. The specimens with the cooling phase included were lifted off the furnace and onto a rack that was 1200 mm above the finished floor such that the entire specimen was in ambient air conditions. During a natural fire, the decay phase typically has lower gas temperatures when compared to the fully developed

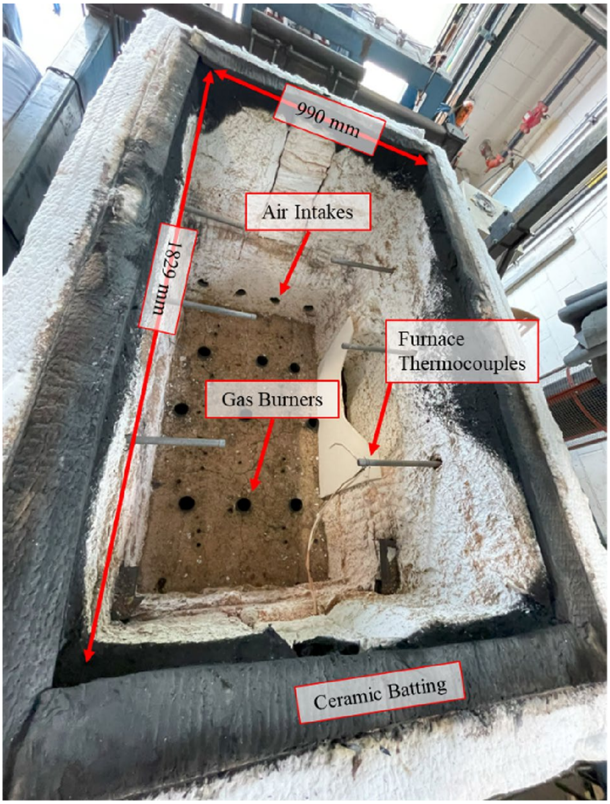

Fig. 4 Furnace configuration

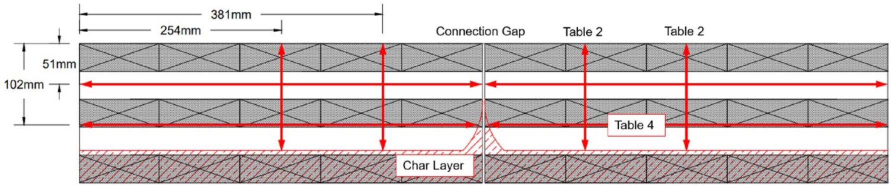

Fig. 5 Post-test specimen charring with measurement locations

phase [17, 19, 29]. The cooling phase associated with the research within this paper represents the specimens being exposed to ambient conditions throughout the entire 1-h duration.

The specimens were disassembled following each test, and 152 mm wide samples were cut at each measurement location (A, B, and C) on either side of the gap. Vertical and horizontal char depth measurements were taken at various points at and away from the gap, shown in Fig. 5, on both faces of each sample. The end of the char layer was defined prior to recording measurements as the edge of CLT discoloration. These measurements were used to compare against the thermocouple char depth measurements calculated using the 300 °C isotherm as well as supplement data where thermocouples were not located.

5 Results

5.1 Test Observations

Visual observations of specimen behaviours were recorded during all tests. At 5 min of fire exposure, smoking through the gap at the unexposed surface was observed for all specimens and all connections. By 10 to 20 min, small pieces of char fell from the exposed surface of the specimens [30]. Between 15 and 30 min, discoloration and moisture occurred at the unexposed surface near the connection gap in all specimens, excluding the plywood spline specimens. Between 50 and 55 min, all 6 mm gap butt joint specimens had flaming combustion through the gap on the unexposed surface. The least amount of smoking through the connections occurred in the plywood spline specimens whereas thick smoke was observed through the connection gap for all butt joint specimens (Fig. 6).

Excluding the butt joint specimens, char penetration was not observed post-test through the entirety of the connection cross section. Corner rounding was observed in almost all samples at the entrance of the gap cavity. Charring observed did not vary substantially based on the measurement location (e.g., side of the specimen or the measurement section (A, B, or C)). As previously mentioned, plywood supports were installed at the ends of the specimens to maintain structural stability and safety while moving the specimens on and off the furnace. Due to the placement of the half lap connection specimens within the steel supporting frame, the plywood supports combusted during the 1-h exposure. This additional combustion resulted in substantially greater char depths at the end of the half lap connections (at sections 'A' or 'C'). Due to this unintended circumstance, data collected from the half lap connection sections A and C has been excluded from some of the following results.

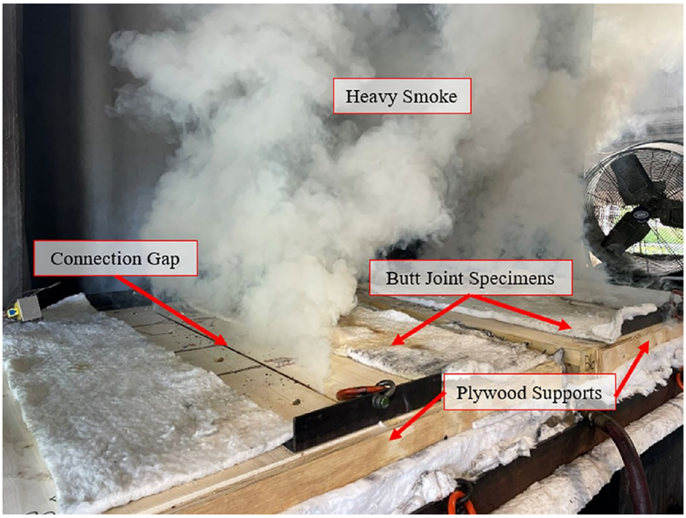

Fig. 6 Butt joint connections during testing

5.2 Char Depths

5.2.1 Statistical Analysis of Char Measurements

Physical char measurements were used to determine the significance of different interaction terms considered during testing. Three factors were considered: connection type (B, HL, PS, SS), gap size (3 or 6 mm), and fire exposure (heating only or heating/cooling). Vertical char depth measurements away from the gap were used to compare to prescribed char depths at the end of 1-h exposure [6, 7]. An ANOVA model, with a sample of 576 measurements, was used to compare the differences between groups considering each factor [31]. Two-sided t-tests were used to determine the significance of measured versus prescribed char depth values.

Horizontal char depth measurements within the joint were used to quantify the impact of the three factors. Using a sample of 288 measurements, a generalized linear model (GLM) was fitted with a Tweedie distribution, given a variance power parameter of 1.5 [31]. The level of significance for all interactions was then calculated using Tukey's Honestly Significant Difference with a significance level of 0.05. The following results and discussion used this model to indicate significant differences between the groups and prescribed values.

5.2.2 Vertical Char Depths in CLT

Measurements after each test are summarized in the following tables (Table 2–4). Table 2 summarizes the average vertical char depths away from the connection gap (254 mm and 381 mm from the panel edge). The average char depths were calculated using twenty-four individual vertical measurements for each specimen (Fig. 5). The percent difference in the vertical measurements was calculated with respect to the butt joint specimen with no gap (0 mm). Across all specimens, there was a maximum deviation from the control zero gap specimen of 5% when considering the one-dimensional char depth. Comparing between specimens, the was no significant difference in the one-dimensional char depth of any connection at both gap sizes with the control butt joint. These results demonstrate that at 127 mm away from the gap edge, the vertical char depths in the CLT panels are consistent regardless of connection type or gap size.

