WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

EXPERIMENTAL TESTS ON CONNECTIONS WITH DOWELS AND SLOTTED-IN STEEL PLATES UNDER CYCLIC LOADING

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ABSTRACT: In dowel-type connections, the occurrence of brittle failure modes before yielding can significantly limit the ductility and energy dissipation capacity of structural systems during major earthquakes. To address these challenges, experimental cyclic tests were conducted on four different glulam connection series, featuring dowels installed in single slotted-in steel plates, designed following the Canadian timber design standard CSA O86. This paper presents the results of these experimental tests, including connection stiffness, strength, ductility, failure modes, and the influence of connection configurations on overall performance.

KEYWORDS: Brittle failure modes, Dowel-type connections, Mass-timber braced frames

1 – INTRODUCTION

In recent years, the timber construction industry has witnessed significant advancements due to engineering innovations and the development of engineered wood products as primary structural materials for mid- and high-rise timber structures [1]. The extensive use of mass timber products in such structures necessitates more efficient lateral force-resisting systems (LFRS) to address challenges such as insufficient moment-resisting capacity, unexpected brittle failure modes in connections, and inadequate lateral stiffness [2] [3]. Among the most widely accepted LFRS for timber structures are timber-braced frames [4]. Modern mass timber-braced frames rely on the design of connections as energy-dissipating fuses to achieve ductility and improve performance. A commonly used connection in mass timber-braced frame systems employs steel dowel-type fasteners (e.g., bolts and dowels) with slotted-in steel plates. These connections can exhibit either ductile or brittle failure modes. However, the occurrence of brittle failure modes—such as net tension, row shear, and group tear-out (block shear)—before the yielding of fasteners in dowel-type connections restricts the system's ductility and energy dissipation capacity. To overcome these limitations and achieve the desired system-level ductility, experimental cyclic tests were performed on glulam timber connections using dowels inserted in one slotted-in steel plates. These connections were designed in various configurations following the Canadian timber design standard CSA O86 [5] guidelines. The objectives of this study are to evaluate the stiffness, resistance, ductility, and failure modes of the connections and validate the CSA O86 design approach.

2 – BACKGROUND

Extensive research has been conducted on the behaviour of connections in mass timber structures, with a predominant focus on small-scale connections. These studies have explored the influence of parameters such as dowel slenderness, fastener spacing, end distance, and pre-tensioning on connection performance. In the literature on dowel-type connections with slotted-in steel plates loaded parallel to wood grain, Mohammad and Quenneville [6] proposed design equations based on a test campaign involving 30 groups of connections, each featuring up to four bolts, 12.7 mm and 19.1 mm in diameter, placed in one or two rows, under static load. Sandhaas and van de Kuilen [7] tested 322 timber joints with up to five dowels, ranging from 8 mm to 30 mm in diameter, placed in one row under static load. Bocquet et al. investigated the Beam-On-Foundation (BOF) modelling of the bolted connections and made some recommendations for dimensioning dowel-type connections with multiple shear planes [8]. Breijinck et al. [9] tested 12 connection specimens with one or two dowels, 11 mm and 16 mm in diameter, with and without reinforcing screws. Their findings highlighted the brittle failure modes inherent in timber connections with traditional fasteners and demonstrated the need for further studies to enhance ductile behaviour. More

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https://doi.org/10.52202/080513-0262

recently, Baird et al. [10] examined 12 specimens of connections with bolts, 9.5 mm and 12.7 mm in diameter, installed in one or two slotted-in steel plates and subjected to static and cyclic loading. Their results underscored the critical importance of considering the ratio of the connection strength under ductile failure mode to that under brittle failure mode in the design process.

3 – EXPERIMENTAL PROGRAM

The experimental program detailed in this paper comprised 32 tests conducted on four series of glulam connections, featuring configurations with one slotted-in steel plates and steel dowels. Each series included eight specimens, with two static and six cyclic tests performed per series. The primary parameters investigated were the dowel spacing parallel and perpendicular to the grain, and the end distance.

3.1 TEST SPECIMENS

Fig. 1 shows the connection configurations used in this study. The variables were examined in the following categories:

a) Spacing parallel to the grain: 4d vs 7d (Series S1 vs S2),
b) Spacing perpendicular to the grain: 3d vs 5d (Series S1 vs S1A),
c) End distance: 7d and 10d (Series S2 vs S2+)

The glulam timber members measured 215×241×1500 mm. The glulam members were Nordic Lam+ grade 24F-ES/NPG fabricated and supplied by Nordic Structures. This glulam is fabricated mostly of black spruce (*Picea Mariana*) and has a mean relative density of 0.47, modulus of elasticity of 13.1 GPa, specified parallel-to-grain tensile strength of 20.4 MPa, and shear strength of 2.5 MPa [11].

