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FASTENER-BASED COMPUTATIONAL MODELS FOR PREDICTION OF SEISMIC BEHAVIOR OF CFS SHEAR WALLS

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ABSTRACT

A common lateral force resisting system for cold-formed steel (CFS) buildings consists of shear walls sheathed with oriented strand board (OSB). Previous experimental and computational research on CFS shear walls, as well as those with other framing materials, has demonstrated that the complex interaction of the fasteners with the sheathing is an important factor in the non-linear behavior of the shear wall. The research described in this paper develops and validates fastener-based computational models of CFS shear walls. The basic computational model in OpenSees consists of beam-column elements for the CFS framing and a rigid diaphragm for the sheathing. The framing and sheathing are connected with zero-length, non-linear fastener elements in which the non-linearity captures the sheathing material damage in the area surrounding the fastener. Fastener properties are determined based on independent testing of fastener groups. Shear wall widths of 4 ft, 8 ft and 12 ft were studied, considering various methods of modeling the hold-downs, shear anchors, sheathing seams and ledger track. The computational results are validated against full-scale tests of similar shear walls. The results indicate that this type of model can accurately represent the initial stiffness, strength and non-linear behavior of CFS shear walls.

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Fastener-based computational models for prediction of seismic behavior of CFS shear walls

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ABSTRACT

A common lateral force resisting system for cold-formed steel (CFS) buildings consists of shear walls sheathed with oriented strand board (OSB). Previous experimental and computational research on CFS shear walls, as well as those with other framing materials, has demonstrated that the complex interaction of the fasteners with the sheathing is an important factor in the non-linear behavior of the shear wall. The research described in this paper develops and validates fastener-based computational models of CFS shear walls. The basic computational model in OpenSees consists of beam-column elements for the CFS framing and a rigid diaphragm for the sheathing. The framing and sheathing are connected with zero-length, non-linear fastener elements in which the non-linearity captures the sheathing material damage in the area surrounding the fastener. Fastener properties are determined based on independent testing of fastener groups. Shear wall widths of 4 ft, 8 ft and 12 ft were studied, considering various methods of modeling the hold-downs, shear anchors, sheathing seams and ledger track. The computational results are validated against full-scale tests of similar shear walls. The results indicate that this type of model can accurately represent the initial stiffness, strength and non-linear behavior of CFS shear walls.

Introduction

The development of performance-based seismic design methods for cold-formed steel (CFS) relies on the ability to perform advanced, non-linear computational modeling of the CFS structures. One of the objectives of the CFS-NEES project "Enabling Performance-Based Seismic Design of Multi-Story Cold-Formed Steel Structures" is to develop improved computational models for enhance the design of CFS structures under seismic loading.

Cold-formed steel structures commonly use shear walls sheathed with oriented-strand board (OSB) to provide lateral resistance for seismic loads. Previous research on the behavior of CFS shear walls has identified the importance of the local behavior at the individual fasteners as a major determinant of the global wall behavior; including stiffness, strength, degradation and

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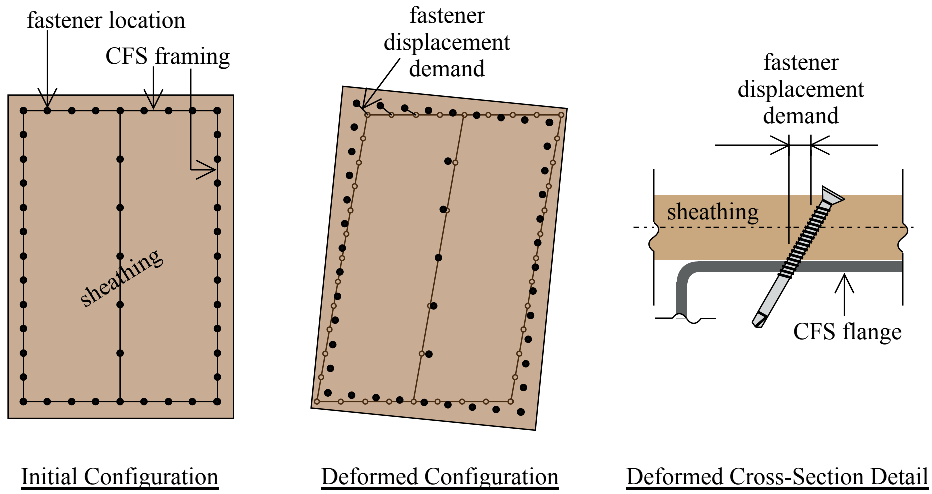

