



FIRE PERFORMANCE OF SCREWED BUILT-UP GLULAM BOX-SECTION BEAMS

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Abstract: The main objective of the experimental study presented herein this paper is to investigate the structural behaviour of built-up glulam box-section beams under four-point flexural bending at both ambient and elevated temperatures. A total of four 3000-mm simply-supported beam assemblies were experimentally examined: three of them were tested at ambient temperature and one beam assembly was subjected to CAN/ULC-S101 standard fire. Self-tapping screws were used in three different patterns to form the three beam assemblies tested at ambient temperature. Each beam built-up section was made of four glulam panels, each of 44-mm thickness except the bottom flange panel which had 86 mm thickness. Ambient testing showed that reducing the spacing from 800 mm to 200 mm for the screws connecting the built-up section's top and bottom flange panels to the web panels increased the beam flexural bending strength by about 45%. While reducing the spacing from 200 mm to 100 mm only for the screws connecting the bottom flange to the web panels over a distance equal to one-third beam span length from each support, where the maximum shear stresses existed, increased the beam flexural bending strength by an additional 10%. Only the strongest beam assembly was tested under the effect of standard fire while subjected to monotonic loading that resulted in a bending moment equivalent to the beam's full resistance design moment calculated at ambient temperature. Fire resistance testing revealed that such built-up glulam box-section beam can sustain the applied design load under standard fire exposure for slightly more than 30 minutes with no fire protection.

1 INTRODUCTION

The increasing trend of using sustainable construction materials has made timber gaining great attention and high utilization in building construction in Canada. Although sawn lumber can be easily attained, it has some size limitations that usually restrain designers when larger structural timber sections are required. Fortunately, the development of engineered wood, such as glued-laminated timber (glulam) and cross-laminated timber (CLT) significantly helped in encountering this problem. Glulam sections are made by utilizing smaller sections of wood and gluing them together to form a final product with larger cross-sectional dimensions than its individual components. Creating built-up sections made of engineered-wood products like glulam is one step further. Unfortunately, the design of such built-up sections hasn't been fully incorporated yet in most wood design standards available around the world including the Canadian Design Standard, CSA 086 (Canadian Wood Council 2015). Thus, this lack of design specifications brings forth the demand of developing acceptable techniques to analyse and design such built-up sections. The findings of some research studies showed that weakness of the bond between web and flange panels of a built-up timber section is the main cause of premature failure of such built-up sections (Hoger et al. 2013). Accordingly, it is very crucial to strengthen the bond between the panels of a built-up section. Some

researchers used nails at a dense spacing to enable this type of built-up sections to behave more rigidly as a full-composite, or consolidated, section (Milner and Tan 2001). However, because of low shear resistance capacity of nails, they are more prone to rapid deformation causing considerable decrease in the flexural bending strength of built-up section beams. Therefore, to enhance the composite action of built-up section timber beams, fasteners with high withdrawal and shear strengths, such as self-tapping screws, are a more practical option. Some European standards provide guidelines on the required minimum and maximum spacing between screws to be used in built-up sections of structural members (ETA 12/0062, 2012 and ETA 11/0190, 2013). The techniques of utilizing self-tapping screws to fabricate and/or strengthen built-up timber beams have been explored by very few researchers (Hashim 2012). Also, with the increasing awareness of structural fire safety, building codes and design standards are being amended to incorporate procedures to determine the fire resistance of structural elements based on the performance of these elements in experimental fire testing. Timber being a combustible material, study of the behaviour of timber structures subjected to fire is more crucial in comparison to other construction materials, such as concrete or steel. Built-up timber beams have been used in construction as insulating components to protect inner post-tensioning systems (Costello et al. 2014). Accordingly, there is a lack of good understanding of the flexural bending behaviour of built-up timber beams fabricated using screws, so that they can be efficiently implemented in building construction.

As a pilot investigation into the subject, three full-size built-up glulam box-section beams were fabricated using self-tapping screws, and then experimentally examined under four-point flexure bending until failure at ambient temperature. Based on the outcomes of ambient tests, only the beam of the greatest flexural bending resistance was experimentally examined at evaluated temperatures.

