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The post-buckling strength and tension-field action mechanism of Cold-Formed Steel Shear Walls with Steel Sheeting

S. Mohebbi[1], S.R. Mirghaderi [2], F. Farahbod [3], S. Torabian [4]

Abstract
AISI standard, section C2.1 mentioned that "For walls with material of the same type and nominal strength applied to opposite face of the same wall the available strength of material of the same capacity is cumulative". This means in CFS shear wall if we use sheeting in both sides, the strength of the wall will be two time of a wall with similar materials and sheeting in one side. Due to the lack of data, a research project was undertaken to evaluate the inelastic performance of CFS shear wall. The paper presents an experimental investigation on 1.2 m wide, 3 m high cold-formed steel (CFS) stud framed shear walls using steel sheet sheathing in one face and both faces. Four walls with 1.2mm and 2.5mm framing thickness were tested through cyclic tests. The test results indicated that use of steel sheeting in both faces, do not result double shear strength for tested walls. Shear strength improvement ratio for walls with thicker frame member (2.5mm) was better than walls with 1.2mm frame thickness.

1. Introduction

Steel-framed houses are usually built of light thin-walled load bearing structures having different solutions for interior and exterior cladding. This technology is popular and accounts for an important and increasing market share in US, Japan, Australia and Europe. In recent years the use of these structures has in common in Iran. In such structures shear walls are the main structural elements which act against horizontal loads, e.g. wind and earthquake. However, the behavior of shear walls subjected to earthquake is not yet fully understood and, in recent years, an important effort has been made to clarify certain aspects related to their shear strength, stiffness and ductility (Dubina, D. 2008).

The current American Iron and Steel Institute (AISI) Standard for Cold-Formed Steel Framing Lateral Design 2007 Edition provides nominal shear strength for sheet steel sheathed CFS shear wall configurations in terms of the sheathing thickness (0.457mm and 0.686mm) and the wall

[1] PhD. Candidate, School of Civil Engineering, College of Engineering, University of Tehran, <sdmohebbi@ ut.ac.ir >
[2] Assistant Professor, School of Civil Engineering, College of Engineering, University of Tehran, < rmirghaderi@ut.ac.ir >
[3] Assistant Professor, Building and Housing Research Center of Iran (BHRC), <f.farahbod@bhrc.ac.ir>
[4] School of Civil Engineering, College of Engineering, University of Tehran, <torabian@ut.ac.ir>
Visiting Researcher, Department of Civil Engineering, Johns Hopkins University, <storabi2@jhu.edu>

aspect ratio (height divided by width).The wall aspect ratio is up to 2:1 for walls with 0.457 mm steel sheathing, and up to 4:1 for walls using 0.686 mm steel sheathing. The published shear strength for sheet steel sheathed CFS shear wall in AISI 2007 Lateral Design Standard are based on the research conducted by Serrette et al. who focused on relatively thin steel sheathing. Serrette et al. discovered that for shear walls with fasteners spaced further apart, sheathing fastener pullout and significant deformation of sheathing were observed. For the shear walls with less fasteners spacing, the failure mode was buckling in the sheathing as well as in the studs (Serrette, R.L. 1996). Similar research was employed by Ellis (Ellis, J. 20007)

As the CFS applications become more popular, wider range options of the wall aspect ratio and the steel sheathing thickness was desired by engineers. Cheng Yu conducted a test program at the University of North Texas to determine the shear strengths of CFS framed shear walls using 0.762 mm or 0.838 mm steel sheet sheathing with an aspect ratio of 4:1 or 2:1, and 0.686 mm steel sheet sheathing with an aspect ratio of 2:1 (Yu, C. 2010). The buckling of the steel sheathing and pullout of sheathing screws were the primary failure modes for sheet steel CFS shear walls. Flange distortion of the boundary studs subjected to tension was also observed on the walls with 251 mm/305 mm screw spacing. Yu concluded that the thicker steel sheets did not significantly increase the shear resistance of CFS shear walls. Current AISI Lateral Design Standard employs a reduction factor 2w/h to account for the flexibility of narrow shear walls that have an aspect ratio exceeding 2:1. The test results indicate that the code reduction factor is a simple reduction factor that represents fairly well the strength reduction based on the drift limit for walls that have an aspect ratio of 4:1(Yu, C. 2010).

