Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Orlando, Florida, April 12-15, 2016

Cyclic Simulation of Cold-Formed Steel Shear Walls with Corrugated Steel Sheathing

Mahsa Mahdavian[1], Wenying Zhang[2], Chu Ding[3], Cris Moen[4], Cheng Yu[5]

Abstract

This paper presents cyclic finite element modeling and analysis on cold-formed steel framed shear walls sheathed by corrugated steel sheets. Full-scale shear wall tests on this type of shear wall system have been conducted and it was found that the corrugated sheathing had rigid board behavior before it failed in shear buckling in the sheathing and sometimes simultaneously in screw connection failures. The research goal of this presented work was to simulate the behavior and failure mechanism of such shear wall system in ABAQUS so that more complex shear wall systems can be analyzed numerically without full scale tests. The tiling and bearing behaviors of the screw connections in the sheathing was modeled in ABAQUS. Various connection modeling approaches in ABAQUS were studied in this paper and it was found that the SPRING2 element was capable of simulating the monotonic behavior of screw connections and therefore was recommended in shear wall modeling. For cyclic tests, the cold-formed steel shear wall experienced significant pinching behavior before the failure. It was suggested that a general user-defined element (user subroutine UEL) in ABAQUS could be used to simulate the screw behavior under cyclic loading. The research found that the ABAQUS models had good agreements with the shear wall tests. The modeling details and analysis results are presented in this paper.

1. Introduction

1.1 Research motivation

Wind loads and seismic loads create lateral forces in structures. Shear walls are designed and constructed to provide the necessary lateral strength to resist these horizontal forces in the structure. Currently in the U.S., most shear walls are designed through empirical methods derived from full scale tests. The cold-formed steel (CFS) shear walls with corrugated steel sheathing are a new lateral resistance system introduced to the construction industry. This new

[1] Graduate Research Assistant, University of North Texas, <Mahsa_Mahdavian@yahoo.com>
[2] Visiting Graduate Student, Tongji University, <WenyingChangan@163.com>
[3] Graduate Student, Virginia Tech
[4] Associate Professor, Virginia Tech, <Cmoen@vt.edu>
[5] Associate Professor, University of North Texas, <Cheng.Yu@unt.edu>

classification of shear walls is unexplored and is not included in building codes. Computational simulations allow researchers to study the performance of these walls, and to share findings with designers. The aim of this paper is to improve the computational simulation capability to inform next generation design codes through parameter studies. Finite element modeling allows us to explore new shear wall products and configurations, such as the one introduced in this paper, to improve the accuracy and efficiency of future designs.

1.2 CFS shear wall testing and design

CFS is a widely acceptable material option for mid-rise construction therefore the usage of CFS has significantly increased in today's market. Common lateral force resisting systems (LFRS) for CFS framed shear walls are sheathed by steel sheets, wood based panels or other systems (AISI-S213-07). Due to the International Building Code requirements (IBC 2006) for Type I and II construction, steel sheet shear walls and strap braced shear walls are the only economical choices for mid-rise buildings. Due to the performance limitations of current all steel shear walls, a new configuration is essential. The solution to a high structural performance all steel shear wall could be to use corrugated steel sheathings. Corrugated steel sheathings have high in-plane strength and stiffness as a result of the cross sectional shape of the sheet.

In order to have a better understanding about the behavior of this new type of shear wall a series of tests were conducted at University of North Texas to observe the behavior of the new shear walls with corrugated steel sheathings. Furthermore, finite element models were developed in ABAQUS to achieve realistic results by pushing the state-of-the-art.

