INNOVATIVE COLD-FORMED STEEL SHEAR WALLS WITH CORRUGATED STEEL SHEATHING

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Thesis Prepared for the Degree of

MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

May 2016

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Mahdavian, Mahsa. *Innovative Cold-Formed Steel Shear Walls with Corrugated Steel Sheathing*. Master of Science (Engineering Systems-Construction Management), May 2016, 175 pp., 10 tables, 71 figures, references, 12 titles.

This thesis presents two major sections with the objective of introducing a new cold-formed steel (CFS) shear wall system with corrugated steel sheathings. The work shown herein includes the development of an optimal shear wall system as well as an optimal slit configuration for the CFS corrugated sheathings which result in a CFS shear wall with high ductility, high strength, high stiffness and overall high performance. The conclusion is based on the results of 36 full-scale shear wall tests performed in the structural laboratory of the University of North Texas. A variety of shear walls were the subject of this research to make further discussions and conclusions based on different sheathing materials, slit configurations, wall configurations, sheathing connection methods, wall dimensions, shear wall member thicknesses, and etc. The walls were subject to cyclic (CUREE protocol) lateral loading to study their deformations and structural performances. The optimal sit configuration for CFS shear walls with corrugated steel sheathings was found to be 12×2 in. vertical slits in 6 rows. The failure mode observed in this shear wall system was the connection failure between the sheathing and the framing members. Also, most of the shear walls tested displayed local buckling of the chord framing members located above the hold-down locations.

The second section includes details of developing a Finite Element Model (FEM) in ABAQUS software to analyze the lateral response of the new shear wall systems. Different modeling techniques were used to define each element of the CFS shear wall and are reported herein. Material properties from coupon test results are applied. Connection tests are performed to define pinching paths to model fasteners with hysteretic user-defined elements. Element

interactions, boundary conditions and loading applications are consistent with full scale tests. CFS members and corrugated sheathings are modeled with shell elements, sheathing-to-frame fasteners are modeled using nonlinear springs (SPRING2 elements) for monotonic models and a general user defined element (user subroutine UEL) for cyclic models. Hold-downs are defined by boundary conditions. A total of three models were developed and validated by comparing ABAQUS results to full scale test results.

ACKNOWLEDGMENTS

So many individuals have helped me through this journey and have contributed to this research. I would like to start by thanking Dr. Cheng Yu for seeing the potential in me and giving me a chance to take on this research. Thank you to all my professors and peers at University of North Texas: Dr. DeSimone, Dr. Shenoda, Dr. Anaya, Dr. Huang, Dr. Nasrazadani and all the other faculty members. We got to know each other from Spring 2011 and you have helped me grow academically and personally. I would also like to thank Bobby Grimes for all the help and technical advice in lab.

A large credit goes to all my friends who worked in the laboratory and helped to perform all the tests needed for this research. Graduate students Mohamad Yousof, Karam Salahia, Pengchun Jia, Adam Johnson, Xing Lan, Zhishan Yan; Undergraduate students Kevin Holden, Emmanuel Velasco, Nathan Derrick, Chris Lavezo, Nick O’Connor, Jeremy Artman; and of course my dear friend, Wenying Zhang, visiting Ph.D scholar from Tongji University, China. We worked so hard together and we became incredible friends during this time.

I would also like to thank our donors, Steel Stud Manufacturers Association, Nucor Vulcraft, and Simpson Strong-Tie for their contributions; as well as our industry advisors Jeff Martin and Rick Haws.

Lastly, I am grateful for my family and their endless support during these years. Thank you to my dad, Mohammad Hadi Mahdavian, for always having my back. Thank you to my mom, Parvin Moghaddam Yazdan, for being my emotional support. Thank you to my sister and her husband, Mitra Mahdavian and Amir Ehsan Kavousian, for being great role models for me.

Thank you ☺

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CHAPTER 1

INTRODUCTION AND RESEARCH OBJECTIVES

Cold-formed steel members are steel products shaped at room temperature from steel sheets, plates, or bars by roll-forming, press braking, or bending brake operations. These products can be produced at a high speed and in large quantities using computer controlled automatic machining processes which lead to consistence in member dimensions and mechanical properties. CFS has many advantages such as: light weight, high strength and stiffness, easy erection, and recyclable nature. As a result, CFS has been widely used in curtain walls, exterior walls, floor systems, and roof systems for low-rise and mid-rise structures. American Iron and Steel Institute (AISI) is front and center of developing iron and steel standards in North America.

The International Building Code (IBC 2012) Section 602.2 states that building elements of Type I and Type II construction must be of noncombustible materials. These building elements consist of: structural frames, bearing walls, nonbearing walls, floor construction, and roof construction. The CFS light frame buildings primarily use sheathed shear walls as the lateral force resisting system. The IBC (2012) and the North American Standard for Cold-Formed Steel Framing – Lateral Design (AISI S213-07) provide design provisions for CFS shear walls using plywood, OSB and steel sheets. Steel strap cross bracing shear walls are also used to provide shear strength. Following the IBC (2012) requirements, steel sheet shear walls and steel strap cross bracing shear walls are the only noncombustible options available for mid-rise construction.

Steel strap cross bracing shear walls and steel sheet shear walls are not desirable shear resistance building elements. Steel strap bracing requires special plates to be installed and need special finishing material which results into higher design loads. In the end, steel strap bracing shear walls are known to be labor intensive. Last option available for lateral resistance system is steel sheet shear walls which provide low shear strength in comparison to all other shear resistance systems. As a result of this limitation, steel sheet shear walls is not an ideal lateral system for CFS mid-rise buildings in high seismic and wind hazardous areas. A noncombustible CFS shear wall with high structural performance is of great need by the industry for the mid-rise construction market.

To satisfy this need, a new shear wall system with corrugated steel sheathings is being explored. Corrugated steel decks were mainly used in flooring and roofing systems, but they have recently been introduced in load bearing walls. Corrugated steel sheathings have high in-plane strength and stiffness due to the cross sectional shape of the sheet. These characteristics result to a high strength and stiffness shear wall system but rather low ductility. The objectives of this thesis were to: 1. discover a new shear wall system using corrugated steel sheathings and 2. to develop an accurate finite element model to predict the performance of the new shear wall system. Every small detail in a shear wall system contributes to its performance; therefore these details were studied, discussed and reported herein.

CHAPTER 2

LITERATURE REVIEW

The study of CFS shear walls with corrugated steel sheathing started by Fulop and Dubina (2004). Fulop and Dubina studied a series of full-scale tests on 11.81 ft. × 7.87 ft. shear walls with different sheathing materials including corrugated steel sheets, gypsum board, and OSB. For all test specimens tested in their research, all walls consisted of the same framing materials (studs and tracks). A total of 7 monotonic tests and 8 cyclic tests were performed. Fulop and Dubina (2004) concluded that the CFS walls were rigid and capable of resisting lateral loading. The failure of seam fasteners was the reported failure mechanism for corrugated sheet specimens.

Stojadinavic and Tipping (2007) conducted a series of 44 cyclic tests on CFS shear walls with corrugated steel sheathing. A total of six design parameters were selected to vary in their tests including gauge of corrugated sheet steel, gauge of frame members, fastener type and size, seams fastener spacing, inclusion of gypsum board on one side, and applying corrugated sheet steel on one or both sides of the wall specimens. Stojadinavic and Tipping reported that in all the tests, the failure mode observed was the eventual pulling out of screws due to the warping of corrugated steel sheets.

Emami, Mofid and Vafai (2012) performed experimental studies on cyclic behavior of corrugated steel shear walls. The experiments were conducted to compare the stiffness, ductility and energy dissipation capacity of three different steel shear walls with unstiffened sheathing, vertical corrugated sheathing, and horizontal corrugated sheathing. Their results revealed that the ultimate strength of the unstiffened specimen was higher compared to the two corrugated specimens; though, the energy dissipation capacity, ductility, and the initial stiffness of the corrugated specimens were reported 52%, 40%, and 20% larger in comparison to the unstiffened specimen.

Overall, the studies on CFS shear walls with corrugated steel sheathing indicate high strength and high initial stiffness but low ductility in comparison to all other shear wall systems. In 2013, Guowang Yu reported his research at University of North Texas aiming to improve the ductility of CFS shear walls with corrugated steel sheathings (running horizontally). Guowang Yu and Professor Cheng Yu proposed a method to create openings (perforation) on the corrugated sheathing to improve the wall's ductility and to control the failure mechanism and failure locations on the shear wall. A total of 9 types of openings and patterns were introduced and tested in Yu's research including: different diameter circular holes, different lengths of horizontal slits and vertical slits. Based on the results reported, Yu recommended further research on shear walls with 24×2 in. vertical slits and 24×3 in. vertical slits on corrugated sheathings. Figure 1 and Figure 2 are taken from Yu (2013).

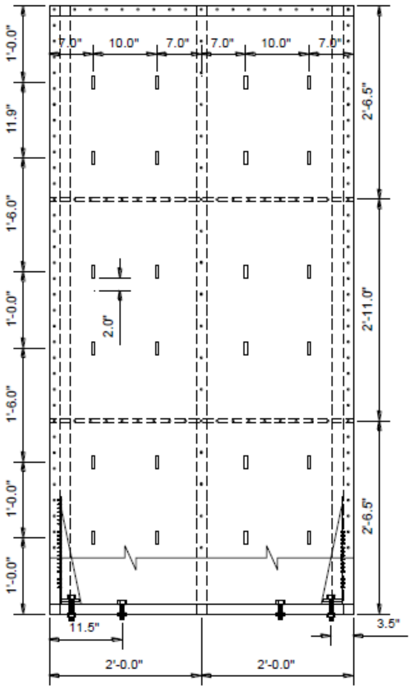


Figure 1 - 24×2 in. vertical slits

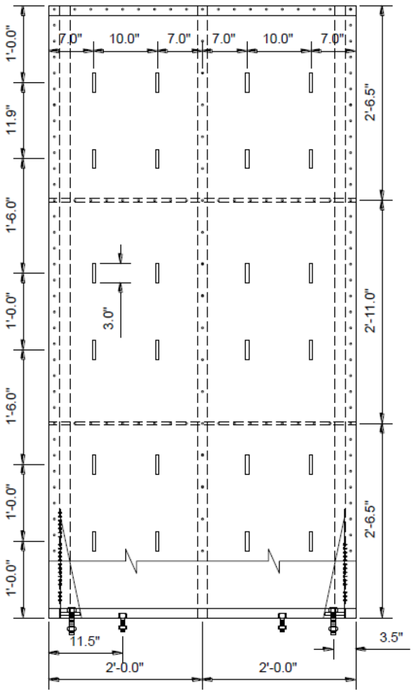


Figure 2 - 24×3 in. vertical slits

Performing full-scale shear wall tests are expensive, time consuming, labor intensive and effected by human error. Developing a finite element model in ABAQUS allows researchers to study the performance of the new shear wall systems and to share findings with designers. By improving computational simulation capabilities, we can reduce the number of full-scale tests and increase the accuracy and efficiency of future designs.

Finite element modeling of CFS shear walls has been a subject of study for researchers. A study on spring-element and frame-element based finite element model of CFS framed shear walls with Oriented Strand Board (OSB) sheathing has been established by Bian (2015) to capture both fastener-based and member-based limit states in shear walls. An extensive study was completed by Hung Huy Ngo (2014) to develop a high fidelity computational model of wood-sheathed CFS framed shear walls. Sufficient progress has been made on component to system-level simulations though previous computational modeling has been on OSB and flat steel sheets without the introduction of perforations.

The performance and failure of shear walls, particularly under seismic loading, is found to be dominated by the sheathing connections. Up until recently, despite the importance of the sheathing connection failure mechanism, there has not been an element in ABAQUS which could fully simulate the connection behaviors of the CFS shear walls under lateral loading. In 2015, Ding introduced a user element (UEL) that provides a nonlinear hysteretic model to simulate CFS screw-fastened connections in ABAQUS and to make it applicable to shear wall numerical analysis. FEM recommendations from earlier research may be applicable to the new type of shear wall. This paper compiles all these establishments to achieve effective simulations of CFS shear walls with perforated corrugated steel sheathing.

CHAPTER 3

TEST PROGRAM

The test program for this research was conducted from August 2014 to March 2016 in the Structural Laboratory at Discovery Park of the university in Denton, Texas. A total of 35 cyclic tests and one monotonic test were included in the scope of this research. A total of 4 wall configurations and 6 slit patterns were designed as the tests were performed. In cases which specimens observed satisfactory performance, multiple tests were carried to validate test results.

The objective of this section was to develop the optimal CFS shear wall configuration with corrugated steel sheathings. These configurations consisted of: sheet out, sheet in, sheet in triple track, and sheet in with 300T. Also, the optimal slit configuration on the corrugated sheathings, to increase the ductility of the shear walls, was a subject of interest. The slit configurations studied herein are: 24×2 in., 12×2 in. 3 rows, 12×2 in. 6 rows, 12×2 in. staggered, and 24×1in. vertical slits for 8 ft. by 4 ft. walls and 6×2 in. vertical slits for 8 ft. by 2 ft. walls. Other objective of this research was to investigate new sheathing-to-frame connection methods such as spot-welding. Details of all specimens and results are further discussed herein.

3.1 Test Setup

Shear wall tests were conducted on a 16 ft. by 13.3 ft. high self-equilibrating steel testing frame located in the Structural Laboratory at the University of North Texas. The testing frame is equipped with a MTS 35 kip hydraulic actuator with a 10 in. stroke. A MTS 407 controller and a 20-GPM MTS hydraulic power unit was used to drive the loading system. A 20 kip TRANSDUCER TECHNIQUES SWO universal compression/tension load cell was used to pin-connected the actuator shaft to the T-shape loading beam. A total of five NOVOTECHNIC position transducers were used to measure the horizontal displacement at the top of the shear wall, and to measure the vertical and horizontal displacements at the bottom of the two boundary frame members. The data acquisition system consisted of a National Instruments unit and an HP Compaq desktop. The applied force and the five displacements were recorded instantaneously during each test. Details of the testing frame and the location of the position transducers are shown in Figure 3.

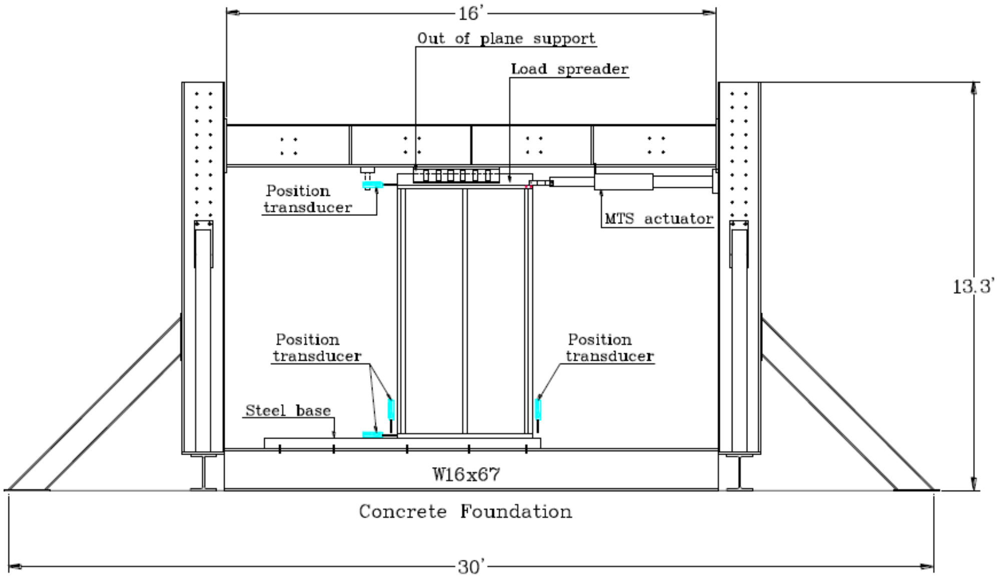


Figure 3 - Details of testing frame and position transducer locations

The specimens were bolted to the base of the testing frame and loaded horizontally at the top. The base beam is a 5 in. × 5 in. × ½ in. structural steel tube and is bolted to a W16×67 structural steel beam which is anchored to the floor. One web of the base beam has cut outs in several locations to provide access of the anchor bolts connection hold-downs to the base beam. Figure 4 and Figure 5 demonstrate the testing frame with an 8 ft. × 4 ft. shear wall installed.

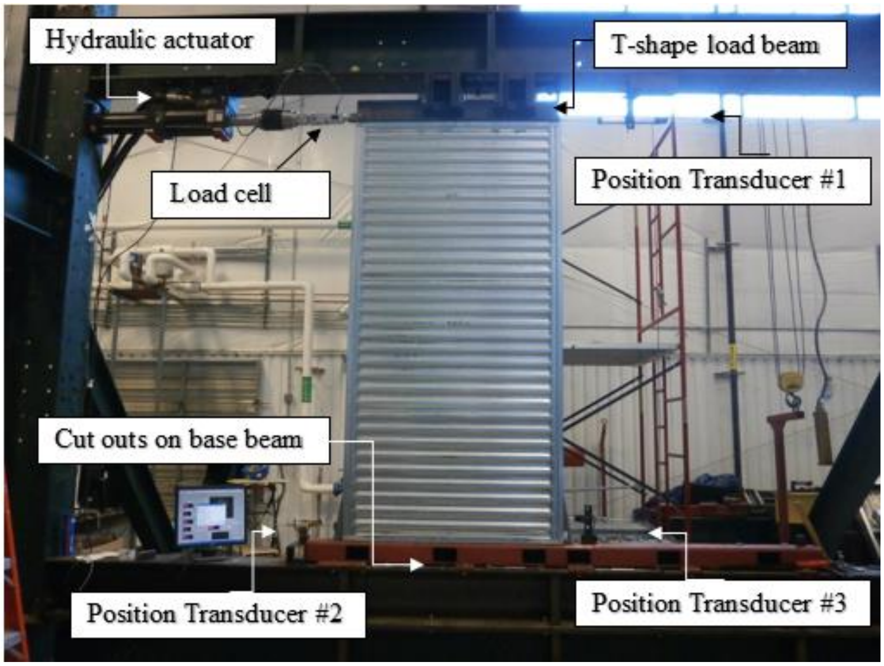


Figure 4 - Front view of testing frame

Figure 5 - Back view of test setup

The lateral loading was applied directly to the T-shaped load beam by the actuator. The load beam was attached to the web of the top track using a pair of No. 12-14 × 1 ¼ in. hex head self-drilling screws every 3 in. on center so that a uniform linear racking force could be transmitted to the top track of the shear wall. The stem of the T-shape beam was placed in the gap between the rollers located at the top of the testing frame to prevent out-of-plane movement of the walls. The rotation of the rollers were able to reduce the friction generated by the movement of the T-shape during the test procedure and were also able to guide the loading T-shape beam. To anchor the specimen to the base beam of the testing frame, two Simpson Strong-Tie S/HD15S hold-downs with 33 pre-drilled holes corresponding to No. 14-14 × 1 in. hex washer head self-drilling screws were used. In cases which studs had a punch-out at the hold-down location, additional welding around the edge of the punch-out was used to reinforce the hold-down to stud attachment. In addition, two Grade 8 3/4 in. bolts and two Grade 8 5/8 in. bolts were used in the anchorage system.

3.2 Test Method

Both monotonic and cyclic tests were conducted in a displacement control mode. The shear wall under monotonic lateral loading traveled a total of 5 in. at a uniform rate of 0.0075 in./sec. The cyclic tests used the CUREE protocol, in accordance with the ICC-ES AC130 (2004). The CUREE basic loading history is shown in Figure 6 which includes 43 cycles with specific displacement amplitudes, listed in Table 1. The specified displacement amplitudes are based on Guowang Yu’s research (2013). A constant cycling frequency of 0.2-Hz (5 seconds) for the CUREE loading history was adopted for all the cyclic tests included in this research.

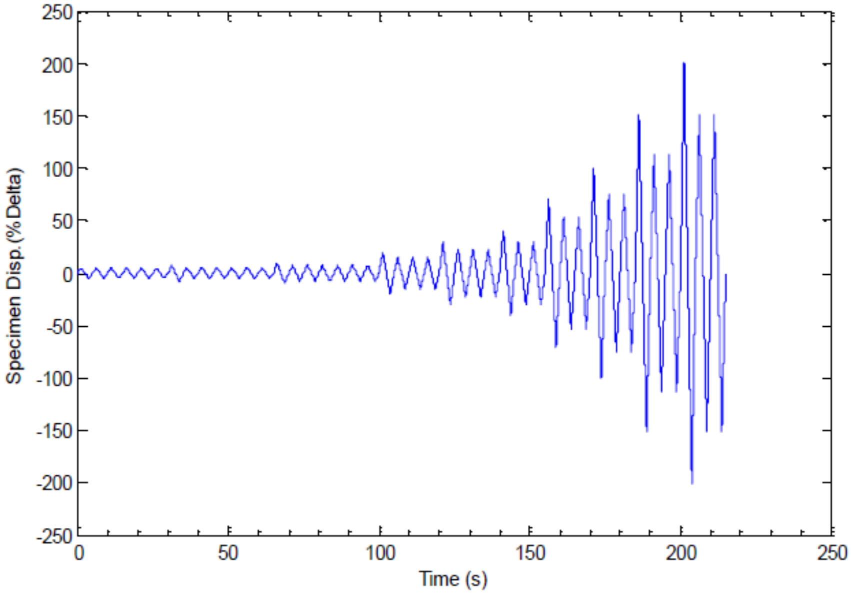


Figure 6 - CUREE basic loading history (0.2 Hz)

Table 1 - CUREE basic loading history

Cyclic No.	***% Δ***	**Cyclic No.**	***% Δ***	**Cyclic No.**	***% Δ***	**Cyclic No.**	***% Δ***
1	*5*	12	*5.6*	23	*15*	34	*53*
2	*5*	13	*5.6*	24	*15*	35	*100*
3	*5*	14	*10*	25	*30*	36	*75*
4	*5*	15	*7.5*	26	*23*	37	*75*
5	*5*	16	*7.5*	27	*23*	38	*150*
6	*5*	17	*7.5*	28	*23*	39	*113*
7	*7.5*	18	*7.5*	29	*40*	40	*113*
8	*5.6*	19	*7.5*	30	*30*	41	*200*
9	*5.6*	20	*7.5*	31	*30*	42	*150*
10	*5.6*	21	*20*	32	*70*	43	*150*
11	*5.6*	22	*15*	33	*53*	-	-

3.3 Test Specimens

The specimens tested in this research included two wall dimensions: 8 ft. (high) × 4 ft. (wide) and 8 ft. (high) × 2 ft. (wide). The 8 ft. × 4 ft. wall specimens include four wall configurations: sheet out, sheet in, sheet in triple tracks, and sheet in 300T. The 8ft. × 2 ft. walls include two wall configurations: sheet out, and sheet in. All framing members are connected using a pair of No. 12-14 × 1 ¼ in. hex washer head self-drilling screws every 6 in. on center starting from above the hold-downs. Hold-downs are placed depending on the sheathing configuration. In walls with corrugated sheathing placed on top of the frame, hold-downs are placed inside the frame and on the contrary, in walls with corrugated sheathing placed within the frame, due to the height of the sheathing, the hold-downs are placed outside the frame connected to the outer framing members. Tests are labeled by following: "wall height (ft.) × wall width (ft.) × framing thickness (mil) × sheathing thickness (mil) – wall configuration and opening pattern." Slit patterns are labeled following: "number of slits × length of slits." Further details of each wall configuration are described herein. Table 2 lists the major parameters of the 36 shear tests in this research.

Table 2 - Test matrix

Wall width	Wall overall dimension	Framing members thickness	Sheathing thickness
3.5 in.	8 ft. x 2 ft.	0.068 in.	0.027 in.
	8 ft. x 4 ft.		
	8 ft. x 4 ft.	0.054 in.	0.018 in.

3.3.1 (8 ft. × 4 ft.) Sheet Out

This group consists of Tests 3, 5, 6, 7, 15, 19, 29, and 30. The framing of this group includes double C-shaped studs (350S162–68, 50 ksi) fastened together back-to-back as boundary studs while the middle stud used a single C-shaped member. One U-shaped steel member (350T150–68, 50 ksi) was used as top and bottom track. The studs were inserted into tracks and flanges connected using No. 12-14 × 1 ¼ in. hex washer head self-drilling screws on both sides of each wall. The sheathing is Verco Decking SV36 27 mil thick corrugated steel sheet with 9/16 in. rib height. For each wall specimen, the sheathing was made of three corrugated steel sheets which over-lapped by two ribs and connected by a single line of screws at the over-lapped locations. The sheathing is installed on one side of the wall and on the outside of the frame using No. 12-14 × 1 ¼ in. hex washer head self-drilling screws. Due to the sheathing profile (Figure 7), the spacing of the screws were limited to 3 in. on the boundary studs and tracks as well as the seams locations, and 6 in. fastener spacing along the middle stud. A cross sectional view of this shear wall configuration is shown in Figure 8 and an image of this configuration is shown in Figure 9.

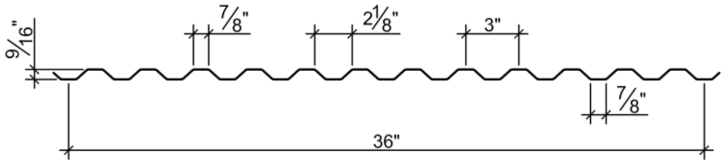


Figure 7 - Verco Decking SV36 sheathing profile (www.vercodeck.com)

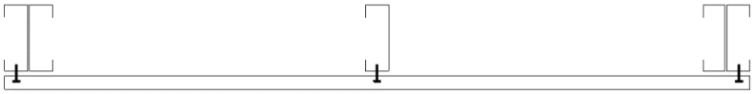


Figure 8 - Sheet out (8 ft. × 4 ft.)

In order to verify that a CFS shear wall with corrugated steel sheathing has higher strength and stiffness compared to a CFS shear wall with plywood or flat steel sheathing, the two other sheathing types were tested as part of this research. Tests 11 with plywood sheathing and Test 12 with a single 27 mil flat steel sheet are CFS shear wall with 362S162–68, 70 ksi and 362T150–68, 50 ksi frame members. The sheathing in both walls are connected to the frame by No. 12-14 × 1 ¼ in. pan head self-drilling screws.

Figure 9 - Sheet out wall configuration

It is appropriate to note that the top and bottom corrugated sheathings in Tests 5 and 6 were cut so they would only over-lap on one rib. The numerical results as well as the performance of the walls were compared to the same configuration of walls with double lapped sheathings to detect any major differences. The results, which will be further discussed in section 3.6. of this thesis, indicated less than 10% difference in numerical results therefore corrugated sheets were no longer cut and it was appropriate to over-lap sheathings on two ribs.

Tests 13, 54, 62, 63, 64 and 68 all follow the same wall configuration though with different framing members, sheathing screws and/or sheathing screw spacing.

Tests 28 and 59 also had the same wall configuration with different framing members, but the major difference was the sheathing connection method. Instead of using screws, a spot-welding machine, shown in Figure 10, was employed for all sheathing connections. The spot-welder “EQUA-PRESS Dual Tip Holders“ model 4010 was purchased from LORS Machinery. Also, two “A” pointed double bent shanks with ½ in. diameter points (Figure 11) were purchased. Due to the double bent shank, the spacing between the two welders could be adjusted (between 2 in. to 4 in.) to meet our design requirements. A designated spot-welding power supply was purchased from TECNA, seen in Figure 12, to be able to control the power and the rest time between each cycle to obtain stronger welds. Further details about the spot-welding tests will be discussed in section 3.6. of this report.

Figure 10 - Spot-welding machine

Figure 11 - "A" pointed double bent shanks

Figure 12 - Spot-welding power supply

3.3.2 (8ft. × 4 ft.) Sheet In

This group consists of Tests 8 and 9. The framing of this group includes double U-shaped tracks (350T150–68, 50 ksi) fastened together back-to-back for the vertical (8 ft.) boundary members. There are no middle framing members in this configuration. One U-shaped steel member (362T150–68, 50 ksi) was used as top and bottom track. The vertical tracks were inserted into the top and bottom tracks and flanges were connected using No. 12-14 × 1 ¼ in. hex washer head self-drilling screws on both sides of each wall. The sheathing is Verco Decking SV36 27 mil thick corrugated steel sheet with 9/16 in. rib height. The three sheathings were cut to 44 ¼ in. width to be able to fit inside the framing. Sheets were over-lapped by two ribs and connected by a single line of screws at the over-lapped locations. The sheathing is installed inside the framing, using No. 12-14 × 1 ¼ in. pan head self-drilling screws. In Test 8, the spacing of the sheathing screws were 3 in. all over. In Test 9, the spacing of the sheathing screws were also 3 in. all over though 1.5 in. spacing along the top track. A cross sectional view of this shear wall configuration is shown in Figure 13. Figure 14 and Figure 15 show an image of the front and back view of this wall configuration.

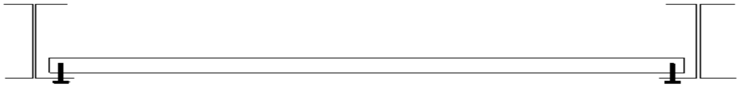


Figure 13 - Sheet in (8 ft. × 4 ft.)

Figure 15 - Sheet in wall configuration (front view)

Figure 14 - Sheet in wall configuration (back view)

3.3.3 (8 ft. × 4 ft.) Sheet In Triple Tracks

Tests 10, 14 and 21 make this group of wall configurations. The framing of this group includes double U-shaped tracks (350T150–68, 50 ksi) fastened together back-to-back for the vertical (8 ft.) boundary members. The middle stud is replaced with a double track (350T150–68, 50 ksi) fastened back-to-back with a pair of No. 12-14 × 1 ¼ in. hex washer head self-drilling screws every 6 in. along the entire length of the members. One U-shaped steel member

(362T150–68, 50 ksi) was used as top and bottom track. Due to the design characteristics, using three pairs of track, this group of wall configurations were named “triple tracks”. The vertical tracks were inserted into the top and bottom tracks and flanges were connected using No. 12-14 × 1 ¼ in. pan head self-drilling screws on both sides of each wall. The sheathing is Verco Decking SV36 27 mil thick corrugated steel sheet with 9/16 in. rib height. The three sheathings were cut to 22 ¼ in. width to be able to fit inside the two framing sections. Sheets were over-lapped by two ribs and connected by a single line of screws at the over-lapped locations. The sheathing is installed inside the framing, using No. 12-14 × 1 ¼ in. pan head self-drilling screws. The spacing between all sheathing connections were 3 in. A cross sectional view of this shear wall configuration is shown in Figure 16. Figure 17 and Figure 18 show an image of the front and back view of the wall configuration.

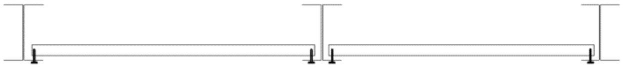


Figure 16 - Sheet in triple tracks (8 ft. × 4 ft.)

Figure 17 - Sheet in triple track

Figure 18 - Sheet in triple track

3.3.4 (8 ft. × 4 ft.) Sheet In with 300T

Tests 55, 56, 57, 58, and 61 make this group of wall configurations. The framing of this group includes double U-shaped tracks (350T150–68, 50 ksi) fastened together back-to-back for the vertical (8 ft.) boundary members. The middle track was made specifically based on our design recommendations. Our objective was to eliminate the labor work and also to not have two separate sheathing sections. Therefore, a 3 in. webbed track (300T200–68, 50 ksi) was designed to fit behind the sheathing and inside the framing. One U-shaped steel member (362T150–68, 50 ksi) was used as top and bottom track. The vertical tracks were inserted into the top and bottom tracks and flanges were connected using No. 12-14 × 1 ¼ in. hex head self-drilling screws on both sides of each wall. The sheathing is Verco Decking SV36 27 mil thick corrugated steel sheet with 9/16 in. rib height. The three sheathings were cut to 44 ¼ in. width to be able to fit inside the framing. Sheets were over-lapped by two ribs and connected by a single line of screws at the over-lapped locations. The sheathing is installed inside the framing, using No. 12-14 × 1 ¼ in. pan head self-drilling screws. The spacing between sheathing connections were 3 in. along the boundary members and the seams, as well as 6 in. screw spacing along the middle track. A cross sectional view of this shear wall configuration is shown in Figure 19. Figure 20 and Figure 21 show an image of the front and back view of the wall configuration.

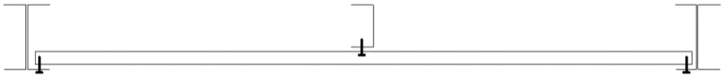


Figure 19 - Sheet in with 300T (8 ft. × 4 ft.)

Figure 20 - Sheet in with 300T wall

Figure 21 - Sheet in with 300T wall

Tests 66, 67, 69, and 70 also follow this wall configuration but with different framing members and sheathing connections.

3.3.5 (8 ft. × 2 ft.) Sheet Out

This group consists of Tests 32 and 33. The framing of this group includes double C-shaped studs (350S162–68, 50 ksi) fastened together back-to-back as boundary studs. One U-shaped steel member (350T150–68, 50 ksi) was used as top and bottom track. The studs were inserted into tracks and flanges were connected using No. 12-14 × 1 ¼ in. hex washer head self-drilling screws on both sides of each wall. The sheathing is Verco Decking SV36 27 mil thick corrugated steel sheet with 9/16 in. rib height and was cut to a 2 ft. width. The sheathing was made of three corrugated steel sheets which over-lapped by two ribs and were connected by a single line of screws at the over-lapped locations. The sheathing is installed on one side of the wall and on the outside of the frame using No. 12-14 × 1 ¼ in. hex washer head self-drilling screws every 3 in. all over. A cross sectional view of this shear wall configuration is shown in Figure 22 and an image of this configuration is shown in Figure 23.

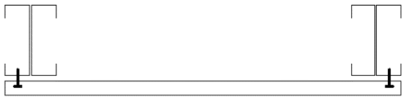


Figure 22 - Sheet out (8 ft. × 2 ft.)

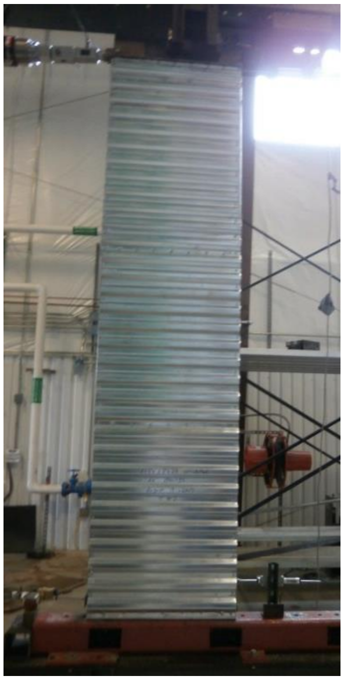


Figure 23 - Sheet out wall configuration

3.3.6 (8 ft. × 2 ft.) Sheet In

This group includes Tests 45, 46, 47, and 48. The framing of this group includes double U-shaped tracks (350T150–68, 50 ksi) fastened together back-to-back for the vertical (8 ft.) boundary members. One U-shaped steel member (362T150–68, 50 ksi) was used as top and bottom track. The vertical tracks were inserted into the top and bottom tracks and flanges were connected using No. 12-14 × 1 ¼ in. hex washer head self-drilling screws on both sides of each wall. The sheathing is Verco Decking SV36 27 mil thick corrugated steel sheet with 9/16 in. rib height cut to a width of 22 ¼ in. and placed inside the framing. Sheets were over-lapped by two ribs and connected by a single line of screws at the over-lapped locations. The sheathing was connected to the frame using No. 12-14 × 1 ¼ in. pan head self-drilling screws every 3 in. all around and at seams. A cross sectional view of this shear wall configuration is shown in Figure 24. Figure 25 and Figure 26 show the front and back view of this wall configuration.

