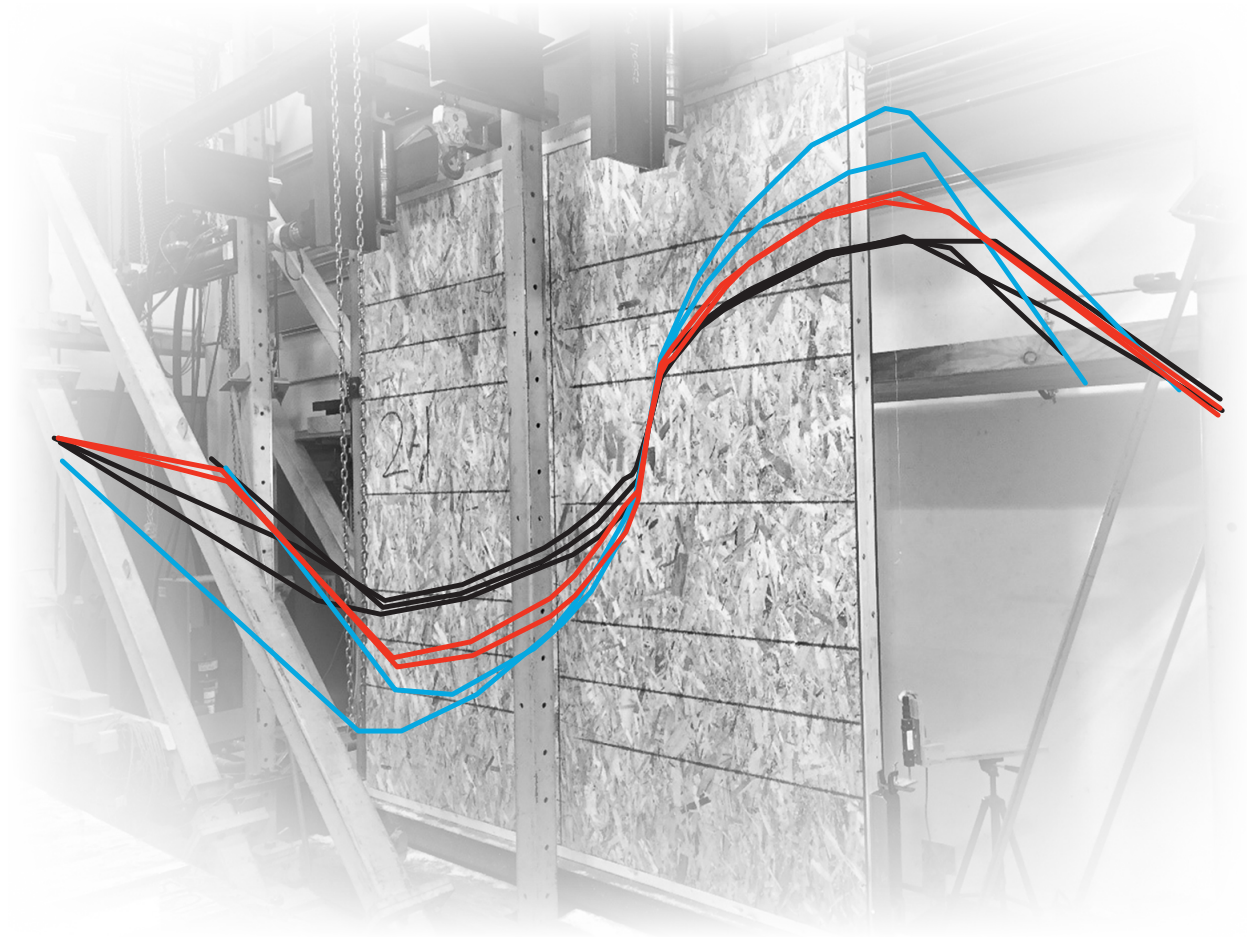




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Lateral Load Performance of SIP Walls with Full Bearing

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Forest Service

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Abstract

The purpose of this study was to develop test data needed to characterize lateral load performance of structural insulated panel (SIP) walls with full bearing (restrained). The research program involved structural testing of 29 full-size SIP walls (8 ft tall by 8 ft long) of various configurations that bracket a range of SIP wall configurations commonly used in the field. Results indicated that the cyclic performance parameters for all walls tested in this study met the over-strength and ductility capacities of ICC-ES AC04, although some walls had drift capacities slightly lower than the AC04 criterion. The one exception was the SIP wall without any vertical joints, which showed a significantly low drift capacity.

Keywords: Cyclic performance, drift, ductility, full bearing, over-strength, structural insulated panel (SIP)

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Executive Summary

Structural insulated panels (SIPs), as defined in ANSI/APA PRS 610.1, are a structurally strong and energy-efficient construction system that utilizes the strength of wood structural panels (WSPs) and thermal energy attributes of foam plastic insulation to provide cost-effective solutions for compliance with the governing building codes. However, the acceptance of SIPs by many design professionals has been hindered by the lack of a systematical evaluation of their lateral load performance in wall applications. As SIP walls are required to bear on the cap and sill plates (so-called restrained) so that vertical loads from the story above can be transferred to the story below or to the foundation, it is imperative that the lateral load performance of SIP walls reflects this configuration because this is representative of how SIP walls are constructed in the field. Unfortunately, most SIP walls have historically been evaluated by testing in a manner similar to conventional light-frame walls such that the oriented strandboard (OSB) facers are not allowed to bear on either cap plate or sill plate (so-called unrestrained), and therefore the actual lateral performance of SIP walls may not have been realistically characterized.

Based on a limited study conducted by APA in 2010, the restrained SIP walls seemed to have a significantly higher over-strength factor and lower ductility than conventionally framed wood walls. These research results led to the development of a lateral load test method specified in ANSI/APA PRS 610.1 for the qualification of SIP walls. However, the APA Standards Committee on ANSI/APA PRS 610.1 was concerned about the use of the test method for the development of SIP lateral load design values because of the lack of sufficient data for a comprehensive evaluation.

The purpose of this study was to develop test data needed to characterize the lateral load performance of SIP walls with full bearing (restrained). The research program involved structural testing of 29 full-size SIP walls (8 ft tall by 8 ft long) of various configurations that bracket a range of SIP wall configurations commonly used in the field.

Based on results obtained from this study, the lateral load resistance of SIP walls fabricated with various configurations tested in this study performed well when evaluated in accordance with the cyclic performance parameters of over-strength, drift, and ductility capacities, as defined in International Code Council Evaluation Service (ICC-ES) Acceptance Criteria AC04 and ASTM D7989, equivalent to light-frame walls. The only exception was the SIP wall without vertical joints in the wall, which had a significantly low drift capacity.

Introduction

Structural insulated panels (SIPs), as defined in ANSI/APA PRS 610.1 (ANSI/APA 2013), are a structurally strong and energy-efficient construction system that utilizes the strength of wood structural panels (WSPs) and thermal energy attributes of foam plastic insulation to provide cost-effective solutions for compliance with the governing building codes. However, the acceptance of SIPs by many design professionals has been hindered by the lack of a systematical evaluation of their lateral load performance in wall applications. As SIP walls are required to bear on the cap and sill plates (so-called restrained) so that vertical loads from the story above can be transferred to the story below or to the foundation, it is imperative that the lateral load performance of SIP walls reflects this configuration because this is representative of how SIP walls are constructed in the field. Unfortunately, most SIP walls have historically been evaluated by testing in a manner similar to conventional light-frame walls such that the oriented strandboard (OSB) facers are not allowed to bear on either cap plate or sill plate (so-called unrestrained), and therefore the actual lateral performance of SIP walls may not have been realistically characterized.

In a 2010 pilot study by APA, as documented in APA Report T2010P-17 (APA 2010), in conjunction with the Structural Insulated Panel Association (SIPA), full-size SIP walls (two SIP panels of 4-1/2-in.-thick by 4 ft wide by 8 ft tall) were tested in accordance with both monotonic and cyclic loading

protocols with the SIP walls constructed to bear on wood cap and sill plates. It was noted that the SIP walls so constructed have a significantly higher over-strength factor and lower ductility than conventional light-frame walls. These research results led to the development of a lateral load test method specified in ANSI/APA PRS 610.1 for the qualification of SIP walls. However, the APA Standards Committee on ANSI/APA PRS 610.1 (ANSI/APA 2013) was concerned about the use of the test method for development of SIP lateral load design values because of the lack of sufficient data for a comprehensive evaluation.

Objective and Scope

The purpose of this research was to develop test data needed to characterize the lateral load performance of SIP walls with full bearing (restrained). The research program involved structural testing of 29 full-size SIP walls of various configurations that bracket a range of SIP wall configurations commonly used in the field. Only restrained configurations were tested in this project because the comparison with unrestrained configurations had been previously evaluated in the 2010 study (APA 2010). The following SIP wall variables were examined:

1. Test protocol (monotonic and cyclic)
2. Nail size for panel connection (8d Box and 8d Common)
3. Nail spacing (6 in., 4 in., and 3 in.)
4. Wall bearing type (wood and steel bearing)
5. Spline type (block spline and two 2× lumber spline)
6. Number of panel joints (no joint, one joint, two joints, and three joints)
7. SIP thickness (4-1/2 in. and 6-1/2 in.)
8. Orientation of OSB facers (strength axis horizontal and vertical)
9. Bottom plate washer geometry (square, large round, and small round)

The results obtained from this testing were intended to provide engineering information for the design of SIP walls as lateral load resisting systems.

Test Plan

SIP Wall Construction

The test matrix encompassing the key variables is provided in Table 1. All walls tested were 8 ft tall by 8 ft long. The specific construction details for the individual walls are described below for different wall series.

Wall 1a—Construction followed the “basic wall” construction (Wall 2a). Wall 1a included one replication and was tested following the ASTM E72 test method, which is

monotonic. This wall configuration is shown in Figure 1; however, the HDQ-8 holddown was not used for this wall because overturning restraint was provided by rods, as described in ASTM E72.

Wall 1b—Construction followed the “basic wall” construction (Wall 2a). Wall 1b included two replications and was tested following ASTM E564 test method, which is a monotonic test. This wall configuration is shown in Figure 1.

“Trial” Wall—Construction followed the “basic wall” construction (Wall 2a). This wall was used as a preliminary test, hence the name, “trial.” The only difference between this wall and Wall 2a was that the strength axis of the OSB facers was oriented horizontally (i.e., cross-oriented OSB).

Wall 2a, “Basic Wall”—This construction is the control case for the different variables studied. Wall 2a included three replications and was tested following the ASTM E2126 CUREE test protocol (ASTM 2011) in reversed cyclic. The wall configuration was constructed from two 48-by 96-in. SIP segments, as shown in Figure 2. The strength axis of the OSB facer was oriented vertically. The overall SIP thickness was 4-1/2 in. The vertical joint between the two SIP panels was connected with a nominal 4× block spline. The top and bottom plates of the SIPs were 2×4 No. 2 and Better untreated Spruce–Pine–Fir (SPF). The top and bottom of each wall assembly were capped with 2×6 No. 2 and Better untreated SPF pieces, which were trimmed to match the overall SIP wall thickness. The facers were nailed with 8d Box nails (0.113 by 2-1/2 in.), spaced at 6 in. on center on the SIP panel perimeters, and nailed into framing from both sides of the wall. The walls had external HDQ-8 holddowns, attached with 12 evenly spaced 1/4- by 3-in. self-tapping/drilling lag screws, as shown in Figure 3. The double 2×4 end posts were stitched together with 12 evenly spaced 1/4- by 3-in. self-tapping/drilling lag screws, also shown in Figure 3. Two 5/8-in.-diameter anchor bolts were placed on the recessed 2×4 bottom plate at the center of each SIP segment. The basic wall used a 0.229- by 3- by 3-in. square washer at each anchor bolt, as shown in Figure 4a.

Wall 2b—This wall was built identical to Wall 2a with two deviations: (1) the anchor bolt washers were 0.229-in. by 3-in.-diameter round washers, and (2) the strength axis of the OSB facer was oriented horizontally (i.e., cross-oriented). The round anchor bolt washers are shown in Figure 4b. There was one replication of Wall 2b.

Wall 2c—This wall was built identical to Wall 2a with two deviations: (1) the anchor bolt washers were 0.134-in. by 1.75-in.-diameter standard cut round washers, which corresponded to the 5/8-in. washer from table L6 in the 2015 NDS, and (2) the strength axis of the OSB facer was oriented horizontally (i.e., cross-oriented). The round anchor bolt washers are shown in Figure 4c. There was one replication of Wall 2c.

