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Abstract

The objective of this paper is to validate a tool that design engineers could employ to develop mechanics-based predictions of the lateral response of wood-sheathed cold-formed steel (CFS) framed shear walls applicable in a wide variety of situations. Wood framed shear walls enjoy a variety of tools, most notably SAPWood and its predecessor CASHEW, that provide a means to predict the complete hysteretic behavior of a shear wall based on the nail fastener schedule and board selection. The existence of these tools helps engineers in unique design situations, encourages innovation in shear wall design particularly for Type I shear walls, and provides enabling modeling details critical for seismic performance-based design. Recently, as part of the CFS-NEES effort, the cyclic performance of CFS stud-to-sheathing connections has been characterized. In addition, the cyclic performance of full CFS shear walls, utilizing the same connections, has also been characterized. This paper explores an engineering model implemented in OpenSees that directly employs the fastener-based characterization as the essential nonlinearity in a CFS framed shear wall. CFS shear wall framing is modeled with beam elements, hold downs are modeled with linear springs, sheathing is modeled as a rigid diaphragm, and the stud-to-sheathing connections as zero-length springs utilizing the Pinching04 material model in OpenSees. Production, analysis, and post-processing of the model are automated with custom Matlab scripts that form the basis for a future engineering tool. The model is validated against monotonic and cyclic shear wall tests, and is shown to have good agreement. In addition to providing a

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mechanical means to assess shear walls, high fidelity shell finite element models are completed in ABAQUS to shed additional light on the mechanics-based OpenSees model. The long-term goal of the modelling is to provide a reliable means to predict the lateral response of any CFS framed system that relies on connection deformations, such as gravity walls or wood-sheathed floor diaphragms in addition to shear walls.

Introduction

In the design of cold-formed steel buildings, shear walls are typically used to provide lateral resistance for seismic or wind load. The wood sheathing, such as oriented strand board, is screw-fastened to the cold-formed studs and tracks to develop shear stiffness as well as strength in the wall system. Cold-formed steel (CFS) shear walls have been extensively studied for such applications. The North American Standard for Cold-Formed Steel Framing: Lateral Design (e.g., AISI S213-07) provides nominal strength for different types of sheathing, fastener spacing, and stud and track thickness and Branston et al. (2006) provides additional guidance based on extensive shear wall testing conducted primarily at McGill university under the direction of Rogers.

The composite shear wall response is dominated by the local behavior at each steel-fastener-sheathing connection. For example, Folz et al. (2001) has experimentally shown the importance of this local “fastener” behavior in the global response of a shear wall. Several modeling approaches have been used by researchers to capture CFS shear wall behavior, but in general these approaches have been to lump the overall nonlinearity in the response down to one or a few degrees of freedom, for example by modeling the shear walls as pin-connected panels with diagonals calibrated to the desired nonlinearity. These approaches do not fully capture the complexity of the behavior, nor are they easily extensible.

As part of the NSF-funded CFS-NEES effort, a series of cyclic CFS shear wall tests were conducted by Liu et al. (2012a, b). Following this work cyclic steel-fastener-sheathing “fastener” tests covering the details employed in the shear wall tests were conducted by Peterman and Schafer (2013). Buonopane et al. (2014) then developed an OpenSees model of Liu’s shear walls that employed the fastener test data from Peterman and Schafer and demonstrated that the basic elastic and initial backbone (pushover) response of the shear walls could be predicted based on the fastener-based results. The work did not explore the complete nonlinear backbone response, nor the cyclic response.

This paper is a continuation of the work in Buonopane et al. (2014). Additional details are added in the model: ledger track, strap, multiple sheathing boards, etc. such that the full suite of testing configurations from Liu et al. (2012a,b) may be explored. In addition, the full non-linear cyclic response of the shear walls is predicted from the developed OpenSees models so that the performance of these models for use in developing the necessary hysteretic response for subsequent building analysis can be fully evaluated.

