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Seismic Performance of Midply Shear Wall

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ABSTRACT

Wood-frame construction is predominant for single family and low-rise multi-family dwellings in North America. Surveys from past earthquakes reveal that wood-frame buildings have generally performed well under seismic events, primarily due to the shear walls in the structures which provide sufficient lateral load resistance against earthquakes. As the shift from single-family to multi-family construction continues in North America, there is a growing need for stronger shear walls in wood-frame construction to address higher code force demands and performance expectations by the public.

Midply shear wall, which was originally developed by researchers at Forintek Canada Corp. (predecessor of FPInnovations) and the University of British Columbia, is a high-capacity wood-frame shear wall system that is suitable for high wind and seismic loadings. The original Midply shear wall, however, had limited applications due to its low resistance to vertical load and difficulty to accommodate electrical and plumbing installations. In collaboration with APA – The Engineered Wood Association, a modified Midply shear wall has been developed to increase the vertical load resistance and make it easier to accommodate electrical and plumbing installations.

This paper presents the cyclic lateral load test results on the modified Midply shear walls with the selected sheathing thicknesses and nail spacing. The results showed that the modified Midply shear walls have approximately doubled the lateral load capacity of a comparable conventional shear wall. The overstrength capacity, ductility, and drift capacity of the Midply shear wall meet the seismic equivalency parameters (SEPs) specified in ASTM D7989.

Keywords: Wood-frame Construction; Midply Shearwall; Lateral Load Resistance; Seismic Equivalency.

INTRODUCTION

Wood-frame construction is the predominant method of construction for single family and low-rise multi-family dwellings in North America. Surveys from past earthquakes reveal that the wood-frame buildings have generally performed well under seismic events, primarily due to the shear walls in the structures which provide sufficient lateral load resistance against earthquakes [1].

As the shift from single family to multi-family construction is happening in North America, there is a growing need for stronger and stiffer shear walls in wood-frame construction because of increased seismic and wind loads and higher performance expectations by the public. The introduction of mid-rise wood-frame buildings and new construction practices such as large openings, long spans, and concrete toppings has created additional demand for lateral load resistance [2]. In addition, the seismic design spectra in the 2020 NBCC [3] have been increased substantially for all site classes, which would result in higher seismic demands. The combined effects above make it difficult, if not impossible, for designers to use the existing design solutions to resist the seismic loads in mid-rise wood-frame building in high seismic zones. New effective solutions need to be developed to accommodate the increased seismic loads so that designers can continue to use mid-rise wood-frame construction in the highest seismic zones.

Midply shear wall (hereafter Midply), which was originally developed in the 1990s by researchers at Forintek Canada Corp. (predecessor of FPInnovations) and the University of British Columbia [4,5], is a high-capacity lateral load resisting system that is suitable for high wind and seismic loadings. It consists of structural components used in standard shear walls but rearranged in such a way that the lateral resistance and the dissipated energy of the system significantly exceed those in standard wall arrangements. Its superior seismic performance was demonstrated in a full-scale earthquake simulation test of a 6-storey wood-frame building in Japan [6]. Figure 1 illustrates a cross-section of a standard and a Midply shear wall that use the same size of dimension lumber studs. As the nailed connections to the sheathing work in double shear (Figure 2), Midply provides approximately double the lateral resistance than a standard single-sided wood shear wall with the same nailing schedule and wall length [4,5]. Midply has been implemented in the Canadian design standard, CSA O86-2019 [7], and in the Japanese standard.

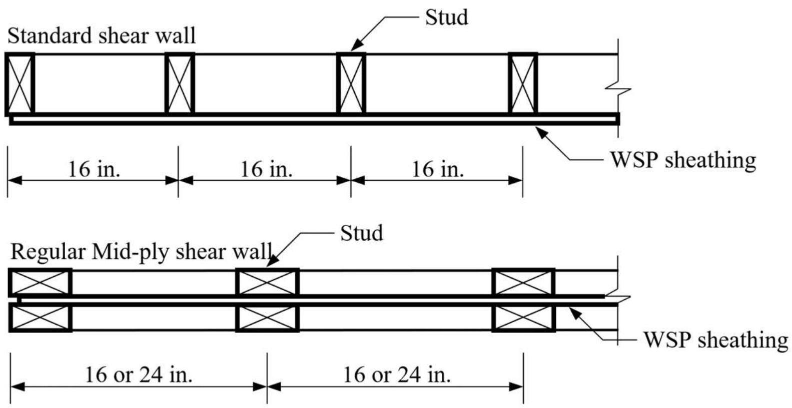


Figure 1. Cross-section of a standard shear wall (top) and a Midply (bottom) with single-layer of panel.

