USDA

United States Department of Agriculture

# SIP Shear Walls

## Cyclic Performance of High-Aspect-Ratio Segments and Perforated Walls

**Vladimir Kochkin**
**Douglas R. Rammer**
**Kevin Kauffman**
**Thomas Williamson**
**Robert J. Ross**

Forest Service

Forest Products Laboratory

Research Paper
FPL–RP–682

December
2015

## Abstract

Increasing stringency of energy codes and the growing market demand for more energy efficient buildings gives structural insulated panel (SIP) construction an opportunity to increase its use in commercial and residential buildings. However, shear wall aspect ratio limitations and lack of knowledge on how to design SIPs with window and door openings are barriers to the wider adoption of SIP technology. An experimental study was conducted to evaluate the lateral resistance performance of high-aspect-ratio SIP shear wall segments and SIP shear walls with window and door openings. At most two replicates of fully anchored SIP shear walls were cyclically tested at the following aspects ratios: 1:1, 2:1, 3:1, and 4:1. Five additional tests were conducted with multiple SIP wall panels that contained various sized door and window openings. Based on the experiments, the unit stiffness of the SIP shear wall varied by aspect ratio and the unit shear capacity decreased with increasing aspect ratio. Spline joints between wall segments also decreased capacity. Finally, test results indicate that multiple segment SIP shear walls with openings follow the overall trend predicted by the perforated shear wall method for both strength and stiffness.

Keywords: cyclic, shear wall, structural insulated panels, perforated shear walls

## Contents



December 2015

Kochkin, Vladimir; Rammer, Douglas R.; Kauffman, Kevin; Williamson, Thomas; Ross, Robert J. 2015. SIP shear walls: cyclic performance of high-aspect-ratio segments and perforated walls. Research Paper FPL-RP-682. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 19 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726–2398. This publication is also available online at www.fpl.fs.fed.us. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

# SIP Shear Walls

## Cyclic Performance of High-Aspect-Ratio Segments and Perforated Walls

**Vladimir Kochkin,** Director of Applied Engineering
Home Innovations, Upper Marlboro, Maryland

**Douglas R. Rammer,** Research General Engineer
Forest Products Laboratory, Madison, Wisconsin

**Kevin Kauffman**
Home Innovations, Upper Marlboro, Maryland

**Thomas Williamson**
T. Williamson – Timber Engineering, LLC, Vancouver, Washington

**Robert J. Ross,** Supervisory Research General Engineer
Forest Products Laboratory, Madison, Wisconsin

## Introduction

This study addresses the single structural insulated panel (SIP) panel length to height ratio (aspect ratio) limitations for a single SIP, as imposed by product evaluation agencies. NTA Inc. (Nappanee, IN) is a third party design review and inspection agency that provides product certification and testing services, and independently verifies both quality and standards compliance for many building products. The NTA listing report limits the aspect ratio to 2:1 for low seismic risk areas and 1:1 for high seismic risk areas. Many ICC-ES Evaluation Service (ICC-ES, Brea, California) evaluation reports currently limit the aspect ratio for SIP shear walls to 1:1. These limitations have significant implications for engineered shear walls in nonresidential and residential construction where narrow aspect ratio segments are common as a result of doors and windows closely spaced or placed near building corners. With the increasing stringency of energy codes and the growing market demand for more energy efficient buildings, the SIP construction is well postured to increase its market. However, in some markets the aspect ratio limitation is a barrier to the wider adoption of SIP technology.

Wood design provisions (AWC 2015a) include two methodologies for shear wall design: segmented shear wall and perforated shear wall methods. The results of the testing program summarized in this report provide information for both design approaches. Both approaches are investigated because high-aspect-ratio segments can be included in shear wall designed using either of the two methods.

## Objectives

The overall goal of this study is to develop performance test data on the response of SIP shear walls with high-aspect-ratio segments. The results will provide the basis for developing design methodologies for future code, standard, or acceptance criteria proposals. The specific objectives of this study include the following:

1. Measure the performance of individual, fully anchored shear segments with the following aspect ratios: 1:1, 2:1, 3:1, and 4:1.
2. Conduct a preliminary evaluation of the applicability of the perforated shear wall (PSW) method to SIP shear walls based on an initial limited set of perforated shear walls with high-aspect-ratio segments.

## Background

### SIP Lateral Wall Testing

Kermani and Hairstans (2006) researched the performance of 2.4 m by 2.4 m (8 ft by 8 ft) SIP wall systems with and without openings. Opening sizes ranged between 6% and 65% of the wall specimen area. Segment aspect ratio varied from 1:1 to 8:1. The wall specimens were constructed with 2 panels, spliced with a 50 mm by 102 mm (2 in. by 4 in.) lumber spline. Fastening of the panels to the perimeter boundary members was achieved with 35.1 mm (1.38 in.) long by 2.64 mm (0.104 in.) diameter screws at approximately 254 mm (10 in.) on center. Loading was applied monotonically, and each type of wall configuration was tested under two separate vertical loading conditions; the first condition was without any vertical load applied, and the second was with a 10.21 kN/m (700 lb/ft) gravity load along the top of the specimens. For walls without openings, the peak shear load ranged between 4.67 kN/m (320 lb/ft) for walls without vertical load to 11.38 kN/m (780 lb/ft) for walls with vertical load. For walls with openings, the research confirmed that capacity followed the general trend of the PSW method.

Jamison (1997) tested 2.4-m by 2.4-m (8-ft by 8-ft) wall specimens with various boundary and anchorage detailing.

**Table 1—Manufacturer's shear wall capacities**

| ESR #/NTA #[a] | Manufacturer | Allowable shear capacity (kN/m) | Fastening detail/lumber specific gravity (SG) |
|---|---|---|---|
| | | 4.38 | Nails at 152 mm (6 in.) oc/0.50 SG lumber |
| ICC-ES ESR 1882 | Premier SIPS by INSULFOAM | 8.76 | Nails at perimeter at 102 mm (4 in.) oc and screws at splice at 102 mm (4 in.) oc/0.50 SG lumber |
| ICC-ES ESR 1138 | Precision Panel Structures | 2.48 | Nails at 102 mm (4 in.) oc/0.50 SG lumber |
| ICC-ES ESR 1295 | PFB America Corporation | 5.34–9.33 | Nails at 152 mm (6 in.) to 76 mm (3 in.) oc/0.42 SG lumber |
| ICC-ES ESR 1802 | Korwall | 2.63 | Staples at 102 mm (4 in.) oc/0.55 SG lumber |
| ICC-ES ESR 2139 | Stress Panel Manufacturing, Inc. | 1.90 | Nails or staples at 152 mm (6 in.)/0.50 SG lumber |
| ICC-ES ESR 2233 | R-Control | 4.89–13.43 | Nails at 152 mm (6 in.) to 51 mm (2 in.) oc/0.42 SG lumber |
| NTA SIPA120908-10 | Listed SIPA members | 5.55–13.13 | Nails at 152 mm (6 in.) to 76 mm (3 in.) oc/0.42 SG lumber |
| NTA PRS032808-3 | Insulfoam, a Carlisle Company | 5.25–13.43 | Nails at 152 mm (6 in.) to 51 mm (2 in.) oc/0.50 SG lumber |
| NTA Assembly Report: AFM031809-18 | AFM Corporation | 13.43 | Nails at 51 mm (2 in.) oc/0.50 SG lumber |

[a]ICC-ES reports can be downloaded from www.icc-es.org. NTA reports can be downloaded from www.ntainc.com.

The panels used an 11.1-mm (7/16-in.) OSB facing on one side and 12.7-mm (1/2-in.) drywall facing on the other. Nominal 50-mm by 102-mm (2-in. by 4-in.) lumber and 12.7-mm (1/2-in.) OSB block spline connections were tested. The tested end-wall boundary conditions included 25-mm by 102-mm (1-in. by 4-in.) lumber, 50-mm by 102-mm (2-in. by 4-in.) lumber, and 12.7-mm (1/2-in.) OSB surface splines. One configuration also included a double 50-mm by 102-mm (2-in. by 4-in.) bottom plate member. Fastening of the panels to the perimeter boundary and splice members was with 41.3 mm (1-5/8-in.) drywall screws spaced at 152 mm (6 in.) on center and construction adhesive. Specimens were tested monotonically or cyclically without vertical loading. Only one of the five configurations included end-wall hold-down anchors. Peak shear loads for the monotonically tested specimens ranged between 4.82 kN/m (330 lb/ ft) and 12.84 kN/m (880 lb/ft), with the specimen with hold-down anchors achieving the greatest capacity. Cyclic testing of the same configurations resulted in peak shear loads ranging between 4.67 kN/m (320 lb/ft) and 12.70 kN/m (870 lb/ ft).

### APA 2010

APA – The Engineered Wood Association (2010) summarizes testing of a single 2.4-m by 2.4-m (8-ft by 8-ft) SIP wall configuration subjected to various types of boundary restraint. The tested specimens were constructed with two panels, spliced together with an OSB box spline and attached to the boundary and spline members with 8d common nails spaced at 152 mm (6 in.) on center. The following configurations were tested monotonically: (1) only E72 type hold-downs with facers unrestrained from rotation, (2) E72 type hold-downs and 50-mm by 152-mm (2-in. by 6-in.) top and bottom cap plates restraining facer panel edge rotation, or (3) Simpson Strong-Tie end-wall hold-downs, 50-mm by 102-mm (2-in. by 6-in.) cap plates and additional 46.70 kN/m (3,200 lb/ft) gravity load applied. The respective peak loads were 15.15 kN/m (1,038 lb/ft), 23.09 kN/m (1,582 lb/ft), and 30.94 kN/m (2,120 lb/ft) showing that facer bearing and gravity load contribute significantly to the wall's capacity. Cyclic testing was conducted on walls with only Simpson Strong-Tie hold-downs and 50-mm by 152-mm (2-in. by 6-in.) plate caps without gravity load with the walls reaching an average peak load of 17.19 kN/m (1,178 lb/ft), indicating a substantial reduction in capacity because of the cyclic protocol (however, out of the three tests, at least in two specimens the failure was at hold-down fasteners or post, not at the spline as with the monotonic tests).

### Manufacturer's Evaluation Reports Data

Table 1 presents a summary of published allowable shear wall capacities obtained from ICC-ES Evaluation Reports (ESR) for several SIP manufacturers and NTA SIPA Listing Report. The summary includes allowable capacities as well as fastening schedules and boundary member lumber requirements.

