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SEISMIC PERFORMANCE OF RIVETED CONNECTIONS IN HEAVY TIMBER CONSTRUCTION

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SUMMARY

Results from a test program on the seismic behaviour of timber rivets used in heavy timber construction are presented, with emphasis on braced timber frames. First a literature review on timber rivets is presented, including the historical development of the fastener and previous research work. This is followed by the results from quasi-static tension and cyclic tests on riveted connections in four different engineered wood products: glued laminated timber (Glulam), laminated veneer lumber (LVL), parallel strand lumber (PSL) and laminated strand lumber (LSL). All connections were designed to fail in rivet yielding mode according to the Canadian CSAO86 Standard for Engineering Design in Wood. Based on the test results, characteristics of these riveted connections under seismic loads are discussed.

INTRODUCTION

Timber rivets, also known as glulam rivets, are high-strength steel nails with a flattened oval-shaped shank and a wedge shaped head. They are available in lengths of 40 mm, 65 mm and 90 mm. Timber rivets are typically used in connections for heavy trusses (Figure 1a), purlin to beam or beam to column connections, column to diagonal brace, or as base connections for arches (Figure 1b). The hot-dip galvanized rivet is made to have Rockwell hardness (Rc) from 32 to 39, and an ultimate tensile strength of at least 1,000 MPa. The rivet is driven through a pre-drilled mild steel side plate with a minimum thickness of 6.4 mm until the tapered head deforms the 6.8 mm diameter hole and wedges tightly. The wedging provides a certain degree of fixity, which restricts the rotation of the nail head. This increases the stiffness and strength of the joint and allows rivets to have a greater load transfer per unit contact area than most other conventional wood fasteners.

PREVIOUS RESEARCH IN RIVETED CONNECTIONS

Timber rivets were originally developed in Canada in the 1960s by Borg Madsen and William McGowan [1], at that time researchers of the Western Forest Products Laboratory (Forintek Canada Corp. since 1979). They considered many nail geometries and finally came out with an oval shape nail type fastener to be used in conjunction with pre drilled metal plates. The oval shape was chosen because of its greater

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cross-section modulus, while the high strength steel was chosen to increase the length over which the load is transferred. The oval shaped cross section of the rivet placed with its long dimension parallel to the grain does not cut the wood fibers, but instead pushes them aside as the rivet is driven into place.

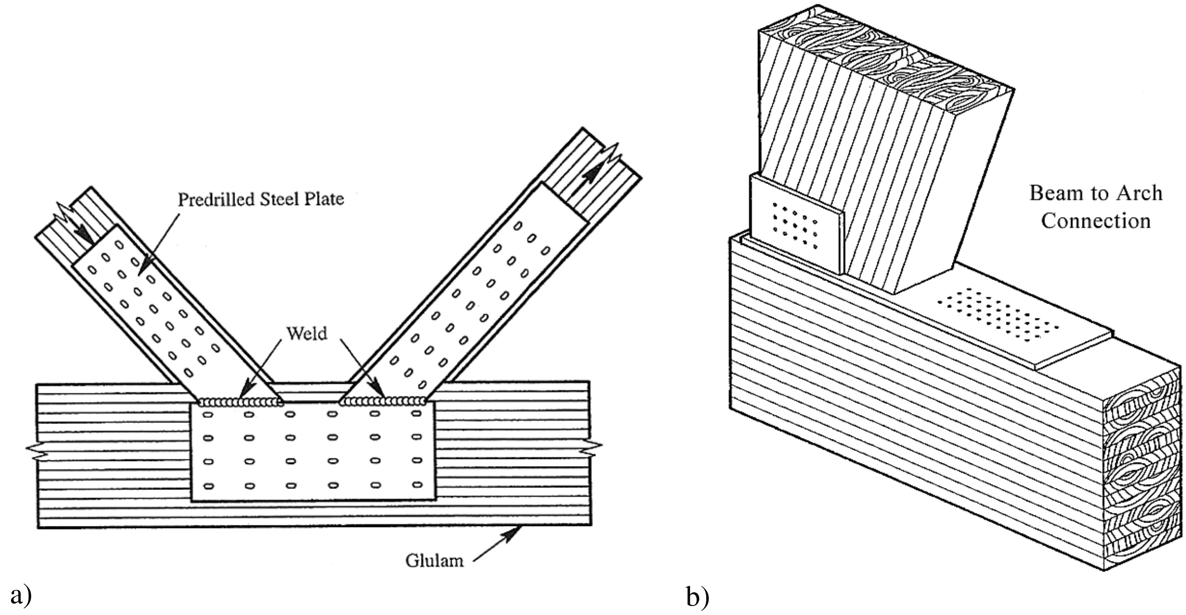


Figure 1. a) Typical heavy truss riveted connection; b) Beam to arch riveted connection.