Table 2 Vertical char measurements away from the gap

Connection type	Gap size (mm)	Mean char depth (mm)	Std dev (mm)	% Difference compared to butt joint zero gap specimen
Butt joint	0	41.5	3.0	0.0
	3	42.3	3.8	1.8
	6	41.3	3.1	− 0.5
Half lap	3	39.4	2.9	− 5.1
	6	41.9	2.2	0.9
Plywood spline	3	41.0	3.0	− 1.3
	6	41.8	2.5	0.7
Steel spline	3	41.1	2.6	− 0.9
	6	40.9	5.7	− 1.5

Table 3 shows the percent difference between the vertical char depths measured in testing and current design-prescribed char depths per FDS and EN 1995-1-2:2004 [6, 7]. FDS suggests a nominal char rate of 1.5 in/hr (0.635 mm/min) for 1-h fire exposure and an effective char depth factor of 1.2 to account for corner rounding effects and the additional layer of zero stiffness in a member. FDS prescribes char depths unique to cross laminated timber to reflect an assumption of additional charring due to unglued spaces in adjacent ply edges. For CLT with 35 mm laminations, a char depth of 1.6 inches (40.6 mm) is given for a 1-h fire exposure. EN 1995-1-2:2004 provides similar guidance for expected char depths with a notional char depth of 39 mm (0.65 mm/min) and effective char depth of 46 mm after a 1-h fire exposure.

Both EN 1995-1-2:2004 and FDS reasonably predicted the char depths within the CLT using the nominal values. The true mean measured char depth was 41.1 mm, a significant difference from FDS and EN1995-1-2:2004 respectively using a two-sided t-test. However, there was a maximum difference of 8.4% across all specimens using the EN 1995-1-2:2004 char depth and a maximum difference of 4% using FDS. This comparison demonstrates that at 127 mm (5 inches) away from the connection, the gap and the connection configuration are not influencing the char depth in the timber and that both FDS and EN 1995-1-2:2004 reasonably predict the char depths in the CLT.

5.2.3 Char Depths Within Connection

Per FDS [6], abutting members with gaps less than or equal to 3 mm are expected to have a vertical char penetration into the gap equal to two times the one-dimensional char depth. Gaps larger than 3 mm or any gap with unmitigated airflow are assumed to be fully fire exposed for the duration of a fire (Fig. 1). Horizontal char depth measurements were made 73 mm from the exposed surface (at the bottom of the 3rd ply) and 124 mm from the exposed surface. In all specimens excluding the butt joints, the horizontal char depth at 124 mm was negligible and therefore was not included in the data presented within this paper. For the 3 mm gap specimens, the measured char depth values were compared against those calculated corresponding to the triangular distribution at 73 mm from bottom, calculated to be 4.1 mm. For 6 mm gap specimens, the FDS prescribed char distribution would

Table 3 Percent difference of actual char measurements away from the gap and 1-h prescribed char depths. Negative values indicate the experimentally measured char depths were less than those predicted by standards

Connection type	Gap size (mm)	FDS		EN1995-1-2:2004	
		Char depth a_char (mm)	Difference (%)	Notional char depth d_char, n (mm)	Difference (%)
Butt joint	0	40.6	2.2	39.0	6.5
	3		4.0		8.4
	6		1.7		6.0
Half lap	3		−3.0		1.1
	6		3.1		7.4
Plywood Spline	3		0.8		5.1
	6		2.9		7.2
Steel Spline	3		1.2		5.5
	6		0.7		4.9

be rectangular, therefore, the calculated char depth at 73 mm from the exposed surface was 40.6 mm (a_{char}). The same char distribution holds for the 3 mm butt joint specimens where airflow was unrestricted. Table 4 summarizes the average horizontal measurements for each connection type and gap size compared to the prescribed char depths provided by FDS.

For all connection types and all gap sizes, FDS significantly overestimated the horizontal char depth that penetrates the gap between abutting members. For 3 mm gaps, there was less than 1.6 mm of horizontal charring at 73 mm from the exposed surface for all connection types excluding the butt joint. All 6 mm connection types excluding the butt joint had average char depths less than 7.5 mm, 81% less than the one-dimensional char depth. The half lap, steel spline, and plywood spline all provided a partial restriction of airflow through the gap cavity. The horizontal char depth in the butt joint connections cross section shows that even when airflow is unmitigated, the FDS prescribed char depths are very conservative. Despite this, due to unmitigated airflow, there was flame spread through the connection itself with flames visible on the unexposed surface. The condition of unmitigated airflow would only occur during erection of the structure, with sheathing or a topping covering the CLT floor panels and preventing airflow during finished use, further emphasizing the conservatism in FDS.

In all cases except the half lap connection, there was a significant increase in horizontal charring when gap size increased from 3 to 6 mm. Additionally, at both gap sizes, the butt joint specimens had significantly higher horizontal charring when compared to the other connection types.

5.3 Connection Temperatures

Thermocouple data was used to quantify the thermal wave propagation in each connection at the intersection between members. Temperature was recorded along the gap cross section and in the solid CLT. To quantify the differences between gap size and connection type, average specimen temperatures at 15-min intervals at the mid-height of the connection gap (87 mm vertically from the exposed surface) are provided in Table 5. The butt joint specimens had the highest temperatures at each gap size and for each time interval with a 361% increase in temperature at 60 min as compared to all other connection types with a 3 mm gap size. The temperature at 60 min for the 6 mm gap size butt joints was 781, 512, and 52% higher than the half lap, plywood spline, and steel spline specimens respectively. This

Table 4 Horizontal gap char measurements with FDS comparison. positive % differences indicate an overestimation by FDS compared to experimentally measured values

Connection type	Gap size (mm)	Mean char depth (mm)	Std dev (mm)	FDS			
				≤ 3 mm	% Difference	> 3 mm	% Difference
Butt joint	0	0.1	0.5	4.1	96.8	40.6	–
	3	16.0	3.0		–		60.6
	6	34.8	4.3		–		14.4
Half lap	3	1.6	4.0		61.5		–
	6	2.5	4.1		–		93.8
Plywood spline	3	0.0	0.0		100.0		–
	6	5.8	6.3		–		85.7
Steel spline	3	0.1	0.3		98.4		–
	6	7.5	8.0		–		81.5

Table 5 Average gap temperatures

Connection type	Gap size (mm)	Gap temperature (87 mm from exposed surface) (°C)			
		15 min	30 min	45 min	60 min
Butt joint	3	102.5	193.9	341.7	468.5
	6	452.3	570.7	659.1	722.2
Half lap	3	77.0	83.4	88.4	86.6
	6	63.9	72.7	76.0	82.0
Plywood spline	3	39.5	61.6	89.1	100.8
	6	77.1	87.7	103.8	118.0
Steel spline	3	68.9	85.9	100.6	124.0
	6	124.2	233.5	360.4	475.2

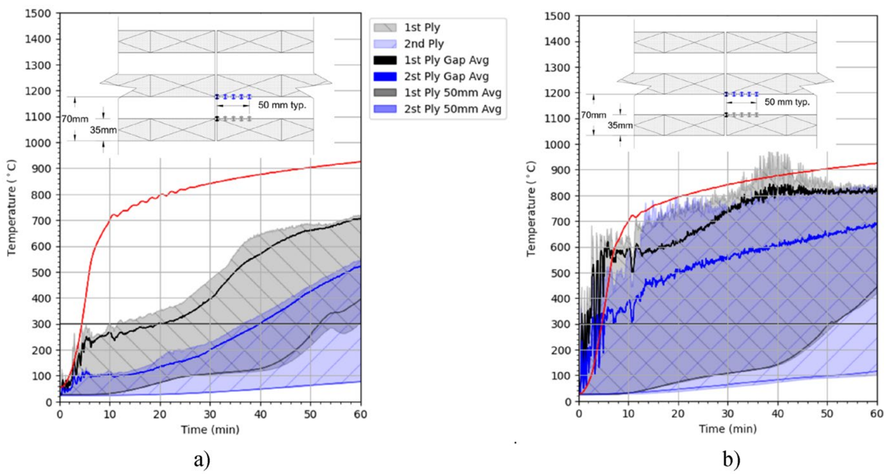

Fig. 7 Butt joint temperatures: **a** 3 mm gap, **b** 6 mm gap. Furnace temperature in red

substantial increase can be explained by the restriction of airflow present in all connections but the butt joint. Average gap temperatures increased from 3 to 6 mm in all cases except the half lap connection. This is likely due to the gap in the half lap connection being only between the sides of the CLT and the horizontal surfaces having minimal to no gap. However, despite this increase, only the butt joint specimens and steel spline 6 mm specimens exceeded 125 °C by the end of fire exposure at the mid-height of the gap.

