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FIRE PERFORMANCE OF PENETRATIONS IN GLULAM BEAMS: A PRELIMINARY STUDY

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ABSTRACT: Glue laminated timber (glulam) is an engineered wood product composed of wood laminations bonded together with durable adhesives. Glulam is versatile ranging from simple, straight beams to complex, curved structural members and are used in a variety of applications including residential and commercial construction where they are often exposed due to the timeless aesthetic of wood. Glulam beams are also resource-efficient and offer designers highly predictable structural and fire performance when used in accordance with design specifications. However, factory-cut or field modifications to glulam beams, such as notching and drilling for routing piping and ductwork, has become common practice, which has the potential to impact structural integrity. There are prescriptive recommendations for these unplanned penetrations to ensure structural capacity remains intact but, in the event of a fire, the field modifications may enlarge and further reduce the beam's cross-section. Here, we present an experimental method to evaluate the char rate and growth of various standard-fire exposed penetrations in glulam beams.

KEYWORDS: Glulam, penetration, char depth, fire performance

1 INTRODUCTION

Structural glue-laminated timber (glulam) beams are engineered building components manufactured from specially identified and placed lumber laminations of varying strength and stiffness. Because of their strength and ability to be specified for unique situations, glulam beams are often highly stressed under design loads and alterations to the beams could result in failure to carry these loads.

Prior to or during construction and installation of glulam beams, it has become common practice to drill horizontal penetrations, also known as horizontal holes, to allow building services (e.g., pipes, ducts, cable trays, etc.) to run through glulam beams such as those shown in Figure 1. Whether factory-cut or field-modified, these penetrations remove wood fibre, reducing the cross-sectional area of the beam at that location. This results in strength reductions and localized stress concentrations [1]. Because of these potential issues, prescriptive recommendations based on a combination of practical experience and engineering analysis for in-field penetrations can be found in a Technical Note S560J published by APA – The Engineered Wood Association [2]. Several investigations have evaluated the fracture behaviour and design of glulam beams with both round and rectangular penetrations that support the recommendations by APA including [3 – 6]. Non-critical zones for simply supported beams are identified in Technical Note S560J as portions of a glulam beam where the stresses are less than 50% of the design bending stress and design shear stress. Additional design guidelines for penetrations that exceed the guidance provided in S560J, Technical Note V700B [7] provides an analytical tool and engineering equations to ensure the structural integrity is not compromised.

Methods for calculating the fire resistance ratings of structural building members are specified by building codes and require the member to endure a specified fire without loss of its loadbearing capabilities. The codified procedure to calculate the fire-resistance ratings for exposed mass timber, such as glulam beams have allowed their use in fire-rated buildings. This mechanistic approach, found within the National Design Specification for Wood Construction (NDS) [8] and the Fire Design Specification for Wood Construction [9], applies to all wood structural members designed per NDS including structural composite materials such as glulam. In this method, the engineering calculations of the ultimate load capacity are adjusted to take into consideration the reduced dimensions with time due to the formation of char. Nominally, a char depth of 38 mm at 1 hour is used for exposed (i.e., no fire protection applied) solid-sawn and structural glued-laminated softwood members with a 20% increase to account for rounding at the corners and loss of strength in the preheated zone located just beyond the char layer.

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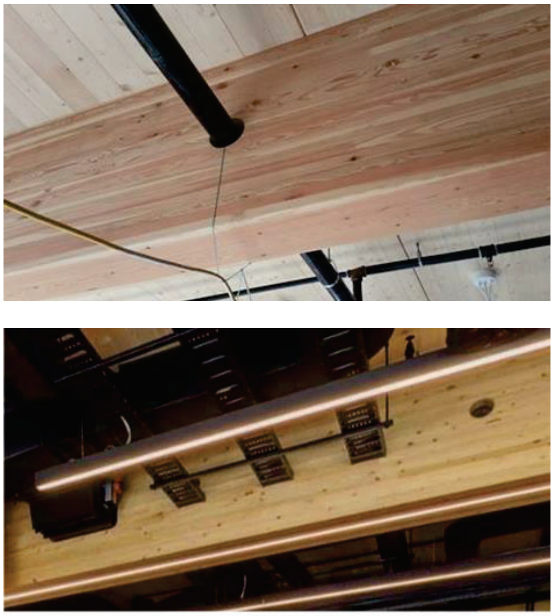

Figure 1: Glulam beam with field penetrations for a pipe (top) and cable trays (bottom). Photos provided by Barber.