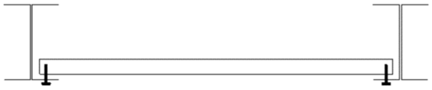


Figure 24 - Sheet in (8 ft. × 2 ft.)

Figure 25 - Sheet in configuration

Figure 26 - Sheet in configuration

It is important to note that for all types of wall configurations, a section of the top and bottom corrugation, as viewed in Figure 27, had to be cut off so that the length of the sheathings would not exceed the height of the wall but also to have a flat surface to be able to use as the connection surface between the sheets and the bottom and top track member. The sheets were cut using a Kett Pn-1020 18 Gauge Straight Handle Pneumatic Nibbler (Figure 28). Also, when the vertical framing members were inserted in the top and bottom tracks, the members didn't completely flush and a gap between the vertical framing members and the horizontal framing members were observant. As a result, the shear wall heights were a little longer, varying between 8 ft. 0.1 in. to 8 ft. 0.2 in. total height.

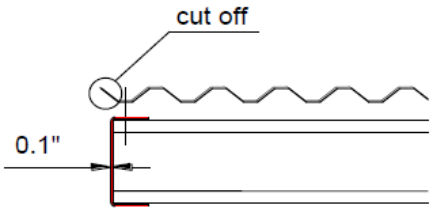


Figure 27 - Corrugated sheet cutting pattern

Figure 28 - Kett Pn-1020 Nibbler

Based on Guowang Yu (2013) recommendations, further research was conducted on 8 ft. by 4 ft. shear walls with 24×2 in. vertical slits and 24×3 in. vertical slits. Other slit configuration patterns were subsequently developed based on numerical results and performances of the shear walls. Slits were made using a hand-held grinder with a 0.045 in. thick sand blade. Figures 29 through 35 show a number of the CAD drawings of opening configurations on the corrugated steel sheets. Within each category of configuration patterns, slits are created similar to the displayed design but with a slight degree of differentiation due to human error. Enlarged figures and details of each wall configuration as well as slit details are included in Appendix A.

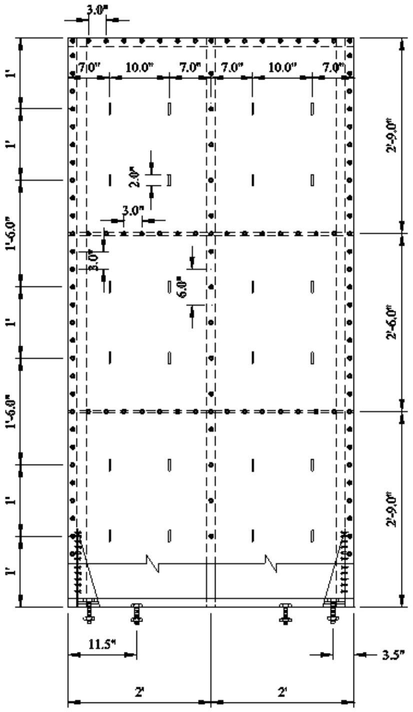


Figure 29 - Sheet out with 24×2 in. slits

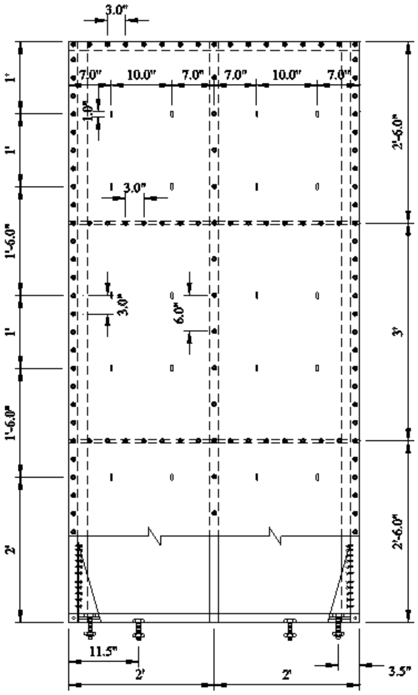


Figure 30 - Sheet out with 24×1 in. slits

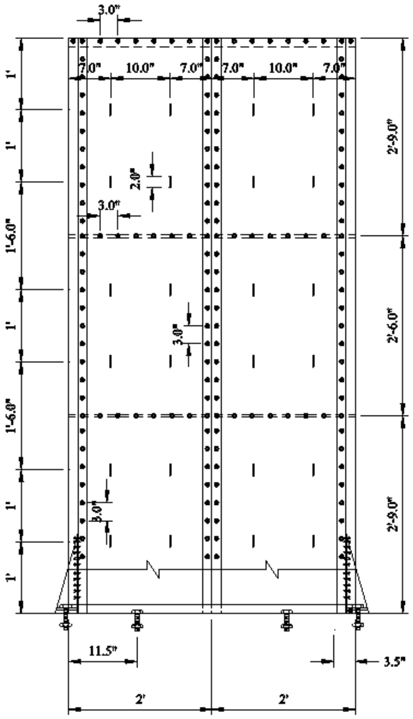


Figure 31 - Sheet in triple tracks 24×2 in. slits

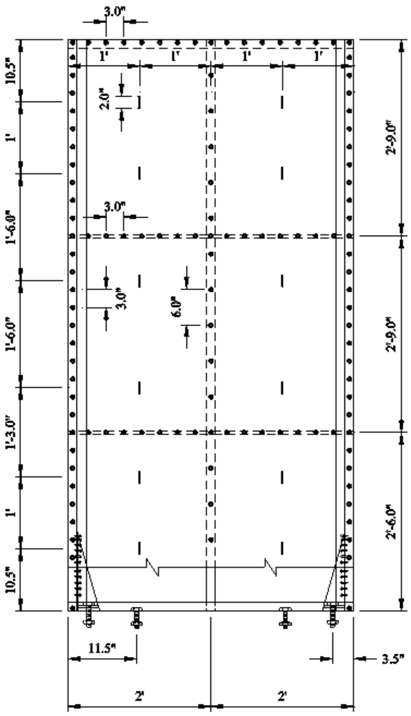


Figure 32 - Sheet out 12×2 in. slits

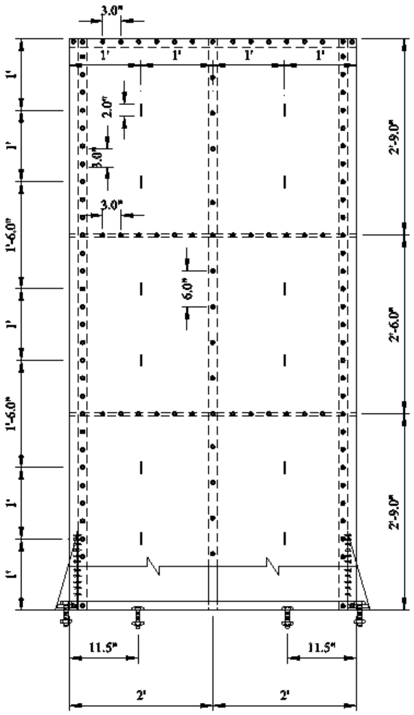
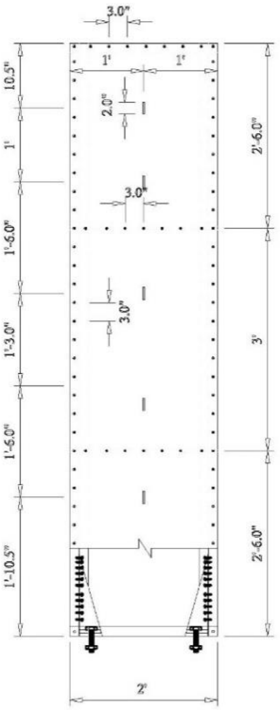


Figure 33 - Sheet in with 300T 12×2 in. slits



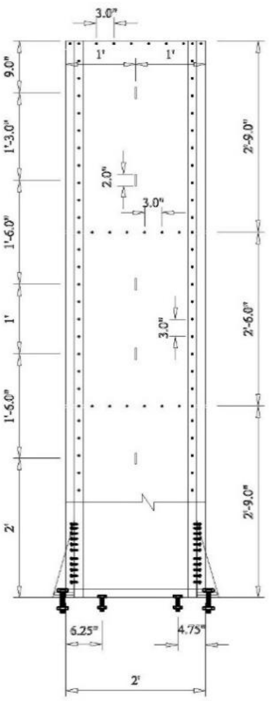


Figure 34 - Sheet out with 6×2 in. slits

Figure 35 - Sheet in with 6×2 in. slits

3.4 Material Properties

The dimensions and thicknesses of shear wall framing components followed the Steel Stud Manufacturers Associating product catalog (SSMA 2014). All material strengths (yield strength and ultimate strength) were obtained by coupon tests according to the ASTM A370 (2006) "Standard Test Methods and Definitions for Mechanical Testing of Steel Products". The coatings on the steel samples were removed by hydrochloric acid before testing. The coupon tests were tensioned on an INSTRON 4482 universal testing machine and an INSTRON 2630-106 extensometer was used to measure the tensile strain. The coupon tests were conducted in displacement control at a constant tension rate of 0.05 in./min. A total of three coupon tests were performed for each member, and the average results are provided in Table 3. Properties of the 27 mil flat steel sheet were not recorded.

Table 3 - Material properties of wall components

Components	Uncoated Thickness (in.)	Yield Stress Fy (ksi)	Tensile Strength Fu (ksi)
SV36 - 27	0.02942	87.30	92.09
SV36 - 18	0.01896	87.43	99.83
350 S 162 - 68, 50 ksi	0.07035	56.82	72.16
350 S 200 - 68, 50 ksi	0.06939	56.25	77.37
362 S 162 - 68, 50 ksi	0.06924	54.48	68.10
362 S 162 - 68, 70 ksi	-	72.38	94.91
350 S 162 - 54, 30 ksi	0.05528	38.90	54.84
350 T 150 - 68, 50 ksi	0.06981	56.38	70.96
362 T 150 - 68, 50 ksi	-	53.15	70.07
350 T 125 - 54, 50 ksi	0.05549	52.99	68.47
300 T 200 - 68, 50 ksi	0.07092	55.00	71.07

3.5 Test Results and Discussions

A total of 36 cyclic and monotonic tests were conducted in this research. Due to the various shear wall systems, a test specimen flow-chart (Figure 36) was created to better address the progress of performed tests. First, CFS shear walls with different sheathing materials are tested to prove higher strength and stiffness of corrugate sheathed shear walls. The first group to be studied is 8 ft. × 4 ft. shear walls with 68 mil framing members and 27 mil corrugated sheathing. Following Yu's recommendations, the corrugated sheathing is placed on top of the frame and a total of six slit configurations are tested to determine the optimal pattern. 12×2 in. vertical slits in 6 rows showed best results in comparison to other five slit patterns. It is appropriate to mention, in general, creating slits result in lower strength of the shear wall but increase the ductility. Therefore, the goal is to find a balance between the strength, stiffness, ductility, and performance of the shear wall.

Next group to be studied is the "sheet in" configuration. The regular sheet in with no openings showed low numerical results therefore creating slits would have resulted in even lower strength of the wall. Therefore, the wall configuration was no longer suitable to study.

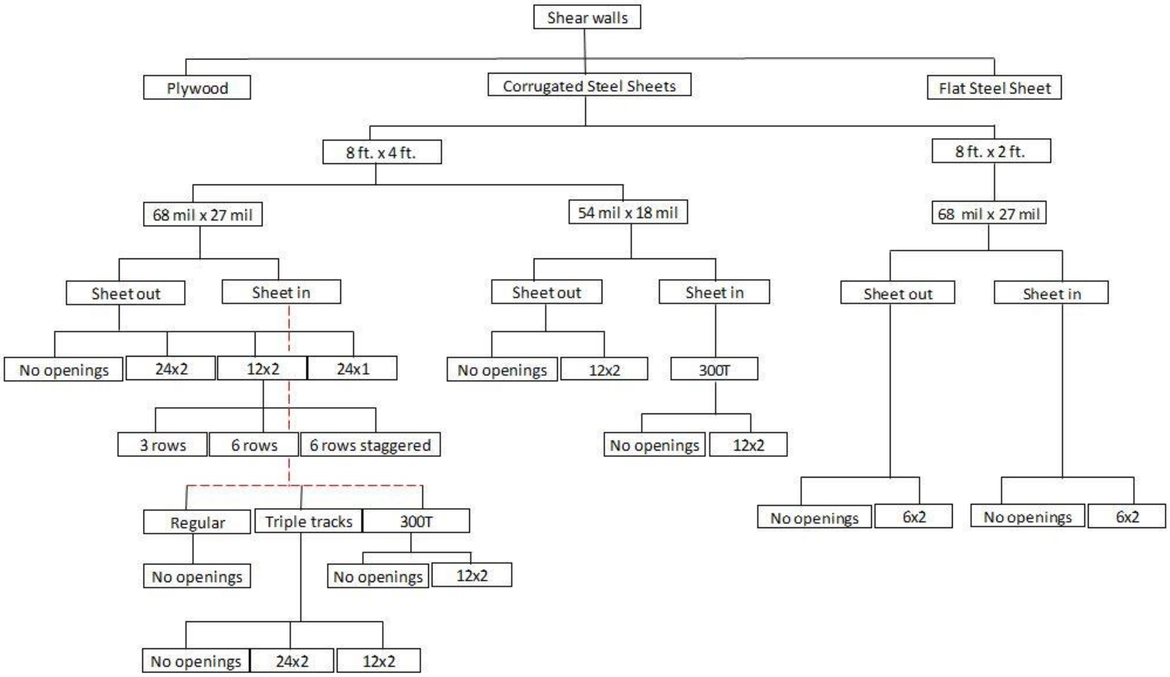


Figure 36 - Test specimen flow-chart

Sheet in with triple tracks were the next topic to be studied. To confirm that the 12×2 in. vertical slits in 6 rows would also generate the best results for other wall configurations, other patterns were tested for comparison reasons. At this point in the research, it was concluded that 12×2 in. vertical slits in 6 rows were the optimal slit configuration for 8 ft. × 4 ft. CFS shear walls with corrugated steel sheathing. Though, constructing the sheet in triple track shear walls were extremely labor intensive, time consuming and required assembly skills. It was later decided against the wall configuration. Next, Sheet in with 300T specimens were tested with no openings and the optimal slit configuration (12×2 in. vertical slits). The sheet in with 300T wall system is the preferred sheet in configuration.

The most significant shear wall systems were then tested for 8 ft. × 4 ft. shear walls with 54 mil framing members and 18 mil corrugated sheathings. Also, a group of 8 ft. × 2 ft. shear walls systems were studied. Due to the width of this group of shear walls, an interior vertical framing member is not applicable so only one configuration of “sheet-in” is probable.

The test results for this research are summarized in Table 4. The results reported herein are the average of the positive and negative cycle results. The displacement in Table 4 is the lateral displacement of the wall top at the peak load. The ductility factor, μ, is defined by the Equivalent Energy Elastic Plastic (EEEP) concept and calculated as the ratio of the ultimate displacement (Δu) to the maximum elastic displacement (Δy), $\mu = {}^{\Delta u}/_{\Delta y}$. The ultimate displacement, Δu, is defined as the intersection point of the EEEP curve and the test curve. The maximum elastic displacement, Δy, is defined as the intersection point of the EEEP curve elastic and plastic portion. For cyclic tests, a backbone curve was first created by connecting the peak point of each cycle using linear lines. Then the EEEP calculation was applied on the backbone curve of each test.

A detailed analysis and comparison of all shear walls are reported in this section. Furthermore, detailed test results are provided in Appendix A, in which construction details, measured responses of all tested shear walls, Matlab EEEP plotting, and related photos showing shear wall behaviors are included.

Table 4 - Summary of shear wall test results

Test #	Test label	Sheet in/out	Average peak load (lbs)	plf	Average disp (in.)	Average µ ductility factor	Drift %	Initial stiffness k (lbs/in)
11	8x4x68 - plywood T #1	out	9,607	2,402	2.2637	3.17	2.36%	8,089
12	8x4x68x27 - flat sheet T #1	out	6,090	1,523	1.9928	4.85	2.08%	6,656
54*	8x4x68x27 - no openings T#1	out	18,171	4,543	2.6980	2.37	2.81%	10,265
5	8x4x68x27 - no openings T #2	out	14,217	3,554	2.4768	1.84	2.58%	7,573
3	8x4x68x27 - 24x2 in. vertical slits T #1	out	10,865	2,716	2.6005	4.00	2.71%	8,249
6	8x4x68x27 - 24x2 in. vertical slits T #3	out	11,179	2,795	2.4525	3.43	2.55%	7,935
7	8x4x68x27 - 24x2 in. vertical slits T #4	out	11,793	2,948	2.2259	1.96	2.32%	5,749
13	8x4x68x27 - 12x2 in (3 rows) vertical slits T #1	out	11,955	2,989	3.0355	3.95	3.16%	10,861
15	8x4x68x27 - 12x2 in (6 rows) vertical slits T#1	out	12,514	3,128	2.4050	4.11	2.51%	10,929
19	8x4x68x27 - 12x2 in (6 rows) vertical slits T#3	out	12,342	3,086	2.3255	3.44	2.42%	9,347
29	8x4x68x27 - 12x2 in vertical slits staggered T#1	out	13,189	3,297	2.2000	3.85	2.29%	11,023
30	8x4x68x27 - 24x1 in vertical slits T#1	out	16,155	4,039	2.4261	2.42	2.53%	10,015
8	8x4x68x27 - sheet in w no openings T #1	in	8,209	2,052	1.4850	2.45	1.55%	6,675
9	8x4x68x27 - sheet in w no openings T #2	in	11,073	2,768	2.1600	3.24	2.25%	9,739
10	8x4x68x27 - triple tracks w no openings T #1	in	13,023	3,256	2.1244	2.22	2.21%	8,131
14	8x4x68x27 - triple tracks 24x2 in. vert slits T#1	in	11,952	2,988	3.1990	4.13	3.33%	9,103
21	8x4x68x27 - triple tracks 12x2 in. vert slits T#2	in	12,445	3,111	2.5635	3.26	2.67%	8,784
55	8x4x68x27 - with 300T no openings T#1	in	15,877	3,969	2.0450	2.34	2.13%	11,332
56	8x4x68x27 - with 300T no openings T#2	in	15,991	3,998	2.3300	2.17	2.43%	9,208
57	8x4x68x27 - with 300T 12x2 in vertical slits T#1	in	13,641	3,410	2.3950	3.03	2.49%	10,945
58	8x4x68x27 - with 300T 12x2 in vertical slits T#2	in	12,003	3,001	1.6550	2.27	1.72%	9,802
61	8x4x68x27 - with 300T 12x2 in vertical slits T#3	in	12,423	3,106	2.4650	2.58	2.57%	10,310
28	8x4x68x27 - no openings SW (7-35) T#1	out	2,709	677	0.2550	2.47	0.27%	15,573
59	8x4x68x27 - no openings SW (9-60) T#1	out	7,357	1,839	0.6300	3.53	0.66%	11,739
32	8x2x68x27 - no openings T#2	out	8,028	4,014	3.9399	1.82	4.10%	3,051
33	8x2x68x27 - 6x2 in. vertical slits T#1	out	7,857	3,928	3.8300	2.36	3.99%	3,112
45	8x2x68x27 - no openings T#1	in	6,478	3,239	2.7095	2.61	2.82%	3,697
46	8x2x68x27 - 6x2 in. vertical slits T#1	in	5,916	2,958	2.6650	2.75	2.78%	4,290
47	8x2x68x27 - no openings T#2	in	7,468	3,734	2.5950	2.82	2.70%	4,035
48	8x2x68x27 - 6x2 in. vertical slits T#2	in	6,939	3,470	3.8710	2.82	4.03%	4,591
62	8x4x54x18 - no openings T#1	out	8,631	2,158	1.3050	3.62	1.36%	10,214
63	8x4x54x18 - no openings T#2	out	8,184	2,046	1.3450	4.12	1.40%	10,372
64	8x4x54x18 - 12x2 in vertical slits T#1	out	5,903	1,476	1.7550	6.55	1.83%	9,392
66	8x4x54x18 - with 300T no openings T#1	in	7,719	1,930	1.7200	2.90	1.79%	8,031
67	8x4x54x18 - with 300T no openings T#2	in	8,453	2,113	1.6400	3.13	1.71%	9,459
68	8x4x54x18 - 12x2 in vertical slits T#3	out	6,505	1,626	1.4350	5.06	1.49%	10,524
69	8x4x54x18 - with 300T 12x2 in vertical slits T#1	in	6,610	1,652	1.6750	2.78	1.74%	9,944
70	8x4x54x18 - with 300T 12x2 in vertical slits T#2	in	6,538	1,634	1.3500	4.05	1.41%	10,066

* Test 54 – shear wall under monotonic lateral loading

3.5.1 Different Sheathing Material

CFS shear walls with different sheathing material including corrugated steel sheet (Test 5), flat steel sheet (Test 12) and plywood sheathing (Test 11) are compared. Figure 37 shows the hysteresis curve for all three walls in one graph. It is concluded that the corrugated specimen has 133% higher strength than the plywood specimen and 48% higher strength compared to the flat steel sheet specimen. Referring back to Table 4, it is observant that the corrugated specimen has a significantly lower ductility factor. The failure mode observed in Test 5 was the shear deformation on the bottom sheet which caused screw pull over at the boundary studs and screw pull out on the middle stud (Figure 38a). The bottom track showed local buckling and most of the sheathing screws on the bottom track had pull over in an unzipping action (Figure 38b). Minor sheet tearing were observed around the sheathing screws and screw pulling out was sighted at the bottom seam screws (Figure 38c).

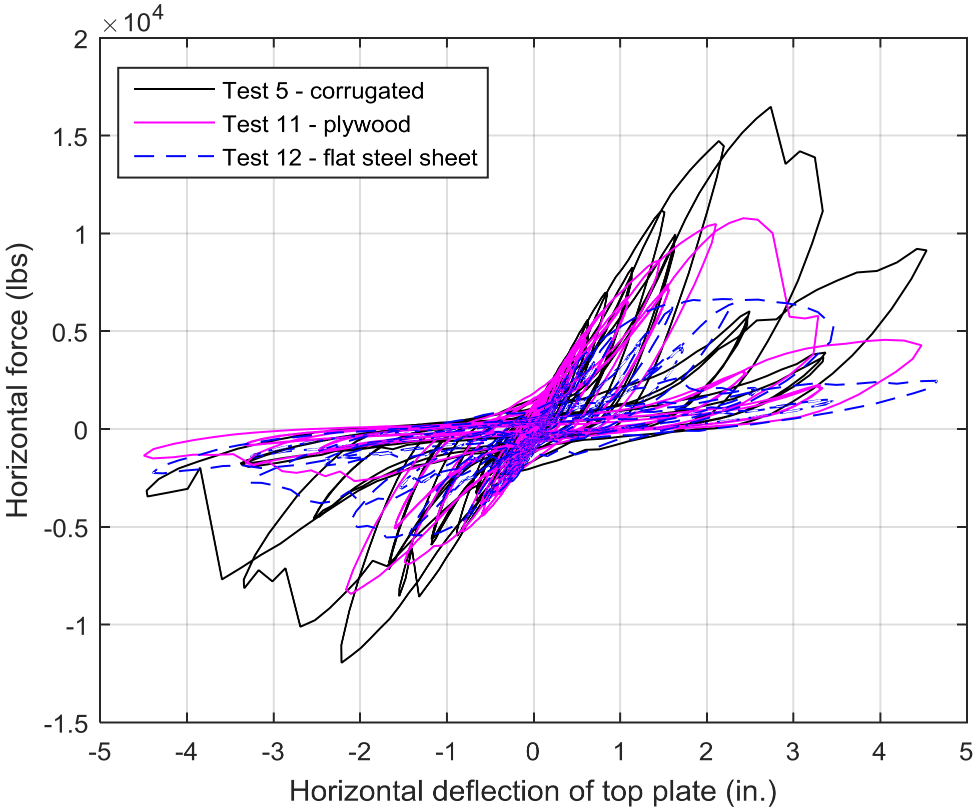


Figure 37 - Different sheathing material, hysteresis curves

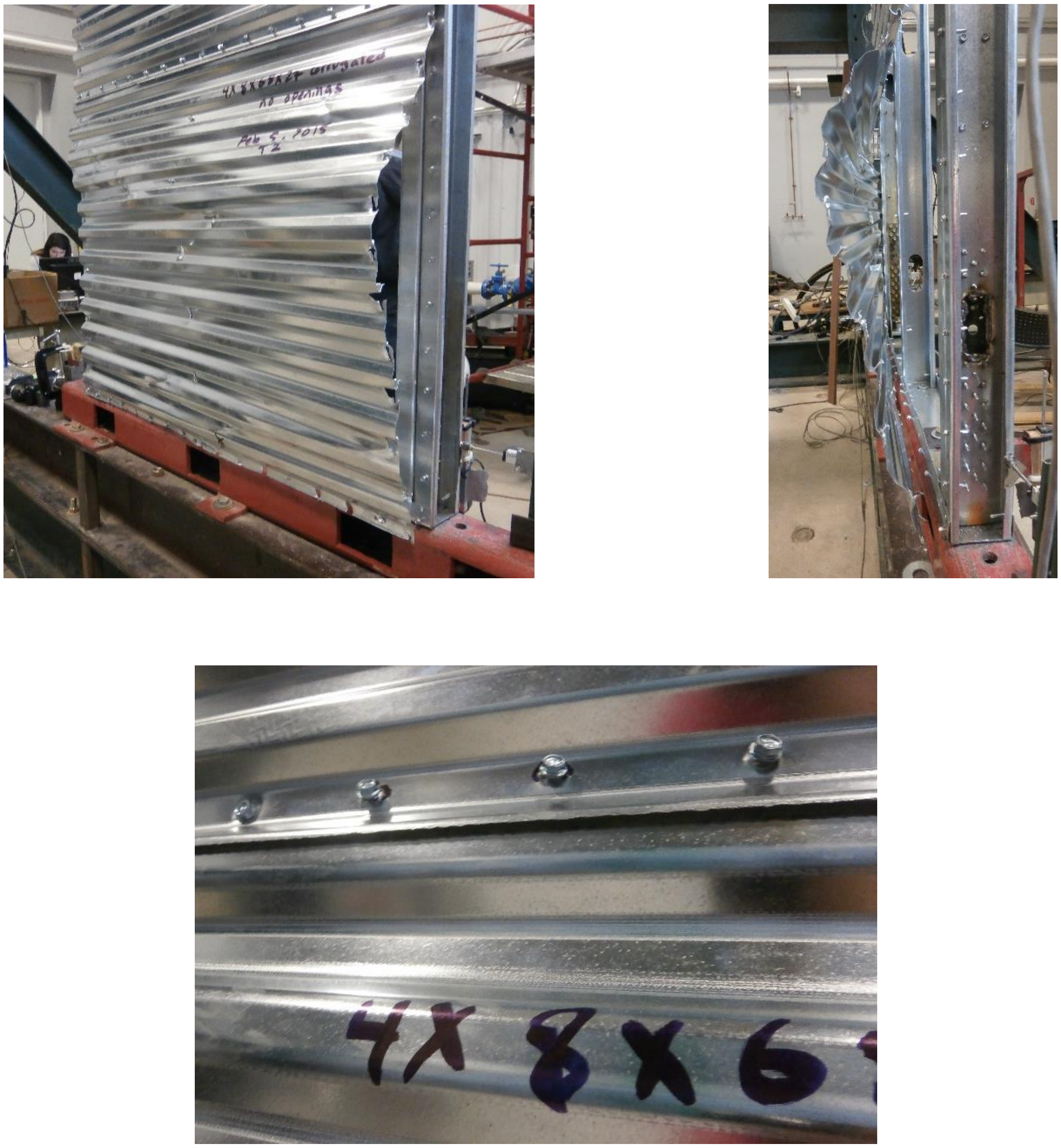


Figure 38 - a. Test 5 failure mode - sheathing connection failure, b. screw failure at bottom track, c. seams screw pull out

The shear wall with plywood sheathing failed due to sheathing screw failure along the boundary stud, shown in Figure 39. Other deformations included local buckling of the top track and sheet breakage at the bottom of the wall.

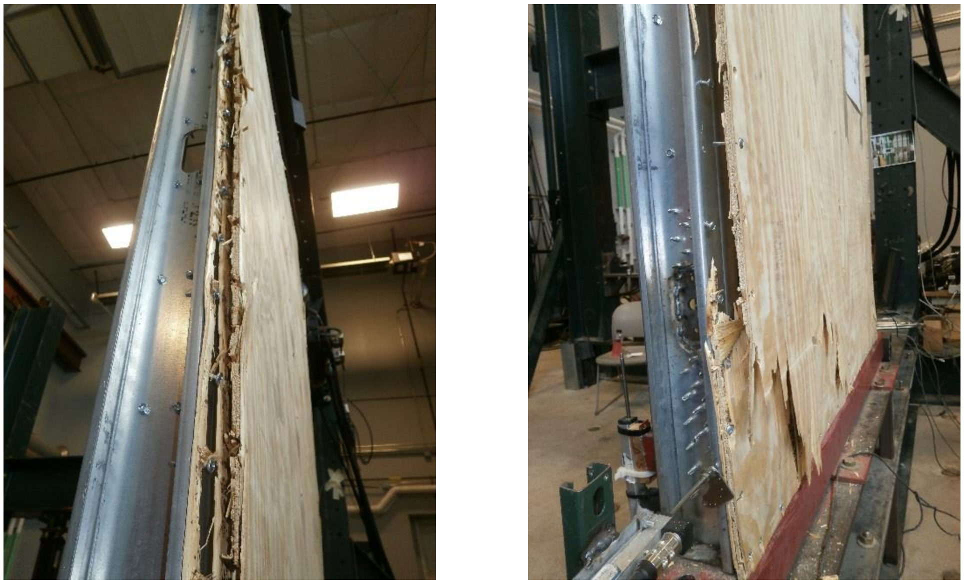


Figure 39 - Test 11 failure mode

Greater damage was observed at the top of the shear wall with flat steel sheathing rather than the bottom of the shear wall. This was caused due to the sheathing connections being too close to the edge of the sheet. Therefore, all sheathing screws along the top track had failed (Figure 40). Local buckling of the boundary stud and screw pull over along the boundary studs were also observed. Last, sheathing screws along the field stud had also pull over.

Figure 40 - Test 12 failure mode - sheathing screw pull over at top track

3.5.2 Optimal Slit Configuration

A comparison is made between 6 slit configurations on 8 ft. × 4 ft. shear walls with 68 mil frame members and 27 mil corrugated sheathing. These walls are similar in framing members and sheathing connections. The only variable is the slit configuration with include: no openings (Test 5), 24×2 in. (Test 3), 12×2 in. in 3 rows (Test 13), 12×2 in. in 6 rows (Test 15 and 19), 12×2 in. staggered (Test 29), and 24×1 in. (Test 30). Table 5 shows all the numerical results of these walls. The average of Test 15 and 19 is reported in this table for comparison purposes.

Table 5 - Slit configuration numerical results

Test #	Test label	Sheet in/out	Average peak load (lbs)	plf	Average disp (in.)	Average µ ductility factor	Drift %	Initial stiffness k (lbs/in)
5	8x4x68x27 - no openings	out	14,217	3,554	2.4768	1.84	2.58%	7,573
3	8x4x68x27 - 24x2 in. vertical slits	out	10,865	2,716	2.6005	4.00	2.71%	8,249
13	8x4x68x27 - 12x2 in (3 rows) vertical slits	out	11,955	2,989	3.0355	3.95	3.16%	10,861
15/19	8x4x68x27 - 12x2 in (6 rows) vertical slits	out	12,428	3,107	2.3653	3.77	2.46%	10,138
29	8x4x68x27 - 12x2 in vertical slits staggered	out	13,189	3,297	2.2000	3.85	2.29%	11,023
30	8x4x68x27 - 24x1 in vertical slits	out	16,155	4,039	2.4261	2.42	2.53%	10,015

Creating perforations on the corrugated sheets have three major objectives: to improve the ductility of the shear wall system (µ>3.0), to eliminate damages to the shear wall framing members, and to eliminate connection failures. Test 3 with 24×2 in. vertical slits was the configuration suggested by Guowang Yu and the numerical results indicated low strength. Also, screw pull out along boundary studs were detected. Test 30 with 24×1 in. vertical slits showed high strength though the ductility was low. It can be concluded that the 24×1 in. vertical slits were too small and had almost no impact on the performance of the shear wall. Screw pull over and pull out along boundary studs, and sheet tearing around screw locations were observed. And lastly, the framing members showed local buckling in multiple locations.

All three configurations of shear walls with 12×2 in. vertical slits showed close numerical results. Test 29 with 12×2 in. vertical slits staggered displayed local buckling of boundary studs in multiple locations. Therefore, slit configurations were narrowed down to 12×2 in. vertical slits in 3 rows or 6 rows. Both walls showed identical deformations thus the design with the highest strength was presented as the optimal slit configuration. Figure 41 compares the hysteresis curves of the unperforated shear wall vs. perforated shear wall. Figure 42 shows the details of the optimal slit configuration.