1.3 CFS shear wall simulations

Different elements of CFS shear walls have 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 to capture both fastener-based and member-based limit states in shear walls (Bian et al. 2015). An extensive study has been established at John Hopkins University to develop a high fidelity computational model of wood-sheathed CFS framed shear walls (Hung Huy Ngo 2014). In addition, a series of tests were conducted to study the impact of building details, such as ledger tracks and locations of panel seams, on the performance of shear walls sheathed with OSB (Peng Liu et al. 2012). Sufficient progress has been made on component to system-level simulations. Performance and failure of shear walls, particularly under seismic loading, is dominated by the sheathing connections. Therefore, further investigations were performed by introducing 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 (Ding et al. 2015). This paper compiles all these establishments to achieve effective simulations of CFS shear walls.

2. Full-Scale Shear Wall Tests

A monotonic and a cyclic test were performed at the University of North Texas's structural laboratory. The walls were bolted to a 16 ft. by 13.3 ft. structural steel testing frame and loaded horizontally at the top. Fig. 1 shows the testing frame and Fig. 2 is an image of the frame and setup. A “T” shaped loading beam is connected to the shear walls at the top by two rows of #12 x 1-1/4 in. hex washer head self-drilling screws every 3 in. The out-of-plane displacement of the shear walls were prevented by placing the “T” bar web in-between the rollers at the top of the testing frame. A total of 5 position transducers are used for each test to measure the displacement of the shear wall horizontally and vertically (Fig. 1). Shear walls are anchored to the testing frame by a Simpson Strong Tie S/HD15S hold-down at each end of the shear wall. In addition, two Grade 8 3/4-in. bolts and two Grade 8 5/8-in. bolts were used in the anchorage system.

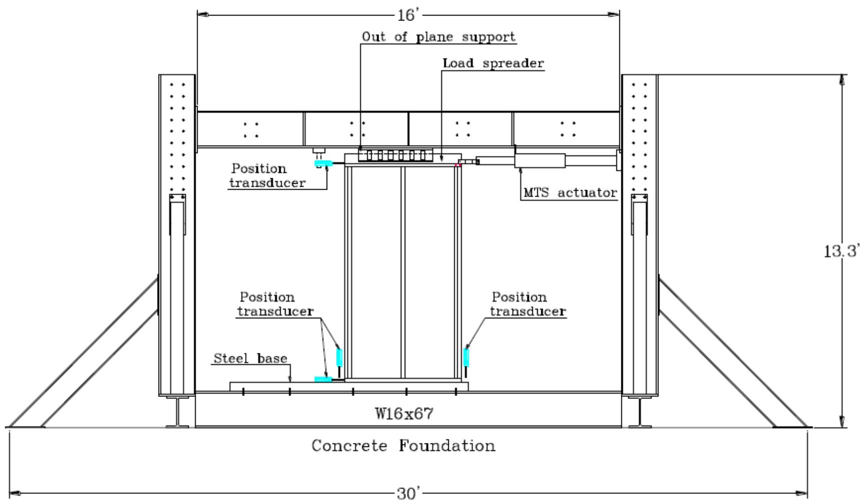


Figure 1: Shear Wall Testing Frame

Figure 2: Shear Wall Frame and Setup

The shear wall specimens studied were 8 ft. high by 4 ft. wide (2:1 aspect ratio). Specimens are labeled by wall width (ft.) x wall height (ft.) x framing thickness (mil) x sheathing thickness (mil) – test protocol. Three Verco Decking corrugated steel sheets were installed on one side of each shear wall. These sheets were overlapped by two ribs and were connected by a line of screws. Boundary studs were connected back-to-back at the webs by two #12 x 1 – 1/4 in. hex washer head self-drilling screw every 6 in. starting from above the hold-downs. Framing members and sheathings were connected using #12 x 1 – 1/4 in. hex washer head self-drilling screws every 3 in. at the sheathing edge and seam joints, and every 6 in. on the field stud. Finally, hold-downs were connected at the bottom of the boundary studs using thirty three #14 x 1 in. hex washer head self-drilling screws. Further details of the components of the shear walls are listed in Table 1.