2 EXPERIMENTAL TESTING PROGRAM

According to the preliminary analytical calculations performed for the three screwed built-up beam assemblies at ambient temperature, summarised in Table 1, it was observed that the flexural bending capacity of the beam assemblies increases more considerably by reducing the spacing of screws connecting the beam's bottom flange to the web panels over a distance of one-third beam span length from the supports. As the interface between the bottom flange and the web panels lies in the proximity of the cross section neutral axis, this region exerts excessive shear stresses, thus causing the beam to exhibit lower design load capacity. Therefore, at ambient condition, test assemblies were loaded till failure to observe the failure modes and ultimate load carrying capacities of each assembly. Whereas for fire resistance testing, the strongest beam assembly was subjected to monotonic loading resulted in a bending moment equivalent to the beam's full resistance design moment calculated at ambient condition. The resistance moment design capacities of the different built-up beam assemblies were determined by calculating the shear flow between the beam's bottom flange and the web panels in comparison to the shear resistance capacity of the utilized screws (Hibbeler, 2013), as per Equations 1 and 2, respectively.

$$[1] \text{ Shear Flow, } q = \frac{v \cdot Q}{I} \text{ N/mm;}$$

$$[2] \text{ Spacing of Screws} = \frac{\text{Allowable shear strength of single screw}}{\text{Shear flow in that length}}$$

Where, v = shear force, Q = first moment of area and I = moment of inertia

Table 1: Summary of design load capacities of screwed built-up beam assemblies

| Assembly No. | Side | Screw Spacing (mm) | Design Load Capacity (kN) |
|--------------|--------|-------------------------|------------------------------|
| Pilot Test | Top | 800 | 8.0 |
| | Bottom | 800 | 5.7 |
| Assembly 1 | Top | 200 | 32.0 |
| | Bottom | 200 | 23.0 |
| Assembly 2 | Top | 200 | 32.0 |
| | Bottom | 100 (200 in the middle) | 46.0 |

2.1 MATERIALS

2.1.1 Glulam Panels

All glulam panels used to build the 222 mm X 327 mm glulam box-section beam assemblies were made of black spruce pine fir (SPF), with stress grade of 24f-1.9E. The individual lamina used in these panels was of an average cross-sectional dimensions of 38 mm X 50 mm, which were finger-jointed and glued together in horizontal and vertical layers. Outer lamina was sanded to the designed width and depth of each panel. The mechanical properties of the glulam panels in the longitudinal direction are listed in Table 2.

Table 2: Mechanical properties of glulam panels

| Property | Unit (MPa) |
|---------------------------|--------------------------|
| Comp. parallel to grain | 33.0 |
| Comp. perp. To grain | 7.0 |
| Tension parallel to grain | 20.4 |
| Modulus of Elasticity | 13,100 |
| Density | 560 (kg/m ³) |

2.1.2 Self-Tapping Screws

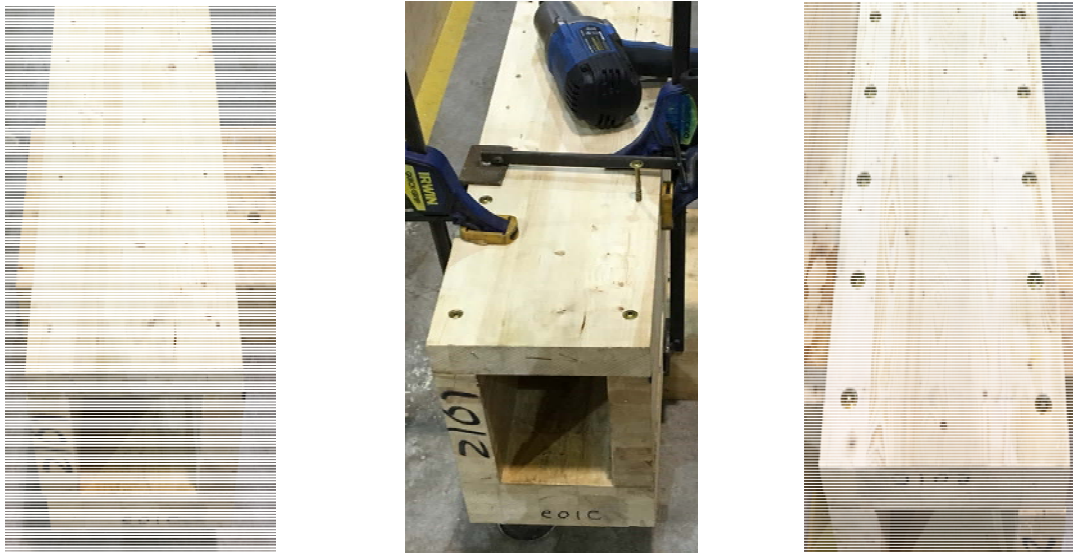
Rugged structural steel screws of lengths 4.0 and 6.0 inches were used to connect the top and bottom flanges to the side web panels, respectively. The screws were made of specially hardened steel to provide higher torque, tensile and shear strengths. In comparison to traditional screws, the employed self-tapping screws had a special thread that helped in slightly enlarging the screw hole to allow easy penetration in wood without the need for pre-drilled (or pilot) holes, which in turn also increases the screws withdrawal strength. Hence, adequately designed connection using self-tapping screws is much stronger than conventional screws. The mechanical properties of the utilized screws are provided in Table 3.