Madsen and McGowan [2] undertook a large testing program, using over 40,000 rivets in numerous joint configurations. The research results from this study laid the foundation for the use of glulam riveted connections in timber construction. Design provisions for glulam rivet connections in the 2001 edition of the Canadian standard for Engineering Design in Wood CSA O86.1 [3] are based primarily on the method developed by Foschi and Longworth [4]. According to that method, riveted connections loaded parallel-to-grain are governed by either (a) a rivet yielding failure mode; (b) a wood tension parallel-to-grain failure at the edge of the connection; or (c) a combined shear and tension failure in the wood around the group of rivets.

The rivet yielding failure mode, exemplified by rivet bending and yielding together with wood crushing, was first studied by Foschi [5]. Foschi also studied the effect of rivet penetration and the effect of direction of loading with respect to grain orientation. Using a similar approach, Erki [6] later developed a model that also accounts for the axial forces in the rivets. The capacity of the glulam riveted connections in rivet yielding mode was also studied using the European Yield Model by Buchanan and Lai [7]. For the wood failure mode, Foschi and Longworth [4] investigated the stress distribution around the rivet cluster using finite element analysis. They verified their analytical model with test results on riveted connections in Douglas-fir glulam and offered the following conclusions: (i) Rivet spacing controls the failure mode; (ii) Larger spacing results in a rivet yielding failure mode; (iii) Smaller spacing produces a wood failure mode, usually a sudden block-shear around the group of rivets even at loads much lower than the rivet yield capacity; (iv) For the same rivet spacing, a larger end distance leads to an increase in the ultimate load based on the wood shear failure.

Fox and Lincoln [8] investigated the effect of plate thickness and hole size on the rivet yielding capacity. Karacabeyli and Foschi [9] performed a theoretical and experimental study on eccentrically loaded glulam riveted connections. They developed a model for predicting the connection capacity in the rivet yielding mode, and made recommendations for avoiding a wood failure mode in moment connections. Buchanan and Lai [7] investigated the behavior of timber rivets in radiata pine glulam timber and found that timber rivets in New Zealand radiata pine glulam have 70% to 90% of the strength of rivets in Canadian Douglas fir. Finally, Karacabeyli and Fraser [10] carried out tests to extend the application of glulam riveted connections to spruce-pine (SP) glulam and sawn timber. Based on the results, a species (material) factor H was introduced in the 1989 Edition of CSA Standard O86.1 to include effects of wood products other than Douglas fir glulam. The value for H ranges from 0.35 for sawn timber (northern species) to 0.8 for SP glulam. This study also resulted in adoption of withdrawal load capacities for riveted connections in CSA O86. Recently, design procedures for timber rivets have been included in the USA wood design standard, the National Design Specification for Wood Construction [11].

MONOTONIC AND CYCLIC TESTS ON DIAGONAL BRACES WITH TIMBER RIVETS

Since the seismic response of braced timber frames largely depends on the brace connections, the main objective of the experimental program was to characterize the behavior and failure modes of diagonal braces with riveted connections subjected to monotonic and cyclic loading.

