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THE CFS-NEES EFFORT: ADVANCING COLD-FORMED STEEL EARTHQUAKE ENGINEERING

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ABSTRACT

The objective of this paper is to summarize a multi-year effort to advance our understanding in the seismic behavior of, and improve the design of, buildings framed from cold-formed steel (CFS). The effort includes a U.S. National Science Foundation funded project and companion industry-funded projects taken together under the abbreviated name: CFS-NEES. Major deliverables in the CFS-NEES effort include: experimental shear wall testing, characterization, and modeling; experimental cyclic member testing, characterization, modeling, and design; and, complete building design, modeling, and shake table testing. The research enables performance-based design by providing the necessary building blocks for developing nonlinear time history models of buildings framed from cold-formed steel. In addition, the experiments demonstrate the large difference between idealized engineering models of the seismic lateral force resisting system and the superior performance of the full building system. Significant work remains to bring the findings to design practice, and this effort is both ongoing and an area of future need.

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Introduction

Seismic design of buildings using repetitively framed cold-formed steel members, i.e. light steel framing, has largely been enabled through a series of dedicated tests conducted on shear walls and compiled for convenient use in the AISI-S213 standard [1] and supported through the seismic response modification coefficients and procedures in ASCE 7 [2]. This approach has

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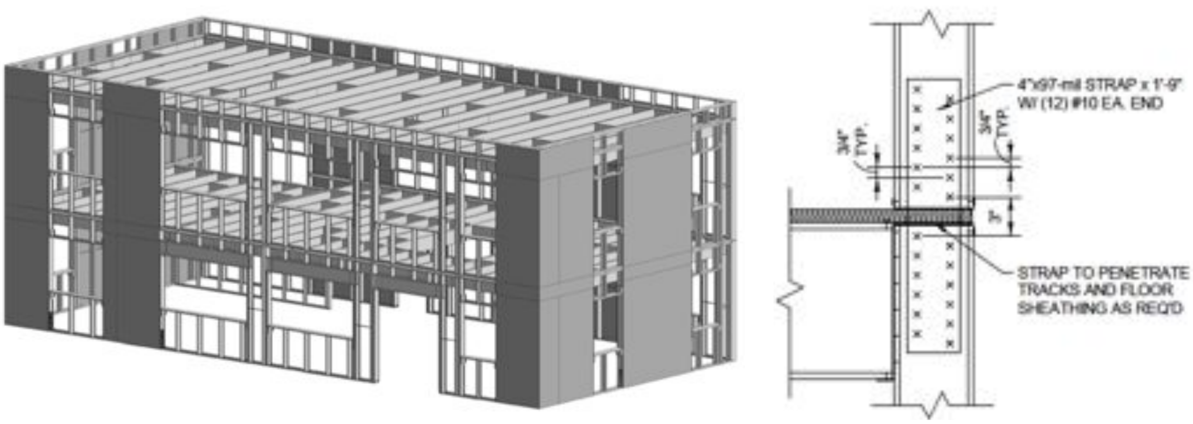
served engineers and industry well, but has not provided a clear path towards the development of new and novel seismic force resisting systems utilizing cold-formed steel, nor does it provide the necessary knowledge for modeling cold-formed steel buildings as systems. At its core, the seismic performance-based design (PBD) paradigm presumes an ability to efficiently model key nonlinearities and redistributions inherent in a building under seismic demands. For cold-formed steel structures important knowledge gaps must be bridged before such models for PBD are possible. To varying degrees, fundamental gaps exist with respect to experimental knowledge of the hysteretic performance of connections, members, assemblages, and full buildings for cold-formed steel structures. Further, characterization, whether fundamental or phenomenological, and implementation into models is also lacking. The CFS-NEES effort has as its aim the development of experimental benchmarks, fundamental characterization, and the demonstration of efficient means to model cold-formed steel structures – even with their inherent complexity.