Table 1: Shear Wall Components

Test Label	Studs	Tracks	Sheathing
4x8x68x27-Monotonic	350 S 162 - 68, 50 ksi	350 T 150 - 68, 50 ksi	SV36, 22 ga, 80 ksi
4x8x68x27-Cyclic	350 S 200 - 68, 50 ksi	350 T 150 - 68, 50 ksi	SV36, 22 ga, 80 ksi

Coupon tests were conducted according to the ASTM A370 (2006) “Standard Test Methods and Definitions for Mechanical Testing of Steel Products” to obtain the material properties of the members used in full scale tests. A total of three coupon tests were performed for each member, and the average results are summarized in Table 2.

Table 2: Material Properties

Components	Uncoated Thickness (in.)	Yield Stress, Fy (ksi)	Tensile Strength, Fu (ksi)
350 S 162 - 68	0.0703	56.82	72.16
350 S 200 - 68	0.0694	56.25	77.37
350 T 150 - 68	0.0698	56.38	70.96
SV36 - 27	0.0287	88.51	94.25

ABAQUS requires the material properties to be recorded in the form of true stress and true strain. The true stress (σ_{true}) and true strain (ϵ_{true}) are converted from engineering stress and engineering strain following Eq. 1 and Eq. 2 respectively:

$$\sigma_{true} = \sigma_{eng} (1 + \epsilon_{eng}) \tag{1}$$

$$\epsilon_{true} = \ln (1 + \epsilon_{eng}) \tag{2}$$

Both monotonic and cyclic tests were conducted in a displacement control mode. The monotonic shear wall was loaded at a rate of 0.0075 in./sec and traveled a total distance of 5 in. The cyclic shear wall was loaded based on CUREE protocol in accordance with ICC-ES AC 130 (2004). The CUREE basic loading history includes a total of 43 cycles and is shown in Fig. 3.

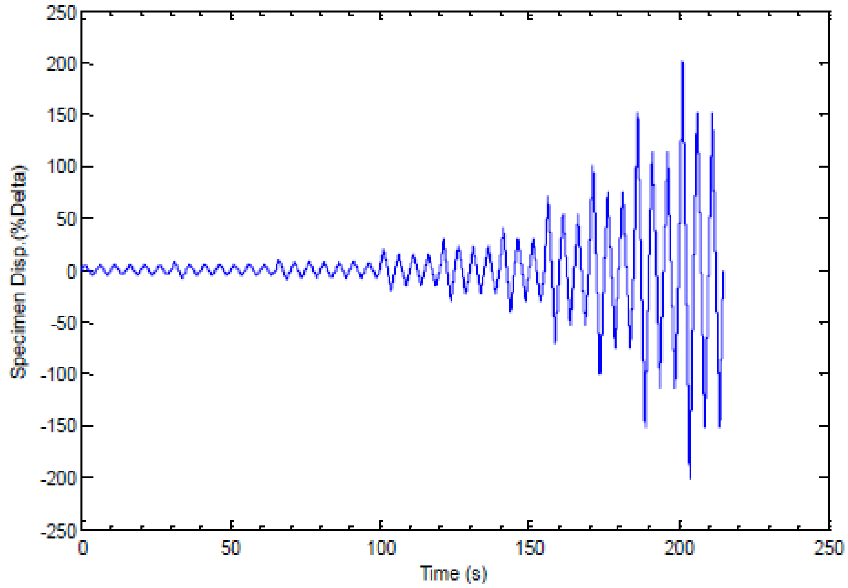


Figure 3: CUREE Basic Loading History

The load-deformation responses for both tests are shown in Fig. 4. The x-axis reports the lateral displacement (in.) of the wall from the top position transducer. The y-axis reports the lateral load (lbs) applied to the wall by the actuator.

