FIRE DESIGN OF GLULAM CONNECTIONS WITH TIMBER-TO-TIMBER BEARING INTERFACES

Hans-Erik Blomgren[1], David Barber[2], Graham Montgomery[3]

ABSTRACT

High-rise mass timber buildings require beam end connections to maintain the fire resistance rating of the beam. Connections where a glulam beam ends bear directly onto a supporting glulam column are commonly utilized because they reduce cost, require only simple CNC fabrication, meet the desired architectural aesthetic, and have high load carrying capacity. In addition, a properly designed bearing connection can achieve a 1hr-to-2hr fire rating. A beam to column bearing connection designed and fire tested for a high-rise building project in the United States is presented in this paper. An assessment of the bearing area required to support the load under fire conditions required detailed review of the scientific literature to understand how the thermally impacted timber ahead of the char front reduces the perpendicular-to-grain mechanical properties at the bearing interface. An estimate of the reduced perpendicular-to-grain stiffness and strength at the bearing area was used to design the connection. Two 2hr fire tests to ASTM E119 were performed to experimentally validate the design assumptions. This paper concludes with a discussion of how engineering guidance for bearing type connections exposed to fire can be further developed.

KEYWORDS: Mass Timber, Connections, Fire Engineering, Structural Engineering, Bearing Behavior, Joints, Intersections, Interfaces

1 INTRODUCTION

The construction of large-scale multi-story mass timber buildings is rapidly expanding across the world as developers, architects, and contractors become more experienced with the new construction type. To market these buildings, there is a strong desire to expose the wood surfaces as the architectural finish. Building Codes require the primary structural frame to be fire rated between 1hr and 2hr depending up on the height and floor area of the structure [1]. The principles of engineering glulam beam and column member cross-sections for fire resistance through a protective charring layer of the timber have been well established in building codes for decades [2]. However, design methods for engineering exposed glulam connections for fire are limited.

This paper provides background, analysis, fire test information and post-test assessment for the fire performance of exposed timber beam-to-column bearing connections. These designs have been employed by the authors on some of the first projects in the US that require up to a 2hr fire resistance rating (Figure 1).

Figure 1: Washington DC - 2hr fire resistance rated building in the United States with exposed glulam beam to column bearing connections (Credit: Arup).

2 FIRE RATED BEARING CONNECTION REQUIREMENTS

Bearing connections are commonly used in North American timber construction and many historic heavy timber buildings utilize this connection type. Traditionally, the beams bear onto the column through an external steel metal cap that provides sufficient support for the beam and direct load transfer to the column while also allowing the column load above to transfer to the

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column below in direct end-grain bearing at the cap plate as shown in Figures 2 and 3.

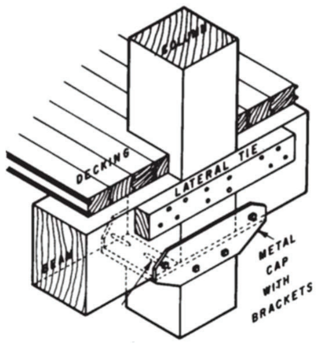

Figure 2: *Heavy Timber beam to column bearing connection with exposed metal cap plate [3].*

Figure 3: *Historic heavy timber beam to column bearing connection with exposed metal cap plate (credit: DeStefano & Chamberlain).*

In modern mass timber construction, beams commonly bear directly on cut-outs or notches in the columns with screws providing the positive fixing as shown in Figure 4. This bearing connection type is utilized because it provides the benefit of reduced cost, simple CNC fabrication, desirable aesthetic, and high load carrying capacity.

When the exposed beam and its end connection are required to have a fire-resistive rating, the use of an external cap plate connection is prohibited because the external steel parts are not protected from the fire exposure temperatures. The bearing capacity of the beam end supported on the column is determined by calculating the reduced bearing area due to char and a zero-strength layer ahead of the char front multiplied by an allowable perpendicular-to-grain bearing stress for fire exposure conditions.

