Impact of Detailing on the Lateral Performance of
Cold-Formed Steel Framed Walls

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ABSTRACT

The main objective of this study is to investigate the impact of structural and non-structural detailing that is not directly accounted for in conventional lateral strength and ductility design of wall-lines constructed of cold-formed steel (CFS) framed steel sheet shear walls. A key structural detail that commonly occurs in wall-lines, but not in shear wall testing, is the presence of a heavy ledger track attached along the top of the wall that facilitates connection of the floor system with the wall. A key non-structural detail, which will impact the wall-line's lateral performance, is the presence and type of finish system (e.g., gypsum board). Herein, a numerical study employing OpenSees is validated and exercised on wall-line models with or without ledger tracks as well as with or without finishes. Modeling results predict the degree by which both strength and ductility of wall-lines increase due to the presence of a ledger track and/or finish system. The strength increase can be attributed to the engagement of ledger track-to-stud connection moment resistance and additional direct shear resistance provided by an applied finish layer. The developed OpenSees model can capture the impact of detailing and can be incorporated into building-level simulations.

Introduction

Cold-formed steel (CFS) framed structures demonstrate favorable characteristics including lightweight, low cost, and multi-hazard resilience. Seismic force resisting systems for CFS structures available in AISI S400-15 [1] include CFS framed shear walls with sheathed panels, CFS framed strap-braced walls, and CFS steel special bolted moment frames, providing resistance to the in-plane seismic forces and featuring energy dissipation.

Recent experimental studies and analysis of a database of CFS framed shear walls show that there exists significant overstrength originating from both structural and non-structural detailing when compared with the nominal strength as calculated per AISI S400-15 [2-5]. A shear wall testing study reveals that a ledger track can have an appreciable

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impact on the strength of the wall [6-7]. The addition of the ledger increases strength and stiffness. However, it also decreases drift at peak strength and drift at 80% post-peak shear strength. The ledger track to stud connection's lateral strength contribution is not included in conventional design. Additionally, recent wall line tests show that the non-structural finish details may contribute considerably to the lateral resistance [8-10].

Validation of seismic response modification coefficients, and advanced design, requires the ability to perform reliable nonlinear time history analysis of CFS-framed building systems. The main goal of this research is to propose an advanced modeling framework implemented in OpenSees for predicting CFS-framed wall-line lateral response, with or without a ledger track and with allowance to account for finishes. The research herein indicates that an adequately developed OpenSees model can capture the impact of structural and non-structural detailing. The model proposed will be useful for incorporation into building-level simulations.

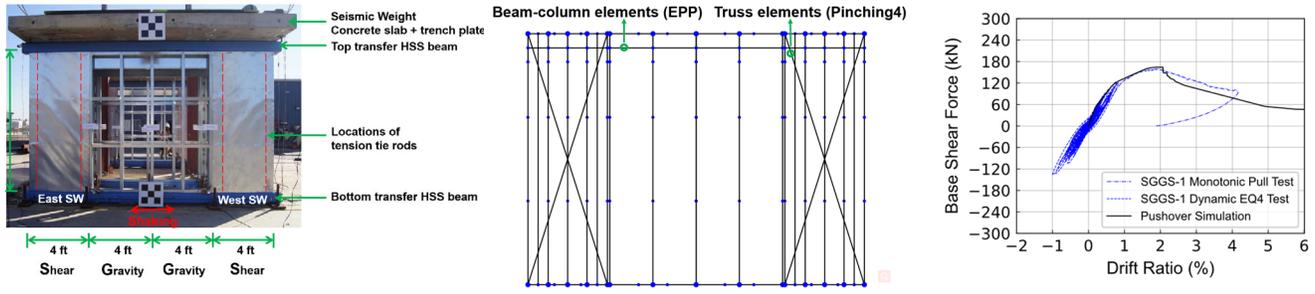## Recent Testing on CFS-framed Steel Sheet Wall Line

The recently completed CFS-framed steel sheet sheathed wall line test program on the National Hazards Engineering Research Infrastructure (NHERI) outdoor shake table at UC San Diego [8-10] incorporated both dynamic tests and quasi-static lateral tests. A series of CFS-framed wall-lines, with steel sheet sheathed shear walls within the wall line, were tested through a series of ground motions scaled to approximate different performance levels: elastic, quasi-elastic, design, and "above" design. After the dynamic tests, selected specimens were subjected to slow, monotonic, in-plane pull loading to examine the post-peak behavior. Two pairs of wall-lines were tested on the shake table at the same time, each pair of specimens featuring the same configuration. The shake table applied one-dimensional excitation along the wall line (long direction) with the wall line pair sharing the top mass composed of a concrete slab and steel trench plates. Each wall line specimen consists of four wall segments each with a 4-ft width. Utilizing the baseline specimen *SGGS-1* nomenclature as an example (shown in Fig. 1a), "S" is the abbreviation for "Shear wall segment", "G" stands for "Gravity wall segment", and "1" implies "Type-I shear wall". Fig. 1c reveals the baseline shear wall line *SGGS-1* specimen's base shear force and top track drift response subject to the design level earthquake followed by a slow monotonic pull test to just beyond 40% strength drop from peak.