Table 1. Test matrix for structural testing of full-size SIP walls of various configurations

Test ID	SIP segment size (in)	SIP thickness (in.)	Test protocol	No. of replicates	Spline type	SIP top/bottom plate	Cap plate	Sill plate	Nail type	Edge nail spacing (in.)						
1a	48 × 96	4.5	ASTM E72 (monotonic)	1	4 × block	2 × 4 No. 2 & BTR SPF (untreated)	2 × 6 No. 2 & BTR SPF (untreated), trimmed to match thickness of SIP	2 × 6 No. 2 & BTR SPF (untreated), trimmed to match thickness of SIP	8d Box (0.113 × 2.5 in.)	6						
1b			ASTM E564 (monotonic)	2												
Trial				1												
2a				3												
2b				1												
2c				1												
3a				2												
4a				2												
4b				2												
5a				2												
6a	96 × 96	4.5	ASTM E2126 (cyclic)	2	(2) 2 × 4 lumber	2 × 6 No. 2 & BTR SPF (untreated)	2 × 6 No. 2 & BTR SPF (untreated), trimmed to match thickness of SIP	Steel plate	8d Box (0.113 × 2.5 in.)	6						
7a				2							No vertical joint					
7b				2												
7c	2			4 × block												
8a	48 × 96			6.5							2	6 × block	2 × 6 No. 2 & BTR SPF (untreated)	2 × 8 No. 2 & BTR SPF (untreated), trimmed to match thickness of SIP		
9a	48 × 96			4.5							2	4 × block	2 × 4 No. 2 & BTR SPF (untreated)	2 × 6 No. 2 & BTR SPF (untreated), trimmed to match thickness of SIP		

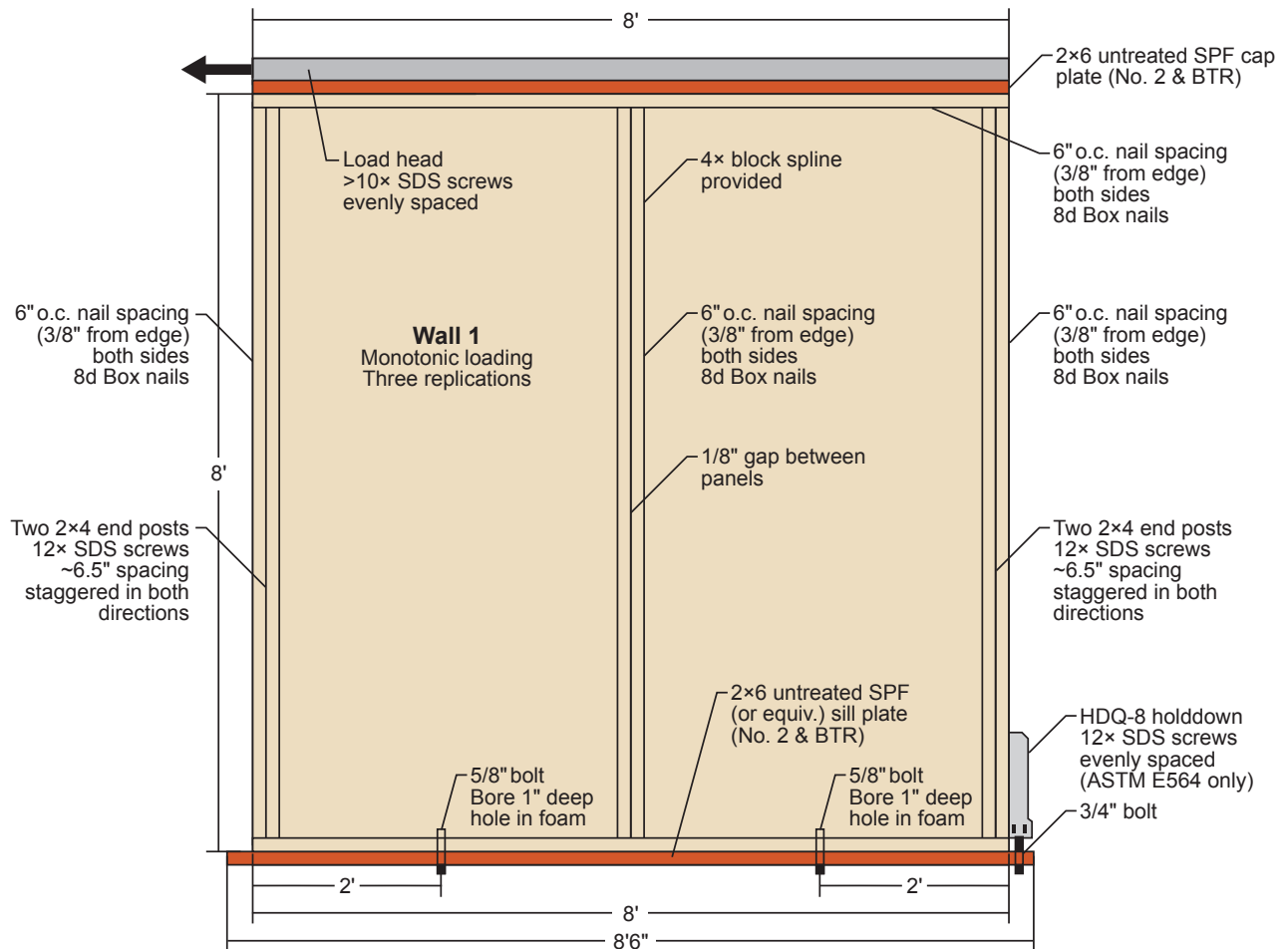


Figure 1. Configuration of Walls 1a and 1b, monotonic E72 (one replication) and E564 loading (two replications), control wall.

Wall 3a—This wall was built identical to Wall 2a with one deviation: the facers were nailed with 8d Common nails (0.131 by 2-1/2 in.), spaced at 6 in. on center on the SIP panel perimeters and nailed into framing from both sides of the wall. There were two replications of Wall 3a.

Wall 4a—This wall was built identical to Wall 2a with three deviations: (1) the nail spacing on the 8d Box facer nails was at 3 in. on center on the SIP panel perimeters, (2) the HDQ-8 holddowns were attached with 20 1/4- by 3-in. self-tapping/drilling lag screws, and (3) the double 2x4 end posts were stitched together with 22 evenly spaced 1/4- by 3-in. self-tapping/drilling lag screws. There were two replications of Wall 4a.

Wall 4b—This wall was built identical to Wall 2a with three deviations: (1) the nail spacing on the 8d Box facer nails was at 4 in. on center on the SIP panel perimeters, (2) the HDQ-8 holddowns were attached with 16 1/4- by 3-in. self-tapping/drilling lag screws, and (3) the double 2x4 end posts were stitched together with 16 evenly spaced 1/4- by 3-in.

self-tapping/drilling lag screws. There were two replications of Wall 4b.

Wall 5a—This wall was built identical to Wall 2a with two deviations: (1) the SIP edge nailing into the block spline that was used to connect the SIPs together had nails at 12 in. on center, and (2) the bottom of the wall assembly, the recessed 2x4 bottom plate, and the OSB facers were bearing directly onto a rigid steel channel. There were two replications of Wall 5a.

Wall 6a—This wall was built identical to Wall 2a with one deviation: the vertical joint between the two SIP panels was connected with two 2x4 lumber studs stitched together with twelve 1/4- by 3-in. self-tapping/drilling lag screws. There were two replications of Wall 6a.

Wall 7a—This wall was built identical to Wall 2a with one deviation: the wall contained no vertical joints and consisted of one SIP panel with dimensions of 96 by 96 in. There were two replications of Wall 7a. This wall configuration is shown in Figure 5a.

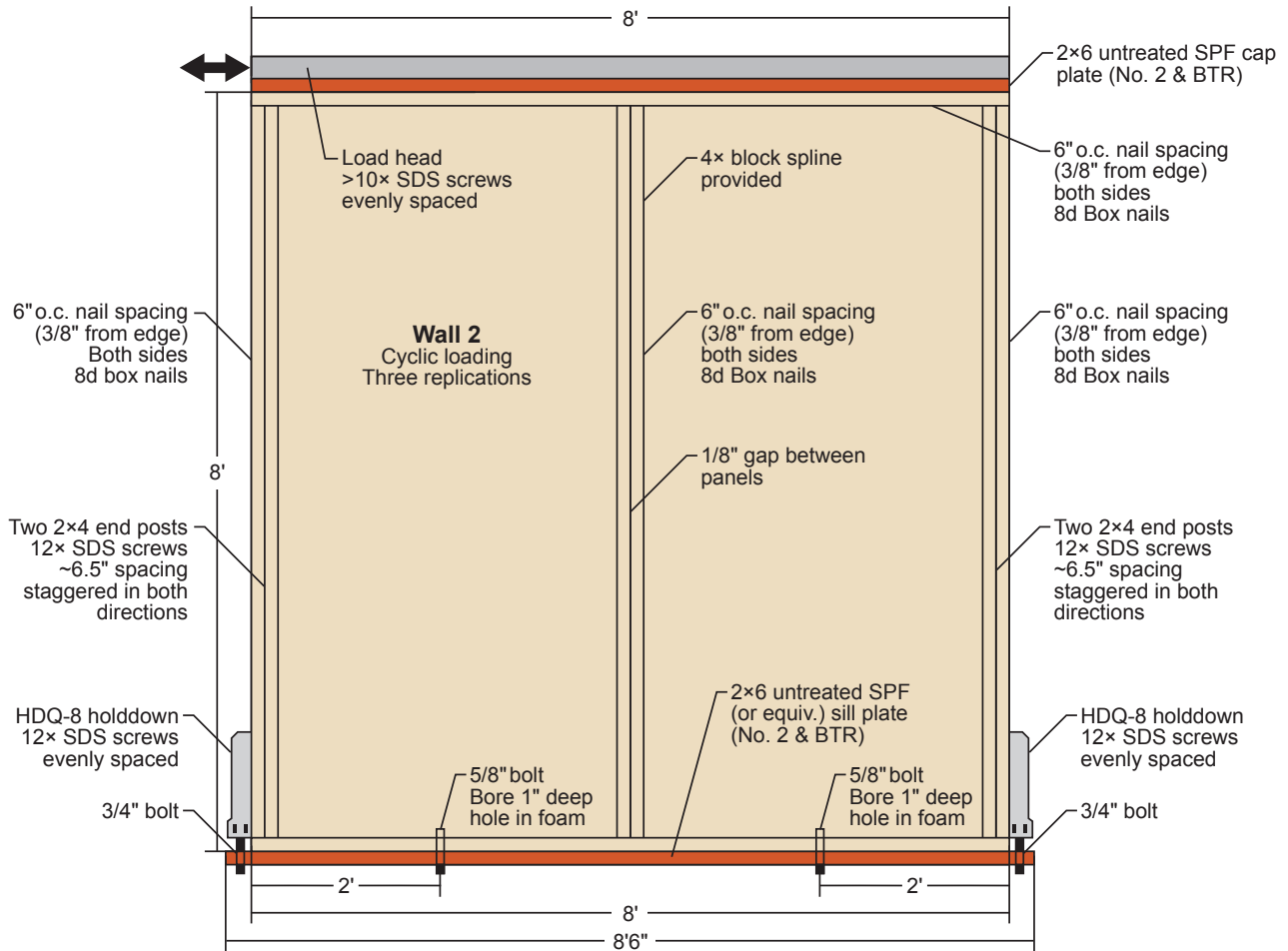


Figure 2. Configuration of Wall 2a, CUREE cyclic protocol, basic wall (three replications). Walls 2b (one replication) and 2c (one replication) were similar construction, but OSB facers were cross-oriented, and anchor bolt washer sizes varied.



Figure 3. External HDQ-8 holddown.

Wall 7b—This wall was built identical to Wall 2a with one deviation: the wall contained two vertical joints and was constructed with three SIP segments with dimensions of 32 by 96 in. each. Block splines were used to connect the SIPs together on the vertical joints. Anchor bolts were centered on each of the three SIP segments. There were two replications of Wall 7b. This wall configuration is shown in Figure 5b.

Wall 7c—This wall was built identical to Wall 2a with one deviation: the wall contained three vertical joints and was constructed with four SIP segments with dimensions of 24 by 96 in. each. Block splines were used to connect the SIPs together on the vertical joints. Anchor bolts were centered on each of the four SIP segments. There were two replications of Wall 7c. This wall configuration is shown in Figure 5c.

Wall 8a—This wall was built identical to Wall 2a with the following deviations related to thicker SIPs: (1) the overall SIP thickness was 6-1/2 in., (2) the only vertical joint

between the two SIP panels was connected with a nominal 6× block spline, (3) the top and bottom plates of the SIPs were 2×6 No. 2 and Better untreated SPF, and (4) the top and bottom of the wall assembly were capped with 2×8 No. 2 and Better SPF pieces, which were trimmed to match the overall SIP wall thickness. There were two replications of Wall 8a.

Wall 9a—This wall was built identical to Wall 2a with one deviation: the strength axes of the OSB facers were oriented horizontally (i.e., cross-oriented). There were two replications of Wall 9a.

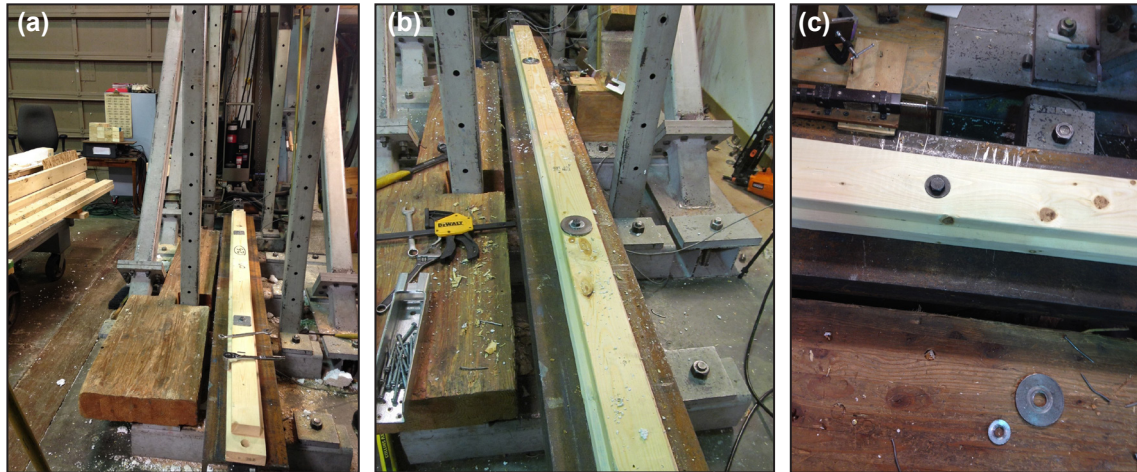


Figure 4. Washers used for anchor bolts: (a) square washer; (b) large round washer; (c) standard cut round washer.

