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OpenSees modeling of wood sheathed cold-formed steel framed shear walls

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Abstract

The objective of this paper is to present an efficient spring-element and frame-element based finite element model of an OSB sheathed cold-formed steel framed shear wall that includes nonlinear hysteretic behavior from damage at the stud-to-sheathing connectors and the potential for buckling of the chord studs. The model is developed in OpenSees and has the potential to be an important building block tool towards modeling full structures framed from cold-formed steel. The authors have recently shown that OpenSees models that include nonlinear stud-to-sheathing fasteners, calibrated only to fastener-level tests, are capable of predicting full shear wall hysteretic performance as long as chord stud buckling or other limit states do not occur. Further, in other work, the authors have experimentally characterized the hysteretic performance of chord studs and developed phenomenological models appropriate for the frame-element in OpenSees. In this work, the two models are brought together to provide a highly adept shear wall model capable of capturing both fastener-based and member-based limit states in the shear wall. The model provides a means to explore the role of gravity load in the shear wall performance, and to study sensitivity of shear walls to these two competing limit states. Thus, the model provides practical design advantages and also provides a means to explore reliability of the shear wall as a system. The long-term goals of the work are to create advanced analysis tools for cold-formed steel seismic design and system reliability knowledge that supports the use of those tools in models and designs of complete buildings.

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1. Introduction

Cold-formed steel (CFS) structural systems continue to grow in use for low and mid-rise construction. Shear walls, combined with the floor and roof diaphragms, often constitute the lateral force resisting system for such cold-formed steel framed buildings. Wood sheathing, such as oriented strand board (OSB), is screw-fastened to cold-formed studs and tracks to develop shear stiffness as well as strength in the wall system. AISI S213 allows only specific shear wall configurations based on type and thickness of sheathing, aspect ratio, fastener spacing, stud and track thickness, and screw size. The configurations available in AISI S213 were largely established based on testing (e.g., Branston et al. 2006; Shamim and Rogers 2012). Methods for establishing shear wall capacities based on robust, but simple, models have been successfully advanced and implemented for wood framed shear walls (Folz and Filiatrault 2001).

Shear wall response is typically dominated by the local behavior at each steel-fastener-sheathing connection. As part of the NSF-funded CFS-NEES effort, a series of cyclic OSB-sheathed CFS-framed shear wall tests were conducted that form benchmark results for shear walls (Liu et al. 2012). In addition, cyclic steel-fastener-sheathing "fastener" tests covering the details employed in the shear wall tests were also completed (Peterman and Schafer 2013). Finally, and most recently, an OpenSees model of the benchmark shear wall tests that employed the cyclic "fastener" results to characterize a nonlinear cyclic phenomenological model at the fastener locations demonstrated that the basic elastic and full non-linear cyclic response of the shear walls could be predicted based on the fastener-based results (Buonopane et al. 2014; Bian et al. 2014).

In seismic design CFS studs in shear walls carry axial force and bending moment from the lateral demands, and from gravity loads (dead, live, etc.). In current designs and experiments shear wall lateral resistance is typically dominated by fastener capacity. This is, in part, because low-rise buildings have more modest gravity demands, and because seismic design requires the studs to be designed for Ω_o force levels (e.g. in OSB sheathed shear walls Ω_o=3 per current ASCE 7 provisions, thus the chord studs are designed with considerable reserve). However, as CFS framing is utilized for higher numbers of stories the gravity loads increase, in addition as capacity-based design methods and system reliability become more sophisticated Ω_o is likely to be reduced. As a result, understanding the potential nonlinear role of the studs in the shear wall response is growing in importance.

As a companion to the CFS-NEES effort testing on the cyclic response of cold-formed steel axial and bending members was recently completed (Padilla-Llano et al. 2013). Specimens were selected such that their predicted monotonic capacity in compression was governed either by local, distortional or global buckling limit states as predicted by the Direct Strength Method in AISI-S100. Cyclic tests were then conducted to develop the full nonlinear hysteretic response including reduced stiffness, buckling, and post-buckling in compression, and yielding and eventually fracture in tension. Non-dimensional parameters were utilized to develop general phenomenological models for members dominated by local, distortional, or global buckling limit states in compression and were implemented using the Pinching04 material in OpenSees (Padilla-Llano et al. 2013).