OpenSees Model

A phenomenological finite element modeling framework, with or without ledger tracks and/or finish systems, is constructed utilizing OpenSeesPy [11-12], a Python 3 interpreter of the OpenSees structural analysis software. The finite element model for the baseline test specimen *SGGS-1* featuring a ledger track installed and no finish system attached is used to explain the model herein. This OpenSees model adopts displacement-based beam-column line elements for all framing members, including studs and tracks, as shown in Fig. 1b. The section aggregator command is employed to define framing member axial and flexural behaviors separately for the beam-column elements. The elastic-perfectly plastic (EPP) material model is applied to capture the nonlinear axial and flexural behavior. The axial yield strength is determined using the nominal section properties (thereby considering local buckling, distortional buckling, and yielding), and the flexural yield strength is determined per AISI S100-16 [13]. Four-point backbone parameters for both local buckling and distortional buckling of chord studs subject to flexural loading, limited per Section 9.8 in American Society of Civil Engineers (ASCE) standard ASCE 41-17 [14], can be applied to its flexural behavior to capture chord stud strength reduction. Global buckling is captured within the model based on unbraced lengths. The ledger track web height (0.3 m) within the baseline specimen *SGGS-1* is explicitly modeled with extra beam elements (0.3 m long) perpendicular to and rigidly connected to the horizontal beam element modeling the long ledger track itself, which allows the ledger-to-stud connection to transfer moment across the depth of the ledger as opposed to a single point. Tie rods are modeled with truss elements and elastic-perfectly plastic material to capture tensile yielding and compression buckling.

The steel sheet sheathing in Fig. 1a is simulated with a pair of diagonal truss elements in Fig. 1b utilizing a Pinching4 hysteretic model calibrated using an isolated CFS-framed steel sheet sheathed shear wall quasi-static test result [15]. Shear wall specimen *CW2*, from the literature [15], is the closest configuration (similar framing thickness, sheathing thickness, and fastener spacing) compared with the wall line test *SGGS-1,* except the single shear wall is 2.44 m tall while the wall line is 2.74 m tall. When a non-structural finish system is included, additional diagonal truss elements with the Pinching4 hysteretic model are incorporated herein for all the shear and gravity wall segments. The Pinching4 model parameters for the gypsum finish are obtained from the quasi-static test results of CFS-framed wall test finished

with gypsum board only [16]. The Pinching4 hysteretic model strength parameters for the Exterior Insulation Finishing System (EIFS) are scaled based on the EIFS strength back-calculated using the wall line tests with and without finish [17]. Other Pinching4 hysteretic parameters are set the same as the former gypsum finish. Pushover analysis is conducted for the baseline specimen *SGGS-1* OpenSees model. The base shear force versus drift behavior for both the simulation and the wall line testing of [8-10] is provided in Fig. 1c, demonstrating a favorable match between simulation and testing results.

(a) Baseline specimen (SGGS-1)   (b) OpenSees finite element model   (c) OpenSees model validation
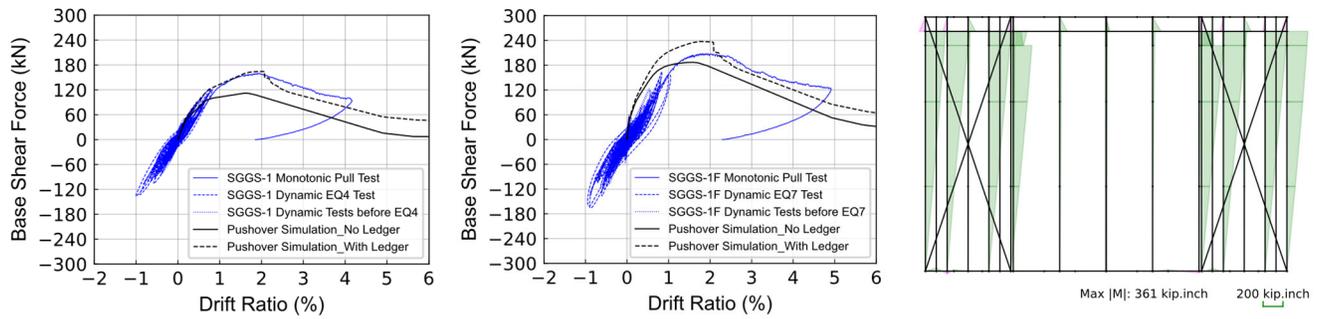Figure 1. Baseline test specimen and OpenSees finite element model and validation.

