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QUANTIFYING CHARRING AND TEMPERATURE RISE OF GAPS IN GLULAM BEAM-TO-COLUMN CONNECTIONS

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ABSTRACT

Mass timber construction often has low tolerances due to offsite manufacturing and fabrication. However, due to dimensional tolerances of the natural material as well as the shrinking and expansion due to moisture changes, gaps typically form between members. These gaps can be up to 6 mm and current standards and codes require fire caulking of the gaps regardless of their sizes. In addition, prescriptive char models indicate that significant charring can occur within these gaps thereby reducing the load-carrying capacity of the structural components and providing a potential pathway for fire integrity failures. For all these reasons, experimental investigations of structural systems with intentional gaps are needed to develop guidelines for mass timber buildings. To address this gap, three unprotected T-shape glue laminated beam-column connections with two connections per specimen were fire tested in a gas fired furnace. Each specimen was exposed to the ASTM E119 standard fire for one hour. Each test used concealed beam hanger connections with average gap sizes of 1-, 3-, and 6-mm. Char depth measurements and temperature data were used to quantify the impact of gap size on char penetration and temperature rise in mass timber connections. Connections with gap sizes greater than 1.8 mm had an increase in char depth yet temperatures at the concealed connection remained outside the heat affected layer. As gap size increased, char penetration at the connection increased, with surface charring of the full width of the connection when gap size exceeded 6 mm. Despite the increasing char penetration for gap sizes up to 8 mm, a fully exposed surface at the connection face, analogous with two-dimensional charring, was not observed in any test. Concealed connection temperatures did not exceed an average temperature rise above 139°C for gaps less than 6 mm. Char depth at the connection gap was accurately predicted by one-dimensional gap char factors established in the 2024 Fire Design Specification yet underpredicted by factors in the upcoming prEN1995-1-2:2025.

Keywords: fire tests; mass timber; connections; gaps

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1 INTRODUCTION

1.1 Mass Timber Connections in Fire

Mass timber construction has various benefits, from carbon sequestration to aesthetic design. One major benefit of mass timber construction is that most of the fabrication can occur offsite thereby increasing the speed of construction onsite. However, a challenge within the construction is that there are dimensional tolerances for mass timber building components and timber expands and contracts under varying moisture exposure conditions. The dimensional tolerances as well as the expansion and contraction of the timber results in small gaps between timber elements (e.g., glue laminated beams and columns). During a fire, hot gasses can move into these gaps and may cause heat transfer within the connection that was not originally designed for (Fig. 1).