In this paper, we bring together the fastener-based shear wall model and the nonlinear (stud) frame element model to provide a model capable of capturing both fastener-based and member-based limit states in a wood-sheathed CFS-framed shear wall. Monotonic and cyclic response of the shear walls are predicted from the developed OpenSees models so that the performance of these models with different limit states can be fully evaluated. The model provides a means to explore the role of gravity load in the shear wall performance, and to study sensitivity of shear walls to these two competing limit states. Thus, the model provides practical design advantages and a means to potentially explore reliability of the shear wall as a system.

2. Description of numerical models in OpenSees

The model developed in this work is implemented in OpenSees (i.e., the Open System for Earthquake Engineering Simulation, (Mazzoni et al. 2003)). OpenSees provides efficient solvers for earthquake building simulation and is widely used in seismic simulations. OpenSees derives much of its efficiency from primarily being a frame element based code, and providing an extensive library of phenomenological based models. The models developed herein are implemented in OpenSees and take advantage of its strengths. Other more general purpose finite element software, e.g. ABAQUS (Simulia 2012), provides more extensive libraries of elements and material models, but is not as efficient or purpose-built as OpenSees. This section provides the details for the OpenSees-based shear wall mode developed here.

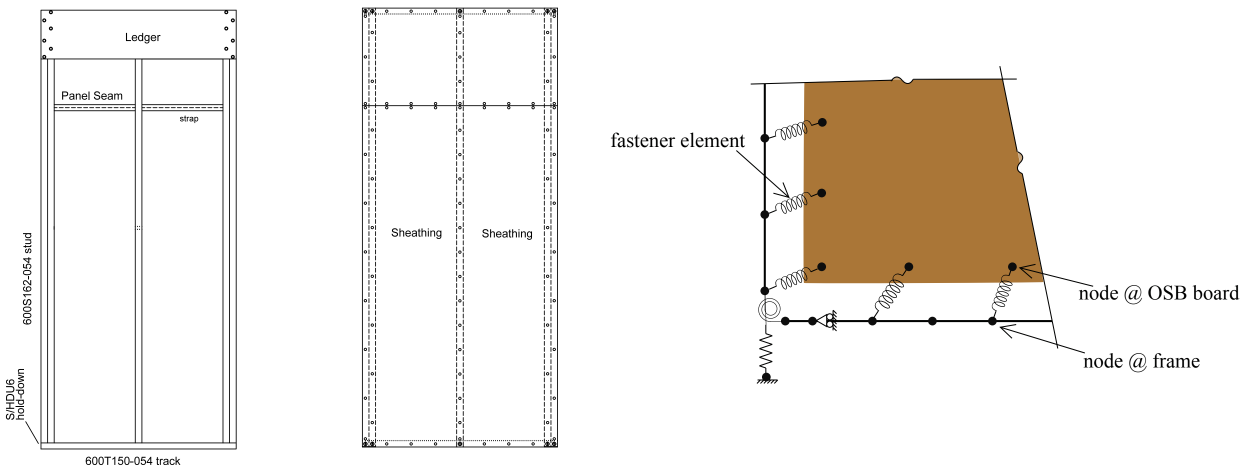
A typical OSB-sheathed, CFS-framed shear wall from Liu et al.'s (2012) testing is selected as a benchmark, see Fig. 1a. The selected specimen is designated as specimen test-2 in Liu et al. (2012) (Liu et al. 2014; Liu et al. 2012). The primary dimensions of the shear wall are 1.22 m [4 ft.] wide by 2.74 m [9 ft.] high. The shear wall is framed with 600S162-54 studs, 11.11 mm [7/16 in.] OSB on one face, using #8 fasteners at 152.4 mm [6 in.] spacing in the perimeter and 304.8 mm [12 in.] spacing in the field connecting the OSB to the CFS framing. A 1200T200-97 ledger was fastened to the back side of the frame at the top of the shear wall. At the base Simpson S/HDU6 hold downs are connected to the chord studs, and 15.88 mm [5/8 in.] diameter bolts through the bottom track to the base. At the top, #10 38.1 mm [1 ½ in.] self-drilling screws spaced at 76.2 mm [3 in.] connect through the top track to the loading beam.

2.1 Material and element in OpenSees

The CFS framing members, including the stud and tracks, are subdivided into 20 and 8 beam-column displacement elements respectively, with nodes at each fastener location. Linear elastic material and beam-column elements were used to model the field stud and tracks. To provide for stiffness reduction, buckling, and post-buckling of the chord studs they were modeled with a purpose-built implementation of the Pinching04 material as detailed in Section 2.2.

Rotational springs were used to connect the studs and top/bottom tracks (See Fig.1b). Stiffness for the rotational spring is set at 113 KN-m/rad [100 kip-in./rad] based on approximations from the measured lateral stiffness of bare CFS frame tests (Liu et al. 2012). Each individual sheathing board was modeled as a rigid diaphragm with slave nodes at each fastener location and a master node at the center of the sheathing board.