Figure 1. Deformed shape of frame and panel, showing fastener displacement demand.

pinching [1,2,3]. Research into sheathed wood frame shear walls has also established the importance of fastener behavior [4].

The CFS members of a shear wall provide negligible lateral resistance as their connections have minimal rotational stiffness, thus forming a hinged frame which deforms in the shape of a parallelogram (Figure 1). In contrast, the sheathing has substantial in-plane rigidity and rotates as a rigid body while remaining nearly rectangular in shape. The incompatible deformations between the deformed shapes of the CFS framing and sheathing create a displacement demand at the fasteners which must be accommodated by a combination of fastener movement, fastener deformation, and local deformation and damage to the sheathing immediately surrounding each fastener. Cyclic testing of CFS shear walls commonly exhibit a variety of failure modes at the fasteners, such as tearing, pull through or fastener fracture [5,6]. Previous research has demonstrated that the force-displacement behavior of the individual fastener-sheathing connections is highly non-linear, exhibiting hysteresis, degradation and pinching [5,7] (Figure 2(a).) Similar behavior has also been documented for fasteners in wood-framed, sheathed shear walls [4].

The effect of the local behavior at each of many individual fasteners combines to create the non-linear force-deflection behavior of the CFS shear wall as a whole (Figure 2). Accounting for the non-linear behavior of each shear wall is critical in predicting seismic performance of CFS structures. One approach to capturing the shear wall behavior in computer models is to calibrate complex spring elements or shell elements using test results from full-scale shear walls [8,9,10]. However, it may be difficult to estimate non-linear properties of wall designs for which no companion test results are available. A second approach involves very detailed finite element models, including shell elements for the sheathing and CFS members and non-linear springs for the fasteners [11]. However it is difficult to model an entire building using this method, or to investigate many possible shear wall configurations. A third approach combines the non-linear force-deformation relationship at each fastener with the relative displacement between the framing and sheathing [1,3,4,12]. The fastener behavior is idealized based on test results and the

