WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

QUANTIFYING FIRE BEHAVIOUR IN GAPS IN CLT PANEL-TO-PANEL CONNECTIONS

Wyatt Garrett[1], Erica Fischer[2], Laura Hasburgh[3]

ABSTRACT: Dimensional tolerances of mass timber construction typically result in small gaps between mass timber panels. The Fire Design Specification prescribes that when gaps within elements exceed 3 mm the mass timber within the gap must be treated as fully fire-exposed surfaces. Therefore, many of these gaps must be filled with fire protection material. However, the process of protecting these gaps is time consuming and costly. To evaluate the influence of gaps on fire dynamics and char propagation, the authors performed a series of experiments on cross laminated timber panel-to-panel connections to evaluate the influence of connection type and gap size. Temperatures were measured to quantify the fire behavior of the mass timber connections. Each specimen was exposed to the standard fire (ASTM E119) for an hour. The development of char within connection gaps was overestimated by the Fire Design Specification in almost all cases. When considering unprotected gaps, connection type and geometry had the greatest impact on fire performance.

KEYWORDS: mass timber, fire, connections, CLT, gap

1 – INTRODUCTION

The proliferation of mass timber construction has been due to faster erection times, aesthetic benefits, and lessened environmental impact. The construction tolerances of panelised mass timber products (e.g., cross laminated timber) has commonly produced in gaps at the panel-to-panel connections. Gaps may have fire safety implications, if flames or smoke breach the gaps at a faster rate. As a combustible material, fire is a crucial consideration for structural performance and occupant safety of mass timber buildings. Smoke infiltration is an immediate hazard to occupants. Wood's mechanical properties permanently diminish as temperatures increase during fire, losing strength as moisture dissipates and char begins to form. In CLT, these gaps coincide with panel-to-panel connections that provide structural diaphragm continuity across panel joints. Therefore, understanding the fundamental behaviour of the material with these gaps is critical for designing safe mass timber buildings.

2 – BACKGROUND

2.1 PANEL-TO-PANEL CONNECTIONS

Cross laminated timber (CLT) panel-to-panel connections create continuity of load paths across the joint. Due to construction tolerances, small gaps (i.e., intersections at abutting edges) can occur and, when exposed to fire, these gaps can have negative consequences on the fire performance of the floor system enabling fire spread from one floor to another. The Fire Design Specification (FDS) for Wood Construction requires that for gaps less than 3 mm, the local char penetration at the gap from the exposed surface is twice the one-dimensional char rate [1]. For gaps greater than 3 mm, the char penetration of the vertical wood surfaces within the gap is equal to that of a fully exposed surface. In both cases, fire protection and restriction of airflow is assumed to mitigate char and hot gas propagation. When

[1] Wyatt Garrett, School of Civil and Construction Engineering, Oregon State University, Corvallis, Oregon, United States of America, garrettw@oregonstate.edu

[2] Erica Fischer, P.E, PhD, School of Civil and Construction Engineering, Department of Wood Science and Engineering, Oregon State University, Corvallis, Oregon, United States of America, erica.fischer@oregonstate.edu

[3] Laura Hasburgh, P.E., PhD, Forest Product Laboratory, United States Forest Service, Madison, Wisconsin, United States of America, laura.e.hasburgh@usda.gov

https://doi.org/10.52202/080513-0451

airflow through the gap cannot be neglected, connection gaps are assumed to be fully exposed to fire.

Eurocode 5 does not provide guidance on calculated char propagation through connection gaps [4]. Connection fire design under Eurocode 5 lists rules to achieve a maximum fire resistance of 60 minutes during standard fire exposure. Modifications to connections such as changes to end and edge spacing of fasteners, increasing side member or plate thicknesses, or adding gypsum board and other fire protection can increase the fire performance of a connection.

The International Building Code [5] provides guidance for mass timber connections and intersections but does not specify tolerance gap behaviours. All buildings in type IV-A, IV-B, and IV-C require sealant at all fire-resistance rated edges and intersections. The sealants add fire protection and restrict airflow through building elements. However, the installation of fire protection increases installation costs, time, and environmental impacts of construction.