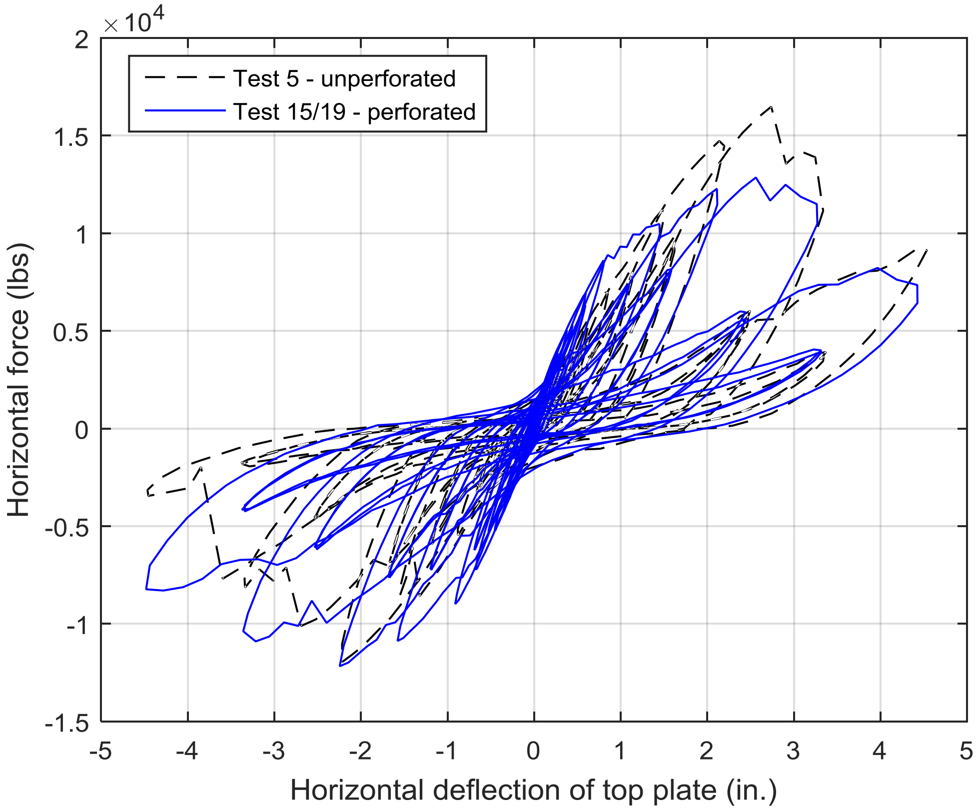


Figure 41 - Hysteresis comparison: unperforated vs. perforated

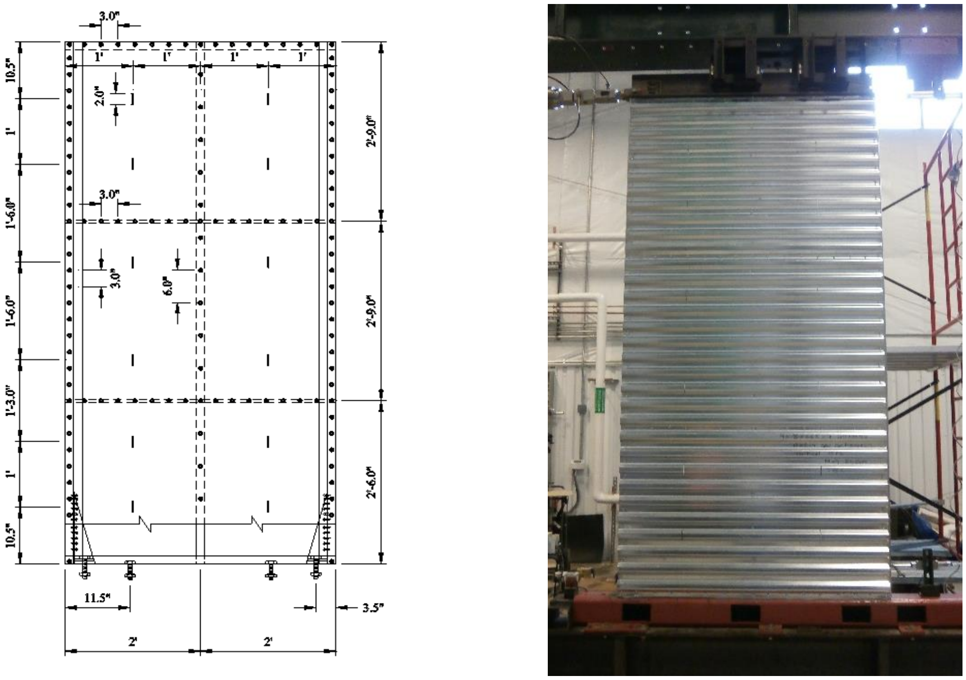


Figure 42 - Optimal slit configuration

3.5.3 Design Details

Initially, the top and bottom sheathing of the shear walls were cut so that sheets would only over-lap on one rib. To shorten the construction time, two identical shear walls were tested, one of which the sheathing had not been cut and sheets over-lapped on two ribs (Test 3), and the sheathing on the other wall had been cut off so only one rib would over-lap (Test 6). Both shear walls failed due to sheathing connection failure along boundary studs. The numerical results were nearly identical showing 3% and 6% difference in average peak load and displacement, respectively. Figure 43 compares the hysteresis curve of these two shear walls. It was appropriate to conclude that shortening the sheets had almost no impact on the shear wall performance therefore sheets were over-lapped on two ribs for the rest of the specimens in this research.

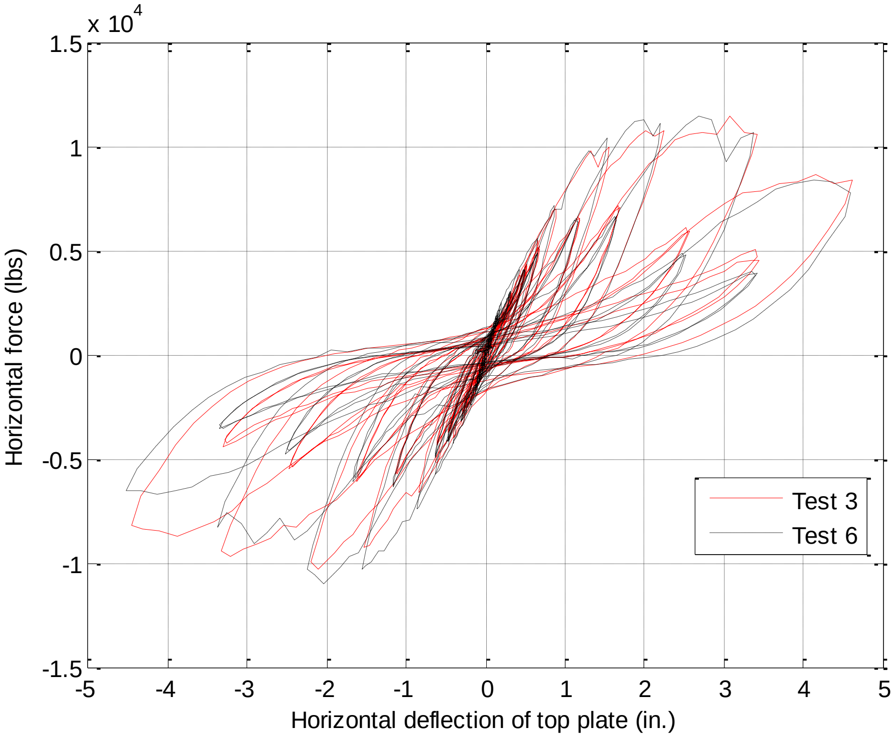


Figure 43 - Hysteresis comparison: single over-lap vs. double over-lap

Creating the perforations on the corrugated sheathing's results in a weak location which allows engineers to be able to control the failure location of the shear wall. The slits take the failure location away from the boundary elements and transfers it into the sheathing. This protects the framing members from any extreme damages and prevents the building from collapse. The idea is to keep the frame in place but change the damaged sheets with new sheets and the shear wall would still be able to resist lateral loading. To prove this idea, the damaged sheathing (bottom sheet) of Test 6 with 24×2 in. vertical slits, was replaced with new sheathing following the same slit pattern. The shear wall with replaced sheathing is Test 7. Figure 44 compares the hysteresis curve of the two shear walls. The shear wall with replaced sheathing was able to resist almost the same amount of lateral loading (5% less) though the ductility of the shear wall was reduced by 41%.

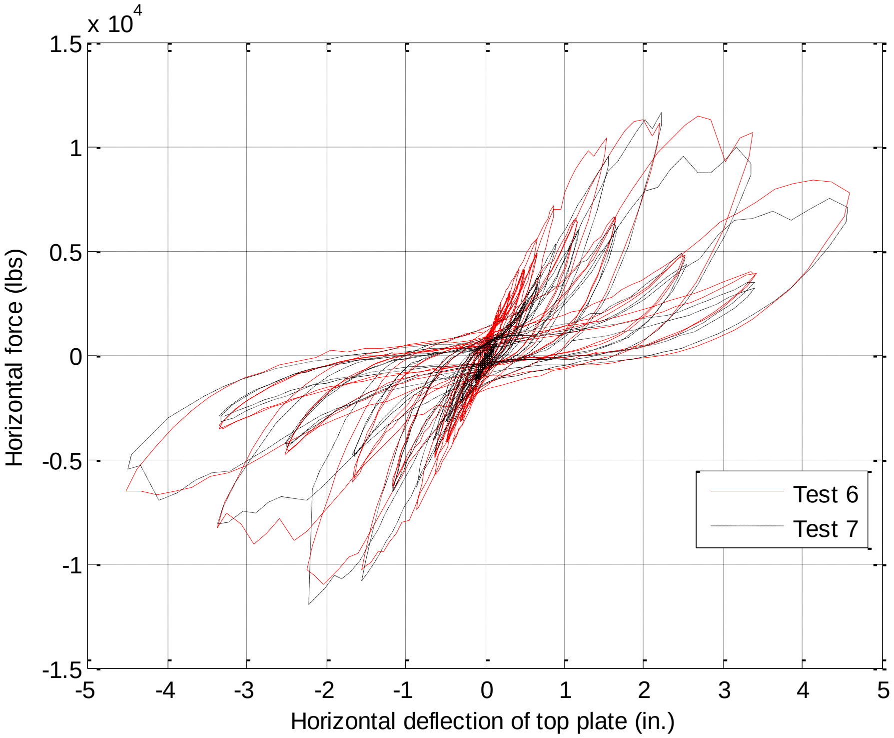


Figure 44 - Hysteresis comparison: original vs. replaced sheathing

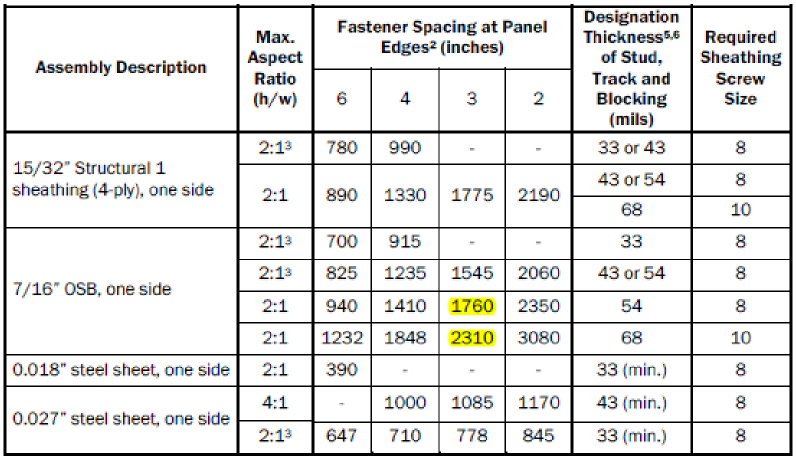
3.5.4 Wall Configurations

Four major groups are subject to discussion in this segment:

1. 8×4×68×27 sheet out
2. 8×4×68×27 sheet in
3. 8×2×68×27
4. 8×4×54×18

Nominal shear strength results from the conducted tests must be comparable to CFS shear walls with OSB sheathing following AISI S213 (2012) design standards. Table 6 shows the nominal shear strength (plf) for seismic and other in-plane loads for shear walls. Table 6 was taken directly from AISI S 213 Table C2.1-3. Based on AISI recommendations, shear walls with 4:1 aspect ratio (8 ft. × 2 ft.) are permitted the same nominal strength (pounds per foot) values.

Table 6 - Nominal shear strength (Rn) for seismic and other in-plane loads for shear walls (pounds per foot)



Assembly Description	Max. Aspect Ratio (h/w)	Fastener Spacing at Panel Edges[2] (inches)				Designation Thickness[5,6] of Stud, Track and Blocking (mils)	Required Sheathing Screw Size
		6	4	3	2		
15/32" Structural 1 sheathing (4-ply), one side	2:1[3]	780	990	-	-	33 or 43	8
	2:1	890	1330	1775	2190	43 or 54	8
						68	10
7/16" OSB, one side	2:1[3]	700	915	-	-	33	8
	2:1[3]	825	1235	1545	2060	43 or 54	8
	2:1	940	1410	1760	2350	54	8
	2:1	1232	1848	2310	3080	68	10
0.018" steel sheet, one side	2:1	390	-	-	-	33 (min.)	8
0.027" steel sheet, one side	4:1	-	1000	1085	1170	43 (min.)	8
	2:1[3]	647	710	778	845	33 (min.)	8

Section 3.6.2. of this research paper concluded that 8×4×68×27 sheet out with 12×2 in. vertical slits showed best results in its category. The same procedure is followed to discuss other groups. Numerical results for “8×4×68×27 sheet in” configuration are summarized in Table 7. For those specimens tested more than once, the average values were reported here.

Table 7 - Summary of 8×4×68×27 sheet in results

Test #	Test label	Average peak load (lbs)	plf	Average disp (in.)	Average μ ductility factor	Drift %	Initial stiffness k (lbs/in)
8 & 9	8x4x68x27 - sheet in w no openings	9,641	2,410	1.8225	2.84	1.90%	8,207
10	8x4x68x27 - triple tracks w no openings	13,023	3,256	2.1244	2.22	2.21%	8,131
14	8x4x68x27 - triple tracks 24x2 in. vert slits	11,952	2,988	3.1990	4.13	3.33%	9,103
21	8x4x68x27 - triple tracks 12x2 in. vert slits	12,445	3,111	2.5635	3.26	2.67%	8,784
55 & 56	8x4x68x27 - with 300T no openings	15,934	3,984	2.1875	2.25	2.28%	10,270
57, 58 & 61	8x4x68x27 - with 300T 12x2 in vertical slits	12,689	3,172	2.1717	2.62	2.26%	10,352

The results in Table 7 once again prove that perforated sheathings increase the ductility of shear walls. Test 8 & 9 indicated low shear strength resistance and low ductility; therefore they weren't studied any further. Comparing Tests 10, 14, and 21, it is definite that the 12×2 in. vertical slits are the optimal slit pattern for sheet in wall configurations as well. Test 21 shear strength and ductility well exceed AISI standard. The design caused the specimen to act as two separate 8 ft. by 2 ft. shear wall sections. The failure was due to the sheet pulling out of screws from behind the wall. Also, the frame was severely damaged around each sheathing screw along the vertical track members (Figure 45). The construction of this type of shear wall was time consuming and extremely labor intensive. Usually, 2-3 skilled students had to work almost two hours to build one of this type shear wall. For those purposes, it was concluded that the construction complexity of the shear wall was not feasible and this type of shear wall was no longer tested.

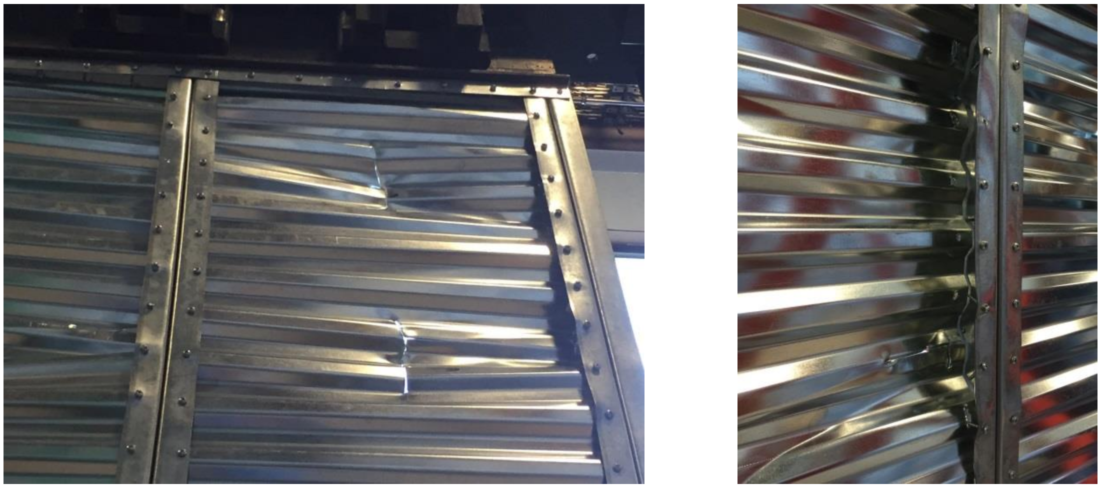


Figure 45 - Test 21 failure mode

As a result, a new sheet in wall configuration was designed using a 3 in. webbed track as the field framing member so the sheathing wouldn't have to be cut in two separate sections. Comparing the performance of the 300T specimens, with perforation and without perforation, it was concluded that the framing of the specimen with slits had shown less damage. In Tests 55 and 56 the framing members above the hold-down area were severely damaged (Figure 46). Some local buckling of frame members were also observant. In comparison, Tests 57, 58, and 61 showed small local buckling above the hold-downs. Local buckling on field track member was seen more in these specimens (Figure 47).

Figure 46 - Sheet in 300T without perforation

Figure 47 - Sheet in 300T without perforation

Table 8 shows a summary of the 8×2×68×27 shear walls results. The average results from specimens which have been tested multiple times are reported herein. Two judgments can be made based on these results. First, creating the slits improved the ductility of the shear walls which proves the initial concept. Second, the sheet in and sheet out wall configurations don’t significantly impact the numerical results of the shear walls, though sheet in configuration indicated higher performance. All tests in this group reacted similarly under lateral cyclic loading. The failure mode for these shear walls were sheathing connection failures mostly due to sheathing pulling over the screw connections. Local buckling of vertical framing members were also observed.

Table 8 - 8×2×68×27 shear wall result summary

Test #	Test label	Sheet in/out	Average peak load (lbs)	plf	Average disp (in.)	Average μ ductility factor	Drift %	Initial stiffness k (lbs/in)
32	8x2x68x27 - no openings	out	8,028	4,014	3.9399	1.82	4.10%	3,051
33	8x2x68x27 - 6x2 in. vertical slits	out	7,857	3,928	3.8300	2.36	3.99%	3,112
45 & 47	8x2x68x27 - no openings	in	6,973	3,486	2.6523	2.71	2.76%	3,866
46 & 48	8x2x68x27 - 6x2 in. vertical slits	in	6,428	3,214	3.2680	2.78	3.40%	4,440

Table 9 is a summary of all 8×4×54×18 shear walls. The average results of identical tests have been reported. Based on AISI S 213, the nominal shear strength of this group of shear walls are to be comparable to 1760 plf. The numerical results indicate that in both sheet in and sheet out wall configurations, creating the slits didn't impact the performance of the shear walls greatly. Shears walls with corrugated steel sheathings have mostly failed due to sheathing-to-frame connection failures. The thin sheathing in these specimens caused weaker connections and were more likely to pull over the screws. Also, sheet in wall configurations have higher initial stiffness in comparison to sheet out configurations. Thus, creating more slits for the sheet in wall configuration are recommended. More tests on 8×4×54×18 shear wall specimens are to be done before any conclusions can be made.

Table 9 - 8×4×54×18 shear wall result summary

Test #	Test label	Sheet in/out	Average peak load (lbs)	plf	Average disp (in.)	Average μ ductility factor	Drift %	Initial stiffness k (lbs/in)
62 & 63	8x4x54x18 - no openings	out	8,407	2,102	1.3250	3.87	1.38%	10,293
64 & 68	8x4x54x18 - 12x2 in vertical slits	out	6,204	1,551	1.5950	5.80	1.66%	9,958
66 & 67	8x4x54x18 - with 300T no openings	in	8,086	2,022	1.6800	3.02	1.75%	8,745
69 & 70	8x4x54x18 - with 300T 12x2 in vertical slits	in	6,574	1,643	1.5125	3.41	1.58%	8,005

3.5.5 Sheathing Connection Method

One of the objectives of this research was to test other connection methods such as pneumatic pins and spot-welding. Pneumatic pins and nails were studied by Bill Gould from Hilti. Based on Gould's report, the pneumatic pin connections were unable to create satisfactory sheathing to frame connections. For the sheet-in configurations, the pins had to go from thicker material (frame) through the thin sheathing. The pins were unable to penetrate the sheathing and often bend the material without creating a connection. For that reason, pneumatic pin connections were not studied further.

As described in Section 3.3. of this report, a spot-welder with two double bent shanks and a spot-welding power supply were purchased and investigated as a possible new sheathing connection method. The spot-welder was first used in Test 28 with 7 volts and 35 cycle time. The shear wall failed prematurely due to weak sheathing connections. Almost all spot-welds were disconnected in an unzipping act (Figure 48). Therefore, connection tests had to be conducted to obtain the best connection results from the spot-welder. It was concluded that high voltage and low cycle time caused the sheet to burn therefore it impacted the surface of the connection area poorly (Figure 49). The best connection with high strength was achieved with high voltage and high cycle time. Another CFS shear wall with spot-welded sheathing connection was performed with 9 volt and 60 cycle time. The nominal shear strength of the wall increased by 172% though the shear wall failed prematurely and the frame was undamaged. For those reasons, spot-welded sheathing connections were not a feasible connection method. Failure mode of Test 59 was also unzipping of sheathing connections. The hysteresis curve of the two tests are shown in Figure 50.

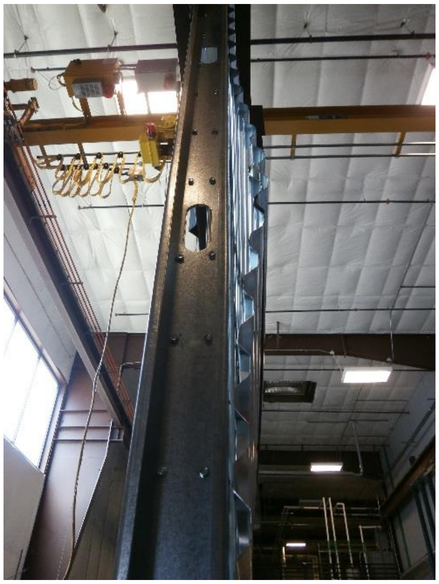


Figure 48 - Unzipping of spot-weld connections

Figure 49 - Burnt spot-welds

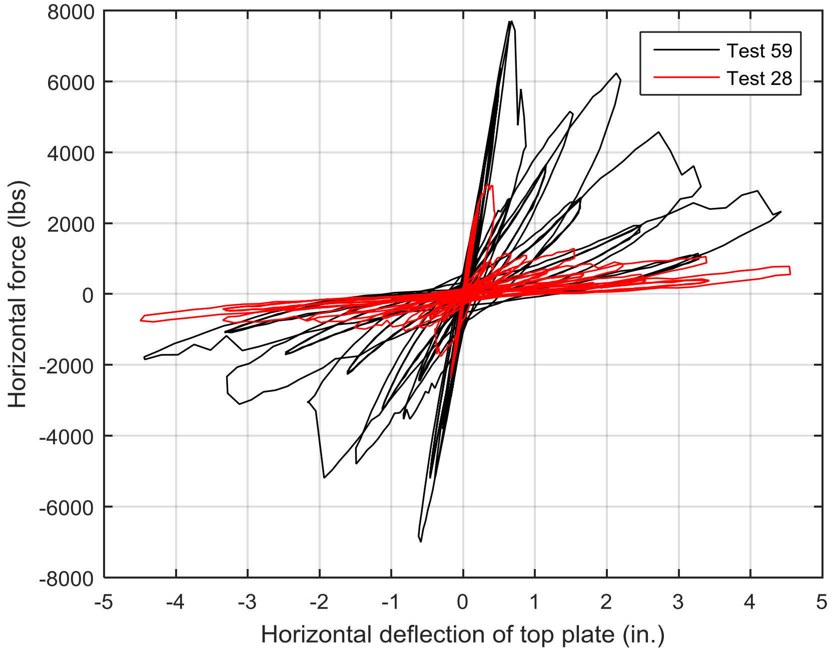


Figure 50 - Spot-welds hysteresis curves

CHAPTER 4

FINITE ELEMENT MODELING

The CFS shear walls with corrugated steel sheathing are a new lateral resistance system. Computational simulations allow researchers to study the performance of these shear walls with a large range of parametric variations and to share findings with designers. The objective of this section is to discuss the finite element modeling techniques that appropriately explore the new shear wall products and configurations. The behavior and failure mechanism of these shear walls are also under investigation. A total of three shear wall finite element models were developed in ABAQUS consisting of two monotonic and one cyclic models. Table 10 shows the models and the corresponding tests.

Table 10 - Test number corresponding to model

Model No.	Test No.	Description
Model 1 - Monotonic	Test 54 - Monotonic	No slits, Sheet out
Model 2 - Cyclic	Test 5 - Cyclic	No slits, Sheet out
Model 3 - Monotonic	Test 3 & 6 - Cyclic	Slits, Sheet out

Performance and failure of shear walls, particularly under seismic loading, is dominated by the sheathing connections, for that, the tilting behavior and bearing behavior of sheathing screw connections were significant to this research. Various connection modeling approaches were studied and it was found that SPRING2 element was capable of simulating the monotonic behavior of sheathing screw connections and was recommended for monotonic shear wall modeling. For cyclic tests, the CFS shear walls experienced significant pinching behavior prior to failure. It was suggested that a general user-defined element (user subroutine UEL) in ABAQUS to be used for simulation the screw behavior under cyclic lateral loading. Further details of the finite element models developed are discussed in this section.

4.1 Components & Geometry

The dimensions and thicknesses of each shear wall components were chosen from the Steel Stud Manufacturers Association product catalog (SSMA 2014). The profile dimensions of the corrugated sheathings are in accordance with those provided by Verco Decking, INC also seen in Figure 7. The edge of the top and bottom corrugated sheets were removed following the construction procedure. Also, the top and bottom tracks were modeled 0.08 in. wider so the studs would fit within the tracks without contact. All components were modeled using 4-node homogeneous shell elements, type S4R in ABAQUS. Framing members and corrugated sheets were meshed using 0.5 in. and 1.5 in. seed size respectively. For Model 3, the slits were created on the sheathing in “assembly”. The width of the slits were 0.045 in. which is equivalent to the width of the grinder blade. Also, a 3-node triangular element type (S3) was used for the sheathing with slits.

4.2 Material Properties

All material properties of shear wall components were obtained by conducting coupon tests in accordance to the ASTM A370 (2006). All members were assigned elastic and plastic material behavior. Elastic material behavior was modeled as isotropic type with Young’s modulus E=29,500 ksi and Poisson’s ratio of v=0.3. For the plastic material properties, a total of 7 points including the yield stress, yield strain and the ultimate stress, ultimate strain were selected from the material properties and converted from engineering stress and engineering strain to true stress (σ_{true}) and true strain (ϵ_{true}) following Equation 1 and Equation 2.

$$\sigma_{true} = \sigma_{eng}(1+\epsilon_{eng}) \qquad \text{Eq. 1}$$

$$\epsilon_{true} = \ln(1+\epsilon_{eng}) \qquad \text{Eq. 2}$$

4.3 Interaction

A “Tie” constraint was used to connect CFS framing members. Boundary studs were tied along the webs following the construction procedure. The framing members were assembled by tying the tracks to studs at 10 points. It is important to mention, members selected as master or slave are of great significance in finite element analysis. Slave nodes “follow” the master nodes and in these models, the studs follow the track since the track is connected to the loading T-bar. Figure 51 shows the stud-to-track frame ties and Figure 52 shows the stud-to-stud connection ties.

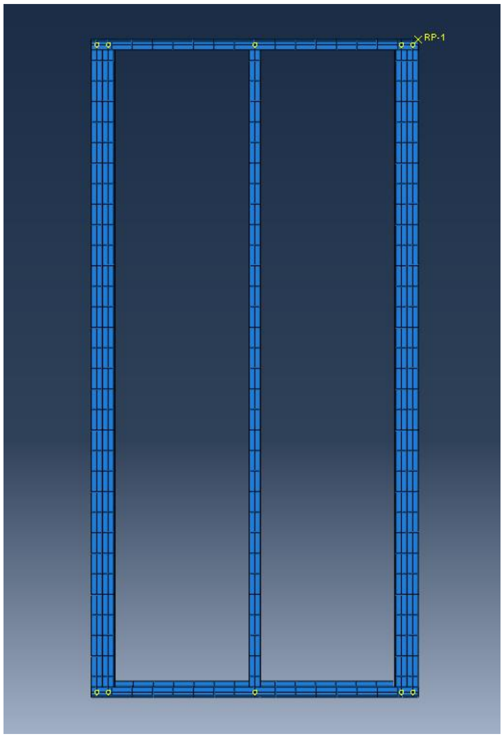


Figure 52 - stud-to-track frame ties

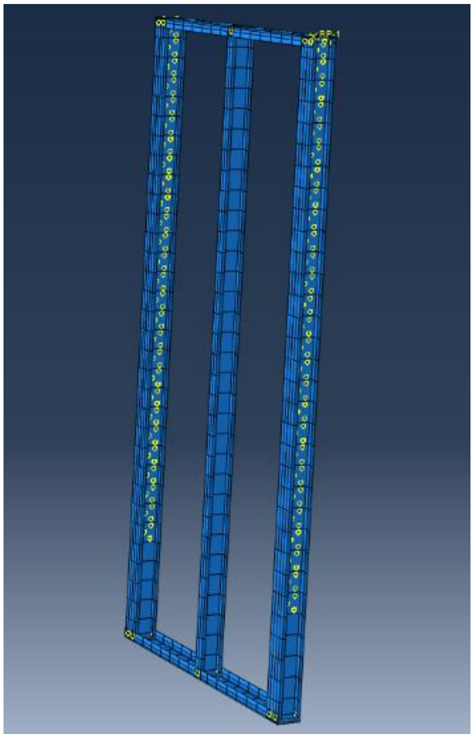


Figure 51 - stud-to-stud connection ties

4.4 Boundary Conditions

To restrict the shear wall from out-of-plane movement, a line of nodes on each flange of the top track were selected and their out of plane displacement was fixed (Figure 53). The shear bolts and hold-down bolts connecting the bottom track to the testing frame are modeled by restricting the bolted areas on the track in all displacement and rotation directions. Hold-downs were modeled in boundary conditions by selecting all nodes in the hold-down area of the boundary studs and fixing them in all displacement directions (Figure 54).

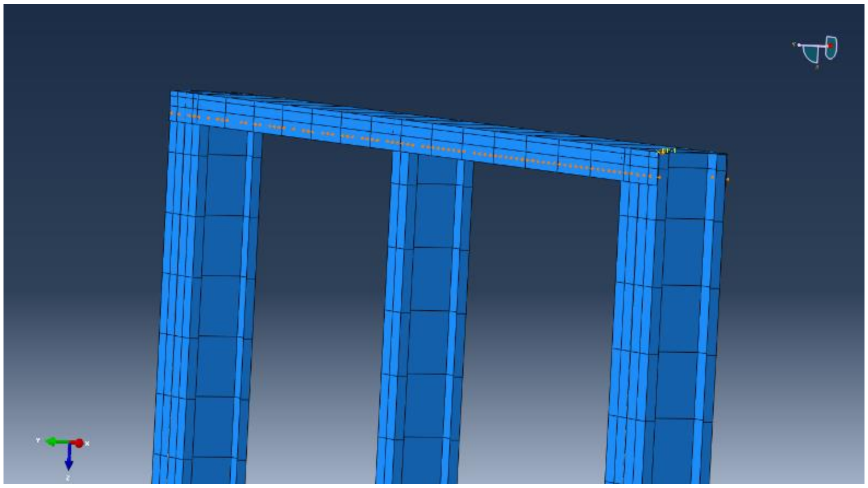


Figure 53 - Out-of-plane boundary condition

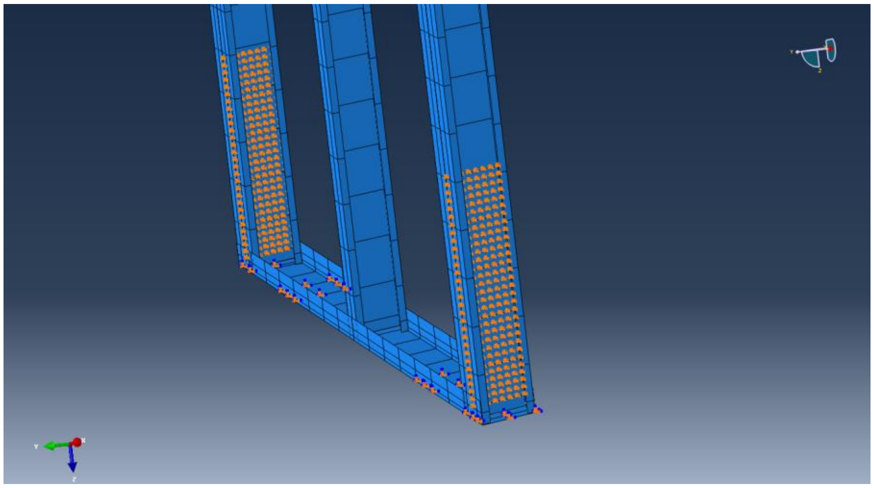


Figure 54 - Hold-down and bolts boundary conditions

4.5 Contact Properties

A contact property was introduced between the surfaces of the corrugated sheathing and the studs to prevent the sheathing from penetrating through the framing members. A “frictionless tangent” behavior and “hard-contact normal” behavior were defined at these locations. Introducing the contact property also reduced the running time for the models. The contact locations can be seen in Figure 55.

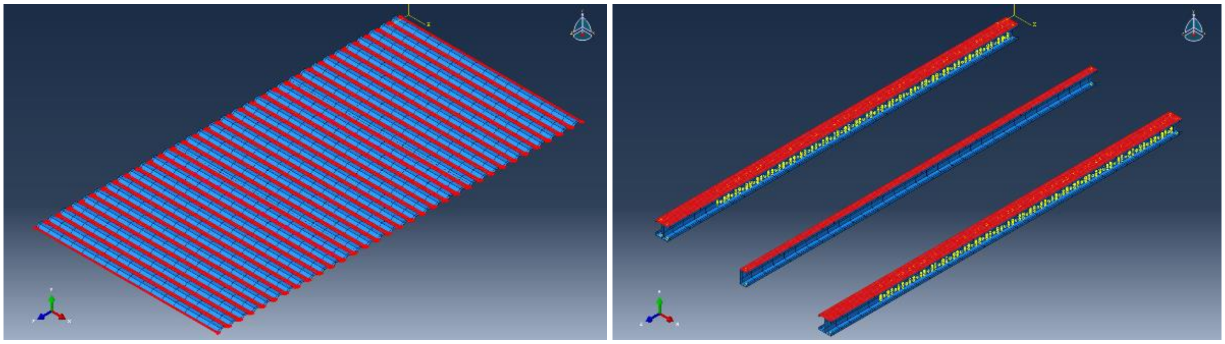


Figure 55 - Contact surface locations

4.6 Sheathing Connections

Connection tests were conducted following AISI S905-13 “Test Standard for Cold-Formed Steel Connections” on No. 12 hex washer head screws. Connection tests results are shown in Figures 56 through Figure 58.

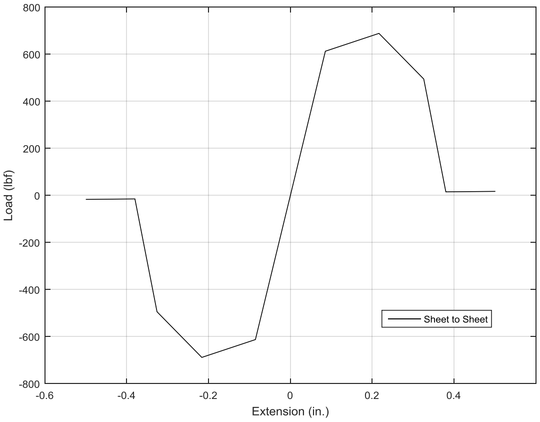


Figure 56 - Sheet to sheet backbone connection curve

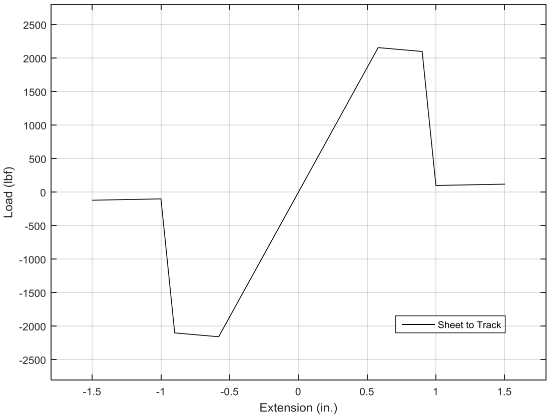


Figure 57 - Sheet to track backbone curve

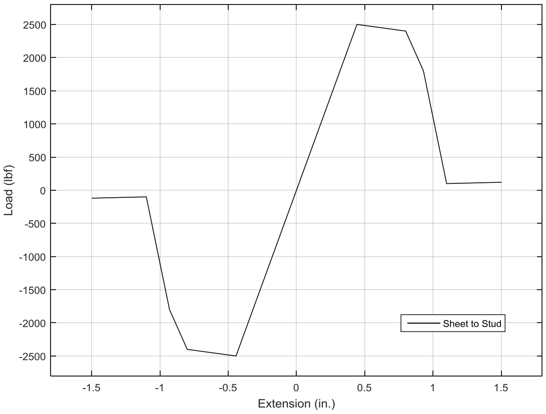


Figure 58 - Sheet to stud backbone curve

4.6.1 Monotonic

Screw connections were modeled using nonlinear SPRING2 elements. The screw stiffness in the vertical and horizontal directions were based on connection test results. The axial screw behavior was calculated in accordance to AISI S100-12(2012) specification.