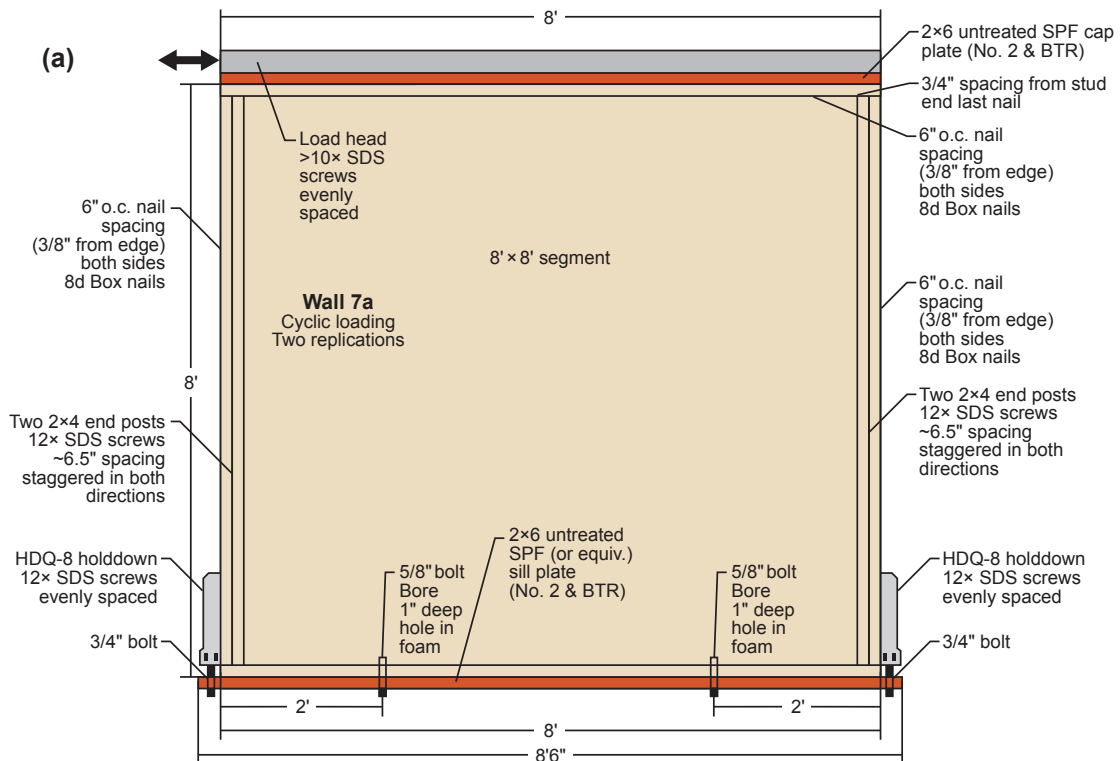


Figure 5. Configuration of Wall 7 series: (a) Wall 7a, 8-ft by 8-ft SIP segment (two replications); (b) Wall 7b, three 32-in. by 8-ft SIP segments, three anchor bolts (two replications); and (c) Wall 7c, four 24-in. by 8-ft SIP segments, four anchor bolts (two replications).

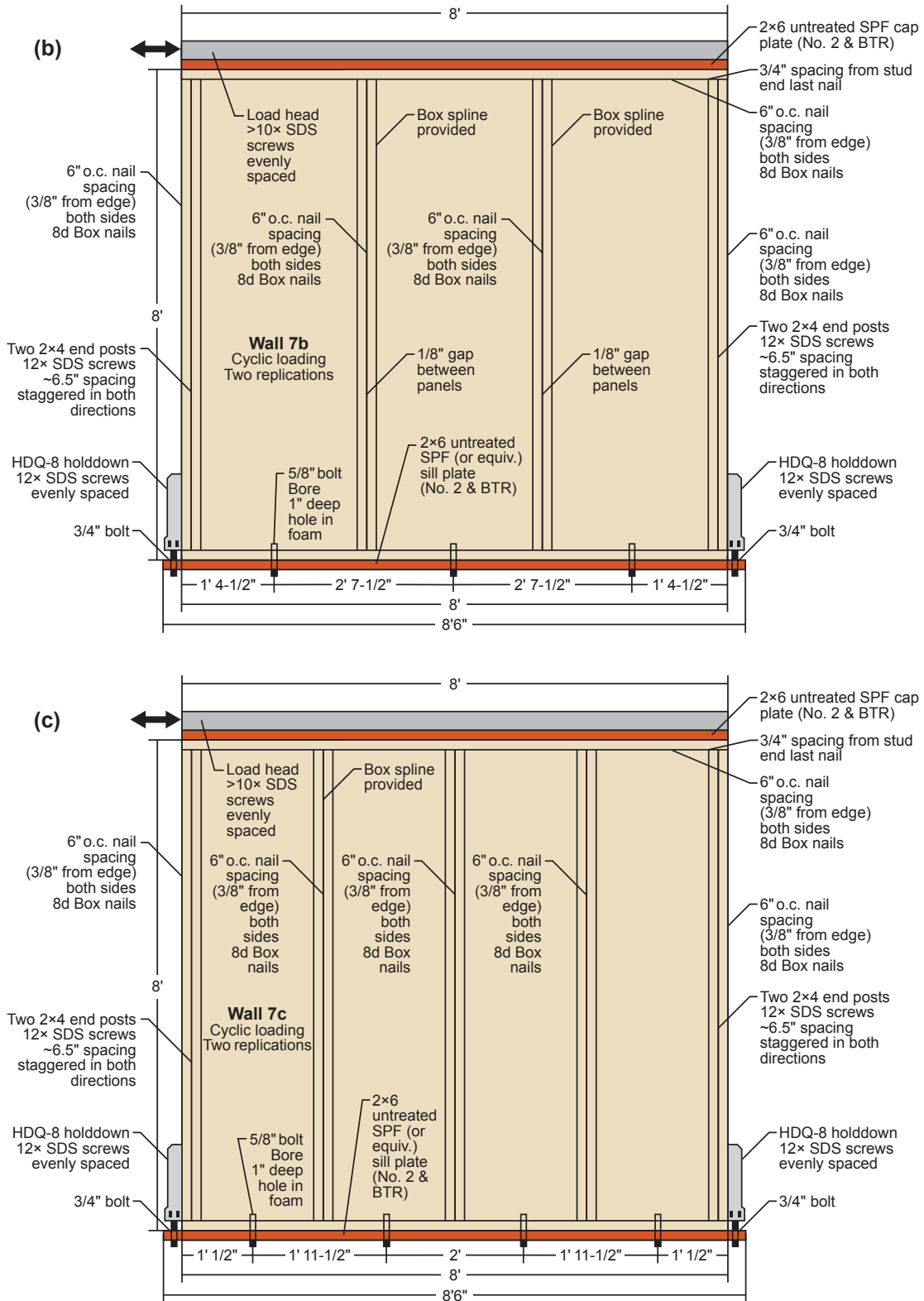


Figure 5 (con.). Configuration of Wall 7 series: (a) Wall 7a, 8-ft by 8-ft SIP segment (two replications); (b) Wall 7b, three 32-in. by 8-ft SIP segments, three anchor bolts (two replications); and (c) Wall 7c, four 24-in. by 8-ft SIP segments, four anchor bolts (two replications).



Figure 6. ASTM E72 monotonic test setup.

Test Setup and Procedures

Wall 1a was tested following a monotonic procedure specified in section 4.5 of ICC-ES Acceptance Criteria AC04 (ICC-ES 2015), which references ASTM E72 (ASTM 2015b). Figure 6 shows the monotonic test setup. Figure 7a shows the holddown rods and rollers to resist overturning, and Figure 7b shows the monotonic load head.

In accordance with section 4.5.5 of ICC-ES AC04, the ASTM E72 “stop” was detailed such that it was bearing on the end of the bottom trimmed 2×6 cap plate, and the loading was applied directly to the top plate of the wall in tension in a load-control mode. The loading was applied at a constant rate as follows:

1. Wall is loaded to the test load (300 pounds per lineal foot (plf)) in 5 min
2. Wall is unloaded to zero load in 1 min
3. Wall is held at zero load for 5 min
4. Wall is loaded to two times test load (600 plf) in 5 min
5. Wall is unloaded to zero load in 1 min
6. Wall is held at zero load for 5 min
7. Wall is loaded to ultimate load. Loading is applied at a rate such that 2.5 times test load (750 plf) is achieved in 5 min

ASTM E72 permits the top of wall deflection to be reduced by the uplift deflection and the lateral translation deflection. The data reported for the monotonic tests are based on this

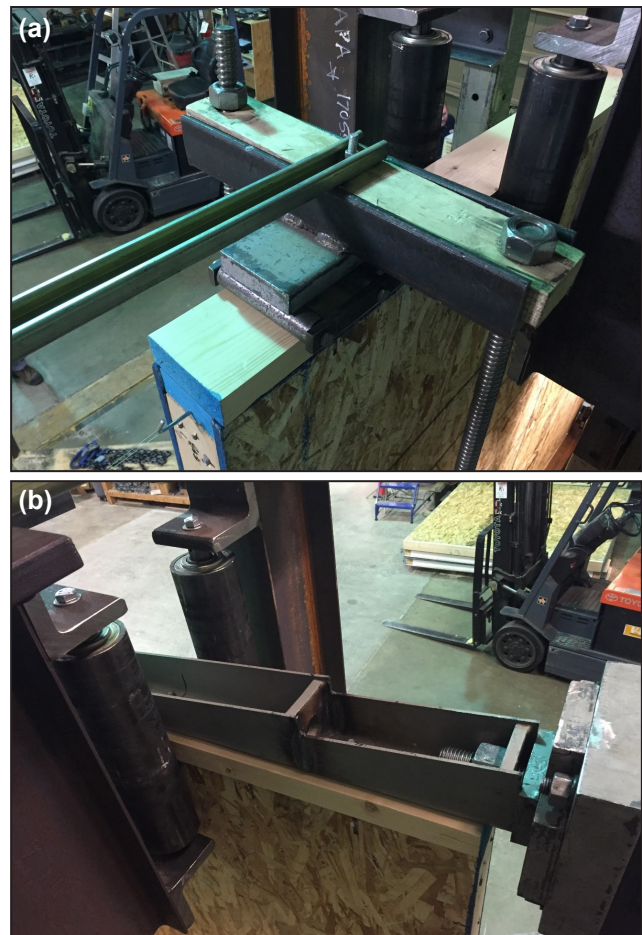


Figure 7. ASTM E72 monotonic test setup: (a) holddown rods and roller to resist overturning; (b) monotonic load head.

net top of wall displacement as well as the gross deflection, which more closely corresponds to ASTM E564 procedure (ASTM 2012).

Wall 1b was tested following a monotonic test in accordance with ASTM E564 (ASTM 2012). The data reported are based on the top of wall deflection.

The rest of the walls were subjected to a cyclic loading protocol following ASTM E2126, Method C, CUREE Basic Loading Protocol (ASTM 2011). Figure 8 shows the cyclic test setup. The reference deflection, Δ , was set as 2.4 in. Each subsequent phase of the CUREE protocol consisted of a primary cycle with an increase in an amplitude of α of 0.5 over the previous primary cycle. Additional cycles were added to the protocol for a potential maximum displacement applied to the wall of ± 9.6 in. The tests were terminated when a significant loss in load was noted. This testing procedure, including the terms for Δ and α , was based on APA’s past experience with cyclic testing of wood structural panel shear walls. The displacement-based protocol was applied to the wall at 0.5 Hz.



Figure 8. CUREE cyclic test setup.

Results and Discussion

Table 2 summarizes the average cyclic performance parameters for different SIP walls as well as comparison to established seismic equivalency parameters for lateral force resisting systems presented in ICC-ES AC04. Individual hysteresis plots are provided in the Appendix. A more detailed summary of these data, including individual cyclic performance parameters, and additional information can be found in the APA report by Yeh et al. (2016).

Based on the cyclic test results obtained from this study, a detailed analysis in accordance with ICC-ES AC04 was conducted. AC04 appendix A was created to provide a methodology for benchmarking SIPs cyclic test data to light-frame walls sheathed with wood structural panels, which was subsequently adopted in ASTM D7989 (ASTM 2015a). The criteria are intended to confirm compatibility with a code-defined seismic-force resisting system for light-frame walls sheathed with wood structural panels (i.e., System A-13) in accordance with table 12-2.1 of ASCE 7-10 (ASCE 2010). The walls summarized herein are considered “Assembly C” in accordance with AC04.

The first criterion is intended to provide similar ductility capacity as light-frame walls sheathed with wood structural panels, which is determined by dividing the ultimate deflection by the deflection at the allowable stress design (ASD) value. The ductility capacity is expected to be equal to or greater than 11. The second criterion is intended to show that the ultimate failure deflection of the walls (drift capacity) is similar to that of light-frame walls sheathed

with wood structural panels. The expected drift capacity is equal to or greater than $0.028H$, where H is the height of the wall. The final criterion is intended to provide load factors (over-strength capacity) that are similar to light-frame walls sheathed with wood structural panels by dividing the peak strength by the design value, yet limits the over-strength capacity of the panels. The over-strength capacity is expected to be between 2.5 and 5.0.