Firestopping for through-systems do exist, but these systems are applicable to penetrations through fire-rated wall and floor assemblies and the fire testing is conducted from a single direction [10]. This fire testing is not applicable for glulam beams, which are typically exposed on three sides.

While the fire resistance of non-modified beams is well documented and the structural implications of penetrations in glulam beams have been addressed, the intersection of these issues has not been evaluated. The char rates used to calculate fire resistance are typically only applied to the exposed sides of a beam and do not account for penetrations through a beam that may widen due to charring during a fire event.

Here, the method used to expose glulam beams with various penetrations sizes and shapes to a standard fire is presented along with char depth analysis techniques. Additionally, preliminary results pertaining to the increase in penetration size due to charring are provided.

2 MATERIALS AND METHODS

2.1 MATERIALS

A total of six Douglas-fir (*Pseudotsuga menziesii*) glulam beams with dimensions of 343 mm deep (10-ply) by 175 mm wide and 3.66 m long were used. Two of the beams were laminated with a phenol-resorcinol-formaldehyde (PRF) adhesive while the other four were manufactured with a polyurethane (PUR) adhesive. Because the beams were unloaded, the differences in adhesives did not affect the charring around the top and sides of the penetrations.

Three beam configurations (A, B, and C) were designed with a range of penetration sizes and shapes. The dimensions and type of the penetrations for each beam configuration are provided in Table 1 and illustrated in Figure 2. There were three types of round penetrations (small, medium, and large pipes) and two rectangular penetrations (small cable tray and large duct) tested. These penetrations were cut along the centreline of the depth of the beam (x-y plane). It is important to note that the penetration configurations for these beams do not conform to the design guidelines for holes/notches for the beams used and, as such, this study focused on the expansion of the penetrations due to fire exposure and not structural integrity. The penetrations were strictly sized and placed such that the expansion of the holes would not interfere with each other and associated thermocouples. Additionally, the penetration configuration optimized the experimental space in the furnace while allowing replicates of each penetration type.

Table 1: *Beam penetration configurations*

Beam ID	Penetration Shape	Penetration Size (mm)	Insert or empty
A1	large round	Ø168	empty
A1	medium round	Ø 139.7	empty
A1	small rectangular	76 x 177.8	empty
A1	small round	Ø 88.9	empty
A2	large round	Ø 168	insert
A2	medium round	Ø 139.7	insert
A2	small rectangular	76 x 177.8	insert
A2	small round	Ø 88.9	insert
B1	large rectangular	127 x 330	insert
B1	large round	Ø 168	insert
B1	small round	Ø 88.9	insert
B2	large rectangular	127 x 330	empty
B2	large round	Ø 168	empty
B2	small round	Ø 88.9	empty
C1	large rectangular	127 x 330	insert
C1	medium round	Ø 139.7	insert
C1	small rectangular	76 x 177.8	insert
C2	large rectangular	127 x 330	empty
C2	medium round	Ø 139.7	empty
C2	small rectangular	76 x 177.8	empty

Each penetration type was separated by at least 305 mm (12 inches) to reduce potential interactions during the fire exposure, allowing for up to four penetrations per beam.