2.2 CURRENT KNOWLEDGE

There is limited research about the influence of gap size on connection fire performance. Plessis et al. investigated the influence of gap size and varying levels of fire protection on the fire behaviour of representative glulam beam-to-column concealed connections [7]. Twenty-one samples were tested using 200 mm x 240 mm GL 24h blocks. Nine samples had an additional 20 mm layer of high-pressure exerting (HPE) intumescent fire sealant protecting the concealed connection within the gap. With a range of gap sizes from 0 mm to 10 mm, the authors concluded that Eurocode 5 methods for predicting temperatures within gaps were nonconservative.

Palma et al. tested a variety of GL 24h beam-to-column slotted-in connections loaded in shear and exposed to a standard fire (ISO 834-1:1999) [6]. The gap between beam and column varied from 0 mm to 20 mm to investigate changes in fire performance. as the results of the research were that as the gap size increased, the average fire resistance rating of the connections decreased.

Ranger et al. tested the influence of gaps between wood members in nail-laminated timber during fire [8]. Steel spacers measuring 1 mm, 2 mm, or 4 mm were installed between 1228 mm long 2 x 8 nail laminated boards to reflect gaps that may occur through moisture changes or material variation. The charring rate for the specimens with 1 mm and 2 mm gaps was equal to that prescribed in codes (0.65 mm/min); however, as the gaps increased to 4 mm, the charring rate increased as well. No fire protection was present during testing, yet plywood covering on the unexposed surface prevented additional combustion caused by unrestricted airflow. Even for the 4 mm gap between the boards, the accelerated char rates occurred close to the fire exposed surface. Temperatures did not exceed 100°C at the unexposed end of the gap, suggesting conservative code assumptions about heat transfer into gap cavities.

Current research into the fire behaviour within gaps in timber construction has concluded that increasing gap size have direct impacts on temperature development within gaps. However, there is not enough data to determine if the code and standard stipulations are conservative. In addition, there is a lack of data on the effect of fire at CLT panel-to-panel gaps.

2.3 RESEARCH OBJECTIVES

The following test series aims to quantify the behavior of CLT panel-to-panel connections with varying gap sizes. The objectives of this research are to (1) investigate the influence of gap size and connection type on char depths and char rates in CLT panel to panel connections and (2) evaluate the conservatism of code prescribed char depths using calculated and measured char depths in CLT panel to panel connections.

3 – METHODOLOGY

3.1 Materials and Specimens

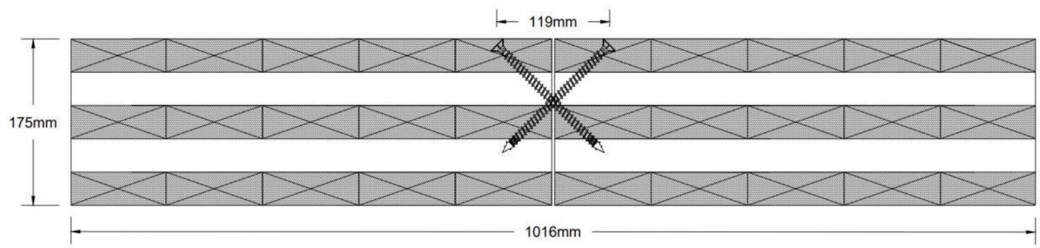
Twenty-five specimens were fabricated using 5-ply (175 mm) Kalesnikoff V2 Spruce Pine Fir CLT panels measuring 1016 mm x 1219 mm. All CLT was manufactured adhering to PRG320-2019 with phenol resorcinol formaldehyde adhesive. Four mass timber floor splice connections were evaluated in testing: plywood single surface spline, steel surface spline, butt joint, and half lap connections. Six specimens of each connection type were constructed, three with a connection gap of 3 mm and three with a connection gap of 6 mm. An additional butt joint specimen was prepared with a 0 mm gap. No fire protection was used and all specimens were unloaded during fire testing.