One of the underlying assumptions of the ICC-ES AC04 analysis is the ASD design value. The assumed ASD design values for these walls are based on the ICC-ES Evaluation Report for Power-Driven Staples and Nails in ESR-1539 (ICC-ES 2016). Because the SIP facers are nominal 7/16-in. Rated Sheathing, the seismic design values published in table 8 of ESR-1539 are used. The single-sided wall design values, when nailed to the Douglas Fir–Larch framing, are 180, 265, and 335 plf for the 0.113-in.-diameter (8d Box) nails spaced at 6, 4, and 3 in. on center, respectively. For the 0.131-in.-diameter (8d Common) nails spaced at 6 in. on center, the seismic design value is 240 plf. The design values are further reduced for nailing into SPF framing following footnote 4 of the table:

The tabulated values are for fasteners installed in Douglas Fir–larch or Southern Pine. For framing of other species ... [information on staples not quoted] (3) For nails find shear values from the applicable table and multiply by the following Specific Gravity Adjustment Factor = $[1 - (0.5 - G)]$, where G = Assigned Specific Gravity of the framing lumber... (ICC-ES 2016)

Table 2. Mean cyclic performance parameters from walls tested and analyzed in accordance with ICC-ES AC04

Wall	Replicates	ASD design value ^a (plf)	ASD design deflection ^b (in.)	Ultimate deflection ^b (in.)	Peak load ^b (plf)	ICC ES AC04 analysis section number		
						A3.3.2 ^c ductility capacity	A3.3.3 ^d drift capacity	A3.3.4 ^e over-strength capacity
Trial	1	331	0.083	2.47	1,034	29.8	0.026 <i>H</i>	3.12
Wall 2a	3	331	0.113	2.83	1,188	28.5	0.029 <i>H</i>	3.59
Wall 2b	1	331	0.156	3.00	965	19.2	0.031 <i>H</i>	2.91
Wall 2c	1	331	0.167	3.32	965	19.8	0.035 <i>H</i>	2.91
Wall 3a	2	442	0.133	2.58	1,204	20.0	0.027 <i>H</i>	2.73
Wall 4a	2	616	0.203	2.63	1,876	13.0	0.028 <i>H</i>	3.04
Wall 4b	2	488	0.171	2.62	1,504	15.3	0.028 <i>H</i>	3.08
Wall 5a	2	331	0.128	2.72	1,024	21.7	0.029 <i>H</i>	3.09
Wall 6a	2	331	0.079	2.55	1,149	32.3	0.027 <i>H</i>	3.47
Wall 7a	2	331	0.063	2.00	1,314	31.9	0.021 <i>H</i>	3.97
Wall 7b	2	331	0.112	3.70	1,052	33.6	0.039 <i>H</i>	3.18
Wall 7c	2	331	0.143	5.00	986	35.7	0.052 <i>H</i>	2.98
Wall 8a	2	331	0.116	3.54	1,110	31.1	0.037 <i>H</i>	3.35
Wall 9a	2	331	0.083	2.45	1,097	29.7	0.026 <i>H</i>	3.31

^aSee Test Plan of this report for more details on wall construction. Allowable design values are based on the seismic shear wall values for 0.113- and 0.131-in.-diameter nails with 7/16-in. (nominal) rated sheathing, as published in table 8 of ICC-ES ESR-1539, multiplied by 2 for double sided nailing. The values were further modified for nailing into Spruce–Pine–Fire (SPF) lumber based on footnote 4 to table 8 of ESR-1539.

^bBased on the average of the absolute value of positive and negative cyclic excursion.

^cUltimate deflection divided by deflection at design value (ductility capacity). ICC-ES AC04 appendix A requires this property to be equal to or greater than 11.

^dMinimum post peak displacement (drift capacity). AC04 appendix A requires this property to be equal to or greater than 0.028*H*, where *H* is the height of the wall, based on tests following the CUREE loading protocol.

^ePeak strength divided by design value (over-strength capacity). AC04 appendix A requires this property to be between 2.5 and 5.0.

For SPF framing, $G = 0.42$ in accordance with NDS. Therefore, the Specific Gravity Adjustment Factor = 0.92. Because the SIP walls were nailed on both sides, the ASD values in table 8 of ESR-1539 are doubled. For the 0.113-in.-diameter (8d Box) nails, the design value is 331, 488, and 616 plf for nails spaced at 6, 4, and 3 in. on center, respectively. For the 0.131-in.-diameter (8d Common) nails spaced at 6 in. on center, the design value is 442 plf.

Based on the information presented in Table 2, all walls tested in this study met the AC04 cyclic performance criteria with the exception of some wall configurations that demonstrated less than the required drift capacity of 0.028*H*. Additional discussion on the cyclic performance parameters and how they were affected by the wall configuration is provided in the sections following.

Test Protocol

Figure 9 shows backbone curves from three replications of the basic wall configuration, Wall 2a. The hysteresis loops for Wall 2a are shown in Appendix A2–A4. Figure 9 also shows the monotonic results from Walls 1a (ASTM E72) and 1b (ASTM E564), based on the wall gross deflection

(i.e., top of wall deflection without adjustments for uplift and sliding in accordance with ICC-ES AC04 and ASTM E72).

Figure 10 shows the amount of uplift occurring during the ASTM E72 monotonic tests. Figure 11 shows the typical failure modes that were observed during the ASTM E2126 cyclic tests and failure of the connection of the top plate to the studs.

According to Figure 9, the mean ultimate load value for Wall 2a was 1,188 plf based on the mean positive loads and the absolute value of the mean negative peak loads. The ultimate load for Wall 1a and 1b was 1,175 plf and 1,062 plf, respectively. Figure 9 also shows a fairly close agreement between the wall deflections, up to around 6,000 lb (750 plf). Beyond that, the ASTM E72 walls show a higher stiffness, which may be associated with the ASTM E72 holddown rods. Although the data are limited, the ultimate load of the cyclic load test data (Wall 2a with three replications) was fairly close to the ASTM E72 data (Wall 1a with one replication) and was approximately 12% higher than the ASTM E564 data (Wall 1b with two replications).

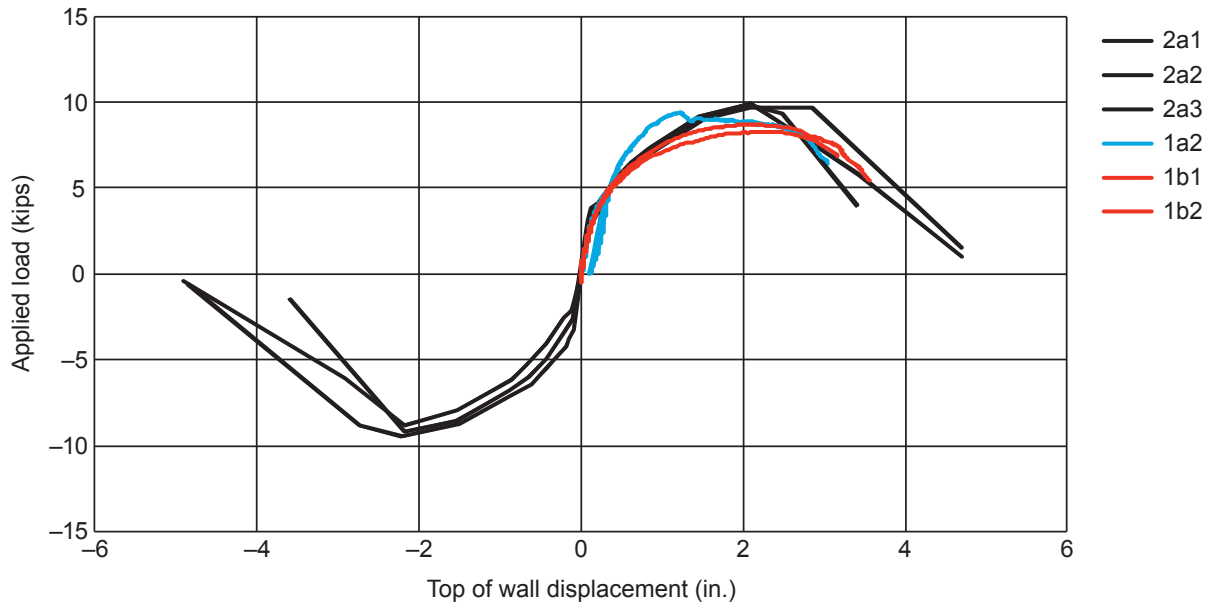


Figure 9. Backbone curves comparing testing based on ASTM E2126 (Wall 2a) with testing based on ASTM E72 (Wall 1a) and E564 (Wall 1b).



Figure 10. Typical uplift for the ASTM E72 racking test.

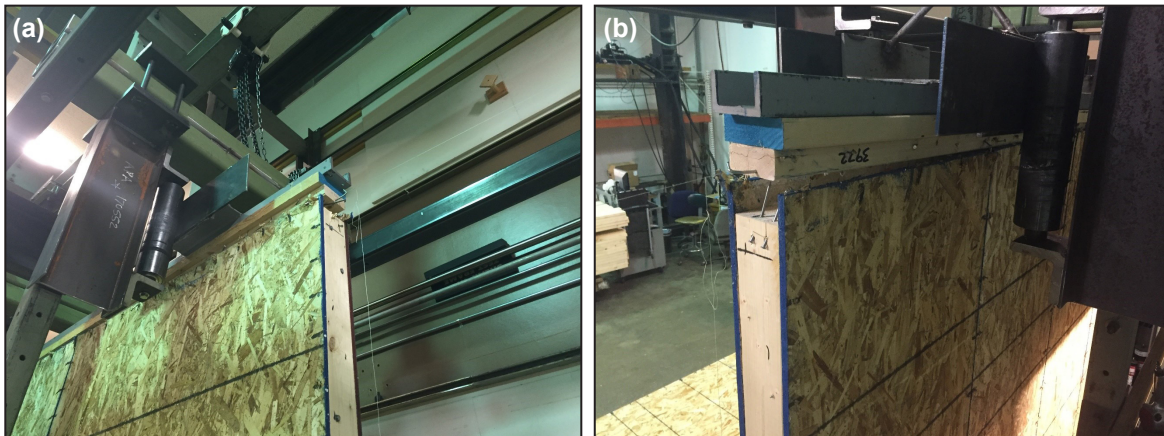


Figure 11. Common failure modes observed during the ASTM E2126 cyclic tests: (a) top plate pulling out of sheathing; (b) failure of the connection of the top plate to the studs.

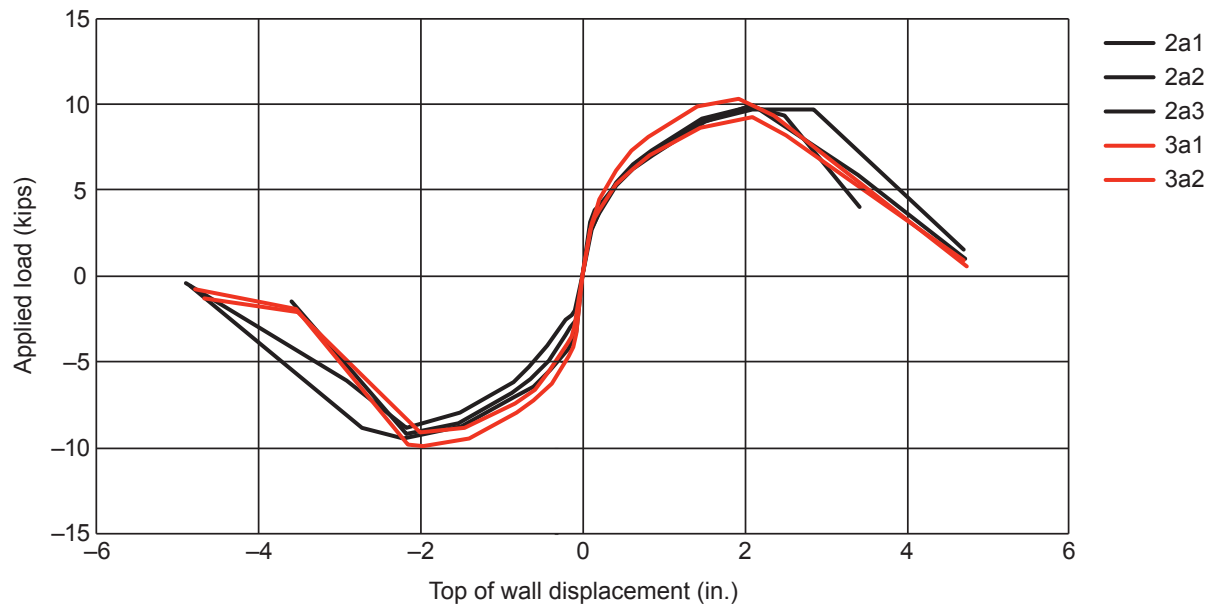


Figure 12. Backbone curves comparing 8d Box nails (Wall 2a) with 8d Common nails (Wall 3a).

Nail Size for Panel Connection

Figure 12 shows the backbone curves from three replications of the basic wall configuration, Wall 2a (8d Box nails) and the two replications of Wall 3a (8d Common nails). The hysteresis loops for these cyclic data are provided in Appendix A2–A4, A7, and A8.