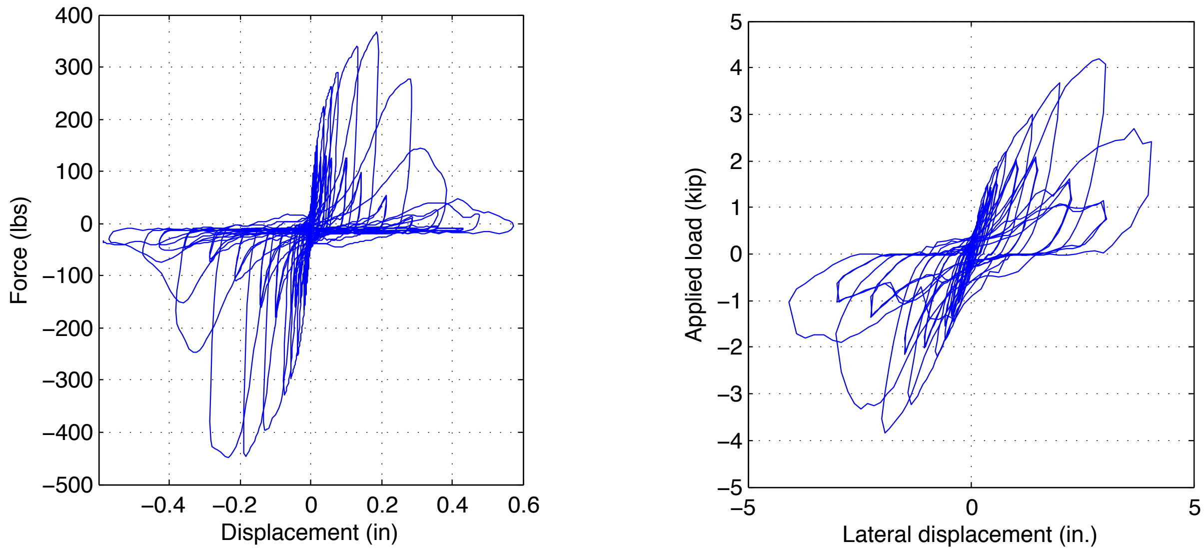

Figure 2. (a) Single fastener force-displacement response (test c54o6_1 of [7]). (b) Shear wall force-displacement response (test 4 of [6]).

formulation may also include shear deformation of the sheathing and axial deformation of the chord studs. This approach may also introduce some simplifying assumptions such as rigid, hinged framing members and may or may not include hold-down flexibility. This approach can be extended to simple models of full building behavior, some of which are solved numerically within special purpose software [4].

The current research explores the use of the OpenSees [13] structural analysis software to create a fastener-based computational model of a CFS shear wall with sheathing. The use of a general purpose non-linear and dynamic analysis software allows for greater flexibility in modeling and the potential to model multiple shear walls or even a full building.

Description of Physical Specimens and Computational Model

The OpenSees models presented in this paper are based on a series of cyclic shear wall tests conducted as part of the CFS-NEES project. See [6] for more details on the construction, design and testing of the shear wall specimens. The physical tests investigated the effects of width (4 ft and 8ft), sheathing type (OSB and gypsum), number and location of sheathing seams, and presence of ledger track on the cyclic response. These shear wall designs were also incorporated into the full-scale, CFS-NEES building, tested on the SEESL shake table at University at Buffalo in 2013. See [14] for more details on the design of the full-scale building.

Basic member sizes and dimensions are given in Figure 3(a). The OSB sheathing is fastened with #8 screws spaced at 6 in on the perimeter of the sheets of sheathing, and spaced at 12 in elsewhere. The physical tests included Simpson S/HDU6 hold-downs at the chord studs and 5/8 in diameter anchor bolts at locations where shear anchors (self-drilling screws or low-velocity fasteners) would normally be used.

