WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

EXPERIMENTAL STUDY ON THE PERFORMANCE OF WOOD CONNECTIONS UNDER SIMULATED WIND/EARTHQUAKE RATE OF LOADING

Jianan Chen[1], Chao Zhang[2], Frank Lam[3], Minghao Li[4], Benoit P. Gilbert[5], Hong Guan[6]

ABSTRACT: This paper presents the effects of simulated seismic and wind loading rates on the performance of mass timber connections and light wood frame connections/systems. Monotonic tests and reversed cyclic tests were conducted on Cross Laminated Timber (CLT) connections, specifically spline joints, hold-down connections, and angle brackets. Furthermore, additional tests were conducted, including light wood frame stud-to-sheathing connections/walls, and Glulam-CLT diaphragm connections. For each configuration, two groups of specimens were tested under two different loading rates. One group was tested at a regular/standard rate of loading, resulting in failure within 5 to 10 minutes, while the other group was subjected to a high rate of loading, simulating seismic or wind loads, with failure occurring within 2 to 10 seconds. The results of the tests revealed that for most connections, the average peak load increased under the higher loading rate compared to the regular loading rate.

KEYWORDS: rate of loading, timber connections, monotonic loading, reversed cyclic, peak resistance

1 – INTRODUCTION

Typically, design values for wood connections in codes are based on a standard rate of loading, which may take 5 to 10 minutes to reach peak loads [1], [2]. However, under seismic or wind load conditions, wood connections may be subjected to individual load pulses with much shorter loading periods. For example, the predominant frequency of earthquake ground motions may range from 1 to 10 Hz, resulting in load pulses of 1 sec to 0.1 sec. Additionally, in severe wind storms, the maximum peak wind gust on a member or connection has a cumulative duration of only several seconds. In combination with the fundamental frequency of typical wood buildings in the range of 2 to 5 Hz, standard static tests with a much longer loading period may not represent the loading conditions in earthquakes and winds realistically.

As a nonlinear viscoelastic material, the mechanical properties of wood depend on the rate of loading. Although various loading rates have been suggested by different standards [2], [3] or examined by different researchers [4], [5], [6], [7], [8], a comprehensive investigation into their effect on the performance of wood connections is needed under seismic and wind loading rates.

2 – PROJECT DESCRIPTION

The mass timber connections investigated as part of this study were all Cross Laminated Timber (CLT) related, including spline joints, hold-downs, angle brackets, and Glued laminated Timber (Glulam)-to-CLT diaphragm connections. Additionally, light wood frame connections were tested. They consisted of stud-to-sheathing connections (lateral loading under seismic, withdrawal under wind) and shear wall hold-downs. Full-size light wood frame exterior walls under lateral loading were also tested. As resource was limited, not all types of specimens were tested in both seismic loading and wind loading. For the seismic loading test, monotonic and reversed cyclic loading (CUREE near-fault protocol [2]) were used; for the wind loading test, only monotonic loading was used due to the nature of wind load. Under simulated wind load, the effect of screw installation angle, screw diameter, and

[1] Jianan Chen, dept. of Wood Science, University of British Columbia, Vancouver, Canada, jianan96@student.ubc.ca

[2] Chao Zhang, dept. of Wood Science, University of British Columbia, Vancouver, Canada, chao.zhang@ubc.ca

[3] Frank Lam, dept. of Wood Science, University of British Columbia, Vancouver, Canada, frank.lam@ubc.ca

[4] Minghao Li, dept. of Wood Science, University of British Columbia, Vancouver, Canada, minghao.li@ubc.ca

[5] Benoit P. Gilbert, School of Engineering and Built Environment, Griffith University, Australia, b.gilbert@griffith.edu.au

[6] Hong Guan, School of Engineering and Built Environment, Griffith University, Australia, h.guan@griffith.edu.au

https://doi.org/10.52202/080513-0470

thread type (partial or full) on the performance of CLT connections were also investigated.