The plywood spline connection ("Fig.1c") had a routing depth of 19 mm and width of 79 mm along the top surface of each 506 mm by 1219 mm CLT panel. 18 mm x 152 mm plywood sheathing was used. The steel surface spline connection ("Fig.1d") used a 121 mm, 18-gauge A1008 steel surface spline. The butt joint connection ("Fig.1a") was constructed using screws installed at 45°. The half lap connection ("Fig.1d") was manufactured with a 76 mm wide lap at the midpoint of each 5-ply panel. All

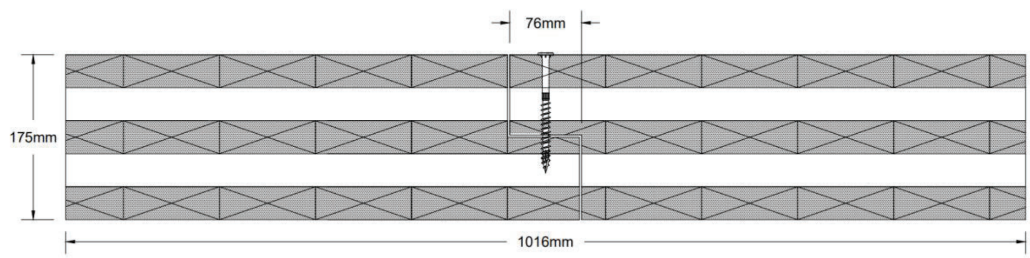
https://doi.org/10.52202/080513-0451

splices extend the full 1219 mm length of the connected panels. "Table 1" summarizes the fasteners and screw spacings used in each specimen. All screw locations adhered to the NDS minimum distance requirements [2].

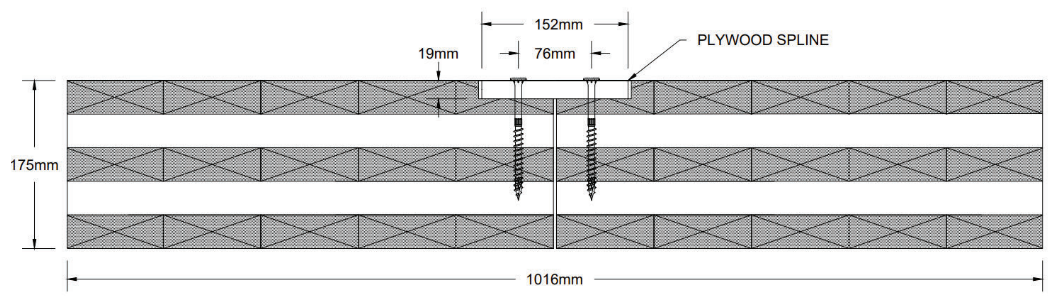
Prior to testing, specimens were conditioned in an environmental chamber with an ambient temperature of 21°C and relative humidity of 50%. The average moisture content of all specimens was 12.5% ± 0.5%.



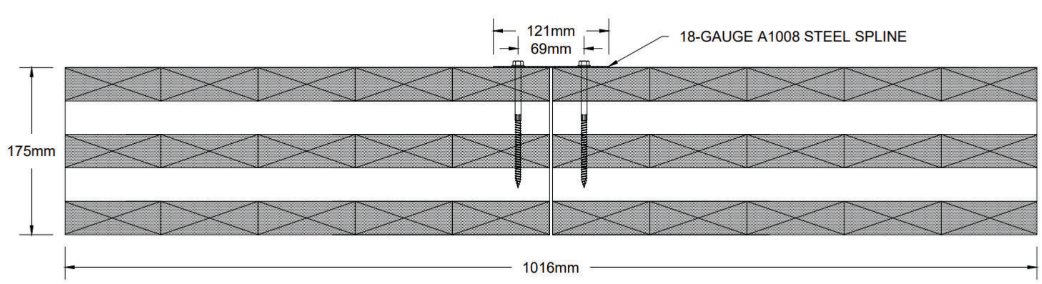
a)



b)



c)



d)

Figure 1: Connection Dimensions a) Butt Joint, b) Half Lap, c) Plywood Spline, d) Steel Spline

https://doi.org/10.52202/080513-0451

Table 1: Fastener Summary

Connection Type	Screw Type	Screw Length	Screw Diameter	End Distance	Edge Distance	Screw Spacing	Row Spacing
Butt Joint (B)	Simpson SDCF27614	159 mm	10 mm	152 mm	57 mm	(STG) 152 mm	114 mm
Half Lap (HL)	Simpson SDWS27500SS	127 mm	7 mm	152 mm	38 mm	152 mm	—
Plywood Spline (PS)	Simpson SDWS27500SS	127 mm	7 mm	152 mm	38 mm	152 mm	76 mm
Steel Spline (SS)	Simpson SDS25500	127 mm	6 mm	152 mm	35 mm	152 mm	70 mm

3.2 Instrumentation

Type K thermocouples were installed in each specimen to collect temperature data throughout testing. Thermocouples were placed within the connection gap cavity and embedded at various depths from the unexposed CLT surface. The thermocouples were installed parallel to the CLT plies at three locations along the length of the connection: 361 mm, 610 mm, and 857 mm (A, B, and C respectively) ("Fig. 2"). The resulting measured temperatures were used to compare temperatures between the 0, 3-, and 6-mm gap and calculate horizontal and vertical char rates.

