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Development of Mass Timber Wall System Based on Nail Laminated Timber

by

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EXECUTIVE SUMMARY

This project studied the feasibility and performance of a mass timber wall system based on Nail Laminated Timber (NLT) for floor/wall applications, in order to quantify the effects of various design parameters. Thirteen 2.4 m × 2.4 m shear walls were manufactured and tested in this phase. Together with another five specimens tested before, a total eighteen shear wall specimens and ten configurations were investigated. The design variables included fastener type, sheathing thickness, number of sheathings, sheathing material, nailing pattern, wall opening, and lumber orientation. The NLT walls were made of Spruce-Pine-Fir (SPF) No. 2 2×4 (38 mm × 89 mm) lumber and Oriented Strand Lumber (OSB) or plywood sheathing. They were tested under monotonic and reverse-cyclic loading protocols, in accordance with ASTM E564-06 (2018) and ASTM E2126-19, respectively.

Compared to traditional wood stud walls, the best performing NLT based shear wall had 2.5 times the peak load and 2 times the stiffness at 0.5-1.5% drift, while retaining high ductility. The advantage of these NLT-based wall was even greater under reverse-cyclic loading due to the internal energy dissipation of NLT.

The wall with ring nails had higher stiffness than the one with smooth nails. But the performance of ring nails deteriorated drastically under reverse-cyclic loading, leading to a considerably lower capacity. Changing the sheathing thickness from 11 mm to 15 mm improved the strength by 6% while having the same initial stiffness. Adding one more face of sheathing increased the peak load and stiffness by at least 50%. The wall was also very ductile as the load dropped less than 10% when the lateral displacement exceeded 150 mm. The difference created by sheathing material was not significant if they were of the same thickness. Reducing the nailing spacing by half led to a 40% increasing in the peak load and stiffness. Having an opening of 25% of the area at the center, the lateral capacity and stiffness reached 75% or more of the full wall.

A simplified method to estimate the lateral resistance of this mass timber wall system was proposed. The estimate was close to the tested capacity and was on the conservative side. Recommendations for design and manufacturing the system were also presented.

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1 INTRODUCTION

Mass timber construction has been recognized as an excellent solution for midrise to tall wood buildings, due to its good structural performance, low carbon footprint, carbon sequestration, and fast completion time. Currently the predominant mass timber product for floor/wall application is Cross Laminated Timber (CLT). Major lumber manufacturing companies in North America are not engaged in the production of massive timber products. Only a small number of companies are producing mass timber products, while most medium-size and start-up companies find the investment for equipment and skilled labor prohibitive. In the end the economic impact of mass timber is quite limited. One solution to this problem is to develop low-cost and structurally efficient mass timber systems.

This project studied the feasibility and performance of a mass timber wall system based on Nail Laminated Timber (NLT), for floor/wall applications. The equipment and labor skills involved in the manufacturing of this product are minimal compared to other mass timber options, which means small and medium-sized companies will have the capability to make it, once the necessary research has been conducted. The successful application of this system will also promote the lumber and composite panel industries in BC.

2 MATERIAL AND METHODS

Previous work had shown the potential of NLT based mass timber walls (TEAM 2017-07). The lateral capacity of the wall came mainly from the connections between sheathing and NLT. This project investigated the effects of seven parameters on the lateral performance of NLT based shear walls: fastener type, sheathing thickness, number of sheathings, sheathing material, nailing pattern, wall opening, and lumber orientation.

The material used in the specimen manufacturing and related properties are shown in Table 1. The lumber was kiln dried Spruce-Pine-Fir (SPF) No. 2 2×4 (38 mm by 89 mm) with an average moisture content of 15.5%. The nails for lumber assembly was 76 mm (3 in) smooth shank nails. Two Oriented Strand Board (OSB) sheathings were used: 11 mm thick and 15 mm thick. Two types of sheathing nails were selected: 50 mm (2 in) smooth shank nail and 61 mm (2-3/8 in) ring shank nail. The lumber and sheathing were used in the as-received condition.

Table 2 and Figure 1 shows the ten configurations considered in this study: seven configurations (*A* to *G*) were tested in the current phase and three (*H*, *J*, and *K*) were from TEAM database. All the configurations had common NLT layout except *G* and *K*. Configuration *G* had a CLT layout. Configuration *K* was a standard wood stud wall, given for comparison. The shear wall specimen was constructed by nailing lumbers together according to the pattern in Appendix A: 63 pieces for *A* to *F*, and 81 pieces for *G*. The nominal dimension of the wall was 2.40 m (94.5 in) by 2.45 m (96.5 in) (width by height). Samples of the nail laminated specimens are shown in Figure 2