Nominal strengths in AISI S213 are based on experimental results on 0.61 and 1.22 m wide and 2.44 m high walls. Cheng Yu experimentally investigate the behavior and shear strength of 1.83 m wide 2.44 m high CFS shear walls to identify the appropriate framing and sheathing details to ensure satisfactory seismic performance (Yu, C. 2011). Four major wall configurations were studied. The test results showed that the interior studs may buckle when the 1.83 m wide shear wall was subjected to cyclic lateral forces if the minimum framing required by AISI S213 [2] is used without additional detailing. The developed special detailing (install blocking and strapping) can be used on 1.092 mm framed shear wall using 0.838 mm or thinner steel sheets to prevent lateral buckling of interior studs meanwhile the shear strength and ductility of the CFS shear wall will be improved (Yu, C. 2011).

54 walls of various configurations were tested at McGill University. The walls varied in framing and sheathing thickness, detailing and aspect ratio. The tests carried out at McGill were used to obtain design values for Canada and to confirm the US values that are listed in the AISI S213 Lateral Design Standard (Balh, N. 2010). Test results were incorporated with data obtained from the US to determine nominal shear resistance values, corresponding resistance factor, overstrength and ductility factors as well as seismic force modification factors, for what can be described as ordinary steel sheathed shear walls (Balh, N. 2010).

All of these studies have a similar point. CFS shear walls were sheathed in one side by steel sheet. The cold-formed steel stud framed shear wall using steel sheet sheathing in both sides is an approved lateral force-resisting system by the current American Iron and Steel Institute Standard for Cold-Formed Steel Framing Lateral Design 2007 Edition. (AISI 2007 – Lateral

Design). **Section C2.1** *For walls with material of the same type and nominal strength [nominal resistance] applied to opposite face of the same wall the available strength [factored resistance] of material of the same capacity is cumulative. Where the material nominal strengths [nominal resistances] are not equal the available strength [factored resistance] shall be either two times the available strength [factored resistance] of the material with the smaller value or shall be taken as the value of the stronger side, whichever is greater.* This means in CFS shear wall if we use sheeting in both sides, the strength of the wall will be two time of a wall with similar materials and sheeting in one side. The authors believe this is un-conservative and using sheeting in both faces is not enough for doubling strength. Due to the lack of data, a research project was undertaken to evaluate the inelastic performance of CFS shear wall with steel sheathing in one face and both faces.

2. The Experimental Investigation

The test program included cyclic shear tests on a total of 4 CFS shear walls using 2 different framing and sheathing configurations. The various test parameters are framing member thickness and steel sheathing in one face or both faces. The following sections address the details of this experimental investigation.

2.1 Specimens

The tested CFS sheet steel shear walls had overall dimensions of 1.2 m wide and 3.0 m high with studs placed at 0.6 m on center. Double studs, back to back, were used at both ends of the wall, and single studs were used at the interior locations. The webs of the double studs were attached together by two lines of No. 14×32 mm hex washer head (HWH) self-drilling tapping screws with 300 mm spacing between two adjacent screws. No: 10×19 mm modified truss head self-drilling tapping screws were used for sheathing and framing. The screws were in a single line on tracks and in the stagger pattern at boundaries with 50 mm spacing between screws. Figure 1 shows the typical framing details and screw spacing arrangement for shear walls tested in cyclic loading.

Shear walls used the same anchorage arrangement. Two ASTM A325 16 mm diameter bolts were installed on the bottom track, two bolts in each section, to resistant shear forces. Special hold-downs using ASTM A490 20 mm diameter bolts were attached to the boundary studs for resisting the overturning forces. To ensure that any uplift would not occur in wall because of hold-downs deformation and high tensional force demand in boundary element, we detail hold-down with relatively thick plates and two bolts for each hold-down, as shown in figure 2. Each hold-down was attached to boundary double stud by three lines of No. 14×32 mm hex washer head (HWH) self-drilling tapping screws with 25 mm spacing between two adjacent screws.

Four different walls were investigated in this research. Table 1 summarizes the differences among those four walls. Specimen 1 [1.2F (Framing th.)-0.8SH (Sheathing th.)-OF (One Face)] and specimen 2 have 1.2 mm framing thickness whereas specimen 3 and 4 have 2.5 mm framing thickness. CFS shear wall sheeted in one face in specimens 1, 3 and sheeted in both faces in specimens 2, 4. All four walls sheeted with 0.8 mm thickness steel sheeting. All the cold-formed steel members and steel sheathing in the shear walls were made of ASTM A653M steel. The material thicknesses of the sheathing and framing members were monitored throughout this test program. Coupon tests were performed to obtain the actual material properties.