Building Archetype

Central to the CFS-NEES effort was the professional design of a two-story commercial building framed from cold-formed steel. The building is sited in Orange County, CA (site class D) and is 49ft-9in. x 23ft in plan and 19ft-3in. tall with a total seismic weight of 78 kips. The design was completed by Devco Engineering, with input from the project team and the Industrial Advisory Board (see acknowledgments). A design narrative, complete calculations, and full drawings are available for the building [3,4].

A key feature of the building was the selection of ledger framing, a choice that was strongly advocated for by the Industrial Advisory Board based on current practice. In ledger framing the building is constructed one floor at a time, but the floor joists are hung from the top of the studs. The joists and studs are not aligned so a ledger, or carrier track, is attached to the interior face of the studs running along its length to provide a connection point for the joists, see Figure 1. A key detail in such a system is the joining of the shear wall chord studs across stories: a flat plate attached to the stud web penetrates through the floor, as shown in Figure 1b.



(a) rendering from BIM model, only shear walls sheathed (b) detail at shear wall chord stud

Figure 1. CFS-NEES archetype building utilized to organize research and for full-scale testing

Member Characterization

Fundamental to the behavior of thin-walled cold-formed steel members is the stiffness reductions that may occur due to local, distortional, and global buckling under load. These reductions must be captured within designs and models if the full system created by cold-formed steel members is to be assessed. Using existing test data a new method was developed for determining the stiffness reduction and backbone moment-rotation and/or moment-curvature response under local and distortional buckling [5, 6, 7, and 8]. The method is general, and in the spirit of the Direct Strength Method of cold-formed steel design, uses the cross-section slenderness to predict the reduced stiffness and full backbone response.

Given a lack of available data on member cyclic response, the American Iron and Steel Institute in collaboration with the CFS-NEES effort funded a companion project to provide explicit data on cyclic response of cold-formed steel members. The effort, conducted at Virginia Tech, carefully selected members and boundary conditions to study local, distortional, and global cyclic response of cold-formed steel members in axial [9,[10]11] and bending [12]. Typical results for local buckling under axial cyclic load are shown in Figure 2. These results form the basis for development of seismic force resisting systems that incorporate complete cold-formed steel member response, as opposed to current systems, that largely seek to use alternative mechanisms, independent from the members (bearing in wood or steel connections, yielding of straps, etc.), to resist seismic demands.

