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STRUCTURAL PERFORMANCE OF GLULAM TIMBER-STEEL BRACE CONNECTIONS REINFORCED WITH SELF-TAPPING SCREWS

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ABSTRACT: Modern mass timber braced frames rely on connection yielding to provide ductility and energy dissipation capacity under earthquake loads. However, the ductility and energy dissipation capacity of steel dowel connections can be limited by the onset of a brittle failure mechanism in the timber (e.g., row-shear, group tear-out, or tension failure) prior to significant dowel yielding. To address this challenge, this paper presents experimental results on the structural performance of timber-steel dowelled connections reinforced with self-tapping screws. Four full-scale connections were tested under monotonic loading with and without reinforcing screws. The tested connections had two internal steel plates that were fastened to the timber using steel dowels. The unreinforced connection was intentionally designed to exhibit a brittle row shear failure prior to yielding of the steel dowels. Results of the study demonstrated the brittle nature of row shear in timber connections and the potential for using self-tapping screws to promote a more ductile failure. While the unreinforced connections exhibited no ductility, the reinforced connections had an average ductility of 4.8. Overall, results of this study demonstrate the potential for using self-tapping screws to retrofit and reinforce a timber-steel brace connection for situations in which a connection may be predisposed to brittle row shear failure.

KEYWORDS: Mass timber, connections, internal steel plates, self-tapping screws, row shear, ductility

1 INTRODUCTION

In the last twenty years, the use of mass timber in mid-rise and high-rise buildings has increased dramatically and is expected to continue to grow in the coming decades [1]. In Canada, the maximum permissible height for mass timber buildings was recently increased to 12 storeys, which is expected to continue to fuel this demand [2]. However, as the height of tall mass timber buildings increases, so does the demand on the structural elements, requiring larger section sizes and higher-capacity connections to safely transfer loads to the structure's foundation. These connections are also key elements of a structure's seismic force resisting system (SFRS), which must be designed to have sufficient ductility in the event of a design-level earthquake. A European study analysing failures in 127 timber structures found that about one quarter of collapses occurred as a result of connection failure, more than half of which occurred in dowel-type connections [3].

One commonly used SFRS for tall timber structures are braced frames. In the seismic design of mass timber braced frames, the brace connections are typically designed to act as fuses, yielding during a large earthquake, dissipating seismic energy, and protecting surrounding structural elements. A common connection detail used in mass timber braced frames involves the use of steel dowel-type fasteners (e.g., bolts, dowels, or drift pins) in combination with steel plates that are inserted into slots in the timber. This type of connection is appealing because high strength and stiffness can be achieved by incorporating multiple slotted-in steel plates, and these plates are inherently protected from fire by the surrounding timber.

Under axial load, these connections can experience a variety of failure modes, including ductile failure through yielding of the steel fasteners and brittle failure of the timber member. Brittle failure modes include fracture over the net section, row shear failure, or group tear-out. In the design of these connections for tall timber frames, which require high-strength brace connections, one convenient approach to increase capacity is to introduced multiple slotted-in steel plates into the connection. However, this reduces the dowel bending length and results in the potential for brittle shear failure (e.g., row shear or group tear-out) with little-to-no ductility if careful attention is not paid to the design and detailing of the connection.

In the literature, there are few reported experiments on timber connections with multiple slotted-in steel plates and dowel-type fasteners tested at scales required for tall timber structures. Furthermore, there is an increasing need to better understand the behaviour of brittle failure modes in these connections and to develop novel strengthening approaches to improve their seismic performance, including ductility and energy dissipation capacity. One such approach that has been proposed in the literature but not studied in large-scale timber brace connections with

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slotted-in steel plates is the use of self-tapping screws as reinforcement. This study aims to address these knowledge gaps through experimental testing of four full-scale glulam timber connections with multiple slotted-in steel plates both with and without reinforcement under monotonic loading. The specific objectives of this study are to: (i) study brittle failure mechanisms in a full-scale timber connection with slotted in steel plates, (ii) determine if the use of self-tapping screws can prevent brittle failure in the tested connection and improve ductility and energy dissipation capacity, (iii) study the influence of end distance on the connection behaviour and the performance of the screw reinforcement.