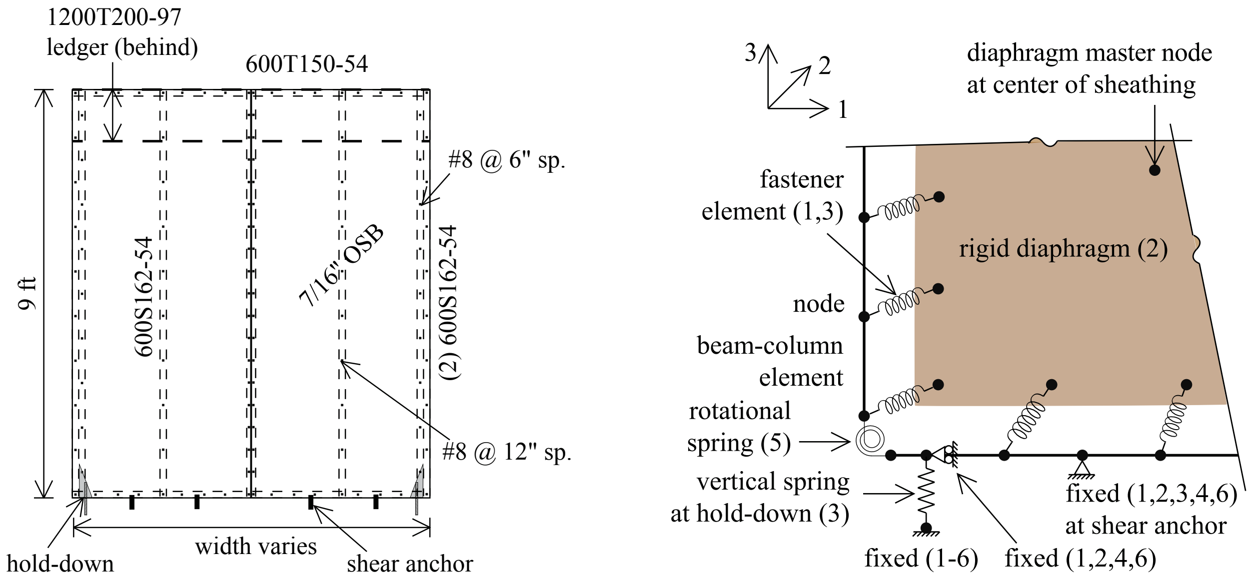

Figure 3. (a) CFS shear wall design (8 ft wide wall shown, other widths similar). (b) Details of OpenSees model. Numbers in parentheses indicate active directions of spring elements or restrained directions of supports.

Shear walls of widths 4 ft, 8 ft and 12 ft and a height of 9 ft were modeled in OpenSees (Figure 3(b), Table 1). The CFS studs and tracks are modeled with displacement-based beam elements with appropriate section properties. The frame members are subdivided with a node at every fastener location. The studs are connected to the top and bottom tracks with rotational springs to allow for semi-rigid connections. The rotational stiffness of the semi-rigid connections was estimated to be 100,000 in-lb/rad, based on the measured lateral stiffness of 4 ft and 8 ft wide bare CFS frames. The sheathing is modeled as a rigid diaphragm with a slave node at every fastener location and master node at the center of the panel. The model does not include shear deformation within the sheathing, although this is generally a small percentage of the total deformation especially at large lateral force levels (Table 2).

At every fastener location, there are two coincident nodes: one on the frame member and one on the sheathing diaphragm. These nodes are connected by an in-plane, radially symmetric, zero length element (*CoupledZeroLength*). The fastener element is assigned uniaxial material properties based on the results of physical testing of fasteners in sheathing. For linear elastic analyses, the fastener element has a stiffness of 12,200 lb/in [7]. For non-linear analyses, the material is defined as a *Pinching4* material, which includes a multi-linear backbone curve and pinching (Figure 2(a)). See [7] for complete *Pinching4* material model parameters. This model assumes that significant deformation in the sheathing occurs locally around the fasteners and can be captured by the stiffness and non-linear properties of the fastener element.

The analyses presented in this paper focus on assessing the accuracy of four specific modeling features: hold-downs, shear anchors, vertical seams and ledger track (Table 1). The hold-downs were modeled either as a pin support or as a uniaxial spring element. The tension stiffness of the hold-down was estimated to be 56.7 kips/in [8] and the compression stiffness was

Table 1. Summary of model variations, linear initial stiffness, and displacement at 1000 lb lateral force.

Analysis Name	Width (ft)	Model Features				Stiffness (lb/in)	Displacement (in)	Comparison Test [5]
		hold down	shear anchors	vertical seam	ledger as diaphragm			
L4_1	4	pinned	none	n/a	no	14292	0.070	4
L4_2	4	elastic	none	n/a	no	5357	0.187	4
L4_3	4	elastic	pinned	n/a	no	9774	0.102	4
L4_4	4	elastic	pinned	n/a	yes	11922	0.084	2
L4_5	4	elastic	none	n/a	yes	5812	0.172	2
L8_1	8	pinned	none	1	no	32219	0.031	14
L8_2d	8	elastic	none	1	no	17714	0.057	14
L8_3	8	elastic	pinned	1	no	27462	0.036	14
L8_4	8	elastic	pinned	1	yes	37188	0.027	12
L8_5d	8	elastic	none	1	yes	20551	0.049	12
L8_2s	8	elastic	none	no	no	22214	0.045	14
L8_5s	8	elastic	none	no	yes	24485	0.041	12
L12_1	12	pinned	none	2	no	48358	0.021	n/a
L12_2t	12	elastic	none	2	no	31757	0.032	n/a
L12_3	12	elastic	pinned	2	no	44953	0.022	n/a
L12_4	12	elastic	pinned	2	yes	64007	0.016	n/a
L12_5t	12	elastic	none	2	yes	38637	0.026	n/a
L12_2s	12	elastic	none	no	no	45497	0.022	n/a
L12_5s	12	elastic	none	no	yes	52730	0.019	n/a