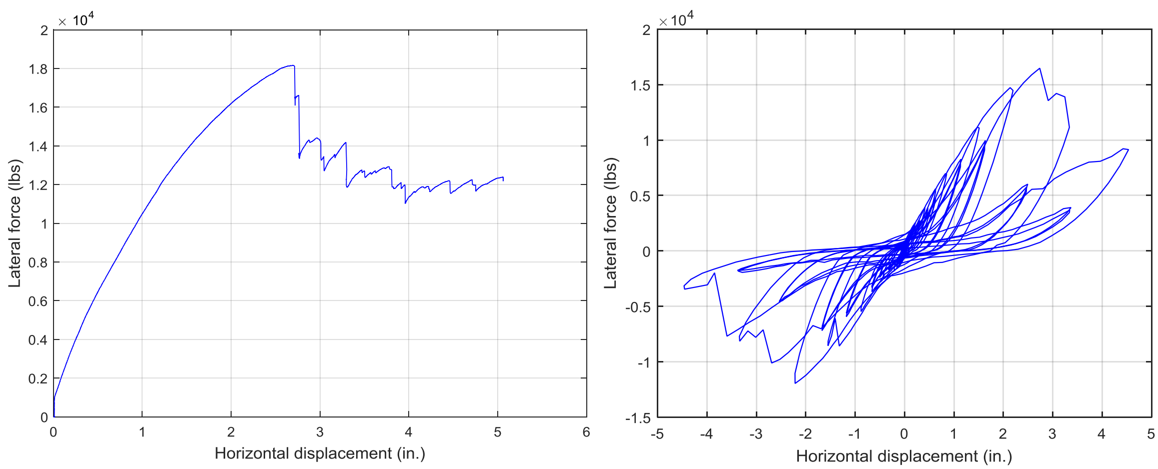


Figure 4: Load-Deformation Response of Monotonic and Cyclic Test

Both monotonic and cyclic tests showed fastener-based and member-based limit states. The failure modes observed in the shear wall under monotonic lateral loading, shown in Fig. 5, included (a) screw pull over on bottom sheet to frame connections, (b) local and torsional buckling of studs on the compression side and (c) shear buckling in bottom corrugated sheet. Also, the shear wall under monotonic lateral loading caused the wall to lift from the testing frame at the tension side (Fig. 5.c). The failure modes observed in the shear wall under cyclic lateral loading, shown in Fig. 6, included (a) screw pull out and screw pull over on bottom sheet to frame connections, (b) minor local buckling of the studs on the opposite direction of the actuator and (c) shear buckling in bottom corrugated sheet.



(a) Screw Pull Over (b) Local and Torsional Buckling (c) Shear Buckling
Figure 5: Observed Failure Modes of Shear Wall under Monotonic Lateral Loading


(a) (c) Screw Pull Over and Shear Buckling (b) Minor Local Buckling
Figure 6: Observed Failure Modes of Shear Wall under Cyclic Lateral Loading

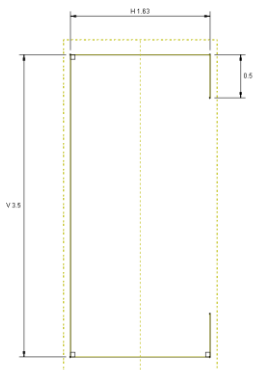
3. Computational Simulation Protocol for a CFS Shear Wall

3.1 Overview

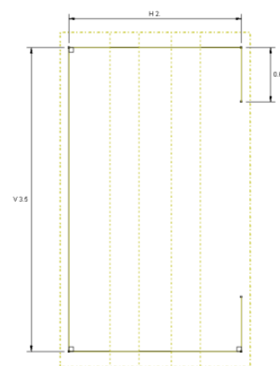
The CFS shear walls with corrugated steel sheathing models are developed in ABAQUS 6.14 (2014). All components of the shear walls are fully modeled with shell elements. Material properties from coupon test results are applied. Connection tests are performed to define pinching paths to model fasteners with hysteretic user-defined elements. Element interactions, boundary conditions and loading applications are consistent with full scale tests. This section provides the details of the shear wall model development.