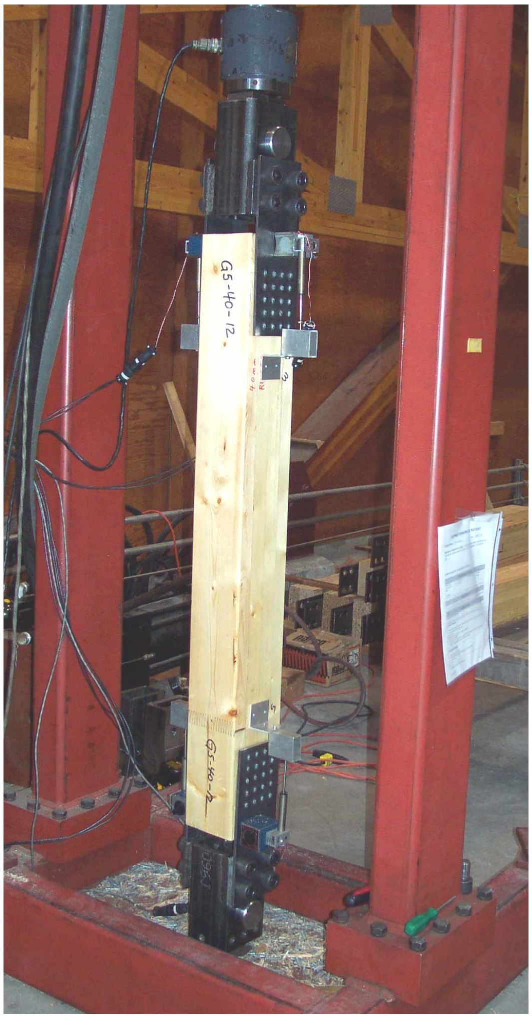
Materials and Methods

Displacement controlled monotonic tension and cyclic tests were conducted on a total of 48 brace specimens with four different wood products. The diagonal brace members consisted of a main wood member (SP Glulam, PSL, LSL, or LVL) and double-sided riveted connections on both ends. Each connection utilized 6.4 mm steel side plates and 20 rivets (4 rows of 5) on each side of the wood member, for a total of 40 rivets on each end of the brace. The spacing between rivets was 25 mm in all directions while the end distance was 75mm. Three brace specimens of each configuration were tested in monotonic tension tests, while five replicates were tested using the cyclic testing protocol [12]. Specifications of the brace members tested including the modulus of elasticity (MOE) obtained from third point loading tests are given in Table 1.

Table 1. The test matrix for diagonal braces with riveted connections.

Material	Designation	Average MOE [MPa]	Cross Section [mm]	Rivet Length [mm]	Number of Replicate	Type of Test
Glulam	SP 20f-EX	10,783	130 x 152	40	3	Tension
				40	5	Cyclic
				65	3	Tension
				65	5	Cyclic
LVL	Aspen 1.8E	10,821	89 x 151	40	3	Tension
				40	5	Cyclic
PSL	D. Fir 2.0E	14,166	89 x 178	40	3	Tension
				40	5	Cyclic
		14,165	130 x 178	65	3	Tension
				65	5	Cyclic
LSL	1.7E	12,089	89 x 300	40	3	Tension
				40	5	Cyclic

The test setup with a brace specimen placed vertically in the testing frame and prepared for testing is shown in Figure 2a, while a simplified diagram is shown in Figure 2b. The brace was connected to a bolted fixture at the top and bottom. The top of the brace was also attached to the load cell and the servocontrolled actuator. In addition, two rotational hinges (pins), one at the top and one at the bottom, were introduced to minimize the influence of secondary bending moments and ensure almost pure axial state of loading for the specimens. A pair of rollers placed on both sides of the specimen prevented out-of-plane movements during the compression half cycles.



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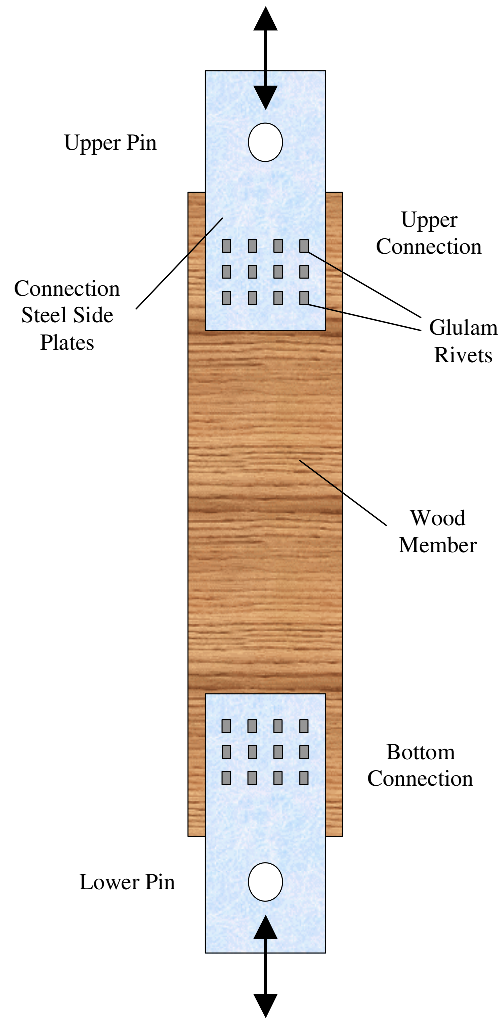

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Figure 2. a) A photo of the test setup for brace specimens with riveted connections; b) Diagram of the test setup (connections shown with fewer rivets that in the specimens tested).