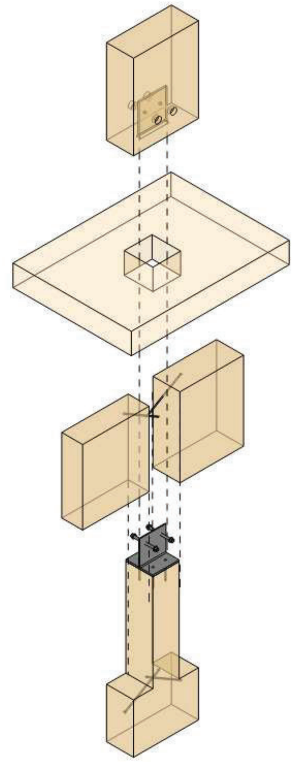

Figure 4: *Exploded view of notched column glulam beam bearing connection (credit: Timberlab).*

3 NOTCHED COLUMN BEARING CONNECTION

A glulam beam end can be designed to bear directly onto a notch fabricated into the column face as shown in Figure 4 to create an efficient connection. The glulam beam end is loaded in perpendicular to grain bearing and the column is loaded parallel to the grain at the contact surfaces. At the vertical abutted interface between the beam end and face of notched column, a small gap is detailed to allow for construction tolerances, and when required by building codes, to accommodate rotations due to the building horizontal seismic design drift [4]. These vertical end gaps are typically in the order of 2 to 6 mm. Fire protection of these interface gaps are discussed in Section 6 of this paper. Note that fire sealing of the fire rated floor assembly (typically CLT panels with a non-combustible topping) around the notched column that penetrates the floor is beyond the scope of this paper.

4 BEARING BEHAVIOR

Before investigating bearing connections under fire exposure, is it warranted to review the behavior of perpendicular-to-grain bearing for the non-fire load case. Perpendicular-to-grain bearing strength is a distinct limit state for timber design because strength is established based on a deformation (serviceability) limit and short

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term (time-dependant) loading stress increases are not applicable.

In the United States, the nationally adopted model code is the International Building Code (IBC) [1], with the 2021 edition the current latest publication. The IBC references the National Design Specification for Wood Construction (NDS) [2] which includes the allowable stress design (ASD) values for various species and grades of timber. The perpendicular-to-grain bearing stress in the NDS is determined from ASTM D143 [5] testing that utilizes small 50mm x 50mm x 150mm clear green wood specimens subjected to compressive pressure from a 50mm x 50mm steel block on the top face and uniform support below on the full specimen surface area. The measured stress at 1mm of deformation for each specimen is measured and the resulting 5th percentile strength is calculated. To convert the tested value to the ASD reference design value, the 5th percentile value is divided by 1.5 for a factor of safety and duration of load. This value is then multiplied by a strength ratio of 1.0 and multiplied by 1.5 for and adjustment for dry use.

From time-to-time the validity of using the small-scale ASTM D143 test method for real large scale building structures has been questioned. Testing in the 1990s by Madsen [6] investigated the behavior of full-scale perpendicular-to-grain bearing of dry-use glulam members for a range of bearing plate sizes from 25mm x 25mm to 177mm x177mm. Bearing at the middle and ends of glulam were tested. Figure 5 presents a representative graph from Madsen's work for the average load-deformation relationship of a 125mm x 125mm bearing plate at the end of a dry use Douglas fir glulam beam. This graph exhibits a gradual transition or "proportional limit" between deformations of 1mm and 2mm where the deformation becomes non-linear resulting in permanent indentation (deformations) in the wood. The occurrence of this transition between 1mm and 2mm was found to be consistent across all tests performed by Madsen.