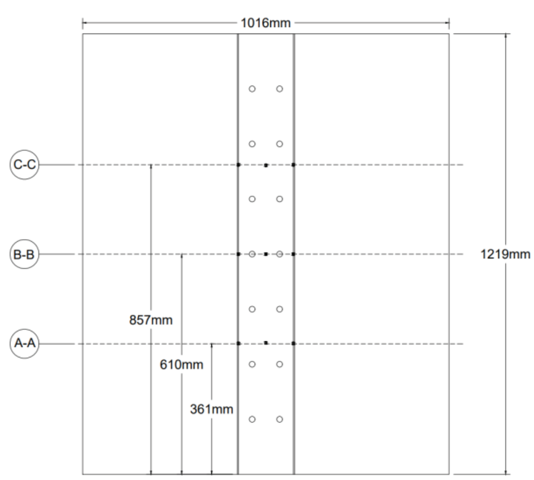


Figure 2: Specimen Plan View with Thermocouple Sections

3.3 Fire Loading

Fire testing occurred at the Forest Products Laboratory in Madison, Wisconsin. For each test, specimens were exposed to the ASTM E119 standard fire for one hour [3]. An intermediate-scale horizontal gas furnace measuring 990 mm x 1829 mm was used. Failure was defined as the loss of connection structural integrity, which did not occur during the test series.

At the end of the one-hour exposure, the frame was lifted off the furnace and the samples were extinguished with water. Two specimens of each connection type, with a 3 mm and 6 mm gap, were allowed to smoulder for an additional hour at the end of fire exposure.

Following each test, connections were disassembled, and 152 mm wide samples were cut from each section on both sides of the gap. With these samples, measurements were taken of horizontal and vertical char depths at various points to the end of CLT discoloration ("Fig. 3").

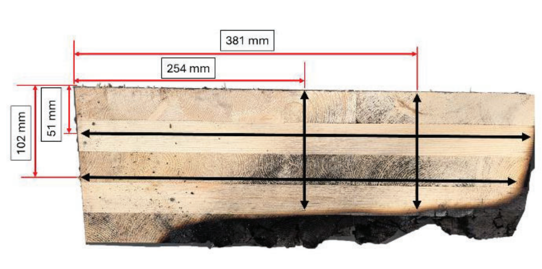


Figure 3: Post-Test Specimen Charring with Measurement Locations

4 – RESULTS

4.1 Test Observations

Physical behaviours of each connection type were noted during testing. For all tests, smoke through the connection gap began within 5 minutes of fire exposure. The plywood spline connections exhibited the least amount of smoke throughout the test duration while the butt joint connections had consistent, heavy smoke through the gap. Char fall-off began around 10 mins for all specimens. Visible moisture and discoloration on the unexposed surface of the connections were noted between 15 and 30 mins for all connections excluding plywood splines, where these behaviours were not observed. For all 6 mm butt joint specimens, flames through the top of the gap occurred between 50 and 55 minutes of the heating phase.

https://doi.org/10.52202/080513-0451

4.2 Char Depths

The post-test char measurements are summarized in "Table 2". For vertical charring of the exposed surface, twenty-four measurements were averaged for each specimen. These vertical char measurements, shown in Table 2, are within the solid CLT away from the gap. All vertical measurements were taken at least 127 mm from the connection gap. Comparing the vertical char depths of connections with a gap to the specimen with no gap, there is a maximum difference of 5.1%. The FDS prescribes expected char rates and depths for CLT. At the end of a one-hour fire exposure, FDS predicts a char depth of 40.6 mm for CLT with lamination thickness of 35 mm using a nominal char rate of 38.1 mm/hr. This aligns with measurements taken post-test ("Table 3"), with a 4% maximum difference in vertical char between the measured char depth and the nominal FDS-prescribed char depth [1]. There is a greater difference between the experimentally measured char depths and the effective char depth from FDS. The difference between the two being a maximum of 18.3%. This increased difference is because the effective char depth considers the depth of the zero-stiffness layer, which is difficult to quantify through physical measurements. Similar to FDS, Eurocode 5: Part 1-2 provides char rates and depths for one sided fire exposure [4]. Using a notional char rate of 0.7 mm/min, the notional and effective char depth is calculated. The notional char depth accurately predicts the post-test one-dimensional char depths for all connection types and gap sizes ("Table 3").