## Shear Wall Design

Two methodologies for shear wall design assist in the National Design Specification for Wood Construction (AWC 2015b) segmented shear wall and perforated shear wall methods. Segmented shear wall considers assume that only the full height sections or segments, which have hold-downs on each segment end, resist the lateral forces. Resist of each

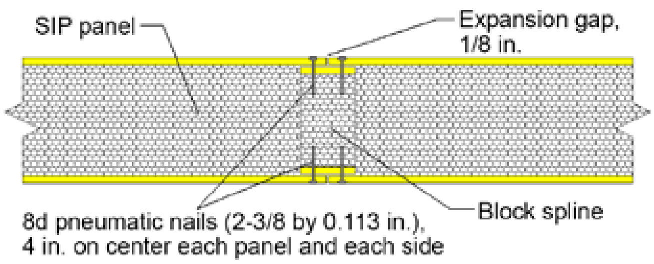



**Figure 1—SIP spline detail.**

full height segment is summed together to determine resistance of the entire length of the shear wall. Resulting resistance is a conservative estimate.

Perforated shear wall methods was first proposed by Sugiyama and Yasumura (1984) based on testing of one-third scale monotonic racking tests of wood stud, plywood-sheathed shear walls with openings. The researchers defined the sheathing ratio (Equation (1)), $r$, to classify walls based on the amount of openings and the empirical relationship to strength and stiffness.

$$r = \frac{1}{1 + \dfrac{A_0}{H\Sigma L_i}} \tag{1}$$

where $A_0$ is total area of openings, $H$ is height of the wall, and $\Sigma L_i$ is summation of length of a full height wall segments.

Subsequently, Sugiyama and Matsumoto (1996) determined an empirical equation to relate shear capacity and sheathing area ratio, based on scaled tests. They determined an empirical equation that related the ratio (Eq. (2)), $F$, of the shear load for a wall with openings to the shear load of a fully sheathed wall at shear deformation angle of 1–100 radians for ultimate capacity.

$$F = \frac{r}{3 - 2r} \tag{2}$$

This method was referred to as the perforated shear wall (PSW) method. The method has since been adopted into the Special Design Provisions for Wind and Seismic (AWC 2015a) for wood shear walls and referenced in U.S. model building codes.

# Experimental Approach

## Wall Specimens

Table 2 provides the test matrix to evaluate the performance of individual, fully anchored shear segments at various aspect ratios, while Table 3 provides the test matrix that evaluated the applicability of the perforated shear wall (PSW) for SIP shear walls.

Tables 4 summarizes the materials and construction details and Table 5 summarizes the fastening schedule used in the construction of the test walls. All specimens were 2.4 m (8 ft) tall and ranged in length from 0.6 m (2 ft) to 6.1 m (20 ft). Each wall specimen was constructed on the laboratory floor adjacent to the test setup and lifted in place with a crane using the loading beam. Temporary bracing was used as needed to ensure specimen integrity during installation in the setup. In 6.1-m (20-ft) walls, splice joints in the top plate/spacer were offset a minimum 610 mm (24 in). Panel joints were constructed using block splines in accordance with Figure 1. All boundary members consisted of 50-mm by 152-mm (2-in. by 6-in.) nominal framing lumber inset into the foam core between the OSB facings of the SIP panel. Single framing members were used for top and bottom plates. Double-stud posts were used at walls' ends to accommodate the attaching of the hold-downs. Single studs were used at cut-out openings and double studs were used with openings framed with individual header panels (one stud inserted into the full-height panel and one jack stud supporting the header panel). Double studs were nailed together using two 16d pneumatic nails every 406 mm (16 in.). Wall openings in Configurations 5, 7, and 8 were constructed in accordance to Figure 2. The wall openings in Configuration 6 were constructed in accordance to Figure 3.

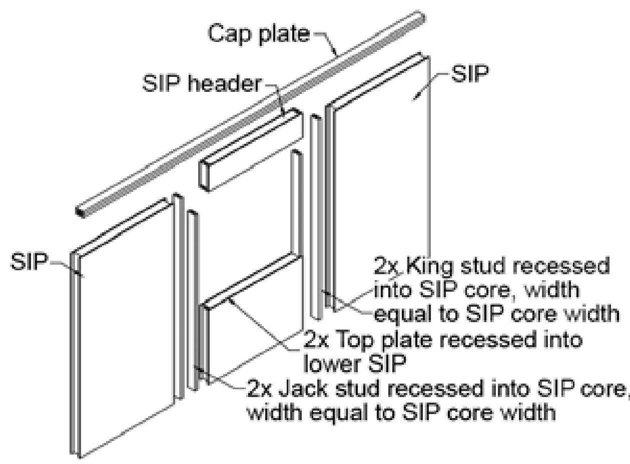



**Figure 2—Segmented SIP header detail for Configurations 5, 7, and 8.**

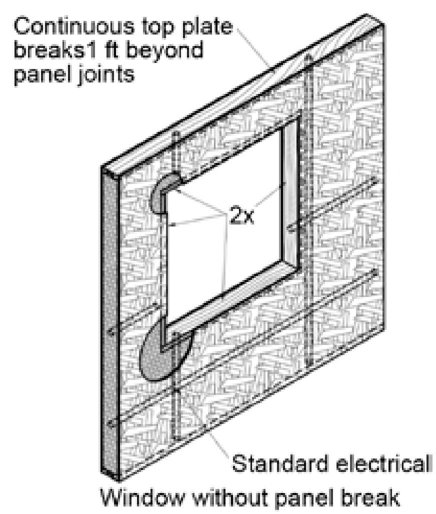



**Figure 3—Continuous SIP header detail for Configuration 6.**

**Table 2—Test matrix for walls without openings**

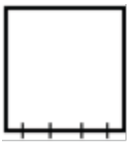
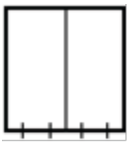
| Configuration | | Specimen width/ height | Aspect ratio | Overturning restraint | Sample size | Loading | Purpose | SIP panel width (m) | Bolt locations (mm from left end) |
|---|---|---|---|---|---|---|---|---|---|
| 1 |  | 2.4/2.4 | 1:1 | Hold-downs at wall ends | 1 | Monotonic | Provide baseline performance under monotonic loading and to establish deformation for CUREE loading | 2.4 | 304, 914, 1524, 2560 |
| $1_{SPL}$ |  | 2.4/2.4 | 1:1 | Hold-downs at wall ends | 1 | CUREE | Provide baseline performance under cyclic loading for spline wall | 1.2 | 304, 914, 1524, 2560 |
| 2 |  | 1.2/2.4 | 2:1 | Hold-downs at wall ends | 2 | CUREE | Evaluate 2:1 aspect ratio | 1.2 | 304, 914 |
| 3 |  | 0.8/2.4 | 3:1 | Hold-downs at wall ends | 2 | CUREE | Evaluate 3:1 aspect ratio | 0.8 | 203, 610 |
| 4 |  | 0.6./2.4 | 4:1 | Hold-downs at wall ends | 2 | CUREE | Evaluate 4:1 aspect ratio | 0.6 | 203, 406 |

**Table 3—Test matrix for walls with openings**

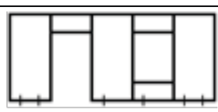
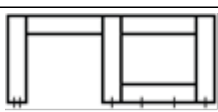
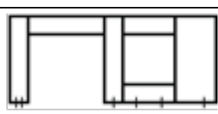
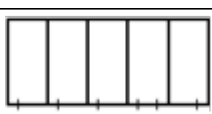
| Configuration | | Specimen width/ height | Segment aspect ratio | Overturning restraint | Loading | Purpose | SIP panel width (m) | Bolt locations (mm from left end) |
|---|---|---|---|---|---|---|---|---|
| 5 |  | 6.1/2.4 | All 2:1 | Hold-downs at wall ends | Monotonic | Evaluate wall with openings, all segments 2:1 | 1.2, 1.2, 1.2, 1.2, 1.2 | 304, 1524, 2743, 3962, 5791 |
| 6 |  | 6.1/2.4 | All 2:1 | Hold-downs at wall ends | CUREE | Same openings as (5) but with continuous panel joints at openings | 0.6, 2.4, 2.4, 0.6 | 304, 1524, 2743, 3962, 5791 |
| 7 |  | 6.1/2.4 | All 4:1 | Hold-downs at wall ends | CUREE | Evaluate wall with opening, all segments 4:1 | 0.6, 2.1, 0.6, 2.1, 0.6 | 203, 406, 3048, 3962, 5181, 5791 |
| 8 |  | 6.1/2.4 | 2:1 and 4:1 | Hold-downs at wall ends | CUREE | Evaluate wall with segment with different aspect ratios | 0.6, 2.1, 0.6, 1.5, 1.2 | 203, 406, 3048, 3962, 4572, 5791 |
| 9 |  | 6.1/2.4 | All 2:1 | Hold-downs at wall ends | CUREE | Evaluate the impact of multiple spline joints on the performance of the wall without openings | 2.4, 2.4, 2.4, 2.4, 2.4 | 304, 1524, 2743, 3962, 5791 |

**Table 4—Construction materials and details**

| Material | Details |
|---|---|
| Wall height | 2.4 m (8 ft) |
| Wall width | Varies according to test matrix (Tables 2 and 3) |
| Openings | Door height: 1.8 m (6 ft) |
| | Door width: varies to achieve segment aspect ratios per test matrix |
| | Windows height: 1.2 m (4 ft) |
| | Window width: varies to achieve segment aspect ratios per test matrix |
| Wall panels | 165 mm (6.5 in.) thick SIP panels; width varies to provide full segment aspect ratios per test matrix; OSB facing thickness: 11.1 mm (7/16 in.) |
| Block spline | 140 mm (5.5 in.) thick by 76 mm (3 in.) wide SIP block used for connecting SIP panels |
| Framing lumber | Nominal 51 mm by 152 mm (2 × 6) Spruce–Pine–Fir (SPF) #2 grade |
| Sill plate | Nominal 51 mm by 203 mm (2 × 8) Southern Yellow Pine (SYP) lumber |
| Hold-down | Simpson Strong-Tie HDU11 raised 25 mm (1 in.) above bottom plate fastened with (30) SDS25212-R25 screws |
| Anchor bolts | 15.9 mm (5/8 in.) diameter bolts with Simpson Strong-Tie BP5/8 – 3 plate washers spaced a maximum of 1.2 m (4 ft) on center and located at 305 mm (12 in.) from corners. For 0.8 m (32 in.) wide walls, anchor bolts located at quarter points; i.e., 203 mm (8 in.) from corners. For 0.6 m (24 in.) wide walls, anchor bolts located at third points, i.e., 203 mm (8 in.) from corners. |
| Sheathing fasteners | 8d pneumatic (60.3 mm by 2.87 mm) nails with full round head |
| Framing fasteners | 16d pneumatic (82.6 mm by 3.33 mm) nails with full round head |
| Interior finish | None (no gypsum installed) |

**Table 5—Fastener schedule**

| Connection | Fastener | Spacing |
|---|---|---|
| Panel sheathing to boundary framing | 8d pneumatic | 102 mm (4 in.) on center |
| Panel sheathing at spline | 8d pneumatic | 102 mm (4 in.) on center |
| Top/bottom plate to stud (end nailed) | (2) 16d pneumatic | Per connection |
| Hold-down bracket to end stud | (30) Simpson Strong-Tie SDS25212-R25 Screws | Per hold-down |
| Double studs (face nailed) | (2) 16d pneumatic | 406 mm (16 in.) on center |
| Top plate to spacer | (2) 16d pneumatic | 152 mm (6 in.) on center |

**Figure 4—2 by 6 bottom plate and 2 by 8 sill plate bolted to setup base.**

**Figure 5—OSB facing resting on sill plate.**

The bottom plate of the wall was placed on top of a preservative-treated 50 mm by 203 mm (2-in. by 8-in.) SYP sill plate and anchored down to the test setup using 15.9-mm- (5/8-in.-) diameter bolts with a 76-mm- by 76-mm- by 6.1-mm- (3-in.- by 3-in.- by 0.24-in.-) thick Simpson Strong-Tie BP5/8 – 3 plate washers (Fig. 4). The anchor bolts were tightened prior to installing the wall in the test frame. All anchor bolts and hold-down bolts were tightened to a 1/8 turn past a hand-tight fit.