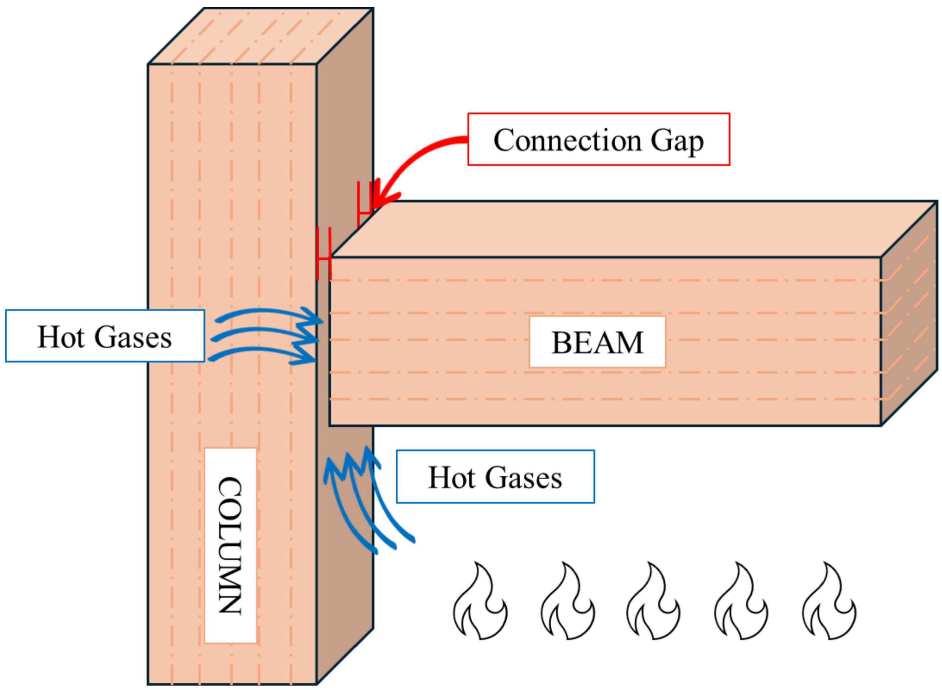

Figure 1: Gap Influence on Beam-Column Connections

Fire is a crucial concern in the design of mass timber building systems. As a combustible material, wood experiences a permanent reduction in material properties when exposed to temperatures exceeding ambient conditions [1]. At connections, this reduction in strength and stiffness results in a loss of embedment strength, excessive deflections, and potential connection failure [2]. To prevent these effects, fire protection is added to the connection, delaying the heat transfer from the fire to the structural components and the heat transfer through the connection itself. [3]

1.2 Connection Gaps

To address the impact on fire performance due to small gaps in glue laminated (glulam) beam-to-column connections, current codes modify prescribed char depths to account for additional thermal penetration. The 2024 Fire Design Specification for Wood Construction (FDS) [4] specifies char modification factors to account for gaps at intersecting members. For timber members with gaps up to 3 mm, a triangular char distribution is expected to penetrate two times the one-dimensional char depth into the gap. For gaps exceeding 3 mm, or when airflow cannot be neglected, two-dimensional charring equal to the one-dimensional char depth is expected, equating the timber within the gap to a fully exposed fire surface. In the upcoming Eurocode prEN1995-1-2:2025, gap factors modify the char rate at intersecting timber members. For members with gaps greater than 2 mm but less than 5 mm, a 1.2 gap factor is applied to the one-dimensional char rate. For gaps greater than 5 mm, two-dimensional charring is assumed, and an additional 1.2 gap factor is applied to the one-dimensional char rate.

To assess the validity of code prescribed gap charring assumptions and investigate the impact of gap size on mass timber connections, several researchers have performed experimental and numerical investigations. The results of this research have demonstrated that temperatures within unprotected mass timber connections substantially increased when the gap size increased above 6 mm [5–8]. However, the presence of fire protection, such as intumescent sealant, or the prevention of airflow through a connection mitigated elevated temperatures of connecting elements and unexposed surfaces to within acceptance criteria established in the International Building Code (IBC) and ASTM E119 [3, 5–7, 9]. When comparing to code prescribed gap char models, prEN1995-1-2:2025 underpredicted the one-dimensional char rates measured in glulam beam-to-column connections with gaps [5–7].

This research addressed the impact of gap size and protection on temperature rise in timber members. however, knowledge gaps remain when analysing the impact of gaps in mass timber connections on the thermal penetration from fire. Specifically, the char depth penetration in addition to the quantification of the heat affected zone due to gaps. To fill these gaps in knowledge, a series of fire tests were performed on glulam beam-to-column connections at the USDA Forest Products Laboratory.

The specific research objectives were to: 1) determine the influence of gap size on char depths and rates within the gaps of these connections, 2) quantify two-dimensional (2D) charring at the connection gap interface, and 3) compare results to gap charring provisions in current fire design standards [1, 4].

2 METHODOLOGY

2.1 Materials and Specimens

Three T-shaped beam-column assemblies were constructed for testing. The beams and columns used were class L2 Duglas Fir Glulam, fabricated by Timberlab. Each beam measured 219 x 457 x 457 mm and were installed on either side of a 222 x 229 x 762 mm column (Fig. 2). To simulate a mass timber building system, a 990 x 1140 mm 5-ply V2M1 Smartlam CLT floor was installed centred on the beam-column assembly using 5.7 x 279 mm self-tapping screws (SDCP221100). Simpson Strong-Tie concealed beam hanger connectors (CBH2.37X5.5B-KT) were embedded on the column faces at mid-height of the beams. Concealed connections were used for all tests to prevent any additional heat-transfer or charring due to exposed steel influence [10].