Description of CFS-NEES shear walls tests

The CFS-NEES shear wall tests (Liu et al. 2012a,b) were based on a two-story ledger-framed building (Madsen et al. 2010) that was subjected to full-scale shake table testing (Peterman et al. 2014). Both monotonic and cyclic (CUREE protocol) tests were conducted on 4 ft × 9 ft (1.22 m × 2.74 m) and 8 ft × 9 ft (2.44 m × 2.74 m) shear walls utilizing 54 mil (1.37 mm) back-to-back chord studs and 7/16 in. (11.1 mm) OSB sheathing on the exterior. The impact of ledger track, interior gypsum sheathing, locations of panel seams and the impact of differing stud thickness and grade for the field studs were studied in the test program. These tests exhibited a variety of failure modes at the fasteners; predominately bearing, tearing, and pull through, and less frequently fastener fracture. The test set-up is shown in Figure 1 (b). Full details on the design and test of the shear wall specimens may be found in Liu et al. (2012a,b).

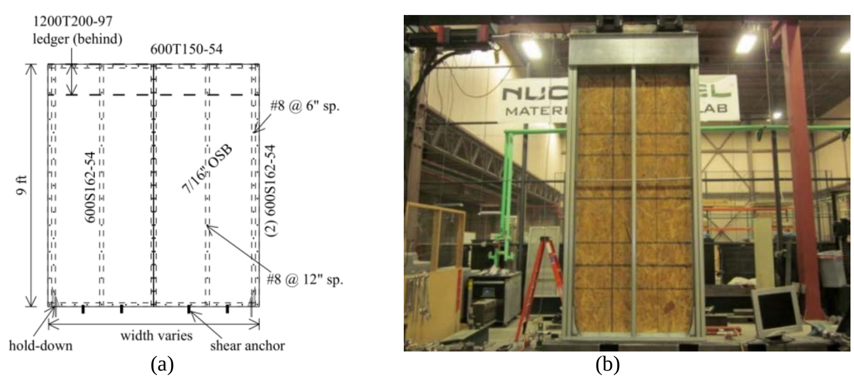


Figure 1. CFS-NEES shear wall test setup: (a) Typical dimensions and member sizes; (b) Interior side of for 4 ft × 9 ft test (Buonopane et al. 2014; Liu et al. 2012)

Numerical models in OpenSees

The Open System for Earthquake Engineering Simulation (OpenSees) software was utilized for all modeling in this study. Although the physical tests investigated the effects of 4 ft (1.22 m) and 8 ft (2.44 m) widths, only the 4 ft (1.22 m) wide shear walls are modeled in this paper.

General materials and elements for OpenSees modelling

The CFS frame members, including the chord studs and tracks, were subdivided into several beam-column displacement elements, with nodes at each fastener location. Linear elastic material and beam-column elements were used to model the CFS frame. The studs were connected to the top and bottom track with rotational springs whose rotational stiffness was estimated to be 100,000 lb-in/rad, based on the measured lateral stiffness of bare CFS frames (Liu et al. 2012). The sheathing was modelled as a rigid diaphragm with slave nodes at each fastener location and a master node at the center of the diaphragm.

Buonopane et al. (2014) has shown that modeling the tension flexibility of the hold-down is necessary. Therefore a tension stiffness for the hold-down of 56.7 kips/in [9.9 kN/mm] based on Leng et al. (2013) was selected. The compression stiffness of the hold down is modeled as 1000 times larger to simulate bearing against a rigid foundation. Previous work also showed that modelling the shear anchor (along the track to foundation) as fully pinned resulted in a lateral stiffness that exceeded the stiffness measured in experimental results. Therefore, the anchors were not modelled in this paper and the hold-down was the only provided connection between the shear wall and the foundation.

Fastener, ledger and horizontal seam details in modelling

At fastener locations, the nodes of the frame members and the sheathing coincide as shown in Figure 2. These nodes were connected using zero-length springs. Pinching04 was assigned as the material model for the zero-length fastener elements. Figure 3 shows the parameters required to define the Pinching04 uniaxial material in OpenSees, which includes the backbone curve, degradation factors, and other force and displacement relation parameters. In this paper, the Pinching04 parameters are estimated from separate physical testing of the fasteners (per the setup shown in Figure 4) as reported by Peterman and Schafer (2013). Tables 1 and 2 provide the parameters used in this paper to define the Pinching04 material for the zero-length fastener springs.