2 BACKGROUND

There have been few studies reported on glulam timber connections for a multi-storey mass timber braced frame with multiple slotted-in steel plates and tested experimentally at full-scale. Several researchers have investigated the performance of small-scale timber-steel connections with a single slotted-in steel plate [4-8]. These studies have shown that the connection ductility depends largely on the connection geometry, fastener spacing, and material properties of the timber. A study by Yurrita et al. [9] examined the potential for brittle failure in large-scale pine glulam and laminated veneer lumber connections with two slotted-in steel plates and nine steel dowels. Fastener spacing and timber thickness were varied, and the results showed that block shear, row shear, net tension, and a combination of block and net shear failure were the observed failure mechanisms.

To determine the potential contribution of self-tapping screws to connection strength and ductility, Piazza et al. [10] tested timber-to-timber self-tapping screw connections with several orientations relative to the shear plane. The results found that that increasing the installation angle of the screw from 0° to 45° improved the load capacity and stiffness of the tested connections. Some researchers have also used reinforcing screws in timber connections with slotted-in steel plates and dowel-type fasteners to prevent brittle failure. In some connections tested by Dorn et al. [11], a clamp was used to simulate the reinforcement provided by self-tapping screws and the results showed the potential for improvements in strength and ductility. Lathuillière et al. [12] tested bolted moment-resisting connections reinforced with self-tapping screws under shear and moment. Although the connections did not simulate a brace connection under direct axial tension, the results did show that reinforcement through self-tapping screws was effective at controlling crack propagation and improving connection ductility.

Studies on small-scale timber connections reinforced with self-tapping screws have also been carried out. Zhang et al. [13] tested small-scale single dowel connections with a single slotted-in steel plate under direct axial tension. The results once again showed potential for reinforcing screws to improve connection ductility.

3 EXPERIMENTAL PROGRAM

The experimental program described in this paper consisted of 4 tests performed on full-scale glulam timber connections with multiple slotted-in steel plates and steel dowel-type fasteners. The specimens included two control connections (without reinforcing screws) and two reinforced connections. Other investigated parameters included the loaded end distance.

3.1 TEST SPECIMENS

Figure 1 shows the geometry of the slotted-in steel plate connections tested in this study. The glulam timber member measured 266 × 265 × 1300 mm. The holes and slots in the glulam member were fabricated using a computer-numerical control (CNC) machine. At one end, each glulam member had two 12 mm wide slots and 6 – 16 mm (5/8") holes perpendicular-to-grain, for the installation of the steel dowels. At the opposite end of the connection, 16 – 22 mm (7/8") diameter holes 310 mm (12") long were drilled in the parallel-to-grain direction for a glued-in-rod connection used to fix the specimen to the test frame, which was fixed to the laboratory floor.

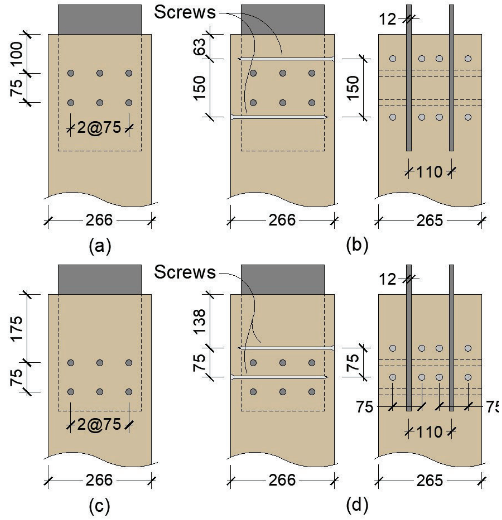

Figure 1: Tested connections with slotted-in steel plates: (a) C100, (b) C100-R, (c) C175, (d) C175-R

The tested connection included two 12 × 214 mm internal slotted-in steel plates. The slotted-in steel plates were connected to the timber using 16 mm diameter (d) steel dowels that were 266 mm long. The connection, based on the geometry in Figure 1, has a slenderness ratio (λ) of 6.9 (110/16 = 6.9), calculated as the ratio of the thickness of the timber (t) between the slotted-in steel plates (110 mm in Figure 1) divided by the dowel diameter (d).