The wall specimen was placed on top of the bottom plate such that the OSB facings of the SIP panels rested on the sill plate (Fig. 5). The facings were nailed to the bottom plate in accordance with the sheathing nailing schedule (8d pneumatic nails at 102 mm (4 in.) on center).

## Testing Procedures

Testing was conducted in accordance with general provisions of ASTM E2126-11 Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Walls for Buildings (ASTM International 2014).

In total, 13 tests were conducted using a racking shear testing apparatus controlled via a computer-based system. Instrument readings including load and deformation measurements were recorded using a computer-based data acquisition system (see Fig. 6 for a schematic of the test setup and instrumentation plan and Fig. 7 for a photo of Configuration 1M specimen).

The load-deformation relationship from the monotonic test (Configuration 1M) was used to determine the reference deformation (Δ) for the cyclic CUREE protocol in accordance with ASTM 2126-11 Test Method C. The reference deformation of 40.6 mm (1.6 in.) was used in all cyclic tests. The cyclic tests were conducted by displacing the top of the specimen in accordance with the CUREE cyclic protocol (Fig. 8) (Method C, ASTM E 2126) at a constant frequency of motion of 0.2 Hz (5 s per cycle). The hydraulic actuator has a total stroke of 305 mm (12 in.) with the maximum excursion set at 146 mm (5.75 in.). The hydraulic cylinder was attached to the load beam using a 51 mm (2 in.) pin. A sampling rate of 20 Hz was used such that 100 data points were recorded for each cycle.

The hydraulic actuator motion was applied using 102-mm by 102-mm by 6.4-mm (4-in. by 4-in. by 0.25-in.) walled steel distribution beam lag-bolted through a 50-mm by 102-mm (2-in. by 6-in.) spacer and the 50-mm by 102-mm (2-in. by 6-in.) top plate with 15.9 mm (5/8 in.) diameter 203 mm (8 in.) long bolts. The spacer was installed in such a manner that the wall panel skins were not allowed to bear on the spacer (the sheathing was able to rotate at the top plate without bearing restraint by framing members, spacer, or load distribution beam). The out-of-plane deformations were restrained by a set of rollers located on the side of the load beam.

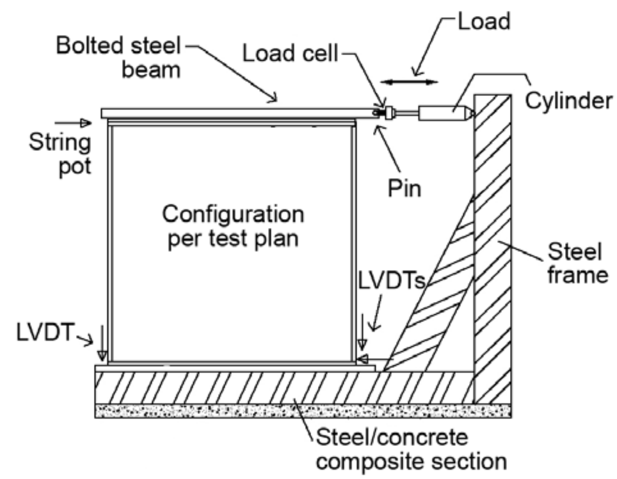



Figure 6—Shear wall test setup.

Figure 7—Shear wall specimen (Configuration 1M).

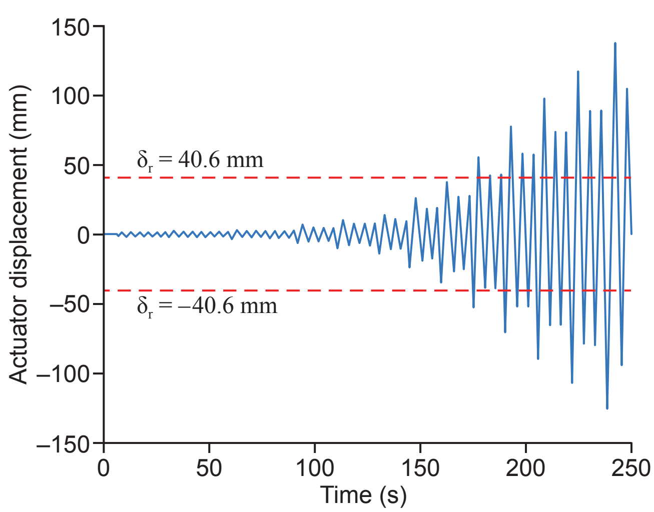



Figure 8—CUREE protocol.

The load was measured using an electronic load cell, with a capacity of 222 kN (50,000 lb), located between the cylinder and the steel distribution beam. The following deformations (Fig. 6) were measured using a string potentiometer and Linear Variable Differential Transformers (LVDT):

1. Displacement of the top plate relative to the setup base
2. Bottom plate slip relative to the setup base
3. Bottom plate slip next to a doorway relative to the 50-mm by 203-mm (2-in. by 2-in.) sill plate (if applicable)
4. Compression and uplift at the specimen corner stud relative to the setup base
5. Compression and uplift at the jack stud inside a doorway relative to the 50-mm by 203-mm (2-in. by 2-in.) sill plate (if applicable)

In addition to lateral wall tests, material property tests were conducted on the SIP ESP foam core, SIP OSB facing, and the wood framing.

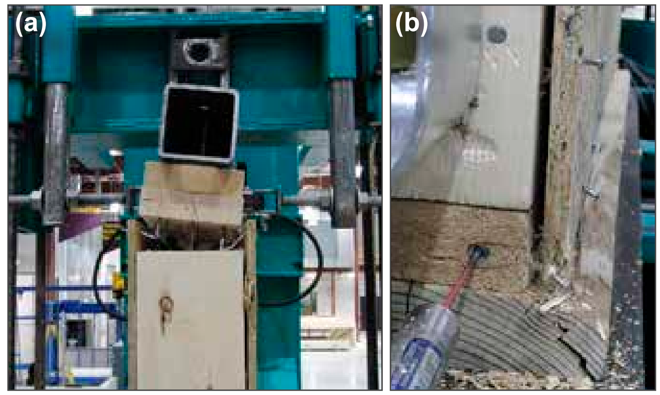


**Figure 9—Typical failure modes. (a) Separation of top plate from OSB facings. (b) Crushing of the sill plate by the OSB facings.**


**Figure 10—Rotation of individual SIP panels.**

## Results

In accordance with ASTM E2126, performance parameters for all cyclic tests were derived as an arithmetic average of the positive and negative envelope curves. The reported performance parameters include peak load, unit shear, shear stiffness at 0.4 (40%) peak load, unit shear stiffness at 0.4 peak load, and deflection at peak load. Results of the lateral wall testing are summarized in Table 6 for the walls tested for the evaluation of aspect ratios and Table 7 for the SIP walls tested to evaluate the effect of openings. Finally, Appendixes 1 and 2 provide load-deformation and backbone curves for all the walls without openings and with openings.

Material properties for framing lumber, SIP OSB panels, and SIP EPS core foam used in the manufacturing the shear wall test specimens were measured (Table 8). EPS foam core material and OSB facings meet the minimum requirements of the 2012 International Residential Code (IRC) for materials used in SIPs (2012 IRC Section R613.3) (International Code Council 2011) and ANSI/APA PRS 610.1-2013 (APA – The Engineered Wood Association 2013). The OSB properties are higher than the minimum specification values required by the IRC. Because the objective of this study is to establish trends rather than establish minimum design values, using SIP panels that potentially have higher capacities will result in conservative conclusions and generalizations.

## Discussion

### Failure Modes

The primary failure modes included separation of the wall top plate from the SIP panel, degradation of the sheathing nail connections, and crushing of the sill plate by the OSB facings (Fig. 9).

Rotation of the individual SIP panels relative to adjacent panels and/or the set-up was observed for all specimens leading to either opening of a gap between the adjacent segments or in some case a complete failure of the fasteners at the spline (Fig. 10).

For walls with perforations, stress concentration at the openings' corners lead to degradation of the connections between panels for walls framed with separate header panels (Configurations 5, 7, 8 – Fig. 11) or cracking of the OSB facings in walls framed with SIPs panels with cutout openings (Configuration 6 – Fig. 12). It should be noted that the separate header SIP panels were not directly attached to the framing of the adjacent SIP full-height panels. This configuration was tested to evaluate the lowest performance boundary.

Configuration 4 specimens (single 4:1 aspect ratio panels) were the only walls to not experience a failure leading to a significant drop in resistance. Although the top plate did begin to separate from the SIP panel, the walls survived the full deformation profile without a catastrophic failure.