Table 1. Pinching04 model backbone parameters (Peterman and Schafer 2013)

Sheathing	Pinching04 Backbone Points															
	eNd4 in.	*eNd3* in.	*eNd2* in.	*eNd1* in.	*ePd1* in.	*ePd2* in.	*ePd3* in.	*ePd4* in.	*eNf4* kip	*eNf3* kip	*eNf2* kip	*eNf1* kip	*ePf1* kip	*ePf2* kip	*ePf3* kip	*ePf4* kip
Monotonic for OSB	symmetric				0.03	0.12	0.52	0.6	symmetric				0.5	1.25	1.83	1.5
Cyclic for Gypsum					0.01	0.05	0.24	0.56					0.05	0.1	0.12	0.12
Cyclic for OSB					0.02	0.08	0.25	0.41					0.22	0.35	0.46	0.05

Table 2. Pinching04 model reloading and unloading parameters (Peterman and Schafer 2013)

Sheathing	Unloading and reloading Pinching04 Parameters					
	rDispP	*rForceP*	*uForceP*	*rDispN*	*rForceN*	*uForceN*
Cyclic for Gypsum	0.56	0.01	0.001	symmetric		
Cyclic for OSB	0.42	0.01	0.001			

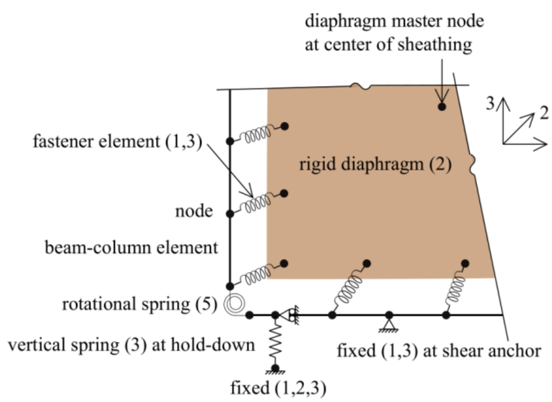


Figure 2. Details for the fastener-based shear wall model (Buonopane et al. 2014)

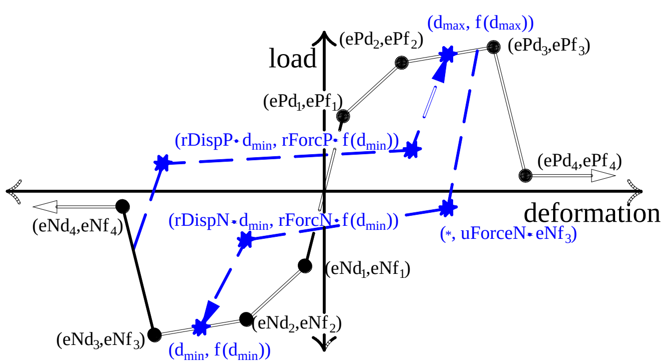


Figure 3. Definition of Pinching04 material parameters in OpenSees (Leng et al. 2013)