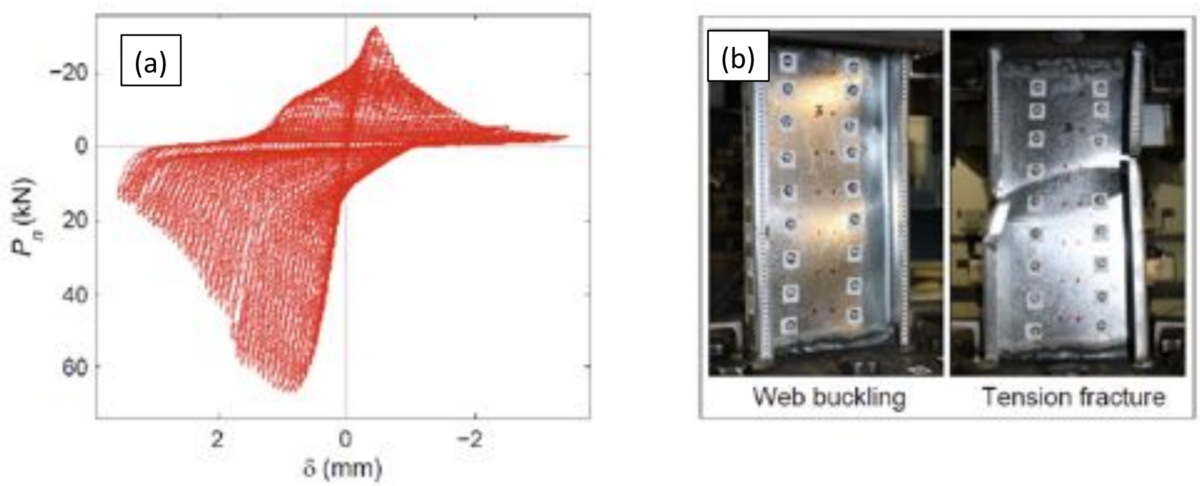


Figure 2. Cyclic load-deformation response in local buckling for 600S162-33

OSB Sheathed Shear Wall Characterization

The CFS-NEES archetype building employs cold-formed steel framed, OSB-sheathed, shear walls. This is a common shear wall type, available in AISI-S213 [1] for prediction of its strength and stiffness. However, actual construction differs from the tests used to develop the AISI-S213 tables: shear wall sizes are not equal to 4ft x 8ft OSB panel, so numerous additional horizontal and vertical seams exist in actual shear walls; a large 0.097 in. thick 12 in. deep carrier or ledger track blocks out the last 12 in. at the top of a shear wall; gypsum board is sheathed on the interior face of the wall; and in some cases the field studs are not the same thickness as the chord studs that frame out the shear wall. In addition, complete hysteretic response of the shear walls is not available, as a result a test program and characterization effort was initiated.

Thanks to a collaboration with the University of North Texas, the CFS-NEES project was able to efficiently test 15 OSB-sheathed shear walls. Testing following the CUREE protocol, and typical response of 4ft x 9ft shear walls are provided in Figure 3, with complete results available in the test report [13] and related papers [14, 15]. Strength degradation initiated at levels between 2% and 4% drift. Developed strength was in excess of AISI-S213 predictions, except in the case where shear wall field studs are thinner than the chord studs, a common practice for lightly loaded upper stories that should be accounted for in design. The addition of panel seams, ledger, and interior gypsum cause some divergence in stiffness predictions from AISI-S213 and can lead to greater than expected overstrength.

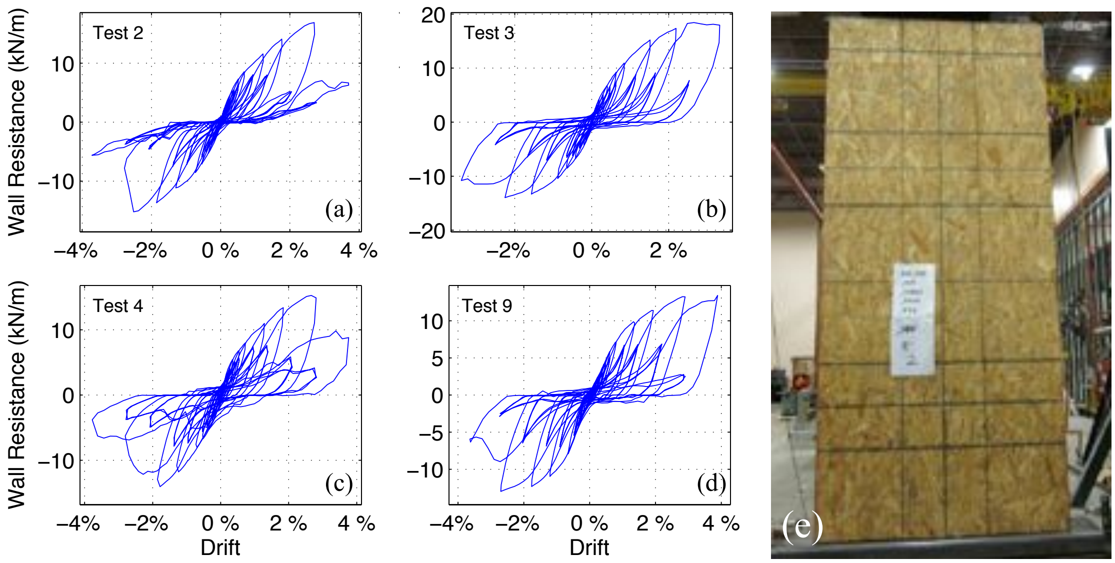


Figure 3. Hysteretic response of 1.22 m x 2.74 m OSB sheathed shear walls (a) with ledger, (b) and gypsum board, (c) baseline, and (d) extra vertical seam (e) front of Test 2

Characterization of the test results was completed by determination of parameters for one-dimensional (V-Δ) phenomenological models employing the equivalent energy elastic-plastic (EEEP) model and the Pinching04 model [16]. EEEP models are not appropriate for time-history analysis of these systems, only for pushover analysis. The Pinching04 models are utilized in the CFS-NEES building models as discussed under Full Scale Building Modeling.