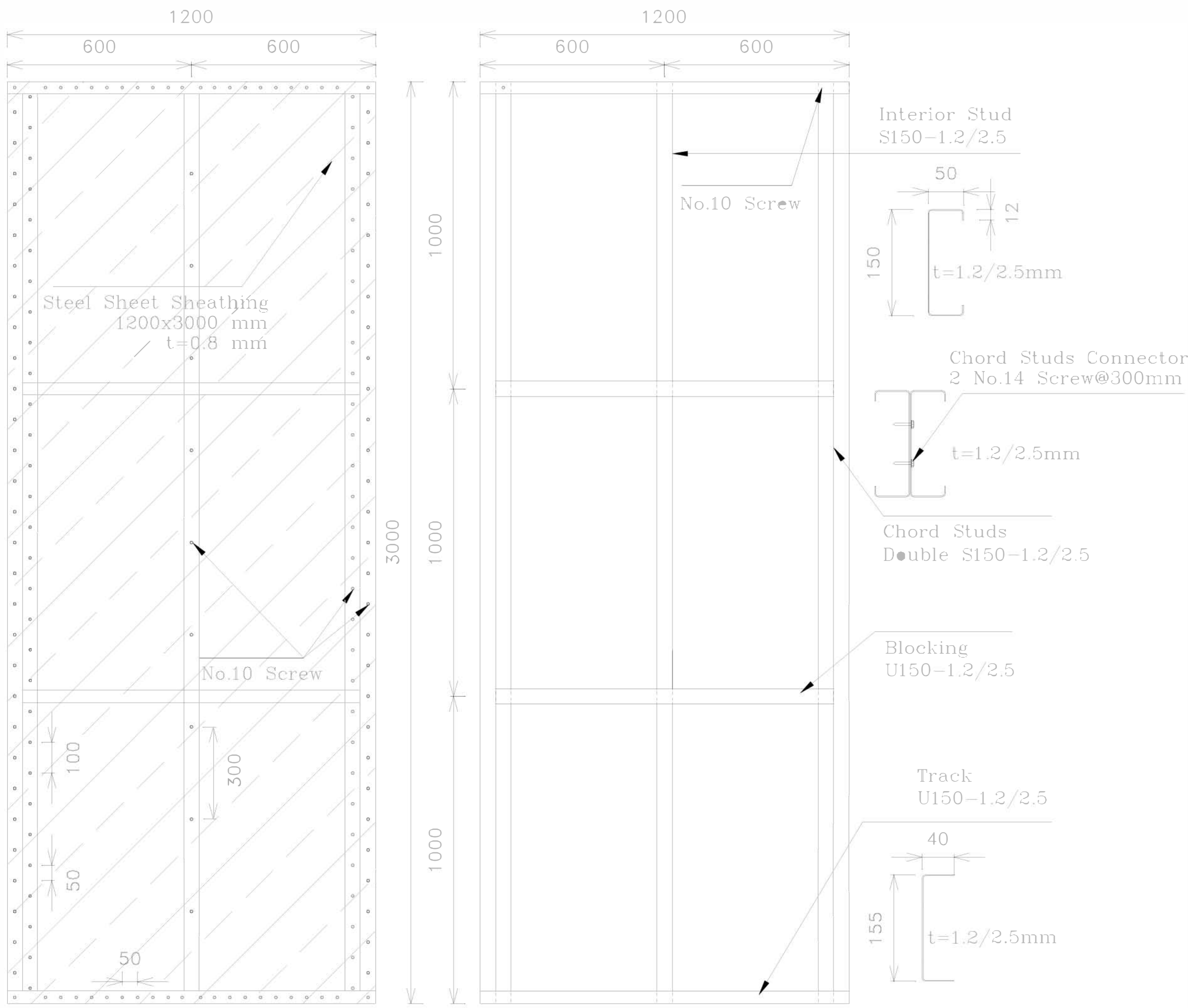

Figure 1: Framing details and screw arrangement for shear walls

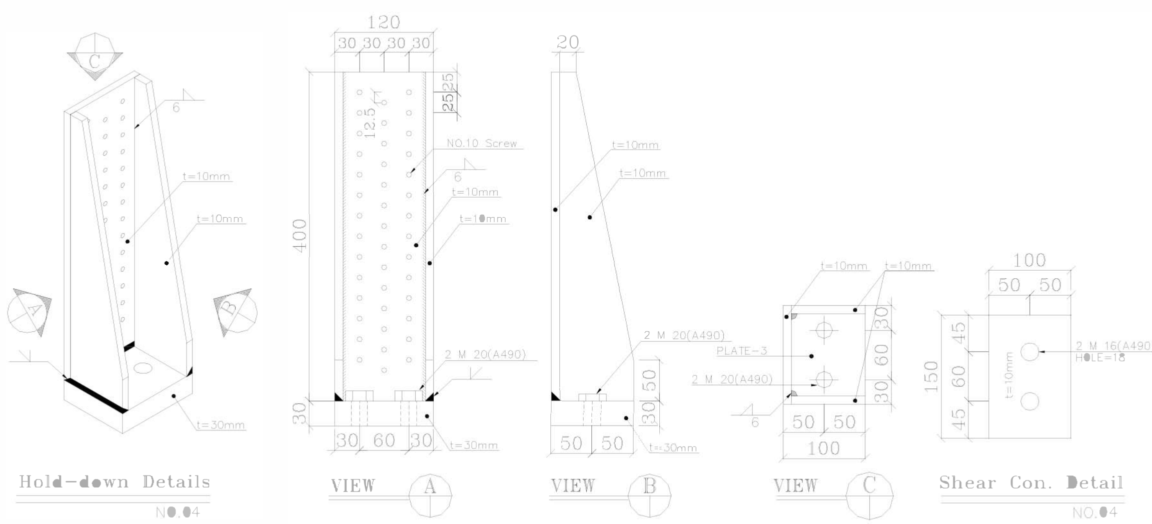

Figure 2: Hold-down and shear connection details

Table 1: Details of shear walls

Specimen	Nominal framing thickness (mm)	Nominal steel sheet thickness (mm)	Sheeted in ●ne face/Both faces
1.2F-0.8Sh-●F	1.2	0.8	●ne face
1.2F-0.8Sh-BF	1.2	0.8	Both faces
2.5F-0.8Sh-●F	2.5	0.8	●ne face
2.5F-0.8Sh-BF	2.5	0.8	Both faces

2.2 Test setup

The shear wall tests were conducted on the Structural Testing Laboratory at the Building and Housing Research Center of Iran. Figure 3 illustrates the testing frame with one shear wall installed. All the shear wall specimens were assembled in a horizontal position and then installed vertically to the test apparatus. The bottom track of the shear wall was bolted to the base beam. The in-plane horizontal load was applied to the top of the wall via two hydraulic jacks. Two universal load cells were placed between hydraulic jacks and the Frame. The movement of the hydraulic jacks was controlled electrically.

