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EXPERIMENTAL FIRE TESTING OF STS-RETROFITTED GLULAM BEAM CONNECTIONS WITH MINIMAL FIRE PROTECTION

Mohamed Hegazi¹, Sam Salem²

ABSTRACT: The main objective of this study is to investigate the enhancement of the fire resistance of damaged glulam beam connections retrofitted using self-tapping screws (STS). This paper presents the results of fire endurance tests on two full-size glulam beam-end bolted connections with two different wood-steel-wood (WSW) configurations retrofitted using STS after being deliberately damaged through physical testing. In both configurations, the metal connecting components, bolt heads, nuts and steel plates were protected with wood plugs and strips to provide minimal fire protection using eco-friendly material like wood. Based on the fire test results, the utilization of STS prevented the propagation of the existing splits in the damaged connections at elevated temperatures. Ultimately, this resulted in at least 75% recovery of the fire resistance time of the STS-retrofitted connections. Accordingly, a simple yet effective STS retrofitting technique has been experimentally proven to enhance the fire resistance of damaged glulam beam-end bolted connections, as presented in the two WSW connection configurations in this paper.

KEYWORDS: glued-laminated timber, wood-steel-wood connections, self-tapping screws, retrofitting, fire testing.

1 – INTRODUCTION

Timber structures exhibit various failures and defects, including checks caused by changes in moisture content or splits resulting from excessive stresses. Several studies have been conducted in ambient conditions to evaluate various retrofitting techniques for timber structures. Some methods used glued-in steel rods, fibre-reinforced polymer wrapping sheets, wood-based panels glued to timber elements and self-tapping screws (STS) for reinforcement purposes [1].

Self-tapping screws (STS) have been proven to be an economical and easy retrofitting technique for deteriorating timber structural components. In ambient conditions, it has been demonstrated that STS reinforcement effectively prevents wood splitting, thereby increasing the moment-resisting capacity and ductility of timber connections [2]. Implementing STS reinforcement increased the moment-carrying capacity of glulam beam wood-steel-wood (WSW) connections by factors up to 2.4 [3]. However, the situation becomes more critical in fire conditions as wood splitting at the connections is common due to glue line delamination at elevated temperatures [4]. Although STS have been proven to be very effective in enhancing the strength of

glulam connections in ambient conditions, there has been minimal research on the influence of STS on strengthening connections in fire conditions [5, 6]. A few experimental studies [7, 8] were conducted to investigate the behaviour of unreinforced WSW bolted connections when exposed to standard fire. The studies involved WSW connection configuration with two different bolt patterns. In the first pattern (P1), two rows of bolts, each of two bolts, were placed symmetrically close to the top and bottom of the glulam beam. In contrast, in the second pattern (P2), the bottom row of bolts was raised to the mid-height of the beam to resist better the tensile stresses developed at the top of the beam section. The bolt heads, nuts, and steel plate edges were fire-protected using wood plugs and strips. A common failure observed in all tests was a sudden glue line failure along the top bolt row, resulting in premature and brittle failure [7].

Additionally, in recent experimental studies conducted by [9, 10] to evaluate the effect of the number of bolts and their pattern on the fire performance of minimally fire-protected glulam beam-end connections reinforced with STS, full-size WSW glulam connections utilizing four different connection configurations were strengthened perpendicular to wood grain with STS and tested under standard fire exposure. The bolt heads, nuts, and the steel

¹ Mohamed Hegazi, M.A.Sc. Graduate, Dept. of Civil Engineering, Lakehead University, Ontario, Canada, <u>mthegazi@lakeheadu.ca</u>

² Sam Salem, Ph.D., P. Eng., Full Professor, Dept. of Civil Engineering, Lakehead University, Ontario, Canada, <u>sam.salem@lakeheadu.ca</u>, <u>https://orcid.org/0000-0001-8660-2181</u>

plate edges were fire-protected using wood plugs and strips. As a result of this simple yet effective protection technique, all four connection configurations had failure times that surpassed the minimum fire resistance rating of 45 min required by the applicable building code [11] for mass timber construction. Additionally, the tendency of brittle failures, such as wood splitting which was common in connection configuration that did not use any reinforcement [3, 4], was prevented by the application of the STS as a mean of perpendicular-to-wood grain reinforcement and thus, all four STS-reinforced connection configurations had increased strength and stiffness and enhanced failure time compared to the connection configurations without corresponding reinforcement.