### Walls without Openings

Table 6 summarizes results for walls without openings. Both the unit shear capacity and unit shear stiffness show a strong

**Table 6—Summary of results for walls without openings**

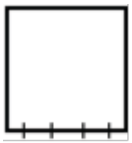
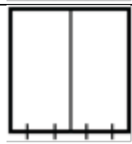
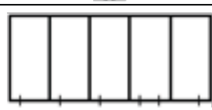
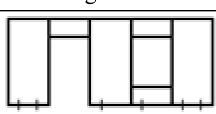
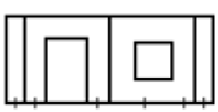
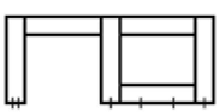
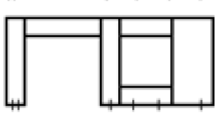
| Configuration | | Specimen width/ height | Aspect ratio | Peak load (kN) | Unit shear (kN/m) | Stiffness at 0.40$P_{load}$ (N/mm) | Unit stiffness at 0.40$P_{load}$ (N/mm/m) | Deflection at peak load (mm) |
|---|---|---|---|---|---|---|---|---|
| 1 |  | 2.4/2.4 | 1:1 | 63.596 | 26.081 | 2071.4 | 849.5 | 55 |
| $1_{SPL}$ |  | 2.4/2.4 | 1:1 | 65.793 | 26.982 | 1747.1 | 716.5 | 67 |
| 2 |  | 1.2/2.4 | 2:1 | 34.166 | 28.024 | 831.2 | 681.7 | 70 |
| | | | | 38.521 | 31.596 | 884.2 | 725.2 | 72 |
| 3 |  | 0.8/2.4 | 3:1 | 21.627 | 26.575 | 404.9 | 497.5 | 92 |
| | | | | 22.148 | 27.215 | 494.6 | 607.7 | 92 |
| 4 |  | 0.6./2.4 | 4:1 | 15.266 | 25.043 | 259.0 | 424.9 | 132 |
| | | | | 15.133 | 24.824 | 303.3 | 497.6 | 108 |
| 9 |  | 6.1/2.4 | 0.4:1 | 123.99 | 20.340 | 5634.4 | 924.3 | 57 |

**Table 7—Summary of results for walls with openings**

| | | | | | | Calculated characteristics: perforated shear wall (PSW) method | | Measured characteristics | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Peak load (kN)[a] | Peak load (kN)[b] | Peak load (kN) | PSW ratio, $F$ | | |
| Configuration | | Specimen width/ height | Aspect ratio | Sheathing ratio, $r$ | PSW ratio, $F$ | Stiffness (N/mm) | Stiffness (N/mm) | Stiffness @0.4$P_{load}$ (N/mm) | Baseline 1 | Baseline 2 | Deflection at peak load (mm) |
| 5 |  | 6.1/2.4 | 2:1 | 0.71 | 0.44 | 73.10 | 55.11 | 68.33 | 0.42[c] | 0.55 | 46 |
| | | | | | | 1941 | 2504 | 2404 | 0.55 | 0.43[c] | |
| 6 |  | 6.1/2.4 | 2:1 | 0.71 | 0.44 | 73.107 | 55.11 | 78.33 | 0.48 | 0.63 | 25 |
| | | | | | | 1941 | 2504 | 4457 | 1.02 | 0.79 | |
| 7 |  | 6.1/2.4 | 4:1 | 0.41 | 0.19 | 30.60 | 23.07 | 41.64 | 0.25 | 0.34 | 49 |
| | | | | | | 812 | 1048 | 1438 | 0.33 | 0.26 | |
| 8 |  | 6.1/2.4 | 2:1 | 0.51 | 0.26 | 42.11 | 31.74 | 57.87 | 0.35 | 0.47 | 44 |
| | | | | | | 1118 | 1442 | 2391 | 0.55 | 0.42 | |

[a]PSW prediction based on Configuration $1_{SPL}$–C as baseline (Baseline 1).
[b]PSW prediction based on Configuration 9 as baseline (Baseline 2).
[c]Cases where the measured PSW ratio ($F$) is below the calculated ratio ($F$).

**Table 8—Material properties**

| | |
|---|---|
| **SIP EPS foam core properties** | |
| Density (kg/m$^3$) | 17.62 |
| Compression strength @ 10% strain (kPa) | 108.9 |
| Tensile strength (kPa) | 211.7 |
| Flexural strength (kpa) | 200.6 |
| **OSB facing properties** | |
| Specific gravity | 0.71 |
| Parallel stiffness (E) (MPa/m) | 2,120 |
| Perpendicular stiffness (E) (MPa/m) | 856.8 |
| Parallel strength (N-m/m) | 656 |
| Perpendicular strength (N-m/m) | 440 |
| **Framing** | |
| Specific gravity | 0.40 |
| Moisture content | 9%–12% |

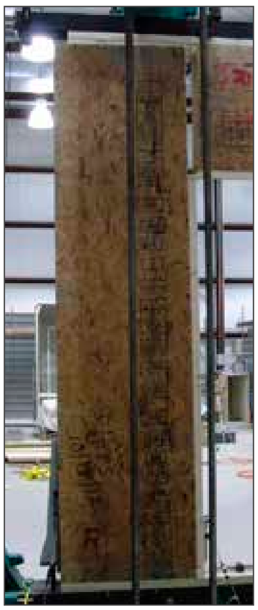


**Figure 11—Segment separated from header.**

**Figure 12—Configuration 6 cracking of OSB skins (black lines indicate location of cracks).**

dependency on the wall's aspect ratio. However, different trends are observed for unit shear capacity and unit shear stiffness. The unit shear capacity follows a "bell" curve with the top of the "bell" associated with the 4-ft single-panel specimen as shown in Figure 13. The "bell" trend is a function of two competing response mechanisms driving the performance of the wall. The reduction in unit shear capacity for longer walls with multiple SIP panels (Configurations $1_{SPL}$-C and 9)—the left side of the "bell"—is associated with the lower stiffness of spline connections between the SIP panels than a connection directly to framing members. For a 6.1-m (20-ft) long wall (Configuration 9) with a total of four spline joints, a reduction of 25% was observed relative to the 2.4-m- (8-ft-) long wall (Configuration $1_{SPL}$-C) with one spline joint and 32% relative to the 1.2-m- (4-ft-) long wall (Configuration 2) without spline joints.

The reduction in unit shear for high-aspect-ratio walls—the right side of the "bell"—is associated with the typical performance of narrow segments that is increasingly dominated by the uplift and bending components of the response. Using a 1.2-m- (4-ft-) long wall (Configuration 2) as a baseline, the 0.8-m- (2.67-ft) wall shows a 10% decrease and the 0.6-m- (2-ft-) wall shows a 16% decrease in unit shear strength. If a 2.4-m (8-ft) wall is used as a baseline (Configuration $1_{SPL}$-C), which is a typical practice for light-frame walls, the 0.8-m (2.67-ft) wall shows no decrease and the 2-ft wall shows an 8% decrease in unit shear strength. As a general observation for establishing design values and guidance, the unit shear reduction from the high-aspect-ratio effects is less than the reduction from the spline joint.

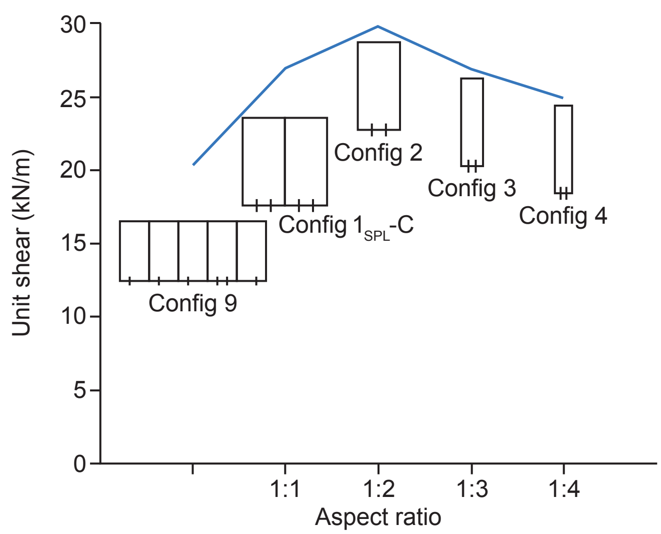



**Figure 13—Unit shear.**

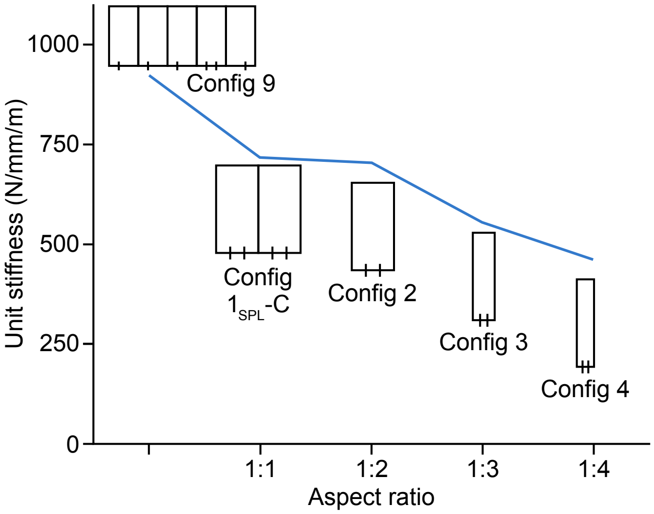



**Figure 14—Unit shear stiffness.**

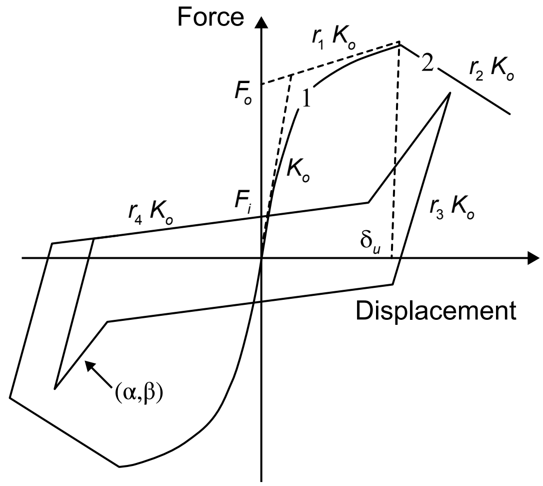



**Figure 15—Illustration of Stewart hysteretic model.**

The unit shear stiffness followed a general trend of a reduction in stiffness with increasing aspect ratio as shown in Figure 14. Configuration 9 showed the highest stiffness with any potential impact of the spline joints on the stiffness of the panel to panel connection outweighed by the increase because of the wall length. Configurations $1_{SPL}$-C and 2 exhibited comparable stiffness, again suggesting that any potential reduction from the higher aspect ratio for Configuration 2 was offset by the attachment of the SIP facings directly to framing members in lieu of the nailed OSB spline. Further increase in aspect ratio for Configurations 3 and 4 resulted in a 20% and 33% reduction in stiffness, respectively.

With the development of nonlinear time history analysis programs for the analysis of wood structures, such as SAWS and SAPWood, there is a need for hysteretic wall behavior data to model structural behavior under seismic events. Two hysteretic models have been for wood wall behavior, the Modified Stewart and the Evolution Damage Parameter models (Pang and others 2007). For the wall panels without openings, the modified Stewart model was fit to the experimental data. The modified Stewart model uses 10 parameters, highlighted in Figure 15, to describe the hysteretic behavior of the structural panel. A MATLAB program developed during the NEESWood program was used to optimize the 10 modeling parameters while minimizing the cumulative energy difference between the experimental and model behavior. Modeling parameters for Wall 1, 2, 3, 4 and 9 are listed in Table 9. Appendix 3 provides load-deformation curves for experimental and modeled behavior for the walls without openings.