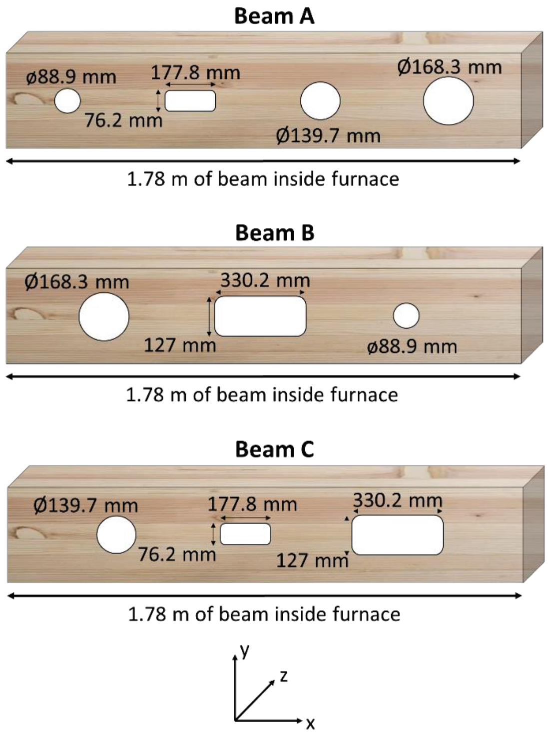

Figure 2: *Glulam beam types with penetration layout: A (top), B (middle) and C (bottom).*

To evaluate the effect of a penetration with equipment through it, two of each beam configuration were run: one with building service components inserted through the penetrations during the fire test and the second with empty penetrations. For the tests with building service components in-place the components were secured with chains as shown in Figure 3. When an insert was included through the beam, a gap of at least 12.7 mm (1/2 inch) around the insert was maintained with sizes of inserts provided in Table 2.

Figure 3: *Glulam beam (Type C) with penetrations for a pipe, cable tray and duct (left to right).*

Table 2: *Building service component details*

Hole Shape	Hole Size (mm)	Insert details	
		Material	Size
large round	Ø168	schedule 40 steel pipe	141 mm diameter with 6.5 mm wall (nominally 5-inch)
medium round	Ø 139.7	schedule 40 steel pipe	114 mm diameter by 6 mm wall (nominally 4-inch)
small round	Ø 88.9	schedule 40 steel pipe	60 mm diameter by 4 mm wall (nominally 2-inch)
large rectangular	127 x 330	galvanized steel duct	102 mm by 305 mm (4 by 12 inches) wall thickness of 0.4 mm (0.02 inches)
small rectangular	76 x 177.8	Cable tray with 5 mm (0.2 inch) steel wire on a 50 mm by 100 mm (2 by 4 inch) with an electro zinc finish	150 mm x 50 mm (6 by 2 inches)

2.2 METHODS

2.2.1 Instrumentation

To obtain the temperature profile around a penetration, 28 thermocouples made in-house from 30-gauge type K wire (Omega GG-K-30-SLE) were embedded in the glulam both above and on each side of every penetration. To install the thermocouples, 2.4 mm (3/32 inch) diameter holes were drilled from the top of the glulam beam to known depths and set distances from each penetration.

For the thermocouples installed on the side of a penetration, arrays of four thermocouples starting at 25.4 mm (1 in) from the penetration edge and spaced at 12.7 mm (1/2 inch) were installed along the centreline of the beam in the x-direction (Figure 4). Above the penetration, four thermocouples were installed along the centreline of the penetration in the z-direction. These four thermocouples started at the top edge of the penetration and were spaced at either 25.4 mm (1 inch) or 12.7 mm

(1/2 inch) in the y-direction and 12.7 mm (1/2 inch) in the z-direction. This installation pattern ensured that the thermocouples were parallel to the isotherm/char front for the side arrays, which has been shown to provide more accurate measurements of temperature. However, the thermocouples arrays above the penetrations were perpendicular to the isotherm. To reduce the impact of this on the data, the holes were filled with fire caulk after the thermocouples were inserted. In addition to the thermocouple data, after the specimens were exposed and cooled, they were sawn and physical measurements of the remaining cross-section were taken to determine the final char depth at 90 minutes.