Table 1 Material list

Item	Material grade/model
Lumber	Kiln dried SPF No. 2 2×4 (38 mm by 89 mm), 2.45 m (96.5 in), average moisture content 15.5%
Nail for lumber assembly	28° wire weld nails with smooth shank, nominal length 76 mm (3 in), nominal diameter 3.1 mm (0.120 in) , head offset; pneumatically driven
OSB sheathing	11 mm (0.418 in) thick, APA rated 24/16, exposure 1, 7/16 category; 15 mm (0.578 in) thick, APA rated 40/20, exposure 1, 19/32 category
Ring nail for sheathing	28° wire weld framing ring nails, nominal length 50 mm (2 in), nominal diameter 2.9 mm (0.113 in), head offset; pneumatically driven
Smooth nail for sheathing	28° wire weld framing smooth shank nails, nominal length 61 mm (2-3/8 in), nominal diameter 3.1 mm (0.120 in), head offset; pneumatically driven
Holdowns	Simpson Strong-Tie HTT5
Angle brackets	Simpson Strong-Tie AE116-R
Nails for connections	76 mm (3 in) common nail, 3.76 mm (0.148 in) in diameter; hand driven

Table 2 and Figure 1 shows the ten configurations considered in this study: seven configurations (*A* to *G*) were tested in the current phase and three (*H*, *J*, and *K*) were from TEAM database. All the configurations had common NLT layout except *G* and *K*. Configuration *G* had a CLT layout. Configuration *K* was a standard wood stud wall, given for comparison. *B*, *C*, and *F* had sheathings on two faces of the wall, *G* and *H* had no sheathing, and the rest had one face of sheathing. The seven parameters were investigated through the following combinations: *A* and *B* for fastener type, *A* and *C* for sheathing numbers, *A* and *D* for nailing spacing, *A* and *E* for sheathing thickness, *B* and *F* for wall opening, *B* and *J* for sheathing material, *G* and *H* for lumber orientation.

The shear wall specimen was constructed by nailing the lumber together through the wide face according to the pattern in Appendix A: 63 pieces each for *A* to *F*, and 81 pieces for *G* (27 per layer). Whenever necessary, the lumbers were clamped during nailing to minimize the effect of twisting and cupping. Lumbers with excessive wane were not used in making specimens. The nominal dimension of the wall was 2.40 m × 2.45 m (width × height, 94.5 in × 96.5 in). Samples of the nail laminated specimens are shown in Figure 2.

The sheathing panels were oriented horizontally, with a gap of 12 mm (0.5 in) in between. The regular spacing for sheathing nails was 150 mm (6 in) along the perimeter and 300 mm (12 in) along the lumber length at every 406 mm (16 in). The nail spacing around the opening in *F* was also 150 mm (6 in). With the dense pattern, two rounds of nails were installed at the perimeters, and the spacing along the lumber was reduced by half. So double the amount of nails were used. The specimens were tested within 24 hours after construction.

Table 2 Configurations of wall specimens

Design	Monotonic test	Reverse -cyclic	Face of sheathing	Sheathing thickness	Sheathing material	Sheathing nail	Sheathing nail spacing	Lumber orientation	Opening	Lumber	# of lumber used
A	1	1	1	11 mm	OSB	Smooth	Regular	NLT	N	SPF #2	63
B	1	1	2	11 mm	OSB	Ring	Regular	NLT	N	SPF #2	63
C	1	1	2	11 mm	OSB	Smooth	Regular	NLT	N	SPF #2	63
D	1	--	1	11 mm	OSB	Smooth	Dense	NLT	N	SPF #2	63
E	1	1	1	15 mm	OSB	Smooth	Regular	NLT	N	SPF #2	63
F	1	1	2	11 mm	OSB	Smooth	Regular	NLT	Y*	SPF #2	63
G	1	1	N/A	N/A	N/A	N/A	N/A	CLT	N	SPF #2	81
H	1	--	N/A	N/A	N/A	N/A	N/A	NLT	N	SPF #1&B	61
J	1	1	1	12.5 mm	Plywood	Ring	Regular	NLT	N	SPF #1&B	61
*K***	1	1	1	12.5 mm	Plywood	Smooth	Regular	Light framing	N	DF #2	15

*: the opening was 25% of the wall area and was in the center of the wall; ** framed with 2×6 (38mm ×140 mm) lumber