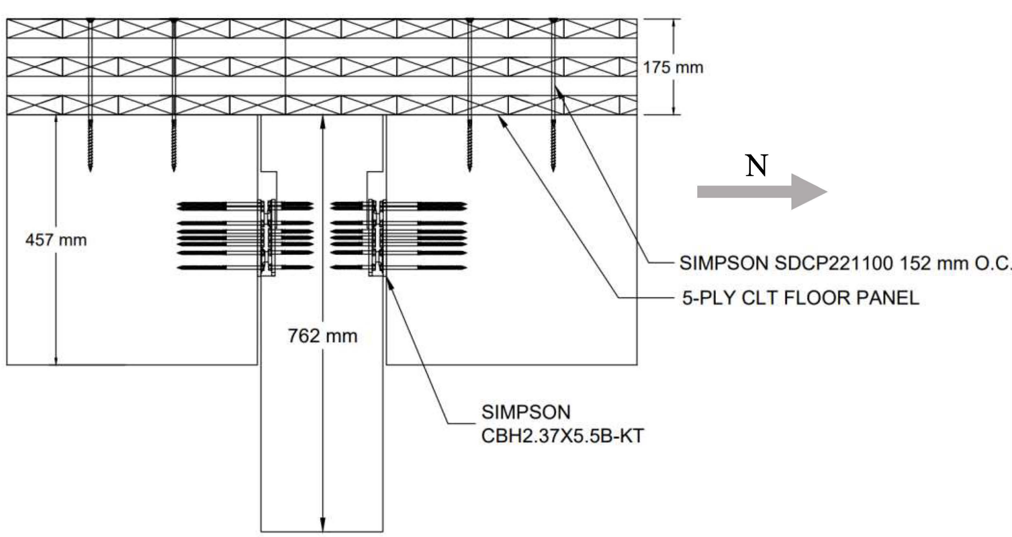

Figure 2: Beam-Column Connection Elevation View (north arrow shown)

To investigate the impact of connection gaps on fire behaviour, the gap size between the beams and column was varied for each test specimen from a 0-,3-, and 6 mm gap. The idealized gap size was enforced by adjusting the embedment depth of the concealed beam hanger assembly. Despite this, variation occurred in the gap width along the height of each side of each beam-column interface. In all specimens, no fire protection (insulation, fire caulk, etc.) was applied within the connection or beam-column interface but fire caulk was applied at the interface of the glulam beam and the CLT floor. Additionally, no mechanical loading was applied.

Throughout the remainder of the paper, the specimens and connections will be noted through the following symbology: *Test_GapSize_Location*. Where the *GapSize* will be noted as the idealized gap size (0, 3, 6 mm) and the *Location* will denote the north (*N*) and south (*S*) connections of the specimen (Fig. 2). For example, *Test_0_N* is the specimen with an idealized gap of 0 mm and on the north end of the specimen.

2.2 Instrumentation

Type-K thermocouples were used to collect temperature data for the duration of each test. Installation locations included thermocouples 110 mm from the side of the connection in-line with the CBH, 41 mm from side of connection, and on the exposed column face. Thermocouples were installed parallel to charring isotherms at and away from the connection gap [11]. To achieve this, section cuts were made in the beams and columns, thermocouples were installed, and the sections were sealed using a phenol resorcinol formaldehyde (PRF) adhesive. Instrumentation 110 mm from the side of the assembly is shown in Fig. 3.