The impact of STS on the strength of a bolted glulam connection subjected to bending was investigated by [12]. In that study, three beam configurations were tested: unreinforced, reinforced, and retrofitted. The STS, 300 mm in length and 8 mm in diameter, was placed perpendicular to the grain in the beam section. A slottedin plate was used to connect the beam end to the supporting column. The glulam beams were subjected to monotonic loading. The results of the testing programs indicate that the maximum moment resistance for the unreinforced connection was 31.49 kN·m at a maximum rotation of 2.97°. On the other hand, the reinforced beam had a moment capacity of 65.88 kN·m at a rotation of 16.59°, whereas the retrofitted beam had a moment capacity of 58.85 kN·m at a rotation of 13.29°. Therefore, the use of STS in the reinforced beam resulted in a moment capacity increase by a factor of 2.1, and the use of STS in the retrofitted beam increased the moment resistance by a factor of 1.87. Additionally, as evident from the rotation values, the ductility of the beam was significantly improved with the use of STS [12].

To understand the effects of STS on the ductility and load-carrying capacity of wood connections, an experimental study was conducted on glulam members with dowel-type connections reinforced with STS and subjected to a tensile load applied parallel to the grain [13]. Three different connection configurations were tested. In the first configuration, no STS reinforcement was used; in the second configuration, ten STS were used, and in the third configuration, twenty STS were used. Upon completion of the testing, it was observed that the unreinforced beams experienced minimal displacement of only 4 mm at the ultimate failure load of 330 kN. When ten STS were used, the ductility and strength of the specimen increased; however, when twenty STS were used, the beam experienced a significant increase in ductility, as well as an increased load-carrying capacity (16 mm maximum displacement at a 400 kN failure load) [13].

2 - BACKGROUND

In fire conditions, and due to the highly conductive nature of metal fasteners, heat can transfer faster into wood members, resulting in a higher charring rate at the connection. Consequently, this degrades the strength and stiffness of the connection, which remains with a much smaller residual cross-section. According to prior related experimental studies on glulam beams with WSW bolted end connections exposed to fire [7, 8], it has been concluded that concealing the steel connecting components considerably enhanced the fire performance of the connections. However, it was also observed that other failure modes can occur in WSW connections, regardless of whether the steel components are concealed or exposed. For instance, sudden and unexpected wood splitting failure along the beam glue lines, due to delamination, resulted in premature brittle failure of the glulam beam connections under fire conditions. Hence, this paper presents the experimental results of the fire tests conducted on glulam connections identical to those experimentally examined by [7, 8] after being deliberately damaged and then retrofitted with STS to investigate their impact on the overall fire resistance of such WSW connections.

3 – PROJECT DESCRIPTION

The damaged glulam beam-end connections examined in ambient conditions as part of prior related studies [6, 7] were preserved for retrofitting using STS as part of this current study. In a subsequent stage, the retrofitted connections were experimentally tested in standard fire conditions while being loaded to the maximum design load of the weakest undamaged, unreinforced connection configuration. The experimental results of the retrofitted glulam beam connections were compared to those of identical but undamaged, unreinforced connections that were experimentally tested in standard fire conditions in the prior related studies [7, 8] to determine the influence of STS in strengthening the damaged connections.

In the connection configuration with the first bolt pattern (4BP1R), two rows of bolts, each of two bolts, were symmetrically positioned near the top and bottom sides of the beam section. In the configuration with the second bolt pattern (4BP2R), the bottom row of bolts was shifted upward to be located at the mid-height of the beam section, further contributing to the moment-resisting capacity of the connection. In both configurations, the metal connecting components, bolt heads, nuts, and steel plates were protected with wood plugs and strips to

provide minimal fire protection using eco-friendly materials, such as wood. Table 1 summarizes the test matrix of the experimental study presented in this paper.