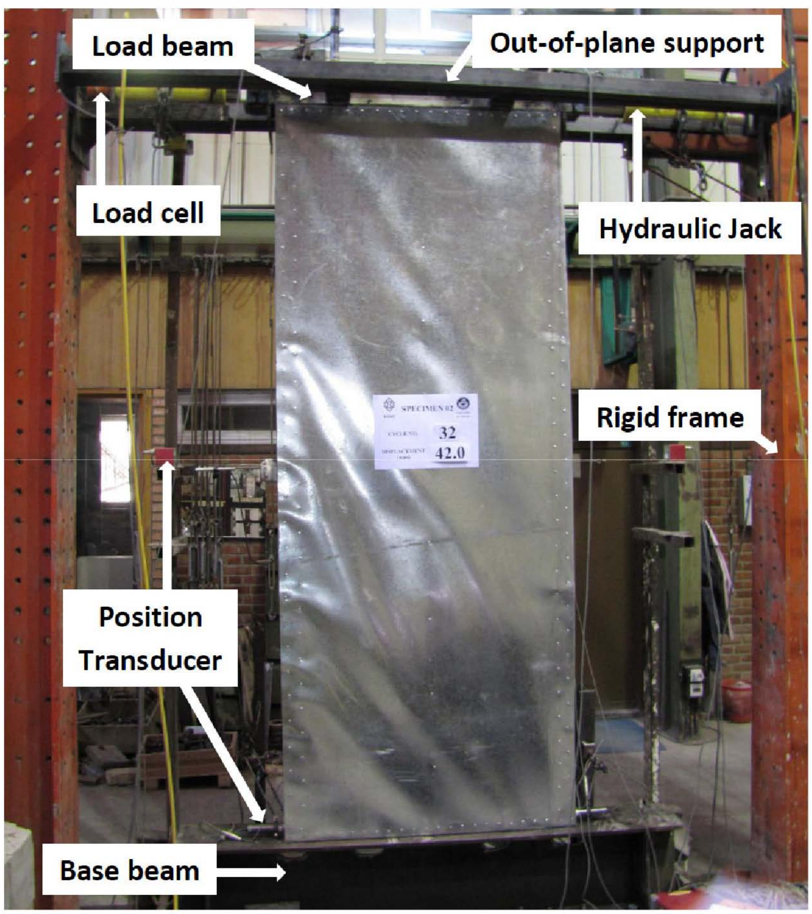

Figure 3: Test setup

2.3 Instrumentation

8 position transducers were employed to measure the vertical and horizontal displacements of boundary studs at bottom and top. Moreover 5 position transducers were employed to measure the horizontal and out-of-plane displacements of boundary and interior studs at middle height of

wall. Three strain gauges (Type: YEFLA-5) were installed on the external web of right boundary stud at 1/6, 3/6 and 5/6 height of wall. This gauge is designed for measurement of large strain up to 10 15%. Also it is durable to the measurement of repeated strain in elastic range (at strain level $\pm 1500 \times 10^{-6}$) like as ordinary strain gauge. The applied force, 13 displacements and the three strains were measured and recorded instantaneously during the test through a data Logger system. Fig. 4 illustrates the arrangement of transducers and strain gauges.