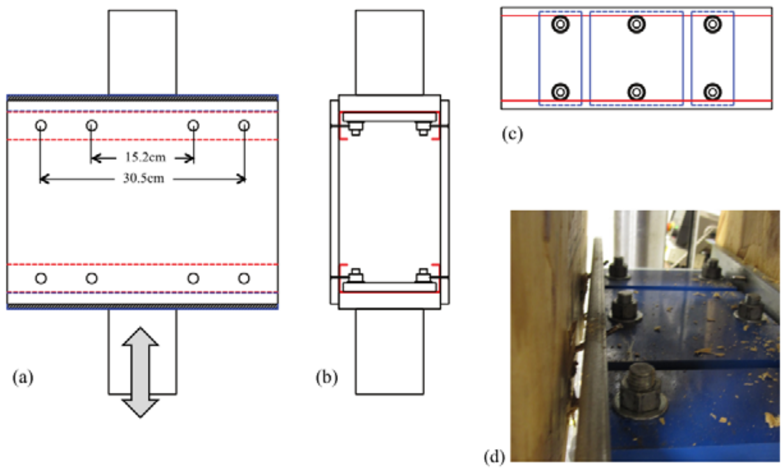


Figure 4. "Fastener" testing rig: (a) front view, (b) side view (c) inside view of stud clamping system (d) fastener-sheathing connection at failure (Peterman and Schafer 2013)

In this paper, the ledger track (see Figure 1) was modelled with a beam-column displacement element with fixed degrees of freedom at the ledger-stud connections. This rigid offset transferred deflection from the studs to the ledger. In Buonopane et al. (2014) the horizontal seam and strap were neglected and a diaphragm across the full vertical 9 ft height was used to model the sheathing. Here, a more detailed model with a strap and horizontal seam (as in the actual shear walls) is employed. Displacement beam-column elements were used to model the strap. The rotational stiffness for the strap-to-stud connection was the same as that for stud-to-track connection. The seam introduces a second rigid diaphragm (one for each board), for simplification, interference between the individual diaphragms through edge bearing was ignored. Table 3 provides a summary of materials and elements for the OpenSees models.

Table 3. Summary of materials and elements used in OpenSees models

Member in the shear wall	Element assigned in OpenSees	Material assigned in OpenSees
Stud	displacement beam-column element	linear elastic cold-formed steel
Track	displacement beam-column element	linear elastic cold-formed steel
Strap	displacement beam-column element	linear elastic cold-formed steel
Ledger track	displacement beam-column element	linear elastic cold-formed steel
Sheathing	Rigid diaphragm	-
Fastener	CoupledZeroLength	Pinching04
Hold-down	zero-length element	linear elastic stiffness
Stud-track connection	zero-length element	linear rotational stiffness

Comparison between numerical models and experimental results

Eight OpenSees models were built to compare with the 4ft × 9ft (1.22 m × 2.74 m) shear wall tests. These models take into account the existence of ledger tack, gypsum board, horizontal and vertical seams, as shown in Table 4.

The monotonic response in Figure 5(a) shows that the OpenSees result is consistent with the test result, but fails at a slightly reduced strength: the peak load in the model is 4.65 kips [20.68 kN] versus 4.9 kips [21.80 kN] in the shear wall test. This discrepancy indicates additional flexibility and redistribution in the actual shear wall that is not included in the model. It is possible that the degrading branch in the Pinching04 "fastener" model is too severe, and it is also possible that a finite stiffness sheathing creates a more favorable load distribution to the fasteners than a rigid sheathing model as damage progresses. While improvements are possible, given that the fastener data was conducted completely independently of the shear wall tests, the basic agreement in the response is more than encouraging, and conservative.

Table 4. Modelling matrix in OpenSees

Model num.	**Test in [10]**	**Wall Size**	**Load Type**	**Front Sheathing**	**Back Sheathing**	**Stud**	**Ledger**	**H. Seam**	**V. Seam**
quantity	*quantity*		*mono/cyclic*	*OSB*	*Gypsum*	*600S162-xx*	*1200T200-97*		
unit	unit	ftxft	-	✔/-	✔/-	1/1000 in.	✔/-	ft	ft
1	1c	4x9	Monotonic	✔	-	54	✔	8'up	-
2	2	4x9	Cyclic	✔	-	54	✔	8'up	-
3	3	4x9	Cyclic	✔	✔	54	✔	8'up	-
4	4	4x9	Cyclic	✔	-	54	-	8'up	-
5	5	4x9	Cyclic	✔	-	54	✔	7'up	-
6	6	4x9	Cyclic	✔	-	54	-	7'up	-
7	9	4x9	Cyclic	✔	-	54	-	8'up	2'over
8	10	4x9	Cyclic	✔	-	54	-	4.5'up	2' over