To further explore the thermal distribution vertically through the gap, thermocouple data was plotted for the first and second CLT ply of the butt joint, plywood spline, and steel spline connections (Figs. 7, 8, 9). The shaded bands represent temperature ranges recorded across all specimen replicates within a horizontal 50 mm distance from the edge of the CLT at the connection. The grey band representing the first ply CLT temperatures and the blue band representing the second ply CLT temperatures. The dark bold lines represent the average gap temperature during the heating phase, and the lightly bold lines represent the average temperature at a horizontal distance of 50 mm from the intersection.

Within all the specimens, regardless of connection type, temperatures exceeded 300 °C above the first lamella (35 mm from the exposed surface). For the butt joint specimens, the second ply temperatures exceeded 300 °C within 5 min and within 40 min with a 6 mm gap

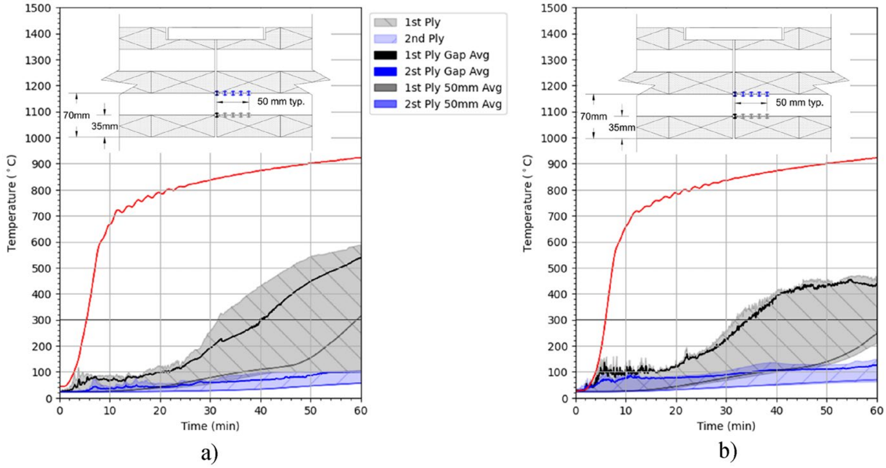

Fig. 8 Plywood spline temperatures: **a** 3 mm gap, **b** 6 mm gap. Furnace temperature in red

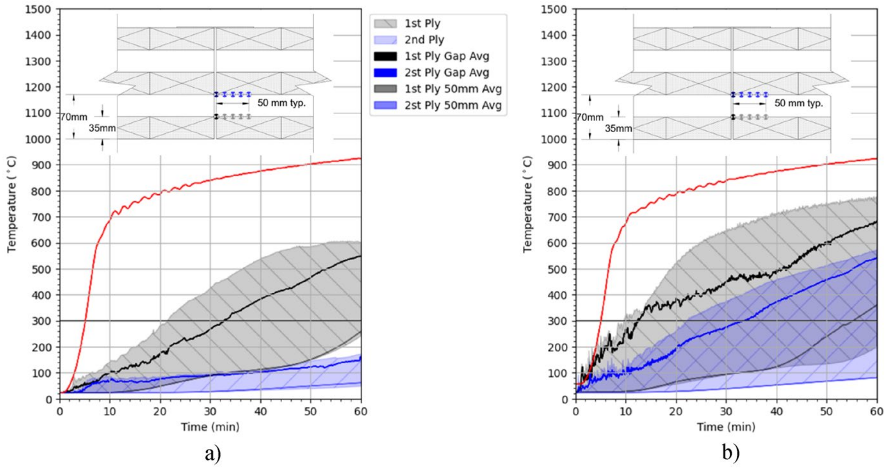

Fig. 9 Steel Spline Temperatures: **a** 3 mm gap, **b** 6 mm gap. Furnace temperature in red

and 3 mm gap, respectively. The 6 mm butt joint specimens had average gap temperatures of 695 °C at a height of 70 mm into the gap cavity (top of second CLT ply) by the end of fire exposure. Despite this temperature rise within the gap itself, temperatures 50 mm into the CLT from the gap at the top of the second ply did not exceed 300 °C throughout the fire exposure. These temperature distributions indicate that charring was limited to within 25 mm of the edge of the CLT except in the 6 mm butt joint (Fig. 10).

The plywood spline connections represented the connection with the most inhibited airflow. While the temperatures within 50 mm of the connection at the top of the first ply exceeded 300 °C, the temperatures within 50 mm of the connection at the top of the second ply did not exceed 150 °C regardless of the gap size (Fig. 8). The steel spline specimens with a 3 mm gap behaved similarly to the plywood spline specimens, with temperatures within

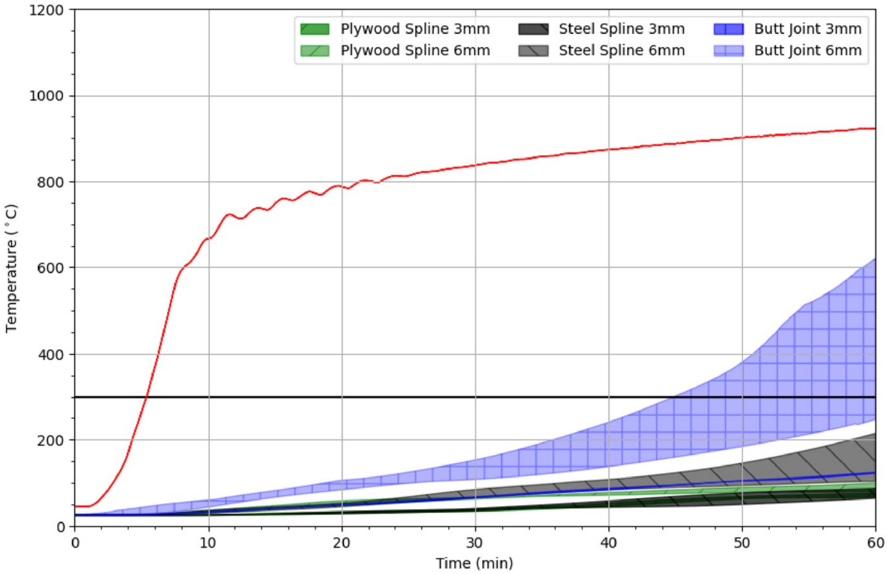

Fig. 10 Second ply (70 mm) temperatures 25 mm from gap (butt joint in blue, plywood spline in green, steel spline in grey, furnace temperature in red)

50 mm of the connection at the top of the second ply less than 200 °C. However, the 6 mm gap steel spline specimens had gap temperatures that reached 530 °C at the end of the 1-h fire exposure (Fig. 9). The differences between spline connections, specifically at a gap size of 6 mm, could be explained by the fastener interactions at the spline-CLT interfaces. In both spline connections, partially threaded, self-tapping screws (STS) of equal length and spacing were installed from the top surface into the CLT (Table 1). In the plywood spline connections, the STS were drilled through both the plywood spline and CLT. Clamping action provided by the STS pulled the plywood-CLT interface tightly together. In the steel spline connections, the light-gauge steel spline was fabricated with pre-drilled holes equal to the nominal screw diameter. Consequently, less clamping between the steel-CLT interface was achieved. As a result, little smoke was observed to escape from the plywood spline connections while smoke and hot gases were observed to escape in the spaces between fasteners in the steel spline connections.