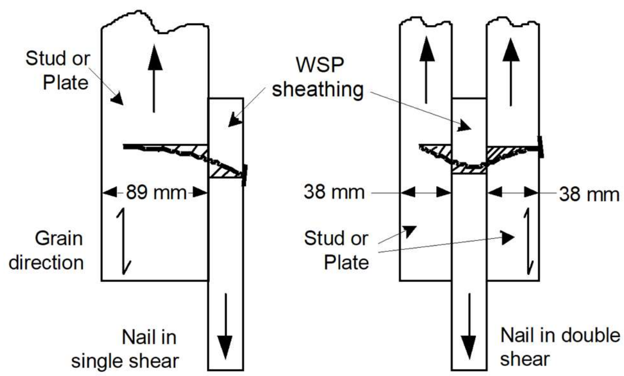


Figure 2. Nailed connection working in single-shear in standard shear wall (left) and double-shear in Midply (right).

Midply, however, has limited applications. With the Midply configuration shown in Figure 1, the vertical load resistance is much less than that of a standard shear wall, as it is prone to buckle out-of-plane of the shear wall. Strength and stiffness for out-of-plane loads, such as wind, is also less than a standard shear wall. In addition, it is difficult to accommodate electrical and plumbing services and install typical connections to maintain structural load path due to narrow cavity depth. For broader applications of Midply, these limitations need to be addressed.

In collaboration with APA–The Engineered Wood Association and the American Wood Council (AWC), a new framing arrangement for Midply was developed to address the above-mentioned issues. A test program was developed to investigate the performance of modified Midply. Assignment of shear strengths and seismic force modification factors for Midply has been developed based on the test results.

MODIFIED MIDPLY CONFIGURATION

Figure 3 shows the new framing arrangement for Midply. Instead of framing members on both sides of the sheathing placed on flat, as in a regular Midply framing arrangement (Figure 1), framing members on one side of the sheathing are arranged in the same way as in a standard shear wall in the modified Midply.

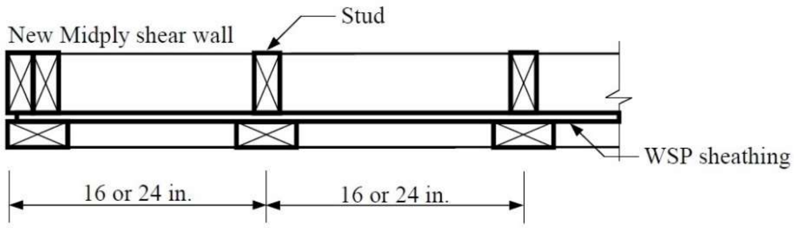
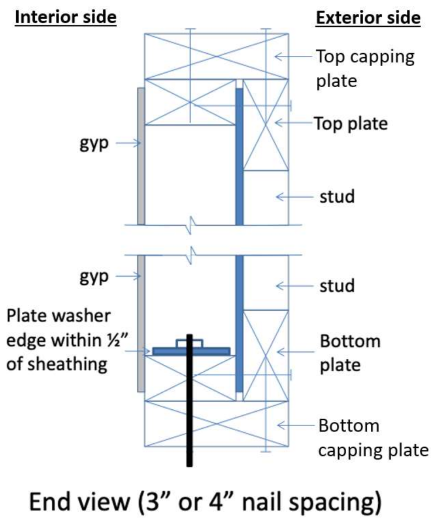
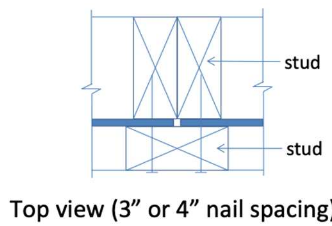


Figure 3. New framing arrangement for Midply.

With this new framing arrangement, it is anticipated that, while maintaining the same lateral resistance as regular Midply, the modified Midply would have at least the same vertical load and out-of-plane load resistance as standard shear walls. To facilitate the installation of Midply and shear force transfer to floor or foundation, top and bottom capping plates are added, as shown in Figure 4a. Figure 4b shows the connection details at studs where structural panels are joined.