"Fastener" Characterization

For cold-formed steel framed, OSB-sheathed, shear walls the key energy dissipating mechanism occurs at the stud-fastener-sheathing connection. As the studs rack laterally the fasteners tilt (and bend) as they bear into and damage the sheathing. Stiffness of the shear walls also relies on this same mechanism. In shear walls framed and sheathed from wood it has been found that a similar mechanism dominates the response and reasonable estimates of shear wall parameters can be derived directly from this local "fastener" response [17].

To characterize this "fastener" response a series of cyclic tests on stud-fastener-sheathing assemblies as depicted in Figure 4a,b were conducted. The tests varied stud thickness, fastener spacing, and sheathing type. Typical force-deformation results are provided in Figure 4c – the direct shear response of the fastener assemblies is similar to the full walls, but even more pinched. Each test was characterized using the Pinching04 model and complete results are provided in a CFS-NEES research report [18] and a related paper [19]. Work connecting the fastener response to the overall shear wall response is underway [20], and initial results indicate that with a little care (particularly with respect to hold-down flexibility), small-scale fastener tests have excellent predictive power for full-scale shear wall tests.

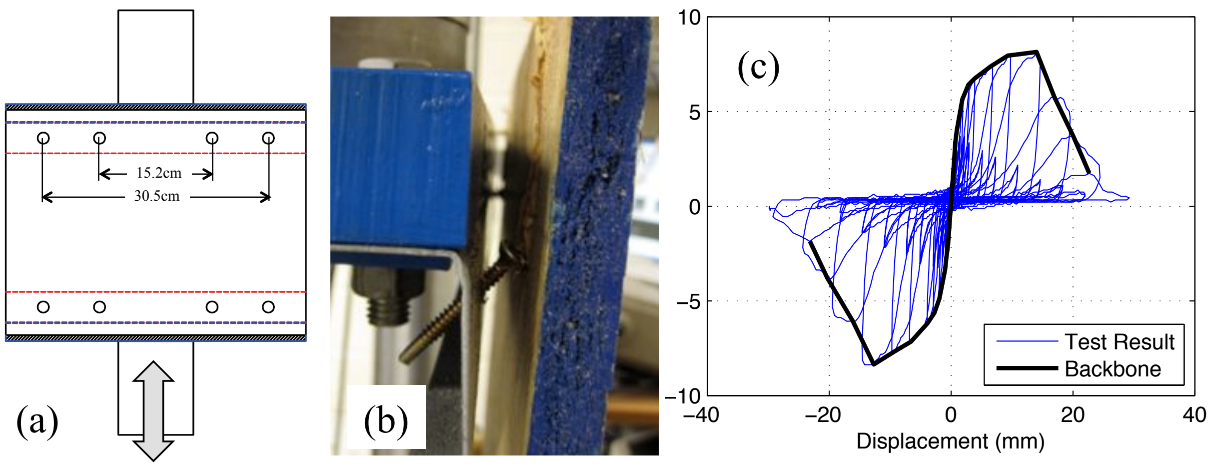


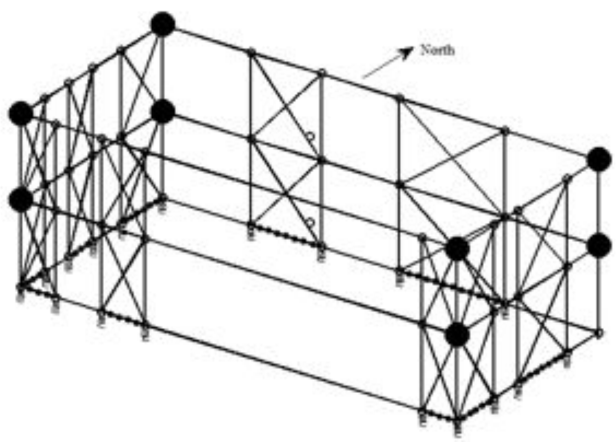
Figure 4. Fastener testing assembly (a) front, (b) side detail, and (c) typical response