assigned a value 1000 times as large to simulate a rigid foundation. Shear forces are transferred rigidly to the foundation. At the locations of shear anchors in a typical CFS shear wall, the OpenSees model was either unrestrained or fully pinned. Specific force-deformation and strength properties of the anchors were not modeled.

In CFS construction vertical sheathing seams occur at a stud location and horizontal seams are joined with steel strap. The OpenSees models consider the cases of no vertical seams or vertical seams spaced every 4 ft. In the case of no vertical seams a single rigid diaphragm is defined across the entire shear wall. In the case of vertical seams, multiple rigid diaphragms are defined, each 4 ft wide by 9 ft tall—two for the 8 ft wide wall; three for the 12 ft wall. The model does not account for the possibility of the individual diaphragms interfering with one another through edge bearing. Preliminary study of horizontal seams in OpenSees demonstrated that modeling of the steel strap would be necessary to prevent large and unrealistic displacements from occurring across the horizontal seams; therefore, all models presented here use a single diaphragm across the full vertical 9 ft height.

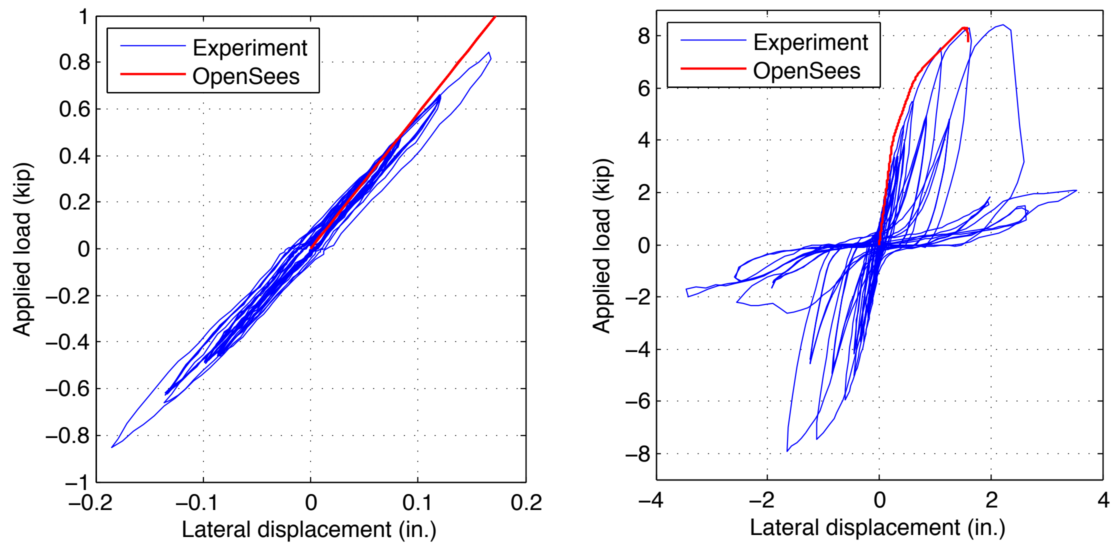

Figure 4. (a) Linear stiffness of model L4_5 superimposed on test 2 of [6]. (b) Non-linear response of model NL8_2d superimposed on test 14 of [6].