Table 2: Vertical Char Measurements

Connection Type	Gap Size	Mean Char Depth (mm)	Std Dev (mm)	% Difference compared to Butt Joint zero gap specimen
Butt Joint	0 mm	41.5	3.0	0.00
	3 mm	42.3	3.8	1.78
	6 mm	41.3	3.1	-0.45
Half Lap	3 mm	39.4	2.9	-5.07
	6 mm	41.9	2.2	0.90
Plywood Spline	3 mm	41.0	3.0	-1.33
	6 mm	41.8	2.5	0.66
Steel Spline	3 mm	41.1	2.6	-0.93
	6 mm	40.9	5.7	-1.49

Table 3: Percent Difference of Actual Char Measurements and Code Prescribed Char Depths

Connection Type	Gap Size	FDS Table 3.3.1.3				Eurocode 1-2 Table 3.1			
		Char Depth a_{char} (mm)	***% Difference***	***Eff. Char Depth a_{eff} (mm)***	***% Difference***	***Notional Char Depth $d_{char,n}$ (mm)***	***% Difference***	***Eff. Char Depth d_{ef} (mm)***	***% Difference***
Butt Joint	0 mm	40.6	-2.19	48.3	-13.95	42.0	1.12	49.0	-15.25
	3 mm		-4.00		-12.42		-0.64		-13.74
	6 mm		-1.73		-14.34		1.57		-15.63
Half Lap	3 mm		2.99		-18.31		6.13		-19.54
	6 mm		-3.11		-13.17		0.23		-14.48
Plywood Spline	3 mm		-0.83		-15.09		2.43		-16.37
	6 mm		-2.86		-13.38		0.46		-14.68
Steel Spline	3 mm		-1.24		-14.75		2.04		-16.03
	6 mm		-0.67		-15.23		2.59		-16.51

FDS states that either when gaps at joints are greater than 3 mm or when airflow cannot be neglected, the charring within the gap should be equal to the one-dimensional charring of the fully exposed surface. At the end of one-hour test exposure, the expected horizontal charring for all specimens is 40.6 mm per FDS table 3.3.1.3 [1]. No additional fire protection or material was present to prevent airflow through the connections. However, in the cases of the plywood spline, steel spline, and half lap connections, clamping action between fasteners and side members reduced airflow through the gap cavity. "Table 4" shows the average horizontal char depth for all connections and gap sizes compared to the prescribed horizontal char depths per FDS.

In all cases, the prescribed char depths in the gap were overestimated by FDS. When considering the 3 mm gap specimens, the horizontal measurements were taken 100 mm from the unexposed surface. The char depths were largest for the butt joint, followed by the half lap connections. Those connections that restricted airflow (steel and plywood splines) had the smallest char depths. Regardless of the connections, the FDS prescribed char depths were not representative of a fully exposed condition.

The largest horizontal char depth in a specimen with a 3 mm gap occurred in the butt joint specimens. This measurement was 61% less than the prescribed char depth. The steel spline and plywood spline specimens had virtually no charring within the gap above the second lamination.

The char depths measured in the specimens with 6 mm gaps, were larger than the specimens with 3 mm gaps, except the half lap specimens. The butt joint had the greatest gap charring yet was still 14.4% less than the fully exposed condition. The other connection types tested had less than 8 mm char depths within the gap.