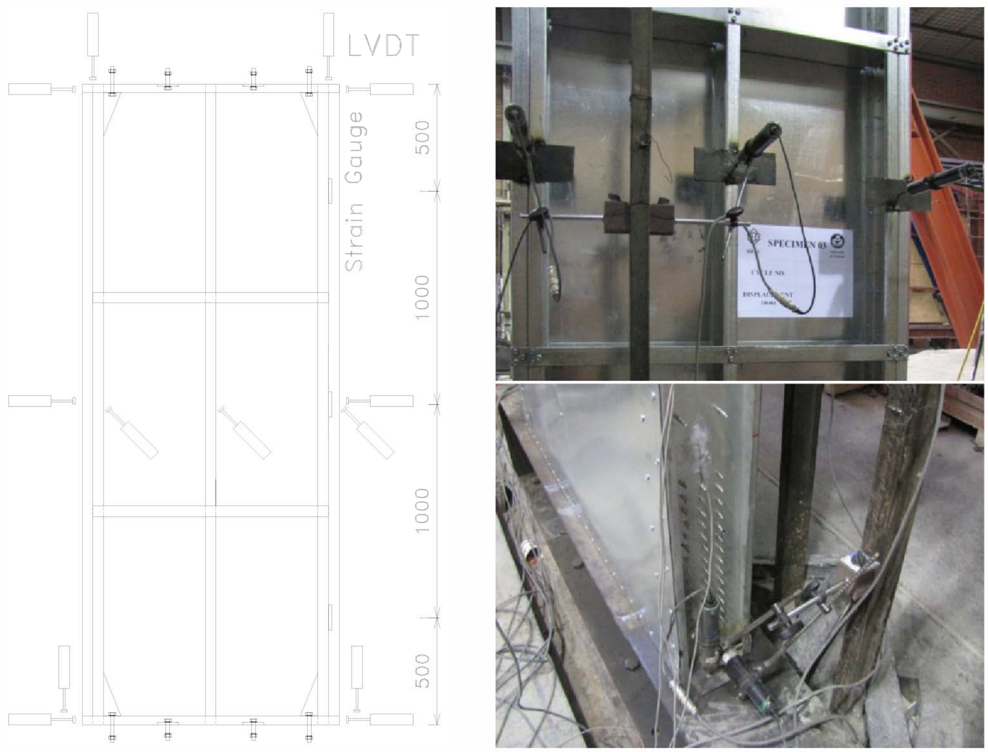

Figure 4: The arrangement of transducers and strain gauges

2.4 Loading conditions

Cyclic tests were conducted in a displacement control mode. The cyclic tests used the CUREE protocol which is in accordance with the method C in ASTM E2126 (2007) "Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings". The CUREE basic loading history adopted in this research, shown in Figure 5, includes 46 cycles with specified displacement amplitudes, Δ. The specified displacement amplitudes are based on 2% drift of the wall equal to 60 mm displacement. Shear walls were not failed at the end of the 60 mm displacement. Therefore additional loading cycles would be added. Each progressive primary cycle added would include an increase of 50% over the previous primary cycle. Two trailing cycles would follow each primary cycle with an added magnitude of 75% of the primary cycle.

3. Test Results

The post-buckling strength and tension-field action mechanism of unstiffened steel plate provide shear strength of cold-formed steel (CFS) shear walls with steel sheeting. The buckling strength of the plate in compression is dependent upon the slenderness of the plate (depth-to-thickness ratio and width-to-thickness ratio). These ratios are typically high for normal building geometries and reasonable cold-formed steel shear wall thicknesses, and buckling strength is correspondingly very low. When the lateral load applied to the wall generates principal compressive stresses that exceed the compression strength of the plate, the plate buckles, generating fold lines in the plate perpendicular to these compressive stresses (and parallel to the principal tensile stresses). At this point, lateral loads are transferred through the plate by the principal tension stresses. This post-buckling behavior is typically referred to as "tension-field action." Cold-formed steel (CFS) shear walls have slender steel sheeting that capable of resisting large tension forces but little or no compression. This behavior is analogous to tension-only bracing, which relies on beams in compression to transmit the horizontal component of a brace force to the brace at the level below, and in which overturning forces are imposed on boundary elements. Overturning forces are resisted by the boundary elements and are delivered by vertical component of the brace forces.