5.4 Cooling Phase

Two specimens of each connection type were allowed to cool naturally for an additional hour following the 1-h fire exposure. As previously mentioned, the cooling phase simulated in testing exposed the specimens to ambient room temperature following fire exposure. During this cooling phase, elevated temperatures within the connection and CLT continued to propagate into the CLT from the fire exposed surface. Vertical char measurements were taken for each specimen at the end of the cooling phase (Fig. 5) at locations 381 and 254 mm away from the connection. When these char depths are compared to those measured on specimens without a cooling phase, differences of less than 5.6% across all connection types were calculated, with some instances where specimens that did not have a cooling phase had

Table 6 Cooling phase vertical char measurement away from connection gap

Connection type	Gap size (mm)	1-h exposure		1-h exposure + 1-h cooling		% difference
		Mean char depth (mm)	Std dev (mm)	Mean char depth (mm)	Std dev (mm)	
Butt joint	3	42.3	3.8	43.1	2.6	2.0
	6	41.3	3.1	40.5	2.4	− 2.1
Half lap	3	39.4	2.9	41.5	3.0	5.4
	6	41.9	2.2	39.6	1.9	− 5.6
Plywood spline	3	41.0	3.0	41.5	1.5	1.4
	6	41.8	2.5	41.1	1.7	− 1.7
Steel spline	3	41.1	2.6	40.2	3.1	− 2.3
	6	40.9	5.7	39.2	2.8	− 4.3

Table 7 Cooling phase horizontal gap char measurements

Horizontal char measurements		1-h exposure		1-h exposure + 1-h cooling		% Difference
Connection type	Gap size (mm)	Mean char depth (mm)	Std dev (mm)	Mean char depth (mm)	Std dev (mm)	
Butt joint	3	16.0	3.0	29.6	7.2	46.0
	6	34.8	4.3	64.0	5.4	45.7
Half lap	3	1.6	4.0	0.0	0.0	− 100.0
	6	2.5	4.1	12.9	8.8	80.5
Plywood spline	3	0.0	0.0	2.0	5.0	100.0
	6	5.8	6.3	3.8	5.9	− 51.7
Steel spline	3	0.07	0.3	0.13	0.5	50.0
	6	7.5	8.0	18.5	6.8	59.3

greater char depths than those with a cooling phase. The results summarized within Table 6 demonstrate that the cooling phase for these tests did not contribute to additional vertical charring within the CLT decks.

Within the gap cavity, horizontal char measurements were made at the end of the additional 1-h cooling period (Table 7). The butt joint specimens had increased horizontal charring, almost double that of the heating phase. The 3 mm butt joint continued to smoke and exhibit glowing smouldering in the cooling phase but did not reignite (Fig. 11a). The butt joint specimen with a 6 mm gap reignited after 18 min into the cooling phase (Fig. 11b).

The other connection specimens did not exhibit reignition, but there was increased horizontal charring within the connections. Overall, the degree of airflow through the gap can be seen as the driving variable in any additional char development during cooling with the butt joint allowing full redevelopment of flaming combustion, compared to the lack of additional propagation seen in the plywood spline connection. The steel spline specimens had increased horizontal char depths of more than 50%. Horizontal charring increased by 81% for the half lap specimen with a 6 mm gap. The plywood spline specimens, with the most restricted airflow, showed little change or additional horizontal char development compared to the plywood spline specimens without a cooling phase. Given the imposed cooling condition, there was no significant increase in horizontal charring when comparing the connections exposed to heating only versus heating/cooling, regardless of gap size.

Fig. 11 Butt Joint Smouldering during Cooling Phase: **a** 3 mm gap, **b** 6 mm gap

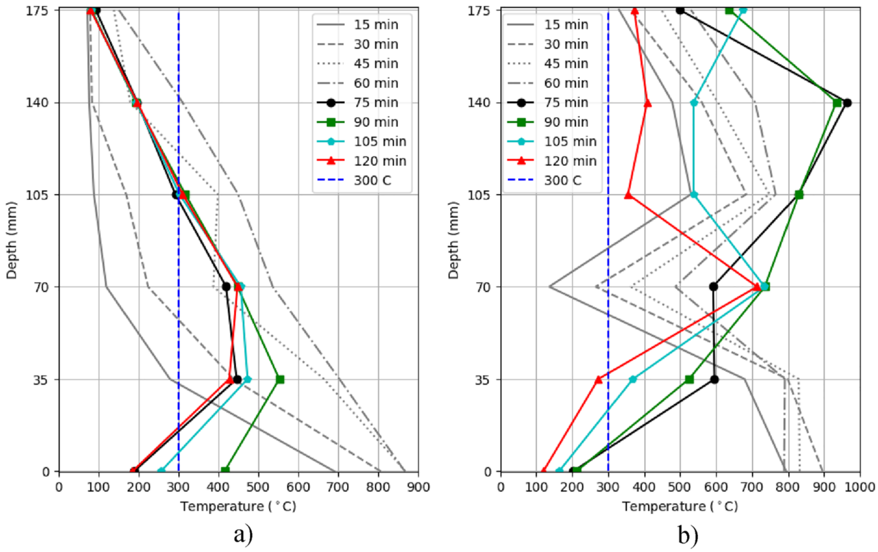

Fig. 12 Depth vs gap temperature, heating and cooling, butt joint: **a** 3 mm gap, **b** 6 mm gap

In addition to the char depth measurements, temperature measurements within the gap were evaluated post-test to observe the thermal wave propagation through the timber (Figs. 12, 13, 14, 15). For all specimens tested with a cooling phase, temperatures at the exposed surface rapidly dropped when the specimens were removed from the furnace. Temperatures above the second ply (70 mm from the fire exposed surface) converged to 100 °C or less during the 1-h cooling phase for specimens with 3 mm gap sizes. All specimens, except the steel splines and butt joint specimens with a 6 mm gap, maintained temperatures between 100 and 150 °C at the mid-height of the connection, about 87 mm from the fire exposed surface. As previously mentioned, the butt joint specimen with a 6 mm gap reignited during the cooling phase. This behaviour is reflected within the temperatures data (Fig. 12b) by temperatures that exceed 300 °C throughout the entire cooling period. Similarly, smoulder-