4.6.2 Cyclic

In order to simulate the pinching behavior of the shear wall, a general user-defined element (UEL) was introduced in the model under cyclic loading. The modified radial spring used herein was recommended by Chu Ding (2015). The Pinching4 material backbone curve is multilinear. In total, 16 parameters are needed for defining a Pinching4 backbone curve. The Pinching4 behavior is simulated by pinching paths which define material reloading and unloading paths. There are 6 parameters required for defining pinching paths. A typical Pincing4 backbone curve and pinching path is shown in Figure 59. The UEL developed was based on opensees Pinching4 material and was able to simulate the unloading stiffness degradation, reloading stiffness degradation and strength degradation.

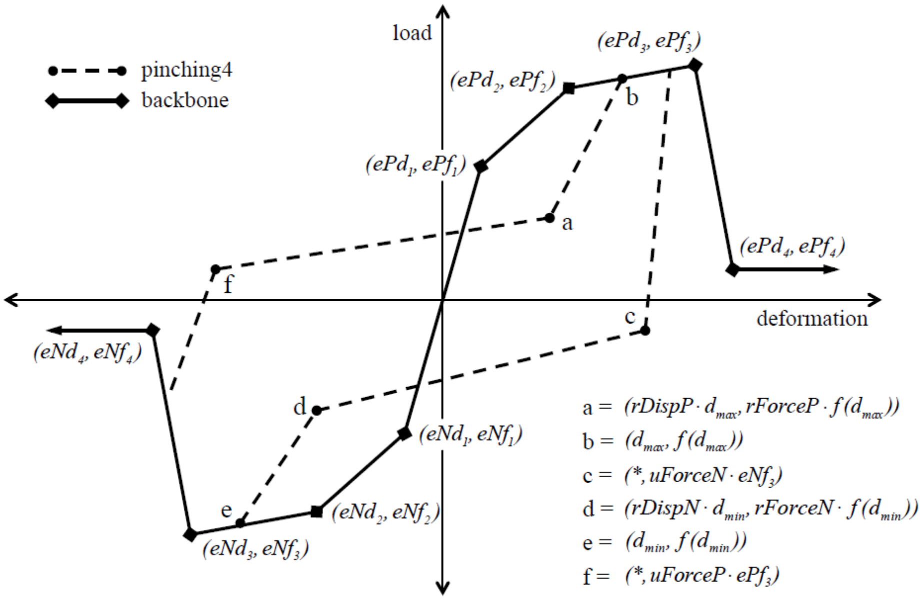


Figure 59 - Typical Pinching4 backbone curve and pinching path

4.7 Loading Method

Loading is simulated by coupling all nodes on the top track web surface to one "Reference Point" located on the edge of the top track (Figure 60). For the monotonic models, a displacement controlled lateral load was applied to the reference point in the horizontal direction at the top of the shear wall. A total of 4.5 in. was traveled. For the cyclic model, an amplitude was created following the CUREE Protocol and applied to the reference point on the top track.

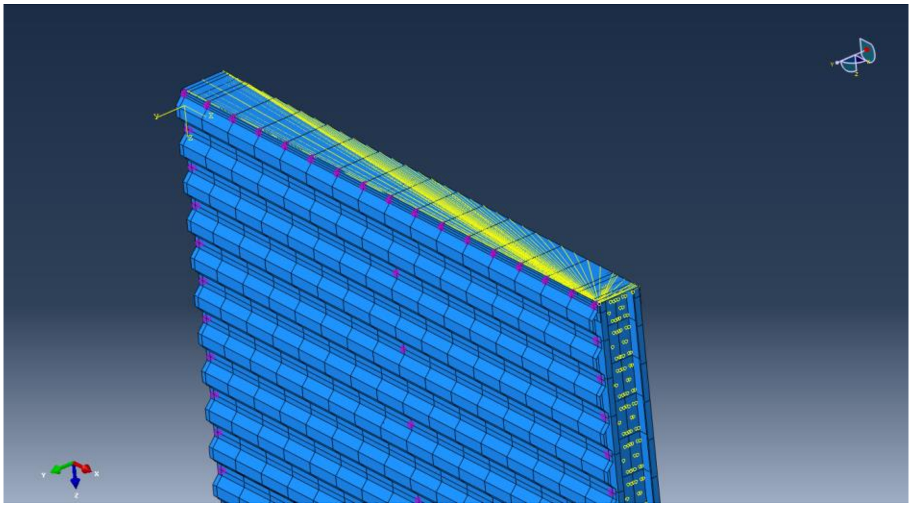


Figure 60 - Loading method

4.8 Simulation Results

Finite element modeling results are compared with test results numerically as well as in terms of deformation and performance. Finite element models were able to show comparable and satisfactory results in both categories and are discussed in this section. The load-deformation response for all models are compared to full scale test results.

Model 1 was able to match the shear wall behavior well prior to the peak load. The peak load from ABAQUS is 13% lower than the test result as shown in Figure 61. The initial stiffness of the model is comparable to the initial stiffness of the full scale test. The ABAQUS model was unable to travel the full displacement due to numerous sheathing connection failures. The shear wall tested failed due to shear buckling of the bottom sheet which cause the screw pull-over failure to happen concurrently. In ABAQUS, the initial failure observed was in the sheathing-to-frame screws. Stress distribution was focused on the bottom corrugated sheet which was in accordance to the test results (Figure 62). The second loss of strength was caused by the local buckling of the chord studs and the distortional buckling of the field stud. Torsional and local buckling of the field stud is also observant in the model (Figure 63).

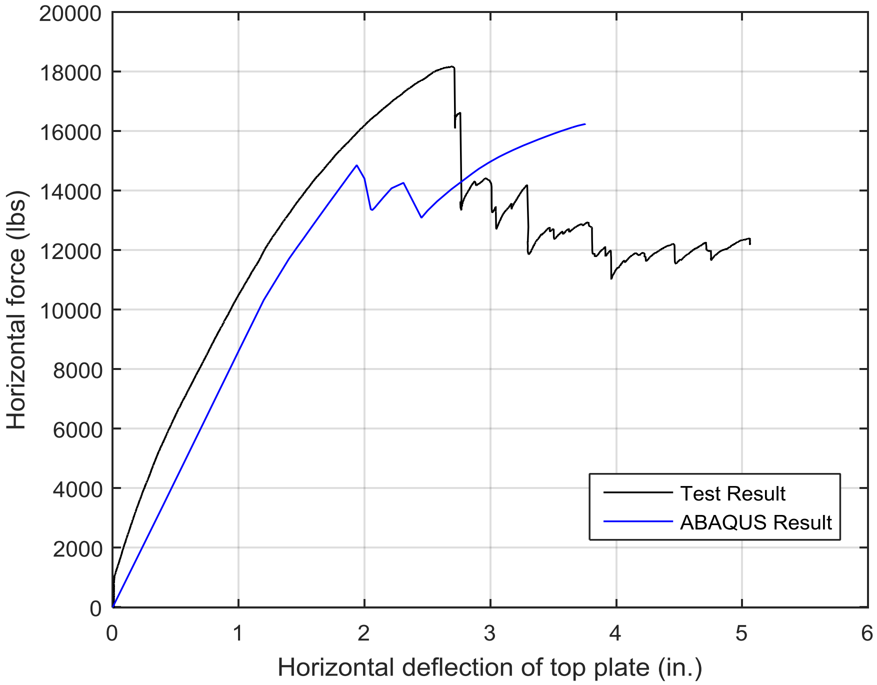


Figure 61 - Model 1 vs. Test 54 results

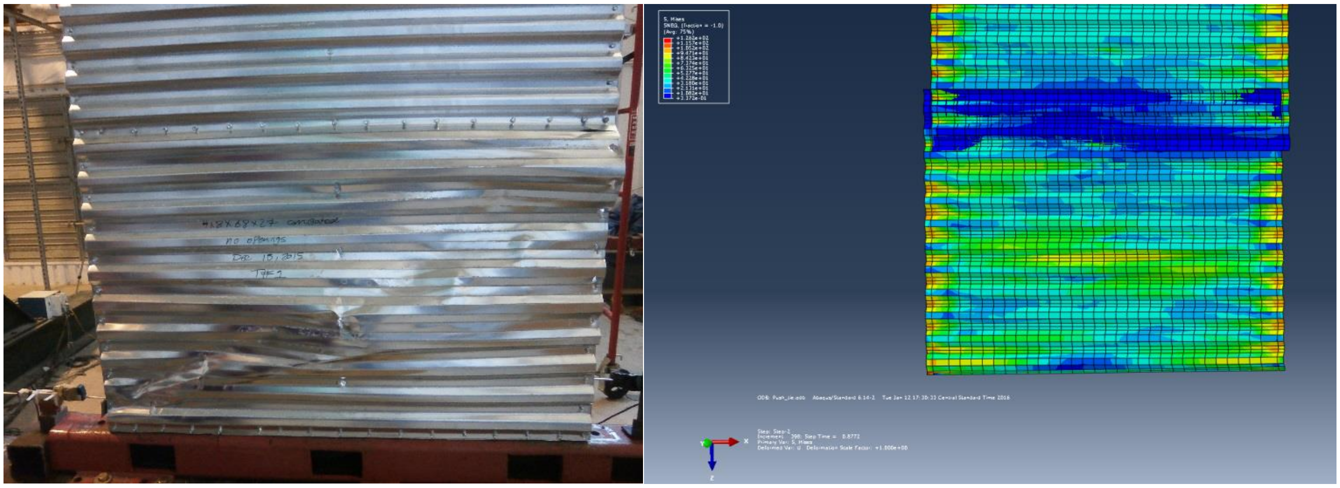


Figure 62 - Model 1: stress distribution on bottom sheet

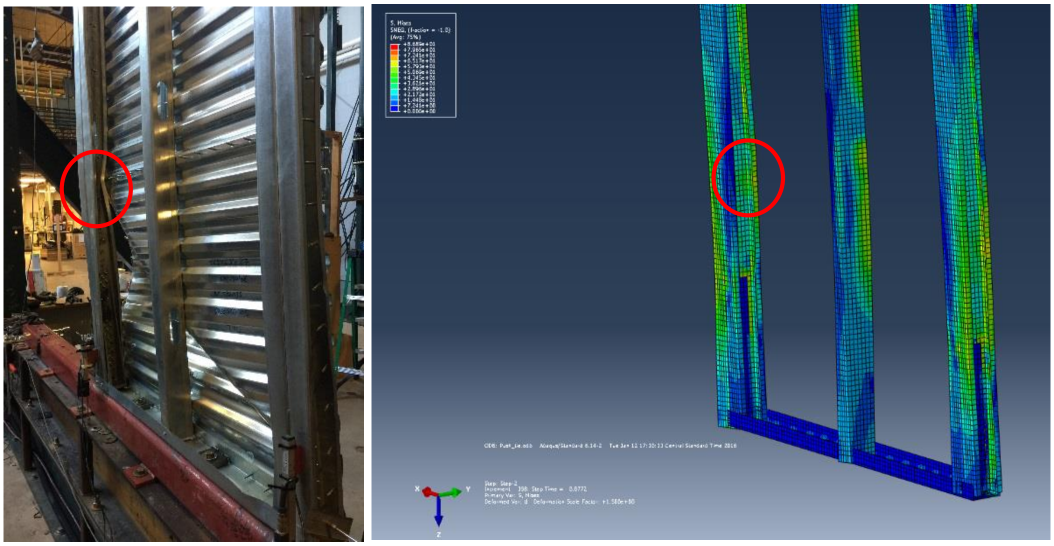


Figure 63 - Model 1: local and distortional buckling of studs

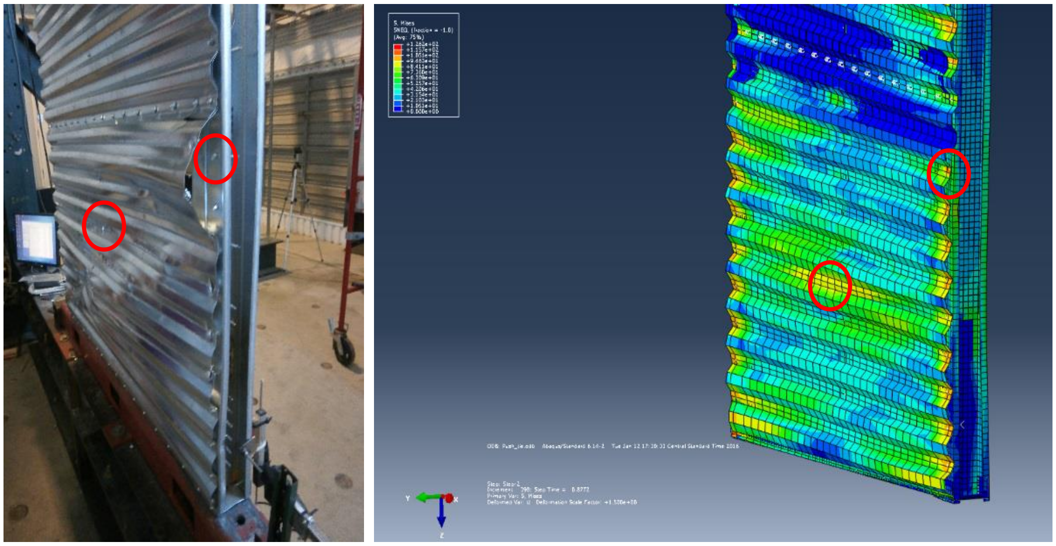


Figure 64 - Model 1: sheathing to frame connection failure

Model 2 was the shear wall model under cyclic lateral loading. This model had an acceptable agreement with the full scale test result. The load-deformation values of the model and the test were nearly identical. The initial stiffness are equal and the average peak loads are only 2% different in value. Figure 65 shows a comparison of the load-deformation responses. The cause of data shortage from ABAQUS can be linked to faulty connection test results. Additional research related to connection tests are necessary to obtain more satisfactory results.

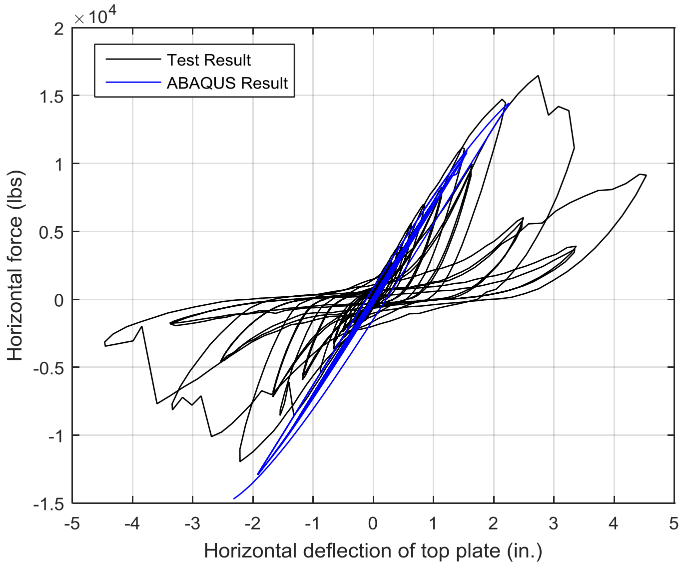


Figure 65 - Model 2 vs. Test 5 results

ABAQUS deformation response illustrated connection failures in the sheathing and stress distribution was concentrated on the middle and top corrugated sheets (Figure 66). Also, a larger local buckling was observant in the studs in comparison to the experimental results (Figure 67). The screw failures at the seams locations were also seen in the model and shown in Figure 68.

Figure 66 - Model 2: sheathing deformation

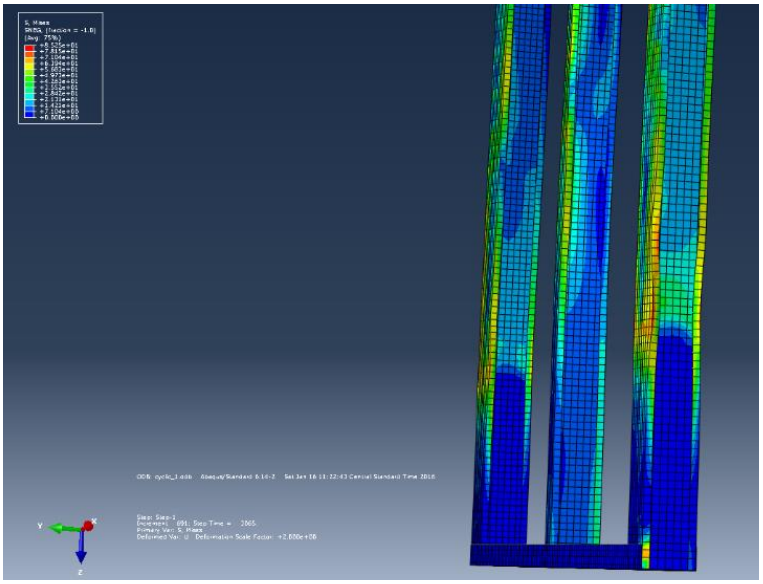


Figure 67 - Model 2: local buckling of stud

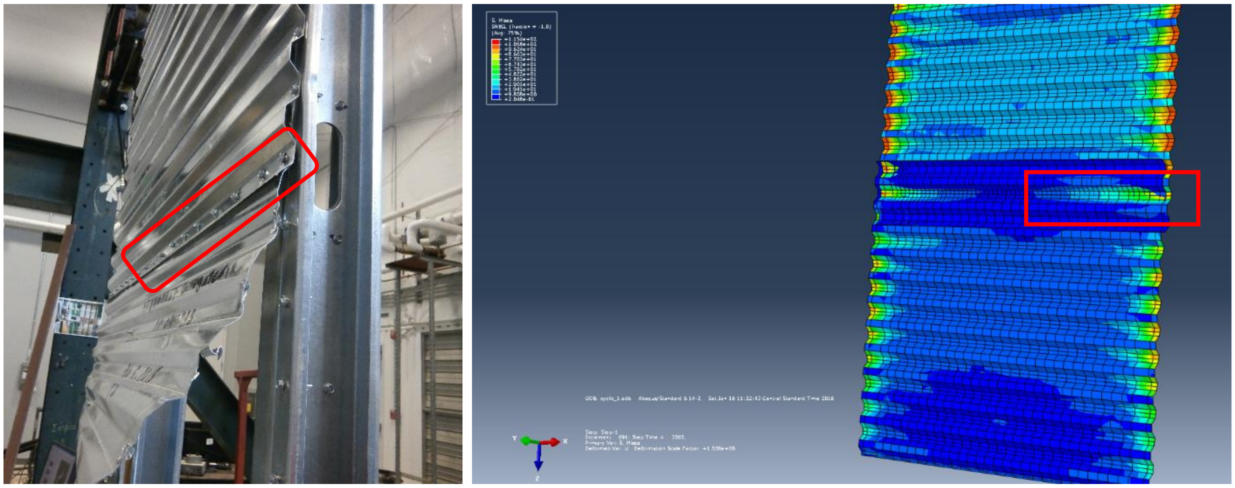


Figure 68 - Model 2: seam screw connection failure

Model 3 is a shear wall under monotonic lateral loading, though it was compared to a shear wall under cyclic loading. Normally, monotonic tests have higher nominal strength and higher initial stiffness in comparison to cyclic tests. The load-deformation results from Model 3 (monotonic) is compared to the average envelope curves of Test 3 and Test 6, shown in Figure 69. For that reason, the strength of the monotonic model is higher than the strength of the cyclic test and is acceptable. The model showed more sheathing deformation on the middle and top sheet in comparison to test results (Figure 70). ABAQUS was unable to show the sheet tearing from the slit locations but did show higher stress at the ends of the slits, shown in Figure 71. The local buckling of the chord stud was also seen in the model. Further work is necessary to be able to characterize the sheet tearing damages and to achieve appropriate tearing simulation results.

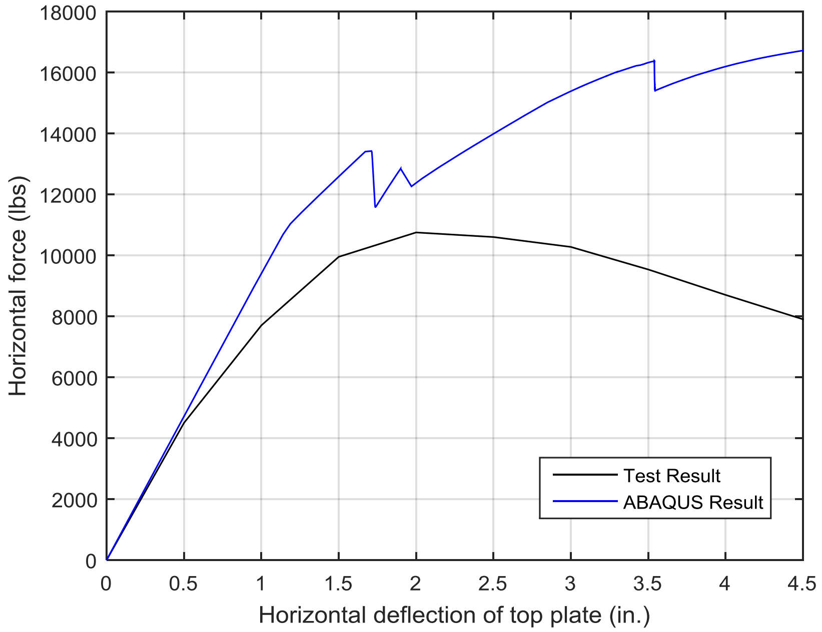


Figure 69 - Model 3 vs. average of Test 3 and Test 6

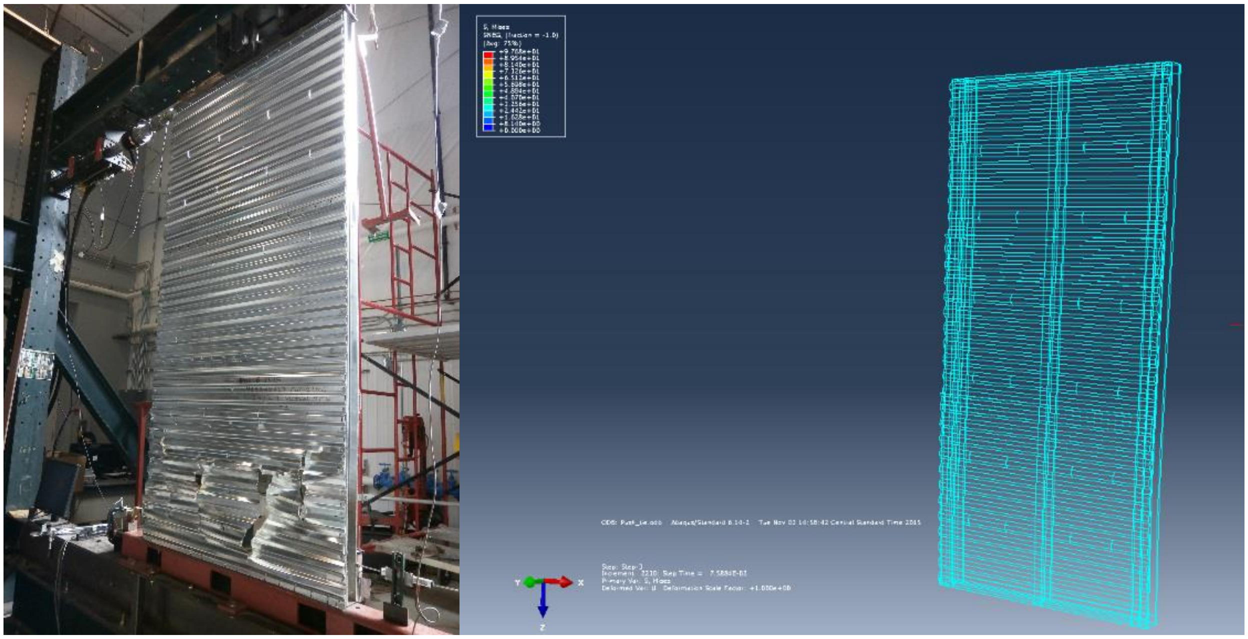


Figure 70 - Model 3: sheathing deformation

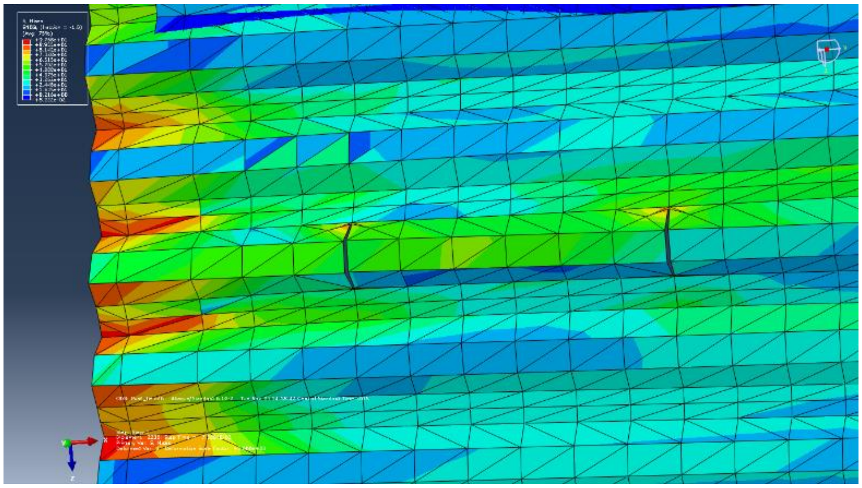


Figure 71 - Model 3: stress distribution at slits

CHAPTER 5

CONCLUSION AND FUTURE WORK

Results from 36 full scale shear wall tests were discussed in details in this thesis. Corrugated steel sheathed shear walls showed higher strength but low ductility in comparison to other shear wall types. Introducing perforations on the sheathing increased the ductility of the new shear wall system. Multiple slit configurations were studied and results indicated that 12×2 in. vertical slits best improved the shear wall performance.

The slits acted as weak points in the shear wall system, therefore the sheathing was damaged the most and the stress focus was taken away from the framing elements. Once the frame has been subject to lateral loading, the sheathing was replaced on the same shear wall framing and tested once again under lateral loading. The shear wall system was able to resist the same amount of lateral loading but showed lower ductility. Using CFS shear walls with perforated corrugated sheathing could be a new seismic retrofitting method for low-rise and mid-rise structures. More research on water proofing, fire resisting, and other improvements have to be done in order to develop a practical product.

Several shear wall configurations were tested. 8×4×68×27 sheet out walls best performed with 12×2 in. vertical slits. 8×4×68×27 sheet in walls showed best results with 300T field framing member and 12×2 in. vertical slits. 8×2×68×27 shear walls performed best with sheet in configuration. It was also concluded that due to the width of the shear wall and reduced surface area, the slits didn't affect the performance of the shear wall system. Lastly, 8×4×54×18 shear walls didn't show satisfactory results due to the thin sheathing which caused weak sheathing connections. The sheathing was more likely to pull over the screws. The 12×2 in. vertical slits may not be the optimal configuration for 54 mil framing and 18 mil sheathing shear walls. Further research is recommended for this shear wall group.

Spot-welded sheathing connections were also investigated in this research. Shear walls with spot-welded connections failed prematurely. Almost all the sheathing connections failed in one unzipping action. The shear wall systems showed low nominal strength and the framing didn’t show any damages. Due to the observed results, it was concluded that spot-welded sheathing connections were inefficient for shear walls.

For the modeling section of this research, various modeling techniques were investigated. It was concluded that framing elements can be tied in shear wall modeling. Contact properties between sheathing and framing surfaces are of great importance. Shear walls under cyclic lateral loading mostly fail due to sheathing connection failure. Therefore, simulating the sheathing connections are of great importance in FEM of shear walls. For shear walls under monotonic lateral loading, SPRING2 nonlinear element was capable of simulating the sheathing connection behavior. For the shear wall under cyclic lateral loading, a general user defined element (UEL) was developed and simulated the screw behavior under cyclic loading. Additional connection tests should be conducted to achieve acceptable results. Also, compatible versions of Fortran and Visual Studio must be available to be able to run the UEL.

Overall, the results from the monotonic model had satisfactory results in comparison to the full scale test. Additional research is needed on the shear wall model under cyclic lateral loading. Also, to simulate the sheet tearing of the perforated corrugated sheathing model, a Fortran subroutine for user defined cohesive elements should be investigated.

This paper was prepared as part of the U.S. National Science Foundation Grant No. 1445065 - Innovative High-Performance Cold-Formed Steel Wall System for Light Framed Construction. The Author would like to thank Verco Decking, Simpson Strong-Tie, and Steel Framing Industry Association for their material donations and contributions.

APPENDIX A

TEST DETAILS

Test No. 11

Opening Type: on openings

Test date: Apr 7, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 362 S 162 - 68, 70 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: plywood

Fastener: # 12 – 14 x 1 - 1/4” pan head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 10780.01 lbs

Lateral displacement of wall top at +peak load: 2.42 in.

-Peak load: 8433.12 lbs

Lateral displacement of wall top at –peak load: 2.107 in.

Average peak load: 9606.565 lbs

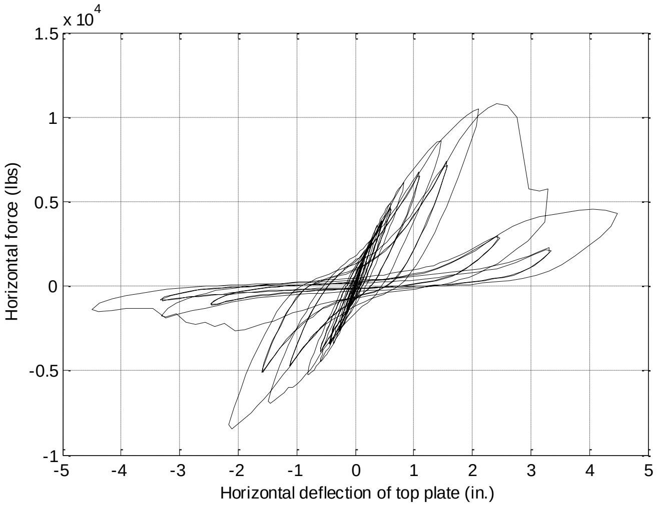
Average lateral displacement of wall top: 2.264 in.

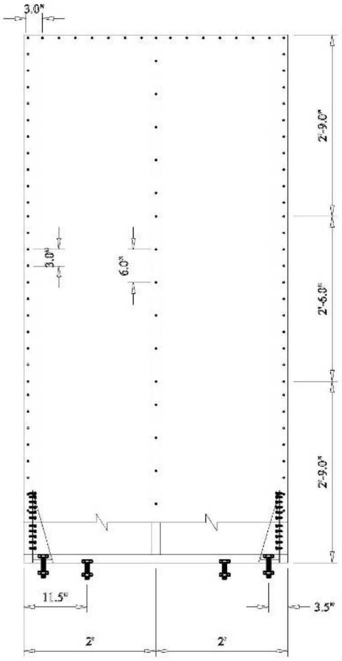
Observed Deformations: local buckling of tracks

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: Yes





Test 11

Test No. 12

Opening Type: on openings

Test date: Apr 9, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 362 S 162 - 68, 70 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: 27 mil flat sheet

Fastener: # 12 – 14 x 1 - 1/4” pan head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 6633.77 lbs

Lateral displacement of wall top at +peak load: 2.2886 in.

-Peak load: 5546.328 lbs

Lateral displacement of wall top at –peak load: 1.6969 in.

Average peak load: 6090.049 lbs

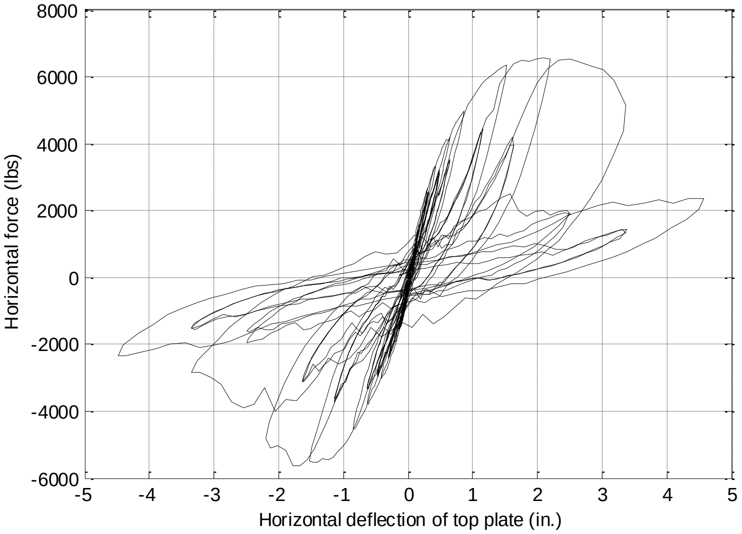
Average lateral displacement of wall top: 2.226 in.

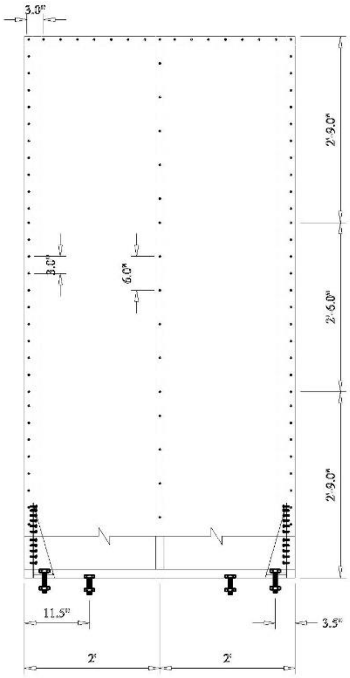
Observed Deformations: local buckling of studs

Screw Pull Out: Yes

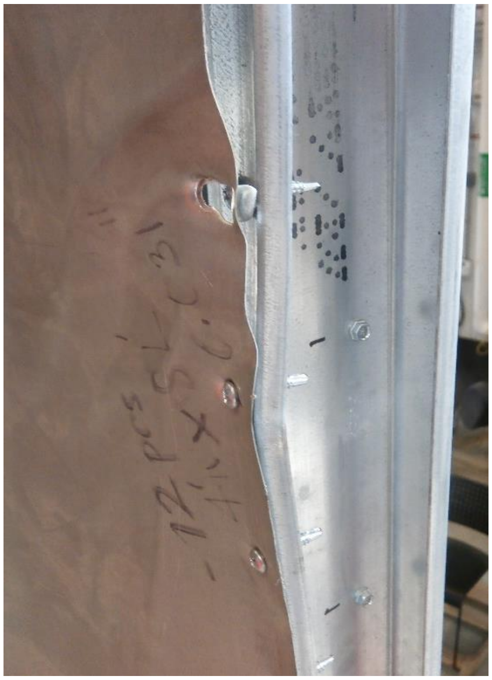
Sheathing Tear: None

Screw Pull Over: Yes





Test 12



Test No. 54

Opening Type: No openings

Test date: Dec. 15, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 200 - 68, 50 ksi Tracks: 350 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4” hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Monotonic

Test results:

+Peak load: 18170.56lbs

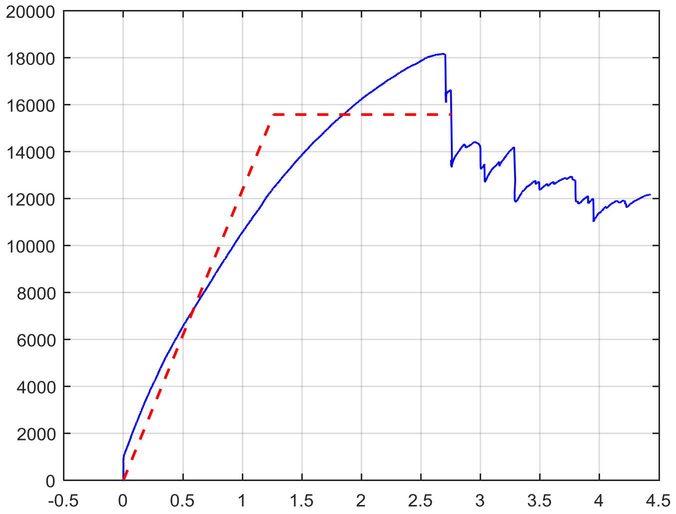
Lateral displacement of wall top at +peak load: 2.70 in.