## Walls with Openings (Perforated Walls)

Table 7 summarizes results for walls with openings. The perforated shear wall (PSW) method is used to evaluate peak load and stiffness at 0.4 peak load. Because unit shear and unit shear stiffness for fully anchored SIP walls depend on the wall length, the PSW method was used with Configurations $1_{SPL}$-C and 9 as baseline for comparison purposes. Figures 16–17 and Figures 18–19 graphically show the predictive power of the PSW method for SIP shear walls using the two respective baselines. The test results indicate that the SIP shear walls closely follow the overall PSW method trend for both load and stiffness. With exception of Configuration 5, all wall specimens exceeded the PSW method predictions for both load and stiffness criteria. Configuration 5 peak load was 6.5% below the predicted PSW value for the Configuration $1_{SPL}$-C baseline; Configuration 5 stiffness was 4% below the predicted PSW value for the Configuration 9 baseline. In Configuration 5, 7, and 8 specimens, the header panels were not directly attached to the adjacent full-height panels in order to simulate a low-bound condition (the OSB facings of the header panels were nailed to the top plate and bottom plate of the header was toe-nailed to the supporting jack studs). The header panels separated from the adjacent panel during the test as shown in Figures 11 and 20.

Configuration 6 with cutout openings shows significantly higher stiffness than Configuration 5 that uses spline joints at the window panels (25.5 kips/in/lb vs. 13.7 kips/in/lb). Similarly, Configuration 6 unit shear stiffness is significantly higher than the PSW method prediction. This observation indicates that the construction method that uses openings cutout from a panel results in increased wall stiffness compared to the practice of constructing openings with individual panel headers. This increase in stiffness does not correspond to a comparable increase in strength (17.9 kips vs. 15.6 kips), likely because of a failure mode change for Configuration 6 that was associated with the facings cracking at window corners.

**Table 9—Modified Stewart parameter for SIP tested without openings**

| Configuration | $K_o$ (N/mm) | $r_1$ — | $r_2$ — | $r_3$ — | $r_4$ — | $F_o$ (N) | $F_i$ (N) | δ (mm) | α — | β — |
|---|---|---|---|---|---|---|---|---|---|---|
| $1_{SPL}$ | 2286 | 0.069 | –0.370 | 1.121 | 0.034 | 65260 | 3956 | 67.2 | 0.35 | 1.05 |
| 2 | 1047 | 0.065 | –0.835 | 1.559 | 0.088 | 34503 | 3925 | 71.1 | 0.22 | 1.08 |
| | 1118 | 0.068 | –0.656 | 1.361 | 0.061 | 41262 | 3477 | 70.2 | 0.65 | 1.15 |
| 3 | 520.5 | 0.100 | –0.125 | 1.500 | 0.032 | 23302 | 1271 | 75.9 | 0.65 | 1.07 |
| | 663.2 | 0.064 | –0.278 | 1.312 | 0.057 | 22812 | 1757 | 75.3 | 0.50 | 1.18 |
| 4 | 354.3 | 0.030 | –0.054 | 1.152 | 0.032 | 15509 | 839.9 | 105.0 | 0.45 | 1.05 |
| | 422.8 | 0.019 | –0.162 | 1.214 | 0.037 | 16124 | 1092 | 104.1 | 0.45 | 1.05 |
| 9 | 6850 | 0.015 | –0.200 | 1.400 | 0.038 | 130083 | 9629 | 68.4 | 0.25 | 1.10 |

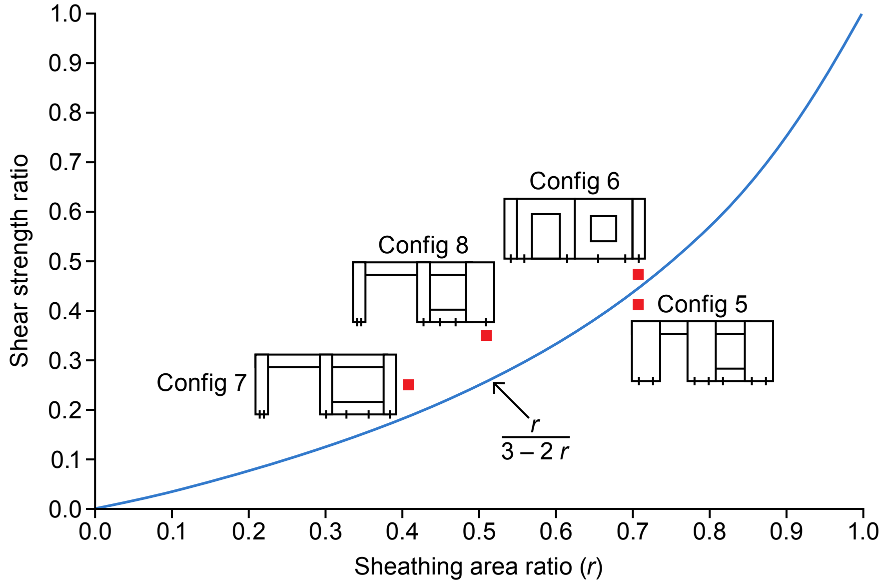



**Figure 16—Shear strength ratio using Configuration $1_{SLP}$-C as baseline.**

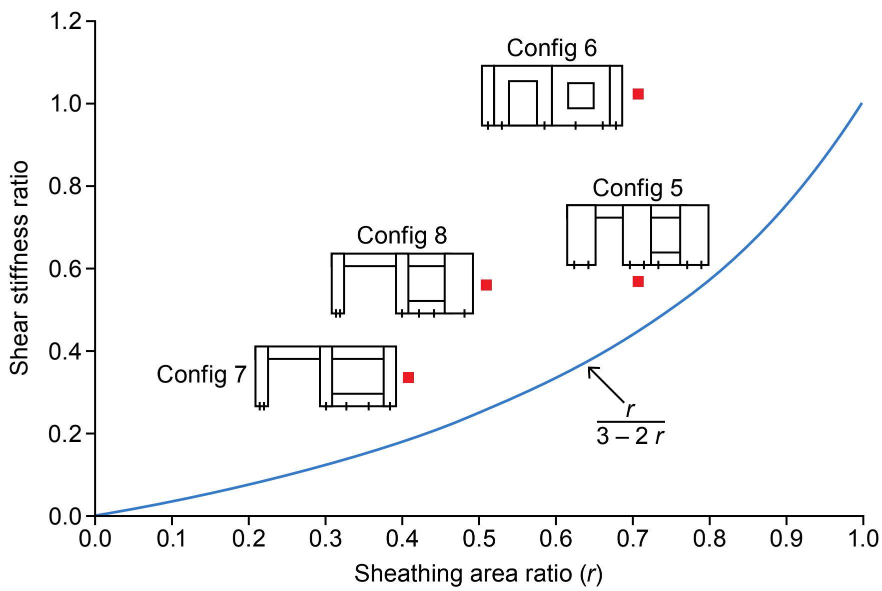



**Figure 17—Shear stiffness ratio using Configuration $1_{SPL}$-C as baseline.**

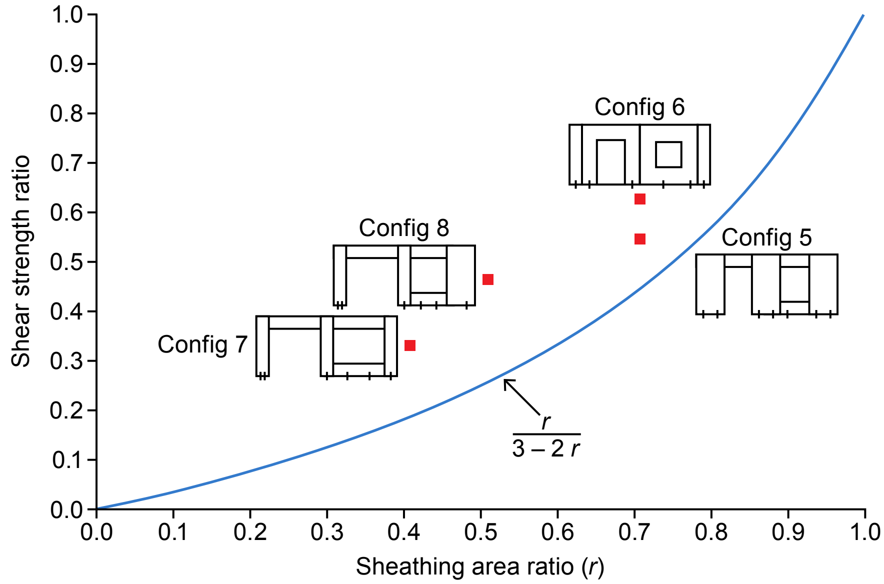



**Figure 18—Shear strength ratio using Configuration 9 as baseline.**

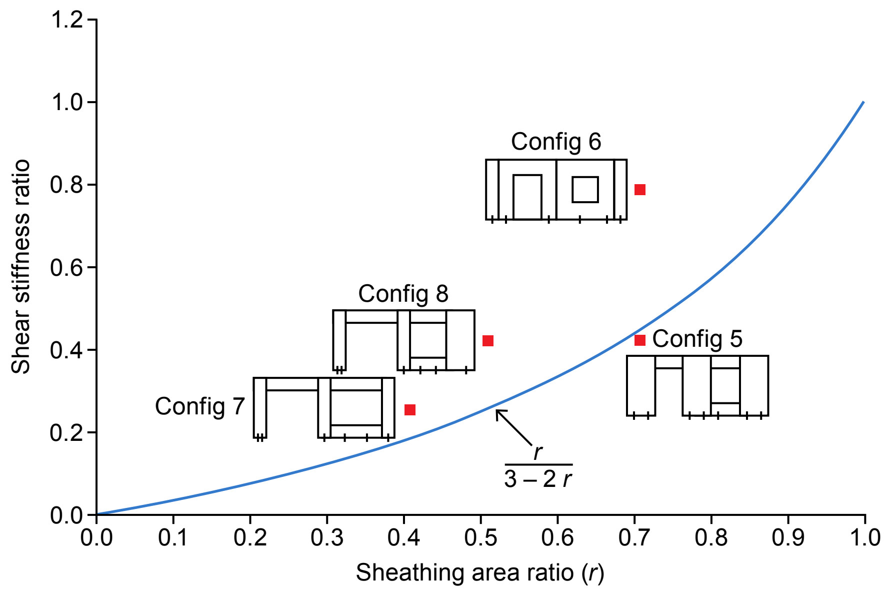



**Figure 19—Shear stiffness ratio using Configuration 9 as baseline.**

**Figure 20—Configuration 5 failure mode at header panel.**

**Table 10—Modified Stewart parameter for SIP tested with openings**

| Configuration | $K_o$ (N/mm) | $r_1$ — | $r_2$ — | $r_3$ — | $r_4$ — | $F_o$ (N) | $F_i$ (N) | δ (mm) | α — | β — |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 3692 | 0.241 | –0.700 | 1.500 | 0.070 | 28182 | 4807 | 50.6 | 0.15 | 1.05 |
| 6 | 5962 | 0.095 | –0.230 | 1.006 | 0.100 | 79034 | 13000 | 24.3 | 0.80 | 1.10 |
| 7 | 2276 | 0.272 | –0.442 | 1.010 | 0.036 | 12449 | 1393 | 48.69 | 0.35 | 1.05 |
| 8 | 3200 | 0.181 | –0.150 | 1.098 | 0.055 | 31723 | 3001 | 44.8 | 0.45 | 1.15 |

Again the 10 parameter modified Stewart hysteretic behavior model was fit to the SIP wall with opening data. Unlike the fits for the walls without openings, some parameters were adjusted outside of the MATLAB program to achieve better visual fits and reduce the cumulative energy difference between the experimental and model behavior. Modeling parameters for Wall 5, 6, 7, and 8 are listed in Table 10. Appendix 4 provides load-deformation curves for experimental and modeled behavior for the walls with openings.