The ledger was modeled 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. At seams between OSB sheets a strap was used. Displacement beam-column elements were used to model the strap with its actual cross sectional properties. The rotational stiffness for the strap-to-stud connection was the same as that for stud-to-track connection. The seam introduces two separated (top and bottom) rigid diaphragms (one for each board). For simplification, interference between the individual diaphragms through edge bearing is ignored.



(a) benchmark CFS-framed shear wall (b) corner modeling detail in OpenSees

Fig. 1 Shear wall model in OpenSees

We used two reference nodes with fixed degrees of freedom as the foundation. Zero-length elements connecting foundation nodes and two nodes at the chord studs were modeled as hold-downs. Based on Simpson Strong-Tie published values of tension strength and displacement, tension stiffness for the hold-down of 9.9 KN/mm [56.7 kips/in] was selected while the compression stiffness of the hold down was modeled as 1000 times larger to simulate bearing against a rigid foundation. The translational degrees of freedom at two bottom-track nodes were fixed to simulate the shear anchors at these locations (See Fig.1b).

Table 1. Cyclic Pinching04 parameters in shear wall model (model is symmetric)

(a) Backbone curve

steel thickness mm	**loading**	***ePd1*** mm	***ePd2*** mm	***ePd3*** mm	***ePd4*** mm	***ePf1*** kN	***ePf2*** kN	***ePf3*** kN	***ePf4*** kN
0.84	Monotonic	0.87	3.70	7.70	10.00	0.76	1.50	1.90	1.50
	Cyclic	0.51	2.10	6.50	12.00	0.71	1.30	1.70	0.12
1.40	Monotonic	0.56	3.10	6.70	8.60	0.86	1.70	2.10	1.70
	Cyclic	0.51	2.00	6.30	10.00	0.98	1.50	2.00	0.22

(b) Unloading and reloading parameters

steel thickness mm	**Unloading and reloading Pinching4 Parameters** *rDispP*	*rForceP*	*uForceP*	*rDispN*	*rForceN*	*uForceN*
0.84	0.41	0.01	0.001	0.41	0.01	0.001
1.40	0.42	0.01	0.001	0.42	0.01	0.001

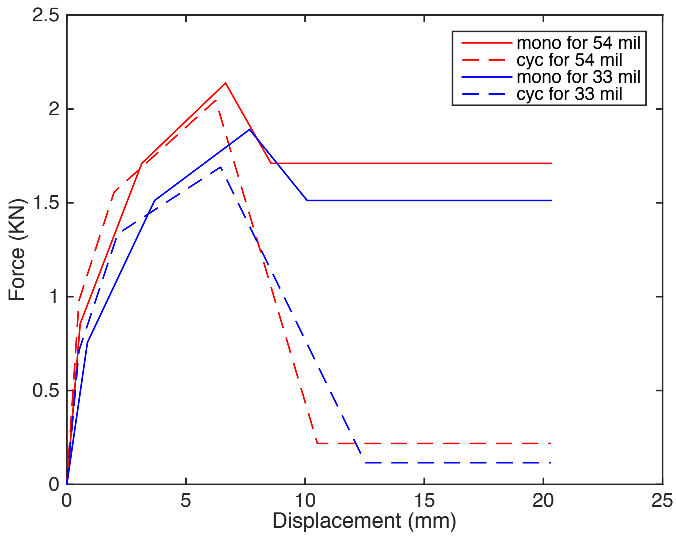


Fig. 2 Backbone definition for fasteners in different chord stud thickness

At fastener locations, the nodes of the frame members and the sheathing coincide. As shown in Fig.1b, these nodes are connected using zero-length springs. Pinching04 (Lowes et al. 2003) was assigned as the material model for the zero-length fastener elements. 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, are estimated from separate physical testing of the fasteners as reported by Peterman and Schafer (2013) (Peterman et al. 2014). Table 1a and b provide the parameters used in cyclic loading to define the Pinching04 material for the zero-length fastener springs. Fastener backbone curves for monotonic and cyclic differ because of the cumulative damage in cyclic loading. The backbone curves of fasteners for monotonic and cyclic loading for two different thickness studs are compared in Fig. 2.