Table 4: Horizontal Char Measurements with FDS Comparison

Connection Type	Gap Size	Mean Char Depth (mm)	Std Dev (mm)	FDS 3.3.1.3 Gap Charring			
				≤1/8" 2(a_{char})	*% Difference*	>1/8" $a_{hori} = a_{char}$	*% Difference*
Butt Joint	0 mm	0.132	0.458		96.80		99.67
	3 mm	16.007	2.958		-287.82		60.61
	6 mm	34.793	4.314		—		14.39
Half Lap	3 mm	5.358	6.748	4.128	-29.81	40.6	86.82
	6 mm	2.514	4.132		—		93.82
Plywood Spline	3 mm	0.000	0.000		100.00		100.00
	6 mm	5.821	6.344		—		85.68
Steel Spline	3 mm	0.066	0.324		98.40		99.84
	6 mm	7.541	8.003		—		81.45

4.3 Connection Gap Behaviour

Thermocouple data was used to quantify the char depths within the connection by identifying the location of the 300˚C isotherm. In "Figs. 47", the 300˚C isotherm was traced at the end of one-hour fire exposure using thermocouple arrays parallel to the connection gap. Vertical measurements map the char development by the end of each test along the exposed surface. Test data was then compared to the FDS estimation of char depth locations for both gaps less than 3 mm and gaps greater than 6 mm, indicated by blue lines.

A triangular char penetration is seen in all 3 mm gap specimens tested. The penetration within the gap does not exceed the second lamination for the half lap, plywood spline, and steel spline connection types. This triangular distribution is similar to but overestimated by the FDS prescribed char depths for a 3 mm gap with no airflow.

The 6 mm gap specimens, excluding the butt joint, did not resemble a fully exposed surface. The butt joint connection had charring along the full gap depth, likely due to the unmitigated airflow and larger gap size. Steel spline specimens had a char penetration of 125 mm, yet this development did not spread horizontally as would be prescribed by the FDS char depths. The plywood spline and half lap connection had triangular char distributions that penetrated 73 mm and 50 mm into the gap from the fire exposed surface, respectively. This is significantly lower than the char penetration depth within FDS. The geometry of the half lap and plywood spline connection block the pathway of airflow through the entire intersection gap.

In "Figs. 8 through 11", the range of thermocouple temperatures at the midpoint of each connection cross-section (between 70 mm and 105 mm) is depicted. The temperature rise within the connection gap, separated by connection type and gap size, is shown for the one-hour fire duration. The shaded regions encompass the maximum and minimum recorded temperature data from the triplicate thermocouples shown. Only the butt joint and 6 mm steel spline connections experienced gap temperatures that exceeded 300˚C by the end of fire exposure. For all other specimens tested, temperatures within the gap cavity did not rise above 200˚C, indicating charring behaviours that did not match the FDS predicted behaviours.

https://doi.org/10.52202/080513-0451

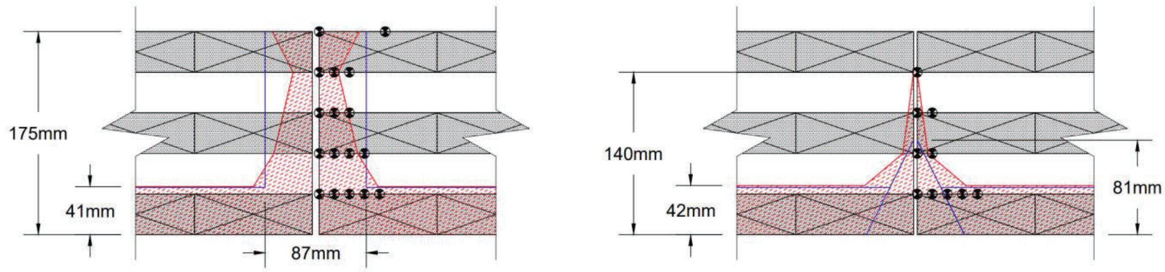


Figure 4: Butt Joint 300˚C isotherm (red) with FDS char assumptions (blue), screws excluded for simplicity: left) 6 mm gap, right) 3 mm gap

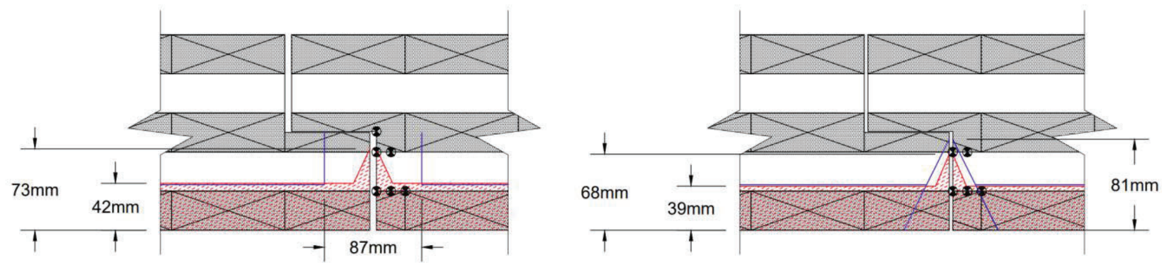


Figure 5: Half Lap 300˚C isotherm (red) with FDS char assumptions (blue), screws excluded for simplicity: left) 6 mm gap, right) 3 mm gap

