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Development of Modular System in Midrise to Tall Wood Buildings Phase II

by

Chao (Tom) Zhang
George Lee
Dr. Frank Lam

Prepared for

Forestry Innovation Investment
1130 W Pender St, Vancouver
BC V6E 4A4

Timber Engineering and Applied Mechanics
(TEAM) Laboratory
Department of Wood Science
Faculty of Forestry
University of British Columbia
Vancouver, B.C., Canada

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EXECUTIVE SUMMARY

This project studied the effect of openings on the lateral performance of CLT shear walls and the system behavior of the walls in a module. Three-layer Cross Laminated Timber (CLT) was used for manufacturing the wall and module specimens. The laminar was Spruce-Pine-Fir (SPF) #2&Better for both the major and minor layers. Each layer was 35 mm thick. The panel size was 2.44 m × 2.44 m.

Four configurations of walls were investigated: no opening, 25% opening, 37.5% opening, and 50% opening. The opening was at the center of the wall and in the shape of a square. A CLT module was made from two walls with 50% openings, with an overall thickness of 660 mm. The specimens were tested under monotonic loading and reverse-cyclic loading, in accordance with ASTM E564-06 (2018) and ASTM E2126-19.

The wall without opening had an average peak load of 111.8 kN. It had little internal deformation and the failure occurred at the connections. With a 25% opening, deformation within the wall was observed but the failure remained at the connections. It had the same peak load as the full wall. When the opening was increased to 37.5%, the peak load decreased by 6% to 104.9 kN and the specimens failed in wood at the corners of the opening. Further increasing the opening to 50%, the peak load dropped drastically to 63.4 kN, only 57% of the full wall.

The load-displacement relationship was approximately linear until the load reached 60% of the peak or more. Compared to the full wall, the wall with 25% opening had 65% of the stiffness. When the opening increased to 37.5% and 50%, the stiffness reduced to 50% and 24% of the full wall, respectively. The relationship between stiffness and opening ratio was approximately linear. The loading protocol had effect on the peak load but not on the stiffness. There was more degradation for larger openings under reverse-cyclic loading.

The performance of the module indicated the presence of system effect that improves the ductility of the wall, which is important for the seismic performance of the proposed midrise to tall wood buildings. The test data was compared to previous models found in literature. Simplified analytical models were also developed to estimate the lateral stiffness and strength of CLT wall with openings.

Reported by:

Chao (Tom) Zhang
Research Engineer

George Lee
Wood Engineering Scientist

Reviewed by:

Frank C.F. Lam, Ph.D., P. Eng.
Professor

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Prefabrication is an efficient construction technique that minimizes construction waste, reduces environmental impact, and expedites construction speed. Wood, especially massive timber, has unique properties suitable for prefabrication since it retains a good balance between strength and weight, structural integrity and flexibility. Prefabricated mass timber modules have a high degree of completion and robust structural integrity, and could be used in the construction of midrise to tall buildings.

This project continues the ongoing study of developing mass timber modular system. Phase I was carried out in 2018-19, focusing on the connections: intra-module, inter-module in the vertical direction, and inter-module in the horizontal direction. Phase II (2019-20) investigated the effect of openings on the lateral performance of shear walls and the system behavior of a mass timber module with openings.

2 MATERIAL AND METHODS

The Cross Laminated Timber (CLT) used in this project was V105 Grade V2M1.1 manufactured by Structurlam Mass Timber Corporation (Penticton, BC). The laminar was Spruce-Pine-Fir (SPF) #2&Better for both the major and minor layers. Each layer was 35 mm thick. The panel size was 2.44 m × 2.44 m.

Four configurations of walls were investigated: no opening, 25% opening, 37.5% opening, and 50% opening, as shown in Figure 1. The opening was at the center of the wall and in the shape of a square. The ratio was the area of the opening divided the total area of the wall. A CLT module (*M1/2*) was made from two walls with 50% openings, as shown in Figure 2. It had an overall width of 660 mm with the width of end walls as 450 mm.

Two specimens were manufactured for every configuration (except *W1/4* and *M1/2*): one tested under monotonic loading and the other under reverse-cyclic loading, as shown in Table 1. The tests were conducted on MTS Flextest System in accordance with ASTM E564-06 (2018) and ASTM E2126-19. The test setup is shown in Figures 2 and 3. The wall was secured to the test base with four HTT5 holdowns and four AE116-R angle brackets. They were installed on the two sides of the wall: holdowns at the ends and angle brackets in the middle, to prevent uplifting and horizontal movement during the test. The loading beam was connected to the top of the wall with holdowns and 12.7 mm lag screws (12. 7 mm bolts used for *M1/2*). The holdowns at the top had equal or higher strength than the ones at the bottom, so that the loading beam would not separate from the wall during the test. For the module, CLT plates were assembled with two angle brackets along each joint. The top plate was connected to the two walls with 26 self-tapping wood screws (Ø 10 mm and 380 mm long) (13 on each wall). With this setup, the top plate served as a loading beam to transfer the load equally to the two side walls. The self-tapping screws ensured there was enough stiffness and strength for this purpose.

Four transducers measured the lateral displacement and corner uplifting of the wall. Another transducer measured the diagonal deformation of the wall. In the test of the module, another two transducers were mounted to measure the displacements between the top plate and side wall and between the end plate and the side wall. The monotonic protocol had a loading rate of 10 mm/min. The cyclic loading used CUREE basic loading protocol, as found in Method C of Section 8.5 in ASTM E2126-19. Its loading history and detailed amplitudes for each cycle/step can be found in Appendix A. The loading rate for cyclic test was 1 mm/s.