Table 3: Mechanical properties of structural screws

| Property | Allowable Strength (MPa) |
|------------------|-----------------------------|
| Bending Strength | 1175.0 |
| Tensile Strength | 1298.0 |
| Shear Strength | 881.0 |

2.2 FABRICATION PROCESS AND TEST ASSEMBLIES DETAILS

All full-size glulam box-section beams were fabricated by joining all four glulam panels together using 8-mm diameter self-tapping screws. The pilot built-up beam assembly had the largest centre-to-centre screw spacing of 800 mm, while beam assembly no. 1 had screws spaced at 200 mm centre-to-centre connecting the top and bottom flanges to the web panels. However, test assembly no. 2 had screws placed at 200 mm connecting the top and bottom flanges to the web panels, except over a distance of one-third beam span length from each support where screws connecting the bottom flange to the web panels were spaced at only 100 mm. Even though the screws were equipped with what so called Zip-Tip, which allowed easy drawing of screws without pre-drilling, pilot holes were drilled so that screws followed straight paths through the glulam flange to the web panels when inserted by an impact wrench, Figures 1a and 1b. The screw end distance is defined as the distance between the end of the beam and the centreline of the first screw, which in this case was kept at 50 mm as specified in (ETA 12/0062, 2012). The test matrix used for ambient and elevated temperature experiments is shown in Table 4 below.



(a) Pilot holes drilling (b) Screws thrusting (c) Finished section (Bottom flange)

Figure 1: Fabrication process of a general screwed built-up glulam box-section beam assembly

Table 4: Test matrix for ambient and fire resistance experiments

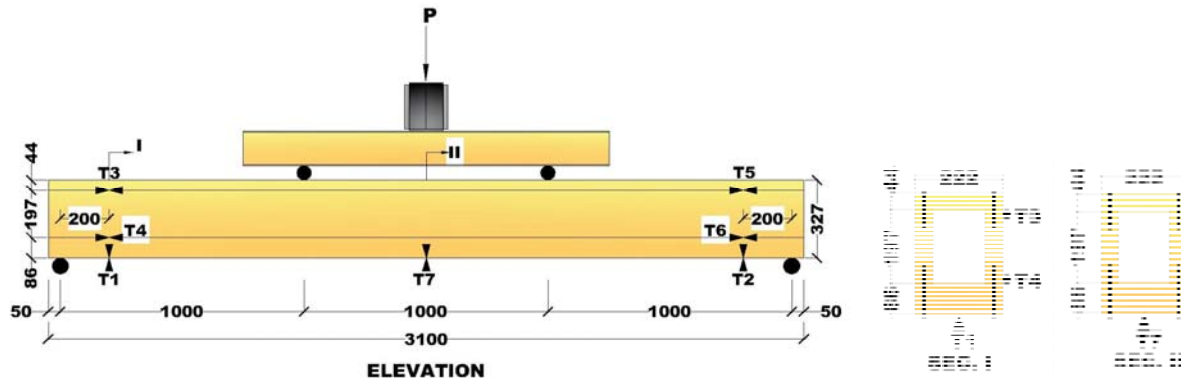
| Test No. | Joining Technique | Top Spacing (mm) | Bottom Spacing (mm) |
|----------------------|-------------------|------------------|---------------------|
| Ambient Temperature | | | |
| Pilot Test | Screwed | 800 | 800 |
| Test 1 | Screwed | 200 | 200 |
| Test 2 | Screwed | 200 | 100 |
| Elevated Temperature | | | |
| Test 2F | Screwed | 200 | 100 |