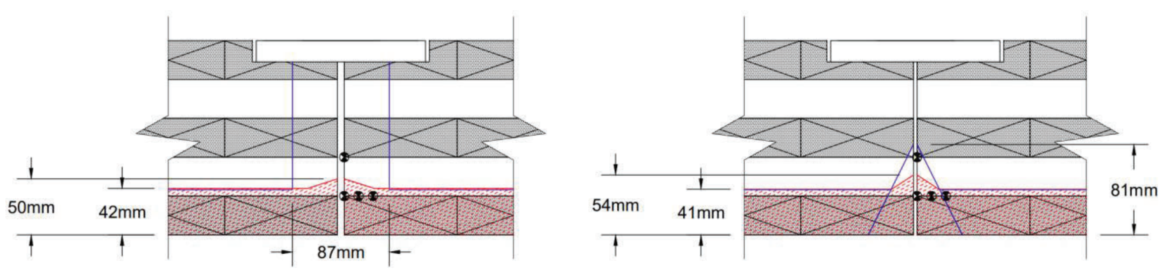


Figure 6: Plywood Spline 300˚C isotherm (red) with FDS char assumptions (blue), screws excluded for simplicity: left) 6 mm gap, right) 3 mm gap

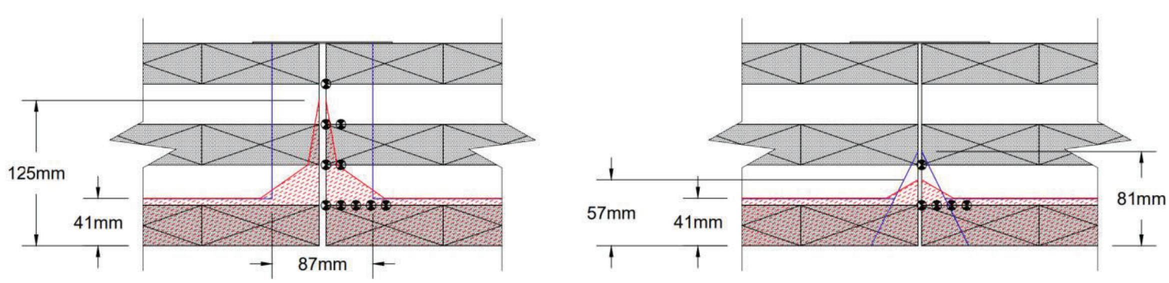


Figure 7: Steel Spline 300˚C isotherm (red) with FDS char assumptions (blue), screws excluded for simplicity: left) 6 mm gap, right) 3 mm gap