RESULTS AND DISCUSSION

During the monotonic tension tests, glulam riveted connections yielded in a ductile single shear mode. The early behavior was almost completely governed by yielding of the fastener, while the failure mode was characterized by extensive wood crushing and fastener pullout from the wood. It was observed during the tests and later confirmed from the data analysis, that the top and bottom brace connections experienced significantly different deformation levels. Once non-linear deformations started to develop in one of the connections, the reduced stiffness of that particular connection would result in an increase of the deformation demand in that particular connection. This connection will be referred to as the "weaker" connection in the remainder of the text. Regardless of which connection in a brace is weaker or stronger, this finding was very important for understanding the seismic behavior of braced timber frames. Average response from the weaker connections in four materials obtained from monotonic tension test of brace specimens with 40 mm rivets is shown in Figure 3. The results showed that riveted connections showed highly ductile behavior when used with any wood-based material. Connections in LSL were able to carry the highest load of all materials used, however, the deformation capacity of these connections was lower than that of the other three materials.

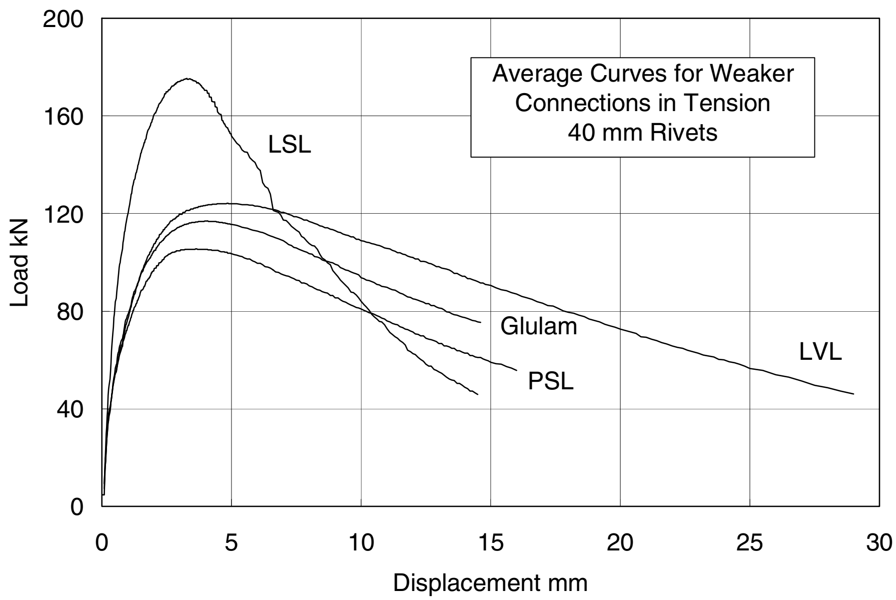
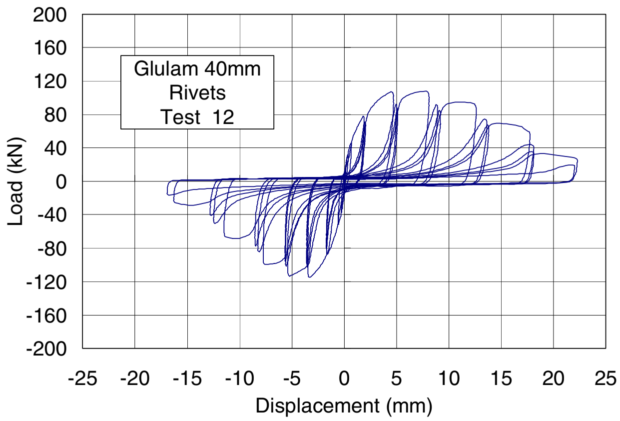


Figure 3. Average response from the weaker connections in four materials obtained form monotonic tension tests.