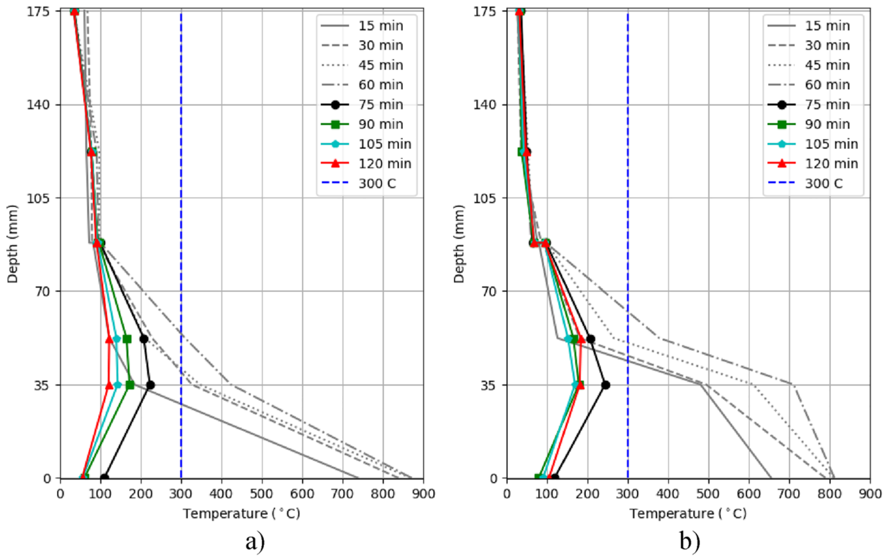

Fig. 13 Depth vs gap temperature, heating and cooling, half lap: **a** 3 mm gap, **b** 6 mm gap

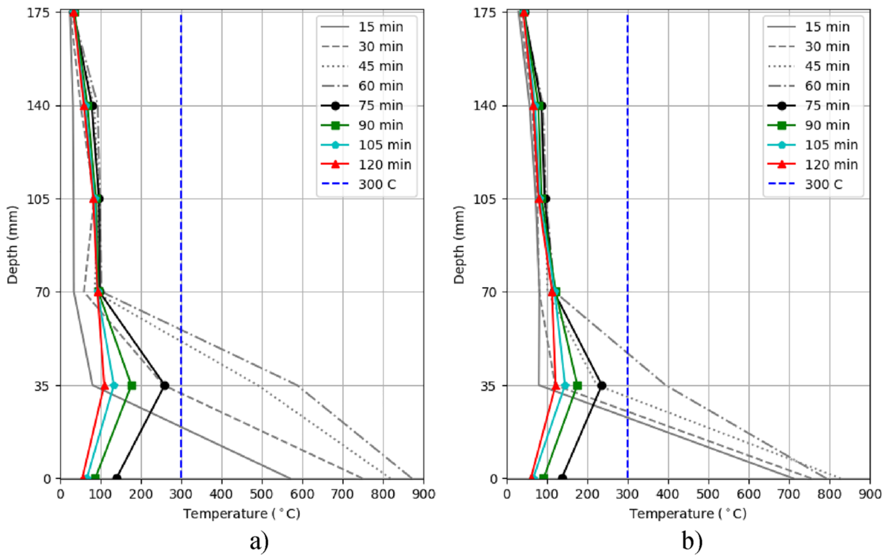

Fig. 14 Depth vs gap temperature, heating and cooling, plywood spline: **a** 3 mm gap, **b** 6 mm gap

ing fuelled by additional airflow was observed in the butt joint specimen with a 3 mm gap as evidence of temperatures exceeding 300 °C within the gap, specifically at distances between 35 and 105 mm from the fire exposed surface.

Thermal wave propagation continued during the cooling phase in the connection gap and the solid CLT. This thermal wave propagation was evident in both the 3 mm (Fig. 16a) and

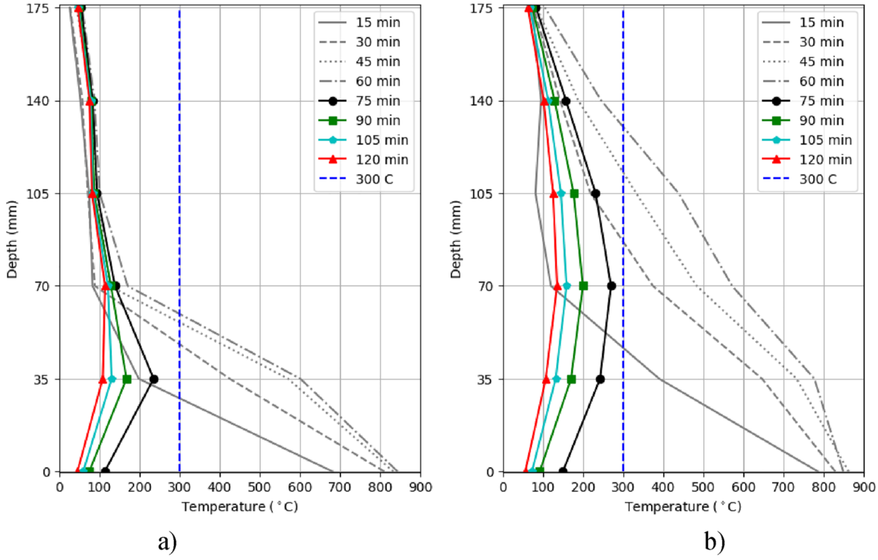

Fig. 15 Depth vs gap temperature, heating and cooling, steel spline: **a** 3 mm gap, **b** 6 mm gap

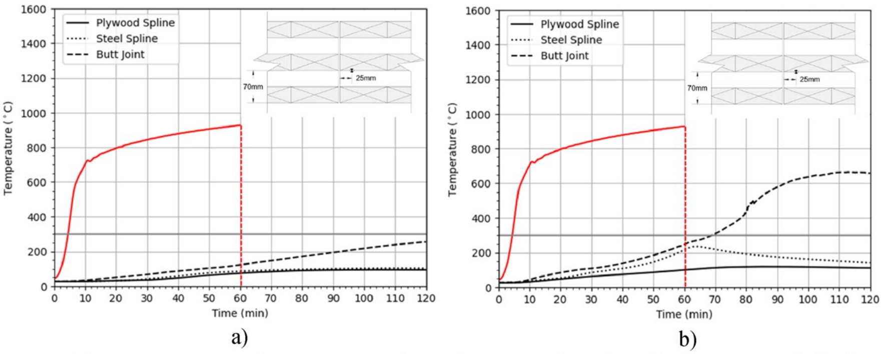

Fig. 16 Temperatures within connection during heating and cooling **a** 3 mm gap and **b** 6 mm gap. Furnace temperature shown in red

the 6 mm gap specimens (Fig. 16b), although more prominent in the 6 mm gap specimens. For the 3 mm gap specimens, temperatures in the spline connections (plywood and steel) did not exceed 300 °C during cooling. Temperatures in these connections reached between 100 and 150 °C at approximately 10 min into cooling and remained within this range through the remainder of the cooling phase. This behaviour is indicative of an initial thermal wave. For the 6 mm gap specimens, the same behaviour is observed for the plywood spline; however, the steel spline specimen temperatures increased to about 240 °C by 5 min into cooling. After this point, temperatures decreased resulting in similar end of test temperatures as the steel spline 3 mm gap size. While these elevated temperatures do not cause additional charring, temperatures above 100 °C can result in significant thermal degradation of the solid CLT strength and stiffness [7]. For both gap sizes, Fig. 16 demonstrates that the lack of inhibited airflow within the butt joint specimen results in continually increasing temperatures throughout the cooling phase regardless of the gap size.