2.3 EXPERIMENTAL TEST SETUP AND DETAILS

2.3.1 Ambient Temperature Test Setup

All beam assemblies tested at ambient temperature were simply supported over two supports 3000 mm apart that were restrained to strong steel bottom beam placed within a large universal testing machine. Test assemblies were linearly loaded to failure to assess their ultimate flexural bending strengths as well as their failure modes. One draw-wire displacement transducer and six Linear Variable Differential Transducers (LVDTs) were attached to each test assembly to monitor the vertical deflections at the beam mid span and near the supports, as well as to detect the relative slip between the flange and web panels. A schematic of a general test setup with transducers layout is shown in Figure 2. The draw-wire transducer labelled T7 was used to measure the increments of the beam mid-span vertical deflection, while the LVDTs labelled T1 and T2 were used to measure the beam vertical displacements near the left and right support, respectively. Subsequently, the readings of the LVDTs labelled T1 and T2 were used to calculate the beam end rotations. To measure the relative slip between the beam top flange and the web panels, the LVDTs labelled T3 and T5 were installed near the left- and right-side supports, respectively. Similarly, the LVDTs labelled T4 and

T6 were installed to monitor the relative slip between the beam bottom flange and the web panels near the left- and right-side supports, respectively.



(a) Elevation of a general ambient-temperature test setup, (b) Transducers layout

Figure 2: A general test setup with transducers layout for ambient temperature testing

2.3.2 Elevated Temperatures Test Setup

Almost similar test setup was followed to test the beam assembly with the greatest flexural bending strength but, at elevated temperatures. The entire built-up beam assembly including supports were placed inside a large-size fire testing furnace accommodated at Lakehead University's Fire Testing and Research Laboratory (LUFTRL), Figures 3(a) and 4(a). The supports were restrained to a sturdy steel beam located underneath the furnace, which is a component of the loading steel frame that is also supporting the furnace above the floor. To stimulate three-face fire exposure on the beam, the top flange of the beam was covered with 25.4 mm (1 inch) ceramic fiber blanket, assuming the top side of the beam will be covered with a slab in real-life application. In addition, the beam ends were also insulated to simulate the existence of two columns blocking the beam ends and prevented the direct passage of heat inside the beam's hollow section. A powerful hydraulic jack installed and attached to the loading steel frame above the furnace was utilized to apply the transverse load on a load-distributing steel beam which in turn divided the applied load into two equal point loads through rollers that were one-third beam span length apart. Throughout the entire fire resistance test duration, the beam assembly was subjected to monotonic loading that resulted in a flexural bending moment equivalent to the full resistance design moment of the weakest beam assembly (Tests 1 and 2 assemblies). Two draw-wire displacement transducers, labelled T2 and T3, were installed outside the furnace and attached to two long ceramic rods that were inserted through little holes in the furnace's roof to monitor the beam's vertical displacements near supports. One ceramic rod was placed on the assembly, 150 mm away from each support, Figure 3(a). In addition, a third displacement transducer, labelled T1, was attached to the top of the insulated loading steel post to monitor the beam's mid-span deflections during fire resistance testing. The readings of transducers T2 and T3 were used to calculate the beam end rotations. Also, to measure the temperatures across the beam cross section as well as the internal temperature of the beam cavity along its length, ten metal-shielded K-Type thermocouples, labelled TC1 through TC10, were installed on each beam assembly, as shown in Figure 3(b). Five thermocouples, TC1 through TC5, were installed at the beam mid-span section with one thermocouple, TC5, located at the centre of the beam cavity; while each of the other four thermocouples was inserted through little hole drilled in the middle of each section panel with the thermocouple bead located at a half-thickness depth of each individual panel. Other five thermocouples, TC6 through TC10, were installed following the same pattern but, were located at 300 mm away from the right-side support, Figure 3(b).