2.2 Development of chord stud model in OpenSees

Modeling the hysteretic behavior, including the effect of buckling deformations in CFS axial and flexural members using nonlinear-beam column elements, has been recently explored in Padilla-Llano et al. (2013, and 2015). In this paper, the nonlinear behavior in the axial direction was modeled using the Pinching04 material, and elastic stiffness was assumed for flexure. The modeling strategy consists of hysteretic behavior at the cross-section level using a nonlinear beam-column element with distributed nonlinear axial load-strain (P-ε) section behavior (see Fig. 3b). The underlying behavior model is depicted in Fig. 3c and is based on the formulation of the Pinching04 material model, as currently implemented in OpenSees.

Three components of the behavior model are needed: backbone curve, unloading-reloading paths that account for pinching, and a damage model for strength and stiffness degradation. The parameters that define these three parts can be obtained from the general expressions for modeling steel columns including local buckling developed by Padilla-Llano et al. (2015). Backbone curves, and parameters for strength degradation, stiffness degradation and pinching were calculated as a function of the local cross-section slenderness λ_{ℓ}. The distributed nonlinearity approach allows flexible modeling of thin-walled steel members subjected to different axial loading conditions, e.g. non-uniform axial load resulting from the contributions of individual fasteners attached to a chord stud in a shear wall. The parameters used in the examples presented in this paper are summarized below.

Pinching04 parameters	600S162-33	600S162-54
gF2	0.43	0.43
gF4	0.57	0.57
gD2	0.46	0.51
gD4	0.08	0.13
rDispP	0.42	0.42
rForceP	0.46	0.46
uForceP	-0.02	-0.02
rDispN	0.38	0.38
rForceN	0.89	0.89
uForceN	0.21	0.21
gE	1.57	2.38

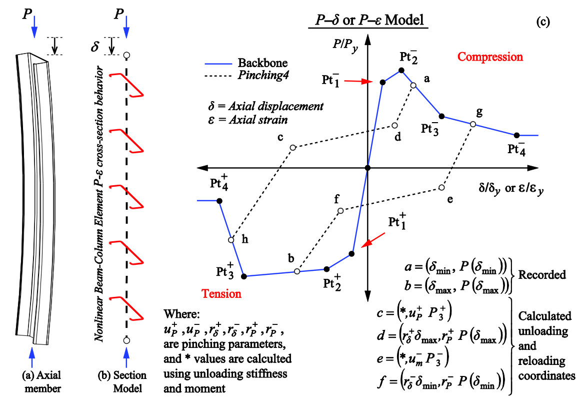


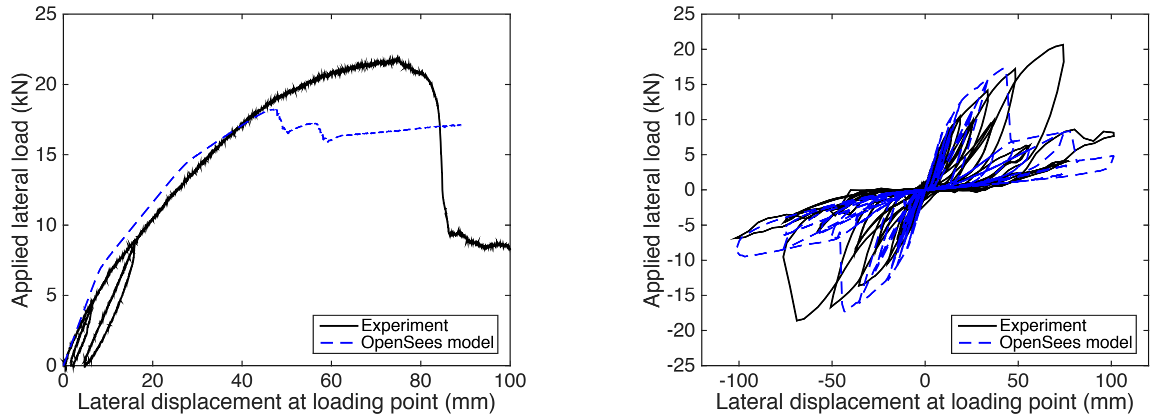
Fig. 3 Axial hysteretic model for CFS axial members experiencing local buckling (Padilla-Llano et al. 2015)

3. Finite element results and discussion

This section explores the impact of loading (monotonic vs. cyclic), gravity load, and chord stud thickness on the predicted response of a CFS-framed shear wall based on the developed OpenSees models. In addition to providing comparison to benchmark shear wall testing, a brief comparison is also provided to a more high fidelity model using shell elements in ABAQUS.