Connection tests included those with and without self-tapping screws. The two control connections (without reinforcing screws) were denoted C100 and C175, in which the '100' or '175' is the loaded end distance in each

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connection. The two other connections had identical geometry to the control connection but were reinforced with self-tapping screws. These connections are referred to as C100-R and C175-R in this paper.

All connections with screw reinforcement had 8 - 250 mm long fully threaded 11 mm diameter Rothoblaas VGS 9380 self-tapping screws with a countersunk head. The screws were installed in pre-drilled holes measuring 6.35 mm (1/4") in diameter, according to the manufacturer's recommendations [14]. Figure 1 shows the configuration of the screws in the reinforced connections. The goal of this screw orientation was to strengthen the shear failure plane and arrest crack development in the direction of the load. Connection C100-R was reinforced with 4 screws across the shear plane and an additional 4 screws outside the loaded end to prevent timber splitting along the length of the member, which was observed in previous tests. In connection C175-R, 8 screws were placed across the shear plane, to examine the influence of additional screws on connection stiffness, strength, and ductility.

3.2 MATERIAL PROPERTIES

The glulam connections were fabricated of 24f-ES Spruce-Pine-Fir (SPF) glulam supplied by Nordic Structures and produced as per CSA O177-06 [15], as specified by CSA O86-19 *Engineering Design for Wood* [16]. This glulam grade has a density of 560 kg/m^3, a mean relative density (G) of 0.47, and a moisture content of 12%. Typical design characteristics are a modulus of elasticity of 13.1 GPa, a parallel-to-grain tension strength of 20.4 MPa, and a shear strength of 2.5 MPa [17].

The material properties of the steel dowels were determined by conducting direct tension tests on three coupons according to the guidelines in ASTM E8 [18]. Figure 2 shows the stress-displacement response of the dowels used in this study. The 16 mm dowel had an average yield strength, determined using the 0.2% offset method, of 825 MPa and an ultimate strength of 946 MPa. The Rothoblaas VGS 9380 reinforcing screws have a manufacturer's reported characteristic yield moment of 45.9 N-m and a yield strength of 1000 MPa [14].

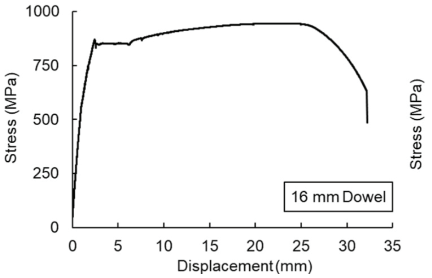

Figure 2: *Stress-displacement behaviour of steel dowel*

3.3 CONNECTION STRENGTH

Prior to the experimental testing, calculation of connection capacity was carried out according to the Canadian Wood Design Standard (CSA O86-19). Table 1 summarizes the calculated resistances of each connection for each failure mode. Additional information on these design calculations is available in [16]. Based on the design provisions in CSA O86-19, the unreinforced connections were expected to fail in brittle row shear Furthermore, the ratio of brittle to ductile failure (φ), taken as the row shear strength divided by the yield resistance, was approximately 0.6 for all of the tested connections. The reinforced connections had additional capacity against row shear and group tear-out because of the self-tapping screws. The results in Table 1 suggest that connection C100-R is still susceptible to row shear failure ($\varphi = 0.9$) while connection C175-R had yielding of the steel dowels as a predicted failure mode ($\varphi = 1.2$), and thus, was expected to exhibit the highest ductility amongst the tested connections.

Table 1: *Connection design strength*

Specimen	*Net Tension* (kN)	*Row Shear* (kN)	*Group Tear-out* (kN)	*Yielding* (kN)
C100	1071	304	684	501
C100-R	1071	446	826	501
C150	1071	304	684	501
C150-R	1071	589	969	501

3.4 EXPERIMENTAL TEST SETUP

Figure 3 shows the experimental setup for the connection tests. The connections were tested under direct axial tension. At one end of the timber member, a 1350 kN hydraulic actuator was used to apply the load, to which a steel double lap splice connection was used to connect the actuator to the slotted-in steel plates in the timber connection. The slotted-in steel plates were bolted to the actuator connection using two 25.4 mm (1") diameter high-strength (Grade 12) steel bolts.