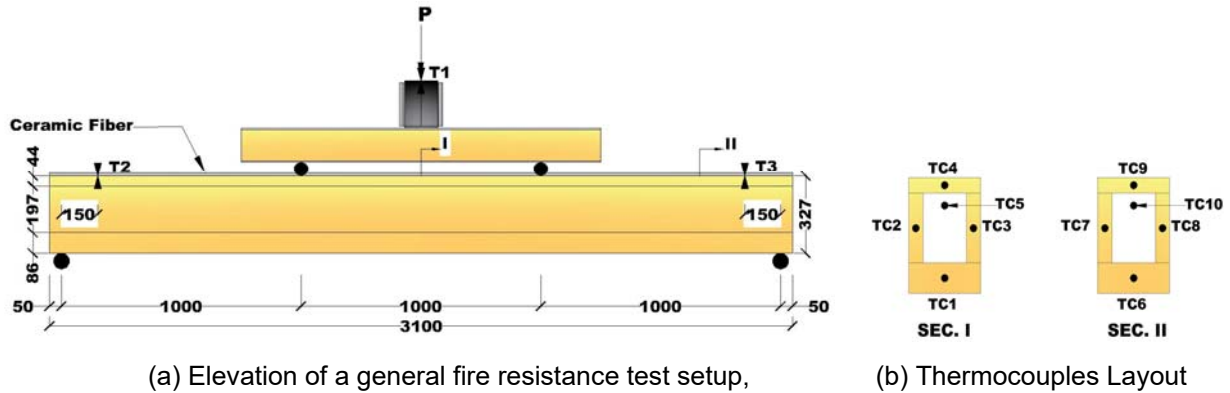


Figure 3: A fire resistance test setup with displacement transducers and thermocouples schematics

Following Clause 6.2.1 of CAN/CSA-S101 Standard, transverse load was applied in four increments, each of 25%, with the total load was achieved at least 30 minutes before the commence of the fire test. The temperature inside the furnace was monitored by three shielded thermocouples installed on the furnace back wall and controlled by a built-in computer system. A glulam box-section beam assembly undergoing fire resistance testing is shown in Figures 4(a) and (b). Beam mid-span deflections were monitored during fire tests, and once the deflection measurement reached a value equal span/20 test was terminated.

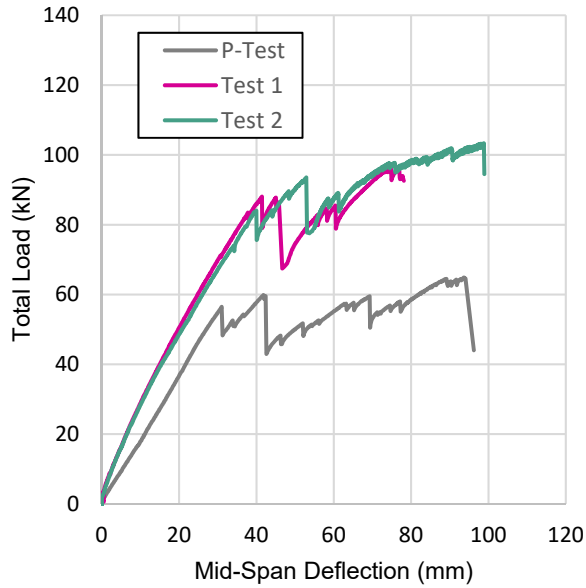


Figure 4: A general test assembly installed inside Lakehead University's fire testing furnace

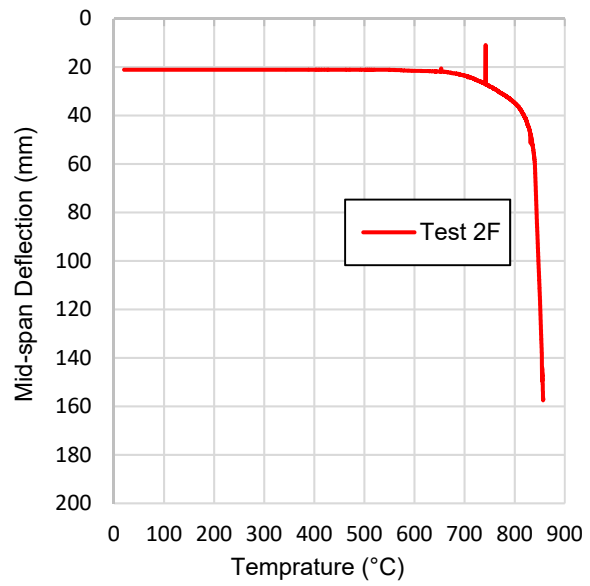
3 RESULTS AND DISCUSSION

3.1 Effect of Elevated Temperatures on Beam Mid-Span Deflections

Analysis of the measurements provided by draw-wire displacement transducer T1 revealed that beam mid-span deflections were stable at 20 mm throughout most of the fire test duration. However, as the time elapsed and the average temperature inside the furnace elevated to about 587°C, the beam deflections started to increase exponentially until the beam reached its failure criterion which was set at span/20, i.e. 150 mm in this case. The beam assembly was able to sustain the applied load under standard fire exposure for slightly more than 30 minutes. Looking at the results of ambient temperature tests shown in Figure 5(a), it is observed that Test 2 beam assembly was able to withstand an average load of 55.0 kN before it exhibited the first crack induced due to rolling-shear failure. Whereas for an identical beam assembly, it was observed that even when the load was kept constant at only 23.0 kN, the rise in temperature caused rapid drop in the beam flexural stiffness and rigidity, which was reflected in the rapidly increased mid-span deflections, as shown in Figure 5(b).