3 – EXPERIMENTAL SETUP

3.1 METHODS

A total of 593 connection specimens were tested in this study. For each configuration, two groups of specimens were tested: one under a regular rate of loading (failure at 5-10 min) and the other under a higher rate of loading simulating seismic and wind load (failure at 2-10 sec). For the cyclic loading, the loading rate was determined by the time used in the final push to failure in the CUREE near-fault protocol. The loading rates for both regular- and high-rate loading conditions, which are used to simulate seismic and wind loading effects, are summarized in Table 1 and Table 2.

The connection specimens were sampled in pairs to minimize the variation of wood properties by screening the overall density or by using two specimens cut next to each other on the CLT or Glulam. Most connection specimens were designed as an H-block with one central member and two side members. Fasteners were used to connect the central member to the side members, and the load was applied on the central member. The only exception to the H-block design was the stud-to-sheathing connection under wind load, for which the nails were tested in withdrawal. The number of replicates of the connections tests was listed in Table 1 and Table 2.

The full-size light wood frame exterior walls were tested within 24 hours after construction. The tests were performed on MTS Flextest System in accordance with ASTM E564-06 (2018) [9] and ASTM E2126-19 [2].

3.2 MATERIALS

3.2.1 MASS TIMBER SYSTEM

Seismic loading conditions

The test setup under seismic loading conditions in mass timber system is shown in Figure 1. The CLT was V105 Grade V2M1.1. The laminar was Spruce-Pine-Fir (SPF) No. 2 & Better for both the longitudinal layers and cross layers. Each layer was 35 mm thick. The spline joint was constructed using 19 mm (3/4 in) thick Douglas fir plywood, secured to the CLT with four self-tapping screws. The HTT5 hold-downs and AE116-R angle brackets, both manufactured by Simpson Strong-Tie, were fastened with four nails each.

Wind loading conditions

Under simulated wind loading conditions, two types of CLT-related connections were tested: CLT spline joints and Glulam-CLT connections. The test setups for these connections are shown in Figure 2 (a) and (b), with arrows indicating the loading directions. The resistance of the CLT diaphragm to wind loads primarily depends on the joints between the CLT panels. Therefore, three configurations of the spline joint were tested with Ø 6 mm screws installed at 90°, Ø 6 mm screws installed at 45°, and Ø 8 mm screws installed at 45°. The Glulam-CLT connection involved a Glulam beam and a CLT floor, with the primary direction of the CLT perpendicular to the length of the Glulam beam. This setup simulated the connection between a CLT diaphragm and a supporting beam under wind loads. Four configurations were tested: Ø 10 mm partially threaded (PT) screws installed at 90°, Ø 8 mm PT screws installed at 90°, Ø 8 mm fully threaded (FT) screws installed at 90°, and Ø 8 mm FT screws installed at 45°. The Glulam used in these tests was Douglas Fir-Larch 24f-E.

3.2.2 LIGHT WOOD FRAME SYSTEM

Seismic loading conditions

The test setup under seismic loading conditions in light wood frame system is shown in Figure 3. The lumber used in the light wood frame connection tests was kiln-dried SPF No. 1 & Better, measuring 38 mm × 89 mm (2 in × 4 in). The choice of No. 1 & Better grade was to minimize the presence of wanes in the studs, ensuring a more uniform and reliable connection between the sheathing and the studs. For sheathing-to-stud connections, two specimen configurations were compared: P-2.0 (Plywood sheathing with 50 mm / 2 in nails), and P-2.375 (Plywood sheathing with 61 mm / 2-3/8 in nails. Since the reaction between the fastener and sheathing was very localized and much depended upon the local density near the fastener head, plywood with its more uniform in-plane density distribution was more suitable for the purpose of this test.