Figures 5(b)-(h) show the cyclic results comparing the OpenSees models and the shear wall tests. In general the OpenSees models can reliably predict the cyclic behavior of the shear walls. For the first few cycles, the hysteretic behavior for each model is identical to the test result. The peak load and displacement for the first few cycles is a highly reliable predictor of the full shear wall test for up to approximately 1% drift. However, similar to the monotonic response, the model does not accurately capture the last few cycles in the test - the predicted peak loads and deflections are smaller than the experimental results, as summarized in Table 5. Modest changes to the fastener Pinching04 models could be used to calibrate the overall response, but the conservative nature is encouraging and suggests that use of independently derived fastener-based nonlinearity and rigid sheathing models leads to useful and conservative predictions of the fundamental nonlinear shear wall response, appropriate for use in design.

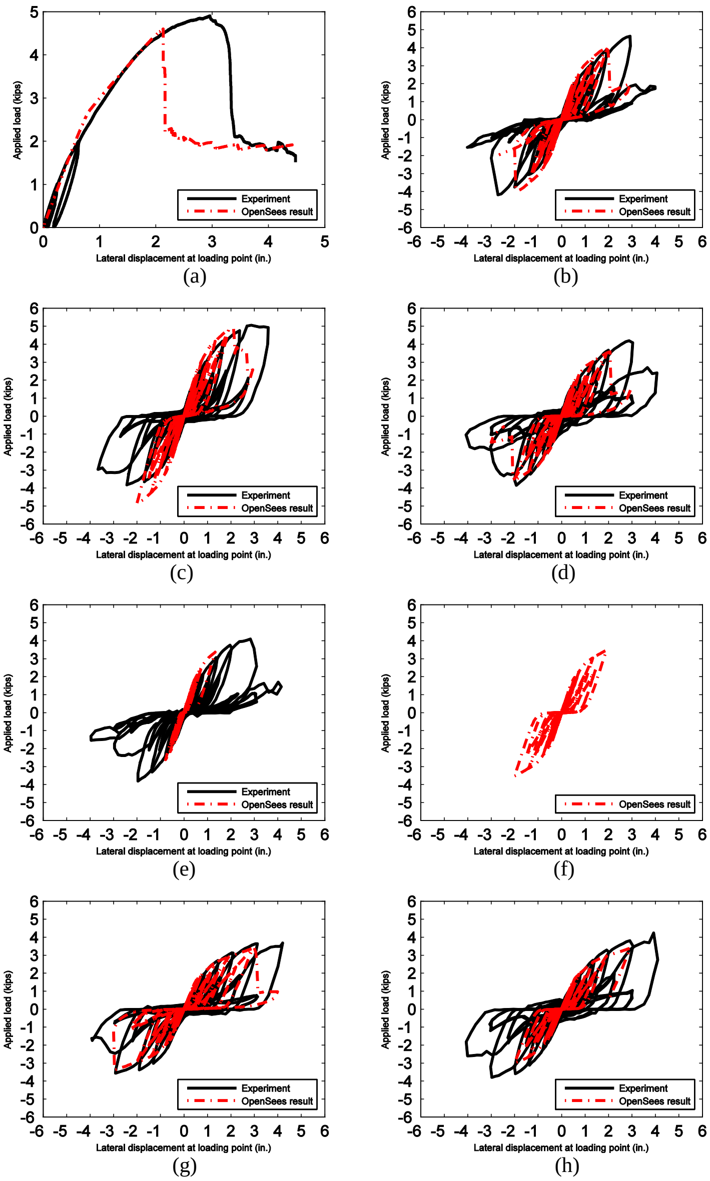


Figure 5. OpenSees result and test response for monotonic (a) and cyclic loading: (b)-(h) for model 2-model 8 of Table 4 (no data record for Test 6 available)