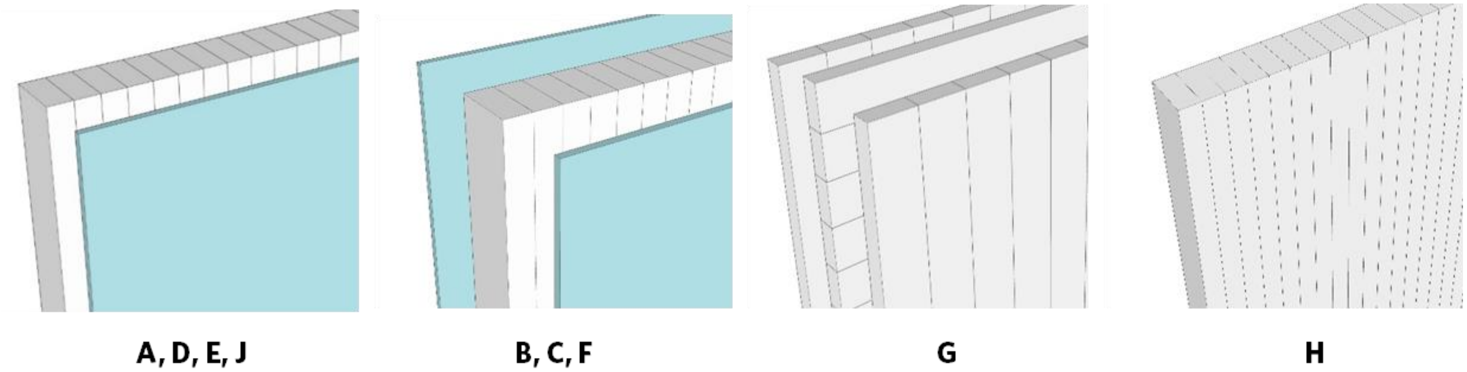

Figure 1 Lumber orientation and sheathing configurations

Figure 2 Nail laminated shear wall specimens

Two specimens were manufactured for every configuration (except *D* and *H*): one tested under monotonic loading and the other under reverse-cyclic loading, as shown in Table 2. 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 3 and 4. The wall was secured to the test base with two HTT5 holdowns and four AE116-R angle brackets. The holdowns were installed at the end and the angle brackets on the two sides, 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. 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.

Four transducers measured the lateral displacement and corner uplifting of the wall. The monotonic loading 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 could be found in Appendix B. The loading rate for cyclic test was 1 mm/s.

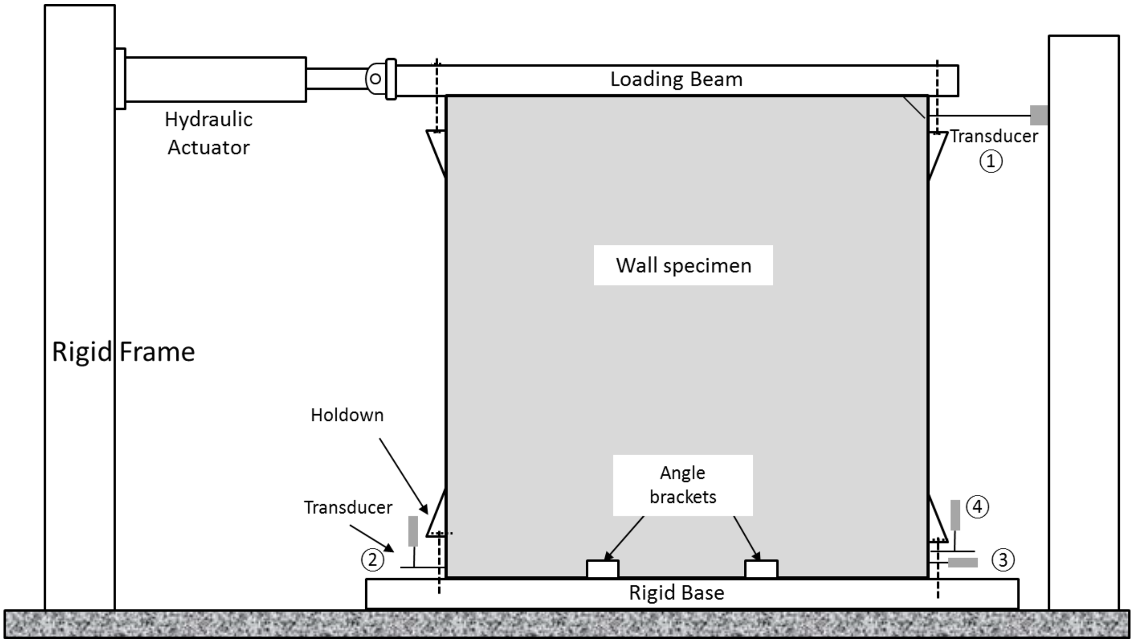

Figure 3 Shear wall test setup and location of transducers

Figure 4 Specimen installation (configuration A and G)

3 RESULTS AND DISCUSSIONS

A summary of the test results are shown in Table 3, including the peak load, displacement at peak load, displacement when the load dropped to 80% of peak, and the load at various drift levels. The load-displacement curves for the monotonic test and the envelope curves for the reverse-cyclic tests are shown in Figures 5 and 6, respectively. In some specimens the peak load did not drop below the 80% of peak, and the test was stopped when the actuator displacement reached over 150 mm.