The tested end of the specimens featured 12.7 mm (1/2”) diameter holes for the installation of steel dowels, along with the slots for the steel plates. The slotted-in plates were made of 350W grade mild steel, with thicknesses of 12.7 mm (1/2”) and they were fit in the slots of 15 mm. The plates were connected to the timber member using 12.7 mm (1/2”) diameter dowels, which were 282 mm long. The holes in the steel plates were 14.7 mm in diameter. The dowels were fabricated from 300W steel, with an ultimate tensile strength of 450 MPa and a tensile yield strength of 300 MPa. The holes and slots in glulam members and the holes in steel plates were machined using a computer numerical control (CNC) machine at the factory.

The opposite end of the specimens was furnished with 30 inclined Rothoblaas VGS self-tapping screws (STS) with countersunk heads to ensure capacity protection during testing and facilitate reuse. The STS connection configuration included fifteen 13×200 mm alternating with fifteen 13×250 mm screws. All screws were installed in pre-drilled holes and were furnished with VGU1345 washers. According to the manufacturer, the STS have the characteristic tensile strength of 53 kN, and characteristic yield strength of 1000 MPa.

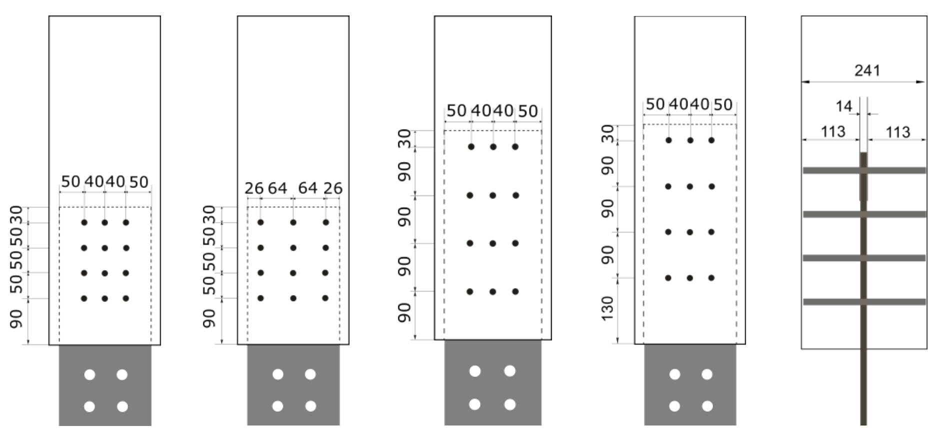

Figure. 1 Configurations of tested connections with slotted-in steel plates

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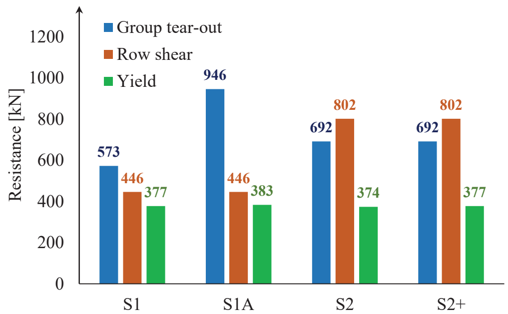


Figure. 2 Predicted mean yield and brittle resistance values

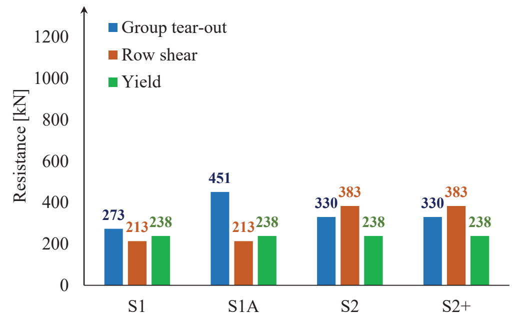


Figure. 3 Predicted design yield and brittle resistance values

3.2 CONNECTION DESIGN

Prior to the experimental testing, the expected mean and design (factored) resistances for short-term loading (wind and seismic) of the connections were estimated according to the CSA O86-24 [5] design standard. The predicted mean and design values for yield and brittle failure modes for each configuration are illustrated in Fig. 2 and 3, respectively. Based on the predicted mean values, the expected failure modes were predominantly ductile (yielding of the dowels). Considering the factored design values, the CSA O86 design procedure predicted a brittle failure mode (row shear) for Series S1 and S1A, while predicting a ductile failure mode for Series S2 and S2+. The ratios of brittle to ductile failure modes for design and mean resistance values are presented in Table 1. When the ratio is less than one, the brittle failure mode is predicted to govern.