The ledger track in OpenSees was modeled by defining a rigid diaphragm equal in dimension to the web of the track and directly connected to the CFS frame nodes. Thus the rectangular area of the ledger track web remains rectangular in shape and the stud-to-top track connections are constrained to remain at right angles. This initial modeling approach does not account for deformation of the ledger track but is simpler than using rigid links between the framing and a series of beam-column elements representing the ledger.

It is important to note that other than the individual fastener material properties and the hold-down tension stiffness, no other properties of the OpenSees model are empirically determined. The lateral load or displacement control is applied at the top center node of the CFS framing.

Results & Discussion

The linear stiffness and lateral displacement at a 1000 lb lateral load is given in Table 1. Figure 4 compares the initial linear stiffness predicted by OpenSees for model L4_5 with the low-level force-displacement response from a full-scale cyclic shear wall test number 2 of [6].

From a comparison of the experimental and computational results of the 4 ft and 8 ft walls, we can conclude that modeling the tension flexibility of the hold-down is necessary. Modeling the shear anchors as fully pinned results in lateral stiffnesses that far exceed the experimental values, while providing no support at the shear anchor locations resulted in lateral stiffnesses that closely matched the experimental results. Note that the shear wall tests used anchor bolts rather than typical shear fasteners at these locations. The OpenSees models do suggest that modeling of the shear anchors can have a significant effect on the lateral stiffness. Future work will include closer examination of the behavior surrounding the shear anchors, modeling of the shear anchor with realistic stiffness properties and comparison to test results that used typical shear anchors.

Modeling of the web of the ledger track as a rigid diaphragm created an increase in lateral stiffness: about 8% for the 4 ft wall, 16% for 8 ft, and 20% for 12 ft. The 8 ft and 12 ft wide walls provided a means to compare the effect of modeling the vertical seams in the sheathing. Including the vertical seams in the model results in a decrease in lateral stiffness: about 25% for the 8 ft wall and 30% for 12 ft. In all of the modeling features considered, the effects on initial stiffness are greatest for wider walls.

Comparison with Deflections Predicted by S213

The deflections predicted by OpenSees can be compared to those calculated using equation C2.1-1 of AISI S213-07 [15,16]. This equation contains four terms, associated with each of the following sources of lateral deflection: cantilever bending, shear deformation of sheathing, non-linear effects, and hold-down extension. Table 2 provides values of deflection and relative percentages for each term at a lateral load of 1000 lb and at the design strength of the wall. The contribution of the hold down and non-linear effects are substantial. As the load on the wall increases, the percentage contribution of the non-linear term becomes very large, on the order of 70% to 80%.

The results from the computational models can be compared to some of the individual terms from the S213 equation. At a 1000 lb lateral load on the 4 ft wall, the predicted lateral deflection due to the hold-downs is 0.089 in from S213 and about 0.117 from the computational model (subtracting the displacements from L4_1 and L4_2). Similarly for the 8 ft wall: 0.022 in and 0.026 in; and for the 12 ft wall: 0.010 in and 0.011 in. The total deflections at 1000 lb force from S213 and the computational model also compare favorably. Note that the OpenSees model does not include the shear flexibility of the sheathing, so the deflections from the computational model could be increased slightly to account for this using the shear term from S213.

Non-Linear Analyses

Several non-linear analyses were also performed for each of the wall widths. In these models each fastener was modeled using a *Pinching4* material definition with the parameters based on

Table 2. Values of displacements calculated from Eq. C2.1-1 of AISI 213-07 [15].

Width (ft)		Displacements at 1000 lb lateral force					Displacements at lateral strength					Strength (lbs)
		bending	shear	non-linear	hold-down	total	bending	shear	non-linear	hold-down	total	
4	(in)	0.011	0.017	0.093	0.089	0.210	0.033	0.050	0.798	0.262	1.142	2932
	%	5.28	8.04	44.17	42.50	100	2.86	4.34	69.89	22.92	100	
8	(in)	0.003	0.008	0.016	0.022	0.050	0.018	0.056	0.715	0.147	0.936	6600
	%	5.61	16.83	32.87	44.69	100	1.95	5.95	76.36	15.74	100	
12	(in)	0.001	0.006	0.006	0.010	0.023	0.012	0.056	0.584	0.098	0.750	9900
	%	5.29	24.67	26.43	43.61	100	1.63	7.43	77.86	13.10	100	

Table 3. Summary of results from non-linear analyses.