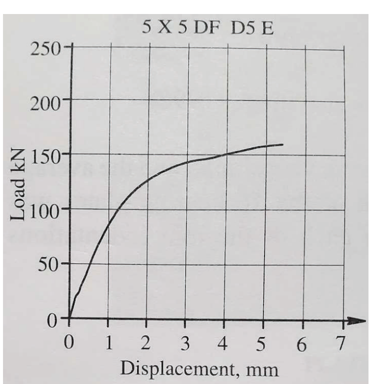

Figure 5: *Perpendicular-to-grain load-deformation plot for a 125mmx125mm plate located at the end of a Douglas Fir glulam, Madsen [6].*

Based on these tests, Madsen proposed a design method that accounted for the effects of i) bearing on the contact surface area ii) the length of bearing edge parallel to grain, and iii) the length of bearing area perpendicular to grain. When the proposed design method is applied to a large bearing plate condition (178mm x 350mm) it is shown that a 2mm indentation in the glulam (deformation) is required to attain the factored design strength calculated using the ASD reference design load multiplied by the LRFD format conversion factors documented in the NDS [2]. This example indicates there is reasonable correlation of strength and deformation between the two design methods for perpendicular-to-grain bearing on large bearing areas.

5 WOOD PROPERTIES AT ELEVATED TEMPERATURE

To properly engineer mass timber elements under the conditions of fire exposure, the change in strength and stiffness of the material as a function of temperature between ambient conditions (20C) and the char temperature (300C) must be quantified. Research in this area has been available for decades and is based on exposing wood samples to a standard fire, such as ASTM E119 [7]. For temperatures in this range, Eurocode 5 [8] provides graphs for parallel to grain tension and compression loads. The reduction of strength and stiffness is characterized by bi-linear lines that exhibit strength losses of 75% (Compression) to 35% (Tension) at 100C and then reducing linearly to zero at 300C. Where timber is heated up to 100C, the strength losses are reversible on cooling. Above 100C, the strength losses are not reversible on cooling [9].

As timber chars due to fire exposure, a thermal penetration depth beyond the char front into the depth of the wood develops. Due to this heating, a portion of the moisture present in the wood is driven ahead of the thermal wave further into the wood. The increase in moisture content and wood temperatures up to 50mm beyond the char font have been experimentally measured by several researchers [10, 11, 12] and found the heat penetration and driven moisture have a combined effect on the immediate mechanical properties of wood. Figure 6 from Schaffer's work [10] plots the temperature and moisture content as a function of the distance from the surface of the charred wood.

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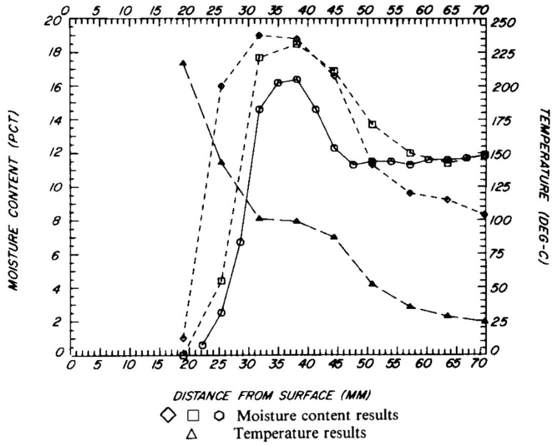

Figure 6: *Measured temperature and moisture content gradients beyond the char front for southern pine specimen with an initial MC of 10%. One face of wood exposed to 538C furnace temperatures for approximately 20mins, Schaffer [10].*

Schaffer's work [10] also experimentally measured the relative parallel-to-grain stiffness and parallel-to-grain compressive and tensile strength beyond the char front, as shown in Figure 7. The lines in this plot show the complexity of the combined effect that increasing temperatures and increasing moisture content have from 0mm to 50mm beyond the char front that need to be accounted for in the structural fire design of exposed timber members.