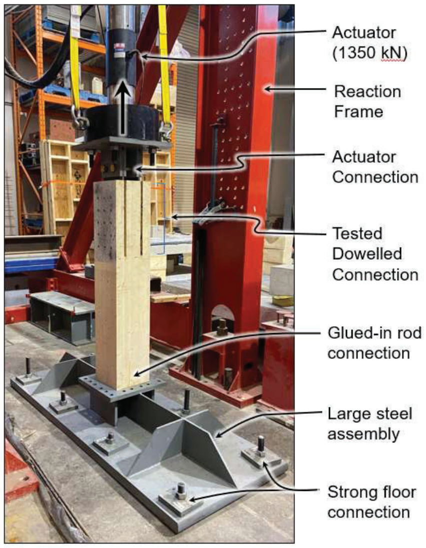

Figure 3: *Experimental test setup*

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The connection was fixed to the lab strong floor using a large steel assembly that included a 50.8 mm (2”) thick base plate and was connected to the laboratory strong floor using 8 – 28.1 mm (1.5”) diameter B7 threaded rods. The timber connection was attached to the steel assembly using a glued-in-rod connection, which was intentionally overdesigned to ensure it remained elastic during the test. The glued-in-rod connection consisted of 16 – 19.1 mm (3/4”) threaded rods embedded 305 mm (12”) into 22 mm (7/8”) holes in the glulam timber. The rods were glued in the timber using Sikadur-35 Hi-Mod LV, which is a two-part high modulus and strength, low-viscosity epoxy resin intended for grouting bolts or dowels in wood [19]. According to the manufacturer, the epoxy has a modulus of elasticity of 2.41 GPa, a tensile strength of 58 MPa, and an elongation at break of 4.2% [19].

3.5 TEST PLAN AND INSTRUMENTATION

The connections were tested under monotonic loading at a constant rate of 1 mm/min up to failure. Figure 4 shows the instrumentation used to measure the response of the connections during the test. The connection deflections were measured using nine linear potentiometers (LPs). Four LPs were installed at the top and bottom of the connection on opposite faces. These LPs were used to measure the displacement of the glued-in rod and actuator connections. Two string potentiometers (SPs) were also used to measure the displacement of the connection. The SPs were affixed beneath the dowelled connection and connected to the underside of the steel plate connected to the actuator. A 2000 kN load cell connected to the hydraulic actuator was used to measure the load applied to the connection during each test. The data was collected at 1 Hz for each test.

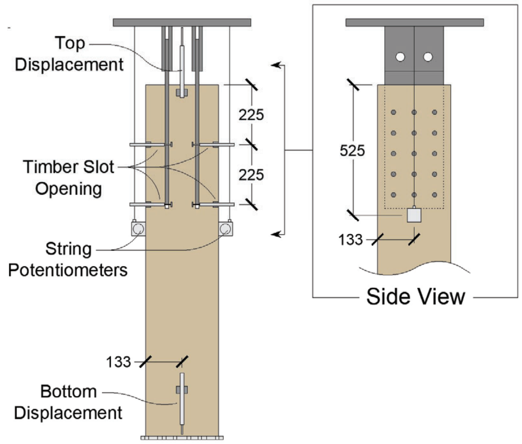

Figure 4: *Typical connection instrumentation*

4 RESULTS AND DISCUSSION

Figure 5 shows the connection force-displacement behaviour, measured using the SPs (see Figure 4) and Table 2 shows the structural response parameters for each connection, including the yield displacement, ultimate load, and ultimate displacement. It is noted that the ultimate displacement was determined as the displacement after the load dropped 20% from the ultimate load. In addition, to assess the potential for the use of self-tapping screws to improve the seismic performance of timber-steel connections, Table 2 also shows the displacement ductility of the connections, which was determined as the ratio of the yield displacement to the ultimate displacement ($\mu_\Delta = \Delta_u/\Delta_y$).