Table 5. Summary of the results for OpenSees model

Model	Computational Result				Experimental Result			
	Peak Load		Lateral Deflection at Peak		Peak Load		Lateral Deflection at Peak	
quantity	*P+*	*P-*	*Δ+*	*Δ-*	*P+*	*P-*	*Δ+*	*Δ-*
unit	lbf	lbf	in.	in.	lbf	lbf	in.	in.
1	4650.0	-	2.13	-	4900.0	-	2.96	-
2	3934.2	3951.8	1.91	1.90	4640.0	4176.0	2.92	2.71
3	4862.7	4852.2	2.07	2.00	5060.0	3830.0	2.87	2.44
4	3569.4	3551.6	2.07	2.07	4184.0	3850.8	2.88	1.93
5	3365.7	2619.2	1.32	0.79	4092.0	3800.8	2.83	1.96
6	3473.8	3529.4	1.91	2.00	4928.0	3320.4	2.78	1.69
7	3388.7	3382.3	3.00	3.00	3683.2	3561.2	4.20	2.92
8	3390.3	2984.4	2.93	2.00	3803.2	3799.2	2.91	2.98

Further exploration of the OpenSees computational models

Fastener force distribution

One advantage of the developed model over lumped nonlinear models is the ability to assess the manner in which the applied shear is carried by the shear wall. In particular, the fastener force distribution for model 1 at a V=4.23 kips [18.82 kN] and Δ=1.8 in. [4.57 mm] is provided in Figure 6. This force level is nearly at the peak load, and several fasteners have reached their maximum capacity. As shown in Figure 1, the top 1 ft [0.30 m] of the wall is blocked by the ledger track and a separate OSB sheathing board, the impact of this detail is that nearly all of the force is carried in the bottom 8 ft [2.44 m] of the shear wall and this is readily apparent in the developed fastener forces. In addition, while the fastener forces are largely aligned with the members (vertical for the chord studs, horizontal for the bottom track and strap) significant deviations exist as well.

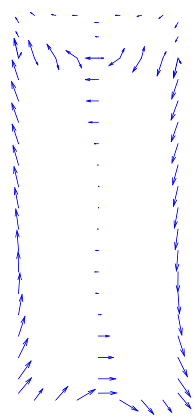


Figure 6. Force distribution for all the fasteners

Force distribution along the studs

The fastener forces result in axial forces and shear forces in the studs as provided in Figures 7 and 8. The axial force in the stud, Figure 7, is nearly linear (as is commonly assumed), but is affected by the fact that the top 1 ft [0.30 m] of the wall is blocked by the ledger track and thus the majority of the forces are actually carried in the lower 8 ft [2.44 m] of the shear wall. Consistent with the basic truss assumption the center stud in the shear wall essentially carries no axial force. As shown in Figure 8, although the largest forces are aligned with the stud (i.e., vertical) shear (and thus bending moment) is carried in the studs even though this is not typically accounted for directly in design.