## Summary and Observations

The results of this testing program provide information on the cyclic performance of SIP shear walls with various aspect ratios tested as individual wall segments or as part of a perforated shear wall line. The applicability of the PSW method to perforated SIP shear walls is also explored. Specific observations based on the test results include the following:

1. The measured unit shear capacity for fully anchored SIP shear wall segments ranged from 20.43 kN/m (1,400 lb/ft) to over 30.65 kN/m (2,100 lb/ft) depending on the segment's aspect ratio.
2. The measured unit shear stiffness for fully anchored SIP shear wall segments varied by a factor of two depending on the segment's aspect ratio.
3. The unit shear wall capacity and stiffness of SIP shear wall segments decreased with an increased number of panels jointed with a nailed spline connection. A 25% decrease in unit shear was observed for a 6.1-m (20-ft) wall with four spline joints compared to a 2.4-m (8-ft) wall with one spline joint.
4. The unit shear wall capacity of SIP shear wall segments decreases with an increased segment's aspect ratio with a 16% decrease for a 0.6-m (2-ft) segment as compared to a 1.2-m (4-ft) segment.
5. The unit shear wall stiffness of SIP shear wall segments decreases with an increased segment's aspect ratio with a maximum 33% decrease for a 0.6-m (2-ft) segment as compared to either a 2.4-m (8-ft) or a 1.2-mm (4-ft) segment.
6. The test results indicate that perforated SIP shear walls follow the overall PSW method trend for both strength and stiffness.

## References

AWC. 2015a. Special design provisions for wind and seismic. AWC SDPWS-2015. Leesburg, VA: American Wood Council.

AWC. 2015b. National Design Specification for Wood Construction. ANSI/AWC NDS-2015. Leesburg, VA: American Wood Council.

APA – The Engineered Wood Association. 2010. Racking test of structural insulated panels (SIPs) with various bearing conditions. APA Report T2010P-17. Tacoma, WA: APA – The Engineered Wood Association.

APA – The Engineered Wood Association. 2013. ANSI/APA PRS 610.1 Standard for performance-rated structural insulated panels in walls applications. Tacoma, WA: APA – The Engineered Wood Association. 18 p.

ASTM. 2014. Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings. E2126-11. West Conshohocken, PA: ASTM. 15 p.

International Code Council. 2011. 2012 international residential code for one- and two-family dwellings. Country Club Hills, IL: International Code Council.

Jamison, J.B. 1997. Monotonic and cyclic performance of structurally insulated panel shear walls. Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering. Blacksburg, VA. 97 p.

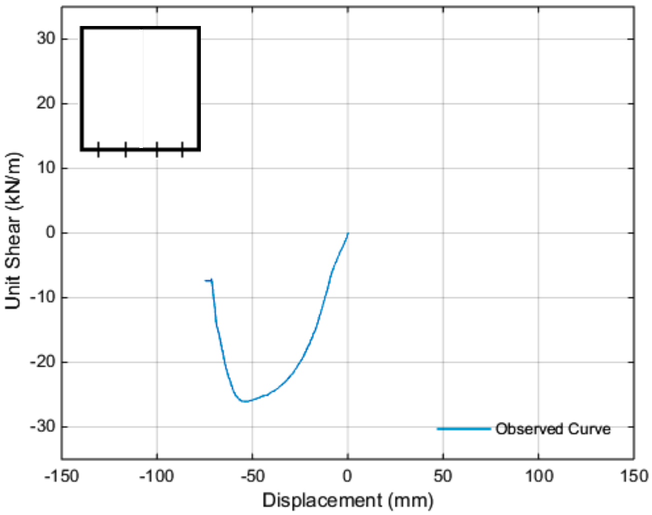
Kermani, A.; Hairstans, R. 2006. Racking performance of structural insulated panels. Journal of Structural Engineering. 132(11): 1806–1812.

Pang, W.C.; Rosowsky, D.V.; Pei, S.; van de Lindt, J.W. 2007. Evolutionary parameter hysteretic model for wood shear walls. ASCE Journal of Structural Engineering. 133(8): 1118–1129.

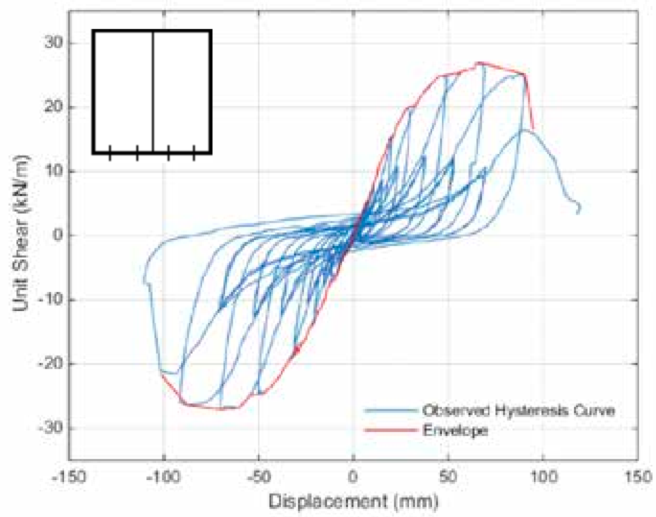
Sugiyama, H.; Yasumura, M. 1984. Shear properties of plywood sheathed wall panels with openings. Transaction of the Architectural Institute of Japan. No. 338. April. pp. 88–98.

Sugiyama, H.; Matsumoto, T. 1994. Empirical equations for the estimation of racking strength of a plywood sheathed shear wall with openings. Summary of Technical Papers, Annual Meetings, Trans. of A.I.J. Japan. pp. 89–90.