6 Discussion

6.1 Unexposed Surface

Intersections with large, unprotected gaps create a passage for the heat transfer and fire spread from exposed to unexposed surfaces, impacting the fire integrity of the structure [8]. The ability of a connection to restrict airflow and prevent fire integrity failure can be represented by the temperatures at the unexposed surface. These temperatures were compared across the connection types as well as gap sizes. For all specimens, the temperatures at the unexposed surface were measured. Figure 17 shows the temperatures on the unexposed surface for the half lap, plywood spline, and steel spline connections at both gap sizes. While meeting the acceptance conditions of ASTM E119 [8] was not an objective of this research, the criteria (average temperature rise of 139 °C above the initial room temperature) is also provided for context within this discussion. The half lap temperatures were measured at the edge of the connection gap while the spline temperatures were measured at the top of the plywood and steel, respectively. Butt joint temperatures are not included because flaming combustion occurred on the unexposed surface by the end of all tests for both gap sizes and connections with uninhibited airflow are not permitted within construction. In all tests, smoke was observed to pass through the connection gaps, another indicator of fire integrity failure. Despite the passage of smoke through the gaps, the temperatures on the unexposed

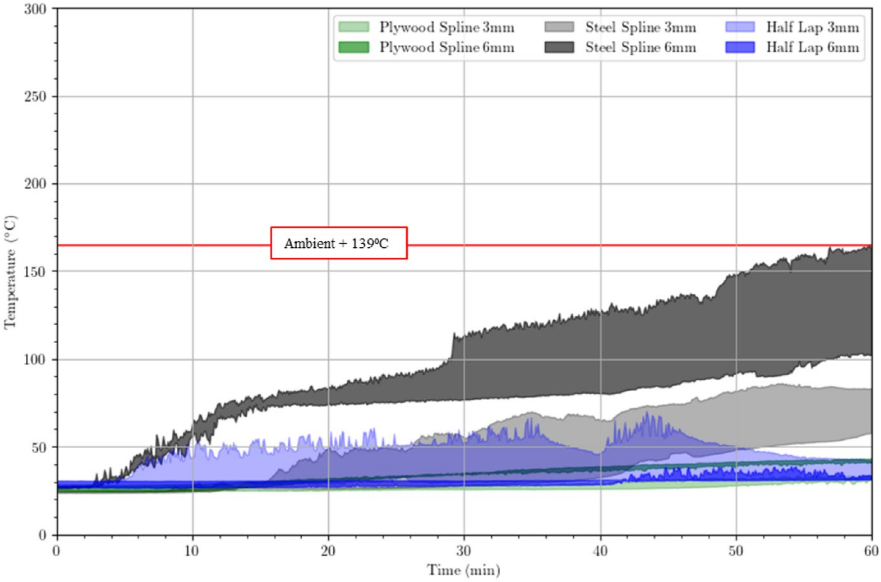

Fig. 17 Unexposed surface temperatures (ASTM E119 Failure Criteria shown in red)

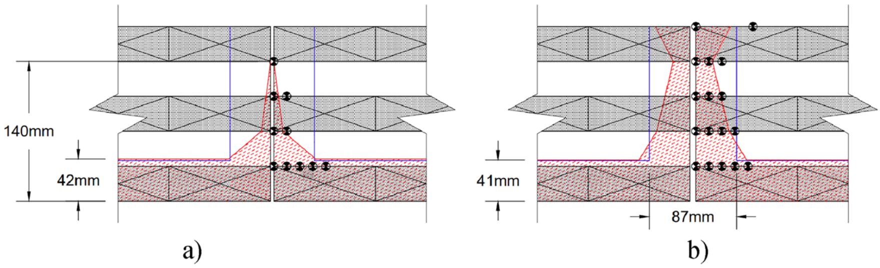

Fig. 18 Butt Joint 300 °C isotherm (red) with FDS char assumptions (blue), screws excluded for simplicity: **a** 3 mm gap, **b** 6 mm gap

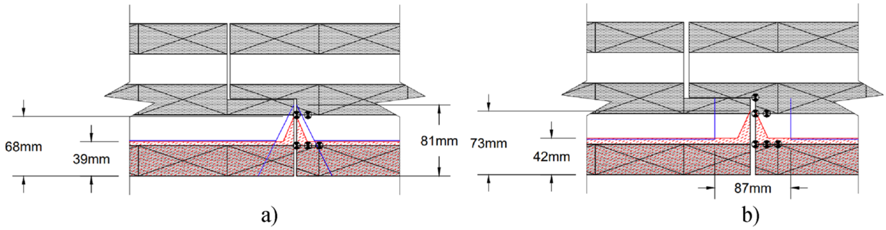

Fig. 19 Half Lap 300 °C isotherm (red) with FDS char assumptions (blue), screws excluded for simplicity: **a** 3 mm gap, **b** 6 mm gap

surface of the unprotected plywood spline, steel spline, and half lap connections were less than 40, 160 °C, and 70 °C respectively.

The steel spline connection had the highest temperatures at the unexposed surface. Despite this, the maximum temperature at both gap sizes remained below 160 °C, with average temperatures much less than 139 °C above the initial room temperature (26 °C). The 6 mm gap steel spline specimens had the highest temperatures at the unexposed surface, potentially due to a partial reduction in airflow at the steel-CLT interface and the higher thermal conductivity of the steel element. While this connection behaviour met the acceptance criteria of ASTM E119 [8], the temperatures ranged from 100–160 °C, indicative of degrading strength and stiffness throughout the cross section. The fire integrity of the panel-to-panel connections was provided by the mechanical restriction of airflow alone, without additional fire protection measures (e.g. caulking). However, all unprotected connections tested did not provide the complete prevention of smoke and hot gas propagation through the joint. At gap sizes up to 6 mm, the unprotected connections, excluding butt joints, meet the temperature threshold established in ASTM E119.

6.2 Fire Design Specification Comparison

The temperature data can be used to quantify char depths by using the 300 °C isotherm. All connections tested show that the FDS prescribed char depths are an overestimation of char development within the gap. Figures 18, 19, 20, 21 use thermocouple data to trace the 300 °C isotherm at the end of 1-h fire exposure for all connections (shaded red region). The

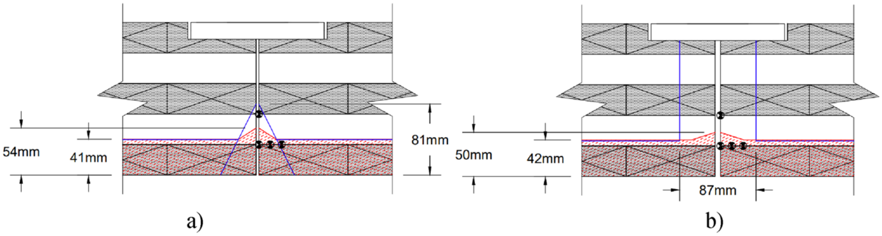

Fig. 20 Plywood Spline 300 °C isotherm (red) with FDS char assumptions (blue), screws excluded for simplicity: **a** 3 mm gap, **b** 6 mm gap

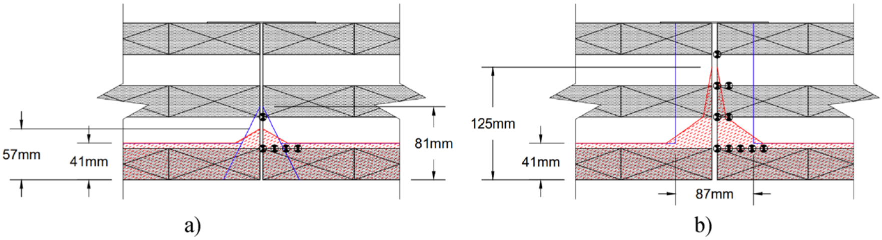

Fig. 21 Steel Spline 300 °C isotherm (red) with FDS char assumptions (blue), screws excluded for simplicity: **a** 3 mm gap, **b** 6 mm gap

black dots represent the thermocouple locations within the connection and CLT during the experiment. The blue lines represent the prescribed char depths from FDS [6].