Table 1 Number of specimens for each loading protocol

Loading protocol	W0	W1/4	W3/8	W1/2	M1/2
Monotonic loading	1	2	1	1	2
Reverse-cyclic loading	1	--	1	1	--

Figure 1 Configurations of wall openings

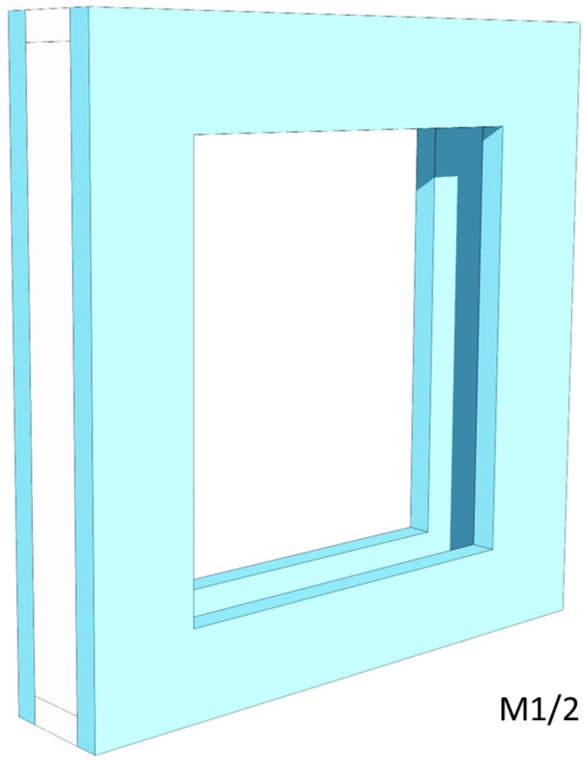


Figure 2 CLT module with 50% opening on walls

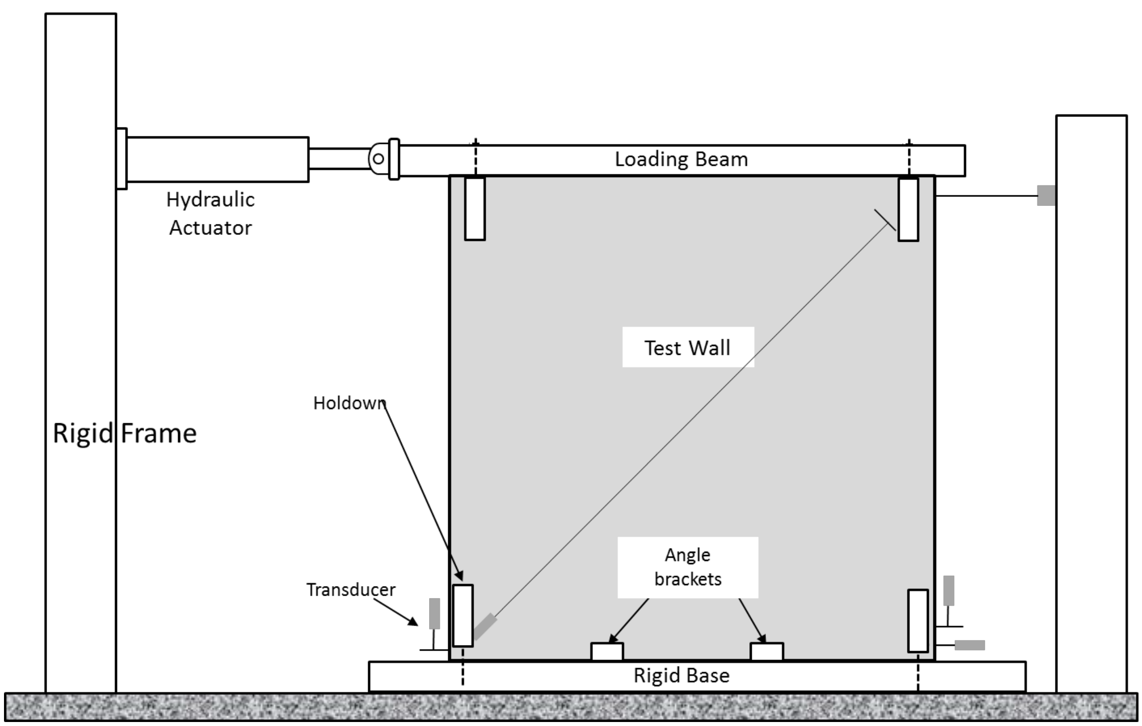


Figure 3 Shear wall test setup and location of transducers

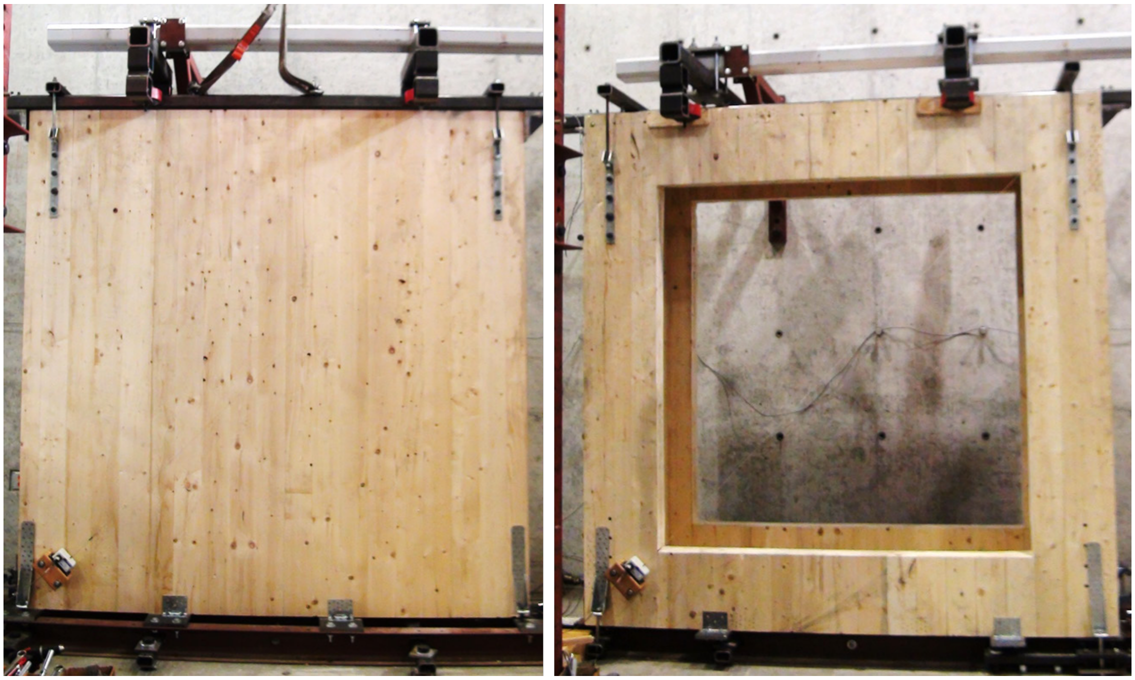


Figure 4 Specimen installation (*W0* and *M1/2*)

3 RESULTS AND DISCUSSIONS

A summary of the test results are shown in Table 2, including the peak load, displacement at peak load, displacement when the load dropped to 80% of the peak load, the load at various drift levels, and the stiffness per unit length *K*.

Table 2 Summary of test results

	Specimen	P_{max} (kN)	Δ_{Pmax} (mm)	$\Delta_{0.8Pmax}$ (mm)	$P_{0.5\%}$ (kN)	$P_{1.0\%}$ (kN)	$P_{1.5\%}$ (kN)	K (kN/mm/m)
Monotonic	W0	115.8	38.4	53.2	70.1	102.3	114.5	2.44
	W1/4-1	103.9	35.8	54.9	46.2	82.4	103.9	1.57
	W1/4-2	119.5	38.2	59.5	50.4	95.3	118.0	1.69
	W3/8	112.1	58.2	69.1	34.4	95.5	89.6	1.17
	W1/2	70.4	58.0	60.0	19.0	34.7	49.7	0.59
	M1/2-1	84.3	41.8	52.1	31.9	57.6	78.2	1.03
	M1/2-2	97.6	56.9	88.0	30.4	58.2	80.5	0.97
Cyclic	W0	107.7	27.0	56.5	74.5	101.4	103.3	2.63
	W3/8	97.7	49.2	63.4	34.1	63.8	84.4	1.15
	W1/2	56.3	44.1	82.2	18.5	35.7	48.2	0.62

The symbols in Table 2 are explained as follows:

P_{max}: peak load;
Δ_{Pmax}: displacement at peak load
$\Delta_{0.8Pmax}$: displacement when load dropped to 80% of the peak
$P_{0.5\%}$: load at 0.5% drift (12 mm)
$P_{1.0\%}$: load at 1.0% drift (24 mm)
$P_{1.5\%}$: load at 1.5% drift (36 mm)
K: stiffness between 10% and 40% of the peak, divided by the width of the wall

3.1 Performance of wall

The load-displacement curves for the monotonic test and the envelope curves for the reverse-cyclic tests are shown in Figure 5 and Figure 6, respectively. The actuator used in this test had a capacity of 86 kN on the reverse direction (in tension). Two specimens reached this limit during some large displacement cycles, so the portion of the curve in this direction was shorter than in the opposite direction (under compression).