(a)

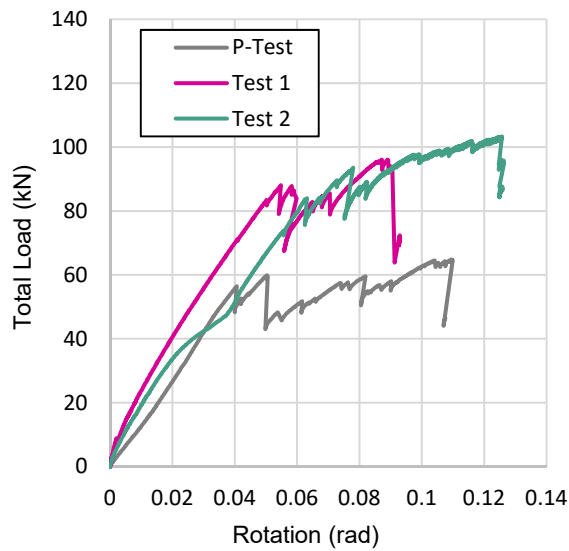


(b)

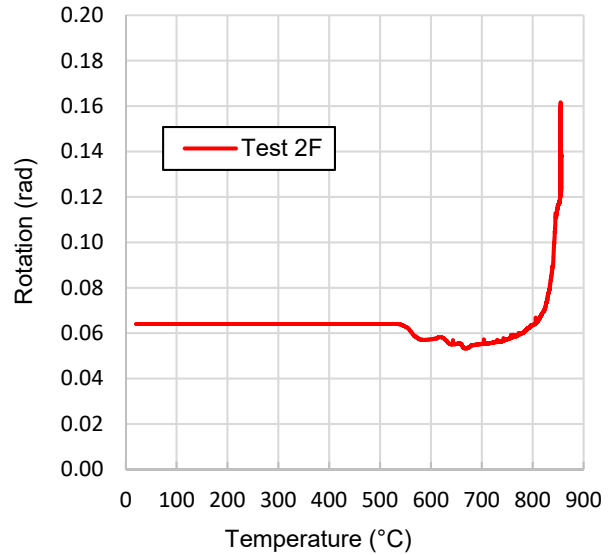
Figure 5: (a) Load vs. mid-span deflection of screwed beam assemblies at ambient temperature; (b) Mid-span deflection vs. temperature in fire resistance Test 2F

3.2 Effect of Elevated Temperatures on Beam End Rotations

The rotations at both beam ends were found to be in good agreement with each other thus, the results of only one side are shared. Figure 6(b) illustrates the effect of elevated temperatures on the beam end rotations. Like beam mid-span deflections, it was observed that the beam end rotations remained stable up to a furnace average temperature of about 520°C. However, unlike mid-span deflections, the beam end rotations showed a prominent drop between 520°C and 600°C till it started to increase exponentially when the beam failure criterion was met, and the test was then terminated.



(a)



(b)

Figure 6: (a) Load vs. beam end rotations at ambient temperature, (b) Beam end rotations vs. temperature in fire resistance test

This unusual drop in the beam end rotations was deduced to occur because of the sudden increase in the beam flexural stiffness that developed due to the additional engagement of screws when subjected to elevated temperatures. After comparing the results of the fire resistance test with those of the tests done at ambient temperature, it was observed that when tested at room temperature, as shown in Figure 6(a), the beam end rotations in Test 2 reached a maximum value of 0.125 radians at a load slightly above 100 kN. Whereas, the exposure to standard fire enforced the beam to experience greater end rotations, as it reached a rotation value of 0.16 radians at about 850°C.

3.3 Time-temperature Curves

From Figure 7 that shows the time-temperature curves of Test 2F, it was observed that the internal temperature of the web panels started to increase within 3 to 4 minutes of the fire exposure. However, it took almost 8 minutes for the temperature of the bottom flange to spike up due to its two-fold thickness. It was also noticed that with the non-linearly increased internal temperatures of the different beam section panels, as shown in Figure 7 with reference to Figure 3(b) for thermocouple locations, the mechanical properties of glulam deteriorated as the char layer started to develop. However, since the top side of the built-up beam section and its hollow ends were covered with ceramic fibre blankets, the thermocouples embedded inside the beam top flange (TC4 and TC9) and the beam hollow core (TC5 and TC10) experienced considerably lower temperatures, where their temperatures reached only up to a maximum of 135°C by the end of the fire test. This illustrates that even though the wood was charred away, the screws were keeping the glulam panels fastened together so that the beam assembly behaved as one consolidated section almost till the end of the fire test.