Table 2 *Structural Response Parameters*

Specimen	Δ_y (mm)	P_u (kN)	Δ_u (mm)	μ_Δ (mm/mm)
C100	-	730	2.4	-
C100-R	4.0	671	14.5	3.6
C150	-	692	5.2	-
C150-R	5.3	715	31.8	6.0

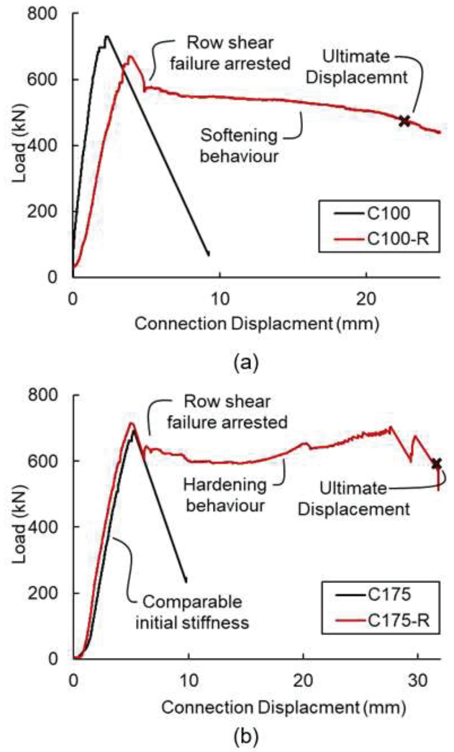

Figure 5: *Connection force-displacement behaviour (a) C100 and C100-R, (b) C175 and C175-R*

4.1 UNREINFORCED CONNECTIONS

The force-deformation responses in Figure 5 show that both unreinforced connections fail in sudden and brittle row shear failure, and as a result, had no ductility. Comparing peak load, the unreinforced connections had an average strength of 711 kN, and the strength of C100 was approximately 5% larger compared with connection C175. The ultimate displacements of the connections were 2.4 and 5.2 mm, respectively, demonstrating the high stiffness exhibited by these connections as well as the potential for very brittle failure if careful attention is not paid to their detailing during design.

Figure 6 shows the row shear failure for connection C100, which was similar to that of C175. The result shows the formation of a distinct shear failure plane for each row of fasteners. In some cases, timber 'plugs' protrude from the specimen along the shear failure plane. Distinct timber plugs were generally observed in the central portion of the connection (between the steel plates), in which the dowel is supported by the slotted-in steel plate on either side. In the timber side members, the row shear failure plane formed as either a timber plug or as a single splitting crack through the centre of the holes, depending on the row of fasteners in the connection.

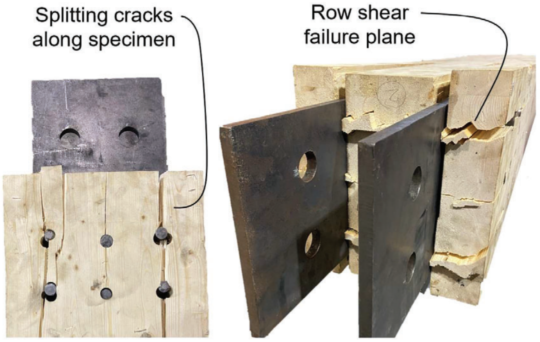

Figure 6: *Row shear failure of connection C100*

Comparing the strength of the unreinforced connections with the design values according to the Canadian Wood Design Standard (CSA O86-19), the results show that the code did correctly predict the mode of failure. However, the observed row shear strength of connections C100 and C175 were 2.4 and 2.3 times greater than the predicted design strengths, respectively. The main difference between connections C100 and C175 was the loaded end distance, which were 100 mm and 175 mm respectively. Despite the increase in loaded end distance, connection C100 had a row shear strength that was within 5% of C175. This suggests that the code requirement that the minimum of the loaded end distance and fastener spacing is an adequate approach to calculating the row shear capacity of the connection. Despite the fact that these design values are based on the characteristic strength of the timber, the results do suggest that current provisions in CSA O86-19 for large timber-steel connections with multiple slotted-in steel plates may be conservative.