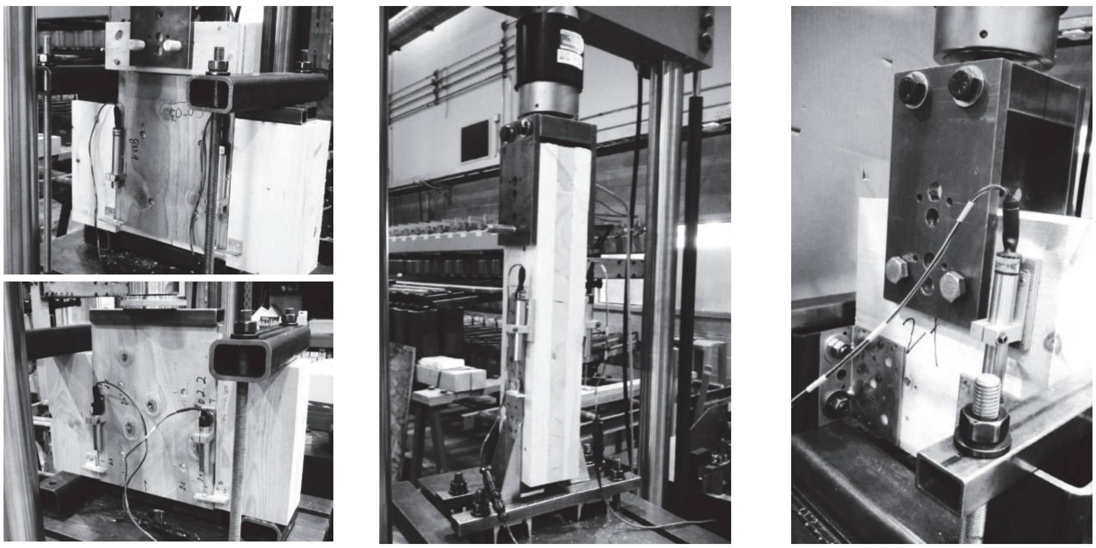
The wall specimens were fabricated with two top/bottom plates and two edge studs. The nominal dimension of the wall was 2.34 m × 2.49 m (width × height, 92 in × 98 in). The sheathings were oriented vertically and the studs were 406 mm (16 in) apart. The spacing of sheathing nails was 150 mm (6 in) along the perimeter and 300 mm (12 in) on the rest of studs. The test setup is shown in Figure 3 (c). The wall was secured to the test base with two HTT5 hold-downs at the ends and three bolts in the middle. The loading beam was connected to the top of the wall with hold-downs and bolts. Six transducers measured the lateral

https://doi.org/10.52202/080513-0470

displacement, diagonal displacement, and corner uplifting/horizontal-shifting of the wall.

Wind loading conditions

When simulating wind loading conditions, the stud-to-sheathing connections with 61 mm nails were tested. For a common lightwood frame exterior wall, the effect of wind load is mainly in the out-of-plane direction, in which case the negative wind pressure pulls the sheathing away from the studs. Therefore, the stud-to-sheathing connection was tested in the withdrawal mode and the load was applied in the axial direction of the nails, as shown in Figure 2 (c).



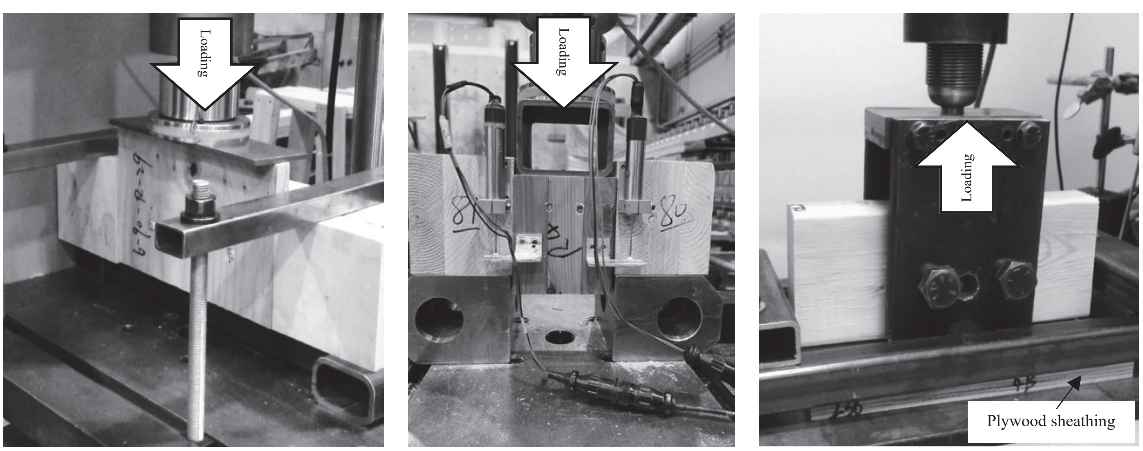
(a) Spline joint for CLT walls or diaphragms (b) Hold-down connection for CLT walls (c) Base shear connection for CLT walls