3.2 Model Components and Geometry

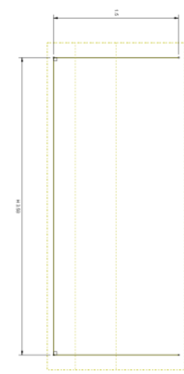
The dimensions and thicknesses of shear wall framing components were chosen from the Steel Stud Manufacturers Association product catalog (SSMA 2014). Profile dimensions of the corrugated sheathings are in accordance with those provided by the manufacturing (Verco Decking, INC.). Fig. 7 displays the cross sectional geometry of the shear wall components. All parts 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.



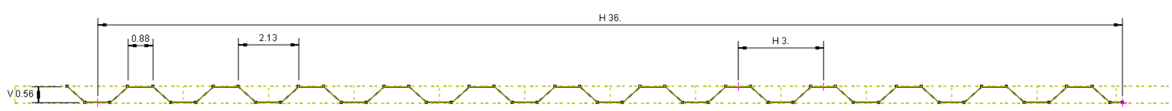
(a) 350 S 162 – 68



(b) 350 S 200 – 68



(c) 350 T 150 – 68

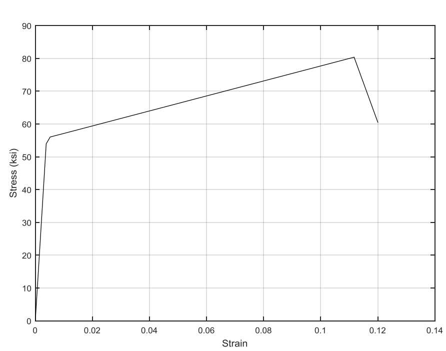


(d) Corrugated Sheet

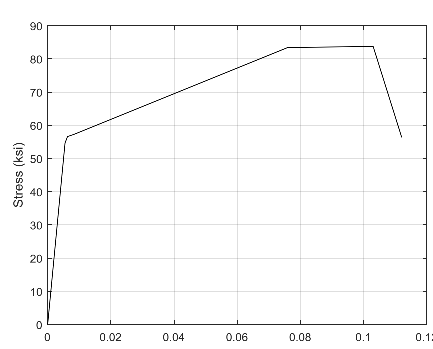
Figure 7: Cross Sectional Geometry of Shear Wall Components

3.3 Material Properties

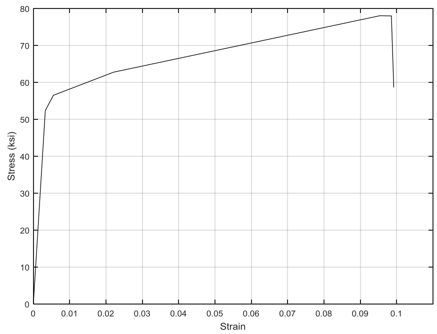
All members were assigned elastic and plastic material behavior. Elastic material behavior was modeled as isotropic type with Young's modulus E=29,500 ksi and Poisson's ratio v=0.3. An average of the three coupon test results were converted to true stress (σ_{true}) and true strain (ϵ_{true}) values, shown in Fig. 8, to define member's plastic material behavior.



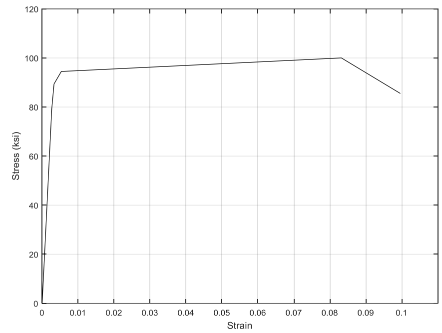
(a) 350 S 162 – 68



(b) 350 S 200 – 68



(a) 350 T 150 – 68



(b) Corrugated Sheet

Figure 8: Material Properties - True Stress vs. True Strain

3.4 Interaction

The CFS frame members were connected using “Tie” constraints. These constraints include track-to-stud and stud-to-stud connections. It is important to mention, members selected as master or slave are of great significance in finite element analysis.