The mean ultimate load value for Wall 2a was 1,188 plf based on the mean positive loads and the absolute value of the mean negative peak loads. The mean ultimate load value for Wall 3a was 1,204 plf. From Figure 12, the variability of Wall 3a walls appears to be higher than that of the base wall case of Wall 2a. This may be associated with small sample size. However, based on these data, there does not appear to be a significant difference in the ultimate load between the SIP walls constructed with 8d Common (Wall 3a) and 8d Box nails (Wall 2a).

When considering the ICC-ES AC04 cyclic analysis, as summarized in Table 2, a few observations are noted. Although the difference in the drift capacity was relatively minor, 0.029H and 0.027H for the 8d Box and 8d Common, respectively, the walls nailed with 8d Common nails had a slightly lower drift capacity than the AC04 criteria. However, the over-strength capacities were relatively higher for the 8d Box nails than the 8d Common nails (3.59 and 2.73, respectively). This indicates that the conventional reduction in allowable lateral load capacity by using smaller diameter nails, as reflected in ICC-ES ESR-1539, may result in very conservative design values for SIP walls, when nailed with small diameter nails.

Nail Spacing

Figure 13 shows the backbone curves from three replications of the “basic wall” configuration, Wall 2a with a nail spacing of 6 in., two replications of Wall 4a with a nail spacing of 3 in. on center, and two replications of Wall 4b with a nail spacing of 4 in. on center. The hysteresis loops for these cyclic data are provided in Appendix A2–A4 and A9–A12.

The mean ultimate load value for Wall 2a was 1,188 plf based on the mean positive loads and the absolute value of the mean negative peak loads. The mean ultimate load values for Walls 4a and 4b cyclic data were 1,876 and 1,504 plf, respectively. The backbone curves, based on the different nail spacing, have similar shapes. Higher density nailing can result in failure modes shifting to the anchorage, as shown in Figure 14, even though these failures occurred toward the end of the cyclic test. Therefore, it did not have a significant impact on the backbone curves. Based on these data, a decrease in nail spacing from 6 to 4 in. and from 6 to 3 in. on center resulted in ultimate load increases of 27% and 58%, respectively.

When considering the ICC-ES AC04 cyclic analysis, as summarized in Table 2, the only cyclic performance parameter that showed significant differences was ductility capacity (28.5, 15.3, and 13.0 for nail spacing of 6, 4, and 3 in. on center, respectively). The significant reduction in ductility capacity due to a reduced nail spacing is likely related to very low deflection at the ASD design value of the “basic wall.” It should be noted that all cyclic performance parameters for these SIP walls met AC04 cyclic criteria.

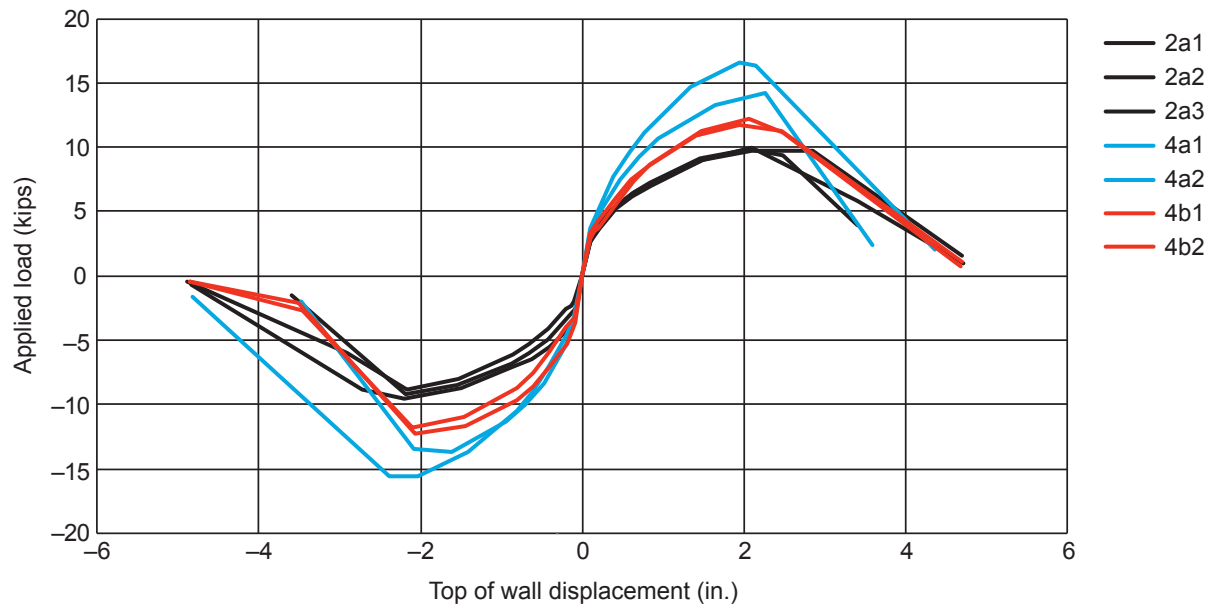


Figure 13. Backbone curves comparing 8d Box nails spaced at 6 in. (Wall 2a), 3 in. (Wall 4a), and 4 in. (Wall 4b) on center.

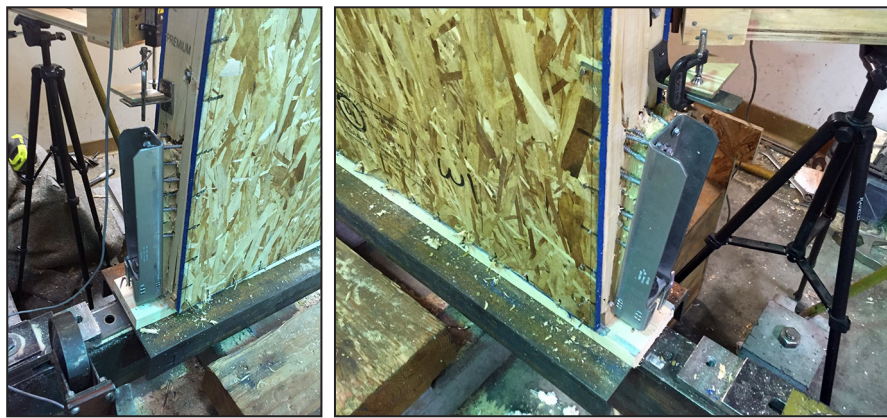


Figure 14. Atypical failure mode with wood plug pulled out of end post by holddown lag screws.

Wall Bearing Type

Figure 15 shows the backbone curves from three replications of the basic wall configuration, Wall 2a, and two replications of Wall 5a with the bottom of the SIP bearing on a rigid steel channel. The hysteresis loops for these cyclic data are provided in Appendix A2–A4, A13, and A14.

The mean ultimate load value for Wall 2a was 1,188 plf based on the mean positive loads and the absolute value of the mean negative peak loads. The mean ultimate load value for Wall 5a was 1,024 plf. Note that the spline nailing for Wall 5a was increased from 6 in. on center to 12 in. on center (the panel edge nailing at end studs remained at 6 in. on center). This increase in the spline nail spacing was rationalized by past experience to provide a higher wall ductility. Based on these data, Wall 5a resulted in an approximately 15% decrease in ultimate load, as compared to the basic

wall configuration. However, this decrease in ultimate load could have been affected by the increase in spline nailing spacing.

When considering the ICC-ES AC04 cyclic analysis, as summarized in Table 2, the cyclic performance parameters for the walls bearing on the wood cap (top) plates and steel bottom plate were fairly similar when the spline nailing spacing is appropriately adjusted. It should be noted that all cyclic performance parameters for these SIP walls met AC04 cyclic criteria.

Spline Type

Figure 16 shows the backbone curves from three replications of the basic wall configuration, Wall 2a, and two replications of Wall 6a with 2×4 stitched lumber spline. The hysteresis loops for these cyclic data are provided in Appendix A2–A4, A15, and A16.

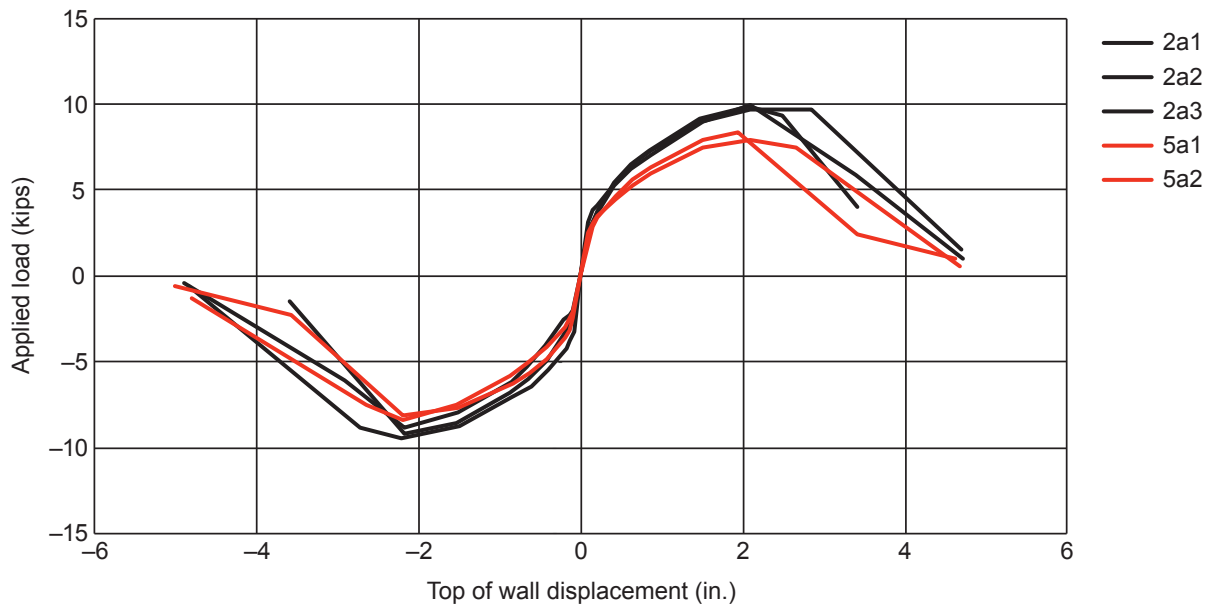


Figure 15. Backbone curves comparing bearing on SPF bottom plate (Wall 2a) and rigid steel base (Wall 5a).

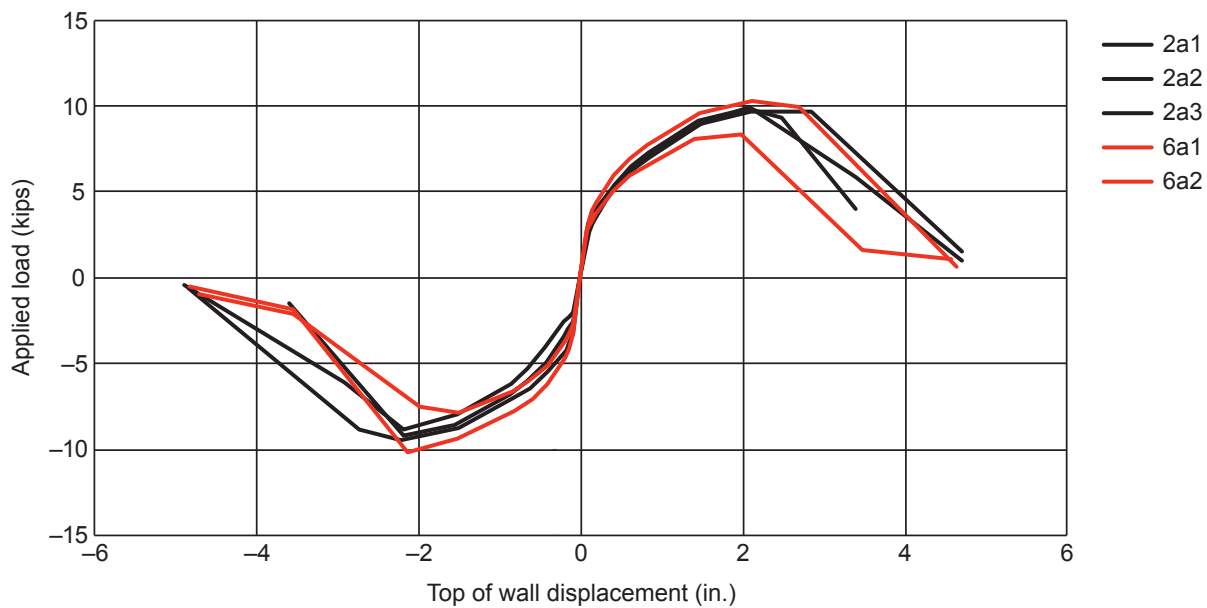


Figure 16. Backbone curves comparing box splines (Wall 2a) with two 2x4 stitched lumber splines (Wall 6a).

The mean ultimate load value for Wall 2a was 1,188 plf based on the mean positive loads and the absolute value of the mean negative peak loads. The mean ultimate load value for Wall 6a was 1,149 plf. Based on these data, SIPs with lumber splines and block splines resulted in very similar ultimate loads (less than 5% difference).

When considering the ICC-ES AC04 cyclic analysis, as summarized in Table 2, the difference in drift capacities was relatively minor, $0.029H$ and $0.027H$ for the box splines and the lumber splines, respectively. The walls nailed with 8d Common nails had a slightly lower drift capacity than the AC04 criteria. However, all other cyclic performance

parameters met the AC04 cyclic criteria for both spline types.

Number of Panel Joints

Figure 17 shows the backbone curves from three replications of the basic wall configuration, Wall 2a, and two replications of Walls 7a, 7b, and 7c with no panel joint, two panel joints, and three panel joints, respectively. The hysteresis loops for these cyclic data are provided in Appendix A2–A4 and A17–A22.