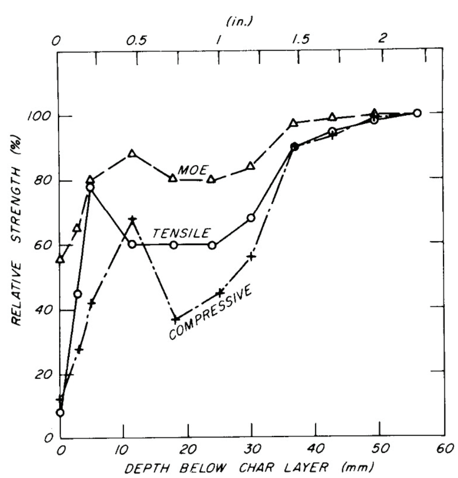

Figure 7: *Measured parallel-to-grain stiffness and compressive and tensile strength of softwood beyond the char front expressed in percent of that at 25C and initial moisture content of 12%. Schaffer [10].*

The strength reduction of wood due to fire exposure discussed so far in this section has only considered parallel-to-grain loading. For the fire design of bearing connections, the strength and stiffness reduction of wood perpendicular-to-grain at elevated temperatures needs to be quantified. The authors of this paper found limited published research on this subject. A report by Gerhards [13] provides a summary of experimental testing that studies the immediate effects on the mechanical properties of wood due to changes in moisture content and temperature. His report includes all mechanical properties for wood including perpendicular-to-grain compressive loading. Gerhards' summary shows that for a relative change in temperature from 20C to 70C the compressive stiffness and strength perpendicular-to-grain decreases by approximately 35%. This reduction is reported at an MC greater than 10% with the trend being clear that a higher MC in combination with higher temperatures increase the reduction in strength and stiffness.

It is noted that Gerhards' report is limited to maximum wood temperatures of 70C creating a gap in knowledge about the mechanical properties of wood in compression perpendicular-to-grain at temperatures from 70C leading up to the 300C char front where strength diminishes to zero. Limited experimental testing on full scale perpendicular-to-grain bearing interface connections have reported large and rapid loss of strength and stiffness due to fire exposure. The publication by Buchanan and Ostman [14] provides a short discussion and photos showing large permanent perpendicular-to-grain deformations in the high stress contact area of test specimens that were dissected after fire testing.

6 JOINTS AND INTERSECTIONS

Notched bearing connection fire performance needs to consider both the horizontal and vertical joints between the beam and column. Figure 8 shows this typical condition where the column is notched on two faces to support beams framing in from each side. The remaining center portion of the column penetrates the CLT floor to support the column above in end-grain bearing. Both of these joints are discussed in the following sections.

Figure 8 *Photo of a beam to notched column bearing connection. This connection creates a horizontal bearing interface and vertical joint at the abutted members (credit: Timberlab).*

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6.1 Fire protection of the Vertical Joint

The vertical timber joint requires a gap to be detailed to account, at a minimum, for fabrication and installation tolerances. Using state-of-the-art CNC equipment, a 2mm gap for tolerances is typically found to be satisfactory. For buildings in high seismic regions of the US, the IBC reference standards require the non-participating gravity system to accommodate seismic design story drifts [4]. This results in cyclic beam-column joint rotation deformations being imposed on the connection which means a larger vertical joint gap may be required. As well, wood shrinkage during the building operational life can also result in gaps forming.

IBC requirements for fire protection of timber-timber gaps such as this have only recently begun to be developed. In the US, the Fire Design Specification (FDS) [15] states that all gaps from 0mm up to 3mm have to account for char penetration into the joint that is 2 times the nominal char rate of timber. For gaps larger than 3mm, the FDS states surfaces within the gap are assumed to be fully exposed to fire for the full depth of the gap.

From a connection design standpoint, advanced charring into the vertical gap has to be prevented as any charring in this area rapidly reduces the beam bearing area and thus the load bearing capacity of the connection. As well the cross-section area of the notched portion of the column supporting floor loads from above is reduced. To address this problem, engineers in the US have begun to use intumescent fire tape products that are concealed in the depth of the vertical gap as shown in Figure 9.