Note:

(1) Screws for spline joints: SWG 6×80/50 ASSY 4 SK screws Washer Head – RW 40.

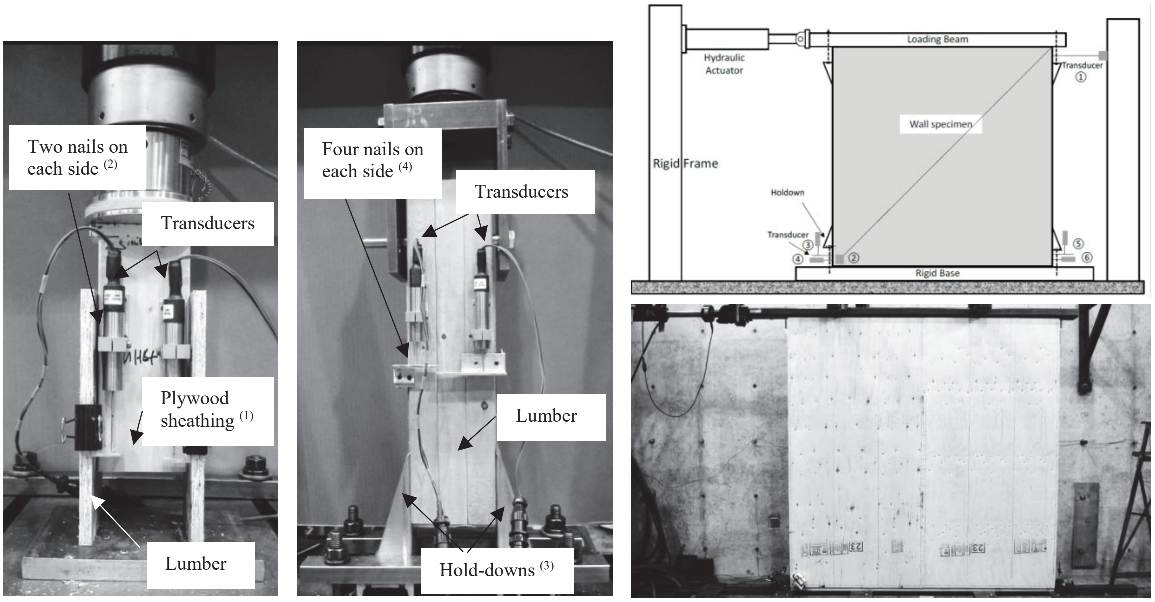
(2) Nails for hold-downs and angle brackets: 76 mm (3 in) common nail, 10D, 3.76 mm (0.148 in) in diameter; hand driven.

Figure 1: Test setup under seismic loading conditions: in mass timber system



(a) CLT spline joint (b) Clulam-CLT (c) Stud-to-sheathing connection

Figure 2: Test setup under wind loading conditions: in mass timber/light wood frame system



(a) Stud-to-sheathing connection (b) Hold-down connection (c) wall

Note:

(1) Plywood sheathing: 12.5 mm (0.469 in) thick, PS1-09 exterior, ½ category, Douglas fir.

(2) Nails for sheathing to stud: 28° wire weld framing ring nails, nominal length 50 mm (2 in), nominal diameter 2.9 mm (0.113 in), nominal length 61 mm (2-3/8 in), nominal diameter 3.1 mm (0.120 in), head offset; pneumatically driven.