Connection Configuration ID.	Load Applied (kN)	Moment Applied (kN·m)	# of Bolts Used	# of STS Used
4BP1R	10.5	14.8	4	6
4BP2R	10.5	14.8	4	6

Table 1: Test Matrix

Figs. 1 and 2 show details of the beam-end connection configurations with four connecting bolts in two different arrangements (i.e., P1 and P2), respectively.



Figure 1: Details of the beam-end connection configuration with bolts arranged in the first pattern (P1).



Figure 2: Details of the beam-end connection configuration with bolts arranged in the second pattern (P2).

4 – EXPERIMENTAL PROGRAM

4.1 MATERIALS

The glulam beams used in the present study's tests are identical to those tested by [7, 8]. The 1600-mm-long beams had cross-sectional dimensions of 184 mm \times 364 mm and were made of black spruce pine glulam with a stress grade of 24F-EX. The laminas used in manufacturing the glulam beam sections had approximately 25 x 50 mm cross-sectional dimensions. The mechanical properties of the glulam beam used are shown in Table 2.

To connect the glulam beam section to the steel supporting column, a T-stub bracket made of a 12.7-mm (1/2") thick steel plate of grade 300W was utilized. Fig. 3 illustrates an isometric view of the steel T-stub bracket for each connection configuration.

Table 2: 24f-EX glulam	beam's mechanical	properties	(Adapted fro)m
	[14])			

Property	Strength	
	(MPa)	
Comp. parallel to the grain	33.0	
Comp. perp. to the grain	7.5	
Tension parallel to the grain	20.4	
Longitudinal shear	2.2	
Flexural bending	30.7	
Modulus of elasticity	13,100	



Figure 3. Schematic of the T-stub steel brackets utilized in the two connections, (a) Configuration with the first bolt pattern (P1); (b) Configuration with the second bolt pattern (P2) (dimensions in mm)

The STS used to retrofit the glulam beam-end connections were SWG ASSY VG plus with certified properties as per the Canadian Construction Materials Centre report [15]. The screws had a length of 300 mm and 8 mm thread outer diameter. Fig. 4 illustrates the details of the STS used.



Figure 4. SWG ASSY VG plus CSK self-tapping screw (Adapted from [15])

Before drilling the STS into the glulam section, a pilot hole was drilled for each screw using a 3-mm-diameter drill bit to a depth of approximately 200 mm (about twothird of the screw total length). The predrilling was deliberately done to prevent splitting in the wood. After all pilot holes were prepared in the beam section, the STS were driven perpendicular to the wood grain from the top side of the beam (tensile side) using an electric wrench.

4.2 TEST SETUP

4.2.1 AMBIENT TESTING

Before fire testing, the two beam-end connection configurations were tested at ambient temperature as part of a prior related study conducted by [7, 8]. Each beam was connected to a steel supporting column by a steel T-stub bracket and four 19.1-mm (3/4") diameter, A325M, high-strength structural steel bolts. The bolt end distance, edge distance, and spacings were designed in accordance with CSA O86-19 [16]. A 15-mm-wide slotted cut was prepared at the centre of the beam cross-section to accommodate the steel T-stub bracket, allowing a clearance of approximately 1 mm on each side of the steel plate, as per CSA O86-19 [16].

The beam-end connections were deliberately loaded under bending moment and indirect shear force until failure, when splits started to develop in the connections along the top and bottom rows of bolts. Fig. 5 illustrates the typical failure mode of the WSW connection configurations, which was observed when the ambient test was terminated [7, 8].





(b)

Figure 5. Failure mode of the WSW connection configurations tested at ambient temperature, (a) Configuration with the first bolt pattern (P1); (b) Configuration with the second bolt pattern (P2).

4.2.2 FIRE TESTING

After the beam-end connections were damaged in ambient tests, they were retrofitted using STS in preparation for the fire tests of the present study. Six STS were used to reinforce the beam sections at their end connections perpendicular to the wood grain. Fig. 6 shows the top side of an STS-retrofitted glulam beam specimen. The STS were installed in pairs and spaced at 100 mm such that the first pair is centred between the beam end and the first column of bolts, the second pair is centred between the two columns of bolts, and the third pair is 50 mm beyond the second column of bolts into the beam away from its connected end.