Figure 9: *Photo of a glulam beam end with fire tape seal applied in a vertical joint before it is installed onto a supporting glulam column (credit: Blomgren)*

Under fire exposure and temperatures in the order of 200C, the intumescent tape activates and expands across the joint providing an effective and durable seal that slows or prevents fire penetration into the joint that is greater than the advancing char depth of the parent timber material. Manufacturers of these tape products have begun to demonstrate the fire protection performance of these products for these applications by testing to ASTM E1966 [16].

6.2 Fire Protection of the Horizontal Bearing Interface

The bottom of the beam delivers its load in perpendicular-to-grain bearing to the end grain of the supporting column. This interface is in compression and assuming accurate fabrication tolerances, the load is applied as a uniform pressure across the full bearing area. To confirm char penetration into this interface does not occur which would severely undermine the bearing capacity of the connection, the American Wood Council (AWC) managed a testing program of these loaded connection types exposed to ASTM E119 furnace temperatures. The testing applied a relatively low pressure to the bearing interface to represent a lower bound lightly loaded beam connection. The AWC reported that thermocouple data from these tests found no advanced char line penetration into the compression bearing joint [17].

7 ENGINEERING CALCULATION

For a 2hr fire rated mass timber building on the east coast of the US, the authors of this paper, designed and fire tested a large timber beam-to-column bearing connection. To efficiently support the beam end loads to the column, they are directly seated onto the column, with each incoming beam end sharing one-half of the column end area. To support the column load from above in end-grain bearing, a steel post with end plates is located within the timber beam depth. Small notches are formed in each abutted beam end to provide space for the post. Photos of the connection specimen being assembled at the testing laboratory are shown in Figure 10. The joint at the vertically abutted beam ends are protected with fire tape as shown above in Figure 9.

Figure 10: *Photos of the test specimen glulam beam ends to column support test specimen being assembled. A steel post to support the column above was included to replicate the actual project detail (credit: Blomgren).*

The design of a bearing connection is a very simple calculation where the applied bearing pressure is compared to the design bearing resistance pressure that includes an appropriate safety factor. However, for a fire condition, design guidance for the engineer is lacking. To design the first test the authors referenced the NDS [2] for timber that states the char depth at 2hrs of fire exposure is 66mm. Following with the NDS provisions, an effective char depth was determined by increasing the char depth by 20% to 79mm to account for the pyrolysis zone and zero strength layer for parallel to grain loading (i.e. bending, axial tension, and axial compression). Charring was assumed to occur on the three faces of the column under the supported beam end, and concurrently the three faces of the beam. This results in a 66% reduction in bearing area as shown in Figure 11. For this design the steel post and base plate were detailed with a minimum wood cover of 89mm which provides sufficient thermal protection for 2hr.

Continuing with the design, the published allowable perpendicular to grain bearing stress for the glulam product used is 4.13MPa. For fire conditions the NDS [2] allows allowable stresses to be increased to account for short term loading and adjusting the 5th percentile strength to an estimated mean strength. Using this method, the perpendicular-to-grain bearing stress increase adjustment for fire design was calculated to be 1.67 x 4.13=6.9MPa.

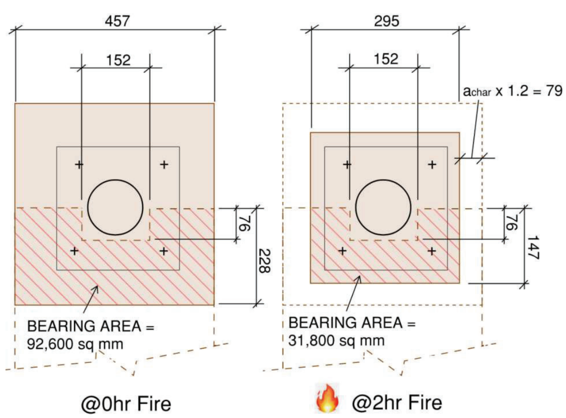

Figure 11: *The calculated bearing area for Test 1 at zero hour and 2hr.*

With the bearing stress design values and bearing area areas calculated, it is evident the fire condition at 2hrs controls the design by limiting the maximum allowable beam end reaction to 6.9MPa x 31,800mm^2 = 219kN.