(a)



(b)

Figure 4. New framing arrangement for Midply: a) vertical cross-section, b) cross-section of studs where panels butt together.

MIDPLY TEST PROGRAM

A test program, encompassing key variables such as panel thickness and nail spacing, was jointly developed by FPInnovations and APA–The Engineered Wood Association. This paper presents only the Midply specimens tested at FPInnovations, as shown in Table 1.

Table 1. Test matrix for Midply

Wall number	Sheathing panel		Nail spacing at panel edge (in.)
	Grade	Thickness (in.)	
5a	Rated Sheathing	7/16	4
17a	Rated Sheathing	7/16	3

Figures 5 and 6 show the shear wall configuration and nailing details of the sheathing. All shear wall specimens, 100-1/8 inches long and 100 inches tall, were constructed with 2 x 4 No. 2 and better grade Douglas Fir dimension lumber, and with 7/16 in. (rated as 1R24/2F16/W24) nominal thick vertically placed OSB Rated Sheathing. Lumber was pre-sorted so that the pieces with relative density within 0.50 ± 0.03 were used for the wall specimens. The moisture contents of end studs, center studs where two panels meet, and top and bottom plates, measured using a moisture meter (Delmhorst RDM-3-PKG) within 30 minutes of testing, were between 9 – 15%. The relative density and moisture content were measured in accordance with ASTM D2395 [8] and D7438 [9], respectively.

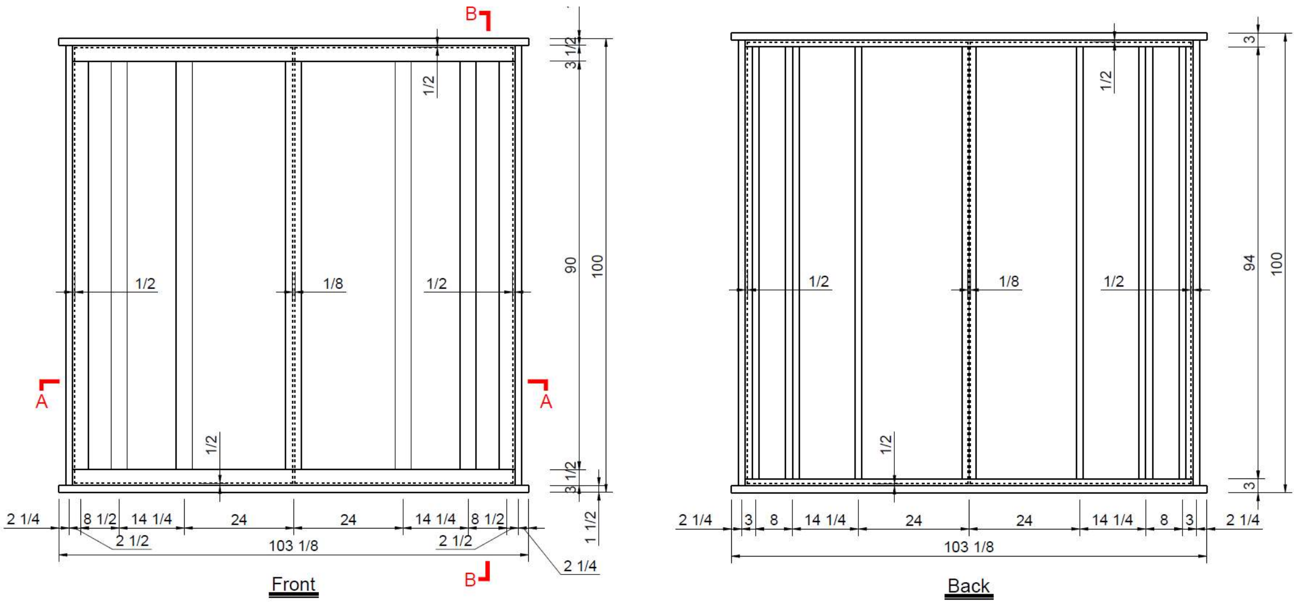
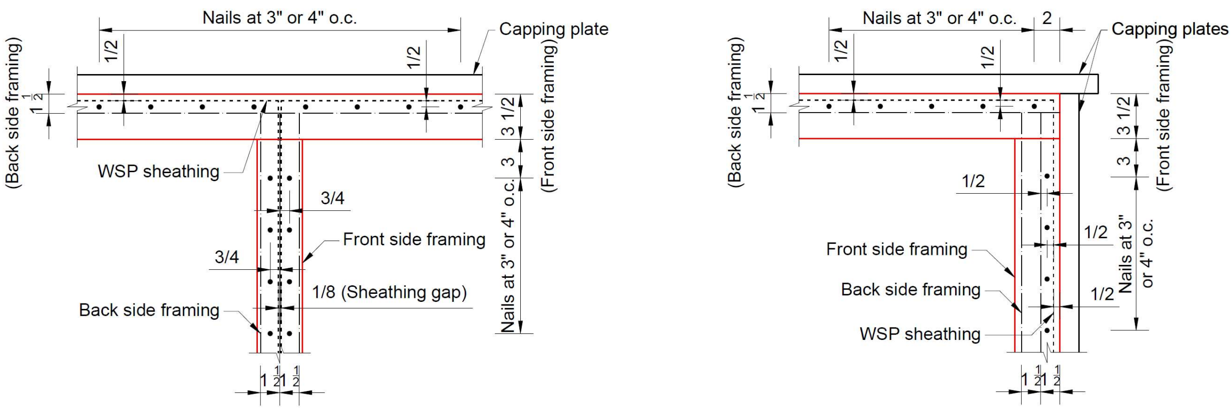