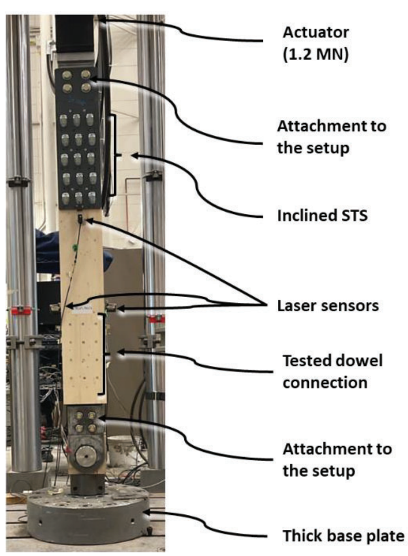


Figure. 4 Test setup

3.3 TEST SETUP AND INSTRUMENTATION

Fig. 4 shows the typical experimental test setup. The specimens were tested in axial tension under monotonic static and non-reversed cyclic loading. At one end of the connection, a hydraulic actuator with a 1.2 MN load cell was used to apply the load. The opposite end was attached to a hinge support fixed to the laboratory's strong floor. Each steel plate was attached to the hinge with 22 mm (7/8”) diameter high-strength steel bolts at each end. Each plate on the top of the specimen was instrumented with one laser sensor (Keyence IL-030), and each slotted-in plate was equipped with two laser sensors (Keyence IL-065), one on each side, to measure the slip of the plates relative to the wood member.

3.4 LOADING PROCEDURES

First, the connections were tested under monotonic static loading at a constant rate of 2.5 mm/min until the load dropped to 80% of its maximum. These tests aimed to evaluate the failure mechanism and determine the connection yield displacement (Δ_y), which was subsequently used to define the cyclic loading protocol. Cyclic loading tests were then conducted based on the European Test Standard EN12512 [12]. Fig. 5 illustrates the cyclic loading protocol developed for this study. The cyclic tests were performed in displacement control, with increments based on the $\Delta_y = 2$ mm determined from the monotonic tests.

Table 1: The ratio of brittle to ductile failure mode for mean and design resistance values

Series	Mean	Design
S1	1.18	0.89
S1A	1.16	0.89
S2	1.85	1.39
S2+	1.84	1.39

https://doi.org/10.52202/080513-0262

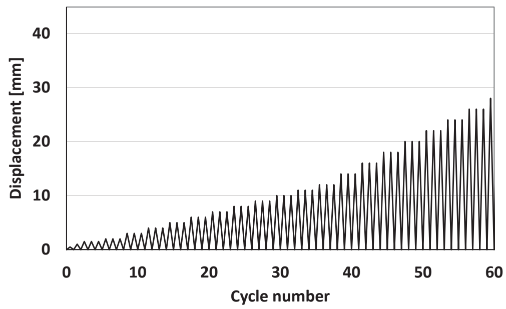


Figure. 5 Tension cyclic load protocol

4 – RESULTS AND DISCUSSION

The typical hysteresis curves for the connections tested under cyclic loading are shown in Fig. 6. Fig. 7 compares the average backbone curves, while Table 2 summarizes the average key response parameters, including the yield load and displacement (P_y and Δ_y), the ultimate load and displacement (P_u and Δ_u), the maximum load (P_{max}), the elastic stiffness (K_e), and the displacement ductility of the connections ($\mu_\Delta = \Delta_u/\Delta_y$). The yield load and displacement were determined using the 5%-diameter offset method explained in [13]. The ultimate displacement was defined as the displacement at which the load dropped to 80% from the maximum load.