Figure 6. Typical STS arrangement.

The two retrofitted connection configurations were then exposed to elevated temperatures following the CAN/ULC-S101 standard fire time-temperature curve [17], while being subjected to a bending moment (14.8 kN·m) equivalent to 100% of the ultimate design moment capacity of the weakest, undamaged, unreinforced connection configuration (4BP1). The fire endurance tests of the retrofitted beam-end connections were conducted in the large-size fire testing furnace located at Lakehead University Fire Testing and Research Laboratory (LUFTRL). The setup of the fire tests is similar to that of the ambient tests, except that 1.0-inchthick ceramic fibre blankets were used to insulate the steel supporting and loading attachments along with the top side of the beam to simulate the existence of a slab above the beam as it would be the case in an actual construction configuration. Accordingly, the glulam beams were exposed to fire on three sides only, as the top side was protected from fire by the applied insulating ceramic fiber blankets. Fig. 7 shows one of the glulam beam test assemblies installed inside the fire testing furnace, with all instrumentation and fire-insulating layers in place. During fire tests, the connection failure criterion was set to a maximum beam end deflection corresponding to a connection rotation of 0.1 radians. However, fire tests were continued beyond this point until the beam could no longer sustain the applied loads.



Figure 7. A typical glulam beam test assembly installed inside the fire testing furnace at LUFTRL.

During the fire tests, the applied load was maintained at 10.5 kN, resulting in a bending moment of 14.8 kN \cdot m at the beam-end connection. This is the same load level applied to the identical but undamaged, unreinforced connection configurations experimentally tested by [7, 8] under standard fire conditions. Consistency in applying the same load level enabled a direct comparison of the fire resistance test results from the present study with those of prior related studies [7, 8]. The load was applied using a loading cylinder connected to a manual hydraulic pump. A load cell was placed outside the furnace, on top of the loading steel post, and under the piston of the hydraulic loading cylinder, to precisely measure the magnitude of the applied loads during fire tests.

5 – RESULTS

5.1 EFFECTS OF USING STS ON THE FIRE RESISTANCE OF THE RETROFITTED CONNECTIONS

The STS-retrofitted connection configuration with the first bolt pattern (4BP1R) had a fire resistance time of 43 minutes and failed due to excessive charring. The fire resistance time of the identical undamaged, unreinforced connection, which was tested twice [7, 8], was 56 and 42 minutes (an average of 49 minutes). The 14 minutes less fire resistance time of the connection examined in the second test compared to the same connection examined in the first test can be attributed to the sudden wood splitting that occurred at a glue line due to delamination [7, 8]. Therefore, the damaged, STS-retrofitted

connection achieved a lower fire resistance time by 13 minutes compared to the undamaged, unreinforced connection, which did not experience glue line delamination. It also had a 1-minute greater fire resistance time than that of the identical undamaged, unreinforced connection in which the glue line delamination caused failure. Based on the above-mentioned results, it can be concluded that the STS restored 77% of the beam's original fire resistance time and prevented the wood splitting failure due to the glue line delamination. Images of the retrofitted connection with the first bolt pattern (4BP1R) taken during fire testing are shown in Fig. 8.



 After 15 minutes
 After 30 minutes
 At failure (43 minutes)

 Figure 8. Fire testing timeline of the STS-retrofitted connection configuration that utilized four bolts in the first bolt pattern (4BP1R).

For the connection configuration with the second bolt pattern (4BP2R), the fire resistance time was 58 minutes, and it failed due to excessive charring. The identical undamaged, unreinforced connection tested by [7, 8] had a fire resistance of 48 minutes, and it failed due to wood splitting resulting from glue line delamination that occurred along the top row of bolts. Therefore, the STS retrofitted connection had 20% surplus fire resistance time compared to the unreinforced connection. The significant increase in the fire resistance time of the STSretrofitted connection compared to that of the undamaged, unreinforced connection tested by [7, 8] is primarily due to the STS preventing wood splitting as a result of glue line delamination, which was common in the fire experiments conducted by [7, 8]. Images of the retrofitted connection (4BP2R) taken during fire testing are shown in Fig. 9.