A lack of knowledge on the stiffness and cyclic response of typical connections in cold-formed steel goes beyond the details common in shear walls. As a result, as a companion to the CFS-NEES effort, a project was undertaken at Virginia Tech to more fully understand the cyclic response of cold-formed steel connections [21]. The results provide a key building block for models of cold-formed steel assemblages and full buildings.

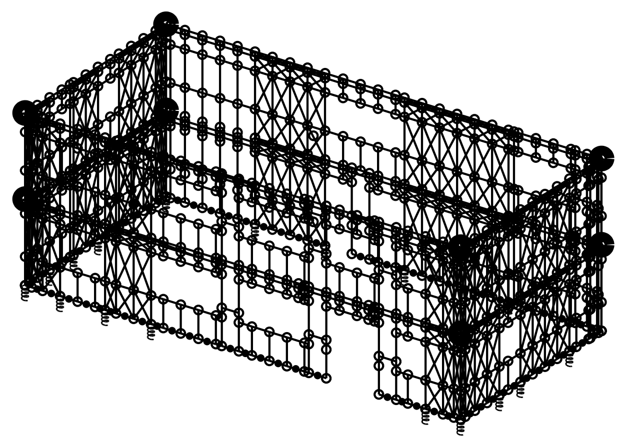
Full Scale Building Modeling

The CFS-NEES full scale building modeling effort has two major goals (1) to provide a model that can meaningfully predict the CFS-NEES building response in order to better understand the behavior of the building and use the model to examine response against a full suite of seismic excitations, and (2) to evaluate what level of model fidelity is necessary for engineers and researchers modeling buildings framed from cold-formed steel. Modeling the response of cold-formed steel buildings, even a particular cold-formed steel building, introduces an enormous number of potential assumptions. A complete model tree spanning from two-dimensional models with strength and stiffness based on specifications available to engineers, e.g. [1], to three-dimensional models with shear walls based on direct experimental characterization and all steel framing explicitly modeled are all explored.

Research is still underway [22,23], but preliminary results indicate a high degree of model complexity is required for developing observed system response. Consider the model of Figure 5a: 3D with only shear walls modeled (rigid diaphragm). The first mode period of this model, even using experimentally calibrated shear wall stiffness, is 0.64 sec. The same building (with only shear walls in place, aka Phase 1) in white noise testing has a first mode period of 0.32 sec. An alternative model, with all wall framing explicitly included as shown in Figure 5b, was created and resulted in a much improved first mode period of 0.38 sec. A key feature of the more detailed model is the inclusion of the full length ledger, or carrier, track, and the larger header members above openings. Work continues on several fronts with respect to the modeling: direct comparison with the full scale building testing, improving the complex model with a semi-rigid diaphragm, investigating how best to use models in engineering practice [24], and developing more robust reduced order models for nonlinear time history analysis.



(a) shear walls only



(b) shear walls and all gravity framing

Figure 5. Three-dimensional OpenSees models of the CFS-NEES archetype building
T=0.64 then 0.38sec, where T=0.32 in the test

Full Scale Building Testing

In the Summer of 2013 the project conducted full-scale tests on the CFS-NEES building at the NEES facility at the University at Buffalo. Two buildings were constructed, the first (Phase 1) had the complete lateral force resisting system sheathed, but otherwise all other gravity framing as bare steel (Figure 7a). After full-scale testing using the Canoga Park motion from the 1994 Northridge earthquake this structure was dis-assembled and a second specimen (Phase 2) constructed. The Phase 2 testing examined the change in building response as a function of construction elements: gypsum, interior non-structural, etc., as summarized in terms of shift in first mode period in Figure 6. For Phase 2e (Figure 7c) the building was subjected to the Rinaldi ground motion, which is consistent with MCE level spectral accelerations.