Width (ft)	Computational Results			Experimental Results		
	Analysis Name	Max. Load (lbs)	Displacement at max. load (in)	Comparison Test [6]	Max. Load (lbs)	Displacement at max. load (in)
4	NL4_2	4078	1.872	4	4016	2.400
	NL4_5	6024	1.852	2	4408	2.815
8	NL8_2d	8315	1.538	14	8710	1.938
	NL8_5d	11522	1.376	12	9246	1.964
12	NL12_2t	12560	1.446	n/a	--	--
	NL12_5t	16871	1.220	n/a	--	--

the results of the fastener testing program [7]. The models were loaded with monotonic displacement control until the peak load was achieved. Table 3 provides the peak load and lateral displacement at peak load. In general the OpenSees models without the ledger closely predict the experimental peak strength, although the predicted deflections are somewhat smaller than the experimental values. The OpenSees models with the ledger modeled as a rigid diaphragm result in lateral strengths that exceed the measured strengths. This suggests that modeling the ledger as a rigid diaphragm is not acceptable beyond low load levels. Future work will include modeling the bending stiffness of the ledger using beam elements and rigid offsets. Figure 4(b) compares the computational load-deflection behavior with the cyclic test results of the 8 ft wide specimen. As can be seen from the plot, the OpenSees model predicts well the strength and the bounding backbone curve from the cyclic tests.

Modeling each individual fastener allows closer examination of the interaction forces between the fasteners, sheathing and framing members. Figure 5 shows a vector plot of the fastener forces at the lateral strength of the 8 ft wide shear wall (NL8_2d). This plot confirms the observed experimental behavior where fasteners near the corners often cause sufficient damage to the sheathing material to pull through. These OpenSees models also provide numerical values and visualization of the internal forces (axial, shear, moment) in the framing members due to the force transfer at each fastener.

Conclusions

The objective of this paper was to develop and validate fastener-based models of CFS shear walls in OpenSees. The ability to accurately predict initial stiffness, non-linear behavior and lateral strength of CFS shear walls using non-linear computational models is critical for the for performance-based seismic design of CFS structures. The models described herein used bean-column elements for the framing members and a rigid diaphragm for the sheathing. Each fastener was represented by a radially symmetric linear or non-linear spring element with parameters determined from fastener tests. Use of the *Pinching4* material model in OpenSees allowed for non-linear loading, pinching and deterioration.

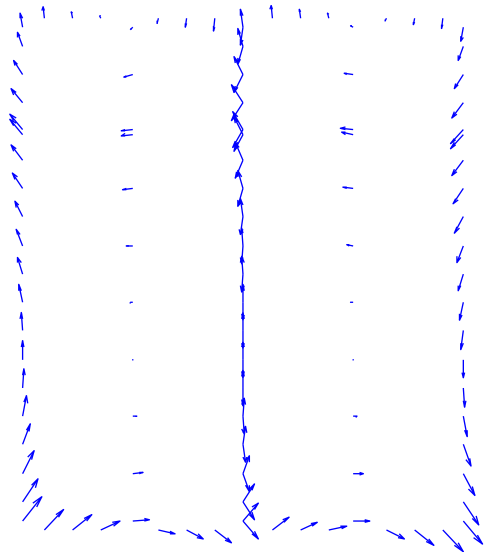

Figure 5. Fastener force vector plot at peak load for model NL8_2d.