Table 3 Summary of shear wall test results

	Monotonic loading protocol						Reverse-cyclic loading protocol					
Design	P_{max} (kN)	Δ_{Pmax} (mm)	$\Delta_{0.8Pmax}$ (mm)	$P_{0.5\%}$ (kN)	$P_{1.0\%}$ (kN)	$P_{1.5\%}$ (kN)	P_{max} (kN)	Δ_{Pmax} (mm)	$\Delta_{0.8Pmax}$ (mm)	$P_{0.5\%}$ (kN)	$P_{1.0\%}$ (kN)	$P_{1.5\%}$ (kN)
A	37.6	81.4	101.9	18.4	25.4	30.0	34.5	74.7	91.7	14.8	22.0	26.8
B	59.9	137.6	>138*	18.3	27.1	34.1	45.3	62.6	99.3	21.5	30.6	37.4
C	61.2	90.4	>168*	24.5	36.8	45.0	53.8	83.8	97.4	23.4	32.4	38.4
D	52.5	90.1	107.9	26.2	35.1	41.4	--	--	--	--	--	--
E	40.3	84.5	115.0	18.8	26.4	31.6	36.7	100.0	118.5	16.8	22.7	26.4
F	45.7	72.2	91.8	19.5	27.9	34.3	42.4	70.8	105.6	14.8	24.7	32.6
G	22.1	185.9	>186*	4.7	6.7	8.5	14.1	107.2	>108*	3.4	5.2	6.6
H	20.8	163.9	>165*	6.7	9.6	11.3	--	--	--	--	--	--
J	40.1	72.5	107.6	17.0	24.8	30.5	32.9	73.5	103.4	11.8	19.3	25.9
K	24.5	72.1	92.7	13.7	17.7	20.4	21.4	58.0	88.5	12.0	16.2	19.0

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)
*: load did not decrease below 80% of the peak