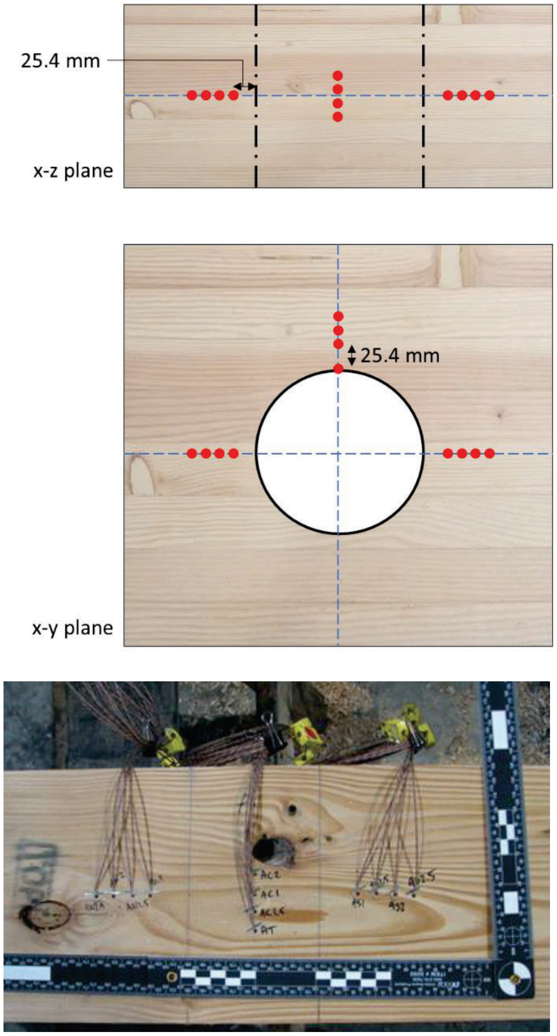

Figure 4: *Top: Schematic of thermocouple placement for a round penetration (not to scale) and Bottom: top of glulam specimen with thermocouples installed.*

2.2.2 Test Furnace

The glulam beams were tested in an intermediate-scale horizontal furnace and subjected to the standard time-temperature curve specified in ASTM E119 [11]. The furnace at the Forest Products Laboratory (FPL) has interior dimensions of 1.8 m long, 1.1 m wide, and 1.3 m high. The furnace has eight diffusion-flame natural gas burners on the floor and all air for combustion was provided by natural draft through vents at the bottom of the furnace. The furnace was controlled via six capped furnace thermocouples located 305 mm from the furnace lid. Approximately 1.78 m of the beam length was exposed to fire within the furnace with 0.94 m on each side of the beam not exposed to the fire. To avoid uneven exposure near the furnace walls, all penetrations were located within the middle 1.5 m of a beam as illustrated in Figure 3. A non-combustible lid was designed such that the top of the beam was not exposed to the fire (Figure 5).

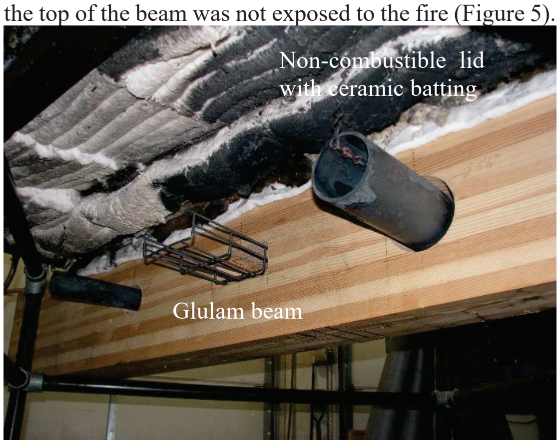

Figure 5: *Glulam beam with non-combustible lid protecting the top of the specimen prior to being placed in the furnace.*

Each beam was exposed for a duration of 90 minutes. The tests were terminated by removing the specimen, extinguishing the fire with water, and scraping all char off to halt smouldering combustion. Figure 6 illustrates these steps through the removal of a burning glulam beam from the furnace, an extinguished beam, and a beam with the char removed for a 127 mm by 330 mm rectangular penetration in beam B that had a duct in place during the fire test.