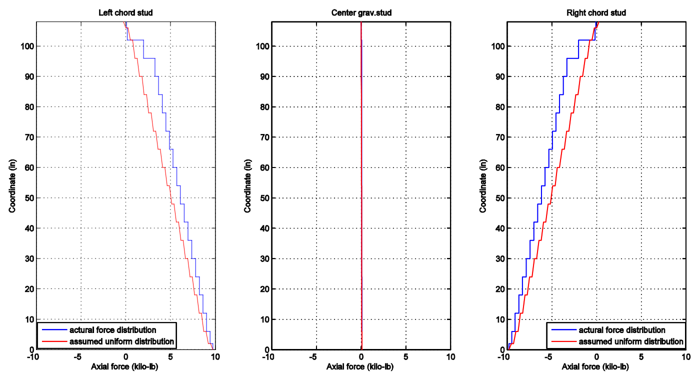


Figure 7. Axial force diagram along studs

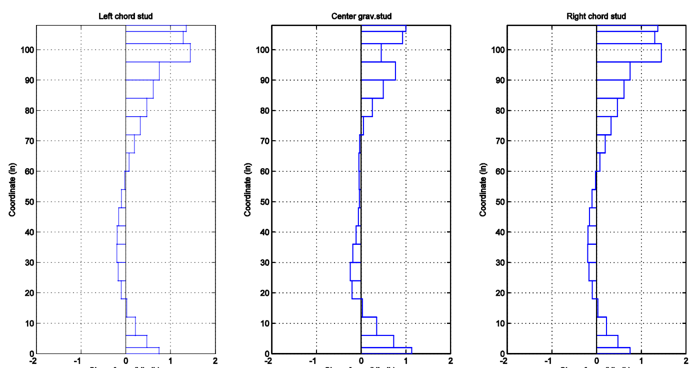


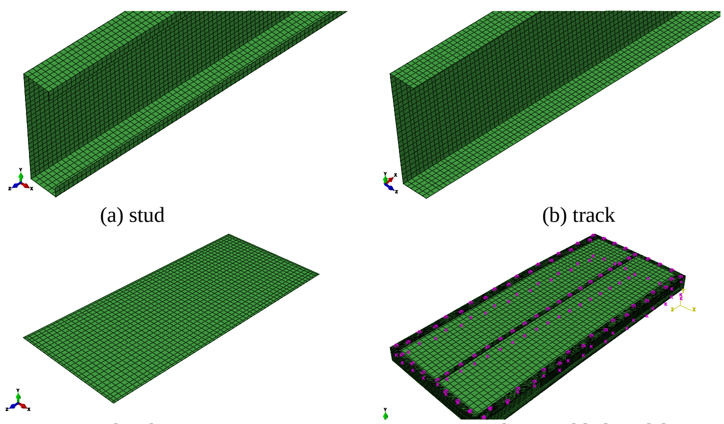
Figure 8. Shear force diagram along studs

High fidelity shell finite element (ABAQUS) modeling

Complementary to the OpenSees-based models a series of high fidelity shell finite element models have also been initiated in ABAQUS. Although these models are at an earlier stage of development, they are included here to provide a more complete picture of the modeling possibilities for shear walls and their integration into and with other nonlinear models for use in seismic design.

Description of ABAQUS computational models

The specimen geometry follows that of Liu et al. (2012a, b) as summarized in Figure 9. The CFS framing members and sheathing are modeled as four-node shell finite elements (S4R in ABAQUS), see Schafer et al. (2010) for further discussion. Five integration points are utilized through the thickness of the element. Mesh discretization is shown in Figure 9. Aspect ratio of the elements is kept as close to one as practical. Steel is modeled as elastic with E=29,500 ksi [203,000 MPa] and μ= 0.3. A relatively coarse mesh is used for the oriented strand board (OSB) sheathing, which is modeled as elastic with E=900 ksi [6200 MPa] and μ=0.3 to minimize diaphragm deformations.



(a) stud (b) track

(c) sheathing (d) assembled model

Figure 9. Shell finite element mesh of studied shear wall

Table 6. Stiffness of sheathing-to-frame fastener

K_x kip/in.	K_y kip/in.	K_z kip/in.
Nonlinear	10,000	Nonlinear

The CFS frame (steel-to-steel) connections are modeled as pinned by means of MPC constraints in ABAQUS. The steel-to-sheathing connections, i.e. the fasteners that form the basis for the OpenSees models are modeled as springs, as summarized in Table 6. The translational springs in the plane of the board (X and Z) are modeled with a nonlinear spring element (Spring 2). The force-displacement response of these springs follows Table 1; however, only the backbone is implemented. Incorporation of reloading/un-loading parameters remains for future work. The translational spring out of the board plane is modeled by means of a linear spring element (Spring 2) with a stiffness k_y=10,000 kip/inch [824,000kN/m] to minimize the board's out-of-plane deformation.

The hold-downs were modeled as springs connecting the bottom edge of the chord studs' web to the ground in the vertical direction by means of nonlinear spring element (Spring 2). Tension stiffness and compression stiffness follow that of the OpenSees models presented above. Sheathing seams were not modeled. The out-of-plane support of the top track in the experiments was included in the model as transverse roller constraints. The shear anchors connecting the bottom track to the foundation were modeled by fixing the bottom edge of the chord studs' web in the longitudinal and transverse directions. In this effort, geometric imperfections, residual stresses and strains were not included.