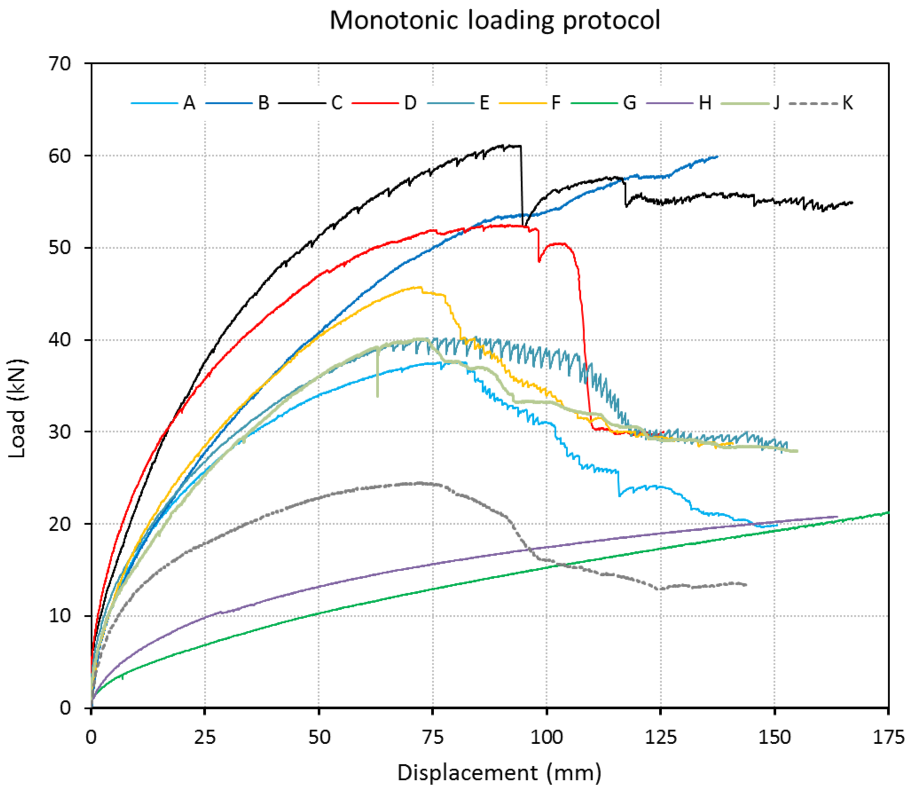

Figure 5 Monotonic test results

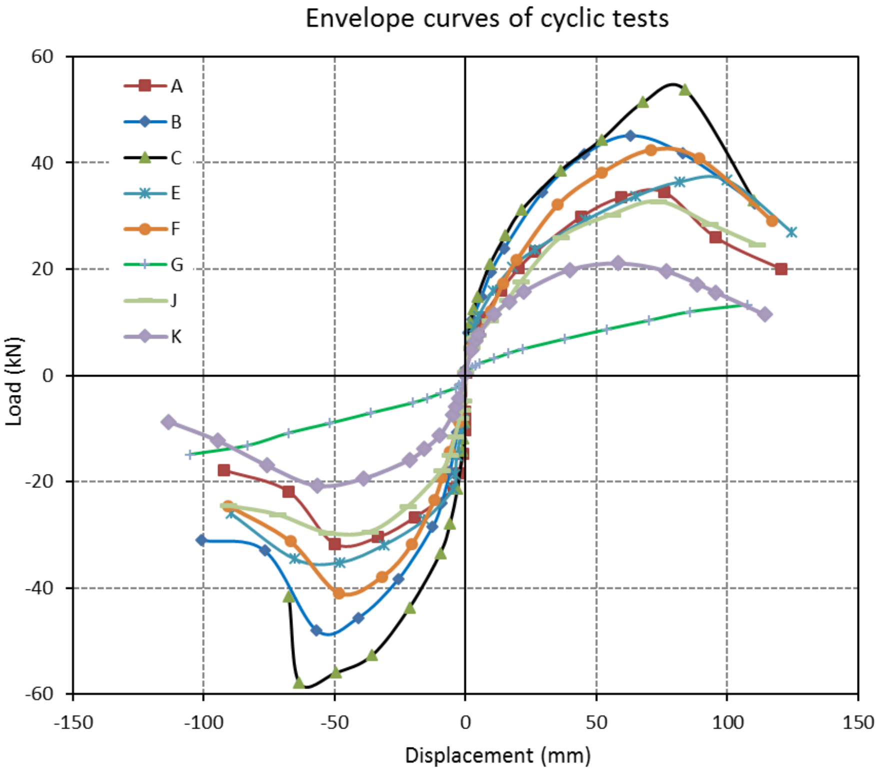

Figure 6 Envelope curves of cyclic tests

3.1 Effects of design parameters

The effects of various design parameters on the shear wall performance under lateral loading are discussed below.

Fastener type: Wall-B and Wall-C

Wall-B and Wall-C had the highest loading carrying capacities amongst all the specimens. Both had double face sheathing with regular nailing spacing. The peak load difference between these two configurations was 2% under monotonic loading and 16% under reverse-cyclic loading. The wall with ring nails had higher stiffness under 0.5-1.5% drift, but its ductility after peak load was lower. The peak load of Wall-C under reverse-cyclic was 24% lower than its peak load under monotonic protocol, the largest difference amongst the sheathed specimens. This indicated the performance of ring nails drastically deteriorated under reverse-cyclic loading. A similar trend was found in Wall-J, though the drop was not as remarkable (at 17%).

Sheathing thickness: Wall-A and Wall-E

Wall-E used 15 mm thick OSB as sheathing and Wall-A used 11 mm. Thicker sheathing increased the peak load by 6-7%, and provided better post-peak ductility. When the load dropped below 80% of the peak, the displacement of Wall-E increased by 15-30%. The improvement in load bearing capacity and ductility came from the higher nail head pull-through strength with thicker sheathing. The initial stiffness of the two configurations was almost identical.

Number of sheathings: Wall A and Wall-C

Wall-C had sheathings on two faces of the wall while Wall-C had only one face. By adding one face of sheathing, the peak load increased by 63% and 56% under monotonic and reverse-cyclic protocols, respectively. The initial stiffness at 0.5-1.5% drift increased by an average of 50%, and this increment was more significant under reverse-cyclic loading. Wall-C also had better ductility than Wall-A, especially under monotonic loading, in which the load of Wall-C remained at a high level after the displacement exceeded 150 mm.

Sheathing material: Wall-A and Wall-J

The effect of 11 mm OSB and 12.5 mm plywood sheathing was investigated by comparing Wall-A and Wall-J. This comparison was based on the above finding that the fastener type did not significantly affect the load bearing capacity under monotonic loading. The difference of peak load was 7% and the difference of stiffness was within 10%. The better ductility of Wall-J was probably more attributed to the ring nails rather than the plywood sheathing.

Nailing pattern: Wall-A, Wall-C, and Wall-D

Wall-D and Wall-A both had one face sheathing while Wall-D had a dense nailing pattern. As a result, both the peak load and stiffness at 0.5-1.5% drift increased by 40%. The improvement in ductility was less significant. The displacement at peak load was 11% higher and the displacement when the load dropped to $0.8P_{max}$ was 6% higher.

Wall-C and Wall-D had the same amount of sheathing nails, but C had two face sheathing with regular spacing while D had one face sheathing with dense spacing. Wall-D reached a peak load of 52.5 kN, 86% of two faced sheathing with regular spacing (Wall-C). the difference of stiffness at 0.5-1.5% drift was within 8%. The unsymmetrical sheathing of Wall-D caused the specimen to move sideways under high loads during the test. This may be the reason of the sudden drop of load found in Wall-D.

Wall opening: Wall-C and Wall-F

Wall-F had an opening of 25% of the area at the center of the wall. Its peak load under monotonic was 75% of Wall-C, and 79% under reverse-cyclic. The stiffness at 0.5-1.5% drift was 70-80% of the full wall. Due to the reduced wall area, the displacement at peak load also decreased by 15-20%. The decreasing of ductility was more notable under monotonic than under reverse-cyclic loading.

Lumber orientation: Wall-G and Wall-H

The CLT layout (Wall-G) had a similar performance as the NLT layout (Wall-H). Wall-H had higher stiffness and strength under the same displacement. In both cases the load did not decrease within the tested displacement range. Without sheathing, neither layout was feasible for stand-alone structural use.

Framing system: Wall-A and Wall-K

The two walls had the same amount of nails and identical nailing pattern. The peak load of Wall-A was 53% and 61% higher than the peak load of Wall-K for monotonic and reverse-cyclic, respectively. The stiffness at 0.5-1.5% drift increased by an average of 40%. The load-displacement curves after the peak were of a similar shape. The NLT-based wall retained the high ductility of the traditional system. And the advantage of NLT-based wall was even greater under reverse-cyclic loading due to the internal energy dissipation of the NLT.