3.1 Fastener-based modeling result in OpenSees

The model developed in Section 2 is implemented and compared with the benchmark testing from Liu et al. (2012) in Fig. 4. The only differences between this model and earlier fastener-based OpenSees models (Buonopane et al. 2014; Bian et al. 2014) are the inclusion of the nonlinear chord stud response, and a slight modification to the location of the hold downs in the model. Previously, the hold downs had been modeled with a small offset, but this lead to numerical difficulties and was simplified here to align directly with the stud. The results for the new model are nearly identical to before and indicate that the model developed in Section 2 can provide a reasonable approximation of shear wall response, and further, that the introduction of the nonlinear chord stud modeling does not influence the results at low levels of axial load.



(a) monotonic (b) cyclic

Fig. 4 Comparison of shear wall force – deformation response

3.2 Shear wall behavior at different gravity levels

To demonstrate the impact of gravity load on the predicted performance of the shear wall we gradually increased the superimposed gravity load in the OpenSees model and examined the monotonic and cyclic response as a function of gravity load. For reference, the axial load capacity of the individual studs considered, P_{nl}, is provided in the final column of Table 2. Consistent with experimental observation it is assumed that the sheathing restricts distortional and global buckling and thus the stub column capacity converges to the fully braced local buckling result. The inputs for the Direct Strength Method of AISI S100 in the determination of P_{nl} are also provided in Table 2.

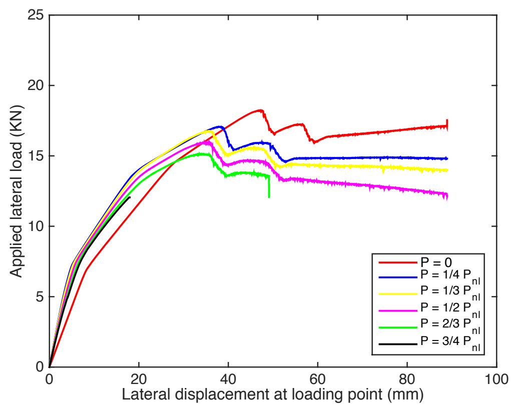
Table 2. Strength for different thickness cross sections

Cross section	F_y (MPa)	P_y (kN)	P_{crl} (kN)	P_{nl} (kN)
600S162-33	340.0	51.0	8.2	23.0
600S162-54	340.0	130.0	35.0	68.0

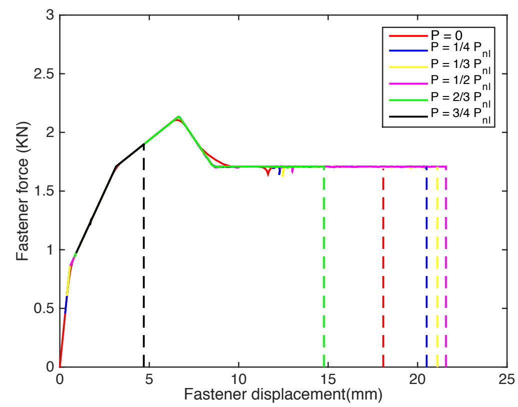
The shear wall lateral response under monotonic loading at different levels of superimposed gravity is provided in Fig. 5a. The gravity load was added at the top of the chord studs only at the values of $1/4P_{nl}$, $1/3P_{nl}$, $1/2P_{nl}$, $2/3P_{nl}$ and $3/4P_{nl}$. The initial stiffness and peak load and displacement are provided in Table 3. As the gravity load increases, the peak strength and its corresponding displacement decrease. However, the decrease is minimal until somewhere between $2/3P_{nl}$ and $3/4P_{nl}$ when the failure mode switches from the fastener to the chord stud. The presence of this limit state near $2/3P_{nl}$ is no accident since the chord studs are capacity protected with an Ω_o of 3. This Ω_o force level is exhausted when the superimposed dead load is 2/3 of the axial capacity (P_{nl}). It is interesting to note that the model predicts a significant increase in initial stiffness for the shear walls. This is due to the superimposed gravity load allowing both chord studs to remain in compression (and thus the higher bearing stiffness as opposed to the lower stiffness based on the hold down in tension) under moderate applied loads.