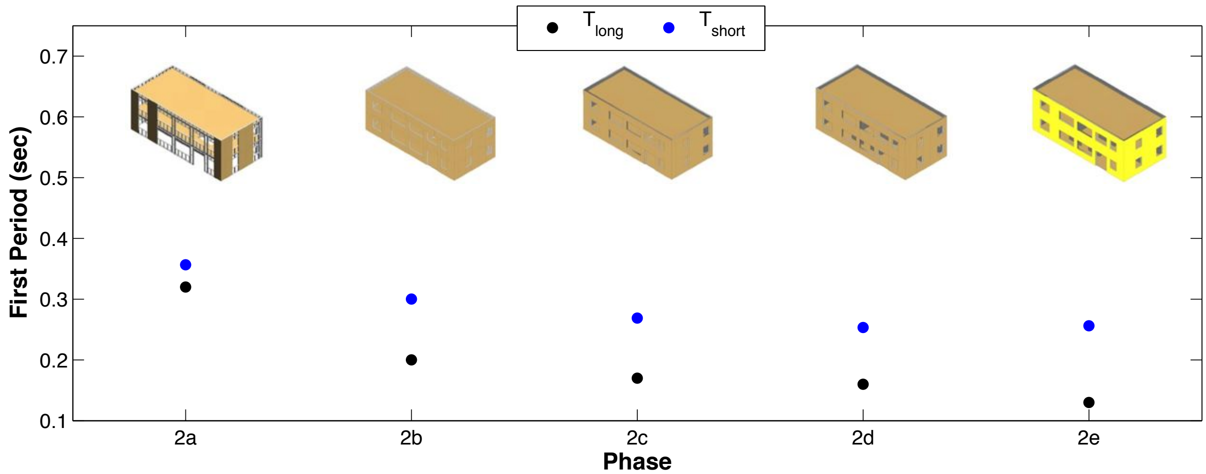
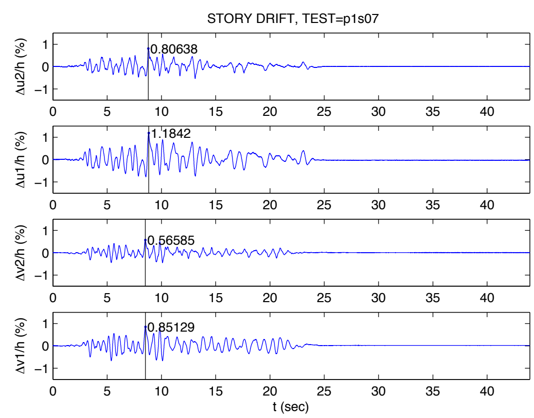
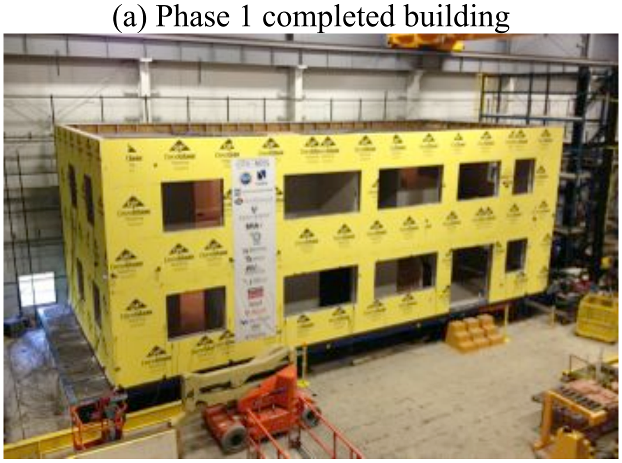