(3) Hold-downs: Simpson Strong-Tie HTT5.

(4) Nails for hold-down connections: 76 mm (3 in) common nail, 10D, 3.76 mm (0.148 in) in diameter; hand driven.

Figure 3: Test setup under seismic loading conditions: in light wood frame system

4 – RESULTS

The connection test results under simulated seismic and wind loading conditions are summarized in Table 1 and Table 2, respectively. In those tables, the mean values and coefficients of variation (CoV) of the peak resistance for each configuration are provided. The ratio of peak resistance under high loading rates to regular loading rates is presented in Figure 4.

Mass timber system

Compared to the regular loading rate, the higher loading rate led to a 6%-10% increase of peak load on average for the CLT spline joint. The amount of increase was greater for the connections with screws installed at 45° compared to those with screws installed at 90°. For 90° screws, the connections failed mostly in screw head pull-through. And for screws at 45°, the connections failed mostly in screw withdrawal.

The higher loading rate did not lead to an increase in connection capacity for CLT hold-downs or base shear connections; in some cases, a decrease was observed. In the hold-down and angle bracket connections of CLT, the nails were loaded perpendicular to the grain in at least one ply. The weak tensile strength perpendicular to the grain may contribute to the observed reduction in strength under reversed-cyclic loading. Additional replicates are needed to confirm these findings. An alternative fastening strategy may be required to effectively harness the rate-of-loading effects in hold-downs and angle bracket connections.

The Glulam-to-CLT diaphragm connections had an increase of average peak load by 9%-19% under higher loading rates for partially threaded screws installed at 90° and fully threaded screw installed at 45°. For fully threaded screws installed at 90°, the increase was lower (6%). However, this configuration is not commonly used in mass timber construction. When the screws were installed at 90°, the connections failed due to screw head pull-through, and the screws deformed under bending. When the screws were installed at 45°, head pull-through occurred, and under high loading rates, some screws fractured.

 https://doi.org/10.52202/080513-0470

Light wood frame system

In the light wood frame system, the higher loading rate was found to have a significant effect on the load carrying capacity of stud-to-sheathing connections. The amount of increase could reach 11-14% for the sheathing-to-stud connections. Under simulated seismic loading conditions, the primary mode of failure for both configurations, P-2.0 and P-2.375, was predominantly characterized by head pull-through. Under simulated wind loading conditions, all stud-to-sheathing connections failed due to nail withdrawal.

The failure observed in hold-down tests was primarily due to nail withdrawal, with occasional instances of nail breakage under reversed-cyclic loading. It was noted that the effect of higher loading rates on the hold-downs of light wood frame walls was not statistically significant.

The amount of increase of the lateral resistance of walls could reach 8-11%. In the wall tests, failure occurred at the sheathing-to-stud connections, primarily in the form of nail head pull-through, which was consistent with the failure mode observed in the connection tests. The deformation of the hold-down connection was minimal.

Table 1: Summary of test results: under seismic loading conditions

Simulated conditions	**System types**	**Specimen types**		**Monotonic loading**		**Reversed-cyclic loading**	
				Regular	***High***	***Regular***	***High***
Seismic loading	Mass timber system	Spline joints	Replicates	10	10	9	10
			Rates (mm/min)	4.5	300	24	720
			Mean (kN)	19.0	20.2	18.4	19.7
			CoV	11%	12%	9%	7%
		Hold-downs	Replicates	10	10	14	14
			Rates (mm/min)	4.5	300	24	720
			Mean (kN)	18.6	18.2	20.3	17.4
			CoV	8%	10%	11%	6%
		Angle brackets	Replicates	10	10	10	10
			Rates (mm/min)	4.5	300	24	720
			Mean (kN)	21.1	20.9	19.7	17.6
			CoV	10%	10%	11%	4%
	Light wood frame system	Stud-to-sheathing connections (P-2.0)	Replicates	12	12	/	/
			Rates (mm/min)	2.3	285	/	/
			Mean (kN)	5.25	5.93	/	/
			CoV	7%	9%	/	/
		Stud-to-sheathing connections (P-2.375)	Replicates	12	12	10	10
			Rates (mm/min)	2.3	285	9	300
			Mean (kN)	6.67	7.61	6.65	7.52
			CoV	5%	10%	5%	11%
		Hold-downs	Replicates	9	9	9	9
			Rates (mm/min)	1.5	285	6	180
			Mean (kN)	16.2	17.0	16.3	16.0
			CoV	6%	6%	8%	4%
		Full-size walls	Replicates	2	1	1	2
			Rates (mm/min)	10	1200	1	1200
			Mean (kN)	29.0	32.2	31.5	34.1