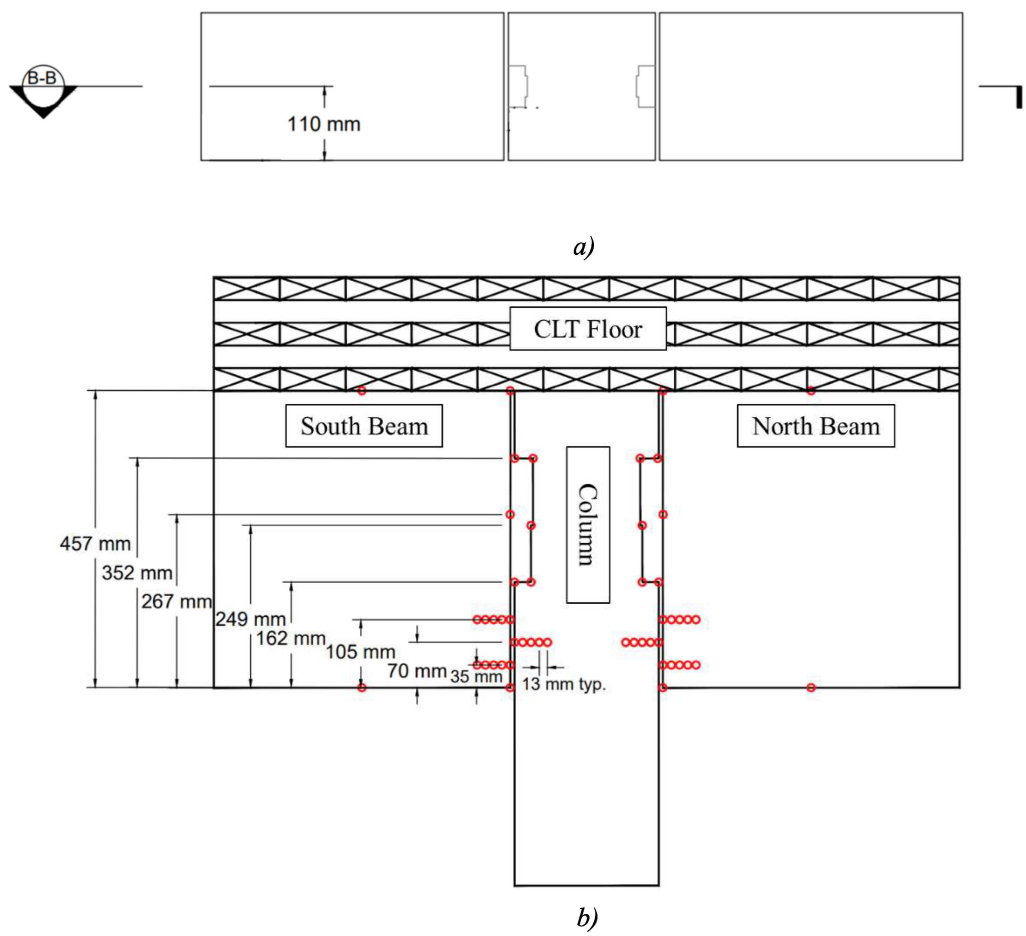

Figure 3: Thermocouple Locations (red dots) at Connection Centreline (CBH not shown for clarity). Horizontal TC groups spaced 13 mm apart. a) Top view, b) Section B-B

2.3 Fire Exposure

Fire testing was conducted using a horizontal gas furnace (990 mm x 1829 mm) with natural air intakes. For each test, the connection assembly was placed on the furnace and exposed to the ASTM E119 [9] standard fire for one hour. At the end of fire exposure, the specimen was removed from the furnace and extinguished with water to prevent any additional charring. The specimen was then disassembled, and char depths were measured at various points at and away from the connection gaps (Fig. 4).