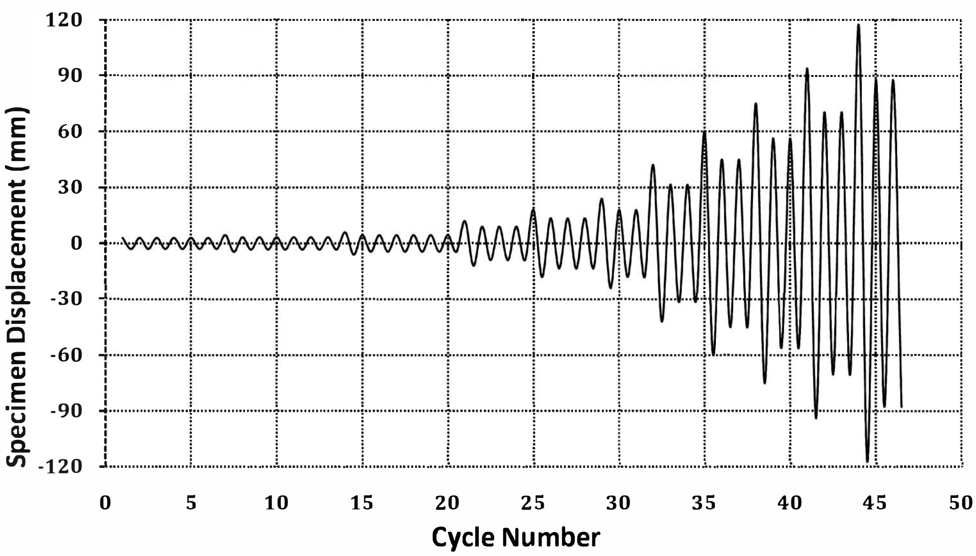

Figure 5: Specimen loading history (CUREE protocol)

A total of 4 cyclic tests were conducted. The peak loads and the corresponding deflections of the shear walls are provided in Table 2. The observed failure modes for test specimens are provided in Table 3. The CFS walls yielded similar peak loads on both the positive and negative loading directions, and the walls were able to remain the stiffness prior to the peak load cycle. After passing the peak load cycle, both strength degradation and stiffness degradation were observed. Figure 6 shows the test hysteresis curve for the 1.2F-0.8Sh-OF specimen.

Table 2: Shear wall test results

Specimen	Peak load P+ (kN/m)	Peak load P- (kN/m)	Peak load Average (kN/m)	Disp. at P+ (mm)	Disp. at P- (mm)	Disp. Average (mm)
1.2F-0.8Sh-OF	31.81	28.26	30.04	55.1	55.6	55.4
1.2F-0.8Sh-BF	40.30	39.24	39.77	34.1	34.1	34.1
2.5F-0.8Sh-OF	50.45	46.83	48.64	75.1	58.0	66.6
2.5F-0.8Sh-BF	81.72	76.44	79.08	59.4	49.0	54.2

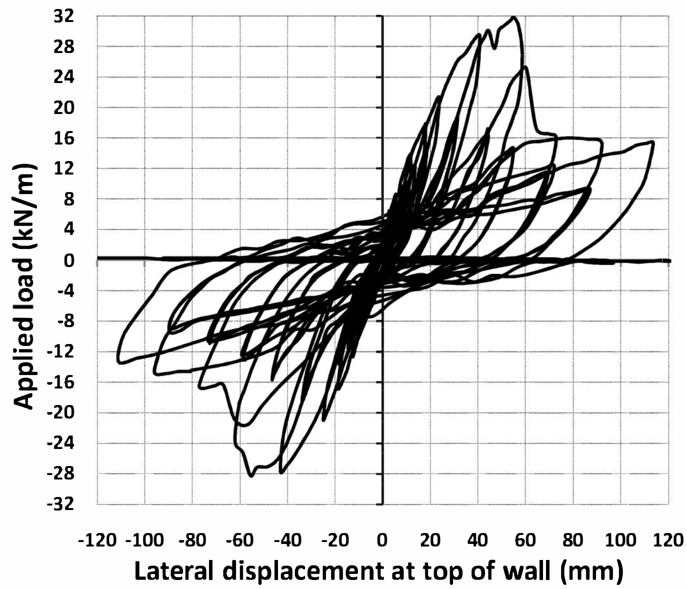

Figure 6: Hysteresis curve for specimen 1.2F-0.8Sh-OF

Table 3: Shear wall failure modes

Specimen	Sheet buckling	Bearing / Tear-out Sheathing	Boundary stud buckling
1.2F-0.8Sh-OF	√		√
1.2F-0.8Sh-BF	√		√
2.5F-0.8Sh-OF	√	√	
2.5F-0.8Sh-BF	√	√	

For walls with 1.2mm framing thickness, steel sheet sheathing buckling was observed. The walls failed by local buckling of boundary studs. Figures 7 and 8 respectively show the test hysteresis envelope curves and failure mode for the 1.2F-0.8Sh specimens.