The current provisions for the fire protection design of abutting wood members [6] could be significantly improved based on the findings. The assumption that gaps greater than 3 mm or without negligible airflow will create a fully exposed condition is an overestimation of the behaviours observed during testing. Even in the experiments with butt joint connections and gap sizes of 6 mm, where the greatest gap char development was observed, the horizontal char depths were 15% below the expected fully exposed depth. While the char penetration was less than expected, flaming combustion at the unexposed surface was observed in the case of 6 mm gaps with uninhibited airflow. In all other tests with 6 mm gap size, vertical char penetration within the gap did not exceed 125 mm ($3a_{char}$) and had minimal horizontal charring. For connections with gap sizes of 3 mm, the current provisions indicate vertical char penetration is twice the one-dimensional char depth. This provision was also an overestimation of the tested behaviours. Recommendations can be made based on gap size and connection type which accounts for the char penetration, corner rounding, and airflow behaviours observed in the unprotected connections with gaps up to 6 mm under standard fire exposure (Fig. 22) (Table 8). The recommended char depth is given in terms of nominal char for each connection type at each gap size for 1-h fire exposure. Figure 23 compares steel spline specimens at 3- and 6-mm gaps using the provided general recommendations. While these recommendations predict the expected char penetration under prescriptive fire design conditions, they do not estimate the thermal degradation of timber elements outside of the char layer, the fire integrity of intersecting members, or predict charring under natural fire scenarios.

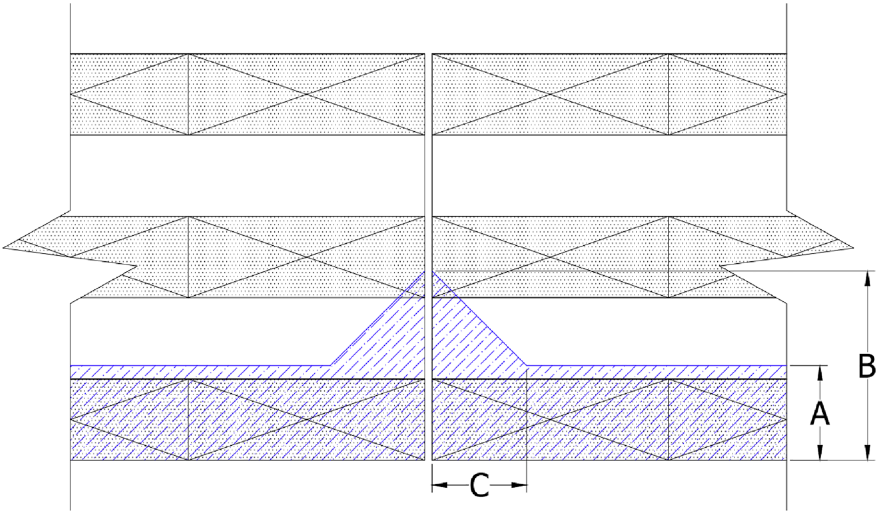

Fig. 22 Gap char depth recommendations

Table 8 Gap char depth recommendations

Connection type	Gap size (mm)	Recommended char depth (in terms of a_{char})		
		A	B	C
Half lap	3	1.0	1.8	0.5
	6		1.9	0.5
Plywood spline	3		1.4	0.8
	6		1.4	0.8
Steel spline	3		1.5	0.8
	6		3.2	1.0
General recommendation	3		2	1.0
	6		3.5	1.0

6.3 Limitations

While the results presented quantify the fire behaviours observed in gaps in CLT panel-to-panel connections, limitations of the study must be considered. The connections tested were all exposed to the standard fire [8] for one hour. The heating-phase behaviours observed would potentially change if fire exposure duration was increased or if natural fire conditions were imposed. Additionally, oxygen content was not recorded in the furnace thereby introducing uncertainty in whether an oxygen deprived environment occurred during heating. In the cooling-phase, the behaviours observed were dependent on the cooling condition imposed. Ambient air temperatures and an oxygen-rich environment controlled the smouldering and thermal wave behaviours presented. If a natural fire was used, gas temperatures, oxygen content, and duration in the decay phase would differ from the tested condition, resulting in potentially different charring, smouldering, and temperature behaviours in the connections. Future work should consider the effects of a natural fire in heating and cooling and expand upon the findings presented in this study.

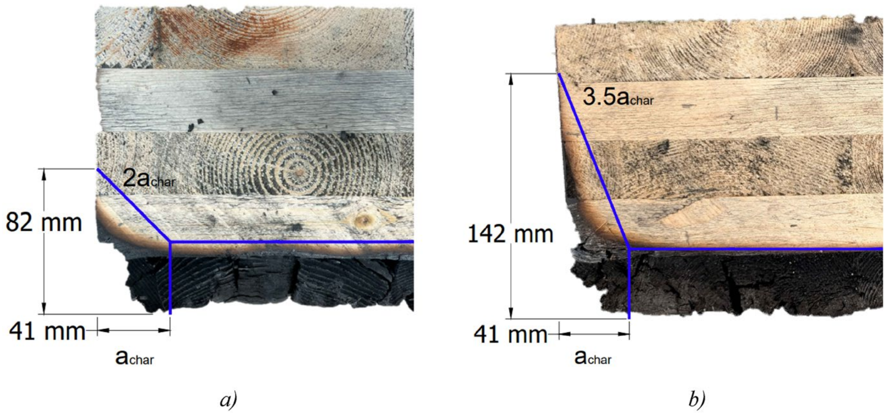

Fig. 23 FDS recommendations steel spline post-Test: **a** 3 mm gap, **b** 6 mm gap. for both figures, the left edge was the abutting edge

7 Conclusions

Small gaps at the intersection between mass timber members can have detrimental impacts on the fire integrity of a structure. To investigate the charring within these gaps when they exist in CLT decks as well as to investigate the heat transfer into the timber itself from the gaps, twenty-five 5-ply CLT panel-to-panel connections were exposed to a 1-h standard fire. Four types of connections were tested unprotected and unloaded: butt joint, half lap, plywood spline, and steel spline, with gaps of 0-, 3-, and 6-mm. Char depths and temperature data were used to quantify the horizontal and vertical char development in the connection gap. This data was used to compare current codes and specifications to assess potential conservatism in prescribed char depths between intersecting members. Additionally, eight connection specimens had an additional 1-h cooling period to investigate the heat transfer, thermal wave propagation, and potential smouldering effects in post-fully developed fire.

Following 1-h fire exposure, horizontal and vertical char was quantified using physical and thermocouple measurements. For nearly all connections tested, as gap size increased from 3 to 6 mm, temperatures and charring within the gap (vertical and horizontal) significantly increased between the abutting members and into the solid CLT. There was a clear connection between char depth and temperatures into the CLT from the gap size and the amount of airflow provided by the connection geometry. In the butt joint specimens, where airflow was completely uninhibited, substantial vertical char penetration in the gap was observed, and flaming combustion occurred at the unexposed surface by the end of testing. Contrasted with the plywood spline specimens, vertical char penetration into the gap did not extend more than 15 mm beyond the one-dimensional char depth and virtually no horizontal charring was recorded. In all connections tested, smoke propagated through the connection gap to the unexposed surface. However, for all specimens excluding butt joints, average unexposed surface temperatures did not increase more than 139 °C from the start of the test. Thereby suggesting that any hot gas penetration through unprotected panel-to-panel connections did not compromise the floor system's ability to prevent fire spread.