https://doi.org/10.52202/080513-0470

Table 2: Summary of test results: under wind loading conditions

Simulated conditions	**System types**	**Specimen types**			**Monotonic loading**	
					Regular	***High***
Wind loading	Mass timber system	Spline joints	Ø 6 mm 90° PT	Replicates	31	31
				Rates (mm/min)	3.1	153
				Mean (kN)	9.9	10.6
				CoV	11%	13%
			Ø 6 mm 45° PT	Replicates	31	31
				Rates (mm/min)	1.6	105
				Mean (kN)	11.0	12.1
				CoV	12%	12%
			Ø 8 mm 90° PT	Replicates	16	16
				Rates (mm/min)	3.4	210
				Mean (kN)	13.9	14.8
				CoV	9%	7%
		Glulam-CLT	Ø 10 mm 90° PT	Replicates	19	19
				Rates (mm/min)	9.1	480
				Mean (kN)	24.0	26.2
				CoV	10%	11%
			Ø 8 mm 90° PT	Replicates	15	15
				Rates (mm/min)	9.1	480
				Mean (kN)	15.6	18.5
				CoV	13%	10%
			Ø 8 mm 90° FT	Replicates	15	15
				Rates (mm/min)	9.1	480
				Mean (kN)	26.2	27.7
				CoV	13%	13%
			Ø 8 mm 45° FT	Replicates	16	16
				Rates (mm/min)	1.3	90
				Mean (kN)	49.4	57.0
				CoV	5%	8%
	Light wood frame system	Stud-to-sheathing connections		Replicates	30	30
				Rates (mm/min)	2.5	20
				Mean (kN)	1.16	1.29
				CoV	20%	12%

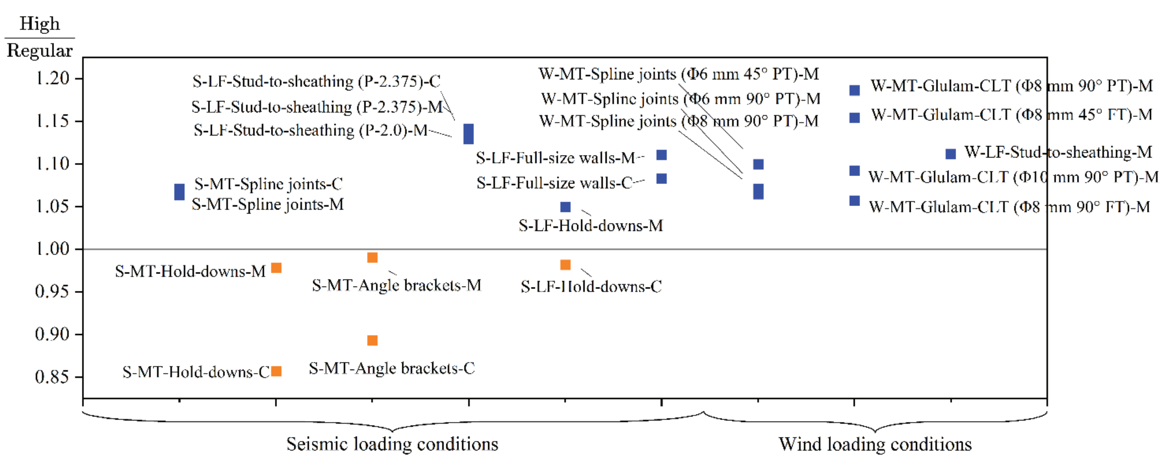


Figure 4: The increase of resistance in wood connections and walls (S: Seismic loading conditions, W: Wind loading conditions, MT: Mass timber systems, LF: Light wood frame systems, M: Monotonic results, C: Cyclic results)