The mean ultimate load value for Wall 2a was 1,188 plf based on the mean positive loads and the absolute value of

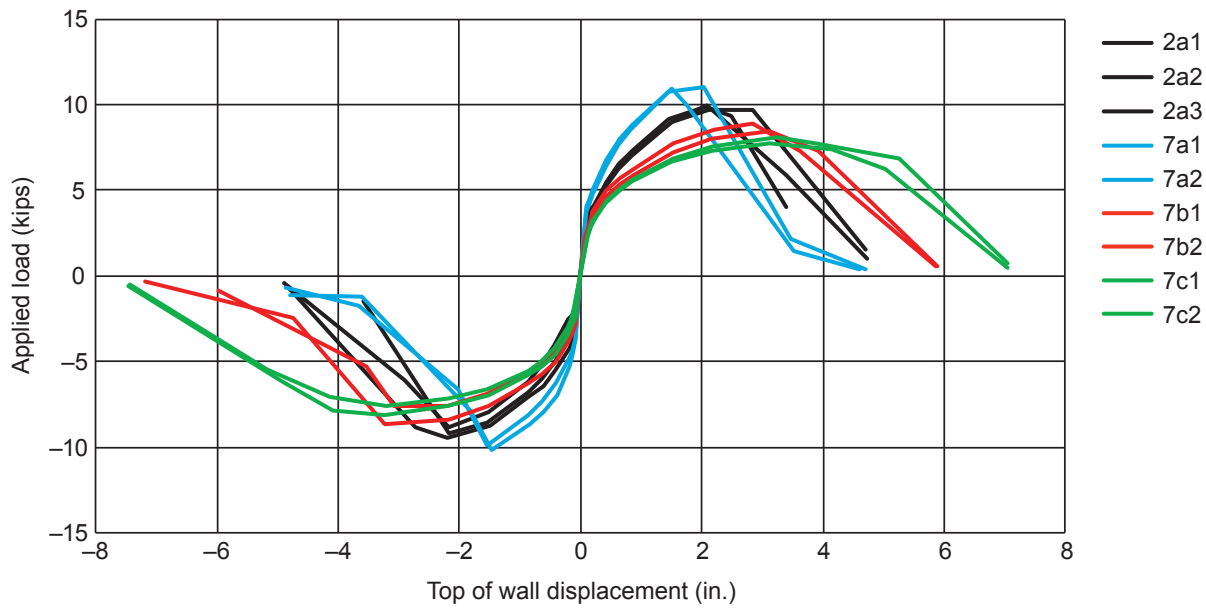


Figure 17. Backbone curves comparing the walls with one joint (Wall 2a), zero joints (Wall 7a), two joints (Wall 7b), and three joints (Wall 7c).

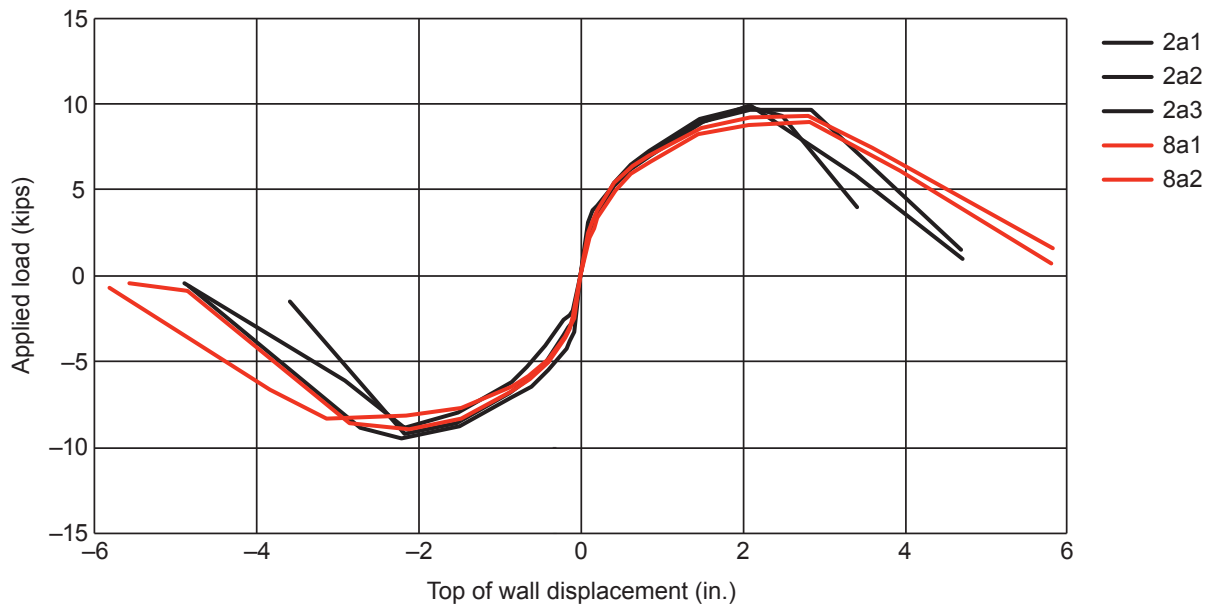


Figure 18. Backbone curves comparing SIPs of 4-1/2-in. thickness (Wall 2a) and 6-1/2-in. thickness (Wall 8a).

the mean negative peak loads. The mean ultimate load values for Walls 7a, 7b, and 7c were 1,314 plf, 1,052 plf, and 986 plf, respectively. Some observations can be noted from Figure 17. The points where the maximum load was observed is clearly a function of the number of joints. This is expected based on the performance of light-frame walls. In terms of the ultimate loads, zero panel joints (Wall 7a) result in an increase in the ultimate load of around 10%. Increasing the number of joints from 1 to 2 (Wall 7b) and from 1 to 3 (Wall 7c) resulted in the ultimate load reduction of 11% and 17%, respectively. All these comparisons are made with the basic wall configuration, Wall 2a.

When considering the ICC-ES AC04 cyclic analysis, as summarized in Table 2, a few observations are noted: The cyclic performance parameters were similar in terms of the ductility capacity. As expected, the drift capacity was significantly affected by the number of splines. The wall without vertical joints, Wall 7a, had the lowest drift capacity, $0.021H$, among all walls tested. The drift capacity was $0.029H$, $0.039H$ and $0.052H$, for 1, 2, and 3 vertical joints, respectively. This indicates the importance of panel joints in SIP walls to ensure drift capacity under seismic loading.

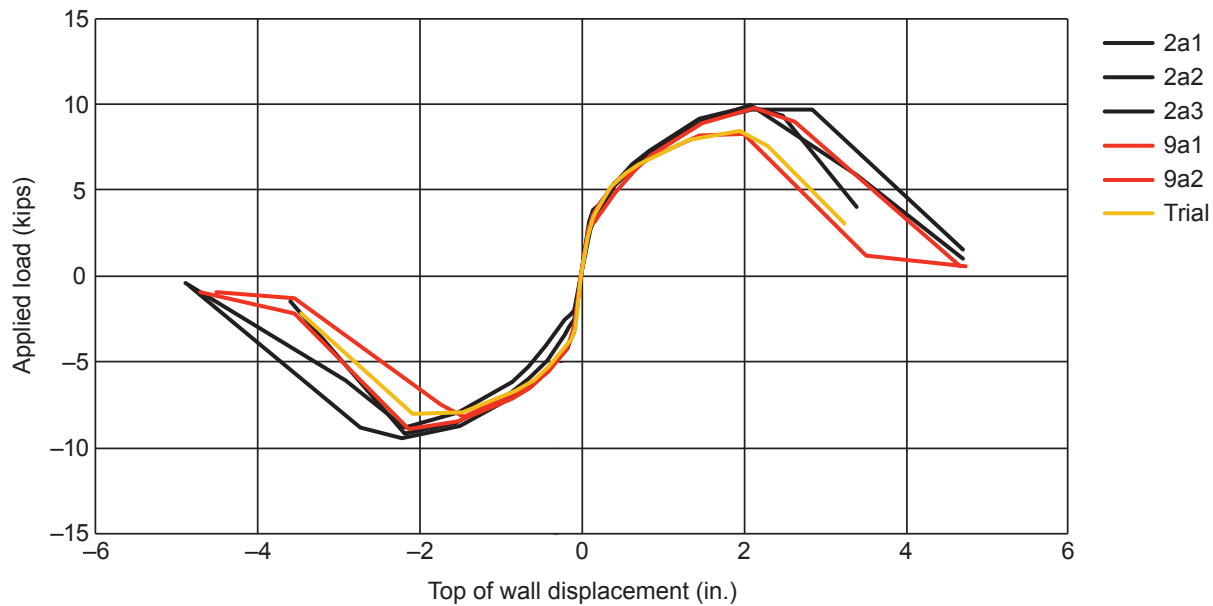


Figure 19. Backbone curves comparing facer orientations between vertical (Wall 2a) and horizontal (Wall 9a).

SIP Thickness

Figure 18 shows the backbone curves from three replications of the basic wall configuration, Wall 2a, and two replications of Wall 8a with a SIP thickness of 6-1/2 in. The hysteresis loops for these cyclic data are provided in Appendix A2–A4, A23, and A24.

The mean ultimate load value for Wall 2a was 1,188 plf based on the mean positive loads and the absolute value of the mean negative peak loads. The mean ultimate load value for Wall 8a was 1,110 plf. In terms of ultimate loads, the 6-1/2-in. thick SIP walls (Wall 8a) were about 7% lower than the 4-1/2-in. thick walls (Wall 2a). However, the magnitude of the difference in the ultimate load (78 plf) is within the testing and material variabilities. Based on these results, SIPs with these wall thicknesses are considered to result in very similar ultimate load performance.

When considering the ICC-ES AC04 cyclic analysis, as summarized in Table 2, all cyclic parameters met the AC04 cyclic criteria. However, the 6-1/2-in. thick walls did have a relatively high drift capacity of 0.037H, compared with 0.029H for the 4-1/2-in. thick walls. From the backbone curves shown in Figure 18, the lateral load performance between these two SIP wall thicknesses is quite compatible.

Orientation of OSB Facers

Figure 19 shows the backbone curves from three replications of the basic wall configuration, Wall 2a, and two replications of Wall 9a with cross-oriented OSB facers. Included in Figure 19 is the “trial” wall test, which was also based on cross-oriented OSB. The hysteresis loops for these cyclic data are provided in Appendix A1–A4, A25, and A26.

The mean ultimate load value for Wall 2a was 1,188 plf based on the mean positive loads and the absolute value of the mean negative peak loads. The mean ultimate load value for Wall 9a was 1,097 plf and the mean value of the trial was 1,034 plf. The cross-oriented OSB facers resulted in an 8% decrease in ultimate load. If the “trial” wall is included, the decrease in ultimate load for cross-oriented OSB facer is about 10%. Given the testing and material variabilities, the effect of OSB facer orientation on ultimate load can be considered as marginal.

When considering the ICC-ES AC04 cyclic analysis, as summarized in Table 2, the cyclic performance parameters for both OSB facer orientations were similar. However, the drift capacity of 0.026H for the cross-oriented OSB facers was slightly lower than the AC04 criteria. This was not expected, because OSB orientation is known to not significantly affect the lateral load performance of light-frame walls.

Bottom Plate Washer Geometry

Figure 20 shows the backbone curves from the SIPs with cross-oriented OSB facers and installed with square (0.229-by 3-by 3-in.) washers (Wall 9a), large (0.229-in. by 3-in.-diameter) round washers (Wall 2b), and standard (0.134-in. by 1.75-in.-diameter) washers (Wall 2c) for the 5/8-in.-diameter anchor bolts. Included in Figure 20 is the “trial” wall test, which was also based on cross-oriented OSB facers. The hysteresis loops for these cyclic data are provided in Appendix A1, A5, A6, A25, and A26.

The mean ultimate load value for Wall 9a was 1,097 plf based on the mean positive loads and the absolute value of the mean negative peak loads. The mean ultimate load values for Walls 2b and 2c were both 965 plf, and the mean

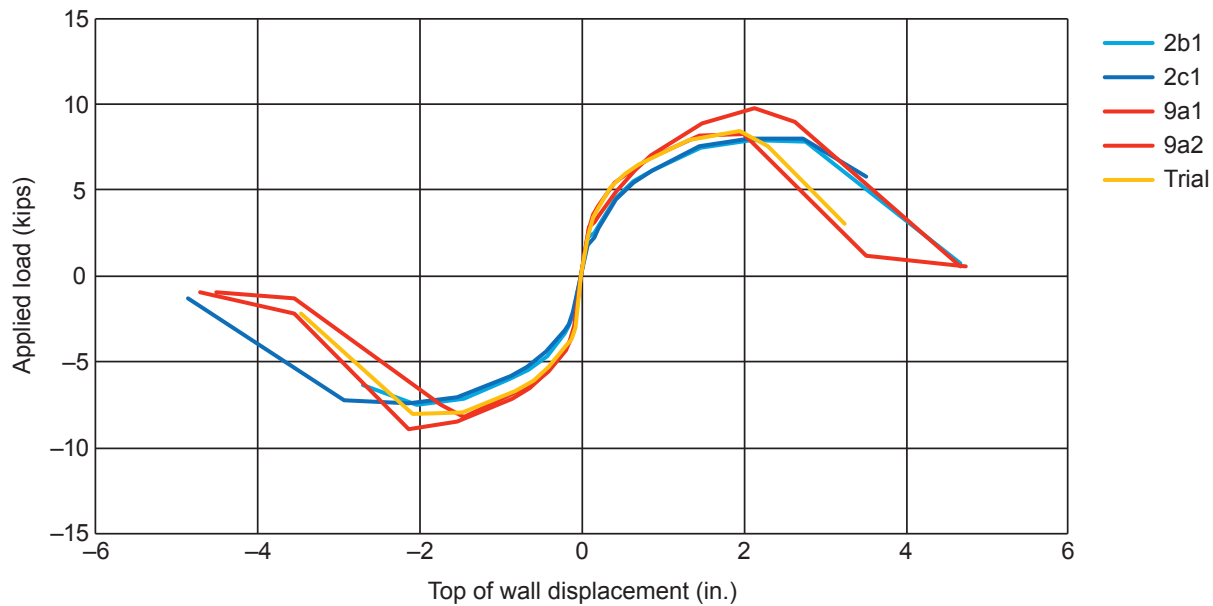


Figure 20. Backbone curves comparing square washers (Wall 9a) and round washers (Walls 2b and 2c).

value for the “trial” wall was 1,034 plf. Based on the small sample sizes, using the round washers (Walls 2b and 2c) reduced the ultimate load by 13%, as compared with square washers (Wall 9a). There is no difference in ultimate load between the large and standard cut round washers. However, because the failure modes were often associated with the top plate, but virtually never associated with the bottom plate, the difference in ultimate load between square and round washers is recommended to be further studied.