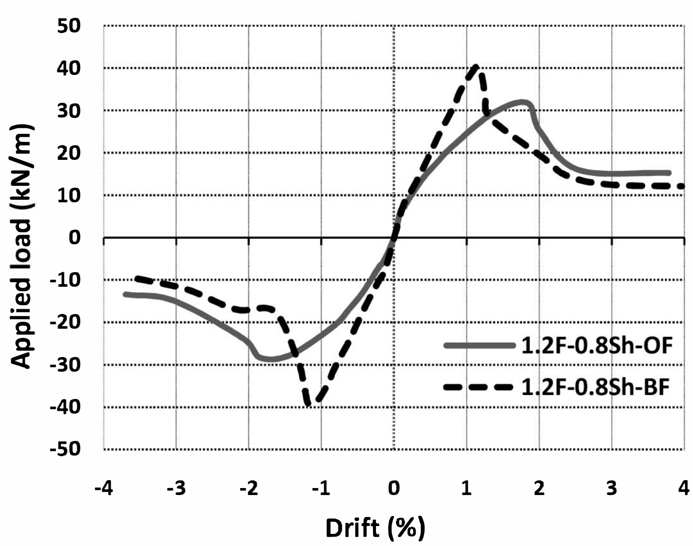

Figure 7: Hysteresis envelope curves for 1.2F-0.8Sh specimens

Figure 8: Failure modes for 1.2F-0.8Sh-OF specimen (left) and 1.2F-0.8Sh-BF specimen (right)

Specimens 1.2F-0.8Sh-OF and 1.2F-0.8Sh-BF failed by local buckling of 1.2 mm thickness boundary studs. This is undesired failure mode and strength of walls dropped immediately after buckling of boundary stud in top of hold-downs. Sheeting in both sides improved shear strength of the wall. Average peak load of the wall was improved about 32% and there is significant difference between test result and AISI standard expression for one side and both sides' sheeted walls. Using sheeting in both faces was not enough for doubling strength and local buckling of boundary element control wall performance.

For the cyclic tests on 2.5F-0.8Sh walls, a combination of steel sheet sheathing buckling and bearing / tear-0ut Sheathing was observed. Some flange distortion on the boundary studs were also observed on walls. Figures 9 and 10 respectively show the test hysteresis envelope curves and failure mode for the 2.5F-0.8Sh specimens.