A series of analyses were used to investigate the effects of specific modeling features (hold-downs, shear anchors, panel seams and ledger track) on the initial stiffness and strength of 4 ft, 8 ft and 12 ft wide shear walls. The results for 4 ft and 8 ft wide walls were compared to previously conducted, full-scale cyclic tests. The models with an elastic hold-down in tension, vertical panel seams, no restraint at the shear anchors and without a ledger track were found to closely predict both the initial stiffness and lateral strength from the companion experiments. Modeling the web of the ledger track as a rigid zone slightly increased the initial stiffness, but led to a lateral strength that substantially exceeded the experimental results. Fastener-based models provide detailed information on the interaction forces between the fasteners, sheathing and framing members.

The availability of fastener-based modeling techniques within a general purpose structural analysis program, such as OpenSees, allows for great flexibility and further development by incorporating other advanced analysis features. Future development of this research is planned to include full non-linear cyclic analysis, application of gravity loads, and seismic excitation. The ledger track will be incorporated using beam elements and rigid offsets. The shear anchors will be modeled with realistic stiffness properties based on test results. Finally the fastener-based modeling approach can be used to model the in-plane stiffness of floor diaphragms and to study the load sharing between gravity and shear walls.

Acknowledgments

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References

1. Della Corte G, Fiorino L, Landolfo R. Seismic behavior of sheathed cold-formed structures: numerical study. *Journal of Structural Engineering* 2006; 132(4):558-569.
2. Dubina D. Behavior and performance of cold-formed steel-framed houses under seismic action. *Journal of Constructional Steel Research* 2008; 64: 896–913.
3. Nithyadharan M, Kalyanaraman V. Modelling hysteretic behaviour of cold-formed steel wall panels. *Engineering Structures* 2013; 46: 643–652
4. Folz B, Filiatrault A. Cyclic analysis of wood shear walls. *Journal of Structural Engineering* 2001; 127(4): 433-441.
5. Fiorino L, Della Corte L, Landolfo R. Experimental tests on typical screw connections for cold-formed steel housing. *Engineering Structures* 2007; 29:1761-1773.
6. Liu P, Peterman KD, Schafer BW. Test report on cold-formed steel shear walls. *Research report CFS-NEES RR03*; June 2012.
7. Peterman KD, Schafer BW. Hysteretic shear response of fasteners connecting sheathing to cold-formed steel studs. *Research report, CFS-NEES, RR04*; January 2013.
8. Leng J, Schafer BW, Buonopane, SG. Modeling the seismic response of cold-formed steel framed buildings: model development for the CFS-NEES building. *Proceedings of the Annual Stability Conference–Structural Stability Research Council*, St. Louis, Missouri, 2013.
9. Fülöp LA, Dubina D. Performance of wall-stud cold-formed shear panels under monotonic and cyclic loading. Part II: Numerical modelling and performance analysis. *Thin-Walled Structures* 2004; 42: 339-349.
10. Martínez-Martínez J, Xu L. Simplified nonlinear finite element analysis of buildings with CFS shear wall panels. *Journal of Constructional Steel Research* 2011; 67(4): 565-575.
11. Xuhong Z, Yu S, Tianhua Z, Yongjian L, Jin D. Study on shear resistance of cold-formed steel stud walls in residential structure. *Advances in Engineering Structures, Mechanics & Construction* 2006; 423-435.
12. Xu L, Martínez J. Strength and stiffness determination of shear wall panels in cold-formed steel framing. *Thin-Walled Structures* 2006; 44: 1084-1095.
13. McKenna F. OpenSees: The Open System for Earthquake Engineering Simulation. http://opensees.berkeley.edu.
14. Madsen RL, Nakata N, Schafer BW. CFS-NEES building structural design narrative. *Research report CFS-NEES RR01c*; revised 2013.
15. American Iron and Steel Institute (AISI). *North American Standard for Cold-Formed Steel Framing–Lateral Design S213*; 2007.
16. Serrette R, Chau K. Estimating the response of cold-formed steel frame shear walls. AISI *Research Report RP03-7*; 2003, revised 2006.