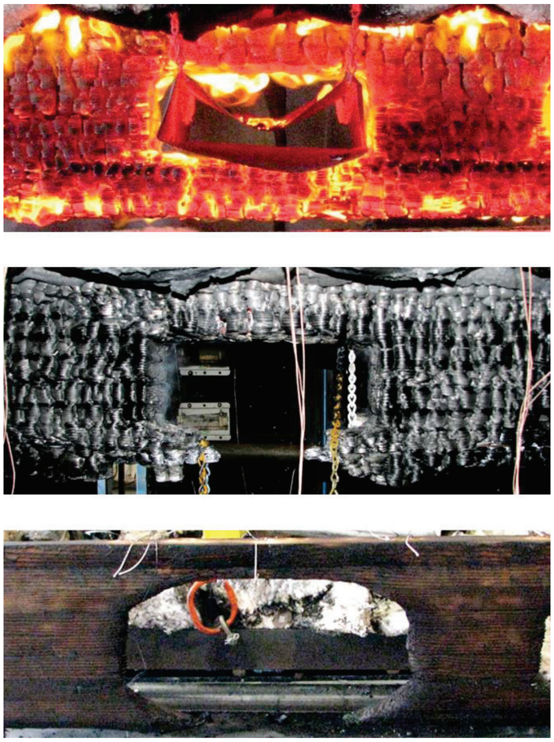

Figure 6: *Image of duct penetration immediately after removal from the furnace (top), once extinguished/cooled (middle), and with the char layer scrapped off (bottom).*

3 RESULTS

During the experiments, the thermocouple data allowed the char front to be monitored by using the commonly-accepted 300°C isotherm as the temperature when wood converts to char [12]. The thermal profile in the glulam beam around a penetration will increase in both temperature and depth with time. As an example, the results collected around one of the penetrations in beam C2 (no building services installed) are provided in Figure 7 with the ASTM E119 standard time-temperature curve provided for reference. The alpha characters identify the penetration type (D = 139.7 mm (5.5 inch) diameter penetration). The side thermocouple arrays are denoted with either N for North or S for South while C indicates the thermocouple array centred above the penetration. The numbers indicate the depth (in mm) of the thermocouple from the exposed interior surface of the penetration.

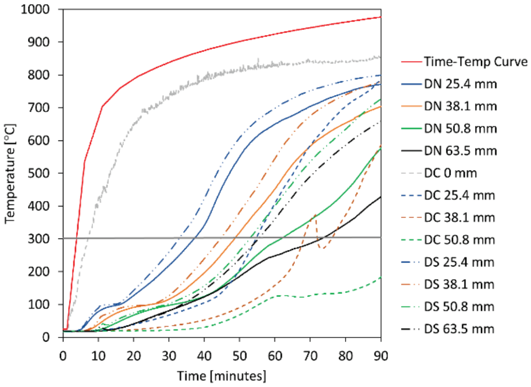

Figure 7: *Thermocouple data around a penetration with a diameter of 139.7 mm (5.5 inch) in beam C2.*

The data in Figure 8 shows that the increase in temperature and the increase in depth at which higher temperatures are measured occurred slightly faster on the side of a penetration versus above the penetration for the specific specimen/penetration configuration. This same trend appears to hold true when evaluating the linear char rates, taken as depth over time (mm/min), for each type of penetration, both with and without pipes/ducts/cable trays in place. Table 3 provides the linear char rates around the perimeter of the various penetrations and with or without a pipe or duct in the penetration. These char rates were calculated for each individual beam/penetration and then averaged for each penetration type at 60 minutes.

Table 3: *Average linear char rates in mm/min for each penetration type.*

Penetration Type	Insert or empty	Char rate at 60 minutes (mm/min)	
		Side	Top[a]
large rectangular	insert	0.65	-
large rectangular	empty	0.92	0.92
large round	insert	0.68	-
large round	empty	0.74	0.47
medium round	insert	0.58	-
medium round	empty	0.99	0.54
small rectangular	insert	0.66	0.48
small rectangular	empty	0.67	0.62
small round	insert	0.51	-
small round	empty	0.69	-

[a] For five tests, the thermocouples above the penetration did not reach a temperature of 300°C at 60 minutes. As such, no data is available.

The results in Table 2 can be compared to the standard nominal char rate of 0.635 mm/min at 60 minutes. Most

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of the penetrations were comparable to the standard char rate. However, the medium to large penetrations without building component inserts have much faster char rates between 0.74 mm/min and 0.99 mm/min.

4 CONCLUSIONS

The perimeter of horizontal glulam beam penetrations will increase during a fire, further reducing the effective cross-section of the member. These preliminary results show the char rate at and around penetrations with building services components installed are near the standard nominal char rate of 0.635 mm/min for glulam beams. Therefore, when designing a structural member, in addition to reducing the overall cross section, an effective penetration size that includes an increase for charring should be considered. The results also indicate that if a horizontal penetration is made for a building service component that is later abandoned, the penetration should be filled with a non-combustible material to avoid rapid increase of the penetration during a fire.

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