Failure mode

For the sheathed NLT walls, the failure occurred mainly at the connection between sheathing panels and lumber in two common modes: nail head pull-through the sheathing and nail shank withdrawal from the lumber, as shown in Figure 7. Initial failures concentrated at the perimeters of the sheathing. Withdrawal occurred more frequently with thicker sheathing, and head pull-through occurred more with ring nails. But both failure modes always coexisted in a wall due to variation of the lumber properties.

The lateral resistance of Wall-F largely depended upon the remaining full-height segments. At the point of failure, there was a complete separation between sheathing and lumber on the left and right side of the opening. Some corners also had sheathing being torn open along the diagonal direction, as shown in Figure 8.

No out-of-plane buckling was observed with the exception of one specimen in Wall-C. Three lag screws were installed to transfer the load from the loading beam to the top of the wall. In this case they broke at high stress levels and only two holdowns at the ends remained. This left little out-of-plane restraint at the top, so the wall buckled in the manner shown in Figure 9. The buckling was exacerbated by the unsymmetrical sheathing on the two faces. Similar phenomenon was not found in other specimens, including the ones with higher load carrying capacities.

No failure was observed at the holdowns or angle brackets, though there was a small amount of uplifting at the corner.

Figure 7 Nail head pull-through and withdrawal failure

Figure 8 Failure of Wall-F with opening

Figure 9 Out-of-plane buckling

3.2 Design considerations

It was possible to design an NLT based shear wall with the current method for light wood framing system. According to the findings above, this approach would severely underestimate the actual performance of the system since it accounted only 60% of the strength and 70% of the stiffness. The actual difference may have been even greater since the stud wall referenced here was made from Douglas-fir lumber.

The design approach proposed here was a simplified method attempting to include the contributions of both NLT and sheathing. The shear resistance per unit length of NLT with sheathing was defined by the sum of the unit length resistance provided by NLT and the unit length resistance provided by the sheathing connections:

$$v_{NS} = v_N + v_S \tag{1}$$

where: v_{NS} – factored shear resistance per unit length of NLT with sheathing, kN/m

v_N – factored shear resistance per unit length provided by NLT, kN/m

v_S – factored shear resistance per unit length provided by sheathing connections, kN/m

The factored shear resistance from the sheathing connections was obtained according to the wood stud wall design method, as outlined in Wood Design Handbook (2017). The shear resistance from NLT may be obtained through computer modeling or a series of tests on NLT walls with various length. Due to the limited resources, neither of them could be conducted before the end of this project. Here the factored NLT resistance per unit length was estimated by the difference of measured capacity between Wall-A and Wall-K, divided by the length of the wall and by a factor of 2. This factor was comparable to but higher than the ratio between the measured capacity and design capacity in the wood stud Wall-K (1.7-1.9). The factored resistance of NLT without sheathing was calculated to be 2.7 kN/m.

The measured lateral capacity of every wall was converted to capacity per unit length in Table 4. The factored shear resistance of the sheathing connections, v_S, was estimated by the factored resistance of an equivalent wood stud wall in Wood Design Manual (2017). The factored shear resistance of an NLT wall with sheathing, v_{NS}, was calculated according to Equation (1). The ratio between measured capacity and factored resistance of every specimen is shown in Table 4. The ratio of NLT walls with sheathing (A to J) was equal to or higher than the ratio of the wood stud wall (K). The ring nailed walls under reverse-cyclic loading had a lower ratio due to the low ductility. The walls with opening (F) had significantly higher ratios because the full-length segment method was very conservative. With the exception of these cases, the ratio of NLT with sheathing was in the range of 2.0-2.3.

Table 4 Measured and design capacity per unit length

Per unit length	A	B	C	D	E	F	J	K
Measured capacity p_M (kN/m) Monotonic	15.4	24.6	25.1	21.5	16.5	18.8	16.4	10.0
Measured capacity p_M (kN/m) Reverse-cyclic	14.1	--	22.1	--	15.0	17.4	--	8.8
Factored resistance v_S (kN/m)	4.19	8.38	8.38	7.86	4.57	4.19	5.23	5.23
Factored resistance v_{NS} (kN/m)	6.87	11.06	11.06	10.54	7.25	6.87	7.91	-
Measured/Factored (mono)	2.2	2.2	2.3	2.0	2.3	2.7	2.1	1.9
Measured/Factored (cyc)	2.1	1.7	2.0	--	2.1	2.5	1.7	1.7

v_S: design resistance according to wood framing wall design;
v_{NS}: design resistance for NLT based shear wall with sheathing;

The lateral capacity of NLT with sheathing could be estimated by

$$P_{max} = v_{NS} \times 2 \times L_s \tag{2}$$

where: P_{max} – maximum load bearing capacity of an NLT wall with sheathing, kN
L_s– length of full-length shear wall segment, m

The estimated peak load and tested peak load of every NLT specimen with sheathing are shown in Figure 10. Except the reverse-cyclic specimens of Wall-B and Wall-G (ring nail), the tested peak load was equal to or higher than the estimated peak load. Equations (1) and (2) could provide a good estimate of the load bearing capacity of the wall and the estimate was on the conservative side.