Table 3. Monotonic lateral loading result

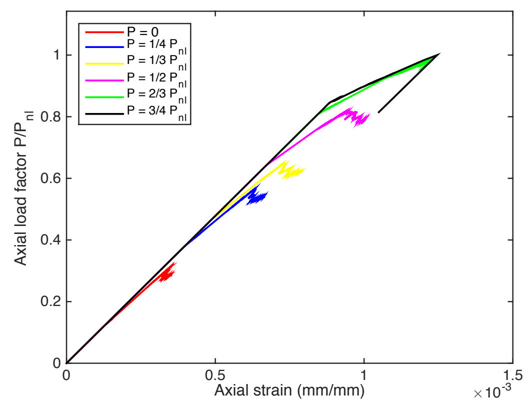
Gravity load level	Peak load (kN)	Disp. @ peak load (mm)	Initial stiffness (kN/mm)	Failure Location
P = 0	18.17	45.54	0.86	Fastener
P = 1/4P_{nl}	17.04	38.21	1.61	Fastener
P = 1/3P_{nl}	16.72	36.23	1.56	Fastener
P = 1/2P_{nl}	15.95	35.88	1.42	Fastener
P = 2/3P_{nl}	15.08	35.49	1.3	Stud
P = 3/4P_{nl}	12.06	17.92	1.25	Stud



(a) shear wall monotonic response



(b) worst case fastener response under loading



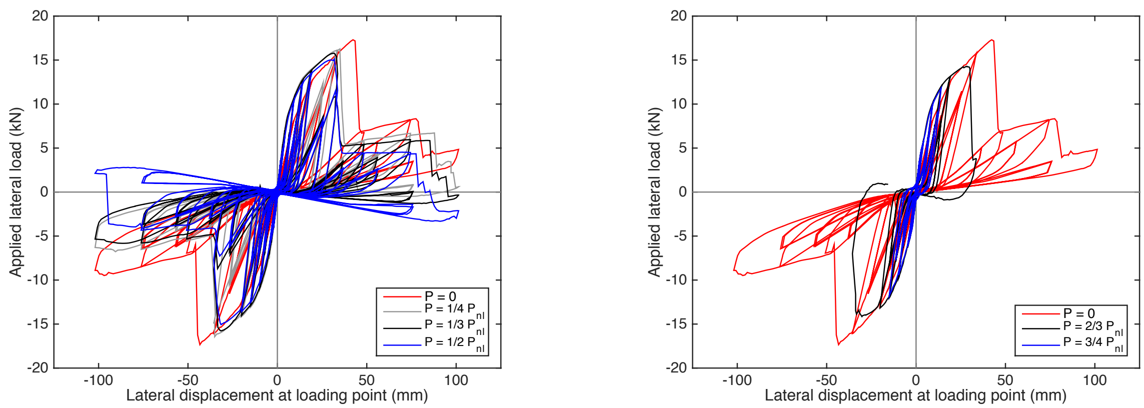
(c) chord stud axial force – strain response

Fig. 5 Shear wall behavior under monotonic lateral loading

The fastener displacement-force curve during the monotonic loading is provided in Fig. 5b. The selected fastener is in the bottom right corner of the shear wall, which has the largest deformation of all the fasteners. Under compression the chord stud is deformed; however the OSB board is modeled as a rigid body and thus cannot be compressed. As a result a small initial incompatibility between the framing and the OSB board exists creating an initial fastener load. All the fasteners follow the same backbone response, but the displacement at failure is demonstrably a function of gravity load. For the highest superimposed gravity load (3/4P_{nl}) the fastener does not reach its peak capacity – as the chord stud failure controls the response.

The normalized axial load vs. axial strain for the chord studs is provided in Fig. 5c for monotonic loading. When the gravity load is at 2/3P_{nl} or larger the axial force in chord stud gets to P_{nl} and then buckles, following the Pinching04 response defined in Section 2.2. The results indicate that the model is capable of capturing both fastener-based and member-based limit states and that at high enough gravity load this may be important.

Fig. 6 provides the results of the shear wall response under cyclic (CUREE protocol) loading. The basic monotonic results as gravity load is increased hold true in the cyclic response: there is an increased stiffness at low force levels, the peak force and displacement decrease modestly until chord stud failure occurs, chord stud failure at high superimposed axial loads significantly limits the response. New phenomena also emerge: the response moves into the 2nd and 4th quadrant even though the model is fully pinched at no axial load, and numerical convergence under high axial load becomes challenging. Additional study is needed to explore these new observations and challenges.