8 ASTM E119 FIRE TESTING

8.1 Test 1

To justify the use of an exposed 2hr fire rated timber bearing connection for the building project, the mass timber supplier chose to perform full scale testing in general accordance with the ASTM E119 fire test standard. Testing is a specific code compliance pathway provided in the 2021 IBC [1] that has adopted new provisions for mass timber high-rise buildings. Project-specific testing was chosen, rather than analysis methods, due to the lack of existing testing data to justify the timber-timber bearing connection design under large loads. Building permit approvals were also more straightforward and efficient with a successful fire test rather than an analysis approach. It should be noted that ASTM E119 does not have a specific section in the standard for the fire testing of connections. The methodology for testing a connection was therefore based on an approach consistent with the standard, based on advice from the testing facility and consistent with other full-scale fire tested connections (timber and steel).

The specimen was constructed and inserted into a self-reacting test frame with an actuator capable of applying a maximum 204kN load to the specimen as shown in Figure 12. The specimen was carefully designed and detailed to ensure the actuator load imposed compressive forces on the beam to column interface with no secondary load paths. To accomplish this, the CLT panel that forms the lid of the furnace was split into two parts with a shearing joint located over the end of the beam. In addition, the CLT perimeter was supported on the four edges of the furnace with multiply layers of compressible ceramic blankets.

Figure 12: *Glulam bearing connection specimen and test frame prior to being lifted and placed in the furnace (credit: Blomgren).*

Testing commenced by applying a 204kN load to the specimen. An immediate actuator extension of 8mm was measured which can be attributed to elastic compression of the specimen through the CLT and beam depth and some flex in the test frame itself. This measurement was zeroed out and the furnace was ignited. The deformation

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grew slowly measuring 10mm at the 60min mark. Soon after this time, the deformation increased exponentially resulting in failure at 86min which was only 72% of the calculated 2hr fire resistance time discussed in Section 7. The actuator extension curve for the test is provided in Figure 13. At the final moment before the actuator force reduced to zero, the recorded actuator extension was 60mm. The actuator briefly extended up to 105mm due to the failed beam end sliding off the supporting column before the test was terminated.

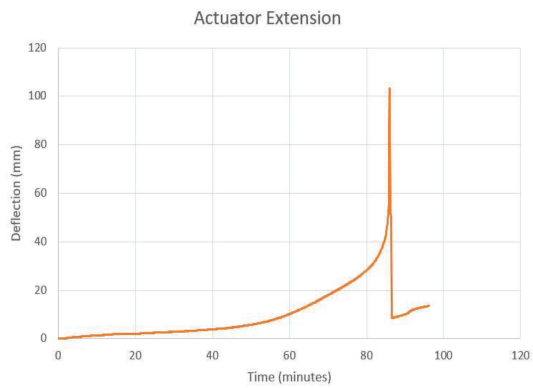

Figure 13: *Plot of the actuator extension vs. time for Test 1 showing test specimen failure at 86m.*

Although the results of the ASTM E119 fire test did not correlate well with the calculated prediction, it did provide a time-to-failure test to learn from. After the test, the data was reviewed, the disassembled specimen was visually observed, and other possible factors that may have caused the early failure time were investigated. After this effort, it was concluded the most likely cause of early failure was due to elevated temperatures in the bearing region that softened and weakened the wood more than anticipated resulting in excessive deformations and loss of strength allowing the beam end to slide off the column support. This result indicated that the 1.2x factor applied to the 2hr char depth to determine the effective bearing area in the engineering calculation discussed in Section 7 was unconservative.