https://doi.org/10.52202/080513-0470

5 – CONCLUSION

This study investigated the performance of wood connections under simulated wind and earthquake loading rates, providing a valuable database for understanding the influence of higher loading rates on the behavior of timber structures. Monotonic and reversed-cyclic tests were conducted on various connection types and walls, demonstrating increased resistance in most of the tested connection types under higher loading rates simulating seismic and wind loads.

The key findings are summarized as follows:

1) Connections for mass timber systems:
    - For the CLT spline joints, higher loading rates resulted in a 6%-10% increase in peak load, with screws installed at 45° exhibiting greater increases than those installed at 90°.
    - No significant effects of high loading rate were observed for the CLT hold-down or base shear connections. However, this conclusion is specific to the tested connection types and may not apply to other designs with differing mechanisms.
    - For the Glulam-to-CLT diaphragm connections, higher loading rates increased the average peak load by 9%-19%, except for fully threaded screws installed at 90°, which showed a smaller increase (6%) and are rarely used in mass timber construction.
2) Connections/walls for light wood frame systems:
    - Higher loading rates significantly increased the load-carrying capacity of the stud-to-sheathing connections (11%-14%) and the lateral resistance of walls (8%-11%).
    - The effect of higher loading rates on the hold-down connections in light wood frame walls was not significant.

6 – ACKNOWLEDGEMENT

Research grant received from Canadian Wood Council is gratefully acknowledged.

7 – REFERENCES

[1] ASTM D4761, *Standard Test Methods for Mechanical Properties of Lumber and Wood-Based Structural Materials*, 2019.

[2] ASTM E2126, *Standard test methods for cyclic (reversed) load test for shear resistance of vertical elements of the lateral force resisting systems for buildings*, 2019.

[3] CSA, “Engineering design in wood. (CSA Standard No. O86:24).” [Online]. Available: https://www.csagroup.org/

[4] D. V. Rosowsky and T. A. Reinhold, “Rate-of-Load and Duration-of-Load Effects for Wood Fasteners,” *J. Struct. Eng.*, vol. 125, no. 7, pp. 719–724, Jul. 1999, doi: 10.1061/(ASCE)0733-9445(1999)125:7(719).

[5] Y. H. Chui and C. Ni, “Load-embedment response of timber to reversed cyclic load,” *Wood and Fiber Science*, vol. 29, no. 2, pp. 148–160, 1997.

[6] S. Shameli Derakhshan, L. Zhou, and C. Ni, “Influence of the Loading Protocol and Loading Rate on the Characteristics of Timber Nail Joints,” *Journal of Renewable Materials*, vol. 10, no. 10, pp. 2655–2667, 2022, doi: 10.32604/jrm.2022.020671.

[7] C. Viau and G. Doudak, “Effect of high strain-rates on heavy timber connections,” presented at the CSCE Annual Conference, Laval (Greater Montreal), Jun. 2019.

[8] X. Cheng, B. P. Gilbert, C. Lyu, and H. Guan, “Strain Rate Effect on the Embedment Mechanical Properties and Fracture Behavior of Softwood Laminated Veneer Lumbers: Implications to Timber Connections,” *J. Struct. Eng.*, vol. 149, no. 9, p. 04023121, Sep. 2023, doi: 10.1061/JSENDH.STENG-12508.

[9] ASTM E564-06, *Practice for Static Load Test for Shear Resistance of Framed Walls for Buildings*, 2018. doi: 10.1520/E0564-06R18.