Figure 5. Construction details of tested Midply specimens (inches).



(a) *(b)*

Figure 6. Nailing pattern of tested Midply specimens (inches): a) middle stud and top plate, b) end stud and top plate.

The sheathing panels were connected to the framing members with ASTM F1667 NLCMMS37 (identification of fasteners used in ASTM F1667 [10]) power- driven common nails (3-1/2" in length and 0.131" in diameter) spaced at 4" or 3" on center along the panel perimeter and 6" on center elsewhere. For the back side framing, the framing members were connected to each other with F1667 NLCMMS69 power-driven common nails (3" in length and 0.120" in diameter). Two rows of F1667 NLCMMS69 common nails spaced at 8" on center were used for the double end studs. Two rows of F1667 NLCMMS69 common nails spaced at 3" on center were used for connecting center studs where panels are joined. Two F1667 NLCMMS69 common nails were end-nailed to each stud from the top or bottom plate. Three rows of F1667 NLCMMS69 power-driven common nails were used to connect 2 x 6 capping plate to the top and bottom plates, with one row of nails spaced at 3" on center connected to the front side of the framing and two rows of nails spaced at 6" on center connected to the back side of the framing. Similarly, three rows of F1667 NLCMMS69 power-driven common nails were used to connect 2 x 6 lumber to the end studs, with one row of nails spaced at 6" on center connected to the front side of the framing and two rows of nails spaced at 12" on center connected to the back side of the framing.

The Midply specimens were fabricated and installed in accordance with the requirements in ASTM E2126 [11]. Figure 7 shows the schematic of the test setup and a Midply shear wall specimen.

Continuous steel rods with 1" (25.4 mm) diameter were used at the ends of the wall specimen to resist overturning moment. Steel plates with dimensions of 6.5" × 4.5" x 1" (165 mm in length x 114.3 mm in width x 25.4 mm in thickness) were placed directly on the top capping plate (Figure 7 cross-section A-A). The steel rods were tightened to finger tight plus a 1/8 turn. Six 5/8" diameter anchor bolts with 3" x 3" x 0.229" steel plates were used to attach the wall specimen to steel beam fixed on the foundation. The holes for the anchor bolts in the bottom plate were 1/16" greater than the anchor bolt diameter. To simulate rigidly affixed anchor bolts, the anchor bolts were threaded into the steel beam, as shown in Figure 7 cross-section B-B. Each anchor bolt was tightened to finger tight plus a 1/8 turn. The 5/8" diameter anchor bolts were also used to attach wall specimen to the steel load spreader beam. These anchor bolts were tightened to reduce the slip between the steel load spreader beam and the wall. A C-section steel beam (C 180 x 18) with a stiffness of 33,000 kips·in.^{2} (95 kN·m^2) was selected as the load spreader beam. No vertical load was applied on the wall specimens.