Impact of Ledger Track and Finish System on Shear Wall Line Performance

Beyond the OpenSees model for the baseline specimen *SGGS-1*, three additional OpenSees models are also established to investigate the impact of the ledger track and finish system on the shear wall line strength, stiffness, and ductility. The three models include a model without ledger track or finish (sheathed steel framing) and a pair of models with a finish system, with or without ledger track (finished steel framing with or without ledger track). Simulation results for all four models are provided in Fig. 2. The base shear force-drift ratio for *SGGS-1* (unfinished) and *SGGS-1F* (finished) wall-line specimens, both numerical (with and /or without a ledger track) and experimental (with a ledger track), are shown in Fig. 2a and 2b, respectively. The corresponding moment diagram generated from the baseline specimen *SGGS-1* simulation is shown in Fig. 2c. The key strength and ductility parameters are tabulated in Table 1. Based on Fig. 2a and 2b, the peak strength of the monotonic pull tests and the elastic stiffness of low-intensity dynamic tests can be utilized as a reference. Pushover simulation results for the two cases with a ledger track in Fig. 2a and 2b demonstrate reasonable strength and initial stiffness (tested wall-lines have a ledger track installed).

Due to the presence of the ledger track, the wall line strength increases 47 % in the unfinished case and 27 % in the finished case based on the statistics in Table 1. As indicated in Fig. 2c, the moment is present within the studs and ledger track due to the existence of the ledger track even though all the stud-to-track connections and bracing-to-framing connections are modeled as pins. This additional moment increases the wall line shear resistance. In addition, the presence of finish increases the wall line strength by 67 % without a ledger and 45 % with a ledger. It can be observed that the presence of a ledger track increases the drift at peak lateral force by 22 % for the unfinished case and 13 % for the finished case, again largely due to the additional moment restraint.

The wall line test baseline specimen configuration does not match Table E2.3-1 in AISI S400-15. Thus, the overstrength ratio in Table 1 is defined as the ratio of simulation peak strength over the single shear wall test strength with a similar configuration [15]. Four simulated wall-lines have the same nominal shear strength of approximately 100 kN contributed by the two shear wall segments and approximated with two times the "CW2" shear wall test peak strength [15] (assume that shear wall segment provides same shear resistance per unit length with the test). The overstrength ratio of *SGGS-1* baseline specimen is 1.12, which is because the calibrated Pinching4 hysteretic model backbone strength was increased 15 % to incorporate the strength degradation behaviors in the future cyclic loading simulation. The existence of ledger track increases the overstrength ratio by 37 % and finish increases it by 56 % on average.

Residual force ratio can be a measure of ductility [18]. Residual force ratio at 5 % drift is adopted herein to evaluate the post-peak performance, with larger values implying that the structure is more ductile. The computed residual force ratios indicate that the presence of a ledger track increases the residual force ratio by 92 %, while the finish increases it by 57 %, on average.

(a) Unfinished shear wall-lines   (b) Finished shear wall-lines   (c) Moment diagram @ peak load

Figure 2. Base shear force-drift relationship and a moment diagram of OpenSees simulations.

Table 1. OpenSees simulation result statistics summary.

	Strength (kN)	Drift[a] (%)	Overstrength Ratio[b]	Residual Force Ratio[c]
Unfinished wall-line, no ledger	112.1	1.63	1.12	0.13
Unfinished wall-line, with ledger	164.3	1.99	1.65	0.33
Finished wall-line, no ledger	187.2	1.55	1.88	0.27
Finished wall-line, with ledger	237.6	1.75	2.38	0.35

[a] Drift ratio @ peak load
[b] Ratio of simulation strength over the single shear wall *CW2* test strength [15]
[c] Residual force ratio @ 5% drift

Conclusions

This research utilizes OpenSees to develop a modeling framework to capture the impact of structural and non-structural detailing for CFS-framed steel sheet sheathed shear walls with focus on wall lines. Four OpenSees models with and without ledger tracks and with and without finish systems are created. Simulation results indicate that both strength and ductility of the shear wall-lines increase due to the presence of ledger tracks and finish systems. The strength and ductility increase can be attributed to the ledger-to-stud connection moment restraint provided by the presence of a ledger track and shear resistance provided by the finish system. This modeling approach can be incorporated into future building-level simulations to help understand the impact of overstrength on the seismic performance of CFS shear wall systems.