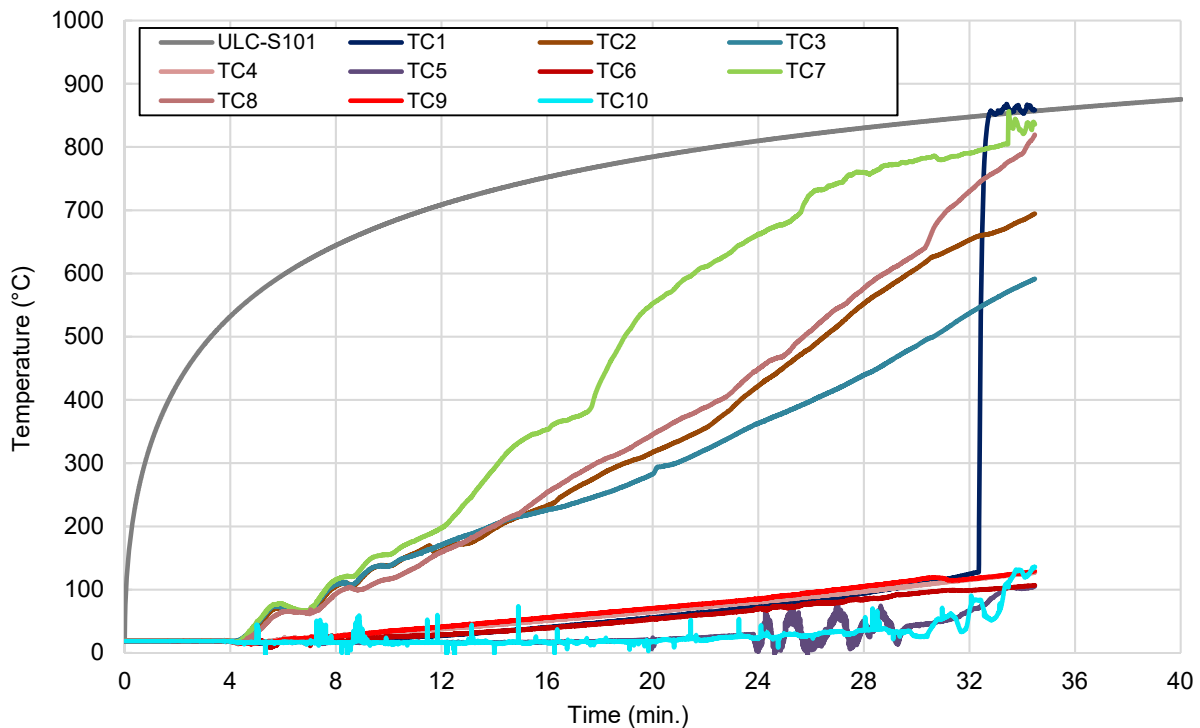


Figure 7: Actual time-temperature curves of all thermal measurements taken in fire resistance Test 2F

3.4 Failure Modes

Through ambient temperature testing, brittle failure modes such as rolling shear and splitting were observed in the built-up beam assemblies. As shown in Figure 8(a), the failure caused by rolling shear occurred in the beam web panel. As per the experiments and the analytical calculations performed prior to conducting

the experiments, it is confirmed that the shear flow was greater at the bottom interface, between the bottom flange and web panels, due to its proximity to the section's neutral axis compared to the top interface, between the top flange and web panels. Only the bottom flange faced splitting failure when the ultimate load capacity of the section was reached eventually in the test, as shown in Figure 8(b). In all three test assemblies experimentally examined at ambient temperature, no damage was noticed in the top flange of the beam assembly.