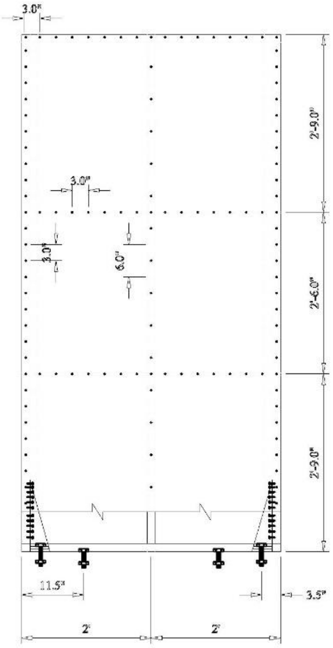
Observed Deformations: local buckling of studs, torsional buckling of stud, track buckled

Screw Pull Out: No

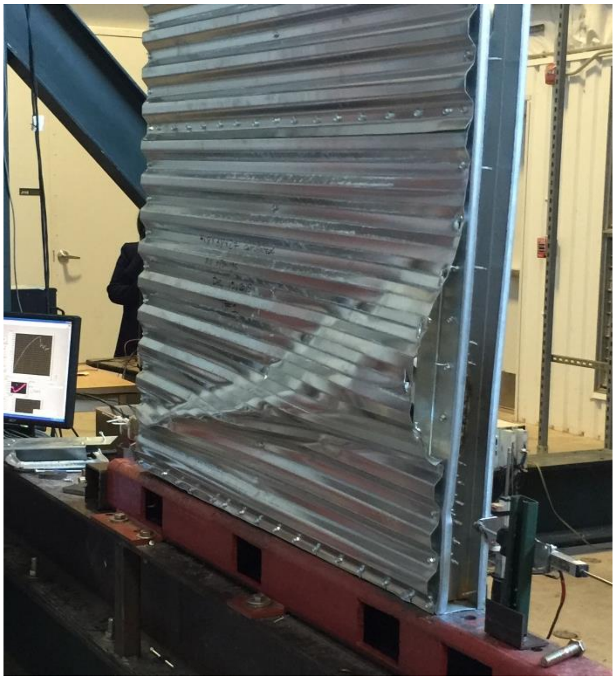
Sheathing Tear: No

Screw Pull Over: Yes





Test 54



Test No. 5

Opening Type: no openings.

Test date: Feb. 05, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4" hex head washer self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 16477.93 lbs

Lateral displacement of wall top at +peak load: 2.737 in.

-Peak load: 11955.79 lbs

Lateral displacement of wall top at –peak load: 2.217 in.

Average peak load: 14216.86 lbs

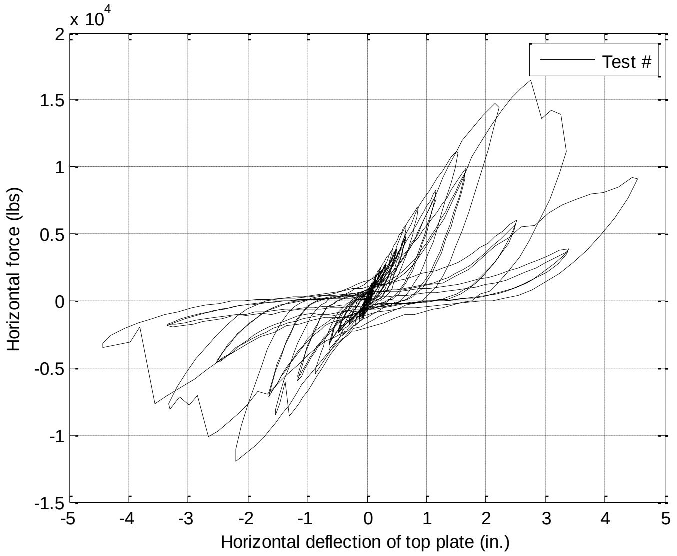
Average lateral displacement of wall top: 2.477 in.

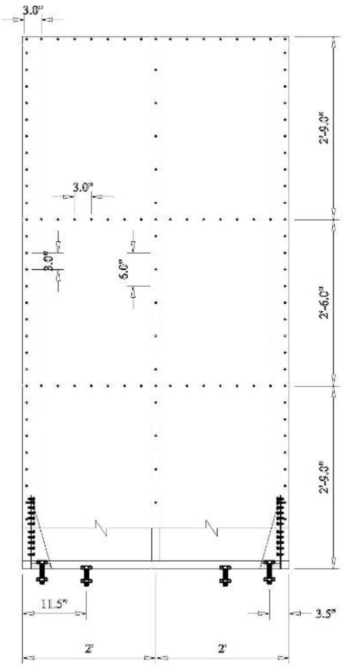
Observed Deformations: bottom track local buckling

Screw Pull Out: Yes

Sheathing Tear: None

Screw pull over: Yes




3.0"
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2'-6.0"
2'-9.0"
11.5"
3.5"
2'
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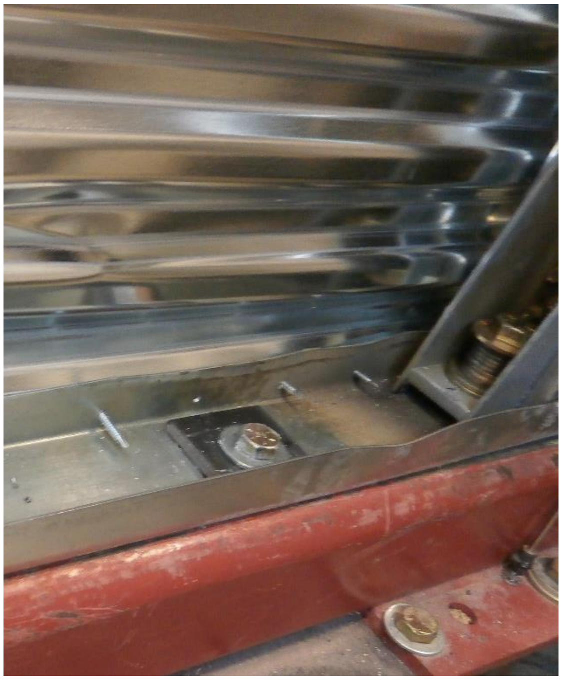
Test 5


4X8X68X24 Corrugated
no openings
Feb 5, 2015
TZ



Test No. 3

Opening Type: 24x2 in. vertical slits

Test date: Jan. 28, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4” hex head washer self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 11448.77 lbs

Lateral displacement of wall top at +peak load: 3.262 in.

-Peak load: 10281.17 lbs

Lateral displacement of wall top at –peak load: 1.939 in.

Average peak load: 10864.97 lbs

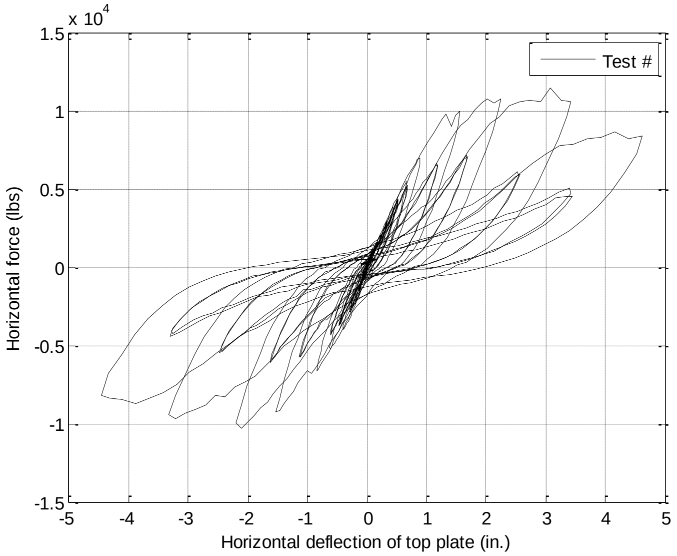
Average lateral displacement of wall top: 2.601 in.

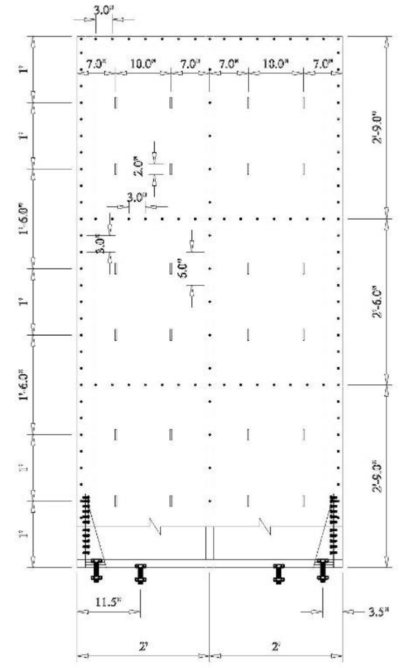
Observed Deformations:

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: Yes

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1'-6.0"
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2'-9.0"
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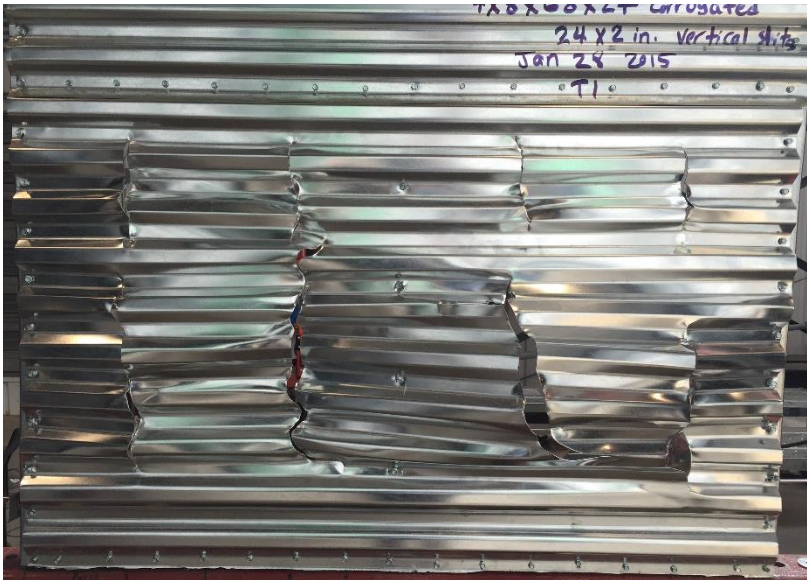
2'-9.0"
2.0"
3.0"
3.0"
5.0"
11.5"
3.5"
2'
2'

Test 3


24 x 2 in. vertical slits
Jan 28 2015
T1

Test No. 6

Opening Type: 24x2-in. vertical slits.

Test date: Feb. 06, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4" hex head washer self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 11318.04 lbs

Lateral displacement of wall top at +peak load: 2.897 in.

-Peak load: 11039.54 lbs

Lateral displacement of wall top at –peak load: 2.008 in.

Average peak load: 11178.79 lbs

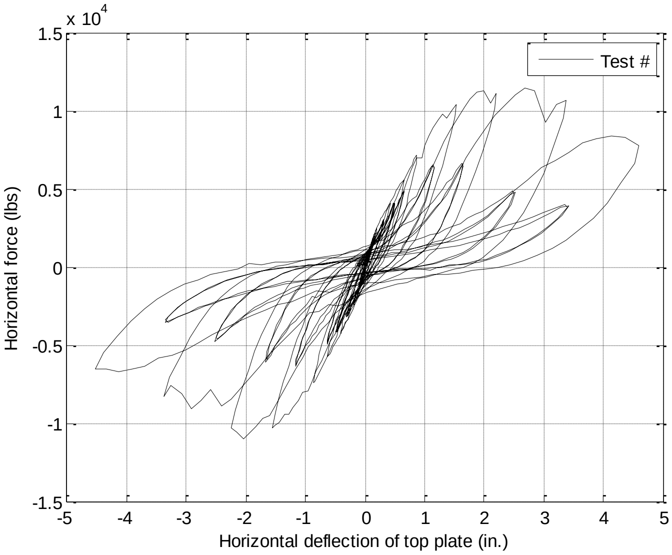
Average lateral displacement of wall top: 2.452 in.

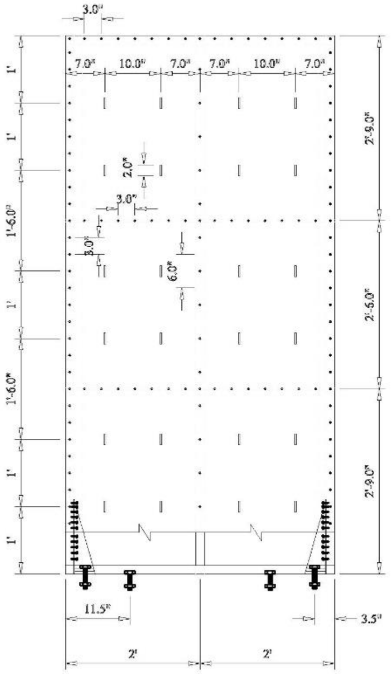
Observed Deformations: local buckling of chord stud, local buckling of track

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: Yes

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2'-6.0"
2'-9.0"
2.0"
3.0"
3.0"
6.0"
11.5"
3.5"
2'
2'

Test 6


Feb 6 2015
4X8X68X27 Corrugated
24X2in. vertical slits
T3

Test No. 7

Opening Type: 24x2 in. vertical slits

Test date: Feb. 11, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4” hex head washer self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 11620.09 lbs

Lateral displacement of wall top at +peak load: 2.237 in.

-Peak load: 11965.94 lbs

Lateral displacement of wall top at –peak load: 2.215 in.

Average peak load: 11793.013 lbs

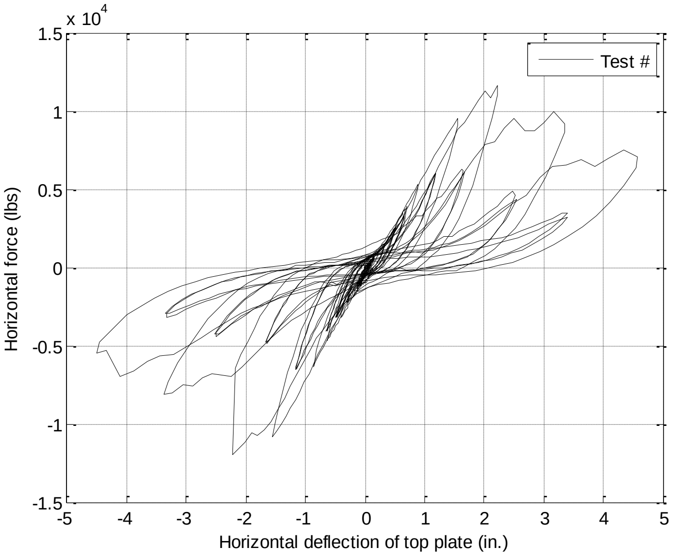
Average lateral displacement of wall top: 2.226 in.

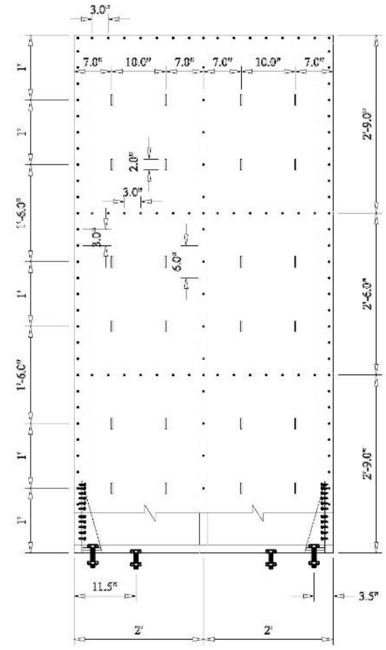
Observed Deformations:

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: Yes

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1'-6.0"
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1'-6.0"
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2'-9.0"
2'-6.0"
2'-9.0"
11.5"
3.5"
2'
2'

Test 7


Feb 11 2015
4x8x68x27 - 24x2 in
vertical slits
T #4

Test No. 13

Opening Type: 12x2 in vertival slits

Test date: Apr 14, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 362 S 162 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 – 14 x 1 - 1/4" pan head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 13280 lbs

Lateral displacement of wall top at +peak load: 2.971 in.

-Peak load: 10630 lbs

Lateral displacement of wall top at –peak load: 3.1 in.

Average peak load: 11955 lbs

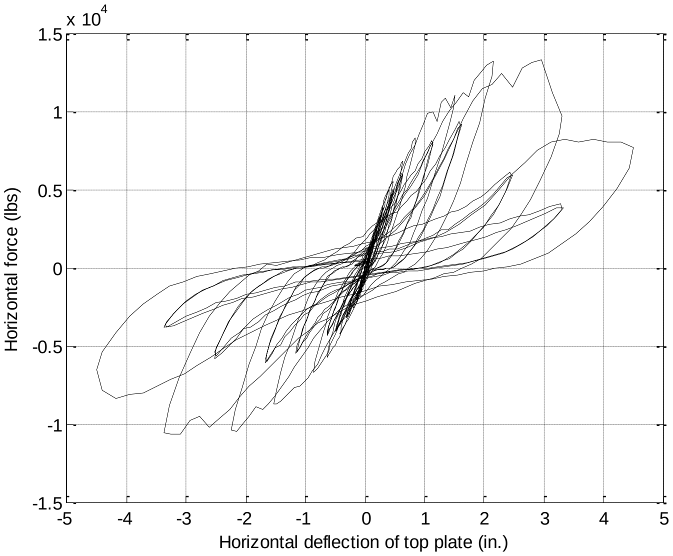
Average lateral displacement of wall top: 3.036 in.

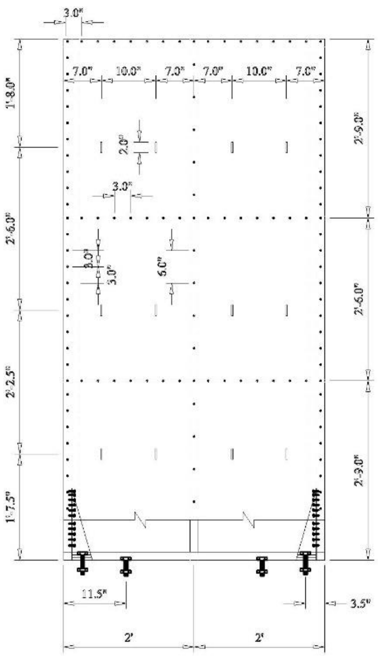
Observed Deformations: local buckling of chord stud

Screw Pull Out: None

Sheathing Tear: Yes

Screw Pull Over: Yes

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2'-6.0"
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2'-9.0"
2'-6.0"
2'-9.0"
2.0"
3.0"
3.0"
3.0"
6.0"
11.5"
3.5"
2'
2'

Test 13


4 x 8 x 68 x 24 corrugated
12 x 2 in. vertical slits
April 14, 2015
T#1

Test No. 15

Opening Type: 12x2 in vertical slits

Test date: May. 21, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft.   Studs: 350 S 162 - 68, 50 ksi   Tracks: 350 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4” hex head washer self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 12852.44 lbs

Lateral displacement of wall top at +peak load: 2.56 in.

-Peak load: 12174.68 lbs

Lateral displacement of wall top at –peak load: 2.25 in.

Average peak load: 12513.56 lbs

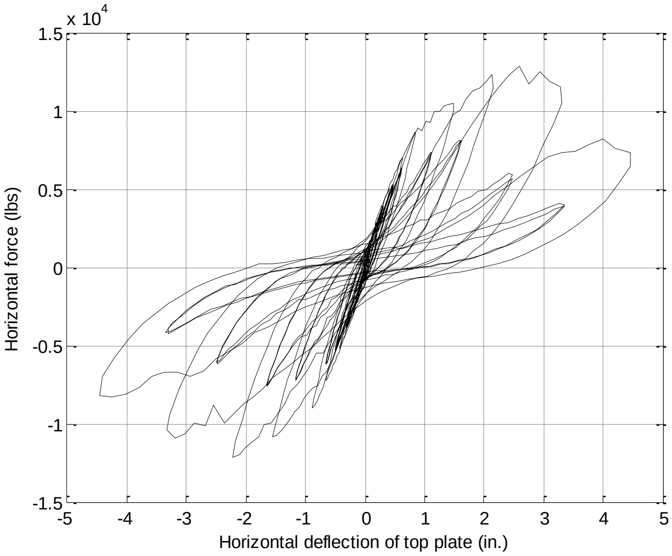
Average lateral displacement of wall top: 2.405 in.

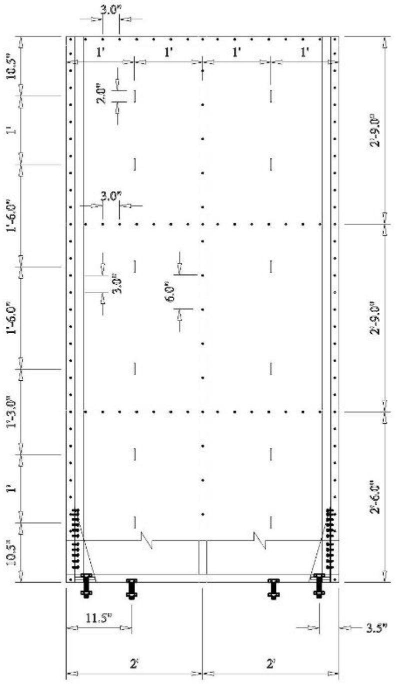
Observed Deformations: no harm to frame

Screw Pull Out: None

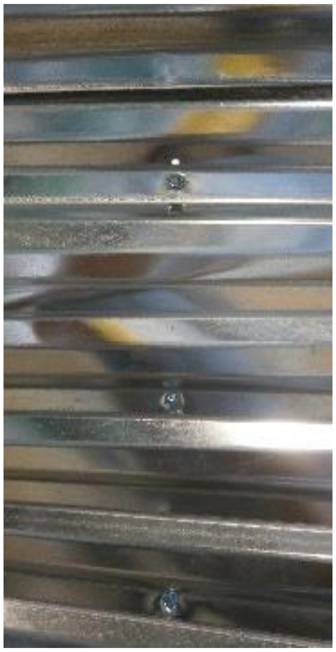
Sheathing Tear: Yes

Screw Pull Over: Yes





Test 15



Test No. 19

Opening Type: 12x2 in vertical slits

Test date: May. 27, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 68, 50 ksi Tracks: 350 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4” hex head washer self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 12260 lbs

Lateral displacement of wall top at +peak load: 2. 52 in.

-Peak load: 12424.25 lbs

Lateral displacement of wall top at –peak load: 2.13 in.

Average peak load: 12342.25 lbs

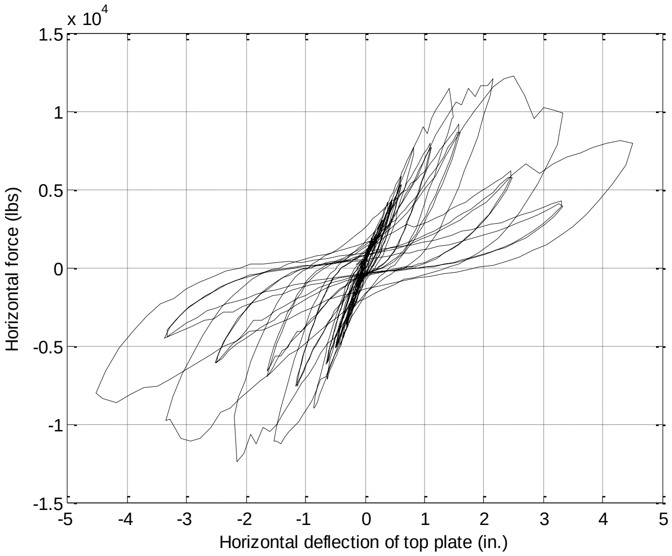
Average lateral displacement of wall top: 2.33 in.

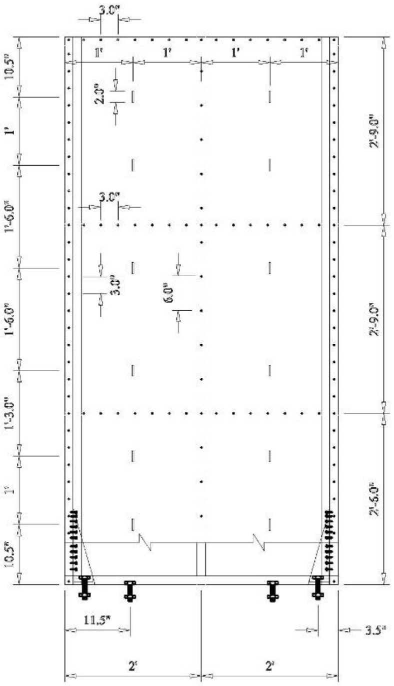
Observed Deformations: local buckling of chord stud

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: Yes





Test 19

Test No. 29

Opening Type: 12x2 in vertical slits staggered

Test date: July. 29, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 68, 50 ksi Tracks: 350 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4” hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 13517.17 lbs

Lateral displacement of wall top at +peak load: 2.22 in.

-Peak load: 12859.7 lbs

Lateral displacement of wall top at –peak load: 2.18 in.

Average peak load: 13188.71 lbs

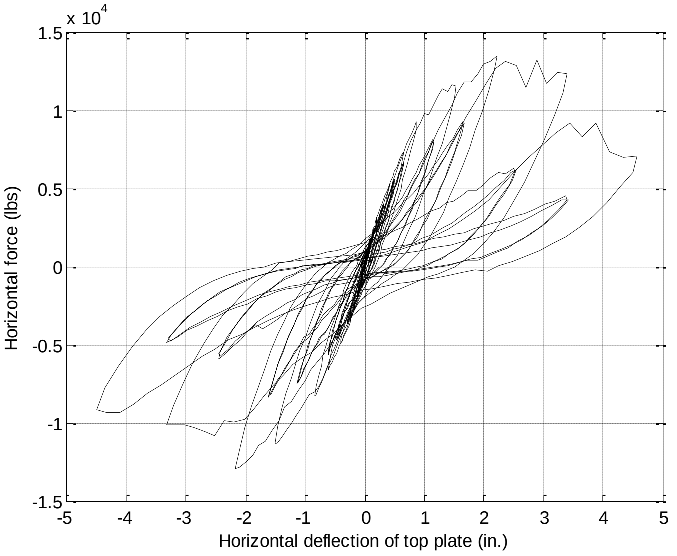
Average lateral displacement of wall top: 2.20 in.

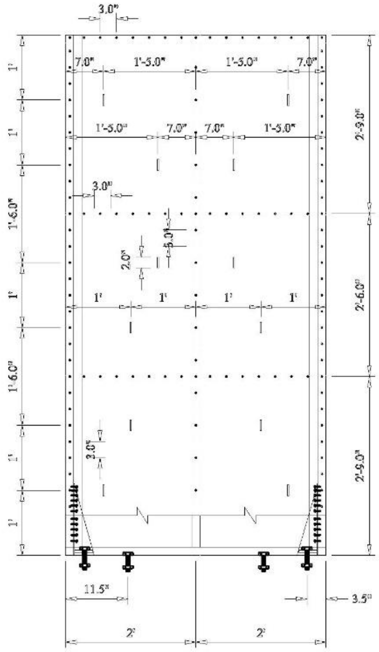
Observed Deformations: minor buckling of chord stud

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: Yes

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2'
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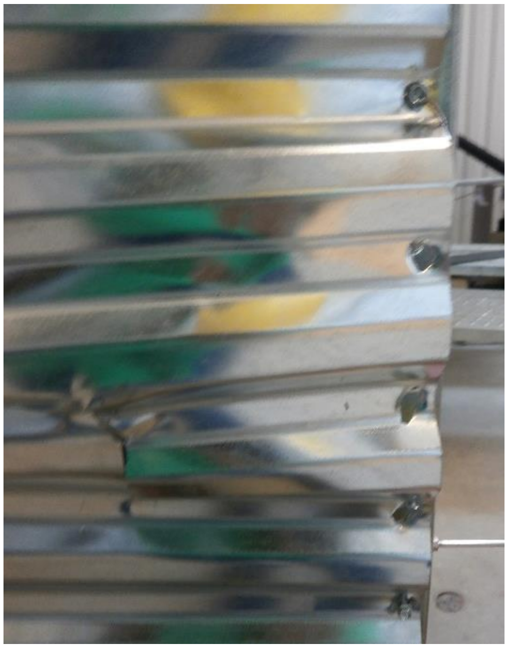
Test 29



Test No. 30

Opening Type: 24x1 in vertical slits

Test date: Aug. 17, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 68, 50 ksi Tracks: 350 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4" hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 16611.94 lbs

Lateral displacement of wall top at +peak load: 2.64 in.

-Peak load: 15698.13 lbs

Lateral displacement of wall top at –peak load: 2.16 in.

Average peak load: 16155.03 lbs

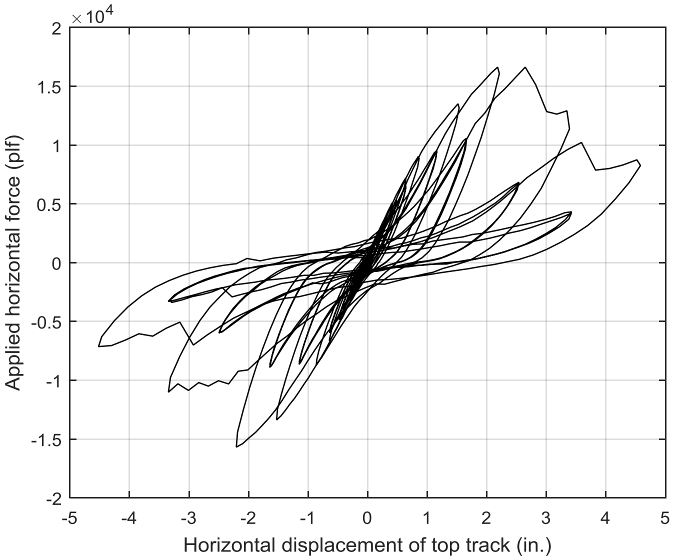
Average lateral displacement of wall top: 2.43 in.

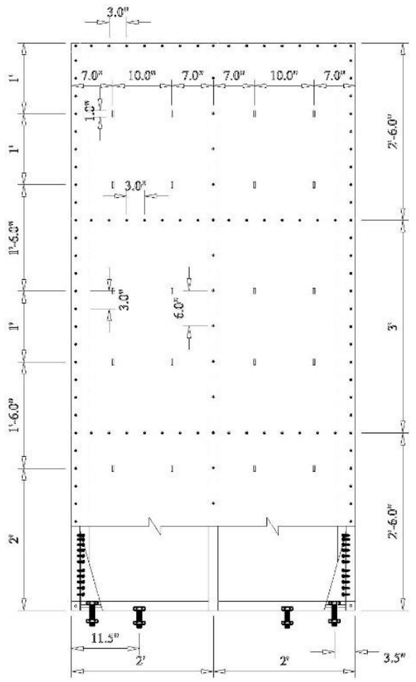
Observed Deformations: local buckling of chord stud and bottom track

Screw Pull Out: None

Sheathing Tear: Yes

Screw Pull Over: Yes

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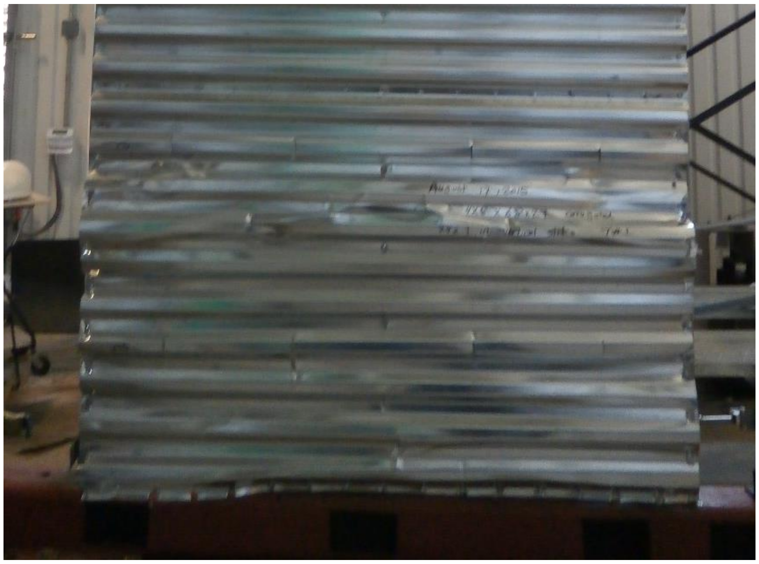
2'
2'
3.5"

Test 30


ated
T#1



Test No. 8

Opening Type: Sheet in - no openings

Test date: Mar. 09, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: " 350 T 150 - 68, 50 ksi " Tracks: 362 T 150 - 68, 33 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 – 14 x 1 - 1/4" pan head washer self-drilling screws, 3 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 8887.83 lbs

Lateral displacement of wall top at +peak load: 1.58 in.

-Peak load: 7529.866 lbs

Lateral displacement of wall top at –peak load: 1.39 in.

Average peak load: 8208.848 lbs

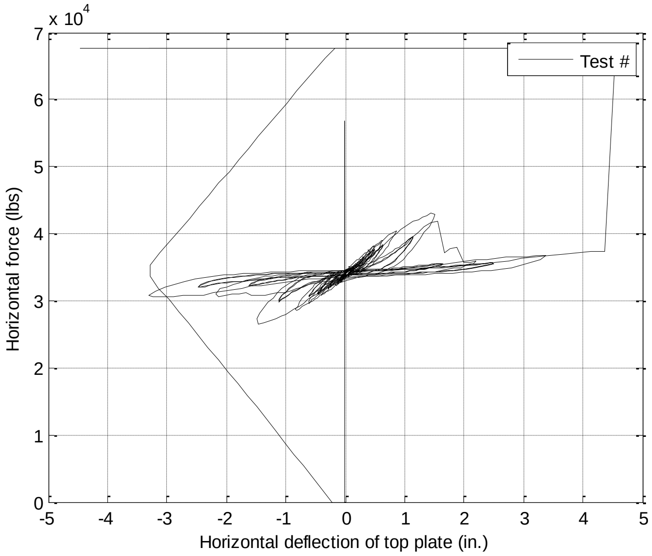
Average lateral displacement of wall top: 1.485 in.