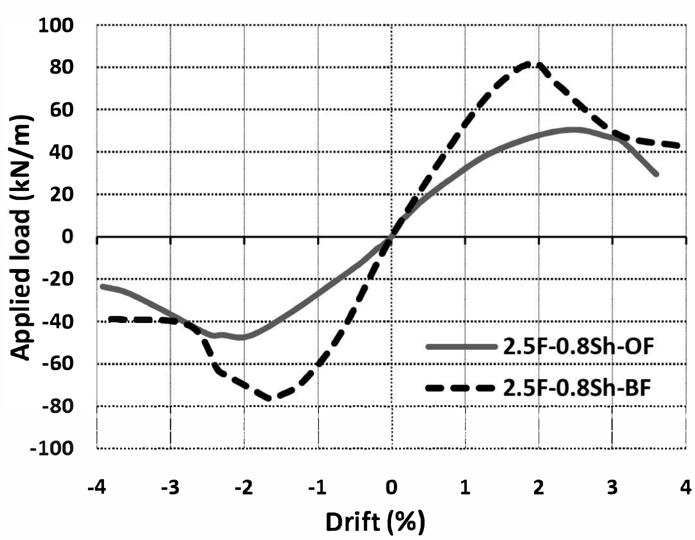

Figure 9: Hysteresis envelope curves for 2.5F-0.8Sh specimens

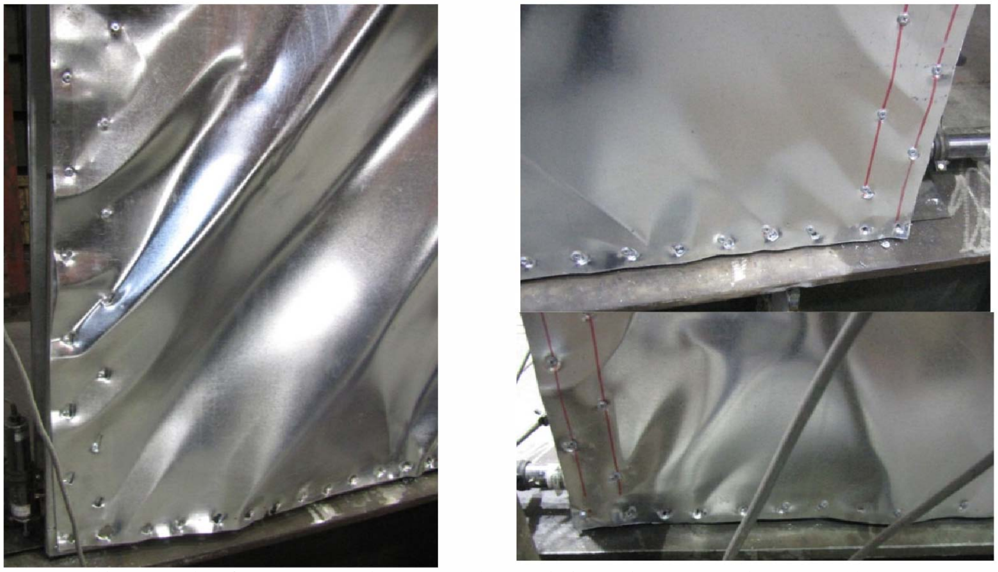

Figure 10: Failure modes for 2.5F-0.8Sh-OF specimen (left) and 2.5F-0.8Sh-BF specimen (right)

Connection failure modes were observed in 2.5F-0.8Sh-OF and 2.5F-0.8Sh-BF walls. The modes involved tilting of the sheathing screw and bearing / tear-out of the sheathing. To a lesser extent screws were observed to pull out of the framing or pull through the sheathing, and in only a few cases screws fractured in shear. Connection failures started with tilting of the screw due to the eccentric shear load placed on the connector. The shear applied on the fastener also led to local bearing in the sheathing which allowed for the connection to become loose. Average peak load of the wall was improved about 62% by using sheeting on both faces. Hence in wall with 2.5 mm frame thickness, shear strength improvement was significant, but two time shear strength was not reached. The outer flange of the boundary double studs distorted slightly due to the buckling of the steel sheet. Because of the closer screw spacing, the load to the framing members was increased. In addition, the sheathing screws were able to hold the steel sheet sheathing to the framing during the test, therefore, transferring a significant amount of load to the outer flange to cause such flange distortion. Figure 11 shows the test hysteresis envelope curves for all specimens.

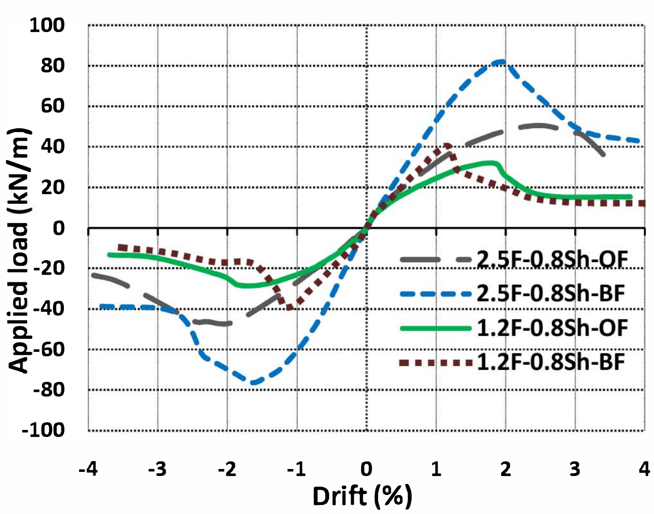

Figure 11: Hysteresis envelope curves for tested specimens

4. Conclusions

Cyclic shear wall tests on CFS framed walls with single and double sided steel sheet sheathing were conducted. For walls with 1.2mm framing thickness, steel sheet sheathing buckling was observed and walls failed by local buckling of boundary studs. The buckling of the steel sheathing and pullout of sheathing screws were the primary failure modes for sheet steel CFS shear walls with 2.5mm framing thickness. Flange distortion of the boundary studs subjected to tension was also observed on the walls with 2.5mm framing thickness.

Average peak load of the wall was improved about 32% (For walls with 1.2mm framing thickness) and 62% (For walls with 2.5mm framing thickness).So there is difference between test result and AISI standard expression for one side and both sides' sheeted walls and AISI standard recommendation is un-conservative and using sheeting in both faces is not enough for doubling strength.

Acknowledgments

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