4.2 REINFORCED CONNECTIONS

Figure 5 compares the response of the connections reinforced with self-tapping screws with their respective controls. Overall, the results show that the self-tapping screws were effective at altering the behaviour of the connections and preventing sudden and brittle row shear failure. The reinforced connections had ultimate strengths that were within 10% of their respective controls, suggesting that the presence of the self-tapping screws did not have a significant effect on the connection strength. Furthermore, the results also show that the addition of the self-tapping screws also did not have a significant effect on the stiffness of the connections. This could be attributed to the fact that the self-tapping screws were not installed directly adjacent to the fasteners, something that is commonly done in practice. Despite not having a large influence on strength or stiffness, the addition of the self-tapping screws did result in large increases in ductility, as connections C100-R and C175-R had a displacement ductility of 3.6 and 6.0, compared with the unreinforced connections which did not exhibit any ductility. The connections also exhibit large increases in dissipated energy of 22.2 kN-m and 18.3 kN-m, for connections C100-R and C175-R, respectively, which is 5.67 and 7.30 times higher than their respective control connections.

With respect to observed behaviour, Figure 7 shows the failure mode for connection C100-R. At a displacement of approximately 4 mm, connection C100-R experienced a small drop in load carrying capacity (~15% from the maximum load), highlighted on Figure 5, which corresponded to the initiation of a row shear failure in the timber. However, the presence of the reinforcing screws effectively prevented propagation of the shear failure plane to the edge of the timber, which is highlighted in Figure 7(a), which prevented further drop in load carrying capacity.

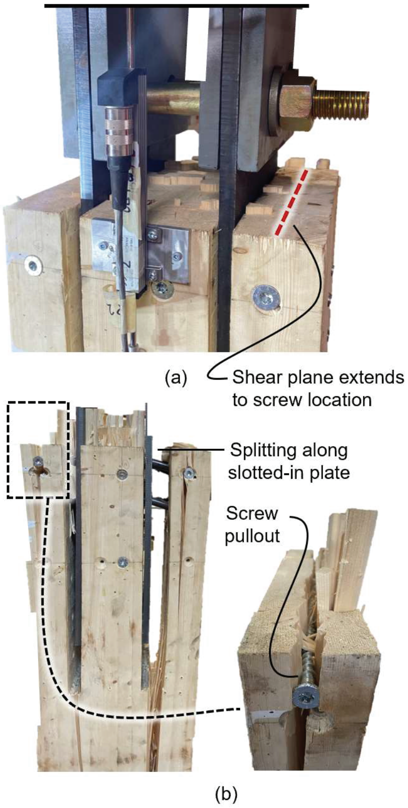

Figure 7: *Glulam timber test specimen*

After the initial drop in load carrying capacity, the force-displacement response of the connection shows a post-peak plateau up to approximately 20 mm, during which the load dropped by 20%. Beyond 25 mm of displacement, the connection exhibited gradual softening to a displacement of 75 mm, at which point the connection was able to carry 15% of its peak load carrying capacity and did not experience any sudden drops in load carrying capacity, and the test was stopped. Gradual softening of the connection was attributed to embedment failure of the self-tapping screws, shown in Figure 7(b), which occurred parallel to the load in a crack along the row of fasteners. Under increasing displacement, the screws (as well as the dowels) were forced out of the splitting cracks in the timber, resulting in a gradual loss in load.

Connection C175-R, which had 8 screws providing additional row shear reinforcement had comparable behaviour to connection C100-R up to the peak load, but the post-peak response was markedly different. Figure 8 shows the failure mode for connection C4-6R. At the peak load, the force deformation behaviour showed a ~15% drop in load carrying capacity which, similar to connection C100-R, corresponded to the formation of a shear failure plane parallel to the load, identified in Figure 8(a). Comparing the deformation patterns in Figure 7(a) and 8(a), the results show indicate that the damage to connection C175-R was much smaller when compared with connection C100-R, which is likely the result of the additional reinforcing screws.