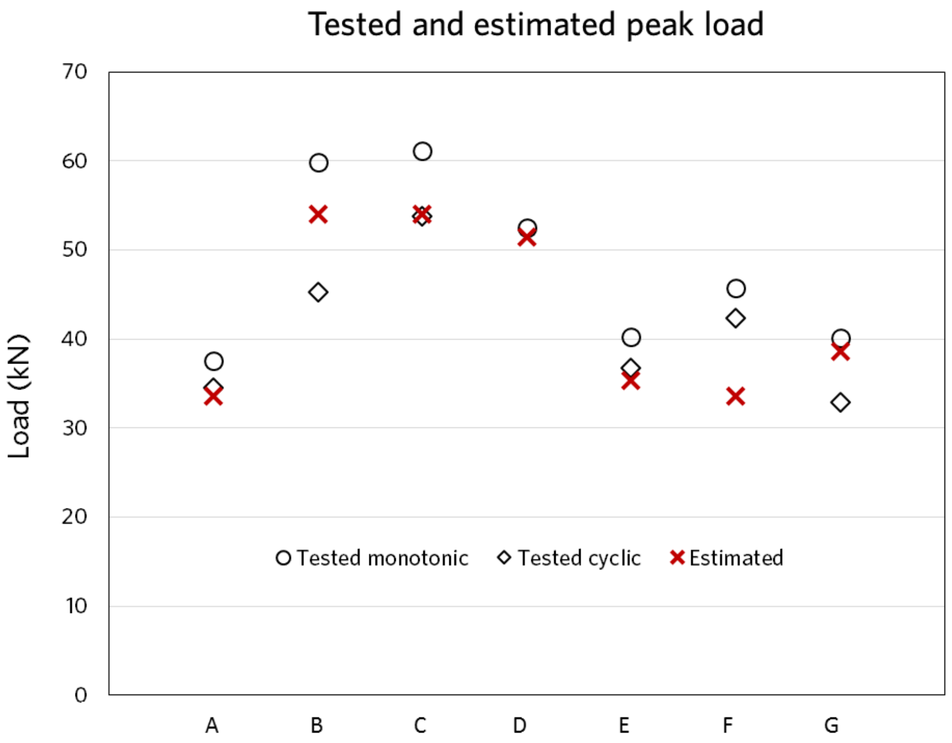

Figure 10 Tested and estimated peak load of every NLT specimen

The following issues identified in this project shall be considered in the design and manufacturing process.

1. Ring nails are not recommended for the sheathing due to its lack of ductility under reverse-cyclic loading.
2. For the same thickness, plywood sheathing and OSB sheathing have comparable performances in terms of lateral resistance. Thicker sheathing leads to a higher lateral stiffness and strength. Very thick sheathing, for example, 22 mm or above, may be used with proper fasteners to achieve optimal results.
3. The strength of the wall can be controlled by the nailing pattern. With a dense nailing spacing and two facing sheathing, the lateral capacity of the wall could reach the range of 80 kN-100 kN.
4. A leveled NLT surface is required for an optimal sheathing connection. Significant cupping or twisting of the lumber would create a gap between sheathing and lumber, thus compromise the critical lateral shear resistance.
5. The design shall consider the possible out-of-plane buckling. There must be enough lateral restraints between the two ends of the wall, for example, by installing angle brackets.
6. Attention shall also be paid to the eccentricity of the lateral resistance due to uneven sheathing on the two sides of the wall. One face sheathed with denser nailing pattern is not recommended.

7. Current holdowns and angle brackets are mostly designed for installation on the wide face of the lumber. But for NLT, they have to be mounted on the narrow face. In this case fasteners may fall into the gaps between lumber members and lose the withdrawal capacity. This problem should be mitigated when choosing the connection hardware and the nailing pattern.

4 CONCLUSIONS

This project studied the lateral performance of a mass timber shear wall system based on NLT. Thirteen 2.4 m × 2.4 m shear walls were manufactured and tested under two loading protocols: monotonic and reverse-cyclic. With another five shear walls tested before, there were a total of eighteen specimens and ten configurations. This database were used to evaluate various design parameters and to identify potential problems in the manufacturing and design processes.

Compared to a traditional wood stud wall, the peak load of the NLT based wall was 53-61% higher, and the stiffness at 0.5-1.5% drift was 40% higher, while retaining the same ductility. The advantage of NLT-based wall was even greater under reverse-cyclic loading due to the internal energy dissipation of NLT.

Walls with ring nails had higher stiffness than walls with smooth nails. But the performance of ring nails deteriorated drastically under reverse-cyclic loading, leading to a considerably lower capacity (16% lower). Changing the sheathing thickness from 11 mm to 15 mm improved the strength by 6% while having the same initial stiffness. Adding one more face of sheathing increased the peak load and stiffness by at least 50%. Its load remained at a high level when the lateral displacement exceeded 150 mm. The difference caused by the sheathing material was not significant if they were of the same thickness. Reducing the nailing spacing by half led to a 40% increasing in the peak load and stiffness. Having an opening of 25% of the area at the center, the lateral capacity and stiffness reached 75% or more of the full wall.