Typical load-deformation relationship obtained from cyclic tests on brace members in different wood products is shown in Figure 4. Significant pinching of the hysteresis curves occurred in all cases. This is as a result of the irrecoverable crushing of the wood that leaves a gap at load reversals. During subsequent excursions through this gap region, lateral resistance and energy dissipation occurs almost entirely in the metal connectors. The first hysteresis loop in a cycle of three therefore is the widest and shows the highest resistance, while subsequent cycles are narrower and typically achieve lower resistance for a given displacement. This degradation of strength stabilized after three cycles and the third cycle should therefore be considered to represent the actual resistance when cyclic loading is expected.

It was found that in riveted connections the pinching effect was most significant at higher deformation levels, while the hysteresis loops were thicker at lower deformation levels. Since the area inside the hysteresis loop for each cycle represents the amount of energy dissipated during that cycle, pinching in riveted connections reduces the hysteretic damping of the structure. However, the shape of the hysteresis loop (pinching) is not the single most important parameter for adequate seismic behavior of the connections. The ability of the connection to sustain large deformations without significant strength deterioration is also very significant [13]. That is exactly the behavior that riveted connections exhibited during the cyclic tests. They showed very ductile behavior and were able to carry a significant portion of the load even at high deformation levels. During the alternating load cycles riveted connections yielded in a ductile single shear mode with one plastic hinge. Wood crushing on both sides of the rivet occurred in both tension and compression half cycles, accompanied by slight rivet pullout of the wood in the early stages of testing (Figure 5a). The failure mode was characterized by extensive wood crushing and significant rivet pull out (Figure 5b).



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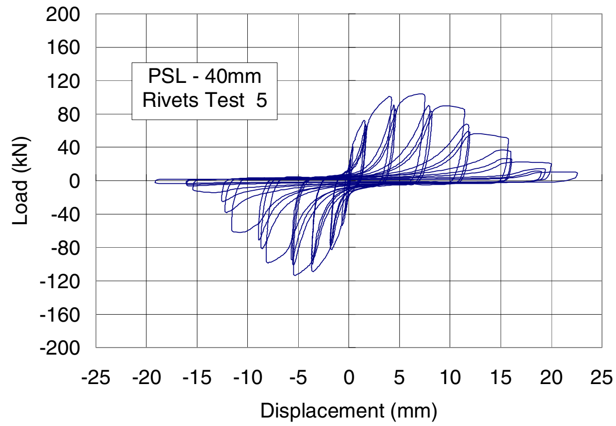

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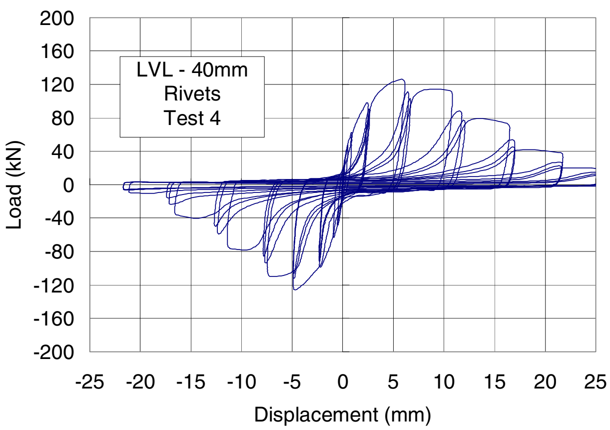

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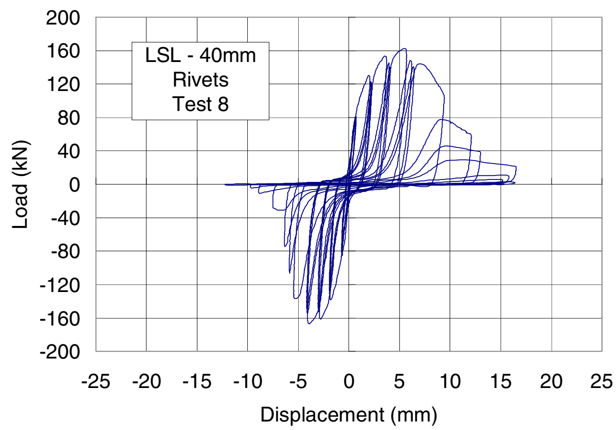