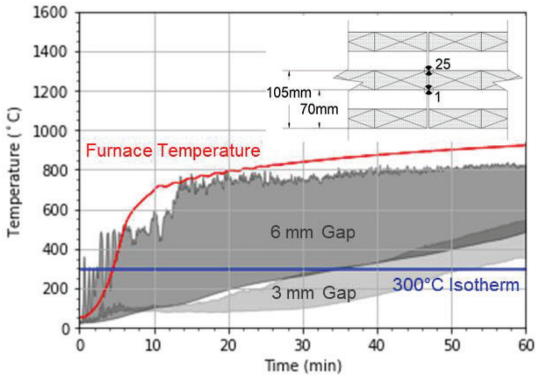


Figure 8: Butt Joint Gap Temperatures

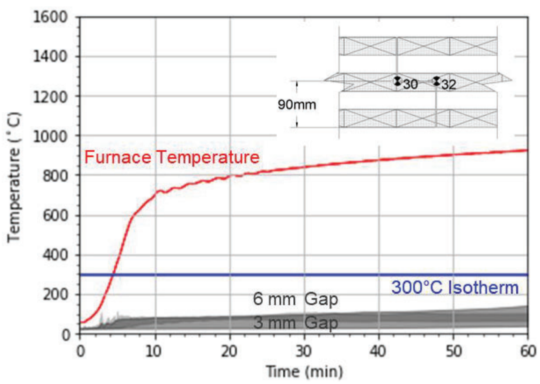


Figure 9: Half Lap Gap Temperatures

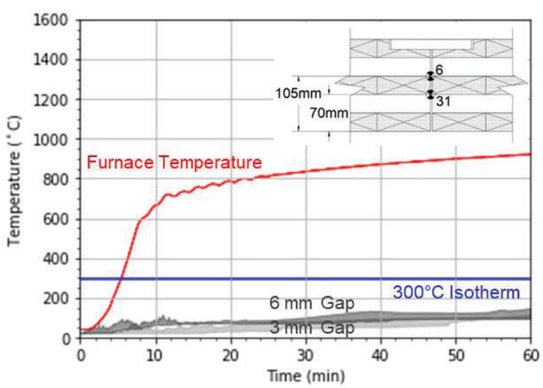


Figure 10: Plywood Spline Gap Temperatures

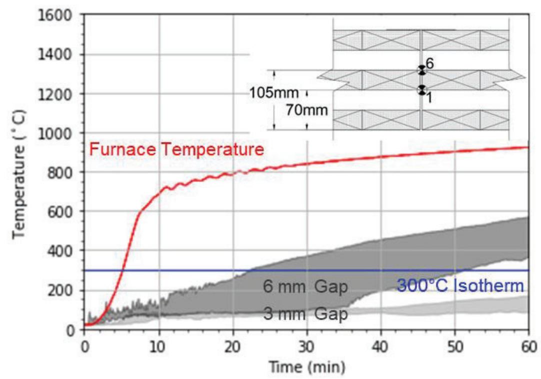


Figure 11: Steel Spline Gap Temperatures

5 – CONCLUSION

Char development within unprotected CLT panel-to-panel connections is overestimated by current code guidance [1]. The configuration and geometry of connections has more influence on the char rates within intersections. Butt joints, develop a 'chimney' for hot gas and temperature propagation. Therefore, these connections exhibited behaviours that matched a fully exposed surface for gaps larger than 3 mm. For the entire test series, air flow inside the intersection could not be neglected, with no fire protection on either surface of the connections. However, the connection types that provided restricted airflow had significantly less horizontal char and lower gap temperatures. The plywood surface spline had lower temperatures and less charring than all other connection types, regardless of gap size.

The FDS estimations of charring distributions within CLT panel-to-panel gaps is an overestimation in all cases. Gap size influences vertical char penetration, but horizontal propagation did not occur at the same rate as a fully exposed surface. While gaps in CLT panel-to-panel connections do allow for a transfer of hot gases into the gaps, it is unclear how varying connection types influence the amount of hot gasses to transfer through the connections. The resulting char depths for butt joints imply significant hot gas transfer; however, the charring was still less than the fully fire exposed surface. However, in other connection types, the transfer of hot gasses was substantially lower. These findings suggest that conservative assumptions overestimate gap behaviours, the extent of airflow influences temperature rise and char development, and connection type vastly varies the fire performance of floor panel-to-panel connections.

https://doi.org/10.52202/080513-0451

6 – REFERENCES

[1] American Wood Council. 2024. “Fire Design Specification for Wood Construction.”

[2] American Wood Council. 2024. “National Design Specification for Wood Construction.”

[3] ASTM. 2020. E119 − 20 Standard Test Methods for Fire Tests of Building Construction and Materials. West Conshohocken, PA.

[4] EN 1995-1-2: Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design. n.d.

[5] International Code Council. 2024. “International Building Code.”

[6] Palma, P. 2016. Fire Behaviour of Timber Connections. Zurich.

[7] du Plessis, M., D. Sulon, D. Streicher, and R. Walls. 2023. “Experimental testing on timber connections considering the influence of gap size and intumescent sealants.” Fire Mater, 48 (1): 1–23. John Wiley and Sons Ltd. https://doi.org/10.1002/fam.3164.

[8] Ranger, L., Mas. Christian Dagenais, C. Dagenais, S. Scientist, S. Gagnon, and Pe. Manager. 2019. EVALUATING FIRE PERFORMANCE OF NAIL-LAMINATED TIMBER: INFLUENCE OF GAPS.

https://doi.org/10.52202/080513-0451