The impact of connection type and gap size was again quantified during the 1-h cooling period. Specimens were exposed to a simulated cooling phase with ambient air temperatures. Smouldering behaviours were observed in the butt joint, steel spline, and half lap specimens through increased horizontal char depths between the abutting members. Even after the end of fire exposure without any external heating, combustion was still occurring within the gap of these specimens. Despite little additional charring, temperatures in the CLT away from the connection increased to temperatures at which the CLT would lose stiffness and strength. In the butt joint specimens, the unrestricted airflow caused the reignition of specimens during the cooling phase.

Current guidance provided in the FDS [6] to account for gaps at intersecting members overestimates char development in the gaps of panel-to-panel connections, regardless of the connection type. In all specimens tested, the vertical and horizontal char penetration into the gap was less than predicted by FDS even in cases of unrestricted airflow. Char development within the connection gaps did not match a fully exposed condition in any specimen tested with unrestricted airflow or gaps of 6 mm. To better reflect the heat transfer mechanisms in mass timber connections, recommendations were developed that match the results from this test series. The recommendations provide estimated char penetration into abutting members that capture vertical and horizontal charring as well as corner rounding (two-dimensional charring) behaviours at the intersection. The results from these tests can help to refine prescriptive design standards for CLT panel-to-panel connections considering gaps within the connections and considering different connection types. The results can also be used as a validation data set for numerical modelling efforts to simulate mass timber floor systems considering gaps between the panels. Further research is suggested to explore the application of the conclusions made within this paper to natural fire scenarios that may have significantly different heating and cooling phases than tested.

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Author Contribution All authors designed, reviewed, and conducted the experimental testing presented in this manuscript. W.G. prepared all figures and tables presented and drafted all text in this manuscript. E.C. and L.H. critically revised the manuscript in its entirety and made changes to all text, figures, and tables as necessary.

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Data Availability Some or all data that support the findings of this study are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Abed J, Rayburg S, Rodwell J, Neave M (2022) A review of the performance and benefits of mass timber as an alternative to concrete and steel for improving the sustainability of structures. Sustainability. https://doi.org/10.3390/su14095570

2. ANSI/AWC (2021) SDPWS-2021 Special Design Provisions for Wind and Seismic, American Wood Council, Leesburg, VA
3. Kinder E, Kingsley G (2021) Mass timber connections index: optimal connection considerations. WoodWorks-Wood Products Council
4. Buchanan A, Dunn A, Just A, et al (2022) Fire safety in timber buildings. In: Fire safe use of wood in buildings: Global Design Guide. CRC Press
5. International Code Council (2023) IBC 2024 : international building code. ICC Publications Country Club Hills, IL
6. ANSI/AWC (2024) Fire design specification for wood construction, 2024 Edition. American wood council, Leesburg, VA
7. CEN (2004) EN 1995-1-2: Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design. European Committee for Standardization
8. ASTM International (2020) E119–20 standard test methods for fire tests of building construction and materials. ASTM. West Conshohocken, PA
9. ISO/TC 92(2014) ISO-834 -11, Fire-resistance test-elements of building construction: Part 1. general requirements.The International Organization for Standardization.
10. du Plessis M, Streicher D, Walls R (2025) Experimental testing on concealed beam hanger mass timber connections considering the influence of gap size and intumescent sealants: testing on timber concealed connections considering gap size and sealants. Fire Technol. https://doi.org/10.1007/s10694-025-01782-2
11. du Plessis MC, Walls RS (2024) Experimental and numerical investigation on the effect of gaps in mass timber connections in fire. Stellenbosch University
12. du Plessis M, Sulon D, Streicher D, Walls R (2024) Experimental testing on timber connections considering the influence of gap size and intumescent sealants. Fire Mater 48:39–61. https://doi.org/10.1002/fam.3164
13. Ranger L, Gagnon S, Dagenais C (2019) Evaluating fire performance of nail-laminated timber: influence of gaps. FPInnov Project No 301013024
14. Sauca A, Pope I, Friðriksdóttir HM et al (2024) The influence of tolerance gaps on the fire performance of aluminium-wood joints. Fire Technol 60:2621–2649. https://doi.org/10.1007/s10694-023-01504-6
15. Brugnara P, Alice S, Sestigiani L (2025) Fire and CLT: Linear Joints. In: Proceedings from the 14th world conference on timber engineering: advancing timber for the future built environment, WCTE 2025. World Conference on Timber Engineering (WCTE), pp 4235–4241
16. Ranger L, Dagenais C, Bénichou N (2019) Solutions for upper mid-rise and high-rise mass timber construction fire resistance of mass timber laminated elements. FP Innov Project No 301013085
17. Wiesner F, Brandon D, Lucherini A, Palma P (2025) Structural fire behaviour. In: Fink G, Jockwer R, Cabrero JM (eds) Holistic design of taller timber buildings. Springer Nature Switzerland, Cham, pp 288–299
18. Lucherini A, Pitelková DŠ, Mózer V (2025) Estimating the effective char depth in structural timber elements exposed to natural fires, considering the heating and cooling phase. Eng Struct 323:119255. https://doi.org/10.1016/j.engstruct.2024.119255
19. Gernay T, Zehfuß J, Brunkhorst S et al (2023) Experimental investigation of structural failure during the cooling phase of a fire: timber columns. Fire Mater 47:445–460. https://doi.org/10.1002/fam.3110
20. Mitchell H, Amin R, Heidari M et al (2023) Structural hazards of smouldering fires in timber buildings. Fire Saf J 140:103861. https://doi.org/10.1016/j.firesaf.2023.103861
21. Bartlett AI, Hadden RM, Bisby LA (2019) A review of factors affecting the burning behaviour of wood for application to tall timber construction. Fire Technol 55:1–49
22. Rein G (2016) Smoldering combustion. SFPE handbook of fire protection engineering, fifth edition, 5th Edition. Springer, pp 581–603
23. Santoso MA, Christensen EG, Yang J, Rein G (2019) Review of the transition from smouldering to flaming combustion in wildfires. Front Mech Eng. https://doi.org/10.3389/fmech.2019.00049
24. Schmidt L, Hadden RM (2024) Conditions for the onset of char oxidation in timber. J Phys: Conf Ser 2885:012010
25. Fischer EC, Bhandari S, Sinha A (2025) Fire testing of glue-laminated beam-to-column connections. J Struct Eng 151:04025020. https://doi.org/10.1061/jsendh.steng-13888
26. ANSI/APA (2025) PRG 320-2025 Standard for Performance-Rated Cross-Laminated Timber. APA-The Engineered Wood Association, Tacoma, WA
27. ANSI/AWC (2023) National Design Specification (NDS) for Wood Construction, 2024 Edition. American Wood Council, Leesburg, VA
28. Fahrni R, Schmid J, Klippel M, Frangi A (2018) Correct temperature measurements in fire exposed wood. ETH Zurich. https://doi.org/10.3929/ethz-b-000289850

29. Lucherini A, Torero JL (2023) Defining the fire decay and the cooling phase of post-flashover compartment fires. Fire Saf J 141:103965. https://doi.org/10.1016/j.firesaf.2023.103965
30. Schmidt L, Hadden RM, Fernando D (2024) Observations and impact of char layer formation and loss for engineered timber. Fire Saf J 147:104196. https://doi.org/10.1016/j.firesaf.2024.104196
31. Posit team (2025) RStudio: Integrated development environment for R