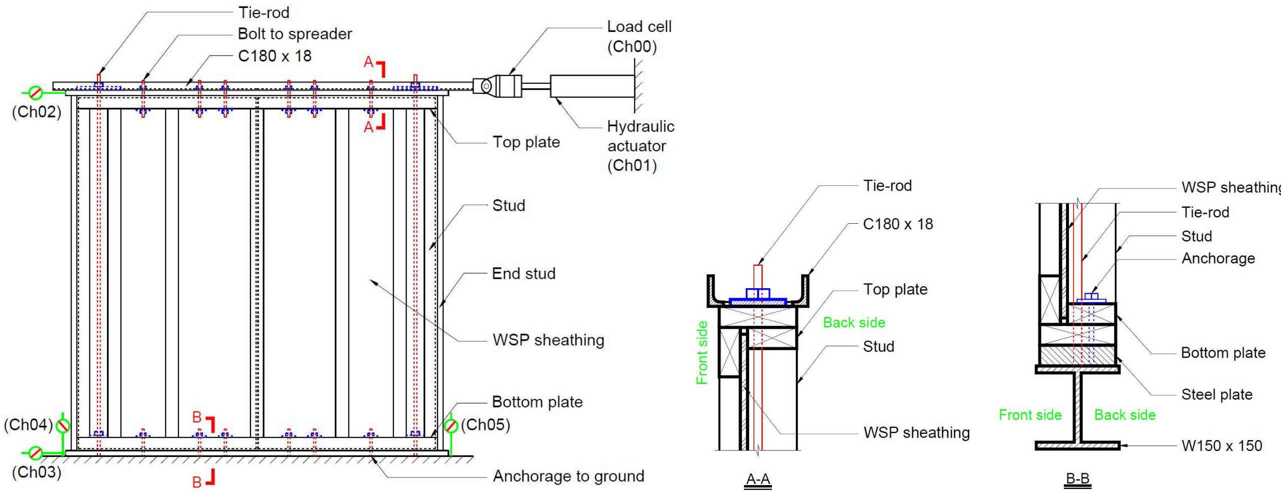


Figure 7. Schematics of Midply test setup.

Figure 8 shows a Midply shear wall specimen which is ready for testing. The lateral load was applied through the steel load spreader beam to the top of the shear wall. The load spreader beam had lateral guides to ensure a steady and consistent unidirectional movement of the wall specimen. The load (Ch00) was measured using a load cell that was located between the actuator and the load spreader beam. Besides the stroke of the actuator (Ch01), two displacement transducers were used to measure the lateral displacement of the top (Ch02) and bottom plate (Ch03), respectively. Two displacement transducers (Ch04 and Ch05) were placed at the bottom of the end-studs to measure the upfit or compression of studs to the foundation.

Figure 8. Test setup with a Midply specimen ready for testing.

All wall specimens were tested under reversed cyclic loading, following the CUREE loading protocol specified as Method C in ASTM E2126. The reference displacement was taken as 2.5" (63.5 mm), which was 0.025 times the height of wall specimens. Each subsequent phase of the CUREE protocol consisted of a primary cycle with an increase in an amplitude of α (0.5 in this study) over the previous primary cycle. Figure 9 shows the loading protocol that was used for the test program. A displacement rate of 0.3" (7.6 mm) per second was used for the reversed cyclic loading tests. The testing was terminated when the load dropped by more than 20% of the maximum load.

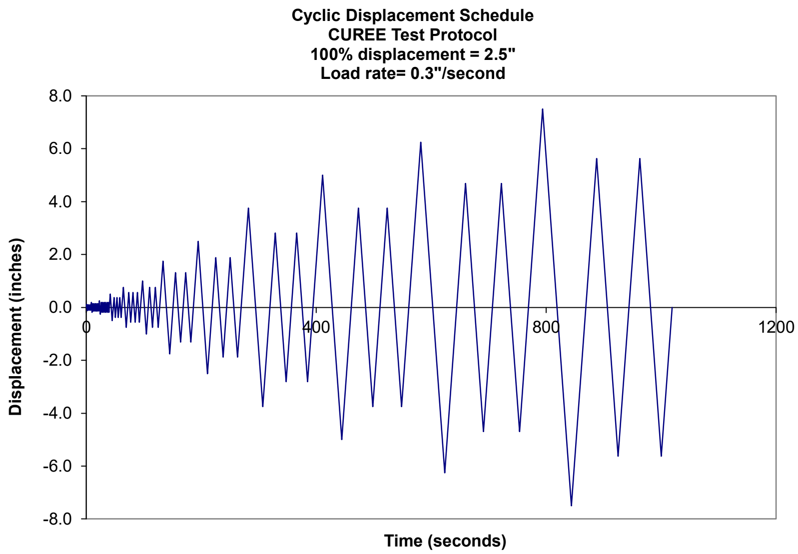


Figure 9. Load protocol used for the Midply test.