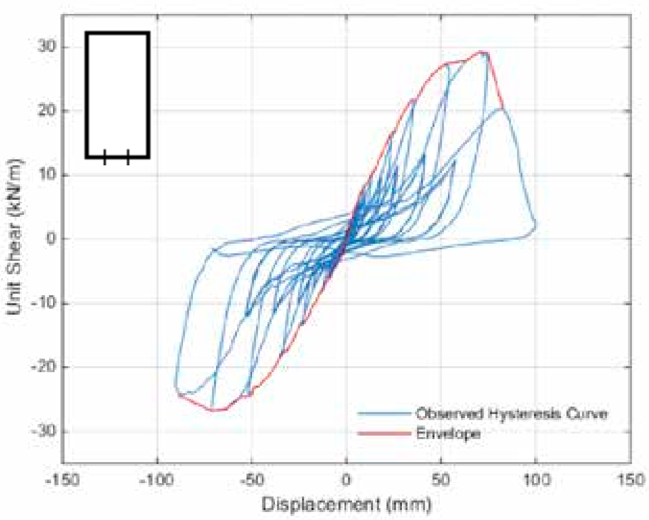
# Appendix 1: Walls without Openings



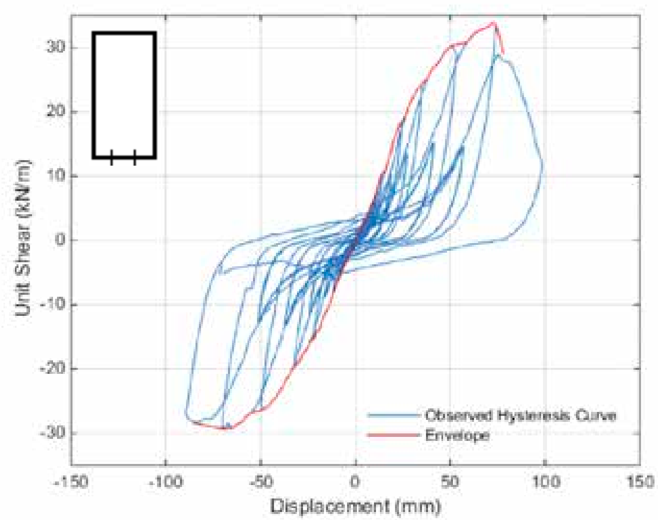

**Configuration 1M**



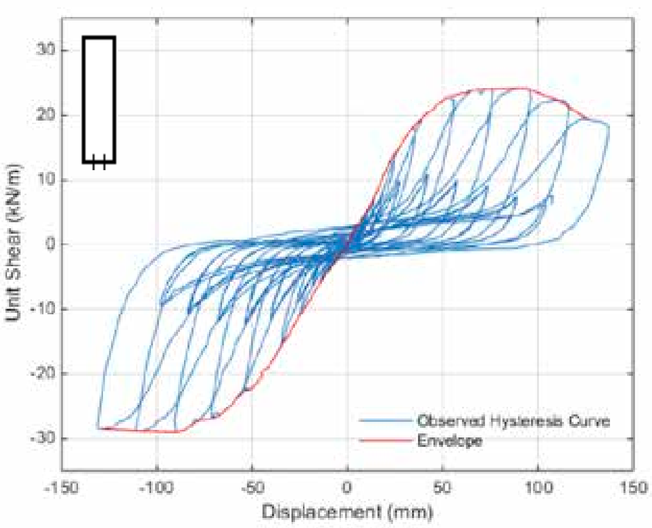

**Configuration $1_{SPL}$-C**



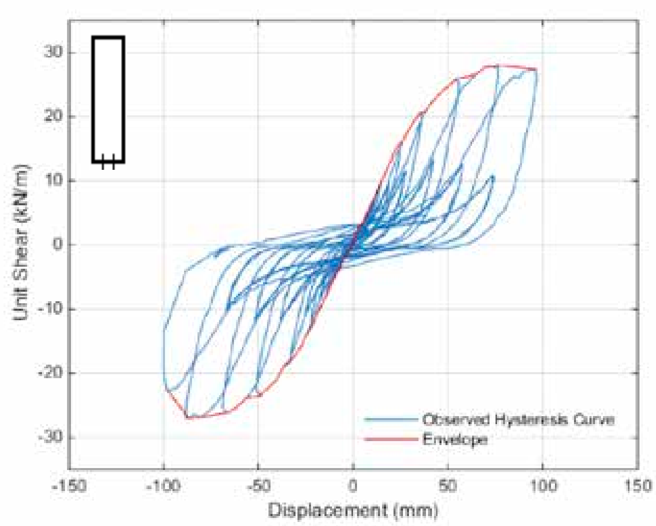

**Configuration 2-1**



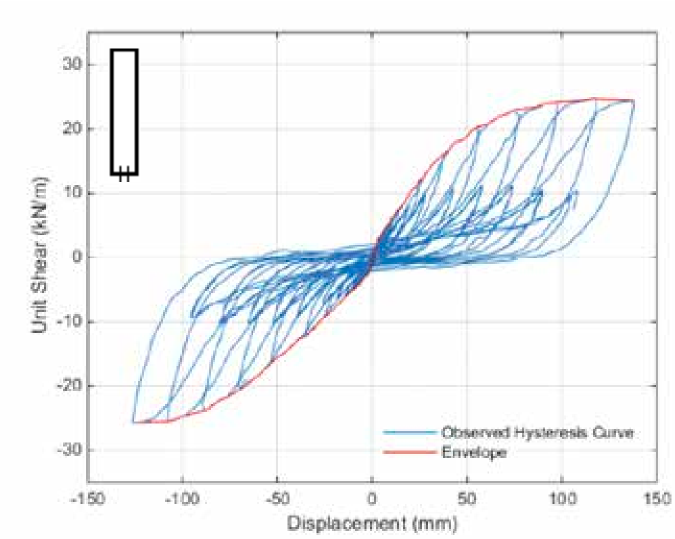

**Configuration 2-2**



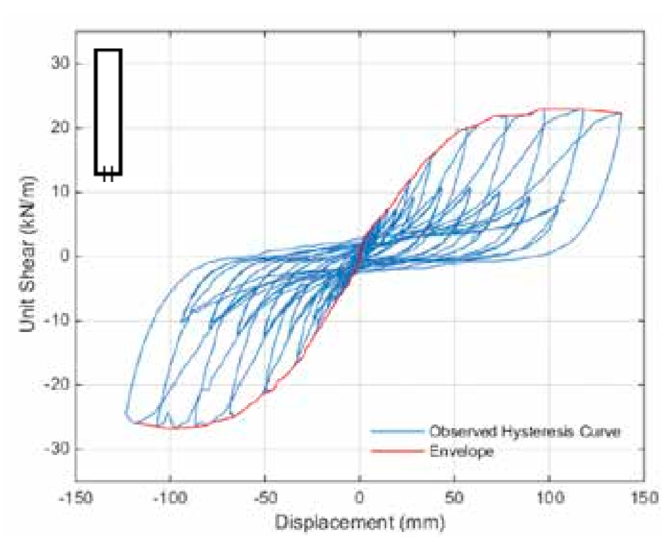

**Configuration 3-1**



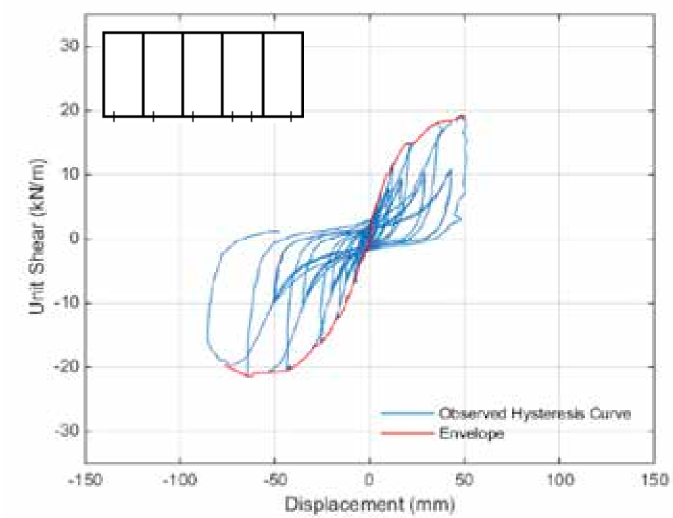

**Configuration 3-2**




**Configuration 4-1**

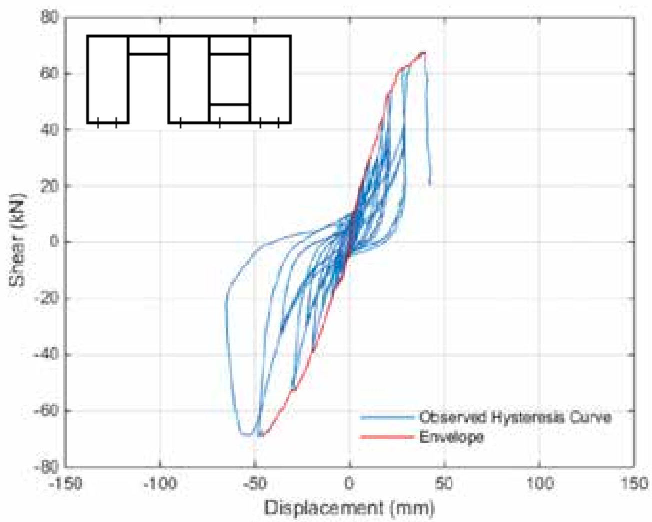



**Configuration 4-2**

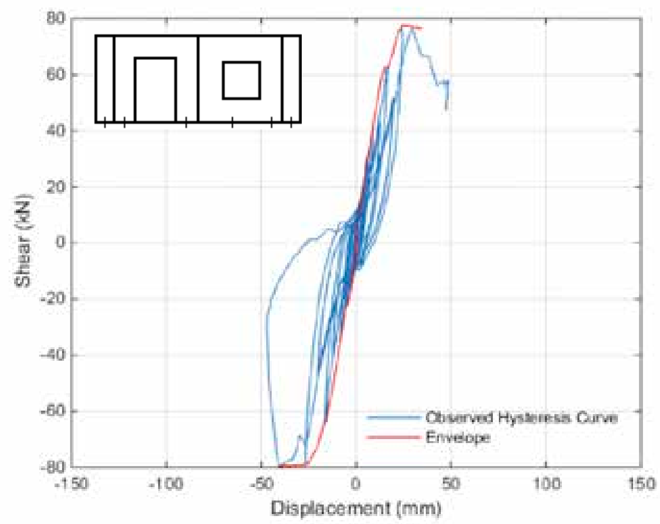



**Configuration 9**

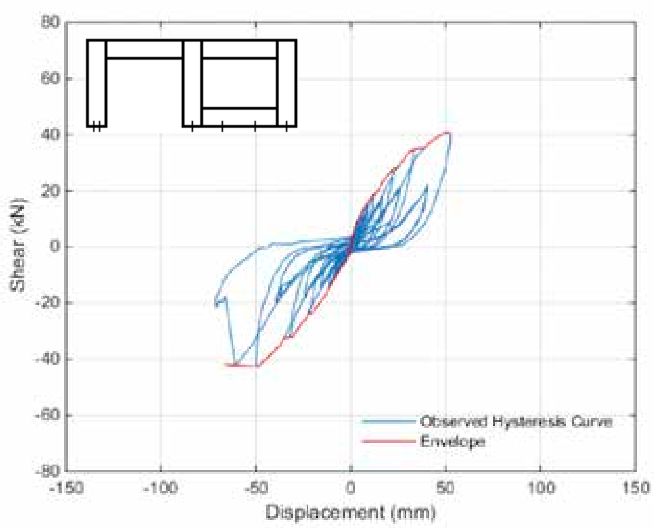
# Appendix 2: Walls with Openings



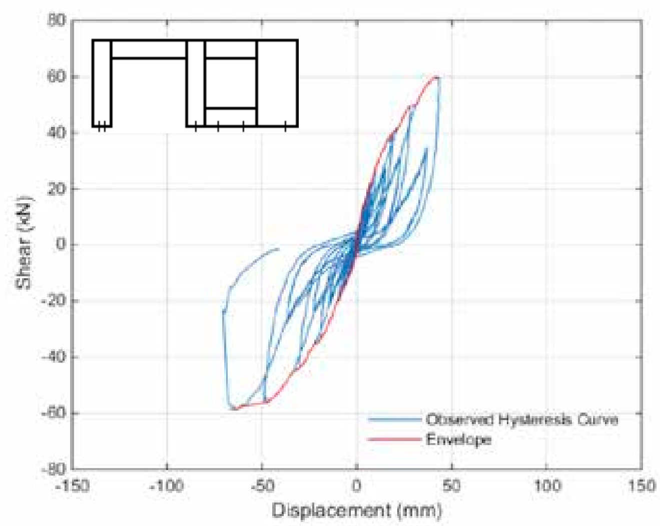

**Configuration 5**




**Configuration 6**

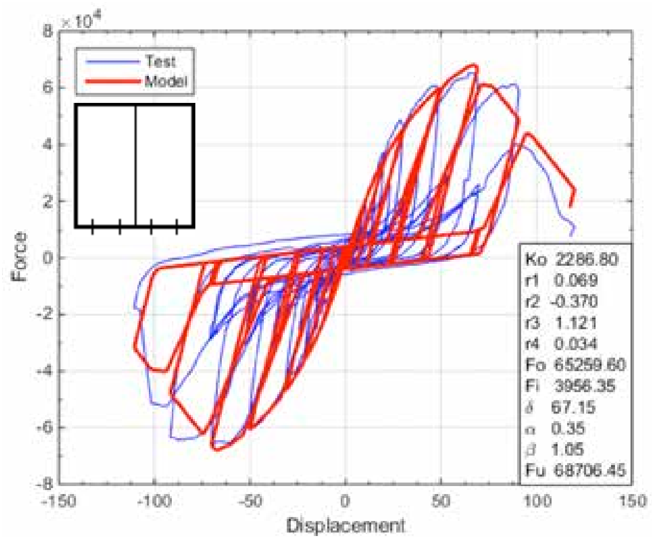



**Configuration 7**

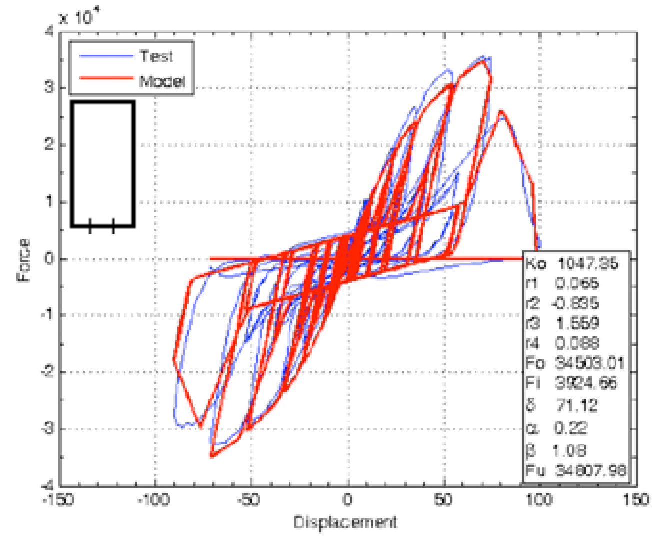



**Configuration 8**

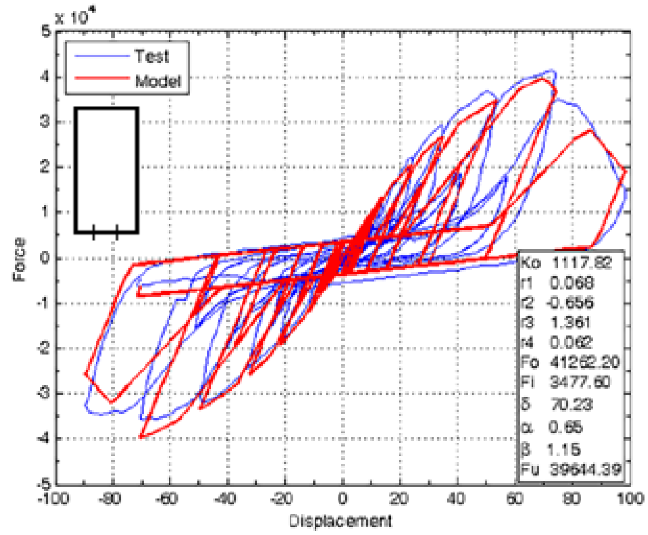
# Appendix 3: Hysteretic Parameter Fits for Walls without Openings