Figure 6. Shift in long and short direction first mode period through construction phases (a – LFRS and gravity steel only, b – ext. sheathed, c – inside face of ext. sheathed w/ gypsum, d – interior non-structural walls & stairs, e – exterior DensGlass sheathed)

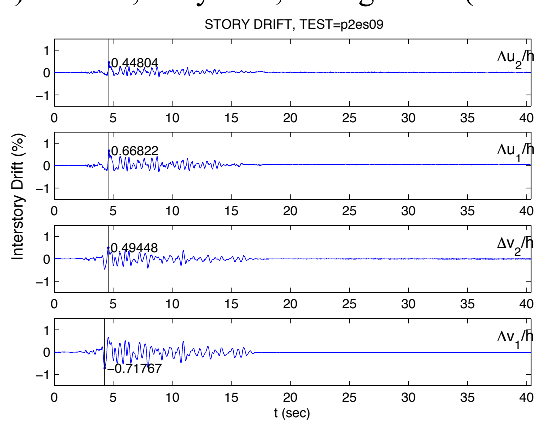
(a) Phase 1 completed building



(b) Phase 1, story drift, Canoga Park (~DBE)



(c) Phase 2e completed building



(d) Phase 2e, story drift, Rinaldi (~MCE)

Figure 7. CFS-NEES Full-scale building testing and measured drift during seismic excitation

Under seismic testing both the Phase 1 and Phase 2e buildings experienced minimal drift and returned to straight after excitation (Figure 7b,d). For the Phase 2e building the story drift under Rinaldi was less than 1% and damage only occurred in the interior non-structural walls - largely confined to corners near openings. This full scale testing provides the first look at the full system effect for buildings framed from cold-formed steel and it is significant across the board: the building is stiffer and stronger than engineering designs suggest; the building responds as a system, not as a set of uncoupled shear walls; and the gravity system contributes to the lateral response. Overall performance for the tested building was far better than code minimums, and far better than advanced engineering models (e.g. Figure 5a), but not necessarily for well understood reasons. Significant work remains to fully decipher the collected data.

Companion Efforts for Steel Sheet Shear Walls

Throughout the CFS-NEES project complementary efforts have also been directed towards advancing an alternative seismic force resisting system employing steel sheet in shear walls instead of wood structural panels. For example, the CFS-NEES building was re-designed for use as an archetype building with steel sheet shear walls. Recent efforts are summarized here [25] and represent the broader initiative to advance seismic design of cold-formed steel structures.

Education and Outreach Efforts

The CFS-NEES project has had a number of educational efforts – the most extensive of which involves the development of scale models, appropriate for instructional shake tables, that illustrate the nonlinear characteristics associated with wood structural panel shear walls [26]. In addition, high school and undergraduate students have been involved in the modeling and testing throughout the project – modeling shear walls [20], developing balsa wood models of the CFS-NEES building, documenting construction, and using digital image correlation methods to examine shear wall deformations. The project has also directed its outreach efforts towards practicing engineers – primarily through updates and workshops with the American Iron and Steel Institute Committee on Specifications and Committee on Framing Standards.

Conclusions

The National Science Foundation initiated project: CFS-NEES, is providing a multi-prong effort to advance our understanding of seismic behavior and perform improved designs for structures framed from cold-formed steel. Significant progress has been made in hysteretic benchmarking and characterization, at a variety of levels, from fastener, to member, to assemblages such as shear walls, as well as whole buildings. In addition, progress has also been made in predictive models, again across scales, progress that that has potential for improved design. Full scale testing of the CFS-NEES building provides a first look at the full system effect for buildings framed from cold-formed steel, and the system effect is significant across the board, requiring new approaches in prediction and design. Work remains to address details not fully explored (e.g., semi-rigid diaphragm behavior), and to fully enable engineers working in this domain.