3.5 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 displacements were fixed. The bolts connecting the bottom track to the testing frame are modeled by restricting the bolted areas on the track in all directions.

All nodes in the hold-down area of each cord stud are bound into a rigid body and tied to a single node at the center of the areas by the rigid body reference node. These reference nodes are then connected to the ground by a bi-linear spring. Also, these nodes are constrained in the axial direction and the rotational degree of freedom about the x-axis.

3.6 Loading

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. A displacement controlled lateral load is applied to the reference point, seen in Fig. 9, in the horizontal direction at the top of the shear walls.

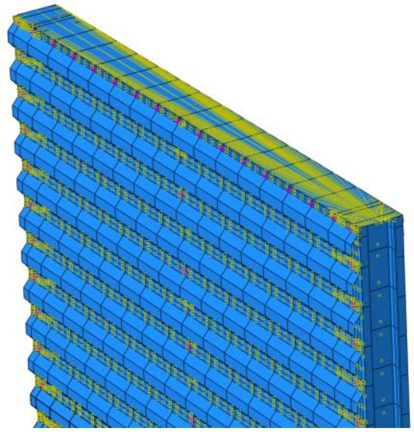


Figure 9: Loading Simulation

3.7 Contact

A contact property was introduced between the surfaces of the corrugated sheathing and the studs to prevent the sheathing from penetrating through the frame members. A frictionless tangent behavior and hard-contact normal behavior were defined at these locations. This contact property can also be observed in Fig. 9.

3.8 Connections

3.8.1 Monotonic Model

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 the AISI-S100-07 (2010).

3.8.2 Cyclic Model

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 from Chu Ding (2015). The UEL developed was based on OpenSees Pinching4 material and was successfully able to simulate the unloading stiffness degradation, reloading stiffness degradation and strength degradation.

4. Shear Wall Computational Simulation Results

4.1 Monotonic

The ABAQUS model was able to match the shear wall behavior well prior to the peak load. A comparison of the load-deformation responses are illustrated in Fig. 10. The peak load from ABAQUS is 13% lower than the test result. The initial stiffness of the ABAQUS model is comparable to the full scale test initial stiffness. The shear wall tested failed due to shear buckling of the bottom sheet which caused the screw pull-over failure to happen concurrently. In ABAQUS, the initial failure observed was in the sheathing-to-frame screws. Stress distribution is mainly focused on the bottom corrugated sheet which is in accordance to the full scale test results. The second failure mode observed was the local buckling of the chord studs at the top of the hold-down locations. Torsional buckling of the field stud is also observant. These failure modes are shown in Fig. 11.

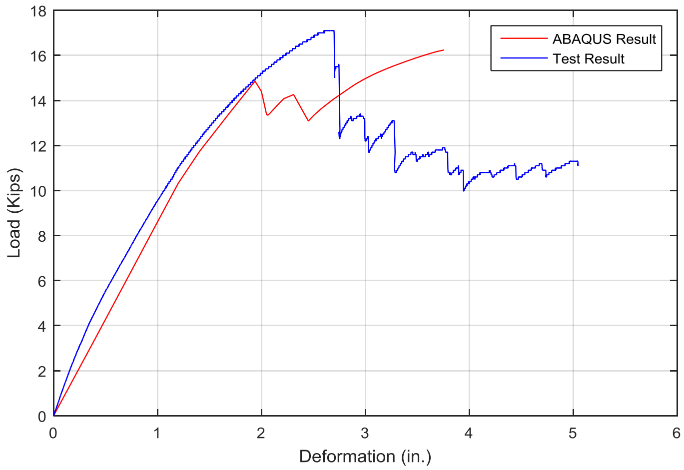
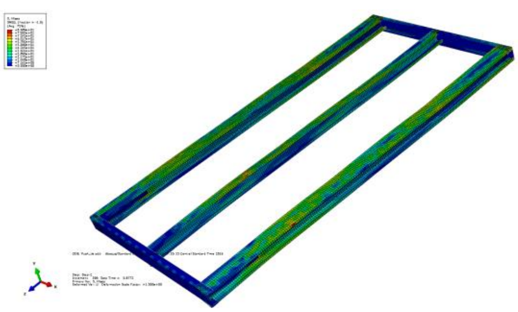
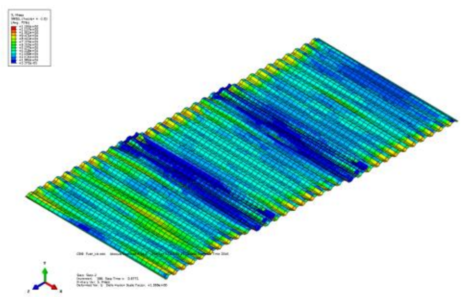