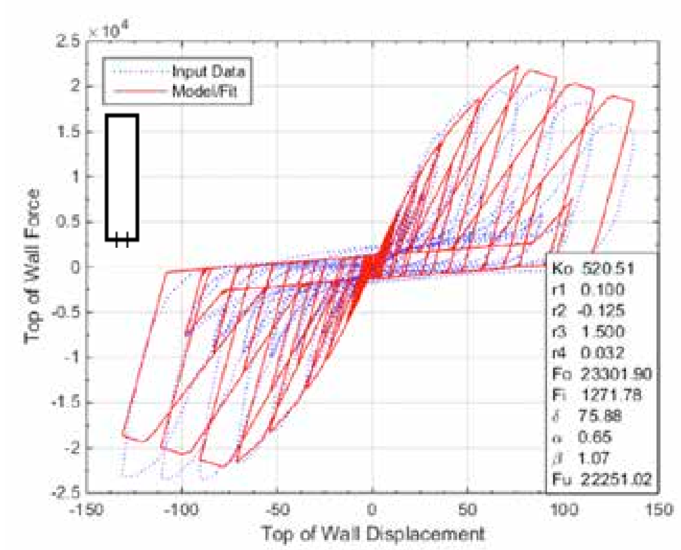

Configuration $1_{SPL}$-C



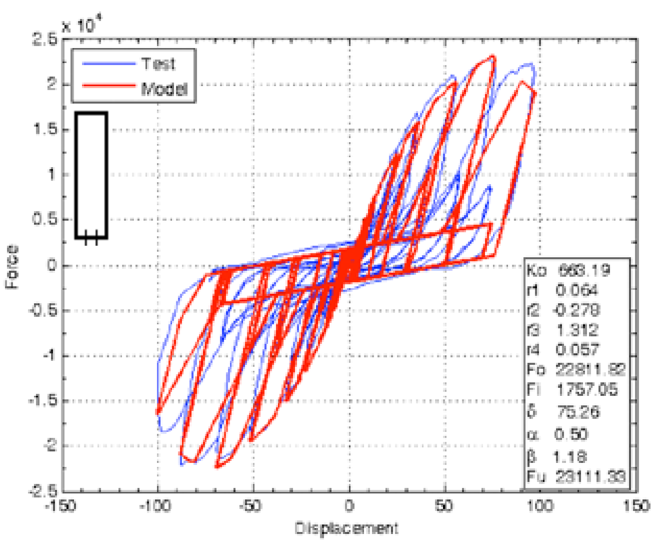

Configuration 2-1



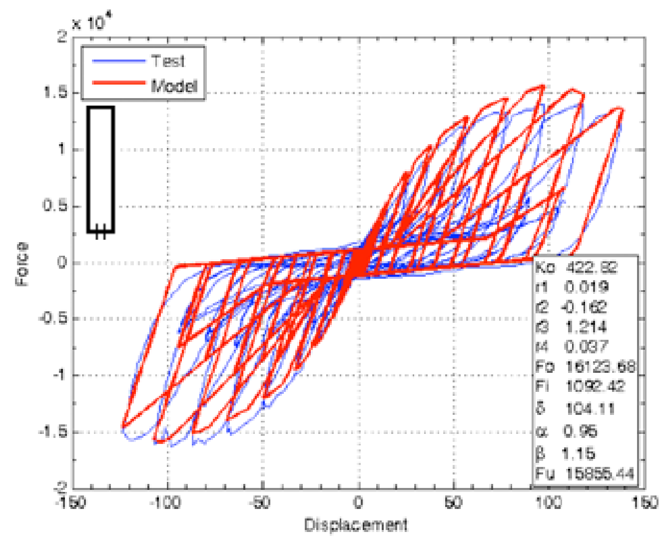

Configuration 2-2



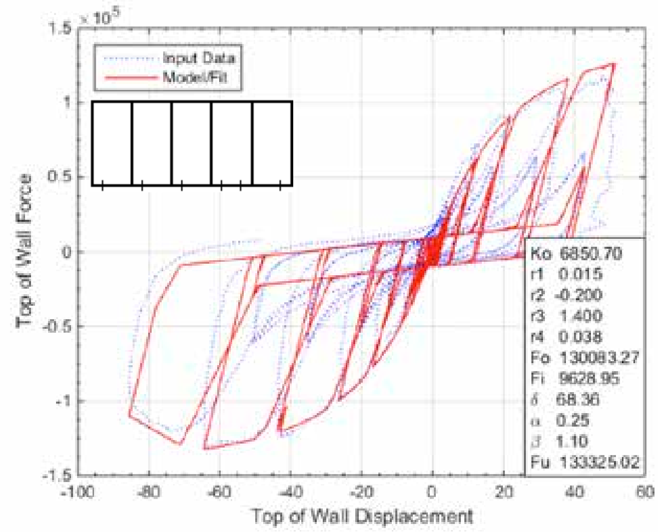

Configuration 3-1




Configuration 3-2

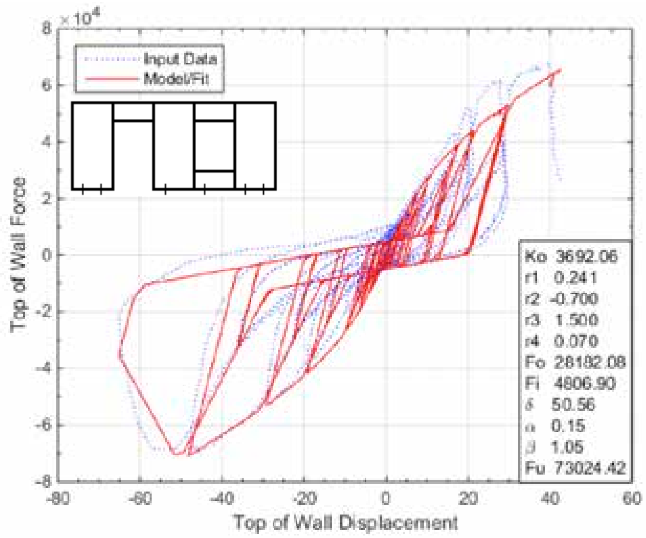



Configuration 4-2

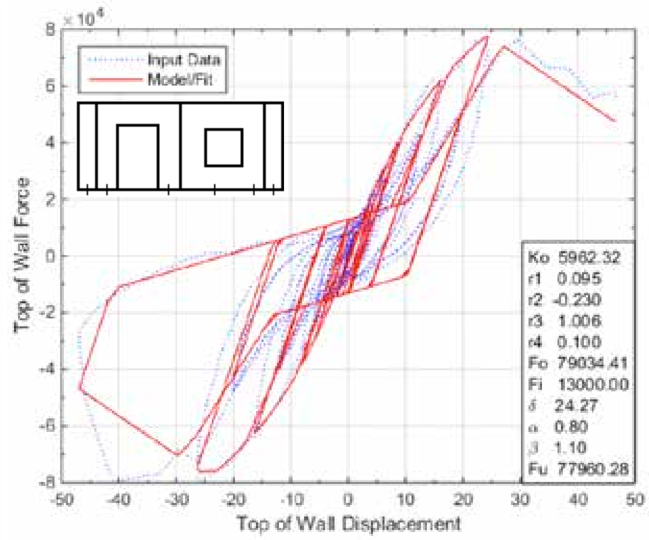



**Configuration 9**

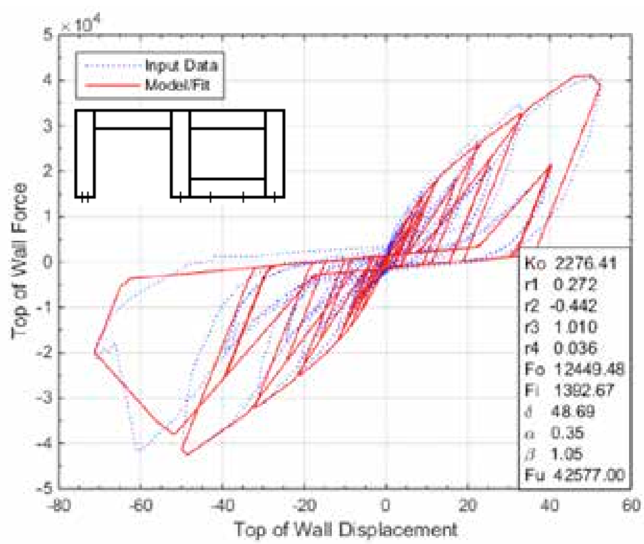
# Appendix 4: Hysteretic Parameter Fits for Walls with Openings



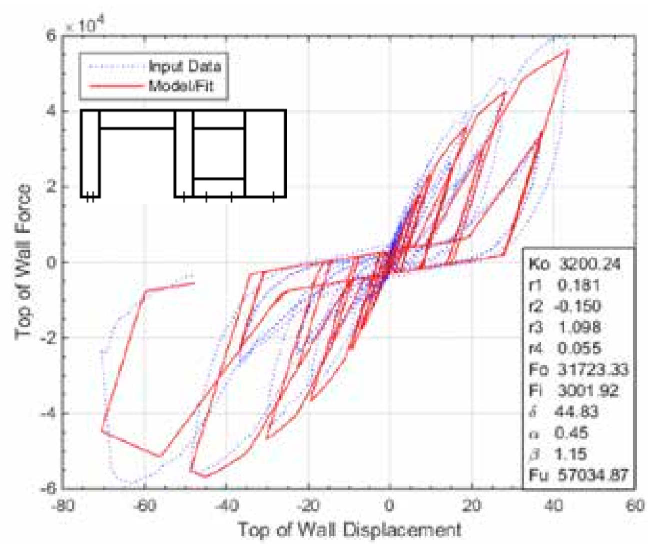

**Configuration 5**




**Configuration 6**




**Configuration 7**




**Configuration 8**