(a) response for low superimposed axial load

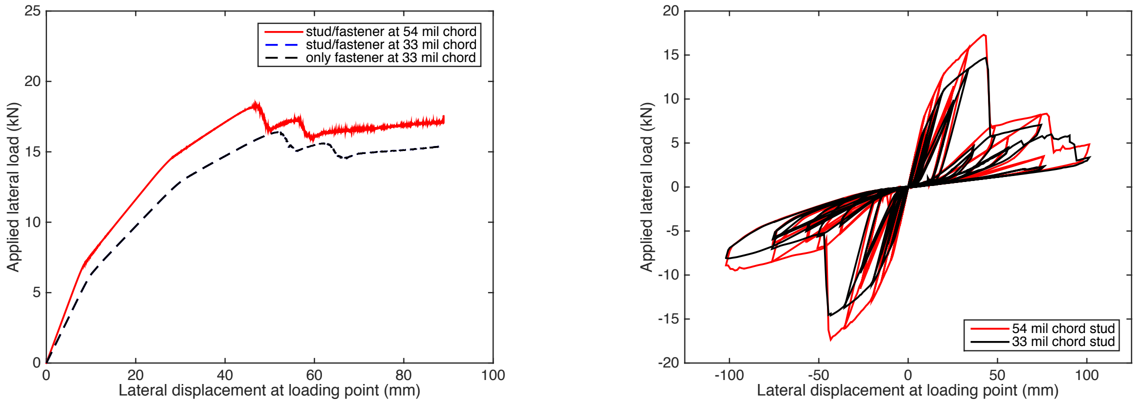
(b) response for high axial load

Fig. 6 Shear wall behavior under cyclic lateral loading

3.3 Shear wall behavior with different thickness chord studs

In the preceding study we considered the superposition of a large gravity load and commented on the fact that at high enough gravity load the seismic design using Ω_o=3 is eventually exhausted. Another option considered for exploring the impact of the chord studs on the response is to begin with a chord stud that has 1/3 the initial capacity. As Table 2 indicates the stud nominal strength P_{nl} decreases by almost exactly a factor of 3 as the stud thickness is reduced from 1.37 mm [54mil] to 0.84 mm [33mil]. However, when the stud thickness is changed the sheathing fastener response also changes, since it is a function of the thickness of steel it is anchored into, and thus the change is not as simple as decreasing only the stud capacity and response.

The monotonic shear wall response with 1.37 mm [54mil] and 0.84 mm [33mil] chord studs and fastener properties is provided in Fig. 7a. For comparison an additional analysis was conducted where the 0.84 mm [33mil] fastener properties were employed, but still the 1.37 mm [54mil] chord stud properties were employed. This results is essentially coincident with the case when the fastener and chord stud are modified, indicating that the change in the fastener response, not the change in the axial stud response, dominates. In the studied case the thinner chord stud influences the response, but only through the fastener, not because it has a reduced axial response. This is borne out in the Fig. 7b cyclic response as well. Further examination under superimposed gravity load is possible and desirable, but has been conducted at this time.



(a) monotonic (b) cyclic

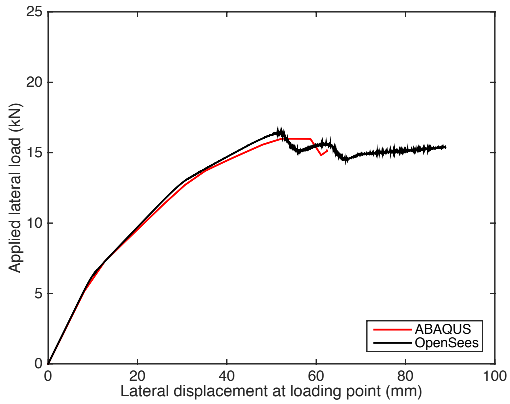
Fig. 7 Shear wall behavior with different stud thickness under: (a) monotonic loading; (b) cyclic loading

3.4 Discussion on failure mode in ABAQUS model

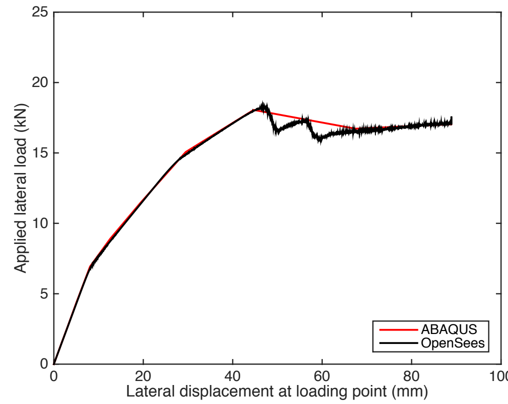
In addition to pursuing efficient fastener-based models in OpenSees we have also been pursuing high fidelity simulations in ABAQUS. In OpenSees the cold-formed steel framing (stud, ledger or track) is modeled using displacement-based beam-column elements. Such elements assume rigid cross-sections and do not allow for localized plate flexibility in the cold-formed steel framing. In addition, in the benchmark shear wall testing the OSB sheathing is attached to one face of the studs and the ledger track to the opposite face. These eccentricities are not included in the OpenSees model. To explore these effects a primarily shell element based shear wall model was developed in ABAQUS.