Figure 9. Fire testing timeline of the STS-retrofitted connection configuration that utilized four bolts in the first bolt pattern (4BP2R).

5.2 EFFECTS OF THE INITIAL SPLIT WIDTH ON THE ROTATIONAL BEHAVIOUR OF THE RETROFITTED CONNECTIONS

For the STS-reinforced connection with four bolts arranged in the first bolt pattern (4BP1R), the rotation increased linearly for the first 23 minutes. Afterward, the rotation rate increased more rapidly, following an exponential trend, until failure at 43 minutes (Fig. 10). In contrast, the connection configuration with four bolts arranged in the second bolt pattern (4BP2R) exhibited linearly increasing rotations for most of the fire test duration. The rotation increased linearly for the first 50 minutes, and then it began to increase more rapidly, following an exponential trend, until failure at 58 minutes. It should be noted that for the configuration that utilized four bolts in the first bolt pattern (4BP1R), the initial split of the beam formed along the top row of bolts before fire testing had a width of approximately 3 mm, whereas the STS-retrofitted configuration that utilized four bolts in the second bolt pattern (4BP2R), the initial split exhibited by the connection before fire testing had a width of less than 1 mm. The wider initial split of the configuration 4BP1R resulted in greater heat penetration into the core of the beam section, leading to accelerated localized wood charring. As a result, configuration 4BP2R exhibited an extended linear time-rotation trend and a fire resistance time that was 8 minutes longer.



Figure 10. Time-rotation relationships of the STS-retrofitted connection configurations that utilized four bolts in the first (4BP1R) and second bolt patterns (4BP2R).

For the undamaged, unreinforced connections tested by [7, 8], it was noticed that for the configuration with four bolts arranged in the second bolt pattern (4BP2) the connection experienced a sharp exponential increase in its rotation after 40 minutes into the fire test, which was a results of the immediate, brittle failure caused by the delamination occurring at the glue line at the top row of

bolts. In contrast, the similar connection configuration with four bolts arranged in the first bolt pattern (4BP1) exhibited linearly increasing rotations for a more extended period compared to the 4BP2 configuration, resulting in a longer fire resistance time. It is worth noting that the time-rotation curve shown for the 4BP1 configuration is for the first test, which had a 56-minute fire resistance time and did not experience any brittle glue-line failure. No time-rotation curve is presented for the second test, which experienced a sudden glue line failure and had a fire resistance time of only 42 minutes.



Figure 11. Time-rotation relationships of the undamaged, unreinforced, connection configurations that utilized four bolts in the first (4BP1) and second bolt patterns (4BP2) [7, 8].

6 – CONCLUSIONS AND RECOMMENDATIONS

In the experimental study presented in this paper, the fire behaviour of damaged WSW glulam beam-end connections with different bolt patterns that were retrofitted using self-tapping screws was investigated. The study examined the performance of the tested connections in terms of their fire resistance time and rotational behaviour. The experimental results of the present study have been compared to those of a related prior study on identical but undamaged, unreinforced connections that was conducted by [7, 8].

Although the utilization of STS resulted in a substantial recovery of strength and fire resistance time (at least 77%) for the connection configuration arranged in the first bolt pattern (4BP1R), the full original strength and fire resistance of the connections were not restored.

Additionally, the use of STS prevented brittle failure, mainly caused by glue line delamination, which was a common failure mode in undamaged, unreinforced connections. This resulted in a full recovery of the fire resistance time and a surplus of approximately 20% compared to the second configuration (4BP2R). Most importantly, the width of the initial splits developed in the connections during ambient tests considerably affected their fire resistance time after being retrofitted using the STS. For instance, more width (i.e., 3 mm) of the initial split existed in the connection configuration with the first bolt pattern (4BP1R) compared to that (i.e., 1 mm) in the configuration with the second bolt pattern (4BP2R), resulting in more heat penetrated the core of the beam section. This led to accelerated localized wood charring, which reduced the fire resistance time of the first connection configuration. Both connection configurations performed better and sustained the applied loads for longer under standard fire exposure compared to the identical damaged, STS-retrofitted connections without the wood plugs and strips protection, experimentally examined in a related prior study conducted by [18, 19].

7 – REFERENCES

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