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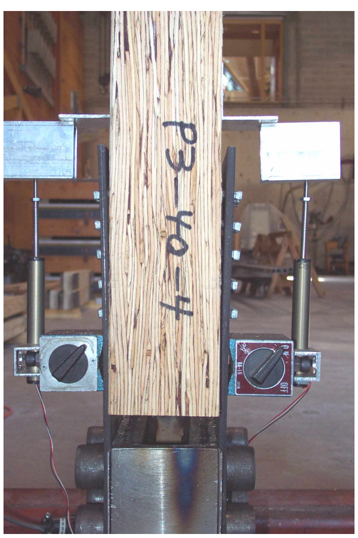
Figure 4. A typical hysteresis loops of the weaker connection obtained form cyclic tests on diagonal braces with riveted 40 mm connections in a) Glulam; b) PSL; c) LVL and d) LSL.



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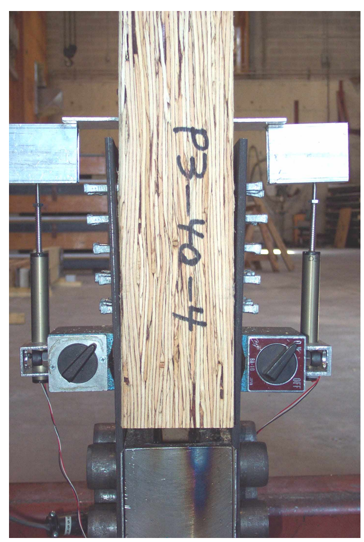

b)

Figure 5. Typical connection deformation observed at (a) lower and (b) higher deformation levels of typical riveted connection during the cyclic tests.

The locus of the extremities of the hysteresis curves is called the backbone or first cycle envelope curve. Connection properties such as initial stiffness, ultimate load, yield load, ultimate displacement, load per rivet and ductility determined on the basis of the first envelope of the weaker connection from the cyclic tests on brace specimens with 40 mm and 65 mm long rivets are presented in Table 2. All properties, rounded to one decimal point, were determined using the European CEN Standard procedure [14]. It should be noted, however, that the sample sizes in the study doesn't allow for any firm quantitative conclusions to be made, particularly between the connections in the various engineered wood products used.

Table 2. Average properties of the weaker connection - first cycle envelope.

	Glulam	PSL	LVL	LSL	Glulam	PSL
Rivet length [mm]	40	40	40	40	65	65
Yield load F_y [kN]	56.5	47.5	64.2	87.0	80.6	73.2
Yield displacement Δ_y [mm]	0.5	0.4	0.5	0.5	1.0	0.9
Maximum load F_{max} [kN]	112.5	99.3	127.2	155.8	144.0	135.0
Displacement at F_{max} [mm]	2.7	3.7	3.3	3.3	4.2	5.1
Ultimate deformation Δ_u [mm]	7.9	7.0	7.7	5.1	9.6	11.5
Initial stiffness [kN/mm]	144.6	163.0	152.9	221.4	98.4	102.2
Ductility [Δ_u / Δ_y]	16.2	19.9	15.0	10.8	9.4	12.8
Maximum load per rivet [kN]	2.8	2.5	3.2	3.9	3.6	3.4
Standard deviation for F_{max} [kN]	10.6	3.3	2.7	25.2	9.9	8.9
Standard deviation for F_{max} [%]	18.8	7.0	4.3	29.0	12.3	12.2

Some differences were noticed in properties obtained from quasi-static monotonic and cyclic tests of the same connections. In general, average curves obtained from monotonic tests showed higher values for maximum load than the average non-stabilized (first cycle) envelope curves. Although a small number of specimens was tested and the obtained hysteresis curves depend on characteristics of the testing protocol such as rate of displacement and number of cycles with high amplitude, it seems that results from cyclic tests should be used as more conservative alternative when determining the seismic properties of timber riveted connections.

CONCLUDING REMARKS

Glulam rivet connections designed to fail in rivet yielding mode, exhibited ductile behavior when subjected to seismic loading. During quasi-static monotonic and cyclic tests, they were capable of resisting many load reversals without significant strength deterioration. In addition, large displacements were attained before failure, which gives reasonable warning before any potential structural failure. Riveted connections consistently showed non-brittle deformations in the wood (crushing) along with yielding of the connectors, even at large displacement levels. They also showed lower variability in strength and deflection properties than most other conventional connectors. Results showed that braced timber frames with glulam riveted connections are capable of dissipating relatively high amount of seismic input energy generated by the earthquake motion.

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