Without opening (W0), the peak load was 107.7 kN under monotonic loading and 115.8 kN under reverse-cyclic loading. The failure occurred at the holdowns/brackets and no wood failure was observed. With a 25% opening (W1/4), the failure remained at the connections, therefore it had almost identical load bearing capacity as the full wall, 111.7 kN compared to 111.8 kN on average. When the opening was increased to 37.5% of the area (W3/8), the peak load decreased by 6% to 104.9 kN on average. Wood failure at the corners of the opening occurred although some deformation of the connections was also found. Further increasing the opening to 50% (W1/2) caused the peak load to drop drastically to 63.4 kN, only 57% of the full wall, with a similar failure mode as W3/8. After the peak, most specimens maintained the load at a high level, including the ones having wood failure.

The load-displacement relationship was approximately linear until the load reached 60% of the peak or more. Compared to the full wall (W0), W1/4 had 65% of its stiffness, W3/8 had 50%, and W1/2 had only 24%.

The loading protocol had an effect on the peak load but not on the stiffness. The reverse-cyclic loading had lower peak load than monotonic loading. The ratio between them two decreased as the opening area increased: 93% for W1, 87% for W3/8, and 80% for W1/2. This indicated that wood failure was more sensitive to reverse-cyclic loading.

The peak load and stiffness of every wall specimen are shown in Figure 7. The average peak load was taken for each configuration and trendlines were plotted in Figure 8. Under the connection conditions used in this project, the capacity of the wall did not change until the opening area increased to about 33%. Then the peak load decreased sharply as the opening ratio increased from 0.33 to 0.50. The peak load – opening ratio relationship may be linear in this range, but this was not conclusive due to lack of data.

The regression between stiffness and opening ratio is shown in Figure 7, based on the results of both monotonic and reverse-cyclic loading. There was a good linearity between the two, and the R^2 for the linear regression was 0.991.