A simplified method to estimate the lateral resistance of this mass timber wall system was proposed. The estimate was close to the tested capacity and was on the conservative side. Recommendations for design and manufacturing the system were also presented.

5 FUTURE WORK

Further research is needed on the computer modeling of this system, especially when dealing with taller and/or wider walls and walls with various aspect ratios. The assumption of the design approach presented here shall be validated under such conditions. The compressive strength of this system may be designed according to the existing method for stud walls. However, since the vertical load applied on NLT is much higher than that on a stud wall, compression tests shall be conducted to ensure there is no buckling issue.

Another area to be studied is the connection, including connecting with horizontal members and connection with other wall plates.

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Appendix A Nailing pattern for manufacturing NLT specimens

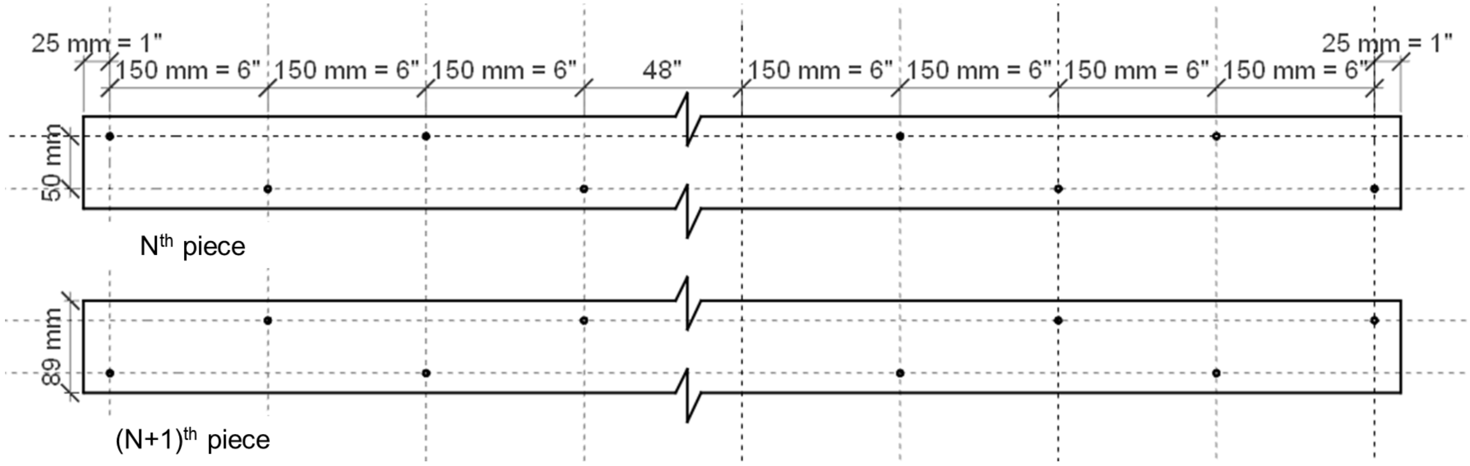

Figure A- 1 NLT wall specimen nailing pattern

Appendix B CUREE basic loading protocol

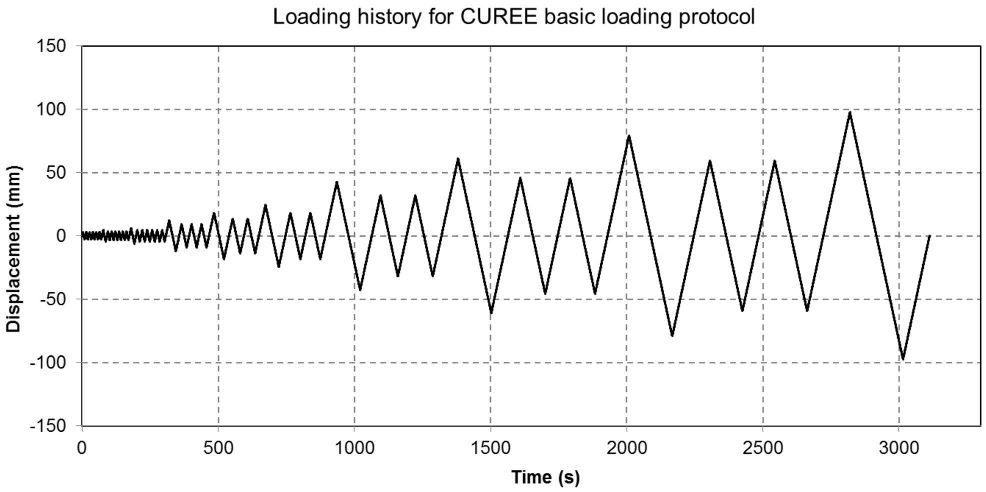

Figure B- 1 Loading history for CUREE basic loading protocol

Table B- 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