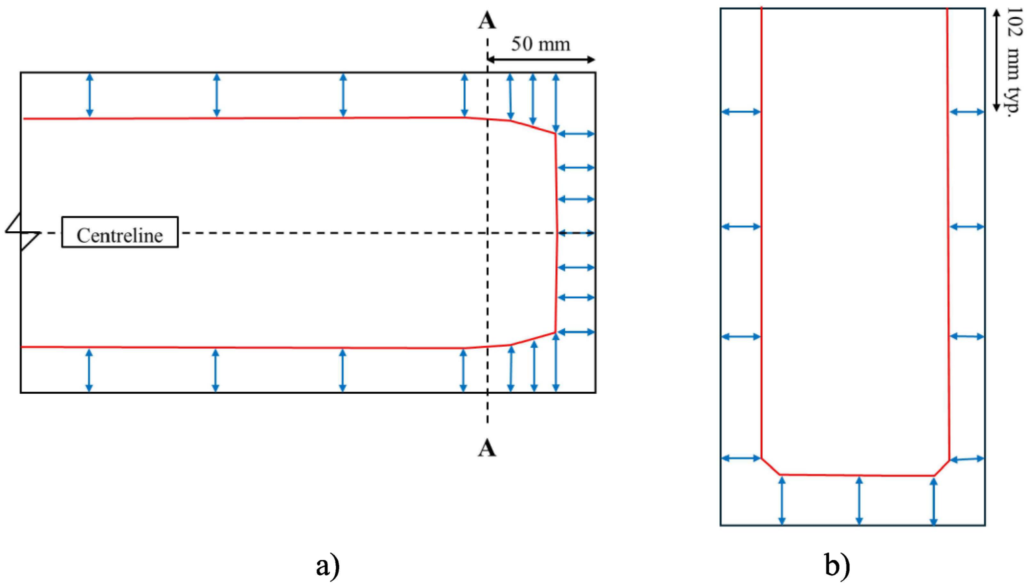

Figure 4: Typical Char Measurement Locations (overlaid on south beam for simplicity). a) Top view, b) Section view A-A

3 RESULTS

3.1 Temperature Data

Thermocouples within the connection gap were used to analyse the temperature distributions at the concealed connection and along the cross section. Fig. 5 shows the temperatures within the gap at the end of one-hour fire exposure through the connection depth. The expected char depth and zero-stiffness layer depicted were calculated using prEN1995-1-2:2025, applying a gap factor of 1.2 (blue lines) and FDS [4], applying a triangular char depth gap factor of 2 (red line). The zero-stiffness layer can be quantified as temperatures of timber between 100-300°C and an additional heat-affected layer (temperatures above ambient) can be calculated to extend 35mm from the end of charring per previous research [2, 7, 12].