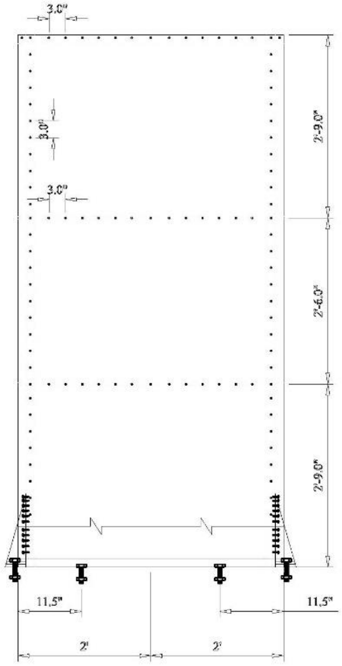
Observed Deformations: local and distortional buckling of vertical tracks

Screw Pull Out: Yes

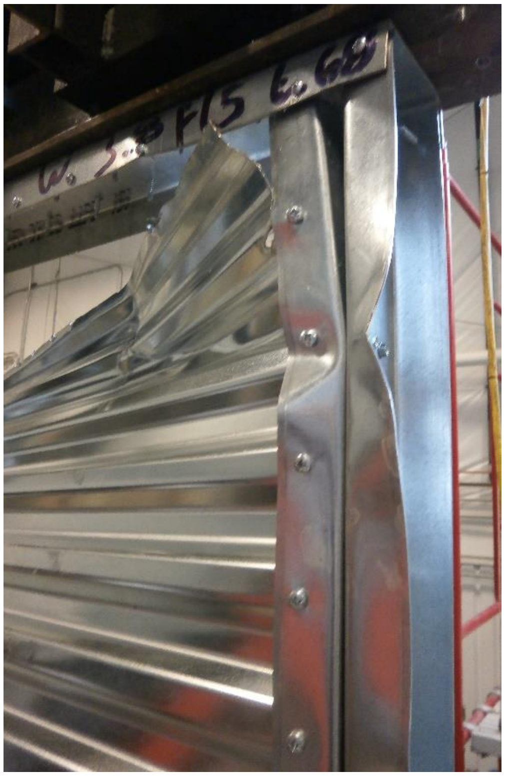
Sheathing Tear: No

Screw Pull Over: Yes





Test 8



Test No. 9

Opening Type: Sheet in - no openings

Test date: Mar. 17, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 T 150 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 -14 x 1 - 1/4” pan head washer self-drilling screws, 3 in. spacing, 1.5 in. on top track

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 11124.82 lbs

Lateral displacement of wall top at +peak load: 2.118 in.

-Peak load: 11022.16 lbs

Lateral displacement of wall top at –peak load: 2.202 in.

Average peak load: 11073.49 lbs

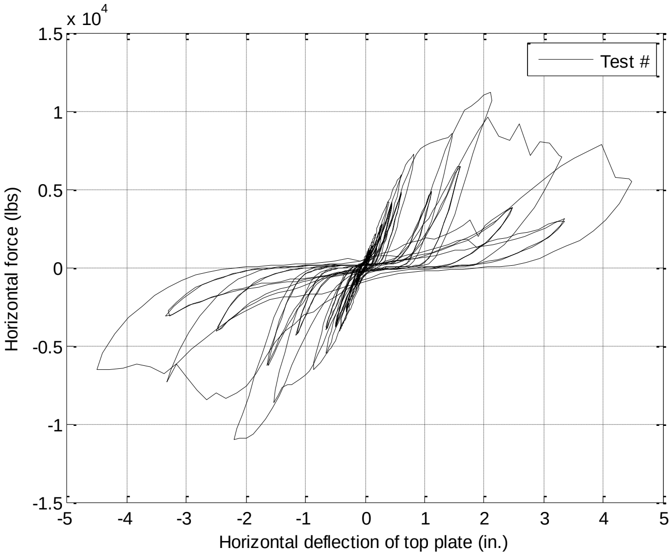
Average lateral displacement of wall top: 2.16 in.

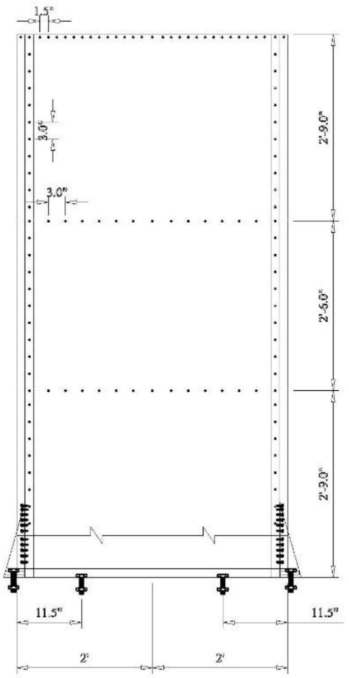
Observed Deformations: local buckling of chrod tracks

Screw Pull Out: Yes

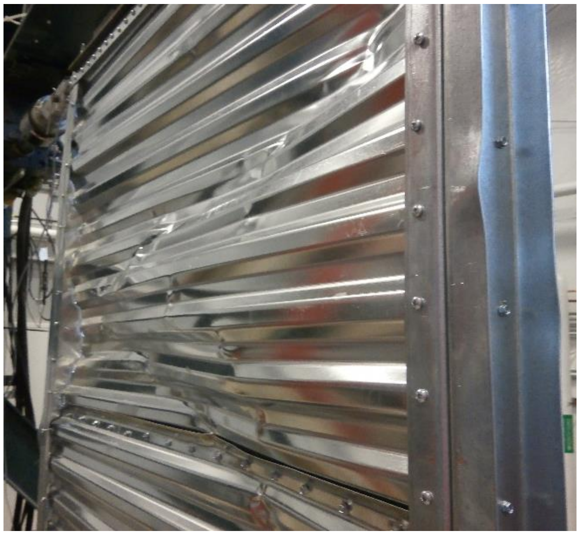
Sheathing Tear: None

Screw Pull Over: None





Test 9



Test No. 10

Opening Type: sheet in – triple tracks – no openings

Test date: Mar. 18, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 T 150 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 -14 x 1 - 1/4” pan head washer self-drilling screws, 3 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 13434.89 lbs

Lateral displacement of wall top at +peak load: 2.057 in.

-Peak load: 12611.12 lbs

Lateral displacement of wall top at –peak load: 2.192 in.

Average peak load: 13023 lbs

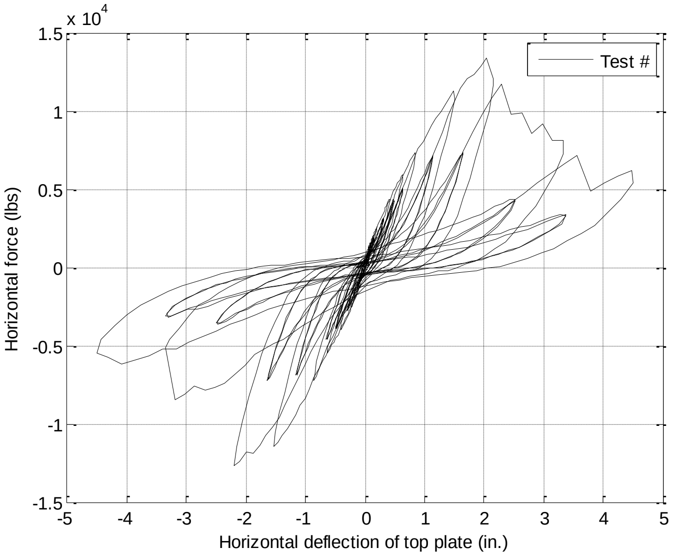
Average lateral displacement of wall top: 2.124 in.

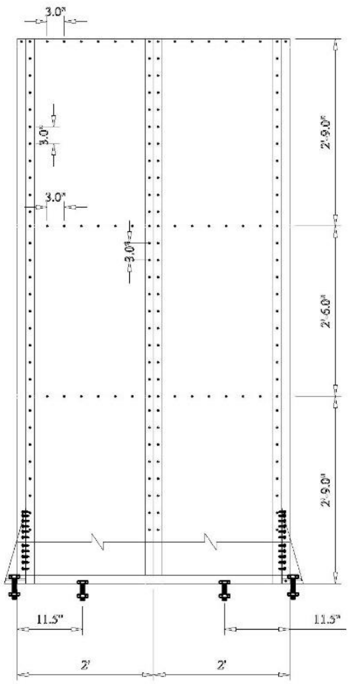
Observed Deformations: local buckling of vertical tracks

Screw Pull Out: None

Sheathing Tear: None

Screw Pull Over: Yes

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3.0"
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2'-5.0"
2'-9.0"
11.5"
11.5"
2'
2'

Test 10


68X27 Corrugated
triple tracks
th no openings
18, 2015

Test No. 14

Opening Type: triple tracks 24x2 in. vert slits

Test date: Apr. 15, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: "350 T 150 - 68, 50 ksi " Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 -14 x 1 - 1/4" pan head washer self-drilling screws, 3 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 12809.33 lbs

Lateral displacement of wall top at +peak load: 3.109 in.

-Peak load: 11094.63 lbs

Lateral displacement of wall top at –peak load: 3.289 in.

Average peak load: 11951.98 lbs

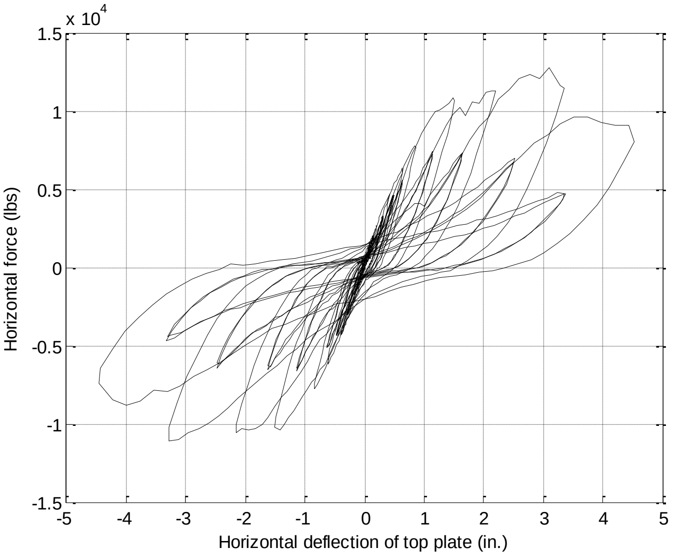
Average lateral displacement of wall top: 3.2 in.

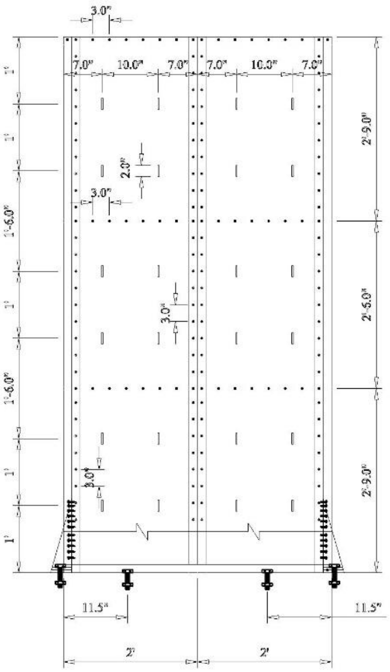
Observed Deformations: local buckling of vertical tracks

Screw Pull Out: None

Sheathing Tear: Yes

Screw Pull Over: Yes

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3.0"
2'-5.0"
3.0"
2'-9.0"
1'
1'
1'-6.0"
1'
1'-6.0"
1'
1'
11.5"
11.5"
2'
2'

Test 14

Test No. 21

Opening Type: triple tracks 12x2 in. vert slits

Test date: May. 28, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 T 150 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 -14 x 1 - 1/4” pan head washer self-drilling screws, 3 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 13341 lbs

Lateral displacement of wall top at +peak load: 2. 97 in.

-Peak load: 11548.8 lbs

Lateral displacement of wall top at –peak load: 2.15 in.

Average peak load: 12444.9 lbs

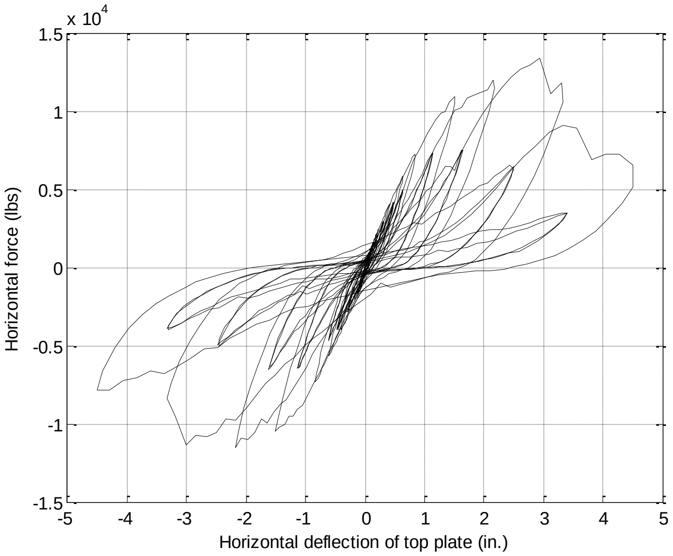
Average lateral displacement of wall top: 2.56 in.

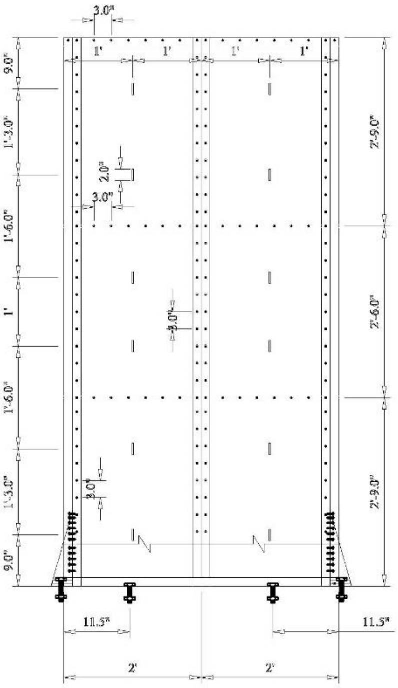
Observed Deformations: local buckling of vertical tracks

Screw Pull Out: None

Sheathing Tear: Yes

Screw Pull Over: Yes





Test 21

Test No. 55

Opening Type: No openings

Test date: Dec. 22, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: " 350 T 150 - 68, 50 ksi " Tracks: 362 T 150 - 68, 50 ksi

Middle track: 300 T 200 – 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 pan head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 16350.08lbs

Lateral displacement of wall top at +peak load: 2.11 in.

-Peak load: 15403.60lbs

Lateral displacement of wall top at –peak load: 1.98 in.

Average peak load: 15876.84 lbs

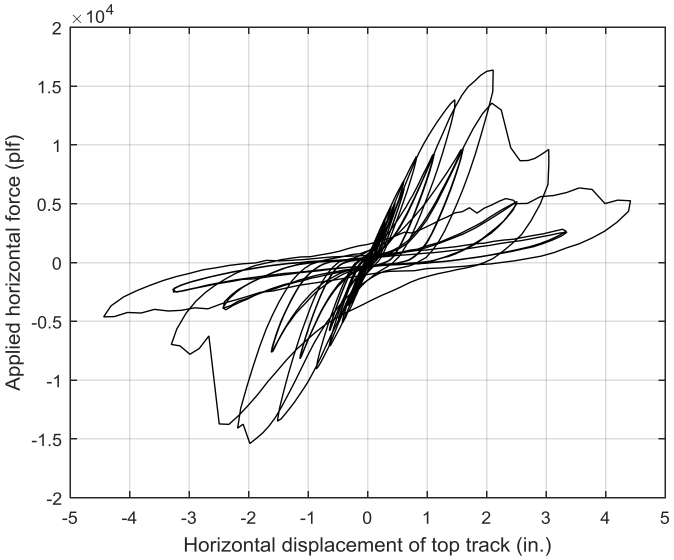
Average lateral displacement of wall top: 2.05 in.

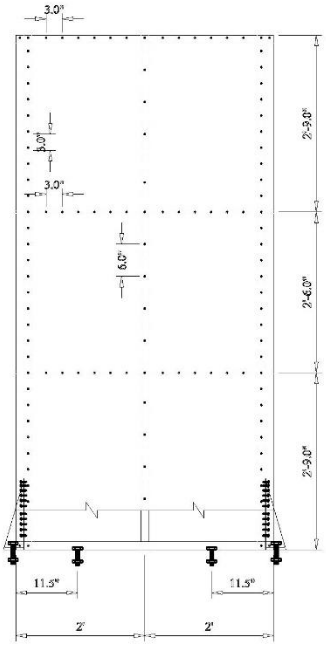
Observed Deformations: torsional buckling of tracks, screw break, middle track local buckling, boundary tracks buckled at bottom

Screw Pull Out: Yes

Sheathing Tear: No

Screw Pull Over: No




3.0"
6.0"
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6.0"
2'-9.0"
2'-6.0"
2'-9.0"
11.5"
11.5"
2'
2'

Test 55


4x8x68x27 corrugated
triple tracks
with 300T
no openings
Dec 22, 2015
T#1

Test No. 56

Opening Type: No openings

Test date: Jan. 13, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: "350 T 150 - 68, 50 ksi" Tracks: 362 T 150 - 68, 50 ksi

Middle track: 300 T 200 – 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 pan head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 15888.85lbs

Lateral displacement of wall top at +peak load: 2.54 in.

-Peak load: 16094.00lbs

Lateral displacement of wall top at –peak load: 2.12 in.

Average peak load: 15991.43 lbs

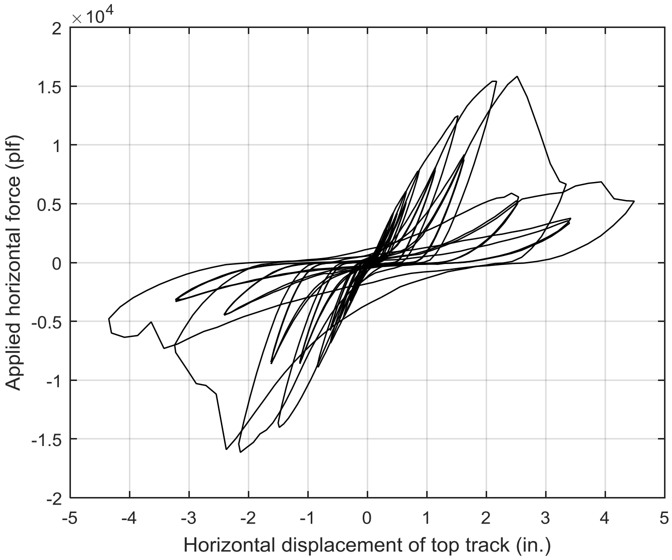
Average lateral displacement of wall top: 2.33 in.

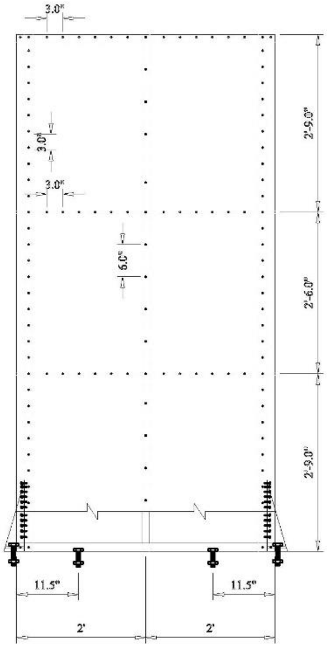
Observed Deformations: screw broken on middle sheet, local buckling of vertical tracks, frame screw on middle track broke

Screw Pull Out: No

Sheathing Tear: No

Screw Pull Over: Yes





Test 56

Test No. 57

Opening Type: 12x2 in. vertical slits

Test date: Jan. 22, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: “350 T 150 - 68, 50 ksi” Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 pan head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 14051.80 lbs

Lateral displacement of wall top at +peak load: 2.64 in.

-Peak load: 13230.90 lbs

Lateral displacement of wall top at –peak load: 2.15 in.

Average peak load: 13641.35 lbs

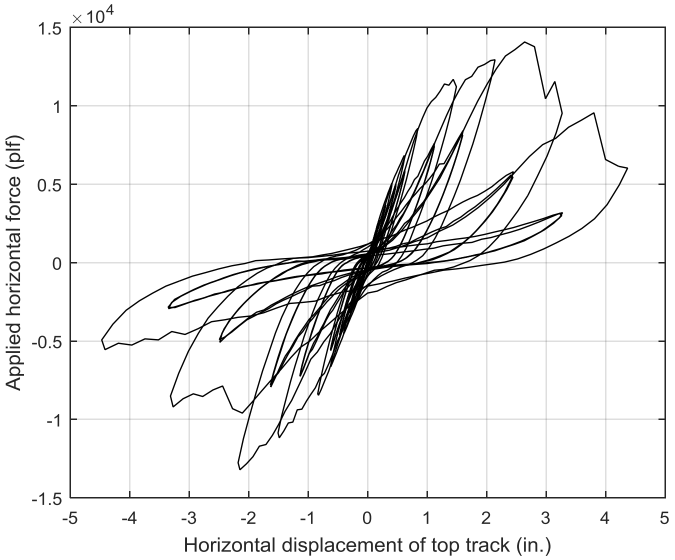
Average lateral displacement of wall top: 2.40 in.

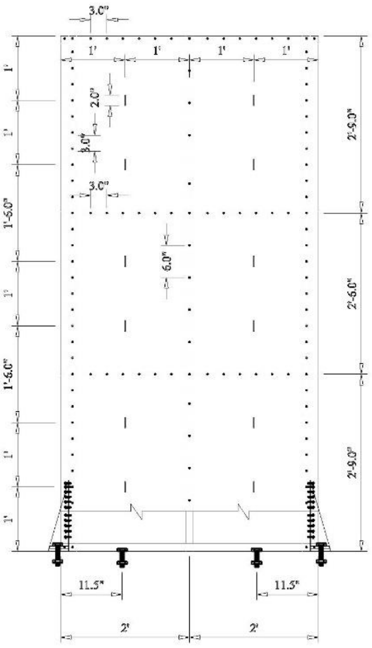
Observed Deformations: screw break on middle sheet, local buckling of vertical tracks

Screw Pull Out: No

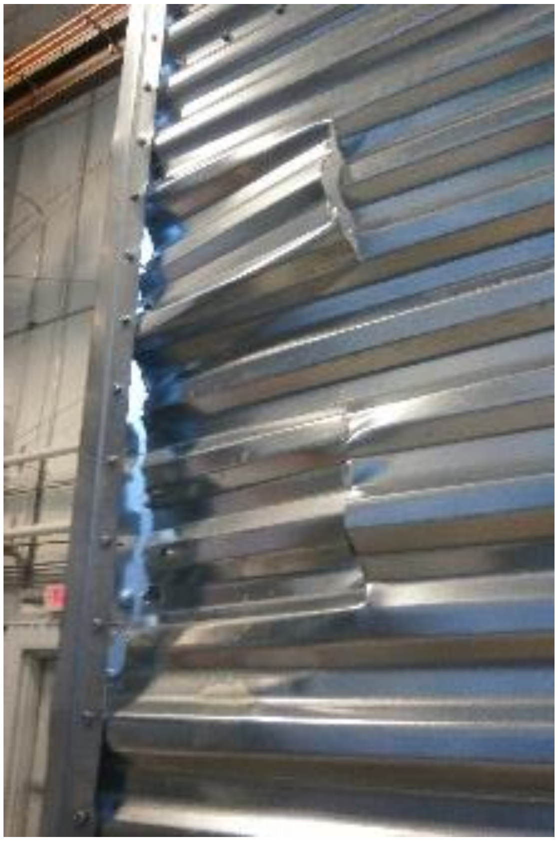
Sheathing Tear: Yes

Screw Pull Over: Yes





Test 57



Test No. 58

Opening Type: 12x2 in. vertical slits

Test date: Feb. 03, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: "350 T 150 - 68, 50 ksi" Tracks: 362 T 150 - 68, 50 ksi

Middle track: 300 T 200 – 86, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 pan head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 12450.81 lbs

Lateral displacement of wall top at +peak load: 1.8 in.

-Peak load: 11554.30 lbs

Lateral displacement of wall top at –peak load: 1.51 in.

Average peak load: 12002.56 lbs

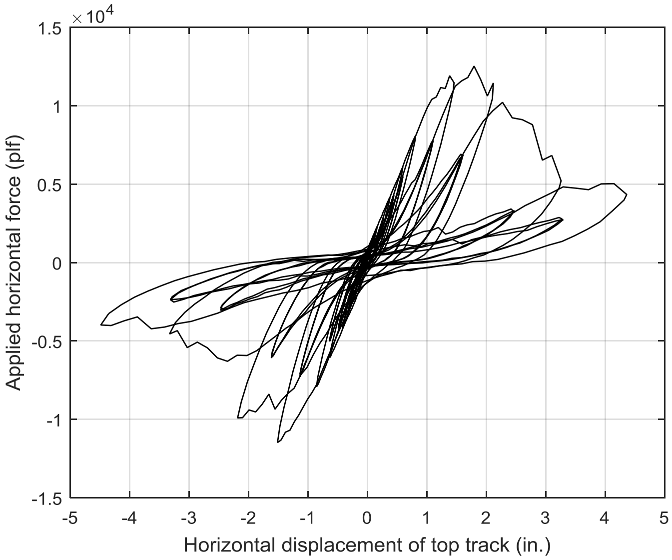
Average lateral displacement of wall top: 1.66 in.

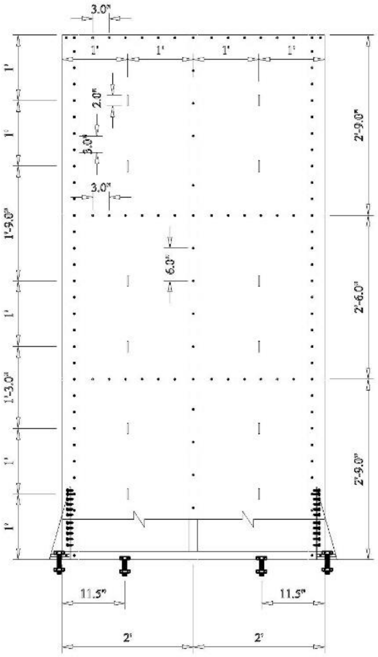
Observed Deformations: gap between middle track and bottom track caused framing screw to break, screw break on bottom and middle sheet, local buckling of vertical tracks

Screw Pull Out: None

Sheathing Tear: Yes

Screw Pull Over: Yes





Test 58

Test No. 61

Opening Type: 12x2 in. vertical slits

Test date: Feb. 08, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: “350 T 150 - 68, 50 ksi” Tracks: 362 T 150 - 68, 50 ksi

Middle track: 300 T 200 – 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 pan head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 13424.31 lbs

Lateral displacement of wall top at +peak load: 2.80 in.

-Peak load: 11423.10 lbs

Lateral displacement of wall top at –peak load: 2.13 in.

Average peak load: 12423.21 lbs

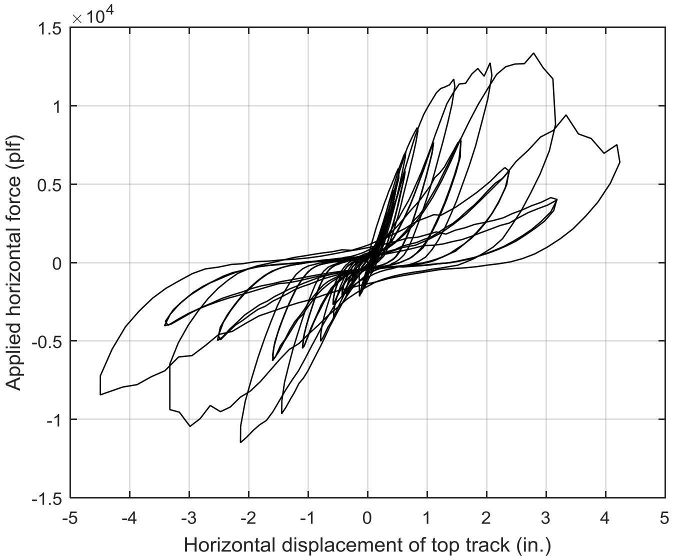
Average lateral displacement of wall top: 2.47 in.

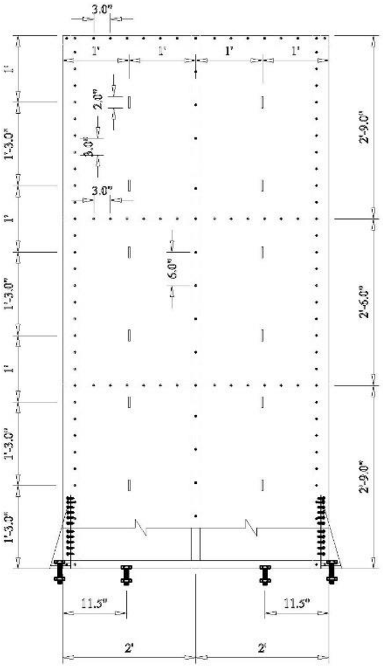
Observed Deformations: local buckling of vertical tracks, screw break, middle sheet most deformation

Screw Pull Out: No

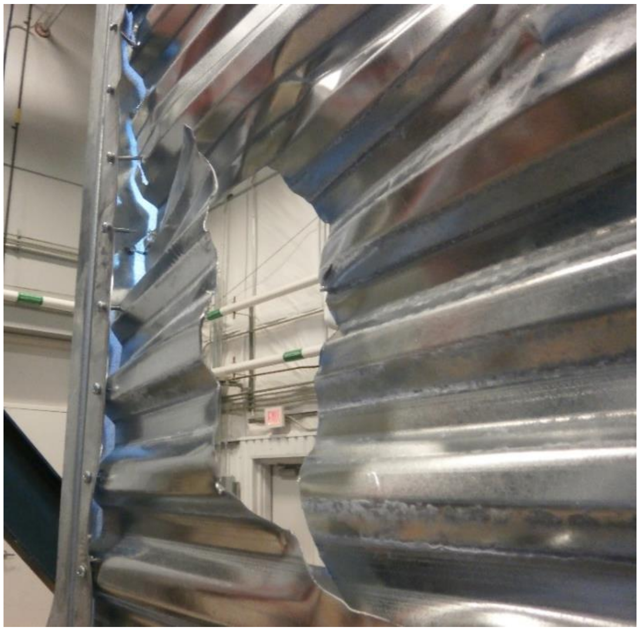
Sheathing Tear: Yes

Screw Pull Over: Yes





Test 61



Test No. 28

Opening Type: no openings SW

Test date: July. 20, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 68, 50 ksi Tracks: 350 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: Spot Weld

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 3105.6 lbs

Lateral displacement of wall top at +peak load: 0.34 in.

-Peak load: 2312.9 lbs

Lateral displacement of wall top at –peak load: 0.17 in.

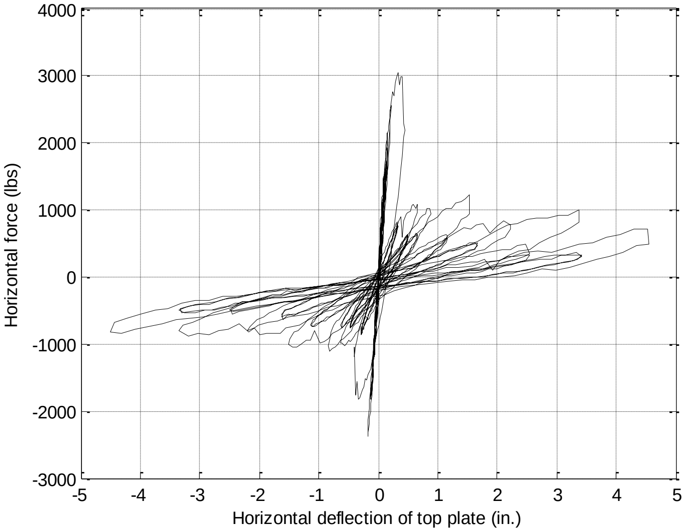
Average peak load: 2709.25 lbs

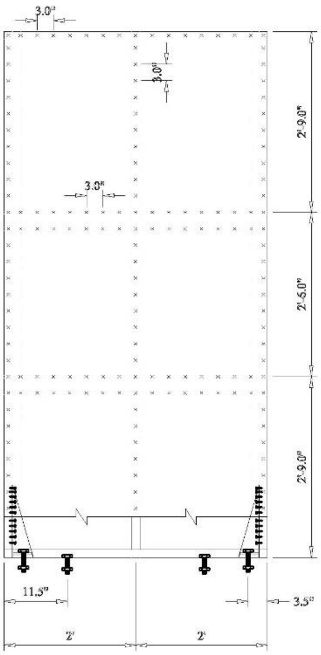
Average lateral displacement of wall top: 0.26 in.

Observed Deformations: no damage to frame

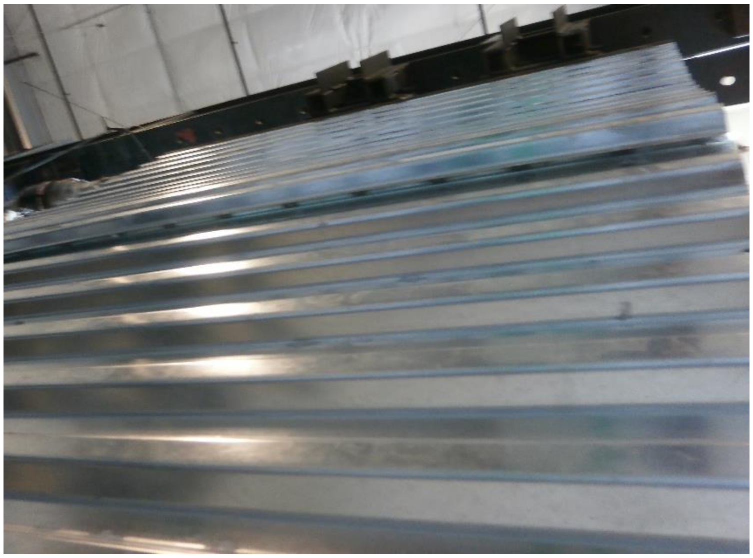
Sheathing Tear: None

Wall failed prematurely, top sheet to sheet separated first then middle sheet, frame unharmed





Test 28



Test No. 59

Opening Type: No openings SW (9-60)

Test date: Feb. 05, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 200 - 68, 50 ksi Tracks: 350 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: Spot welded (9 volt, 60 cycle), 3 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 7710.20 lbs

Lateral displacement of wall top at +peak load: 0.67 in.

-Peak load: 7004.20 lbs

Lateral displacement of wall top at –peak load: 0.59 in.

Average peak load: 7357.20 lbs

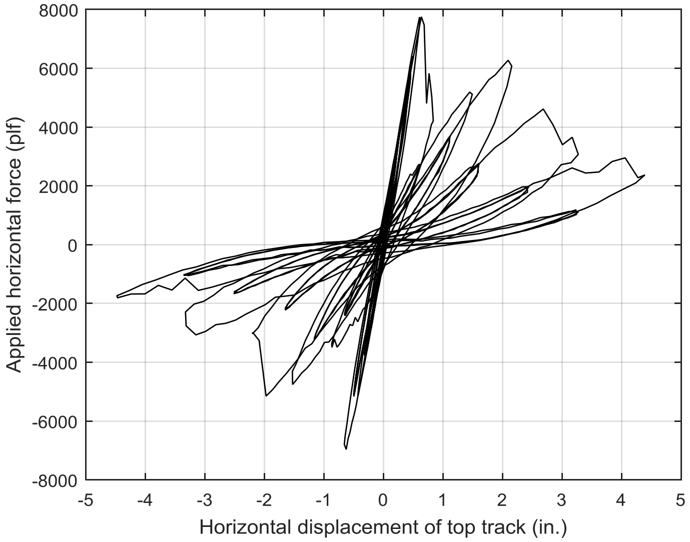
Average lateral displacement of wall top: 0.63 in.

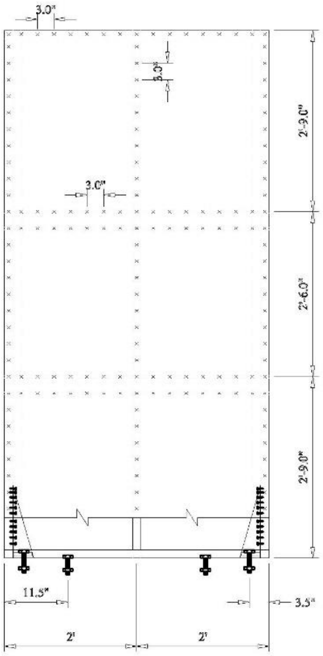
Observed Deformations: connection failure at spot welds occurred in all sheets, no damage to frame

Screw Pull Out: Yes (Sheet corner screw)

Sheathing Tear: No

Screw Pull Over: No





Test 59

Test No. 32

Opening Type: No openings

Test date: Aug. 19, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 2 ft. Studs: 350 S 162 - 68, 50 ksi Tracks: 350 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4" hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 9018.30 lbs

Lateral displacement of wall top at +peak load: 4.61 in.