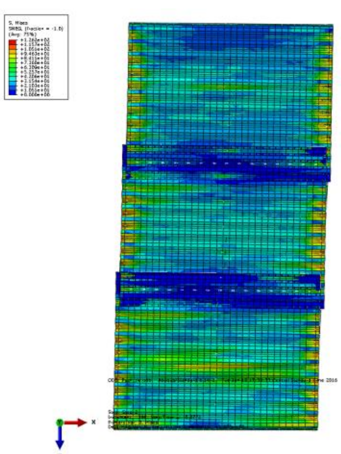
Figure 10: Monotonic Load-Deformation Responses



(a) Stress Distribution on Frame



(b) Stress Distribution on Sheathing

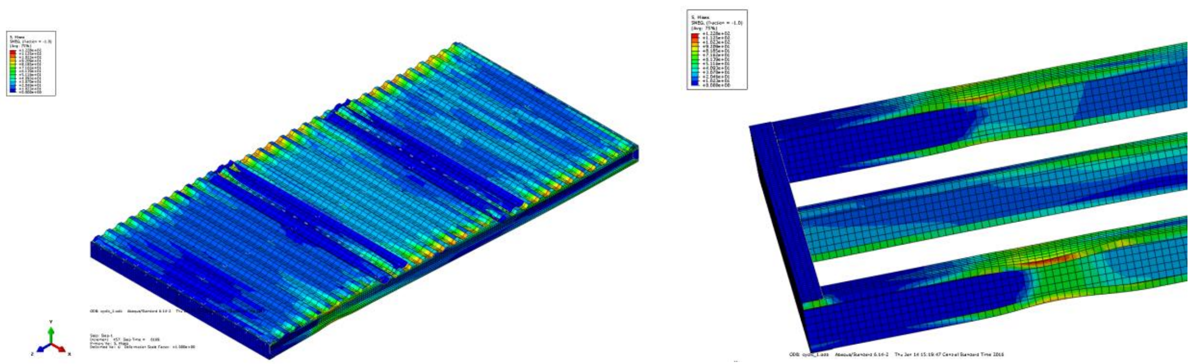


(c) Front View Stress Distribution

Figure 11: ABAQUS Result Analysis

4.2 Cyclic

The shear wall model under cyclic lateral loading had an acceptable agreement with the full scale test results. ABAQUS deformation response illustrated connection failures in the sheathing and the stress distribution was concentrated on the middle and top corrugated sheets. More local buckling was observant in the studs in comparison to the experimental results. Fig. 12 shows details of ABAQUS deformation response. Conversely, the load-deformation of the model and test were nearly identical. The initial stiffness are equal and the average peak loads are only 2% different in value. Fig. 13 shows a comparison of the load-deformation responses. The cause of data shortage from ABAQUS can be linked to unreliable data from connection tests. Additional research related to connection tests are necessary to obtain more satisfactory results.