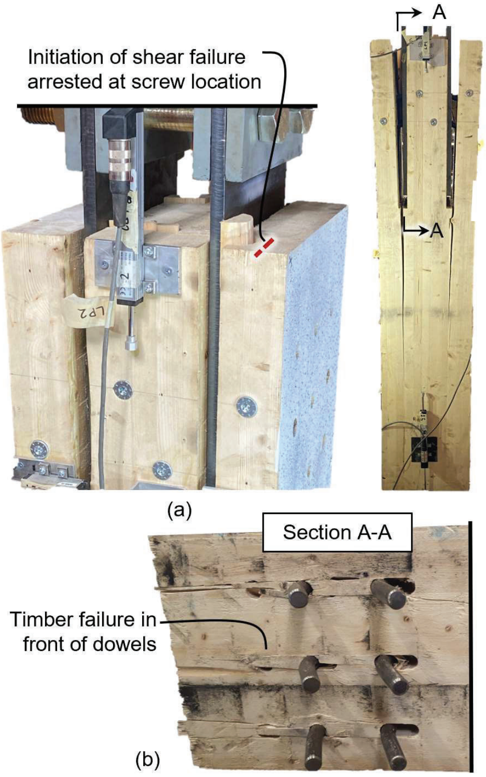

Figure 8: *Glulam timber test specimen*

Examining the force deformation response of connection C175-R in Figure 5, the results once again show that the reinforcing screws were effective at preventing brittle row shear failure of the connection and the force-deformation response shows a relatively constant post-peak plateau following the initial drop in strength up to a connection displacement of approximately 15 mm.

At displacements beyond 15 mm, C175-R shows a hardening response, characterized by an increase in stiffness and strength up to a local maxima of 703 kN, representing 96% of the maximum load, at a connection displacement of 27.5 mm. This behaviour is attributed to interaction between the self-tapping screws and the steel dowels, which come into contact with one another once significant dowel bending has occurred. Eventually, splitting along the length of the slotted-in steel plates resulted in the timber side members separating completely from the main timber member between slotted-in steel plates, shown in Figure 8(b), causing a drop in load carrying capacity of 20% from the peak load. It is worth noting that even after failure of the timber side members, the main member was still capable of carrying over 500 kN of load (roughly 70% of the ultimate capacity).

5 CONCLUSIONS

The goal of this research project was to study the behaviour of large-scale timber-steel connections with multiple slotted-in steel plates and dowel type fasteners prone to brittle row shear failure and investigate the potential use of self-tapping screws to improve their ductility and energy dissipation capacity. The study included tests on 4 large-scale connections under axial monotonic loading. The following specific conclusions are drawn:

1. Connections tested without reinforcing screws failed in sudden and brittle row shear failure with no ductility and little-to-no energy dissipation capacity. The larger loaded end distance in connection C100 was not found to have an influence on the load carrying capacity of the connection.
2. The CSA O86-19 design standard was found to be able to determine the mode of failure in the connections tested without reinforcing screws, however, the standard over-predicted the row shear strength of the connections by 2.3 times on average.
3. The use of self-tapping screws was found to be an effective approach for preventing premature row shear failure and shift the failure mode, permitting a more ductile response. The studied connections with 4 and 8 reinforcing screws had displacement ductilities of 3.6 and 6.0, respectively, a significant improvement in performance when compared to the connections tested without reinforcing screws.
4. The use of self-tapping screws was also found to increase the energy dissipation capacity of the connections by 5.67 and 7.30 times for connections

C2-6R and C4-6R, respectively, compared with the control connections without reinforcing screws.

Overall, the results suggest that timber-steel connections with multiple slotted-in steel plates have the potential to meet the large force demands required for tall mass timber braced frames. However, careful attention must be paid to ensure the connections are detailed to prevent brittle row shear failure. Furthermore, in connections that may be prone to brittle shear failure, results of this study show that the use of self-tapping screws is a feasible approach to shifting the failure mode to a more ductile failure with additional energy dissipation capacity. However, more testing on large-scale connections with varying geometry, dowel slenderness ratio, and self-tapping screw configurations is required.

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