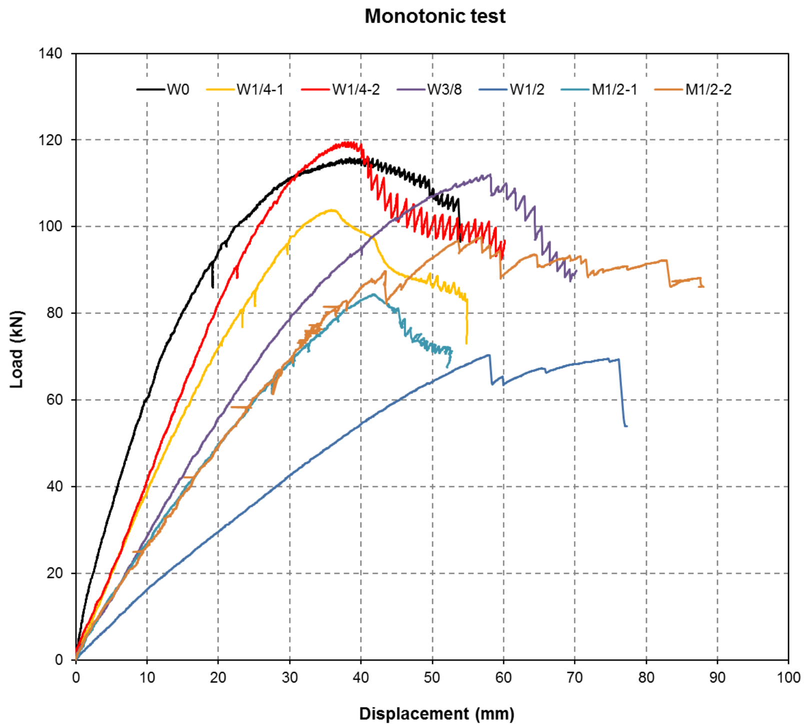


Figure 5 Monotonic test results

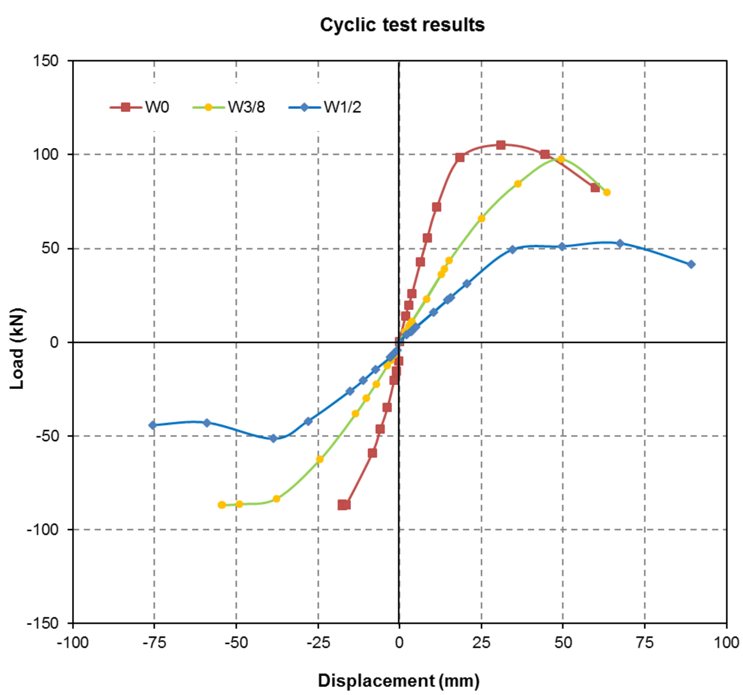


Figure 6 Envelope curves of cyclic tests

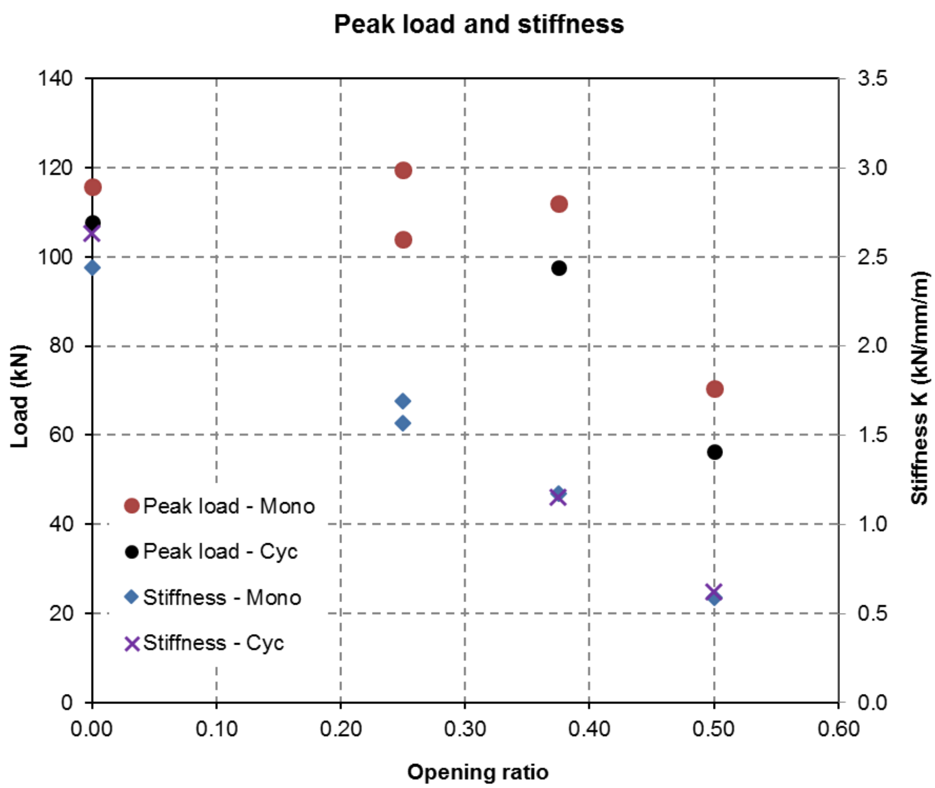


Figure 7 Peak load and stiffness results

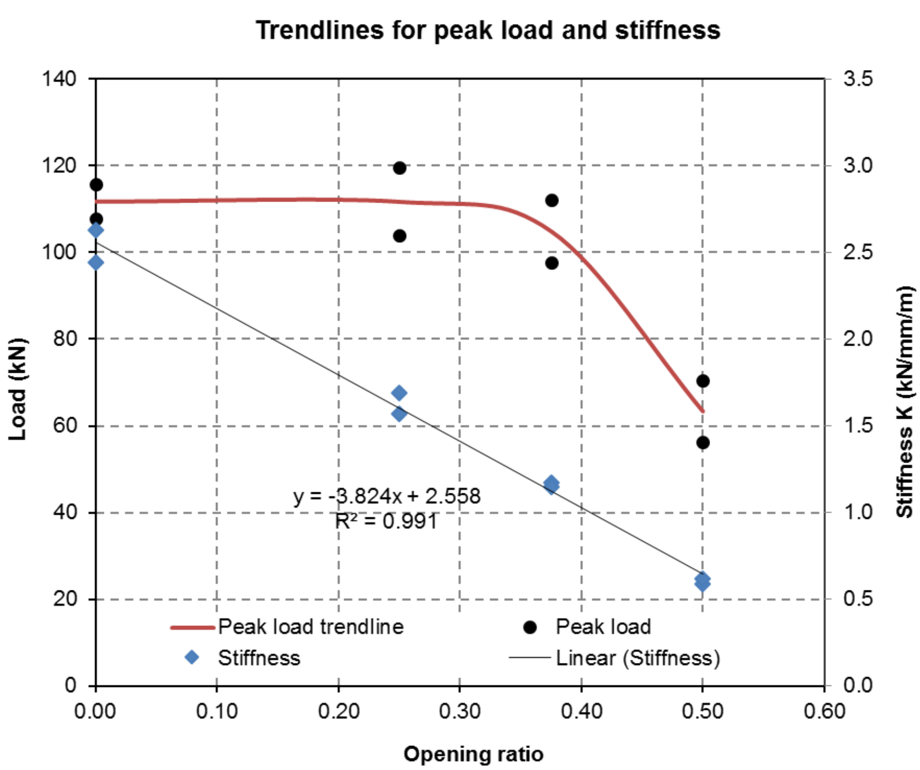


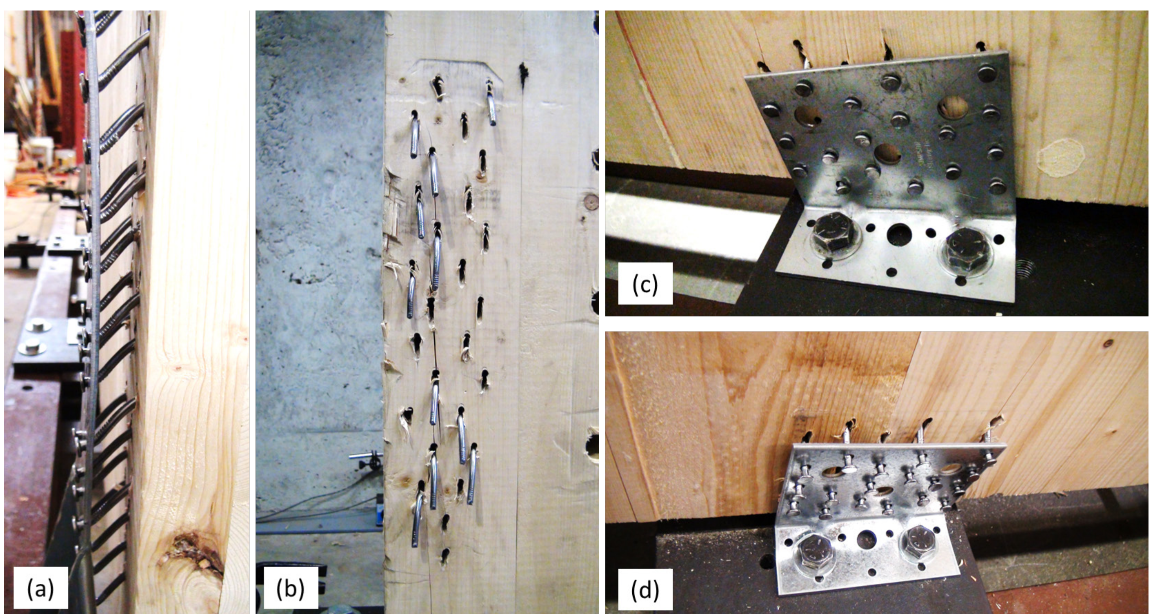
Figure 8 Trendlines for peak load and stiffness

3.2 Performance of module

The peak load of M1/2-1 was 84.3 kN with the failure at the connections. The peak load of M1/2-2 increased to 97.6 kN and both wood failure and connections failure occurred. The average peak load of the module was 91 kN, 43% higher than the peak load of a single wall with the same opening ratio (W1/2). The average stiffness was 1.00 kN/mm/m, 65% higher than W1/2. The performance of the module was not two or more times higher than the single wall, because it used the same number of connections due to limitations of the test fixture. Another contributing factor may be the variability of the wood material. The module specimens had larger horizontal displacement at the bottom of the wall as well as more uplifting, suggesting the wood quality was not as good as the rest. The module had higher ductility than a single wall when wood failure occurred. The integrity of multiple elements created a system effect that could mitigate the damage at one location.

3.3 Failure mode

The failure of the wall/module had two predominant modes: connection failure and wood failure. Connection failure occurred when the fasteners were withdrawn from the wood, the fastener head was sheared off, or the fastener deformed under high uplifting or horizontal force, as shown in Figure 9. The fastener head shear-off was found more in the reverse-cyclic loading due to metal fatigue. The brackets started to deform only after considerable amount of nail withdrawal occurred at the holdowns.