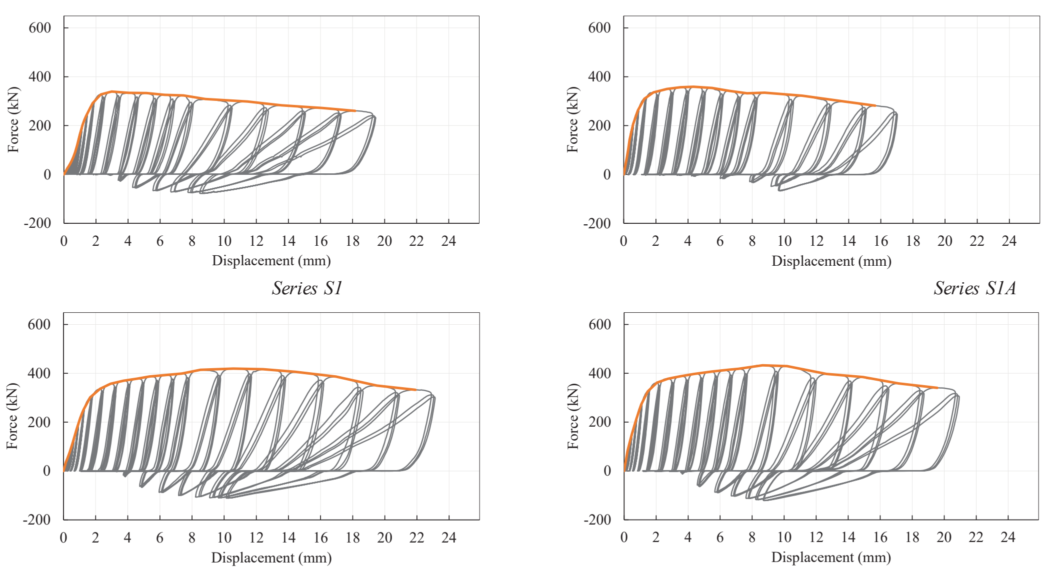
The backbone curves in Fig. 7 for Series S1 and S1A (4d in-row spacing) exhibited a negative slope immediately following the yielding of the dowels, indicating a more brittle behaviour. In contrast, the backbone curves of Series S2, and S2+ (7d in-row spacing) developed a plateau after reaching the yield point, reflecting a more ductile behaviour.

Using data in Table 2, a comparison of the variables listed in Section 3.1 provided the following results:

a) Increasing the spacing parallel to the grain from 4d to 7d improved the strength, and ductility, the connections by 17%, 77%, respectively, while did not significantly affect the stiffness.
b) Increasing the spacing perpendicular to the grain from 3d to 5d had no significant effect on strength stiffness or ductility.
c) Increasing the end distance from 7d to 10d had negligible effects on strength, stiffness, and ductility.

Fig. 8 presents typical failure modes and deformation patterns of the dowels in specimens. It is noteworthy that the observed failure mode in all specimens involved yielding of dowels followed by splitting of the wood along the perimeter rows. In Series S2, a trace of plug shear was observed in the vicinity of the steel plate where the dowels bent the most (see Fig. 8 (c)). These plugs were not observed in series S2+ with a larger end distance.

The predictions of mean resistance recalculated using the measured relative density of wood compared with the experimental maximum loads (Table 3) revealed that CSA O86 method slightly overestimated the mean resistance values for connections with 4 d in-row spacing (Series S1 and S1+) and slightly underestimated the mean resistance for connections with 7d spacing (Series S2 and S2+).



Series S2 *Series S2+*

Figure. 6 Typical hysteresis curves for specimens with single slotted-in plate

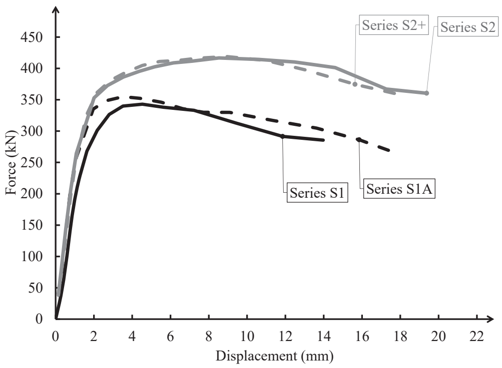


Figure. 7 Average backbone curves for connections

Table 2: Mean values of key structural response parameters of the connections

		S1	S1A	S2	S2+
P_y	kN	319	327	337	342
Δ_y	mm	1.9	1.7	1.7	1.8
P_{max}	kN	347	359	406	421
P_u	kN	280	285	333	339
Δ_u	mm	13.4	16.4	21.5	20.5
K_e	kN/mm	286	297	301	288
μ_Δ		7.1	9.6	12.6	11.4