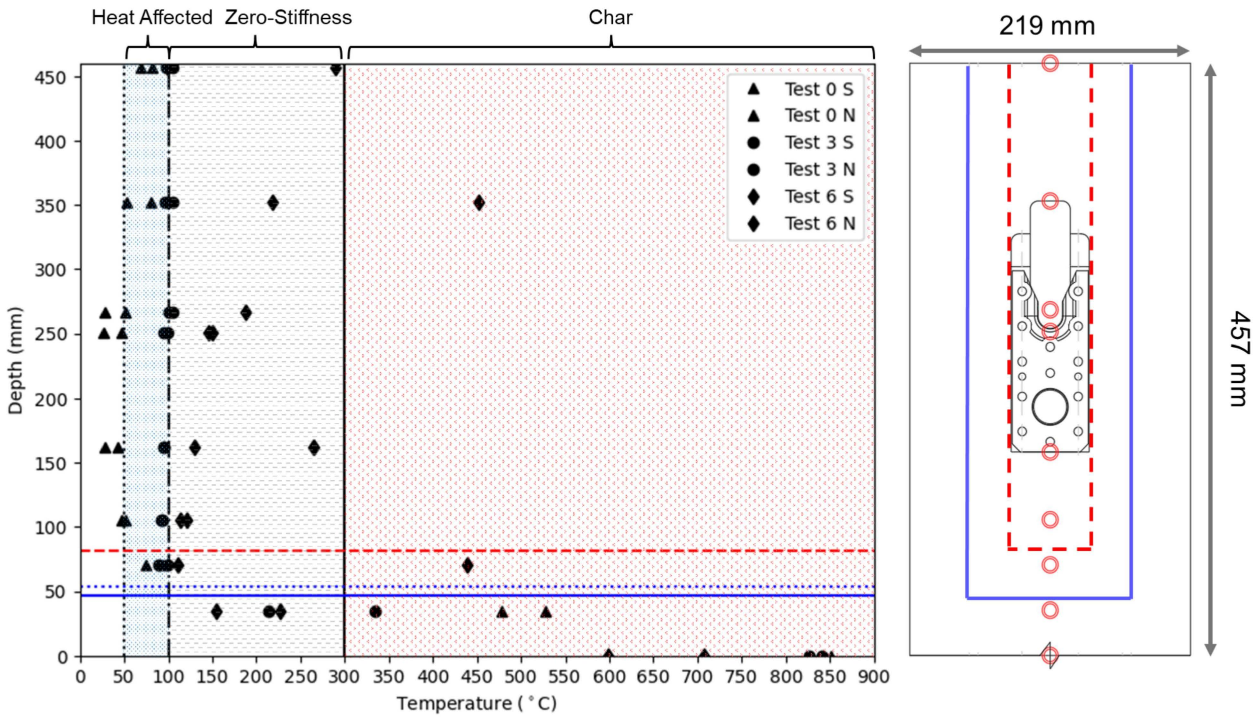

Figure 5: Temperature v Depth at Connection Gap (60 mins). TC locations overlaid on column section with expected gap char layer (red - FDS, blue - prEN1995 1-2)

All temperatures outside of the one-dimensional char depth, measured from the bottom and sides of the beams, for Test_0_N and Test_0_S remained below 100°C. Similarly, temperatures within specimens Test_3_N and Test_3_S did not exceed 110°C outside the char layer. Temperatures exceeded 100°C at all points for specimens Test_6_N and Test_6_S, with charring occurring at the connection face above the concealed connector.

3.2 Char Depths

Char depth measurements were taken at and away from the connection gap at the end of one-hour fire exposure. Physical measurements were taken, defining the end of the char layer as the end of discoloration. Table 1 shows the average char depths for each test. East-West direction as well as North-South column measurements consist of charring perpendicular to grain while beam face measurements are charring parallel to grain. Considering East-West direction charring, char depth close to the gap (<50 mm) increased compared to char depth away from the gap (>75 mm) in all tests excluding Test_0_S. Average percent increase for E-W charring at the gap was 17%, 23%, and 63% for Test_0, Test_3, and Test_6 respectively. At the connection face, no char was measured in Test_0. For all char measurements, a high level of variability can be attributed to the variance in gap size at each connection.

Table 1: Char Depth Summary

Gap Charring Summary	> 75 mm from connection gap (E-W)		< 50 mm from connection gap (E-W)		Connection face (N-S)	
Char Depth (mm)	avg	CV (%)	avg	CV (%)	avg	CV (%)
Test_0_S	40.6	15.1	42.0	27.2	0.0	0.0
Test_0_N	41.3	9.4	50.7	16.9	0.0	0.0
Test_3_S	42.4	8.4	51.3	33.4	5.1	188.0
Test_3_N	39.6	8.3	49.8	37.8	5.2	193.1
Test_6_S	37.1	8.1	62.0	37.1	12.8	114.2
Test_6_N	39.9	9.2	63.4	38.1	17.1	99.2

To quantify the influence of gap size on charring within the glulam beams and columns, char depths at 0-, 13-, 25-, and 75-mm from the connection face were measured for each specimen and shown in Figures 6-8. For brevity, only the beam measurements with the maximum gap size from Test_0, Test_3, and Test_6 are depicted. Gap influence was quantified as a substantial increase, greater than two standard deviations, in char depth when compared to the respective one-dimensional char depth measured (Table 1). In Test_0, gap influence was observed, specifically when the gap size approached 2 mm, with an average increase of 15 mm in Test_0_N, but there was no additional charring due to the gap when greater than 13 mm away from the connection interface. In Test_3, differential charring due to varied gap size was seen. As the gap size exceeded 5 mm, horizontal surface char increased, charring up to the boundary of the concealed connection, with a maximum increase from one-dimensional charring of 48 mm. Despite this, no gap influence was observed at more than 25 mm away from the connection. Test_6 had significantly larger char depths due to the gap size. At the connection interface, surface charring was observed across the full width of the cross section. Additionally, gap influence extended up to 25 mm away from the connection. By 75 mm away, maximum increases in char did not exceed 6 mm from the average. With gap sizes up to 8.4 mm, no charring occurred at the concealed connection in any test.