(a) nail withdrawal at holdown; (b) nail head sheared off; (c) bracket deformation; (d) nail withdrawal at bracket

Figure 9 Connection failure

Wood failure initiated at the corners of the rectangular opening under high stress concentration. Pai et. al. (2016) simulated the torsional moment in each glued surface for a CLT wall with 15% opening, and reported significantly higher inter-lamina stress at the corners. Since the three laminae of CLT did not behave in the same manner (one cross layer), there was shear stress between the layers near the corner, as shown in Figure 10.

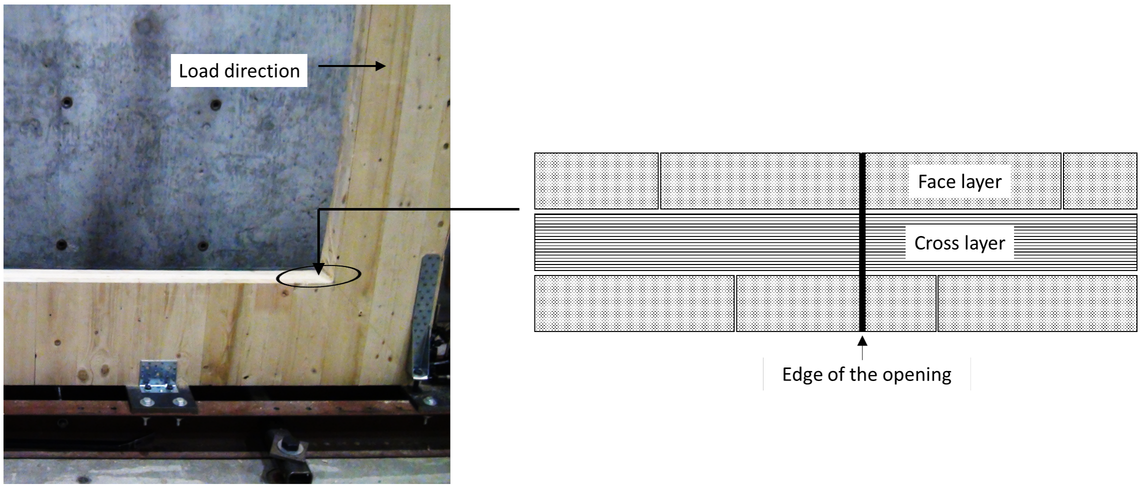


Figure 10 Stress between layers in CLT at the corner

The cross layer was continuous in the horizontal direction while the face layers was discontinuous, besides the fact that the material properties were significantly different in the two directions. In the end, the failure mode was determined by the relation of the following two factors: shear resistance from the bonding between the adjacent layers, and the tensile capacity of the cross layer. If the former was higher, there would be tension failure of the wood in the center lamina, as shown in Figure 11; if the former was lower, there would be shear failure between laminas, as shown in Figure 12.

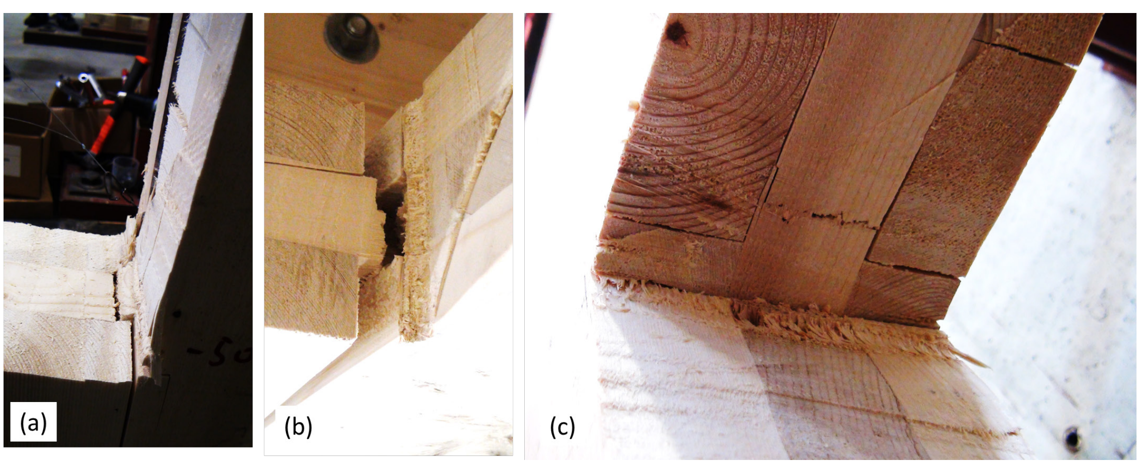


Figure 11 Cross layer tension failure

The two failure modes may occur at the same corner (Figure 11c). When the shear strength of the wood was lower than the bonding between laminas, internal wood shear failure may happen (Figure 12b). Depending on the amount of deformation, shear failure could remain localized or go along the length of the lumber to the edge of the wall, either vertically (Figure 12c) or horizontally. The face layer may break under tension perpendicular to grain or parallel to grain.