When considering the ICC-ES AC04 cyclic analysis, the cyclic performance parameters were similar. The walls with round washers had a higher drift capacity. However, it is difficult to be certain if these differences are significant and if the results are repeatable due to the lack of replicates for the wall with the large round washer and the wall with the standard cut round washer.

Summary and Conclusions

This report covers the testing of 29 full-size SIP walls of various configurations. Table 2 summarizes the cyclic performance parameters based on the assumed allowable design values published in ICC-ES ESR-1539. In general, the cyclic performance parameters for all walls tested in this study met the over-strength and ductility capacities of ICC-ES AC04, although some walls had drift capacities slightly lower than the AC04 criterion. The one exception was the wall without any vertical joints, which showed a significantly low drift capacity of 0.021H.

The findings for the different variables studied can be summarized as follows:

1. Test protocol (monotonic and cyclic)—Testing based on ASTM E72 and ASTM E2126 resulted in similar ultimate loads. Testing based on ASTM E564 and ASTM E2126 resulted in similar deflection profiles, but the ultimate load from monotonic (ASTM E564) tests was approximately 12% lower than that from the cyclic (ASTM E2126) tests. There is not enough evidence to conclude that ASTM E564 will result in a significantly lower ultimate load than the other test methods.
2. Nail size for panel connection (8d Box and 8d Common)—Data showed that there was no practical difference in ultimate load between SIP walls constructed with these two nail sizes.
3. Nail spacing (6, 4, and 3 in.)—Data showed that a decrease in nail spacing from 6 to 4 in. and from 6 to 3 in. on center resulted in ultimate load increases of 27% and 58%, respectively.
4. Wall bearing type (wood and rigid steel bearing)—Data showed that when SIPs bear on steel, as compared to SPF bottom plates, ultimate load is reduced by approximately 15%. However, this decrease in ultimate load could have been affected by the increase in spline nailing spacing from 6 in. to 12 in. for improved wall ductility. In this case, the effect of bearing plate types on cyclic performance parameters was insignificant.
5. Spline type (block spline and two 2× lumber spline)—Data showed that the difference in ultimate load is insignificant (less than 5%).
6. Number of panel joints (no joint, one, two, and three joints)—Data showed that the number of panel joints and the aspect ratio of the individual SIP segments clearly had an effect on the cyclic performance. The more joints, the higher the ductility capacity of the SIP walls. Compared with one panel joint, zero joint resulted in an increase of

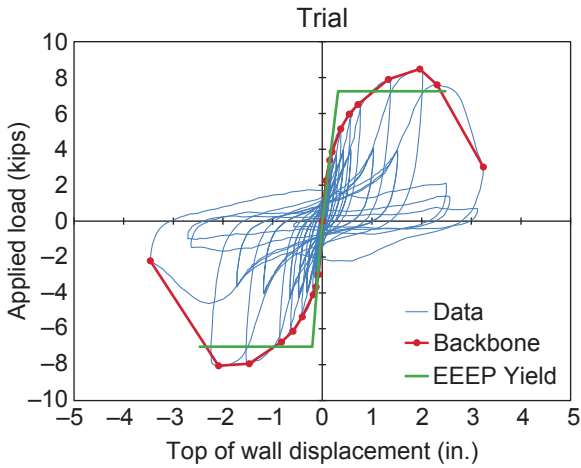
around 10% in ultimate load, whereas two and three joints resulted in a reduction in ultimate load of 11% and 17%, respectively.

7. SIP thickness (4-1/2 and 6-1/2 in.)—Data showed that the ultimate load is similar between SIP wall thicknesses of 4-1/2 and 6-1/2 in. (less than 7% difference).
8. Orientation of OSB facers (strength axis horizontal and vertical)—Data showed that cross-oriented (horizontally oriented) facers resulted in a marginal (approximately 10%) reduction in ultimate load, as compared with vertically oriented OSB facers.
9. Bottom plate washer geometry (square and round)—Data showed no difference between large and standard round washers. However, the square washers showed a 13% higher ultimate load. However, because the failure modes were often associated with the top plate and virtually never associated with the bottom plate, the difference in ultimate load between square and round washers is recommended to be further studied.

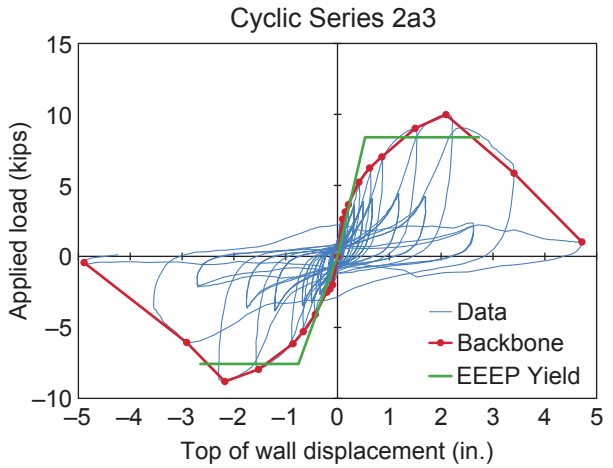
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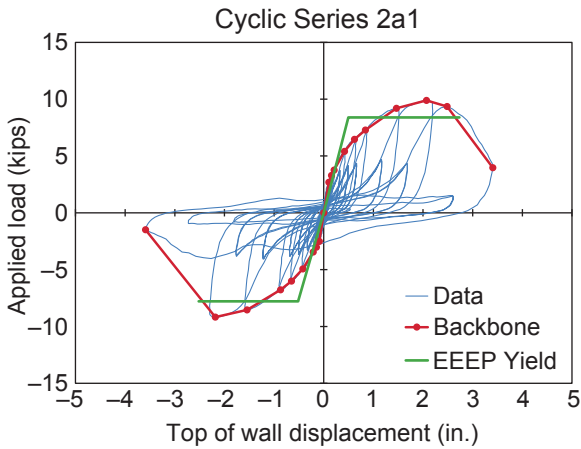
Appendix—Hysteresis Plots of the SIP Walls Subjected to CUREE Loading Protocol



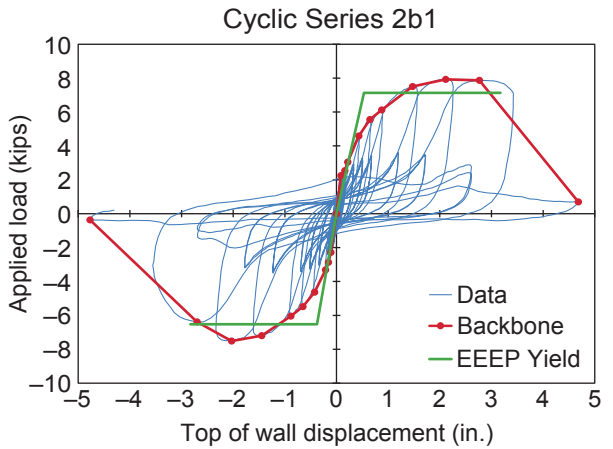
A1. "Trial" wall



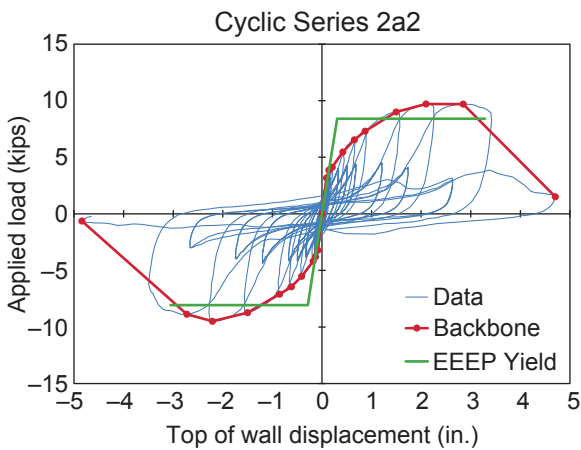
A4. Wall 2a3



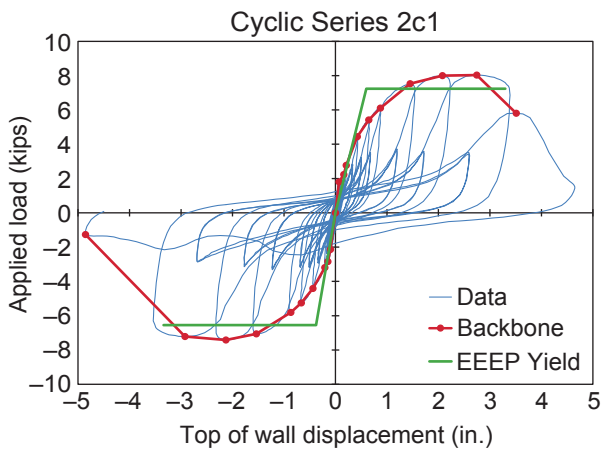
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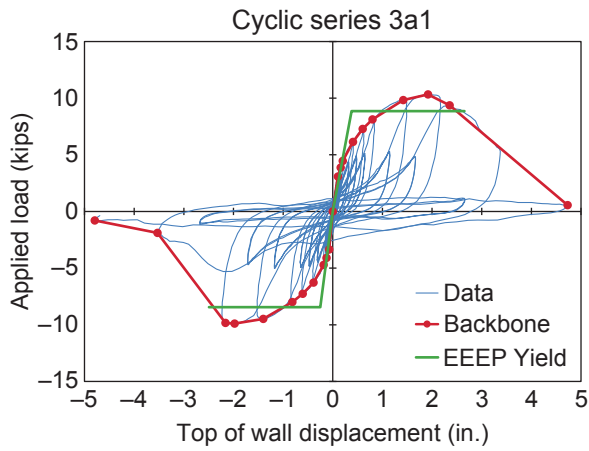
A5. Wall 2b1