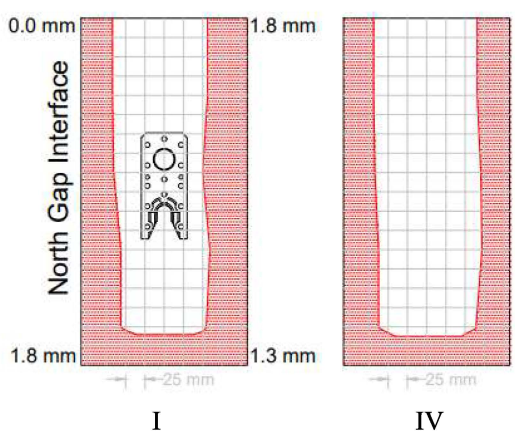

Figure 6: Test 1 North Beam Charring. I - 0 mm, IV - 75 mm

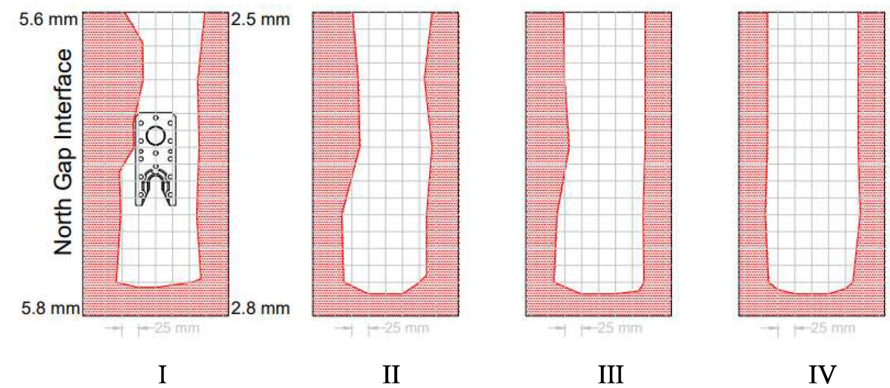

Figure 7: Test 2 North Beam Charring. I - 0 mm, II - 13 mm, III - 25 mm, IV - 75 mm

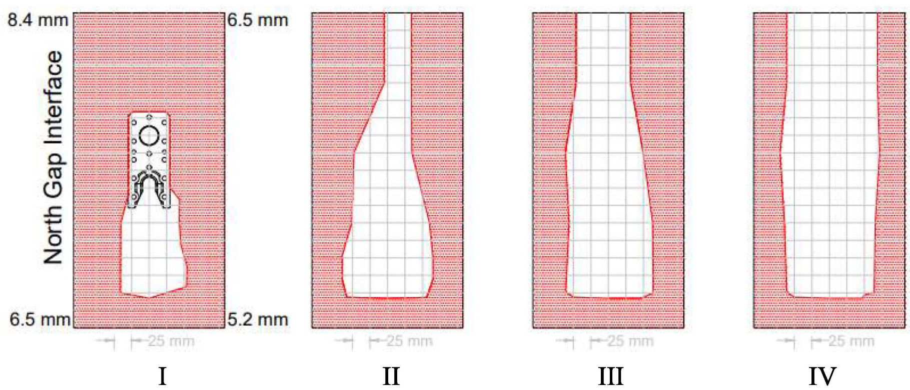

Figure 8: Test 3 North Beam Charring. I - 0 mm, II - 13 mm, III - 25 mm, IV - 75 mm

3.3 Code Comparison

Comparing to temperatures at the centreline (Fig. 5), the additional gap factor within prEN1995 1-2 predicted the char layer (indicated by temperatures above 300°C) for gap sizes up to 5.8 mm. Whereas FDS prescribed char depths for gaps up to 3 mm overestimated the temperatures and char depths in Test_0_N, Test_0_S, and Test_3_N. As mentioned, two-dimensional charring factors are applied when unprotected gap sizes exceed 5 mm or 3 mm per prEN1995-1-2:2025 and FDS respectively. Two-dimensional charring, representative of a fully exposed fire surface for the full depth of the cross section, was not observed in any test, with a maximum gap size of 8.4 mm in Test_3. In addition, specimens Test_0_N, Test_0_S, Test_3_N, and Test_3_S did not have temperatures above an average rise of 139°C or maximum rise of 181°C at any portion of the concealed connectors therefore, adhere to the provisions of the IBC [3] without any additional fire caulking or protection within the gaps.