-Peak load: 7038.09 lbs

Lateral displacement of wall top at –peak load: 3.27 in.

Average peak load: 8028.19 lbs

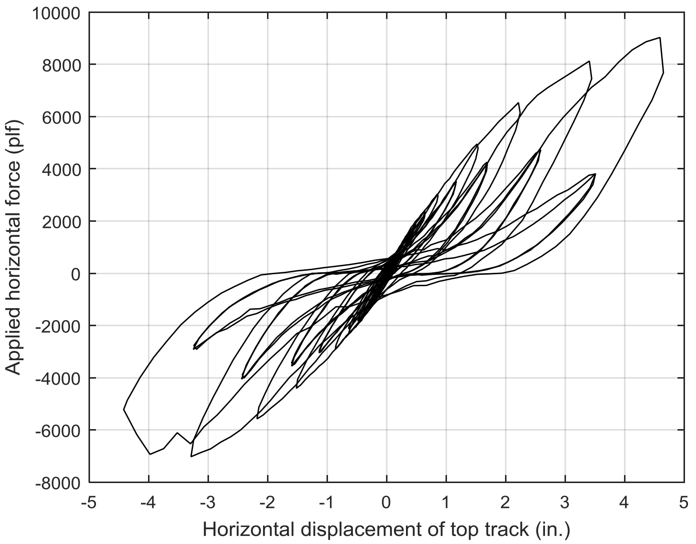
Average lateral displacement of wall top: 3.94 in.

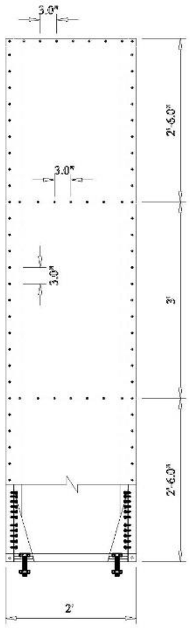
Observed Deformations: local buckling of ottom track

Screw Pull Out: Yes

Sheathing Tear: None

Screw Pull Over: Yes





Test 32

Test No. 33

Opening Type: 6 x 2 in. vertical slits

Test date: Aug. 20, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 2 ft. Studs: 350 S 162 - 68, 50 ksi Tracks: 350 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4” hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 8619.74 lbs

Lateral displacement of wall top at +peak load: 4.48 in.

-Peak load: 7093.93 lbs

Lateral displacement of wall top at –peak load: 3.18 in.

Average peak load: 7856.83 lbs

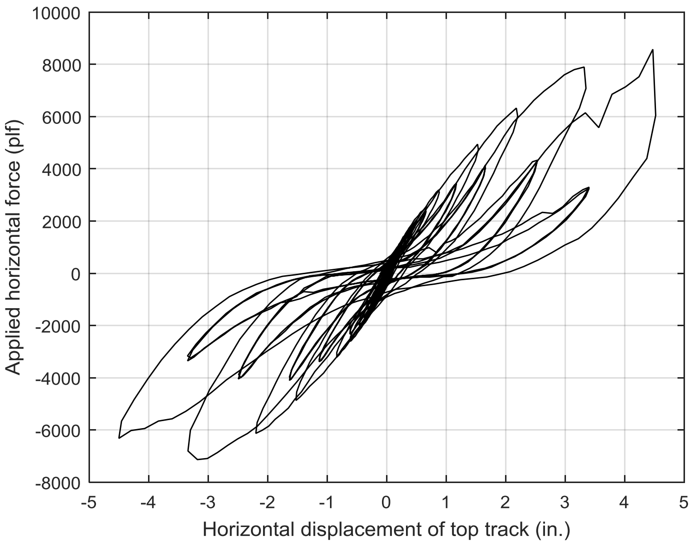
Average lateral displacement of wall top: 3.83 in.

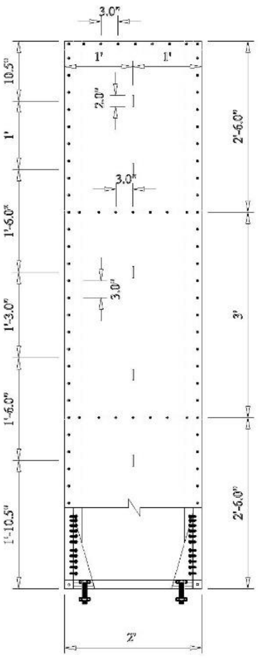
Observed Deformations:

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: Yes





Test 33

Test No. 45

Opening Type: No openings

Test date: Nov. 5, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 2 ft. Studs: 350 T 150 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4” hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 6639.93 lbs

Lateral displacement of wall top at +peak load: 3.29 in.

-Peak load: 6315.43 lbs

Lateral displacement of wall top at –peak load: 2.13 in.

Average peak load: 6477.68 lbs

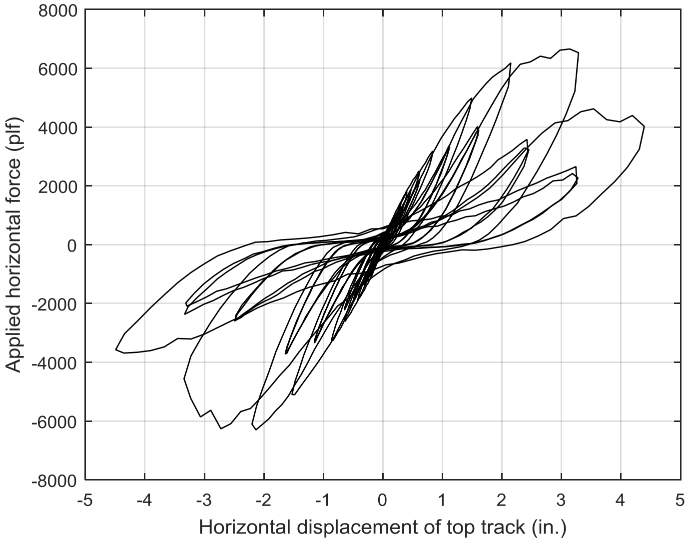
Average lateral displacement of wall top: 2.71 in.

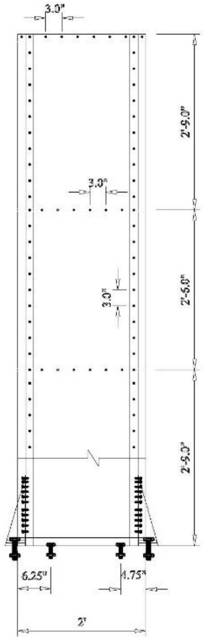
Observed Deformations: local buckling of vertical tracks

Screw Pull Out: None

Sheathing Tear: None

Screw Pull Over: Yes




3.0"
2'-9.0"
3.0"
2'-5.0"
3.0"
2'-9.0"
6.25"
4.75"
2'

Test 45


2x8x68x27 corrugated
all tracks no openings
Nov 5/2015
T#1


corrugated
enings

Test No. 46

Opening Type: 6 x 2 in. vertical slits

Test date: Nov. 6, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 2 ft. Studs: 350 T 150 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4" hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 6174.18 lbs

Lateral displacement of wall top at +peak load: 3.20 in.

-Peak load: 5658.03 lbs

Lateral displacement of wall top at –peak load: 2.14 in.

Average peak load: 5916.11 lbs

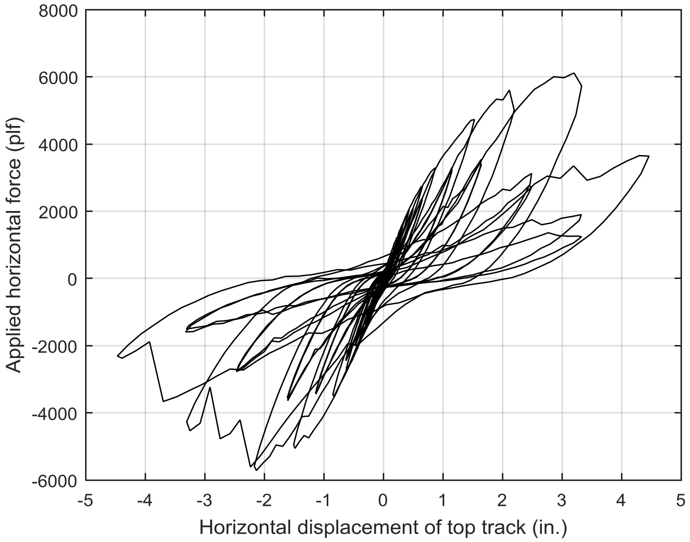
Average lateral displacement of wall top: 2.67 in.

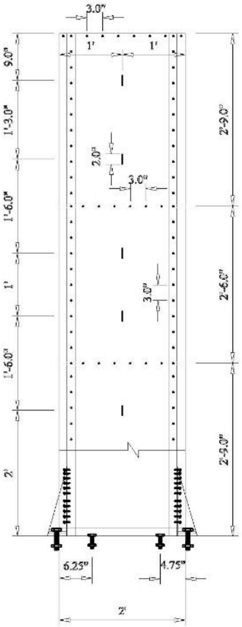
Observed Deformations: local buckling of vertical tracks

Screw Pull Out: None

Sheathing Tear: Yes

Screw Pull Over: Yes





Test 46

Test No. 47

Opening Type: No openings

Test date: Nov. 11, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 2 ft. Studs: 350 T 150 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4” hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 8013.80 lbs

Lateral displacement of wall top at +peak load: 3.03 in.

-Peak load: 6921.51 lbs

Lateral displacement of wall top at –peak load: 2.16 in.

Average peak load: 7467.66 lbs

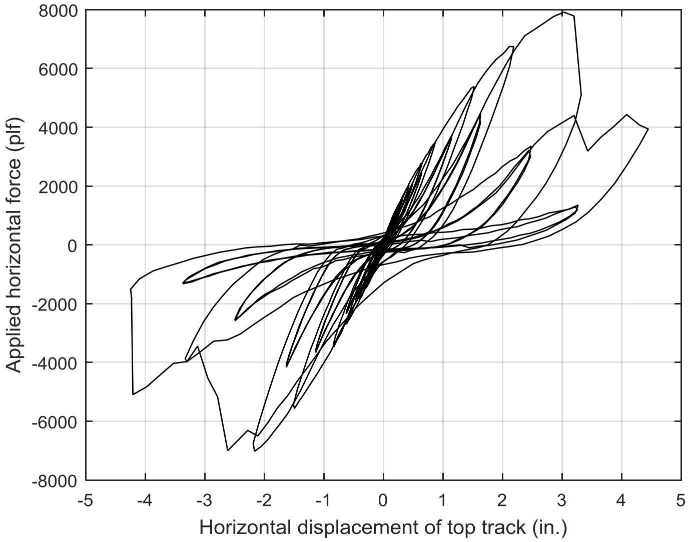
Average lateral displacement of wall top: 2.60 in.

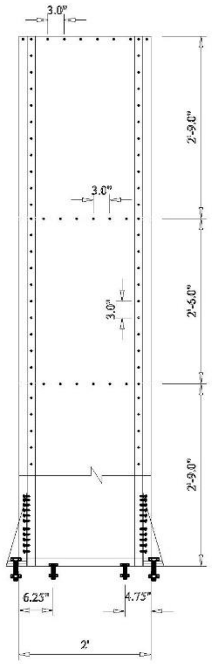
Observed Deformations: local buckling of vertica tracks

Screw Pull Out: None

Sheathing Tear: None

Screw Pull Over: Yes





Test 47

Test No. 48

Opening Type: 6 X 2 in. vertical slits

Test date: Nov. 12, 2015

Specimen Configuration:

Wall dimensions: 8 ft. x 2 ft. Studs: 350 T 150 - 68, 50 ksi Tracks: 362 T 150 - 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 22 ga, 80 ksi

Fastener: # 12 x 1 - 1/4" hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 6992.58 lbs

Lateral displacement of wall top at +peak load: 4.42 in.

-Peak load: 6885.66 lbs

Lateral displacement of wall top at –peak load: 3.33 in.

Average peak load: 6939.12 lbs

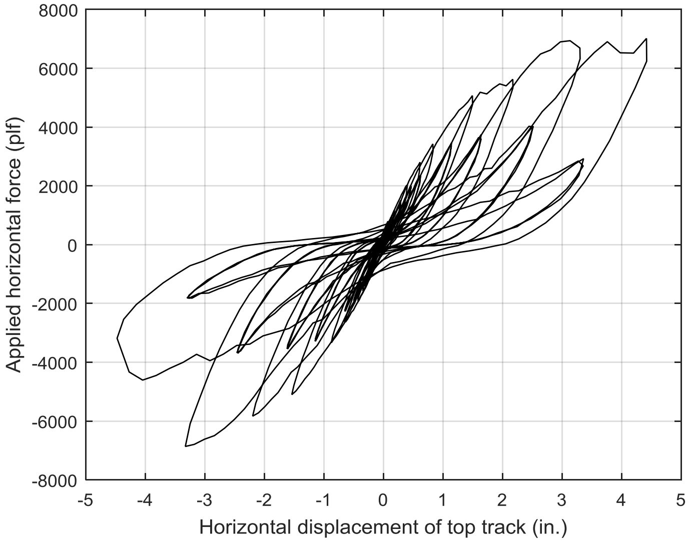
Average lateral displacement of wall top: 3.87 in.

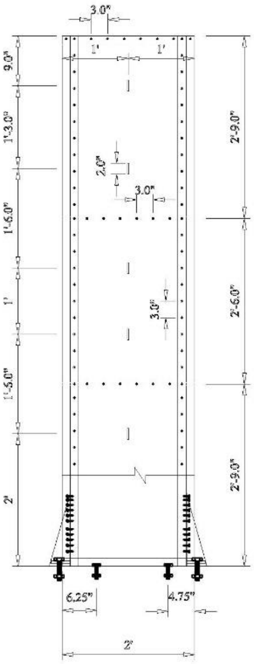
Observed Deformations: local buckling of vertical tracks

Screw Pull Out: None

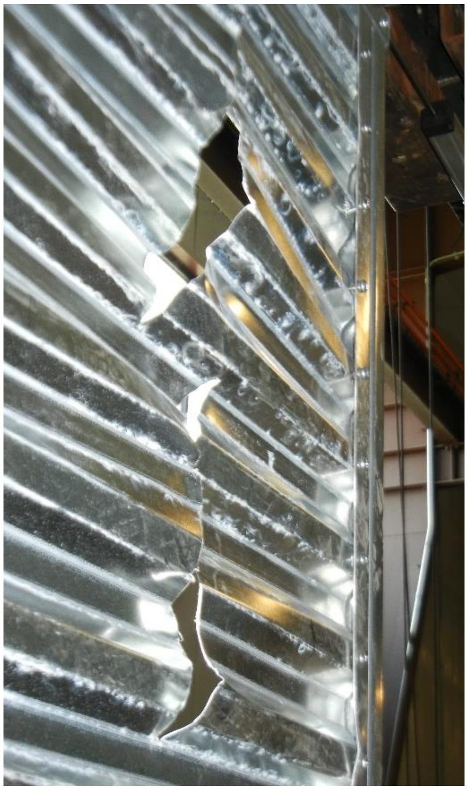
Sheathing Tear: Yes

Screw Pull Over: Yes





Test 48



Test No. 62

Opening Type: No openings

Test date: Feb. 10, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 54, 30 ksi Tracks: 350 T 125 - 54, 50 ksi

Steel sheathing: Verco Decking, SV36, 24 ga, 80 ksi

Fastener: #10 x 3/4" hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 8912.11 lbs

Lateral displacement of wall top at +peak load: 1.31 in.

-Peak load: 8348.99 lbs

Lateral displacement of wall top at –peak load: 1.3 in.

Average peak load: 8630.55 lbs

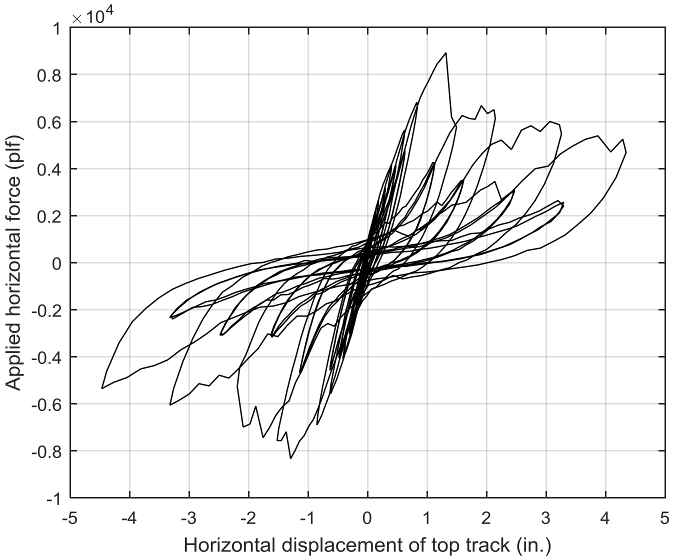
Average lateral displacement of wall top: 1.31 in.

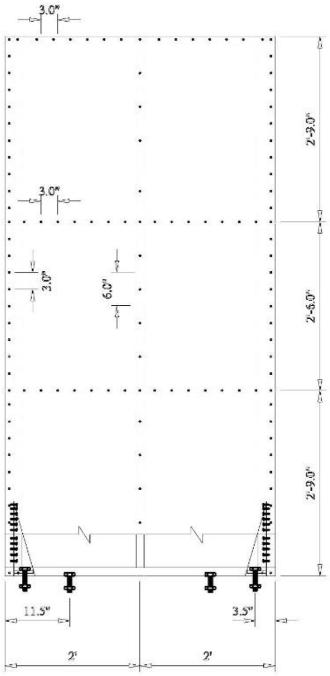
Observed Deformations: local buckling of chord studs

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: Yes





Test 62

Test No. 63

Opening Type: No openings

Test date: Feb. 11, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 54, 30 ksi Tracks: 350 T 125 - 54, 50 ksi

Steel sheathing: Verco Decking, SV36, 24 ga, 80 ksi

Fastener: #10 x 3/4” hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 8715.36 lbs

Lateral displacement of wall top at +peak load: 1.17 in.

-Peak load: 7652.79 lbs

Lateral displacement of wall top at –peak load: 1.52 in.

Average peak load: 8184.08 lbs

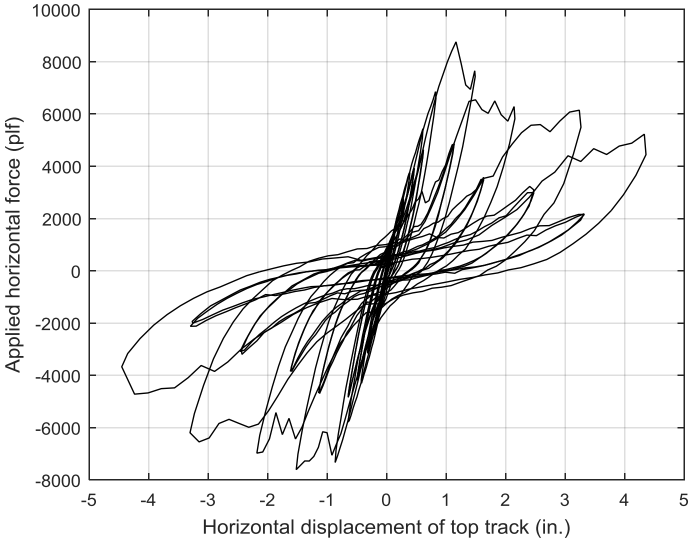
Average lateral displacement of wall top: 1.35 in.

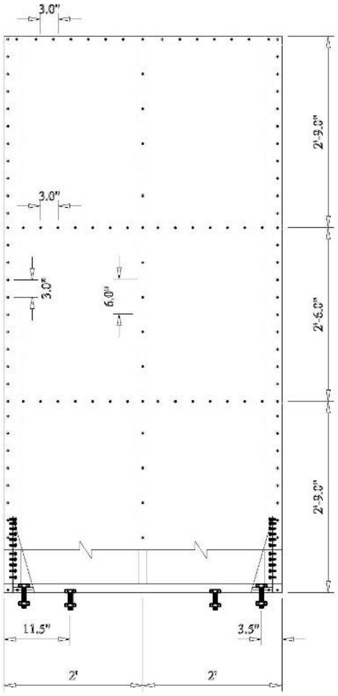
Observed Deformations: local buckling of chord studs

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: Yes





Test 63

Test No. 64

Opening Type: 12x2 in. vertical slits

Test date: Feb. 12, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 54, 30 ksi Tracks: 350 T 125 - 54, 50 ksi

Steel sheathing: Verco Decking, SV36, 24 ga, 80 ksi

Fastener: #10 x 3/4" hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 5979.19 lbs

Lateral displacement of wall top at +peak load: 2.03 in.

-Peak load: 5827.22 lbs

Lateral displacement of wall top at –peak load: 1.48 in.

Average peak load: 5903.21 lbs

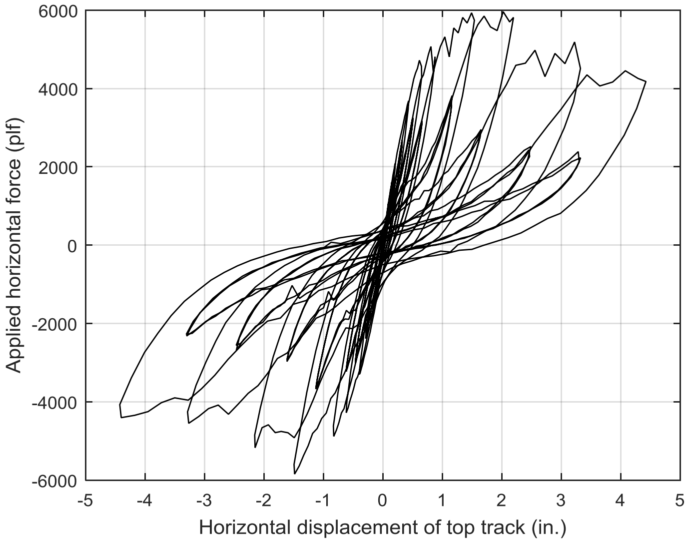
Average lateral displacement of wall top: 1.76 in.

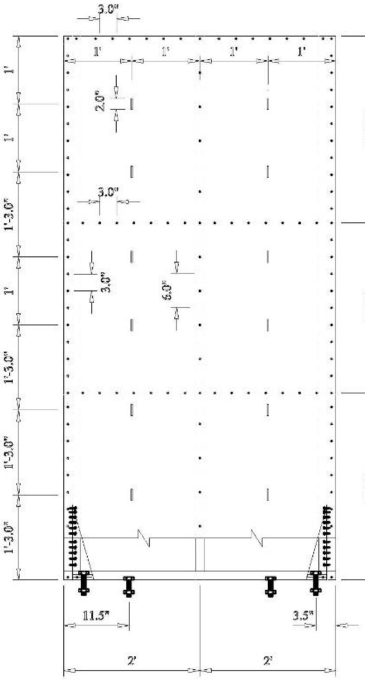
Observed Deformations: minor local buckling of chord studs

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: No




3.0"
1'
1'
1'
1'
2.0"
3.0"
3.0"
6.0"
2'-9.0"
2'-6.0"
2'-9.0"
1'
1'
1'-3.0"
1'
1'-3.0"
1'-3.0"
1'-3.0"
11.5"
3.5"
2'
2'

Test 64


Group 3

Test No. 66

Opening Type: No openings

Test date: Feb. 17, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: “350 T 125 - 54, 50 ksi” Tracks: 350 T 125 - 54, 50 ksi

Middle track: 300 T 200 – 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 24 ga, 80 ksi

Fastener: #10 x 3/4” MTH self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 7906.56 lbs

Lateral displacement of wall top at +peak load: 1.92 in.

-Peak load: 7531.48 lbs

Lateral displacement of wall top at –peak load: 1.52 in.

Average peak load: 7719.02 lbs

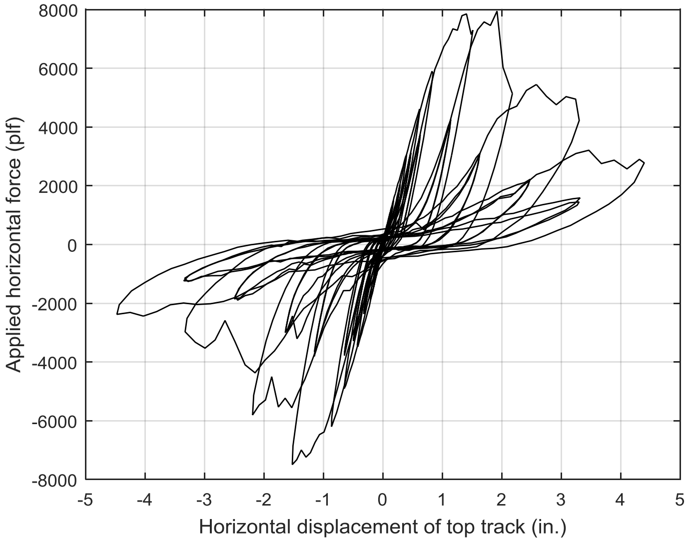
Average lateral displacement of wall top: 1.72 in.

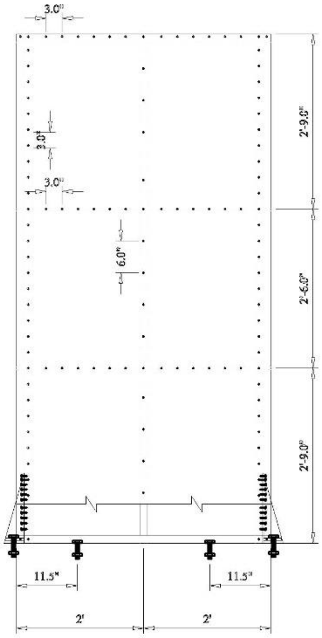
Observed Deformations: local buckling of vertical tracks

Screw Pull Out: Yes

Sheathing Tear: None

Screw Pull Over: Yes





Test 66

Test No. 67

Opening Type: No openings

Test date: Feb. 18, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: “350 T 125 - 54, 50 ksi” Tracks: 350 T 125 - 54, 50 ksi

Middle track: 300 T 200 – 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 24 ga, 80 ksi

Fastener: #10 x 3/4” MTH self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 8365.26 lbs

Lateral displacement of wall top at +peak load: 1.83 in.

-Peak load: 8540.72 lbs

Lateral displacement of wall top at –peak load: 1.45 in.

Average peak load: 8452.99 lbs

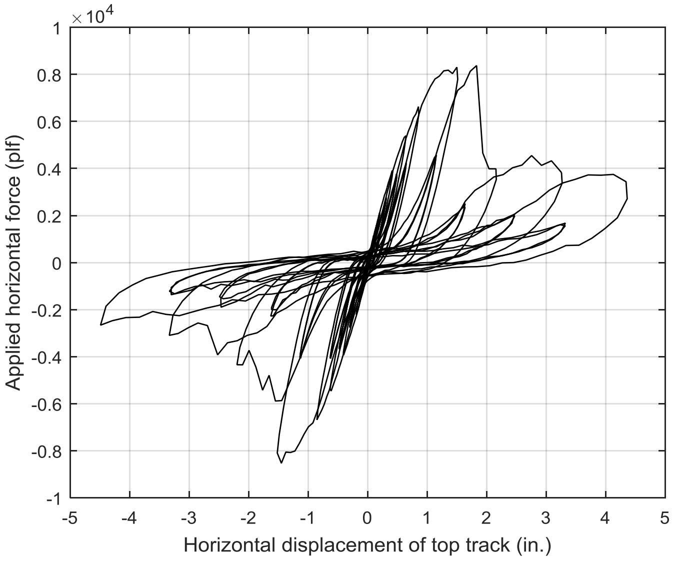
Average lateral displacement of wall top: 1.64 in.

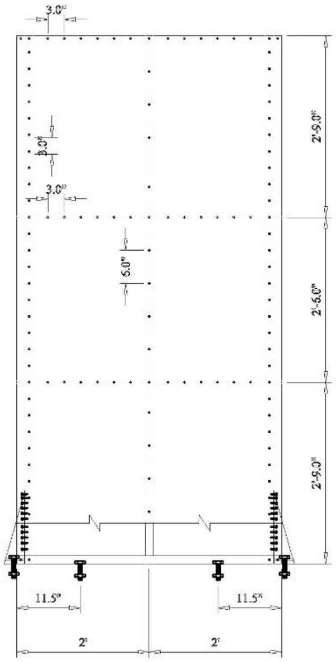
Observed Deformations: local buckling of vertical tracks

Screw Pull Out: No

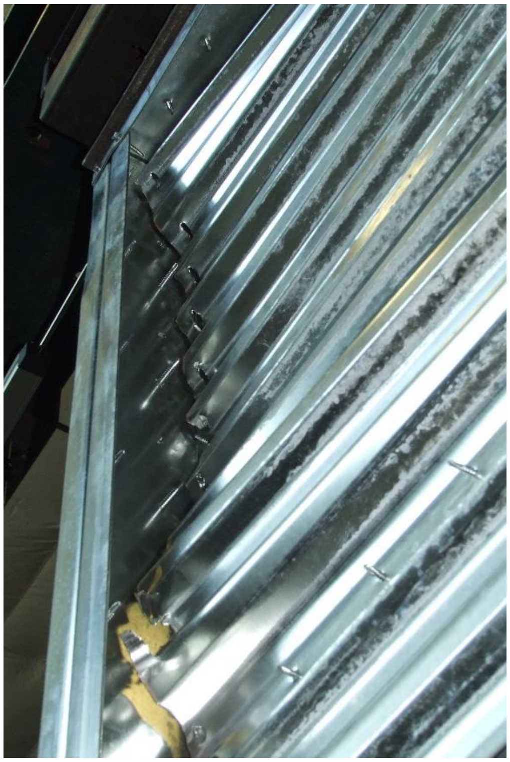
Sheathing Tear: None

Screw Pull Over: Yes





Test 67



Test No. 68

Opening Type: 12x2 in. vertical slits

Test date: Feb. 19, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: 350 S 162 - 54, 30 ksi Tracks: 350 T 125 - 54, 50 ksi

Steel sheathing: Verco Decking, SV36, 24 ga, 80 ksi

Fastener: #10 x 3/4” hex head self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 6761.18 lbs

Lateral displacement of wall top at +peak load: 1.45 in.

-Peak load: 6247.86 lbs

Lateral displacement of wall top at –peak load: 1.42 in.

Average peak load: 6504.52 lbs

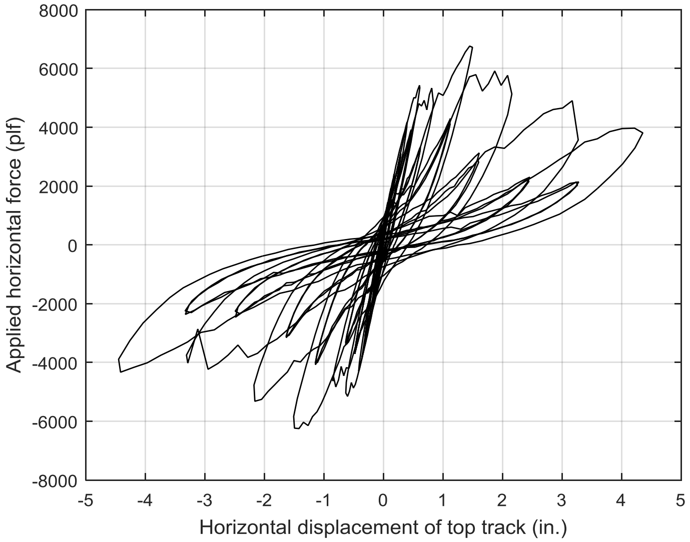
Average lateral displacement of wall top: 1.44 in.

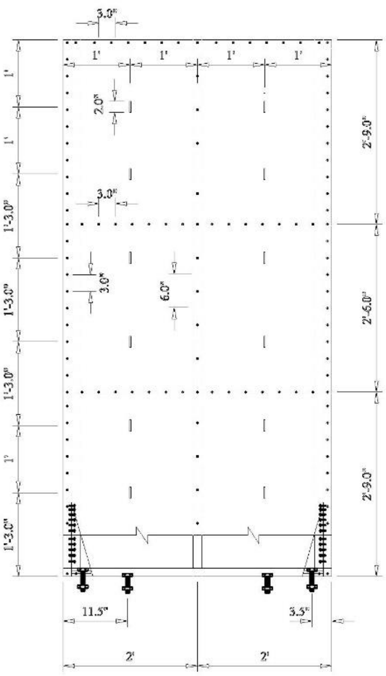
Observed Deformations: local buckling of chord studs

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: No





Test 68

Test No. 69

Opening Type: 12x2 in. vertical slits

Test date: Feb. 19, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: "350 T 125 - 54, 50 ksi" Tracks: 350 T 125 - 54, 50 ksi

Middle track: 300 T 200 – 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 24 ga, 80 ksi

Fastener: #10 x 3/4" MTH self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 7204.29 lbs

Lateral displacement of wall top at +peak load: 1.91 in.

-Peak load: 6015.34 lbs

Lateral displacement of wall top at –peak load: 1.44 in.

Average peak load: 6609.82 lbs

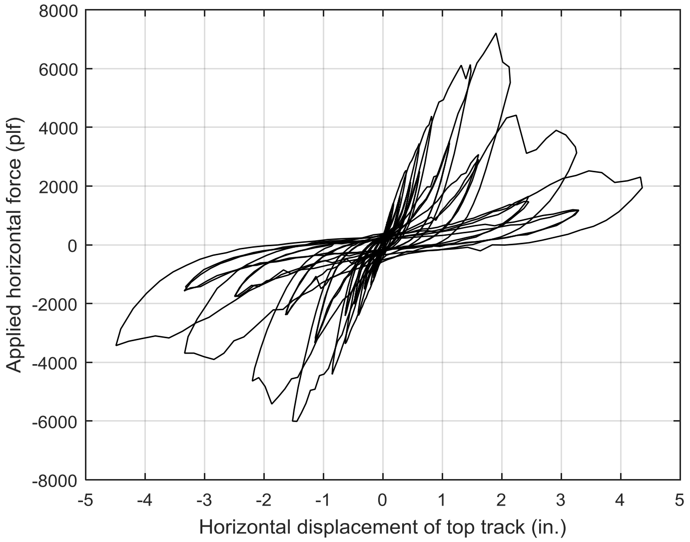
Average lateral displacement of wall top: 1.68 in.