The model was developed based on the previous work (Ngo 2014; Bian et al. 2014). The CFS framing members and sheathing are modeled as four-node shell finite elements (S4R in ABAQUS). A relatively coarse mesh is used for the oriented strand board (OSB) sheathing, which is modeled as elastic but stiff (currently with E=207,000 MPa [30,000 ksi] and μ=0.3) to minimize diaphragm deformations. The CFS frame (steel-to-steel) connections are modeled as pinned by means of MPC constraints in ABAQUS. The steel-to-sheathing connections are modeled as Spring-A elements with the same backbone curve as used in OpenSees. The final result is a model that is similar to the OpenSees model in many ways, but which includes a full and accurate three-dimensional treatment of the framing.

Fig. 8a and b provide the comparison of load-displacement result between OpenSees and ABAQUS for 0.838 mm [33mil] and 1.371 mm [54mil] thickness chord stud. The result shows that the OpenSees and ABAQUS results agree well with one another.



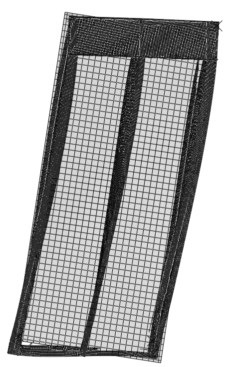
(a) 0.84 mm [33mil] chord stud models



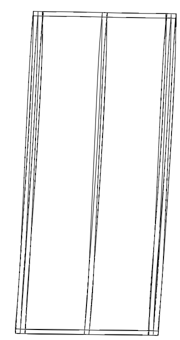
(b) 1.37 mm [54mil] chord stud models

Fig.8 Shear wall modeling result in ABAQUS compared with OpenSees

Fig. 9a and b provide the deformation of the shear wall under monotonic loading. The deformation indicates a modest amount of torsion in the studs, although it does not decrease the shear wall lateral resistance capacity significantly in the studied case.



(a)



(b)

Fig.9 Shear wall deformation in ABAUS

4. Discussion and Future Work

The work presented herein provides an efficient model implemented in OpenSees with two potential nonlinear limit states for wood sheathed CFS-framed shear walls: damage at fastener locations, or local buckling of chord studs. Results are provided where at high levels of superimposed dead load the dominant failure changes from fastener damage to chord stud buckling; however the model has convergence issues that require additional investigation. In addition, initial models using a weaker (0.84 mm [33mil]) chord stud for the shear walls need to be completed at different absolute levels of superimposed dead load to demonstrate the impact of gravity load on weaker chord studs. Formal shear wall design utilizes Ω_o to capacity protect the chord studs – evaluation of archetypical shear wall designs at different levels of Ω_o using the developed OpenSees model would provide a beneficial means to understand the impact of this assumption in seismic design. Addition of superimposed gravity load to the higher fidelity ABAQUS model such that chord stud buckling is initiated and comparison between the two models would be useful. Incorporation of other limit states (hold downs, shear anchors, etc.) would also be beneficial. Monte Carlo simulation utilizing the OpenSees model for reliability simulation would potentially better show the power of including multiple limit states within the model itself and help to develop more rational resistance factors for these systems. Incorporation of gravity walls in the OpenSees model has the potential to efficiently provide insights on the large overstrength often realized in these systems and additionally provides a direct path to robust, accurate, and efficient full-scale building modeling – the long-term goal of this research.

5. Conclusions

Wood sheathed cold-formed steel framed shear walls may be efficiently modeled in OpenSees and provide full nonlinear hysteretic response based on damage at stud-to-sheathing connectors or due to chord stud buckling. This provides engineers with an efficient solution that can predict the shear-deformation response of these shear walls under a multitude of different details and incorporating the two most important limit states. The provided model is an extension of previous work that focused on nonlinearity at the stud-to-sheathing connectors. Here nonlinearity is extended to the chord studs and shear wall models are provided that demonstrate the impact of this inclusion. In particular, the impact of the switch of limit states in a shear wall from fastener-based damage to chord stud buckling at very high levels of superimposed dead load is demonstrated. Verification of the developed model is provided by comparison with experiments and a higher fidelity shell element based model; however, additional verification is needed. Significant additional work remains to utilize the model more formally in seismic shear wall design, to better understand system reliability, and in full building models. Nonetheless, the model represents a significant advancement for efficient computational modeling of cold-formed steel framed shear walls and has wide potential application.

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