Comparing the char distributions to the code prescribed gap charring models in prEN1995 1-2, the char depth gap adjustment factor of 1.0 for member gaps up to 2 mm underpredicted the charring seen in Test_0. For gaps between 2- and 5-mm, the prEN1995-1-2:2025 gap factor of 1.2 again underpredicted the char depths when compared to Test_3. For gaps exceeding 5 mm, two-dimensional charring is assumed to occur within the connection gap. Two-dimensional charring was not seen in any test, for gap sizes up to 8.4 mm.

Gap char penetration did not exceed 76 mm ($2a_{char}$) from a fire exposed surface until the gap size was greater than 5 mm (Test_3) as prescribed by FDS. The char penetration factor prescribed by FDS for gaps up to 3 mm accurately predicted char behaviour up to 5 mm. For gaps greater than 3 mm, two-dimensional charring equal to the one-dimensional char depth is assumed, similar to prEN1995-1-2:2025. Again, gap char depths analogous to two-dimensional charring were not observed in any test.

4 CONCLUSIONS

Three T-shape concealed beam hanger connection assemblies were exposed to the standard fire for one-hour. Average gap sizes of 1.1, 3.6, and 6.4 mm between the beam and column were tested. At the end of one-hour exposure, char depth measurements and temperature data were used to quantify the influence of the gap size on connection behaviour. As gap size increased, the char penetration into the connection increased, with an average gap char depth of up to 66 mm in Test_6. Additionally, char depths substantially increased when comparing gap charring to one-dimensional charring away from the gap when gap size approached and exceeded 2 mm (Test_0_N, Test_3, Test_6). Temperatures at the midpoint of the connection did not exceed 100°C until Test_6, where gap sizes exceeded 5.8 mm. In all tests, two-dimensional charring of the connection face, representative of a fully exposed surface with char equal to the one-dimensional rate, was not observed, and the gap influence did not extend greater than 25 mm from the connection surface.

The one-dimensional charring factor for gaps up to 5 mm in the upcoming prEN1995-1-2:2025 underpredicted the char depths for one-hour exposure. However, the assumption of two-dimensional charring when the gap size exceeded 5 mm was not observed in testing, with average one-dimensional charring in the direction of the connection face not exceeding 17 mm for gaps up to 8.4 mm. The FDS char depth gap factor of $2a_{char}$, applicable for gap sizes up to 3 mm, accurately predicted char penetration into the gap up to gap sizes of 5.8 mm. However, the assumption of two-dimensional charring when gap sizes exceeded 3 mm was not observed. In addition, the pass/fail criteria established in the 2024 IBC for protected connections during fire was compared to each test. Test_0 & Test_3, with unprotected gap sizes up to 5.8 mm, maintained temperatures at the concealed connection below an average rise of 139°C by the end of one-hour exposure demonstrating that these connections performed to acceptable behaviour even without any fire caulking or protection.

These experimental tests showed that gap sizes less than 2 mm had negligible impact on heat transfer and char penetration into unprotected concealed connections. When gap sizes exceeded 2 mm, temperatures consistent with substantial material property reduction were observed across the entire cross section. When gap size exceeded 5.8 mm, char penetrated the full width of the cross section but did not reflect a fully exposed fire surface. prEN1995-1-2:2025 one-dimensional gap factors may be nonconservative when estimating char depths while FDS one-dimensional gap factors accurately predicted char depths for Test_0 & Test_3. Further research should focus on establishing factors that account for multiple sided fire exposures with gaps, apply a natural fire to differing gap sizes, and investigate heat transfer mechanisms considering gap size through numerical modelling.

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