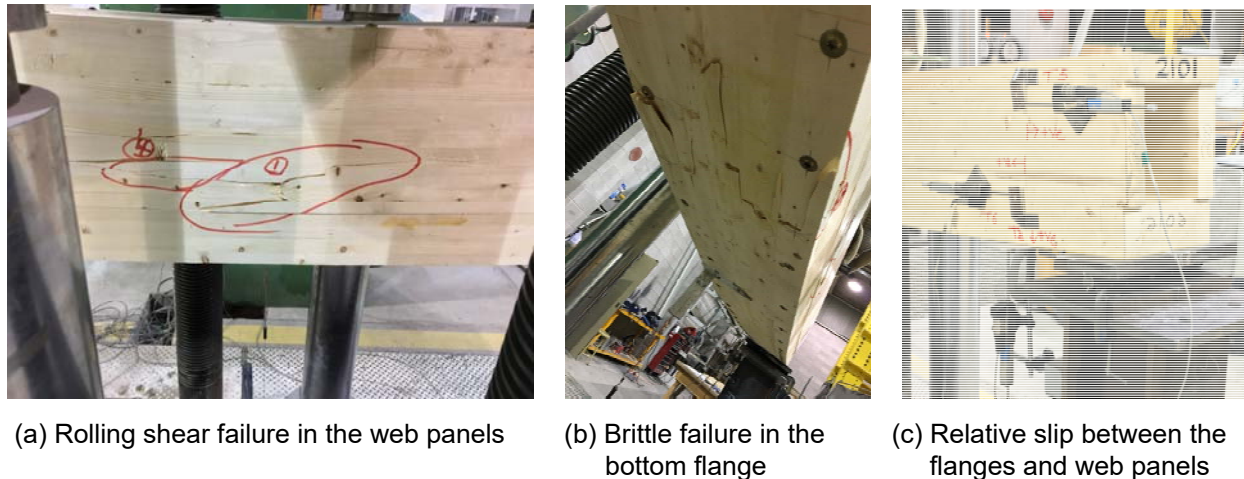


Figure 8: Major failure modes observed in Test 2 beam assembly

In addition, Figure 8(c) shows the relative slip occurred between the flanges and web panels due to the excessive shear stresses that also resulted in yielding of a few screws. This yielding was prominent in the screws closer to the beam supports, and as we moved inwards towards the middle of the beam less yielding was noticed. The screws retrieved from the beam assembly exposed to fire were excessively bent in comparison compared to those retrieved from ambient temperature tests. This illustrates that when half the thickness of the web panels was charred away, the screws were directly exposed to fire, which resulted in considerable degradation of the mechanical properties of the screws causing them to excessively bend.

4 CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis of test results and the comparative study of the flexural bending behaviour of the different beam assemblies at both ambient and elevated temperatures, a few deductions have been made and are listed as follows:

1. Reducing the spacing from 200 mm to 100 mm over one-third beam span length from both supports of the screws connecting the bottom flange to the web panels increased the flexural bending strength of the built-up beam assembly by about 10%;
2. Test assemblies examined at ambient temperature experienced varying flange-to-web relative slips that caused various levels of screws' yielding;
3. In all test assemblies, the web panels experienced higher volume of cracks because of the high rolling shear stresses developed in the proximity of the interface between the bottom flange and web panels. This failure mode was followed by the brittle failure developed in the bottom flange when the beam's ultimate load capacity was attained;
4. With the non-linearly increased internal temperatures of the different beam section panels, the mechanical properties of glulam deteriorated as the char layer started to develop;
5. The fire exposure rapidly decreased the flexural stiffness of the built-up glulam beam assembly, and resulted in greater mid-span deflections as well as end rotations eventually in the test;

6. Excessive shear stresses in addition to elevated temperatures resulted in greater yielding of screws in comparison to that occurred in ambient temperature tests. This also indicates how fire exposure can influence the mechanical characteristics of screws;
7. The built-up glulam box-section beam with its specific cross-sectional dimensions was able to sustain the applied load under standard fire exposure for slightly over 30 minutes with no fire protection.

In addition to the effect of the screw spacings on the flexural bending strength of the tested built-up beam assemblies at ambient condition, the fire resistance test showed that the thickness of the glulam panels also plays a vital role, as the mechanical properties and flexural stiffness of the beam started to degrade as the wood converted into char. Therefore, it is recommended that to increase the fire resistance of such built-up glulam beams, screws should be provided with extra fire insulation by increasing the thickness of the web panels. Also, the extent of this research study should be expanded to investigate the followings: (1) increasing the stiffness of the beam by using industrial grade adhesive to join the flanges to the web panels; and (2) developing strengthening technique to internally reinforce the beam assembly without compromising its entire hollow core. Built-up glulam box-section beam assemblies, such as the ones experimentally examined in this study, may enable designers to utilize lightweight yet strong glulam structural beams with reasonable fire resistance. This will also open new opportunities in the field of pre-fabricated construction and promote mid- and high-rise timber buildings construction in Canada.

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