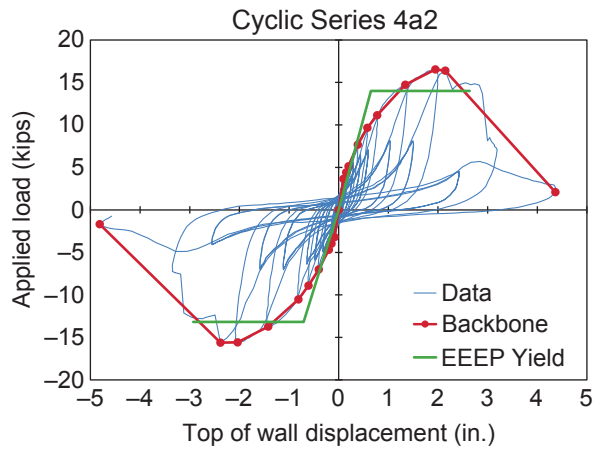
A3. Wall 2a2



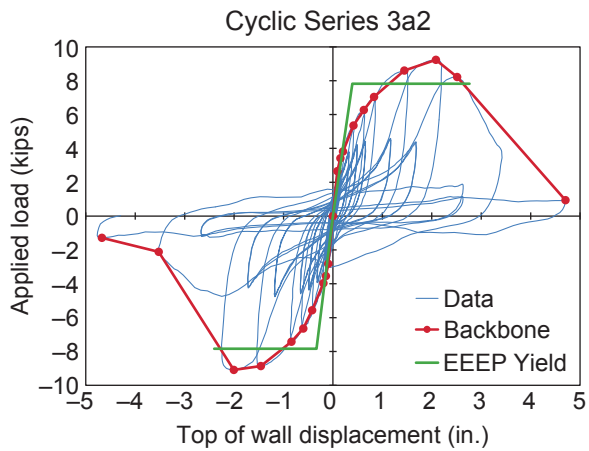
A6. Wall 2c1



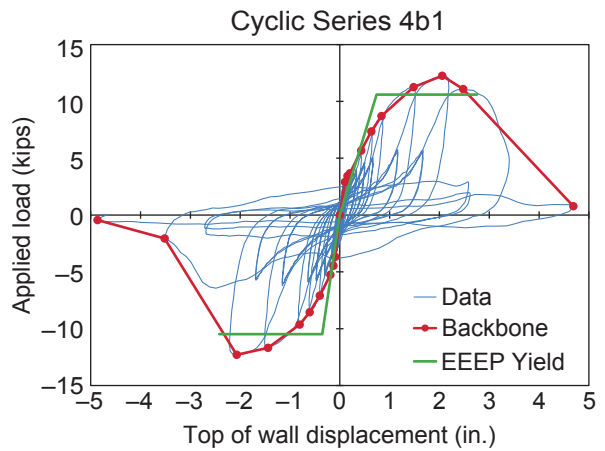
A7. Wall 3a1



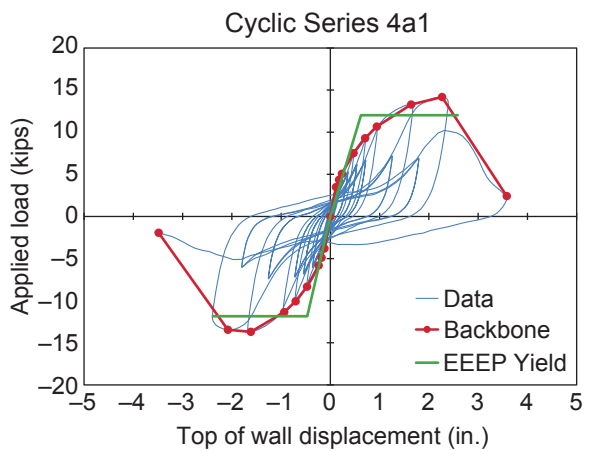
A10. Wall 4a2



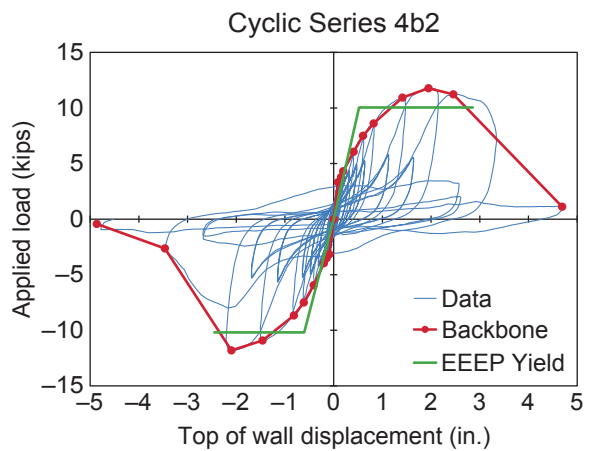
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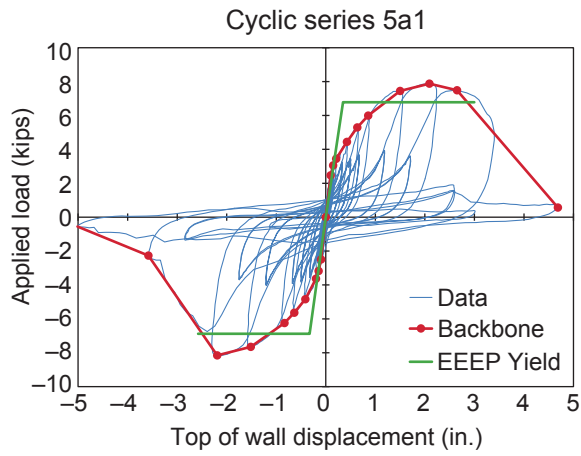
A11. Wall 4b1



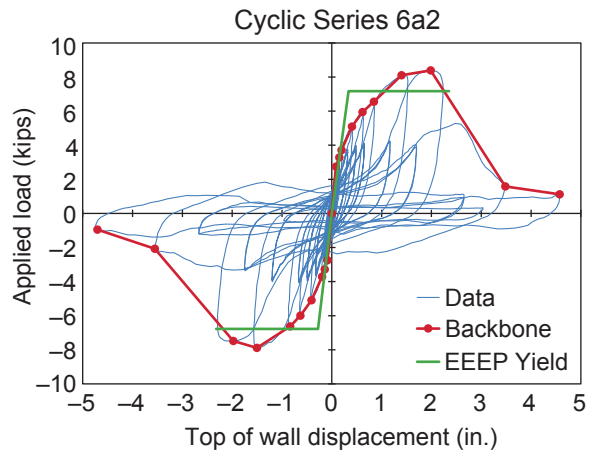
A9. Wall 4a1



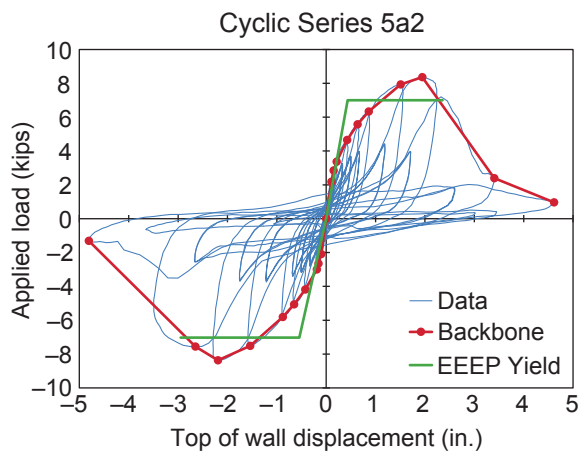
A12. Wall 4b2



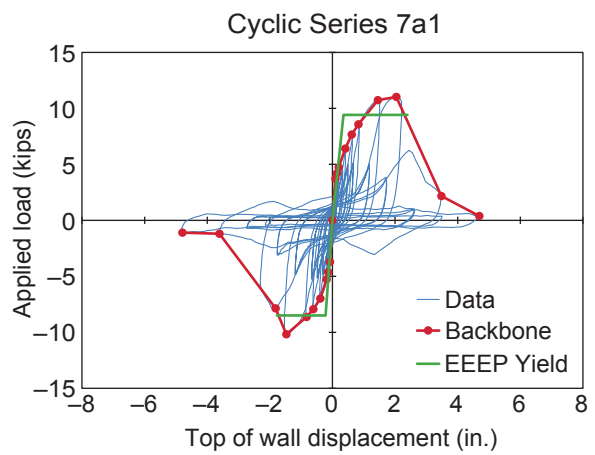
A13. Wall 5a1



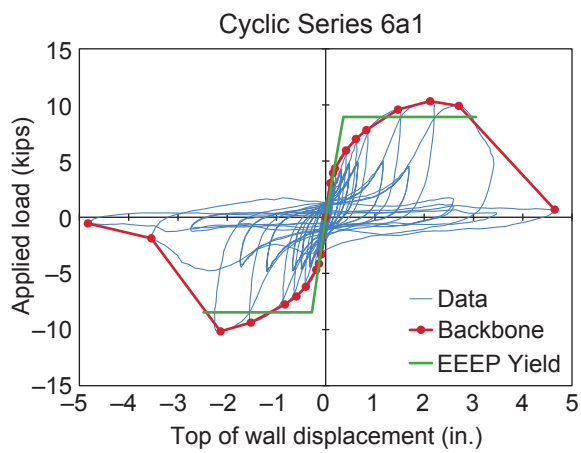
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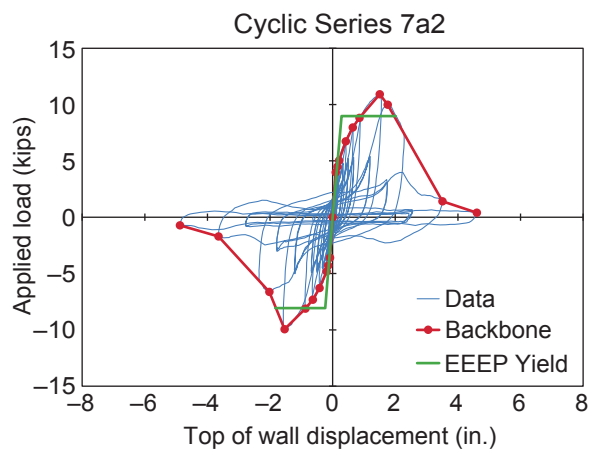
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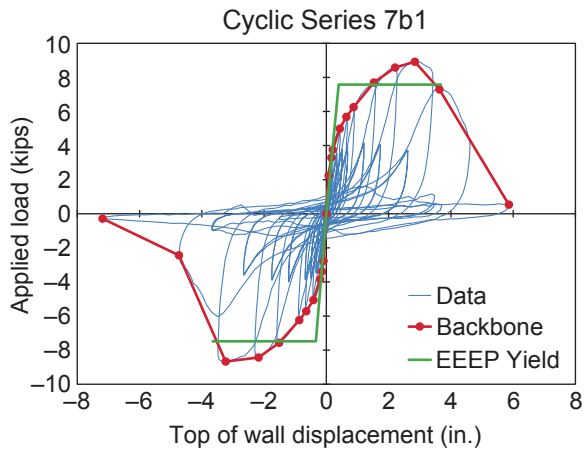
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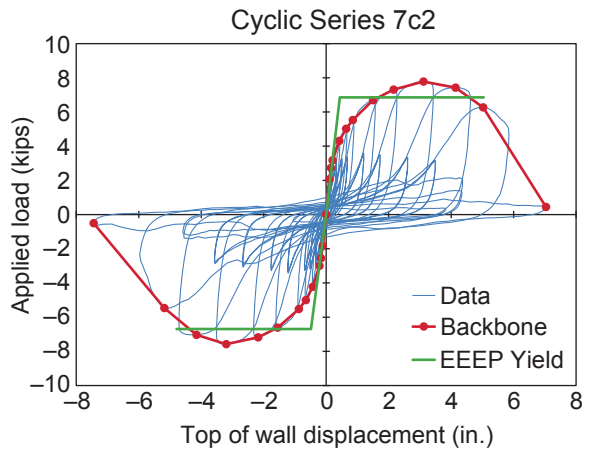
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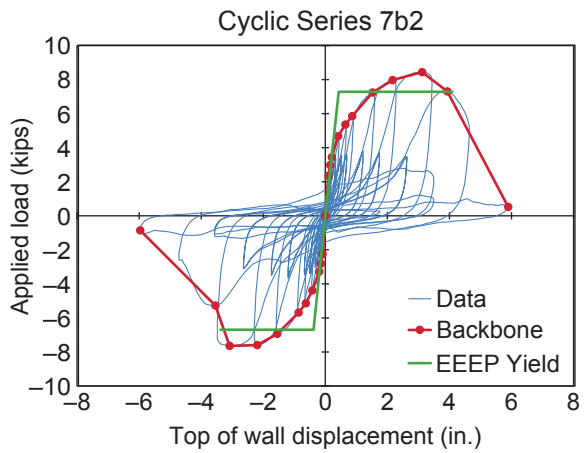
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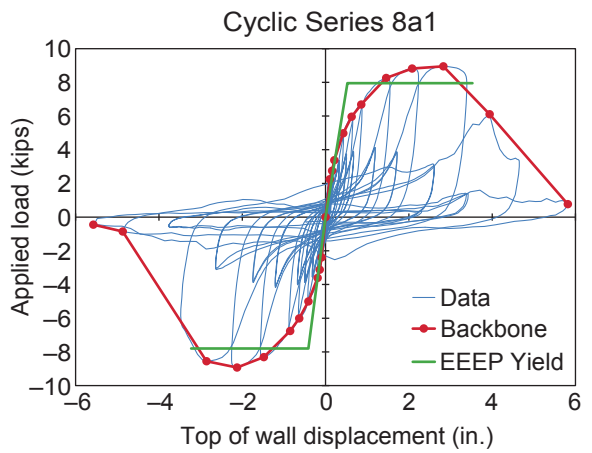
A19. Wall 7b1



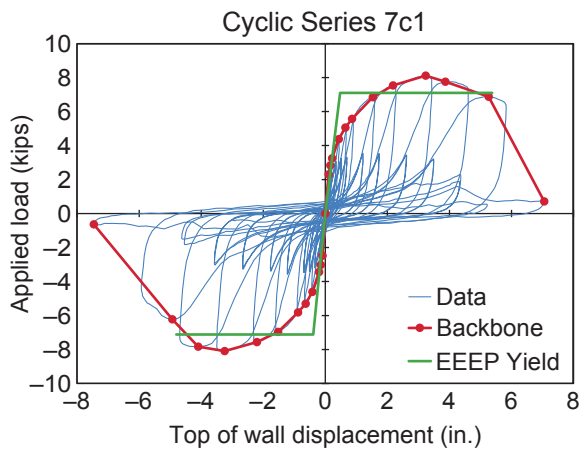
A22. Wall 7c2



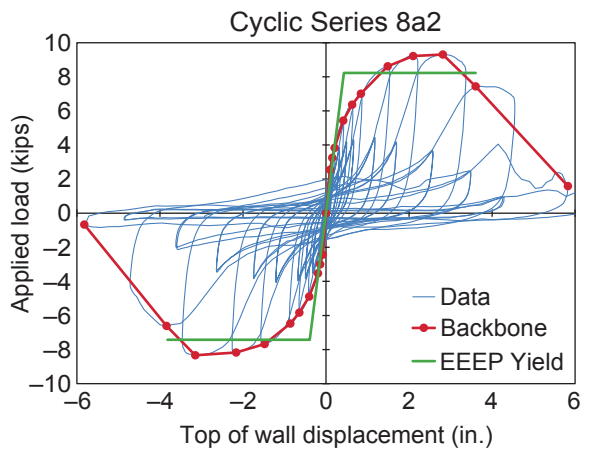
A20. Wall 7b2



A23. Wall 8a1



A21. Wall 7c1



A24. Wall 8a2