At 86min of ASTM E119 fire exposure the calculated char depth per NDS [2] is 51mm. Using this char depth and the allowable fire design bearing pressure of 6.9MPa and bearing area of 31,800mm^2 derived in Section 7, an approximate 1.5x "zero strength layer" adjustment factor was back calculated.

8.2 Test 2

A second specimen was designed and ASTM E119 fire tested to 2hrs. To successfully pass this test the compression bearing area was increased by using a larger supporting glulam column. However, due to project design constraints on glulam member cross-section sizes, it was not possible to increase the bearing area by the full 1.5x adjustment factor determined from the Test 1 results. Only one edge of the column bearing length was increased from 228mm to 254mm. To account for this, the strength and stiffness of the bearing interface connection was supplemented with fully threaded compression reinforcing screws. Seven screws were installed into the underside of the beam with their countersunk heads installed flush and bearing over the bottom steel post base plate. The location of the screws in the connection area had sufficient wood cover to be thermally protected for the 2hr fire exposure as shown in Figure 14.

At a 2hr fire exposure, the screws were calculated to provide 76kN of supplemental ultimate bearing strength while the strength of the bearing area using a 1.5x adjustment factor was calculated to be 128kN. The resulting total calculated bearing capacity was 204kN. The calculated reduction in bearing area at 2hrs was 74% as show in in Figure 14.

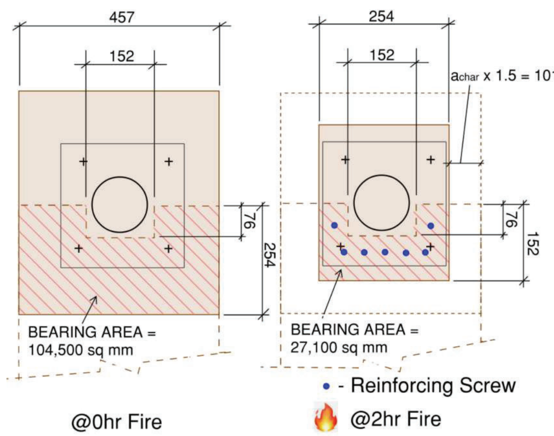

Figure 14: *The calculated bearing area for Test 2 at zero hour and 2hr using a 1.5x adjustment factor on achar.*

The Test 2 specimen successfully carried the applied 204kN actuator load for 2hrs. It is of note that in the last minutes of the test, the actuator extension increased exponentially from 10mm to 35mm indicating the connection was very close to its failure time. The actuator extension curve for Test 2 is provided in Figure 15.

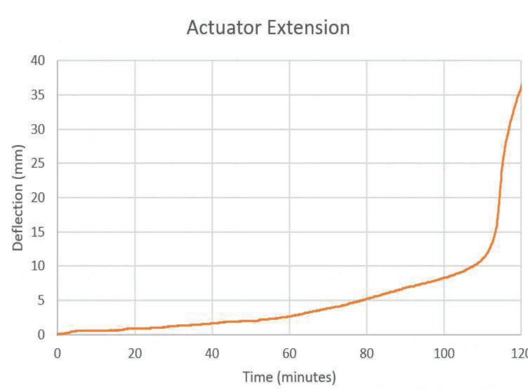

Figure 15: *Plot of the actuator extension vs. time for Test 2. The test was terminated at 120m.*

Figures 16 and 17 show the post-fire test disassembled beam exhibited significant perpendicular-to-grain crushing localized in the high bearing stress contact area. As well, the compression screws were observed to be permanently pushed into beam, providing visual evidence they supported load during the test.