Initial ABAQUS results and discussion

Figure 10 provides the basic results of a nonlinear collapse pushover analysis of the developed shell FE model compared with the experimental result for test 4, and the corresponding OpenSees analysis presented above. Table 7 provides the initial stiffness, the peak load and the corresponding lateral deflections. The shell FE model predicts the initial stiffness and peak load with reasonable accuracy, but is overly stiff after the initial loading stage. One likely source of this error is the steel-to-sheathing connections. In the shell FE model, the behavior of these connections in the board plane is modeled by means of only two separate translational in-plane springs, while radial springs are used in the OpenSees model.

Table 7. Comparison of shell finite element model, OpenSees model, and test result for test 4

Model	Initial Lateral Stiffness*		Peak Load		Lateral Deflection at Peak	
quantity	*K*	*Error*	*P*	*Error*	*Δ*	*Error*
unit	lb/in.	%	lbf	%	in.	%
Experiment	4847.0	--	4016.0	--	2.40	--
Opensees	4132.0	14.8	3560.5	11.3	2.07	13.8
Shell finite element	4790.0	1.2	4257.0	6.0	1.92	20.0

* K at 1000 lb lateral force

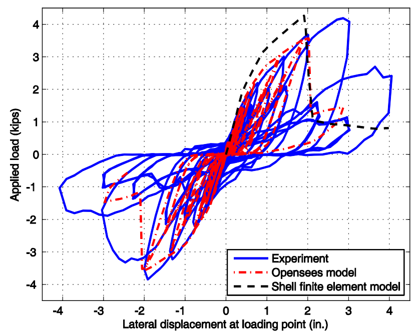


Figure 10. Comparison of CFS framed shear wall response obtained from test result and developed computational models for test 4

Future Work

The developed OpenSees-based model for the shear wall response shows excellent promise for use as a design tool to generate sub-component hysteretic response for unique geometries based on knowledge of only the nonlinear fastener response for a particular steel-fastener-sheathing combination. The sensitivity of the overall response to the post-peak branch of the Pinching04 fastener model needs to be further explored. The sensitivity of the model to the shear anchors (currently ignored) needs to be further explored. The validation studies need to be extended to the wider shear walls tested. Models for gravity walls and diaphragms need to be developed and compared with available data. Final modeling guidance and more user-friendly tools in-line with SAPWood need to be developed.

The developed ABAQUS shell finite element models provide a means to directly explore limit states other than those associated with the fastener, such as chord buckling, and to better understand how cross-section flexibility (thinner members) influence the overall response. However, significant additional work is needed in the model creation to bring the results in line with the observed testing prior to performing such studies. Challenges with modeling degrading springs, and radial springs, are among those issues not yet fully addressed in the developed models. Significant work remains.

Conclusions

This paper extends the development of a mechanics-based approach to predict lateral response of wood sheathed cold-formed steel (CFS) framed shear walls. By providing a means to predict the complete hysteretic behavior of a CFS shear wall, this approach can help engineers in unique design situations. An OpenSees model is developed that uses standard beam-column elements for the framing members and a rigid diaphragm for the sheathing. The stud-to-sheathing connections are represented as zero-length springs utilizing a Pinching04 material response developed based on isolated fastener tests. The OpenSees model is validated against previously conducted, monotonic and cyclic full-scale shear wall tests, and shown to have good general agreement. In addition, the developed force distribution of the fasteners in the studs of a typical shear wall is explored. Work remains to further calibrate the OpenSees model, but the developed results demonstrate that the shear wall response relies on connection deformations and this is the critical nonlinearity. This observation makes the possibility of determining lateral response for gravity walls and wood-sheathed floor diaphragms a distinct possibility – and this capability is critical to better understanding the seismic system-level response of cold-formed steel framed buildings.

Acknowledgements

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