RESULTS AND DISCUSSION

Figure 10 shows typical load-displacement curves of Midply shear walls with nail spacing at 3” and 4” on center. The mechanical properties of the tested Midply shear wall specimens have been derived based on the equivalent energy elastic-plastic (EEEP) method described in ASTM E2126. In the analysis, absolute values of the positive and negative envelope curves were averaged first and then the EEEP curve was derived based on the average envelope curve.

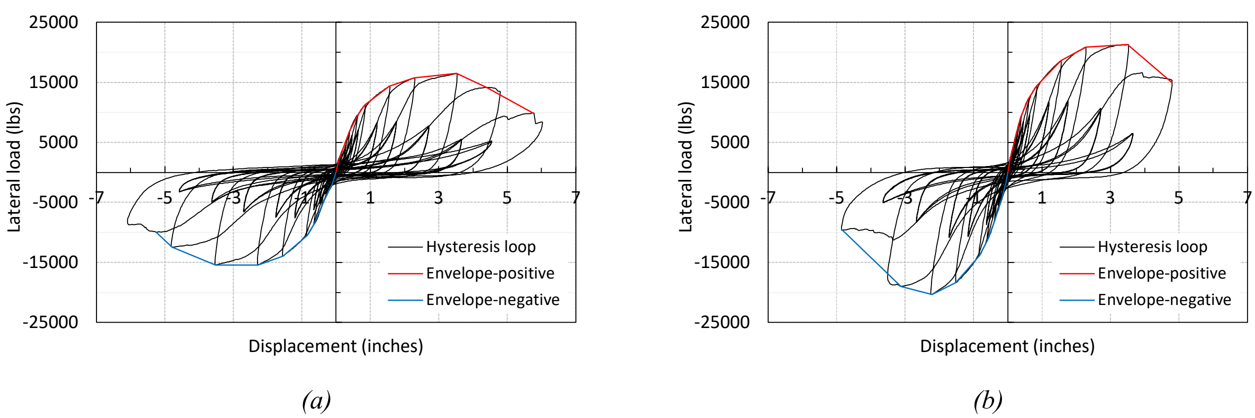


Figure 10. Test setup with a Midply specimen ready for testing: (a) nail spacing at 4” o.c., (b) nail spacing at 3” o.c.

Table 2 summarizes the mechanical properties of Midply shear wall specimens, where K_e is the secant stiffness between origin and the point with 40% of the maximum load; P_y is the yield force based on EEEP method and Δ_y is the corresponding displacement; Δ_u is the ultimate displacement in the post peak region where the load drops to 80% of the maximum load (P_{max}); μ is the ductility ratio, defined as the ratio of ultimate displacement over the yield displacement and E is the total energy dissipated in hysteresis loops.

Test results show that the ultimate displacements of Midply specimens with 4” nail spacing are greater than those with 3” nail spacing. This may be because lumber split during fabrication of some of the specimens with 3” nail spacing. The initial split has further developed with the increase of lateral load and cause the specimen to fail prematurely. It was noticed that Midply specimens that failed at larger displacement cycles and had higher lateral load resistance tended to have higher energy dissipation capacity. This is expected as the specimens were subjected to the same loading protocol.

Table 2. Mechanical properties of the tested shearwalls based on ASTM Standard E2126 (ASTM 2019)

Wall	**K_e (lb/in)**	**Δ_y (in)**	**P_y (lb)**	**Δ_{max} (in)**	**P_{max} (lb)**	**Δ_u (in)**	**μ (Δ_u/Δ_{yield})**	**E [1] (klb·in)**
M5a-1	15302	0.95	14560	3.52	15958	4.74	5.0	355
M5a-2	17040	0.87	14853	2.29	16272	4.70	5.4	371
M5a-3	15082	1.01	15231	3.53	17116	5.29	5.2	355
Avg.	15808	0.94	14881	3.12	16449	4.91	5.2	360
M17a-1	22759	0.82	18572	2.25	20608	4.01	4.9	333
M17a-2	17880	1.04	18546	3.47	20985	4.15	4.0	380
M17a-3	21147	0.87	18399	3.48	20761	4.93	5.7	422
Avg.	20595	0.91	18506	3.07	20785	4.36	4.9	378

Figure 11 shows failure modes observed in the Midply tests. For most of the Midply shear walls, failures occurred around the center studs, as shown in Figure 11a. In addition, nail failure and panel fracture around the corner were also observed, as shown in Figures 11b and 11c, respectively. Lumber split was also noticed in some of the specimens, as shown in Figure 11d.