Figure 16: *The disassembled specimen beam bearing area for Test 2. Note the localized permanent compressed wood at the high contact stress region (credit: Blomgren).*

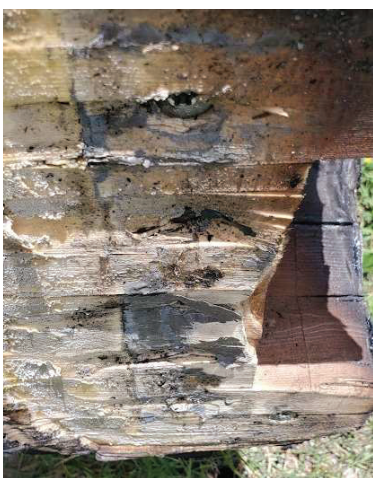

Figure 17: *A close up photo of the Test 2 beam bearing face shows the compression screw heads are permanently pushed into the wood surface (credit: Blomgren).*

9 CONCLUSIONS

Perpendicular-to-grain bearing for glulam beam-to-column connections are an efficient design option for building projects. To achieve a fire resistance rating through charring of the timber members, the bearing area needs to consider the reduced mechanical properties of the timber ahead of the char layer due to elevated temperature and moisture content and detail for construction tolerance gaps at the abutted surfaces. The fire testing in this paper has shown that engineering methods and guidance needs to be improved. A summary of observations and findings from this paper are as follows:

- ASTM D143 test methods and the testing by Madsen for non-fire conditions show that perpendicular-to-grain bearing strength of timber has a consistent transition or "proportional limit" between 1-2mm of indentation of the wood. For fire design, it is generally accepted that serviceability (deformation) limits states are not of concern. The fire tests presented in this paper measured deformations at time of failure that were an order of magnitude larger than for non-fire design conditions.
- Schaffer's research presented in Figure 6 shows temperatures up to 100C for a distance into the timber that is approximately equal to the char depth, when timber members are exposed to a fire temperatures such as ASTM E119. In the same region, the moisture content of the timber can also increase by 1.3x to 2x. Figure 7 from Shaffer's research shows the reduction in parallel-to-grain mechanical properties attributed to these effects.
- The summary report by Gerhards reported middle-trend immediate strength and stiffness loss for compression perpendicular-to-grain as high as 35% at 70C and MC>12%. These reductions are higher than those reported for parallel-to-grain and bending properties. There is a gap in the literature for perpendicular-to-grain mechanical properties greater than 70C.
- Joints and intersections need to be appropriately detailed with gaps to account for installation tolerances, shrinkage, and potentially rotation capacity of the connection due to design seismic drifts. Vertical abutted edges require fire protection products, such as intumescent fire tape to ensure the timber surfaces in the joint are not subject to charring.
- CNC fabrication and construction practices for the horizontal interface needs to assure uniform bearing of this joint. Testing performed by the American Wood Council and the testing presented in this paper found no evidence of accelerated charring at the bearing interface.
- Based on the testing presented in this paper, a 1.2x factor applied to the char depth for bearing strength calculations did not correlate well with Test 1 which failed at 72% of the targeted 2hr mark. Using the results of Test 1, it is possible to back calculate an approximate 1.5x adjustment factor applied to the char depth which correlates with the test outcome. This 1.5x factor has been adopted in the 2022 edition of the FDS for the design of bearing interfaces.
- Test 2 was redesigned based on the results of Test 1. Due to member size constraints for the building project a sufficient bearing area using the 1.5x factor could not be achieved. To provide supplemental connection strength and stiffness, fully threaded compression screws

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were installed into the bottom of the supported beam over a steel post base plate. Test 2 successfully passed the ASTM E119 exposure by supporting the applied actuator load for 2hrs.

Engineering a mass timber bearing connection for fire resistance is more complex than just calculating a simple area of bearing based on ambient temperature strength. The area of weakened timber behind the char layer needs to also be addressed, given the reduced strength. A design approach has been recommended within this paper to address the fundamental issues.

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