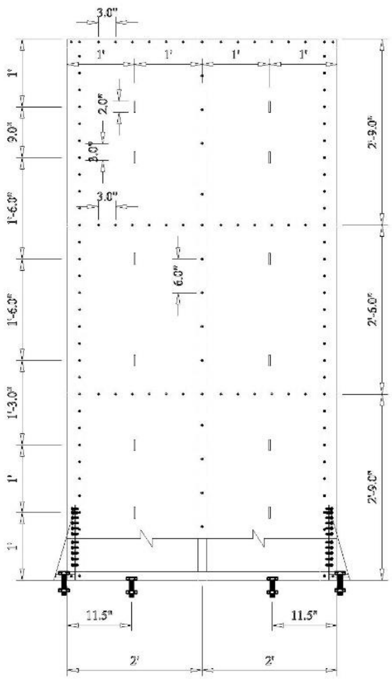
Observed Deformations: local buckling of vertica tracks

Screw Pull Out: Yes

Sheathing Tear: Yes

Screw Pull Over: Yes





Test 69

Test No. 70

Opening Type: 12x2 in. vertical slits

Test date: Feb. 19, 2016

Specimen Configuration:

Wall dimensions: 8 ft. x 4 ft. Studs: "350 T 125 - 54, 50 ksi" Tracks: 350 T 125 - 54, 50 ksi

Middle track: 300 T 200 – 68, 50 ksi

Steel sheathing: Verco Decking, SV36, 24 ga, 80 ksi

Fastener: #10 x 3/4" MTH self-drilling screws, 3/6 in. spacing

Hold-down: Simpson Strong Tie S/HD15S both side

Test protocol: Cyclic-CUREE

Test results:

+Peak load: 7002.29 lbs

Lateral displacement of wall top at +peak load: 1.35 in.

-Peak load: 6072.82 lbs

Lateral displacement of wall top at –peak load: 1.35 in.

Average peak load: 6537.56 lbs

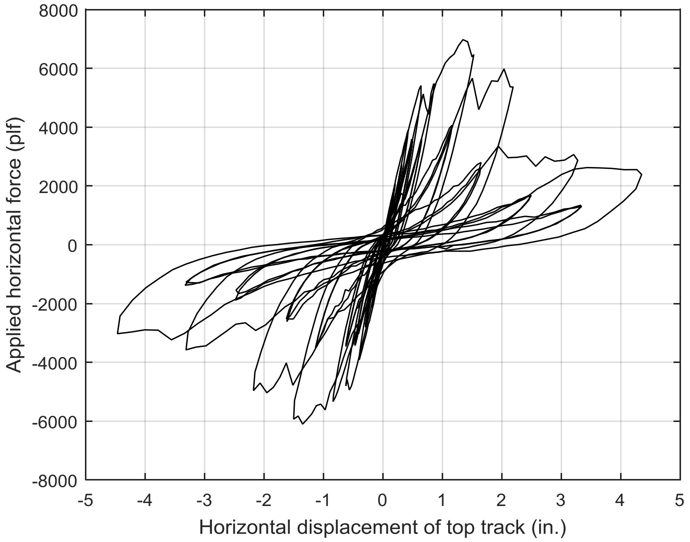
Average lateral displacement of wall top: 1.35 in.

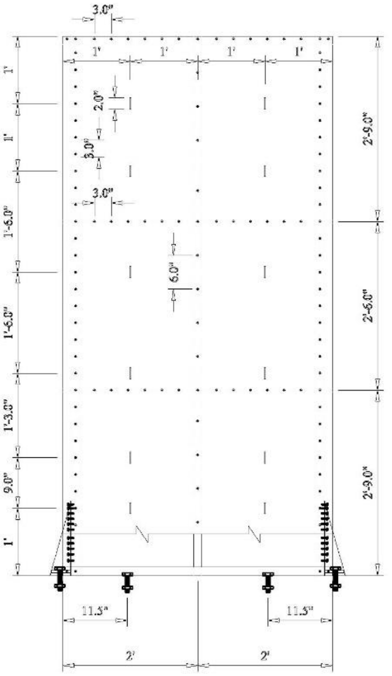
Observed Deformations: local buckling of vertical tracks

Screw Pull Out: No

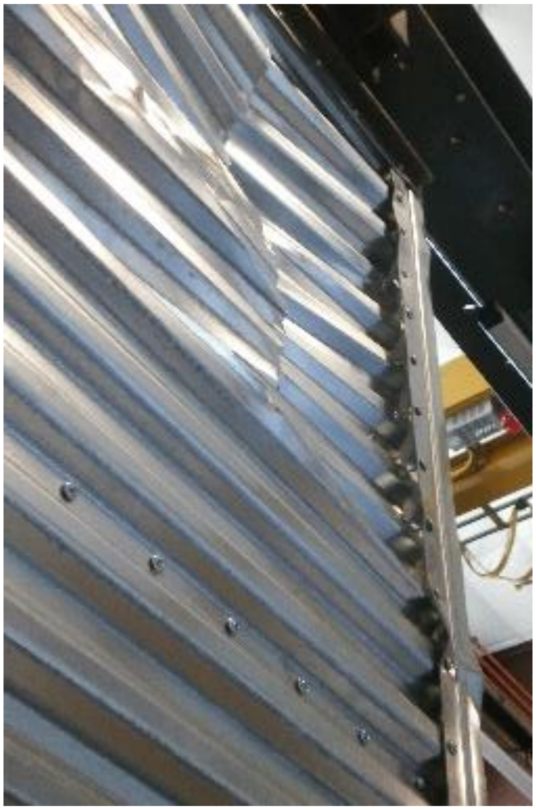
Sheathing Tear: Yes

Screw Pull Over: Yes





Test 70



APPENDIX B

ABAQUS CYCLIC MODEL INPUT FILE

```
*Heading
** Job name: Push_spring Model name: Model-1
** Generated by: Abaqus/CAE 6.10-1
*Preprint, echo=NO, model=NO, history=NO, contact=NO
**
** PARTS
**
*Part, name=bottom_sheet
*Node
      1,      1.0625,          0.,          3.
      2,  1.28250003,          0.,          3.
      3,  1.28250003,          0.,          6.
......
   2077,         1.5,          0.,        43.5
   2078,       2.125,      0.5625,        43.5
   2079,          3.,      0.5625,        43.5
*Element, type=S4
1,    1,    2, 1198, 1199
2, 1199, 1198,    3,    4
3,    2,    5, 1200, 1198
......
1982, 1011, 1012, 1196, 1195
1983, 1012, 1013, 1197, 1196
1984, 1014, 1090, 1197, 1013
*Nset, nset=_PickedSet63, internal, generate
    1,  2079,     1
*Elset, elset=_PickedSet63, internal, generate
    1,  1984,     1
** Section: Sheet
*Shell Section, elset=_PickedSet63, material=Sheet
0.027, 5
*End Part
**
*Part, name=middle_sheet
*Node
      1,          0.,      0.5625,          3.
      2,       0.625,          0.,          3.
      3,       0.625,          0.,          6.
......
   2077,       2.125,      0.5625,        43.5
   2078,          3.,      0.5625,        43.5
   2079,       3.625,          0.,        43.5
*Element, type=S4
1,    1,    2, 1198, 1199
2, 1199, 1198,    3,    4
3,    2,    5, 1200, 1198
```

```
......
1982, 1013, 1014, 1195, 1194
1983, 1014, 1015, 1196, 1195
1984, 1015, 1090, 1197, 1196
*Nset, nset=_PickedSet60, internal, generate
   1,  2079,     1
*Elset, elset=_PickedSet60, internal, generate
   1,  1984,     1
** Section: Sheet
*Shell Section, elset=_PickedSet60, material=Sheet
0.027, 5
*End Part
**
*Part, name=stud
*Node
      1,       1.625,          3.,  0.709999979
      2,       1.625,         3.5,  0.709999979
      3,       1.625,         3.5,           3.
......
   3472,     1.21875,         3.5,         4.5
   3473,     1.21875,         3.5,          4.
   3474,     1.21875,         3.5,         3.5
*Element, type=S4
1,   1,   2, 281, 288
2, 288, 281, 282, 287
3, 287, 282, 283, 286
......
3262,    5,  289, 1894,  275
3263,  289,    2,  279, 1894
3264,   2,   1, 280, 279
*Nset, nset=_PickedSet71, internal, generate
   1,  3474,     1
*Elset, elset=_PickedSet71, internal, generate
   1,  3264,     1
** Section: Stud
*Shell Section, elset=_PickedSet71, material=Stud
0.068, 5
*End Part
**
*Part, name=top_sheet
*Node
      1,          0.,      0.5625,          3.
      2,       0.625,          0.,          3.
      3,       0.625,          0.,          6.
 ......
   2077,         36.,      0.5625,        22.5
```

```
   2078,      37.0625,           0.,         22.5
   2079,           0.,       0.5625,         25.5
*Element, type=S4
1,    1,    2, 1198, 1199
2, 1199, 1198,    3,    4
3,    2,    5, 1200, 1198
......
1982,  501,  502, 1195, 1194
1983,  502,  503, 1196, 1195
1984,  503, 1082, 1197, 1196
*Nset, nset=_PickedSet61, internal, generate
    1,  2079,     1
*Elset, elset=_PickedSet61, internal, generate
    1,  1984,     1
** Section: Sheet
*Shell Section, elset=_PickedSet61, material=Sheet
0.027, 5
*End Part
**
*Part, name=track
*Node
      1,           0.,          1.5,       0.8125
      2,           0.,         0.75,       0.8125
      3,           0.,         0.75,   2.47749996
......
   1550,   2.55714297,           0.,     47.59375
   1551,   3.06857133,           0.,     47.59375
   1552,           0.,        1.125,      0.40625
*Element, type=S4
1,   1, 169, 945, 174
2, 169,   2, 170, 945
3, 174, 945, 946, 173
......
1438,  169,    1,  943, 1552
1439,  932, 1552,  944,  164
1440, 1552,  943,  168,  944
*Nset, nset=_PickedSet45, internal, generate
    1,  1552,     1
*Elset, elset=_PickedSet45, internal, generate
    1,  1440,     1
** Section: Track
*Shell Section, elset=_PickedSet45, material=Track
0.068, 5
*End Part
**
** ---------------------------------- **
```

```
*Include, input=fastener_part.txt
** ----------------------------------- **
**
**
** ASSEMBLY
**
*Assembly, name=Assembly
**
*Instance, name=stud-2, part=stud
          0.,           0.,          96.
*End Instance
**
*Instance, name=stud-1, part=stud
-0.0399999999999883,           0.,         192.
-0.0399999999999883,           0.,         192., -0.0399999999999883,           1.,

192.,         180.
*End Instance
**
......
*Instance, name=top_sheet, part=top_sheet
      -1.665,         3.66,     133.0625
      -1.665,         3.66,     133.0625,       -1.665,         4.66,     133.0625,

90.
*End Instance
**
*Instance, name = fastn_osb_line_1, part = fastn_osb_pro_1
*End instance
......
**
*Instance, name = fastn_osb_line_7, part = fastn_osb_pro_4
*End instance
** ------------- **
*Include, input=fastener_equation.txt
*Include, input=withdrawl_springs.txt
** ------------- **
*Node
      1,   46.3349991,   3.53999996,   95.9599991
*Nset, nset=stud_frame_1, instance=stud-1
 5,
*Nset, nset=stud_frame_2, instance=stud-2
 27,
*Nset, nset=stud_frame_3, instance=stud-3
 27,
......
```

```
*Nset, nset=stud_frame_18, instance=stud-3
 11,
*Nset, nset=stud_frame_19, instance=stud-2
 11,
*Nset, nset=stud_frame_20, instance=stud-1
 21,
*Nset, nset=track_frame_1, instance=bottom_track
 2,
*Nset, nset=track_frame_2, instance=bottom_track
 3,
*Nset, nset=track_frame_3, instance=bottom_track
 73,
......
*Nset, nset=track_frame_18, instance=top_track
 79,
*Nset, nset=track_frame_19, instance=top_track
 143,
*Nset, nset=track_frame_20, instance=top_track
 151,
*Nset, nset=Geo_load_coupling, instance=stud-2
  ......
*Nset, nset=Geo_load_coupling, instance=stud-1
  ......
*Nset, nset=Geo_load_coupling, instance=stud-4
   ......
*Nset, nset=Geo_load_coupling, instance=top_track
   ......
*Nset, nset=Geo_load_coupling, instance=stud-5
  ......
*Nset, nset=Geo_load_coupling, instance=stud-3
   ......
*Elset, elset=Geo_load_coupling, instance=stud-2, generate
 3248,  3264,     1
*Elset, elset=Geo_load_coupling, instance=stud-1
   ......
*Elset, elset=Geo_load_coupling, instance=stud-4
   ......
*Elset, elset=Geo_load_coupling, instance=top_track
   ......
*Elset, elset=Geo_load_coupling, instance=stud-5, generate
 3248,  3264,     1
*Elset, elset=Geo_load_coupling, instance=stud-3, generate
 3248,  3264,     1
*Nset, nset=Load_point
 1,
*Nset, nset=Geo_fix_bottom, instance=stud-2
```

```
    ......
*Nset, nset=Geo_fix_bottom, instance=stud-1
   ......
*Nset, nset=Geo_fix_bottom, instance=stud-4
   ......
*Nset, nset=Geo_fix_bottom, instance=stud-5
    ......
*Nset, nset=Geo_fix_bottom, instance=stud-3
    ......
*Nset, nset=Geo_fix_bottom, instance=bottom_track
    ......
*Elset, elset=Geo_fix_bottom, instance=stud-2
   ......
*Elset, elset=Geo_fix_bottom, instance=stud-1, generate
 3248,  3264,     1
*Elset, elset=Geo_fix_bottom, instance=stud-4, generate
 3248,  3264,     1
*Elset, elset=Geo_fix_bottom, instance=stud-5
  ......
*Elset, elset=Geo_fix_bottom, instance=stud-3
   ......
*Elset, elset=Geo_fix_bottom, instance=bottom_track
  ......
*Nset, nset=HD12, instance=stud-2
  ......
*Nset, nset=HD12, instance=stud-1
    ......
*Nset, nset=HD45, instance=stud-5
   ......
*Nset, nset=HD45, instance=stud-4
    ......
*Nset, nset=Out_plane1, instance=top_track
  ......
*Nset, nset=Out_plane2, instance=top_track
  ......
*Elset, elset=_Stud_1_tie_SPOS, internal, instance=stud-1
  ......
*Surface, type=ELEMENT, name=Stud_1_tie
_Stud_1_tie_SPOS, SPOS
*Elset, elset=_Stud_2_tie_SPOS, internal, instance=stud-2
   ......
*Surface, type=ELEMENT, name=Stud_2_tie
_Stud_2_tie_SPOS, SPOS
*Elset, elset=_Stud_4_tie_SPOS, internal, instance=stud-4
  ......
*Surface, type=ELEMENT, name=Stud_4_tie
```

```
_Stud_4_tie_SPOS, SPOS
*Elset, elset=_Stud_5_tie_SPOS, internal, instance=stud-5
   ......
*Surface, type=ELEMENT, name=Stud_5_tie
_Stud_5_tie_SPOS, SPOS
*Elset, elset=_plate_SPOS, internal, instance=bottom_sheet
   ......
*Elset, elset=_plate_SPOS, internal, instance=middle_sheet
    ......
*Elset, elset=_plate_SPOS, internal, instance=top_sheet
    ......
*Surface, type=ELEMENT, name=plate
_plate_SPOS, SPOS
*Elset, elset=_coloumn_SPOS, internal, instance=stud-2
   ......
*Elset, elset=_coloumn_SPOS, internal, instance=stud-1
   ......
*Elset, elset=_coloumn_SPOS, internal, instance=stud-4
    ......
*Elset, elset=_coloumn_SPOS, internal, instance=top_track
   ......
*Elset, elset=_coloumn_SPOS, internal, instance=stud-5
   ......
*Elset, elset=_coloumn_SPOS, internal, instance=stud-3
   ......
*Elset, elset=_coloumn_SPOS, internal, instance=bottom_track
   ......
*Surface, type=ELEMENT, name=coloumn
_coloumn_SPOS, SPOS
*Surface, type=NODE, name=track_frame_1_CNS_, internal
track_frame_1, 1.
*Surface, type=NODE, name=stud_frame_1_CNS_, internal
stud_frame_1, 1.
*Surface, type=NODE, name=track_frame_2_CNS_, internal
track_frame_2, 1.
*Surface, type=NODE, name=stud_frame_2_CNS_, internal
stud_frame_2, 1.
......
*Surface, type=NODE, name=track_frame_19_CNS_, internal
track_frame_19, 1.
*Surface, type=NODE, name=stud_frame_19_CNS_, internal
stud_frame_19, 1.
*Surface, type=NODE, name=track_frame_20_CNS_, internal
track_frame_20, 1.
*Surface, type=NODE, name=stud_frame_20_CNS_, internal
stud_frame_20, 1.
```

```
**
*Surface, type=NODE, name=Geo_load_coupling_CNS_, internal
Geo_load_coupling, 1.
** Constraint: Frame_1
*Tie, name=Frame_1, adjust=yes
stud_frame_1_CNS_, track_frame_1_CNS_
** Constraint: Frame_2
*Tie, name=Frame_2, adjust=yes
stud_frame_2_CNS_, track_frame_2_CNS_
......
** Constraint: Frame_19
*Tie, name=Frame_19, adjust=yes
stud_frame_19_CNS_, track_frame_19_CNS_
** Constraint: Frame_20
*Tie, name=Frame_20, adjust=yes
stud_frame_20_CNS_, track_frame_20_CNS_
**
** Constraint: Stud12
*Tie, name=Stud12, adjust=yes
Stud_2_tie, Stud_1_tie
** Constraint: Stud45
*Tie, name=Stud45, adjust=yes
Stud_5_tie, Stud_4_tie
** Constraint: load_coupling
*Coupling, constraint name=load_coupling, ref node=Load_point,
surface=Geo_load_coupling_CNS_
*Kinematic
1, 1
2, 2
3, 3
*End Assembly
**
** MATERIALS
**
*Material, name=Sheet
*Elastic
29500., 0.3
*Plastic
  <enter value>
*Material, name=Stud
*Elastic
29500., 0.3
*Plastic
   <enter value>
*Material, name=Track
*Elastic
```

```
29500., 0.3
*Plastic
   <enter value>
**
** INTERACTION PROPERTIES
**
*Surface Interaction, name=IntProp-1
1.,
*Friction
0.,
*Surface Behavior, pressure-overclosure=HARD
**
** BOUNDARY CONDITIONS
**
** Name: Fix_bottom Type: Displacement/Rotation
*Boundary
Geo_fix_bottom, 1, 1
Geo_fix_bottom, 2, 2
Geo_fix_bottom, 3, 3
Geo_fix_bottom, 4, 4
Geo_fix_bottom, 5, 5
Geo_fix_bottom, 6, 6
** Name: HD12 Type: Displacement/Rotation
*Boundary
HD12, 1, 1
HD12, 2, 2
HD12, 3, 3
** Name: HD45 Type: Displacement/Rotation
*Boundary
HD45, 1, 1
HD45, 2, 2
HD45, 3, 3
** Name: Out_plane1 Type: Displacement/Rotation
*Boundary
Out_plane1, 2, 2
** Name: Out_plane2 Type: Displacement/Rotation
*Boundary
Out_plane2, 2, 2
**
** INTERACTIONS
**
** Interaction: Int-1
*Contact Pair, interaction=IntProp-1, small sliding, type=SURFACE TO SURFACE, adjust=0.0
plate, coloumn
** ---------------------------------------------- **
*Include, input=cyc_loading_min.txt
```

```
** ----------------------------------------------------------------
**
** STEP: Step-1
**
*Step, name=Step-1, nlgeom=YES, inc=7000
*Static, stabilize=0.0002, allsdtol=0.05, continue=NO
100, 9954, 1e-13, 1000
**
** BOUNDARY CONDITIONS
**
** Name: Disp_load Type: Displacement/Rotation
** ---------------------------------------------- **
*Boundary, amplitude=cyc_loading
Load_point, 1, 1, 5
** ---------------------------------------------- **
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, variable=PRESELECT
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
```

APPENDIX C

FASTENER PART

```
*Part, name = fastn_osb_pro_1
*Node
1, -0.8525, 3.5, 189
2, -0.8525, 3.5, 186
3, -0.8525, 3.5, 183
.....
29, -0.8525, 3.5, 105
30, -0.8525, 3.5, 102
31, -0.8525, 3.5, 99
101, -0.8525, 3.58, 189
102, -0.8525, 3.58, 186
103, -0.8525, 3.58, 183
.....
129, -0.8525, 3.66, 105
130, -0.8525, 3.66, 102
131, -0.8525, 3.66, 99
*User element, nodes=2, type=U101, properties=41, coordinates=3, variables=200
1, 3
*Element, type=U101, elset=steel_to_osb_spr
1, 1, 101
2, 2, 102
3, 3, 103
.....
29, 29, 129
30, 30, 130
31, 31, 131
*UEL property, elset=steel_to_osb_spr
< insert pinching4 and backbone from connection results here >
*End Part
*Part, name = fastn_osb_pro_3
```

```
*Node
1, -0.8525, 3.54, 191.78
2, 1.335, 3.54, 191.78
3, 4.335, 3.54, 191.78
.....
15, 40.335, 3.54, 191.78
16, 43.335, 3.54, 191.78
17, 45.5225, 3.54, 191.78
101, -0.8525, 3.58, 191.78
102, 1.335, 3.58, 191.78
103, 4.335, 3.58, 191.78
.....
115, 40.335, 3.58, 191.78
116, 43.335, 3.58, 191.78
117, 45.5225, 3.58, 191.78
*User element, nodes=2, type=U101, properties=41, coordinates=3, variables=200
1, 3
*Element, type=U101, elset=steel_to_osb_spr
1, 1, 101
2, 2, 102
3, 3, 103
.....
15, 15, 115
16, 16, 116
17, 17, 117
*UEL property, elset=steel_to_osb_spr
< insert pinching4 and backbone from connection results here >
*End part
*Part, name = fastn_osb_pro_4
*Node
```

```
1, -0.8525, 3.54, 96.22
2, 1.335, 3.54, 96.22
3, 4.335, 3.54, 96.22
.....
15, 40.335, 3.54, 96.22
16, 43.335, 3.54, 96.22
17, 45.5225, 3.54, 96.22
101, -0.8525, 3.66, 96.22
102, 1.335, 3.66, 96.22
103, 4.335, 3.66, 96.22
.....
115, 40.335, 3.66, 96.22
116, 43.335, 3.66, 96.22
117, 45.5225, 3.66, 96.22
*User element, nodes=2, type=U101, properties=41, coordinates=3, variables=200
1, 3
*Element, type=U101, elset=steel_to_osb_spr
1, 1, 101
2, 2, 102
3, 3, 103
.....
15, 15, 115
16, 16, 116
17, 17, 117
*UEL property, elset=steel_to_osb_spr
< insert pinching4 and backbone from connection results here >
*End part
*Part, name = fastn_osb_pro_2
*Node
1, 22.335, 3.5, 186
```

```
2, 22.335, 3.5, 180
3, 22.335, 3.5, 174
.....
13, 22.335, 3.5, 114
14, 22.335, 3.5, 108
15, 22.335, 3.5, 102
101, 22.335, 3.58, 186
102, 22.335, 3.58, 180
103, 22.335, 3.58, 174
.....
113, 22.335, 3.66, 114
114, 22.335, 3.66, 108
115, 22.335, 3.66, 102
*User element, nodes=2, type=U101, properties=41, coordinates=3, variables=200
1, 3
*Element, type=U101, elset=steel_to_osb_spr
1, 1, 101
2, 2, 102
3, 3, 103
.....
13, 13, 113
14, 14, 114
15, 15, 115
*UEL property, elset=steel_to_osb_spr
< insert pinching4 and backbone from connection results here >
*End Part
```

APPENDIX D

FASTENER EQUATION

```
*Equation
2
fastn_osb_line_1.1, 1, 1, Stud-1.6, 1, -1
*Equation
2
fastn_osb_line_1.1, 3, 1, Stud-1.6, 3, -1
*Equation
2
fastn_osb_line_1.2, 1, 1, Stud-1.263, 1, -1
*Equation
2
fastn_osb_line_1.2, 3, 1, Stud-1.263, 3, -1
*Equation
2
fastn_osb_line_1.3, 1, 1, Stud-1.255, 1, -1
*Equation
2
fastn_osb_line_1.3, 3, 1, Stud-1.255, 3, -1
.....
*Equation
2
fastn_osb_line_1.101, 1, 1, bottom_sheet.1009, 1, -1
*Equation
2
fastn_osb_line_1.101, 3, 1, bottom_sheet.1009, 3, -1
*Equation
2
fastn_osb_line_1.102, 1, 1, bottom_sheet.1004, 1, -1
*Equation
2
```

```
fastn_osb_line_1.102, 3, 1, bottom_sheet.1004, 3, -1
*Equation
2
fastn_osb_line_1.103, 1, 1, bottom_sheet.999, 1, -1
*Equation
2
fastn_osb_line_1.103, 3, 1, bottom_sheet.999, 3, -1
.....
*Equation
2
fastn_osb_line_1.111, 1, 1, middle_sheet.1010, 1, -1
*Equation
2
fastn_osb_line_1.111, 3, 1, middle_sheet.1010, 3, -1
*Equation
2
fastn_osb_line_1.112, 1, 1, middle_sheet.1005, 1, -1
*Equation
2
fastn_osb_line_1.112, 3, 1, middle_sheet.1005, 3, -1
*Equation
2
fastn_osb_line_1.113, 1, 1, middle_sheet.1000, 1, -1
*Equation
2
fastn_osb_line_1.113, 3, 1, middle_sheet.1000, 3, -1
.....
*Equation
2
fastn_osb_line_1.121, 1, 1, top_sheet.498, 1, -1
```

```
*Equation
2
fastn_osb_line_1.121, 3, 1, top_sheet.498, 3, -1
*Equation
2
fastn_osb_line_1.122, 1, 1, top_sheet.493, 1, -1
*Equation
2
fastn_osb_line_1.122, 3, 1, top_sheet.493, 3, -1
*Equation
2
fastn_osb_line_1.123, 1, 1, top_sheet.488, 1, -1
*Equation
2
fastn_osb_line_1.123, 3, 1, top_sheet.488, 3, -1
.....
*Equation
2
fastn_osb_line_3.1, 1, 1, stud-3.39, 1, -1
*Equation
2
fastn_osb_line_3.1, 3, 1, stud-3.39, 3, -1
*Equation
2
fastn_osb_line_3.2, 1, 1, stud-3.55, 1, -1
*Equation
2
fastn_osb_line_3.2, 3, 1, stud-3.55, 3, -1
*Equation
2
```

```
fastn_osb_line_3.3, 1, 1, stud-3.71, 1, -1
*Equation
2
fastn_osb_line_3.3, 3, 1, stud-3.71, 3, -1
.....
*Equation
2
fastn_osb_line_3.101, 1, 1, bottom_sheet.453, 1, -1
*Equation
2
fastn_osb_line_3.101, 3, 1, bottom_sheet.453, 3, -1
*Equation
2
fastn_osb_line_3.102, 1, 1, bottom_sheet.463, 1, -1
*Equation
2
fastn_osb_line_3.102, 3, 1, bottom_sheet.463, 3, -1
*Equation
2
fastn_osb_line_3.103, 1, 1, bottom_sheet.473, 1, -1
*Equation
2
fastn_osb_line_3.103, 3, 1, bottom_sheet.473, 3, -1
.....
*Equation
2
fastn_osb_line_3.106, 1, 1, middle_sheet.453, 1, -1
*Equation
2
fastn_osb_line_3.106, 3, 1, middle_sheet.453, 3, -1
```

```
*Equation
2
fastn_osb_line_3.107, 1, 1, middle_sheet.463, 1, -1
*Equation
2
fastn_osb_line_3.107, 3, 1, middle_sheet.463, 3, -1
*Equation
2
fastn_osb_line_3.108, 1, 1, middle_sheet.473, 1, -1
*Equation
2
fastn_osb_line_3.108, 3, 1, middle_sheet.473, 3, -1
.....
*Equation
2
fastn_osb_line_3.111, 1, 1, top_sheet.998, 1, -1
*Equation
2
fastn_osb_line_3.111, 3, 1, top_sheet.998, 3, -1
*Equation
2
fastn_osb_line_3.112, 1, 1, top_sheet.988, 1, -1
*Equation
2
fastn_osb_line_3.112, 3, 1, top_sheet.988, 3, -1
*Equation
2
fastn_osb_line_3.113, 1, 1, top_sheet.978, 1, -1
*Equation
2
```

```
fastn_osb_line_3.113, 3, 1, top_sheet.978, 3, -1
.....
*Equation
2
fastn_osb_line_5.1, 1, 1, stud-5.28, 1, -1
*Equation
2
fastn_osb_line_5.1, 3, 1, stud-5.28, 3, -1
*Equation
2
fastn_osb_line_5.2, 1, 1, stud-5.31, 1, -1
*Equation
2
fastn_osb_line_5.2, 3, 1, stud-5.31, 3, -1
*Equation
2
fastn_osb_line_5.3, 1, 1, stud-5.47, 1, -1
*Equation
2
fastn_osb_line_5.3, 3, 1, stud-5.47, 3, -1
.....
*Equation
2
fastn_osb_line_5.101, 1, 1, bottom_sheet.952, 1, -1
*Equation
2
fastn_osb_line_5.101, 3, 1, bottom_sheet.952, 3, -1
*Equation
2
fastn_osb_line_5.102, 1, 1, bottom_sheet.1081, 1, -1
```

```
*Equation
2
fastn_osb_line_5.102, 3, 1, bottom_sheet.1081, 3, -1
*Equation
2
fastn_osb_line_5.103, 1, 1, bottom_sheet.1074, 1, -1
*Equation
2
fastn_osb_line_5.103, 3, 1, bottom_sheet.1074, 3, -1
.....
*Equation
2
fastn_osb_line_5.111, 1, 1, middle_sheet.951, 1, -1
*Equation
2
fastn_osb_line_5.111, 3, 1, middle_sheet.951, 3, -1
*Equation
2
fastn_osb_line_5.112, 1, 1, middle_sheet.1082, 1, -1
*Equation
2
fastn_osb_line_5.112, 3, 1, middle_sheet.1082, 3, -1
*Equation
2
fastn_osb_line_5.113, 1, 1, middle_sheet.1075, 1, -1
*Equation
2
fastn_osb_line_5.113, 3, 1, middle_sheet.1075, 3, -1
.....
*Equation
```

```
2
fastn_osb_line_5.120, 1, 1, top_sheet.1026, 1, -1
*Equation
2
fastn_osb_line_5.120, 3, 1, top_sheet.1026, 3, -1
*Equation
2
fastn_osb_line_5.121, 1, 1, top_sheet.1077, 1, -1
*Equation
2
fastn_osb_line_5.121, 3, 1, top_sheet.1077, 3, -1
*Equation
2
fastn_osb_line_5.122, 1, 1, top_sheet.1071, 1, -1
*Equation
2
fastn_osb_line_5.122, 3, 1, top_sheet.1071, 3, -1
.....
*Equation
2
fastn_osb_line_6.1, 1, 1, bottom_track.5, 1, -1
*Equation
2
fastn_osb_line_6.1, 3, 1, bottom_track.5, 3, -1
*Equation
2
fastn_osb_line_6.2, 1, 1, bottom_track.19, 1, -1
*Equation
2
fastn_osb_line_6.2, 3, 1, bottom_track.19, 3, -1
```

```
*Equation
2
fastn_osb_line_6.3, 1, 1, bottom_track.27, 1, -1
*Equation
2
fastn_osb_line_6.3, 3, 1, bottom_track.27, 3, -1
.....
*Equation
2
fastn_osb_line_6.101, 1, 1, bottom_sheet.1014, 1, -1
*Equation
2
fastn_osb_line_6.101, 3, 1, bottom_sheet.1014, 3, -1
*Equation
2
fastn_osb_line_6.102, 1, 1, bottom_sheet.2, 1, -1
*Equation
2
fastn_osb_line_6.102, 3, 1, bottom_sheet.2, 3, -1
*Equation
2
fastn_osb_line_6.103, 1, 1, bottom_sheet.3, 1, -1
*Equation
2
fastn_osb_line_6.103, 3, 1, bottom_sheet.3, 3, -1
.....
*Equation
2
fastn_osb_line_7.1, 1, 1, top_track.147, 1, -1
*Equation
```

```
2
fastn_osb_line_7.1, 3, 1, top_track.147, 3, -1
*Equation
2
fastn_osb_line_7.2, 1, 1, top_track.131, 1, -1
*Equation
2
fastn_osb_line_7.2, 3, 1, top_track.131, 3, -1
*Equation
2
fastn_osb_line_7.3, 1, 1, top_track.123, 1, -1
*Equation
2
fastn_osb_line_7.3, 3, 1, top_track.123, 3, -1
.....
*Equation
2
fastn_osb_line_7.101, 1, 1, top_sheet.442, 1, -1
*Equation
2
fastn_osb_line_7.101, 3, 1, top_sheet.442, 3, -1
*Equation
2
fastn_osb_line_7.102, 1, 1, top_sheet.123, 1, -1
*Equation
2
fastn_osb_line_7.102, 3, 1, top_sheet.123, 3, -1
*Equation
2
fastn_osb_line_7.103, 1, 1, top_sheet.124, 1, -1
```

```
*Equation
2
fastn_osb_line_7.103, 3, 1, top_sheet.124, 3, -1
.....
*End Part
```

APPENDIX E

WITHDRAWAL SPRINGS

```
** Define withdrawal springs
*Element, type=Spring2, elset=S1ShF-spring
201,  bottom_sheet.1009,  stud-1.6
202,  bottom_sheet.1004,  stud-1.263
203,  bottom_sheet.999,  stud-1.255
.....
211,  middle_sheet.1010,  stud-1.191
212,  middle_sheet.1005,  stud-1.183
213,  middle_sheet.1000,  stud-1.175
.....
221,  top_sheet.498,  stud-1.111
222,  top_sheet.493,  stud-1.103
223,  top_sheet.488,  stud-1.95
.....
*Spring, elset=S1ShF-spring
2, 2
11.000
*Element, type=Spring2, elset=S3ShF-spring
232,  bottom_sheet.453,  stud-3.39
233,  bottom_sheet.463,  stud-3.55
234,  bottom_sheet.473,  stud-3.71
.....
237,  middle_sheet.453,  stud-3.119
238,  middle_sheet.463,  stud-3.135
239,  middle_sheet.473,  stud-3.151
.....
242,  top_sheet.998,  stud-3.199
243,  top_sheet.988,  stud-3.215
244,  top_sheet.978,  stud-3.231
.....
```

```
*Spring, elset=S3ShF-spring
2, 2
11.000
*Element, type=Spring2, elset=S5ShF-spring
247,  bottom_sheet.952,  stud-5.28
248,  bottom_sheet.1081,  stud-5.39
249,  bottom_sheet.1074,  stud-5.47
.....
257,  middle_sheet.951,  stud-5.111
258,  middle_sheet.1082,  stud-5.119
259,  middle_sheet.1075,  stud-5.127
.....
267,  top_sheet.1077,  stud-5.191
268,  top_sheet.1071,  stud-5.199
269,  top_sheet.1065,  stud-5.207
.....
*Spring, elset=S5ShF-spring
2, 2
11.000
*Element, type=Spring2, elset=T1ShF-spring
278,  bottom_sheet.1014,  bottom_track.5
279,  bottom_sheet.2,          bottom_track.19
280,  bottom_sheet.3,          bottom_track.27
.....
*Spring, elset=T1ShF-spring
2, 2
11.000
*Element, type=Spring2, elset=T2ShF-spring
295,  top_sheet.442,  top_track.147
296,  top_sheet.123,  top_track.131
```

```
297,  top_sheet.124,  top_track.123
.....
*Spring, elset=T2ShF-spring
2, 2
11.000
*Element, type=Spring2, elset=seams1-spring
312,  middle_sheet.13,  bottom_sheet.113
313,  middle_sheet.14,  bottom_sheet.114
314,  middle_sheet.133,  bottom_sheet.183
.....
*Spring, elset=seams1-spring
2, 2
11.000
*Element, type=Spring2, elset=seams2-spring
327,  top_sheet.13,  middle_sheet.113
328,  top_sheet.14,  middle_sheet.114
329,  top_sheet.133,  middle_sheet.183
.....
*Spring, elset=seams2-spring
2, 2
11.000
```

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