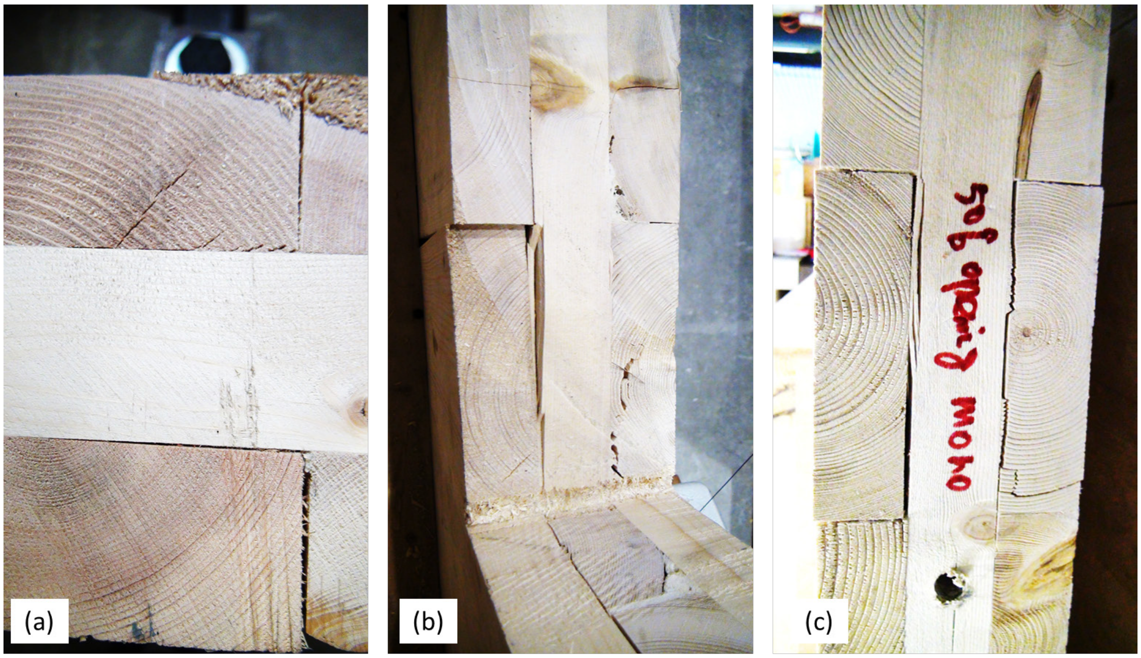


Figure 12 Shear failure between laminas

3.4 Analytical models

The test results were compared to two analytical models developed in previous works to predict the strength/stiffness of CLT walls with openings: Dujic et. al. (2008) and Shahnewaz et. al. (2017). Both provided a ratio of the strength/stiffness between the wall with opening and a full wall. The Dujic model considered the opening ratio and the ratio of the length with full segments. The Shahnewaz model considered the aspect ratio of opening, aspect ratio of the wall, opening ratio, and offset of the opening from the center of the wall. The comparison between test data and model estimates is shown in Figure 13.

The Dujic model underestimated the stiffness and predicted a non-linear relationship between the stiffness and opening ratio. It provided better prediction as the opening ratio went higher. The Shahnewaz model had a linear relationship but overestimated the stiffness by 27-92%. The Dujic model also underestimated the capacity of the wall, especially at the mid-size opening. It suggested that this model did not capture the transition point well. The relationship between stiffness and opening ratio was close to linear.

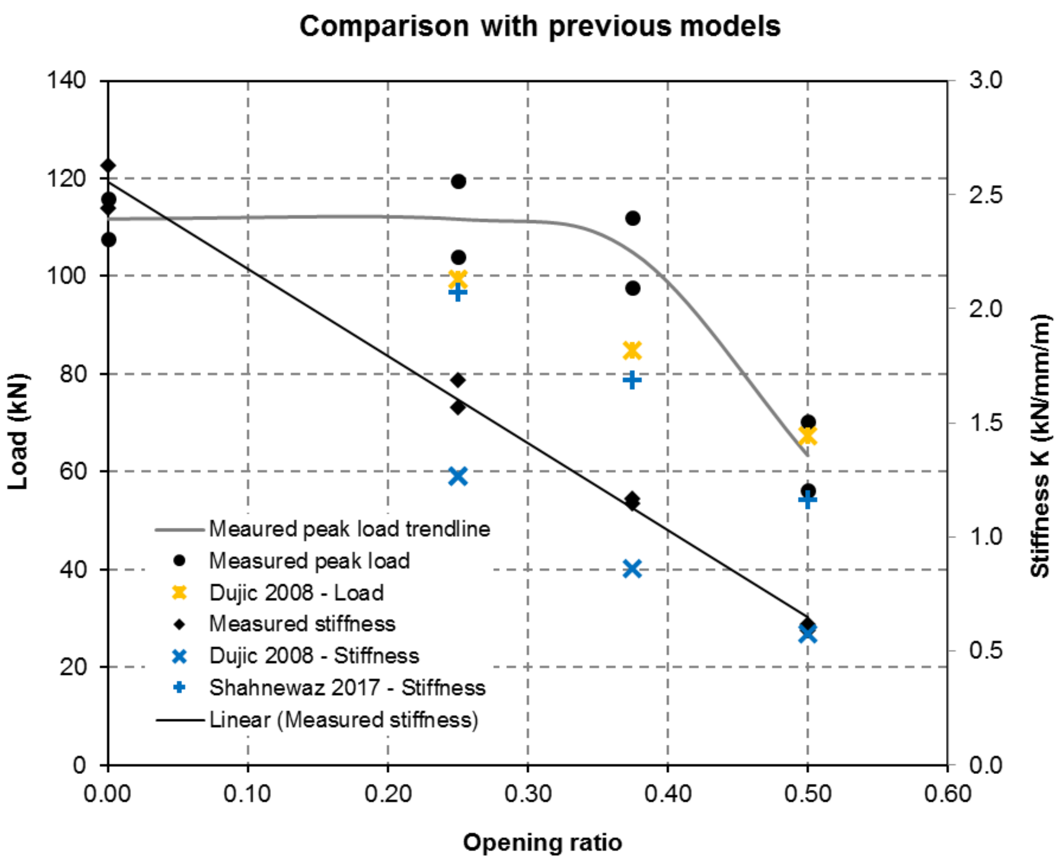


Figure 13 Test data compared to previous models

The stiffness of a wall with opening (K_o) and the stiffness of the full wall (K_f) had the following relationship based on the test results:

$$K_o = K_f \times (1 - r_o \times \frac{3}{2}) \quad (1)$$

where r_o was the opening ratio, calculated by the opening area A_o divided by the full wall area A_f

The load bearing capacity of a wall with opening (F_o) and the capacity of the full wall (F_f) had the following relationship based on the test results:

$$F_o = F_f \; when \; r_o \leq 1/3$$

$$F_o = F_f \times (2 - r_o \times 3) \; when \; r_o > 1/3 \quad (2)$$

The equations did not consider the shape and location of the opening. They may be applied to a similar configuration as used in this project: low aspect ratio of the opening, and the opening was at or close to the center of the wall. Computer models will be developed for other scenarios.