Acknowledgments

References

1. American Iron and Steel Institute (AISI). North American Specification for Seismic Design of Cold-Formed Steel Structural Systems, AISI S400-15. American Iron and Steel Institute: Washington, DC, 2015.

2. Ayhan D, Baer S, Zhang Z, Rogers CA, Schafer BW. Cold-Formed Steel Framed Shear Wall Database. *Proceedings of the Int'l. Spec. Conf. on Cold-Formed Steel Structures*. St. Louis, MO, 2018.

3. Haghpanah F, Schafer BW. Updated Fragility Functions for Cold-Formed Steel Light-Frame Structural Systems. *Proceedings of the 12th National Conference on Earthquake Engineering*. Quebec City, June 17-20, 2019. 8 pp, 2019.

4. Zhang Z, Rogers CA, Schafer BW. Cold-Formed Steel Framed Shear Wall Resistance Factors. *Proceedings of the 12th National*

Conference on Earthquake Engineering. Quebec City, June 17-20, 2019. 8 pp, 2019.

5. Mohebbi S, Mirghaderi SR, Farahbod F, Sabbagh AB, Torabian S. Experiments on seismic behavior of steel sheathed cold-formed steel shear wall cladded by gypsum and fiber cement boards. *Thin-walled Structures* 2016; **104** (2016) 238-247.

6. Liu P, Peterman KD, Yu C, Schafer BW. Cold-formed steel shear walls in ledger-framed buildings. *In Annual Stability Conference, Structural Stability Research Council* 2012; Vol. 4, No. 1, pp. 27-47.

7. Liu P, Peterman KD, Yu C, Schafer BW. Characterization of Cold-formed Steel Shear Wall Behavior under Cyclic Loading for the CFS-NEES Building. *International Specialty Conference on Cold-Formed Steel Structures* 2012; 5.

8. Singh A, Wang X and Hutchinson TC. Lateral Response of Cold-Formed Steel Framed Steel Sheathed In-line Wall Systems Detailed for Mid-Rise Buildings. Part I: Shake Table Test Phase. Structural Systems Research Report SSRP-2019/05, Department of Structural Engineering, University of California San Diego, La Jolla, CA, 2021.

9. Singh A, Hutchinson TC, Wang X, Zhang Z, Schafer BW, Castaneda H, Derveni F and Peterman KD. Wall line tests: phase 1 -- shake table tests. CFS-NHERI: Seismic Resiliency of Repetitively Framed Mid-Rise Cold-Formed Steel Buildings. *DesignSafe-CI*, 2021. DOI: 10.17603/ds2-mvj8-8386.

10. Singh A, Zhang Z, Castaneda H, Peterman KD, Schafer BW and Hutchinson TC. Correlating fastener damage to hysteretic response and performance levels in steel sheet sheathed CFS wall-lines. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

11. Mazzoni S, McKenna F, Scott MH and Fenves GL. OpenSees command language manual. Pacific Earthquake Engineering Research (PEER) Center, 264, 2006.

12. Zhu M, McKenna F, Scott MH. OpenSeesPy: Python library for the OpenSees finite element framework. SoftwareX, 7, pp.6-11, 2018.

13. American Iron and Steel Institute (AISI). North American Specification for the Design of Cold-Formed Steel Structural Members, AISI S100-16. American Iron and Steel Institute: Washington, DC, 2016.

14. American Society of Civil Engineers (ASCE). Seismic Evaluation and Retrofit of Existing Buildings, ASCE/SEI 41-17, Reston, VA, 2017.

15. Rizk R, Rogers CA. Higher strength cold-formed steel framed steel shear walls for mid-rise construction. Res. Rep., Dept. of Civil Engineering and Applied Mechanics, McGill Univ., Montreal, 2017.

16. Morello D. Seismic performance of multi-storey structures with cold-formed steel wood sheathed shear walls. Master Thesis, Dept. of Civil Engineering and Applied Mechanics, McGill Univ., Montreal, 2009.

17. Singh A, Hutchinson TC. Lateral response of cold-formed steel framed steel sheathed in-line wall systems detailed for mid-rise buildings. Part II: quasi-static test phase. Structural Systems Research Project. Report No. SSRP-2019/06. University of California, San Diego. La Jolla, CA, 2021. (In preparation)

18. Vamvatsikos D, Cornell CA. Direct estimation of the seismic demand and capacity of oscillators with multi-linear static pushovers through IDA. *Earthquake engineering & structural dynamics* 2006; 35, **no. 9** (2006): 1097-1117.