5 – CONCLUSION AND FUTURE WORK

This study forms part of a comprehensive investigation into the seismic behaviour of innovative braced timber frame systems. The primary objectives were to assess the structural performance of timber connections with multiple dowels and slotted-in steel plates by testing under cyclic loads and comparing the test results with resistance values predicted by the CSA O86 standard. A total of 32 static and cyclic loading tests were conducted across four series. The findings highlight that increasing dowel spacing parallel to the grain from 50 mm (4d) to 90 mm (7d) enhanced strength and ductility and had no significant effect on the stiffness, while increasing spacing perpendicular to the grain from 40 mm (3d) to 64 mm (5d) primarily improves ductility and did not significantly impact the strength and stiffness of the connections. Failure modes of the specimens were predominantly failing through dowel yielding and wood splitting. Finally, comparisons with the CSA O86 design predictions suggest that the standard provides reasonable estimates for the tested configurations.

The findings demonstrate that connections with dowels and single slotted-in steel plates are capable of withstanding high force demands. However, the risk of brittle failure modes, such as wood plug shear, must be carefully considered in the design process. When applying the design provisions of CSA O86, meticulous attention is required to ensure both accuracy and safety in connection design. Future research will focus on evaluating specimens with double slotted-in steel plates and investigating appropriate reinforcement strategies for these connections. Additionally, a more comprehensive study on the cyclic performance of dowels with single and double slotted-in steel plates across various configurations is planned for publication in the near future.

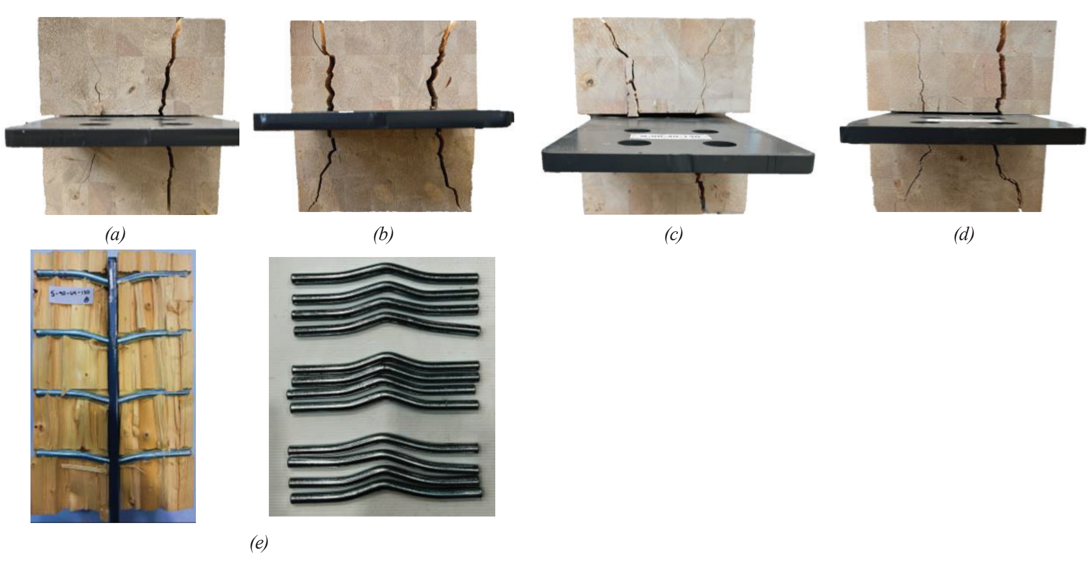


Figure. 8 Typical failure modes of series (a) S1, (b) S1A, (c) S2, (d) S2+, (e) Typical deformation of the dowels

https://doi.org/10.52202/080513-0262

Table 3: Ratio of maximum test load to predicted mean and design resistance

Series	Mean resistance	Design resistance
S1	0.92	1.63
S1A	0.94	1.69
S2	1.09	1.71
S2+	1.12	1.77
Average	1.02	1.70

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support provided by the NSERC Alliance Grant project Next-Generation Wood Construction and the Ministère des Ressources naturelles et des Forêts du Québec (MRNF). We also extend our appreciation to Nordic Structures and Rothoblaas for supplying materials and sharing their technical expertise. Special thanks go to the Centre de recherche sur les matériaux renouvelables (CRMR) technicians Jean Ouellet, Félix Pedneault, Daniel Bourgault, and Jean Brouillette for their invaluable assistance throughout the experimental work.

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