4 CONCLUSIONS

This project studied the effect of openings on the lateral performance of CLT shear walls and the system behavior of the walls in a module. Four configurations of shear walls and one module were tested under monotonic and reverse-cyclic loadings.

The wall without opening had an average peak load of 111.8 kN and the failure occurred at the connections. There was little deformation within the wall. With a 25% opening, deformation within the wall appeared but the failure remained at the connections. This configuration had the same load bearing capacity as the full wall. When the opening was increased to 37.5% of the area, the peak load decreased by 6% to 104.9 kN on average with the failure in wood at the corners of the opening. When further increasing the opening to 50%, the peak load dropped drastically to 63.4 kN, only 57% of the full wall. This showed that the capacity of the wall did not change until the opening area increased to about 33%. Then the peak load decreased sharply as the opening ratio increased from 0.33 to 0.50.

The load-displacement relationship was approximately linear up to 60% of the peak or more. The wall with 25% opening had 65% of the stiffness of the full wall. When the opening increased to 37.5% and 50%, the stiffness reduced to 50% and 24% of the full wall, respectively. The relationship between stiffness and opening ratio had a good linearity and the R^2 for a linear regression was 0.991. The loading protocol had an effect on the peak load but not on the stiffness. The reverse-cyclic loading had lower peak load than monotonic loading for most cases. The ratio between them two seemed to decrease as the opening area increased: 93% for W1, 87% for W3/8, and 80% for W1/2. The specimens with wood failure had more reverse-cyclic degradation.

The failure of the wall/module had two predominant modes: connection failure and wood failure. Connection failure occurred when the fasteners were withdrawn from the wood, the fastener head was sheared off, or the fastener deformed under high uplifting or horizontal force. Wood failure initiated at the corners of the rectangular opening under high stress concentration, manifesting in the form of cross layer breaking under tension or the inter-lamina delamination.

The performance of the module indicated the presence of a system effect that improved the ductility of the wall, which was important to the seismic performance of the proposed midrise to tall wood buildings. The test data was compared to previous models found in literature. Simplified analytical models based on the current data were also developed to estimate the lateral stiffness and strength of CLT wall with openings.

5 FUTURE WORK

Computer modeling works need to be done to simulate more variables, including various aspect ratio of the opening, the location of the opening, and taller/wider walls. The existing models found in literature was not quite accurate in estimating the performance of the wall.

The system effect shall also be studied in computer models since it is very costly and time-consuming to perform full size tests on various module configurations, as shown in this project. The system performance of multiple modules connected together is another critical area to be investigated, based on the connections developed in Phase I and the current work in Phase II.

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Appendix A Loading protocol for reverse-cyclic test

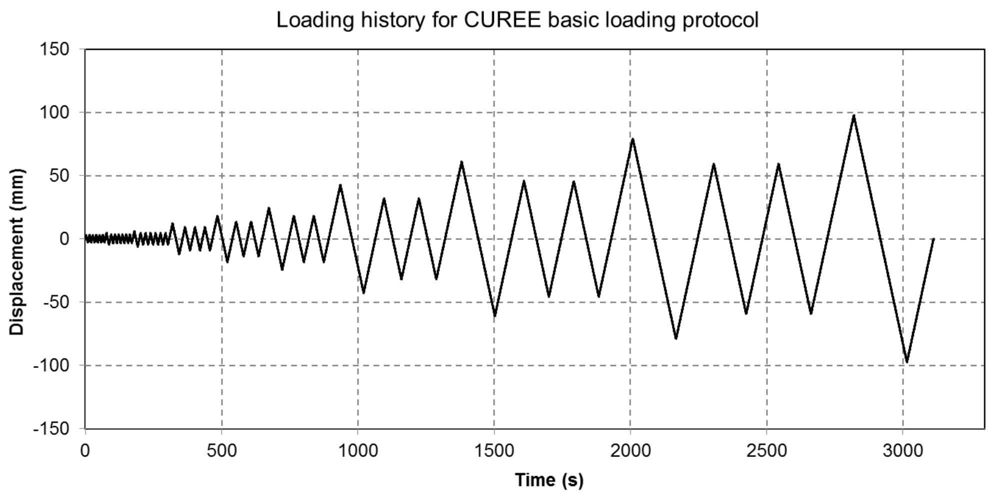

Figure A- 1 Loading history for CUREE basic loading protocol

Table A- 1 Amplitudes of CUREE basic loading protocol

Step	Number of cycles		Amplitude (mm)
1	Equal	6	3.0
2	Primary	1	4.5
	Secondary	6	3.4
3	Primary	1	6.0
	Secondary	6	4.5
4	Primary	1	12.0
	Secondary	3	9.0
5	Primary	1	18.0
	Secondary	3	13.5
6	Primary	1	24.0
	Secondary	2	18.0
7	Primary	1	42.0
	Secondary	2	31.5
8	Primary	1	60.0
	Secondary	2	45.0
9	Primary	1	78.0
	Secondary	2	58.5
10	Primary	1	96.0
	Secondary	2	72.0

THE END