(a) Cyclic Shear Wall Load Distribution (b) Local Buckling of Chord Studs

Figure 12: ABAQUS Deformation Response

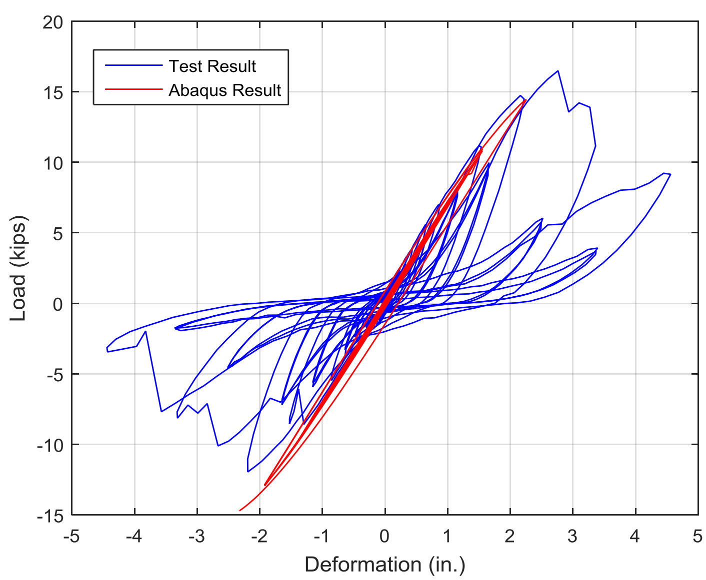


Figure 13: Load-Deformation Response Comparison

5. Conclusions

Shear walls sheathed with corrugated steel sheets are an innovative solution to high performance all steel shear walls and can be modeled in ABAQUS efficiently to study the behavior of these walls more extensively. This paper provides modeling details in ABAQUS for simulating the shear wall system under monotonic and cyclic loading conditions respectively. The provided models were able to identify all limit states and failure modes successfully. The spring and fastener nonlinearity were simulated using a general user-defined element in ABAQUS to demonstrate the impact of screw behaviors on shear walls. Developed models were verified by comparison with full-scale shear wall tests; however additional work is recommended to better utilize the introduced elements. Significant work remains to simulate the cyclic response of shear walls and to achieve satisfactory load-deformation response. Nevertheless, the models represented a significant advancement in computational modeling of CFS shear walls with corrugated steel sheathings and substantiated potential application capabilities.

Acknowledgements

This paper was prepared as part of the U.S. National Science Foundation grants 0955189 and 1445065. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors thank Aritra Chatterjee and Junle Cai for their collaboration.

References

AISI-S213-07. (2007). "AISI North American Standard for Cold-Formed Steel Framing – Lateral Design." American Iron and Steel Institute.

International Code Council (2006). "International Building Code 2006", U.S.A.

Bian, G., Padilla-Llano, D.A., Buonopane, S.G., Moen, C.D., Schafer, B.W. (2015). "OpenSees Modeling of Wood Sheathed Cold-Formed Steel Framed Shear Walls." Proceedings of the Annual Stability Conference, Structural Stability Research Council. Nashville, Tennessee, USA.

Ngo, H.H. (2014). "Numerical and Experimental Studies of Wood Sheathed Cold-Formed Steel Framed Shear Walls." Masters of Science in Engineering, Johns Hopkins University, Baltimore, Maryland.

Liu, P., Peterman, K.D., Schafer, B.W. (2012). "Test Report on Cold-Formed Steel Shear Walls", Research Report, CFS-NEES, RR03.

Ding, C. (2015). "Monotonic and Cyclic Simulations of Screw-Fastened Connections for Cold-Formed Steel Framing." Masters of Science in Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

ASTM A370 (2006). "Standard Test Methods and Definitions for Mechanical Testing of Steel Products." American Association State Highway and Transportation Officials Standards.

ICC-ES AC 130. (2004). "Acceptance Criteria for Prefabricated Wood Shear Panels." International Code Council Evaluation Service.

SSMA (2014). "Product Technical Information", Steel Stud Manufacturers Association.

AISI-S100-07. (2010). “North American Specification for the Design of Cold-Formed Steel Structural Members.” American Iron and steel Institute.