(a) *(b)* *(c)* *(d)*

Figure 11. Failure modes of tested Midply shear wall: (a) panel embedment failure, (b) nail failure, (c) panel fracture at corner, (d) faming member split.

SEISMIC EQUIVALENCY

The ASTM Standard D7989 [12] establishes a method to demonstrate the equivalent seismic performance of an alternative shear wall system to standard shear walls. If the alternative shear wall meets the Seismic Equivalency Parameters (SEPs) specified in D7989, as summarized in Table 3, then the seismic force modification factors for standard shear walls can be used.

Table 3. SEPs for equivalency to standard wood frame shear walls

Parameter	SEP requirement
Component overstrength	$2.5 \leq \frac{P_{max}}{P_{ASD}} \leq 5.0$
Drift capacity	$\Delta_U \geq 0.028h$
Ductility	$\frac{\Delta_U}{\Delta_{ASD}} \geq 11$

Note:
P_{max} *ultimate lateral load of the tested shear wall.*
P_{ASD} *allowable design load of the shear wall.*
Δ_U *ultimate displacement of tested shear wall.*
h *height of the shear wall, and*
Δ_{ASD} *displacement corresponding to the allowable design load of the tested shear wall.*

Table 4 shows the SEPs of the tested Midply walls. Except for Midply M17a-2 in which the specimen failed prematurely due to lumber split, an overstrength factor of 2.5 can be used to assign allowable design strengths to Midply with 7/16" OSB Rated Sheathing.

Table 5. SEPs of the tested Midply in accordance with ASTM Standard D7989 -18

Wall	Δ_{ASD} (in)	P_{ASD} (lb)	P_{max} (lb)	Δ_u (in)	P_{max}/P_{ASD}	Δ_u/Δ_{ASD}	Δ_u/h
M5a-1	0.42	6383	15958	4.74	2.50	11.4	0.047
M5a-2	0.38	6509	16272	4.70	2.50	12.3	0.047
M5a-3	0.45	6846	17116	5.29	2.50	11.7	0.053
Avg	0.42	6580	16449	4.91	2.50	11.8	0.049
M17a-1	0.36	8243	20608	4.01	2.50	11.1	0.040
M17a-2	0.41	7631	20985	4.15	2.75	10.1	0.042
M17a-3	0.39	8304	20761	4.93	2.50	12.5	0.049
Avg	0.39	8059	20785	4.36	2.58	11.2	0.044

In CSA O86, the shear resistance of shear wall is determined based on lateral load resistance of nailed joints along shear wall length. Since the shear resistances of tested Midply determined based on nail joints are lower than the those determined in accordance with ASTM D7989, this indicates that the same R_dR_o factors used for wood-frame construction can be used for Midply.

CONCLUSIONS

In this paper, the performance of Midply was studied in collaboration with APA–The Engineered Wood Association. A total of six Midply specimens with nail spacing at 4" and 3" on center were tested under reversed cyclic loading in accordance with Method C of ASTM E2116. Seismic equivalency of Midply specimens was evaluated according to ASTM D7989. The main findings from the test results are summarized as follows:

- Midply walls with 7/16" OSB Rated Sheathing had comparable ultimate displacement and ductility to standard shear walls. The ultimate displacements and ductility were decreased with closer nail spacing along panel edges.
- The following failure modes were observed: a) nailed joints failure along center studs, b) nail failure, and c) panel fracture around the corner. Lumber split was also noticed in some of the specimens.
- Based on the seismic equivalency criteria in ASTM D7989, Midply walls with 7/16" OSB Rated Sheathing can be assigned a design value based on mechanics-based approach, with the same R_dR_o factors used for wood-frame construction.

ACKNOWLEDGMENTS

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