Acknowledgments

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References

1. AISI S213-07 (2007) “North American Standard for Cold-Formed Steel Farming –Lateral Design”, American Iron and Steel Institute. [AISI S213-12 now available, but not used for CFS-NEES design]
2. ASCE 7-05 (2005) “Minimum Design Loads for Buildings and Other Structures.” American Society of Civil Engineers. [ASCE 7-10 now available, but not used for CFS-NEES design]
3. R.L. Madsen, N. Nakata, B.W. Schafer (2011) "CFS-NEES Building Structural Design Narrative", Research Report, RR01, access at www.ce.jhu.edu/cfsness, October 2011, revised RR01b April 2012, revised RR01c May 2012.
4. N. Nakata, B.W. Schafer, and R.L. Madsen (2012) "Seismic Design of Multi-Story Cold-Formed Steel Buildings: the CFS-NEES Archetype Building,” 2012 Structures Congress, March 2012, Chicago, Illinois. 1507-1517.
5. D. Ayhan, B.W. Schafer (2012). "Moment-Rotation Characterization of Cold-Formed Steel Beams" Research Report, CFS-NEES, RR02, April 2012, access at www.ce.jhu.edu/cfsnees.
6. D. Ayhan, B.W. Schafer (2011) "Impact of cross-section stability on cold-formed steel member stiffness and ductility", Annual Stability Conference, Structural Stability Research Council, May 10-14 2011, Pittsburgh, PA.
7. D. Ayhan, B.W. Schafer (2012) "Characterization of moment-rotation response of cold-formed steel beams", Annual Stability Conference, Structural Stability Research Council, April 2012, Grapevine, Texas.
8. D. Ayhan, B.W. Schafer (2012) "Moment-Rotation Characterization of Cold-Formed Steel Beams Depending on Cross-Section Slenderness" 15th World Conference on Earthquake Engineering, September 24-28, Lisbon, Portugal.
9. Padilla-Llano, D., Moen, C.D., Eatherton, M. (2013). “Cyclic Axial Response and Energy Dissipation of Cold-Formed Steel Framing Members”, Submitted to the Journal Thin-Walled Structures Journal, Sept. 2013.
10. Padilla-Llano, D.A., Moen, C.D., and Eatherton, M.R. (2013), “Energy Dissipation of Thin-Walled Cold-Formed Steel Members”. Virginia Tech Res. Rep. No. CE/VPI-ST-13/06, Blacksburg, VA.
11. Padilla-Llano, D., Eatherton, M., Moen, C.D., (2013). “Axial Hysteretic Modeling of Cold-Formed Steel Members for Computationally Efficient Seismic Simulation”, 2013 Structures Congress, Pittsburgh, PA.

12. Padilla-Llano, D., Moen, C.D., Eatherton, M. (2013). "Cyclic Lateral-Torsional Buckling Response of Cold-Formed Steel C-Section Joists." Proceedings of the Annual Stability Conference, Structural Stability Research Council, St. Louis, MO.
13. P. Liu, K.D. Peterman, B.W. Schafer (2012). "Test Report on Cold-Formed Steel Shear Walls" Research Report, CFS-NEES, RR03, June 2012, access at www.ce.jhu.edu/cfsnees
14. P. Liu, K.D. Peterman, C. Yu, B.W. Schafer (2012) "Cold-formed steel shear walls in ledger-framed buildings", Annual Stability Conference, Structural Stability Research Council, April 2012, Grapevine, Texas.
15. Liu, P., Peterman, K.D., Yu, C., Schafer, B.W. (2012). "Characterization of cold-formed steel shear wall behavior under cyclic loading for the CFS-NEES building." Proc. of the 21st Int'l. Spec. Conf. on Cold-Formed Steel Structures, 24-25 October 2012, St. Louis, MO, 703-722.
16. Lowes, L., Mitra, N., Altoontash, A. (2004). A Beam-Column Joint Model for Simulating the Earthquake Response of Reinforced Concrete Frames. PEER Rep. 2003/10, www.peer.berkeley.edu.
17. Folz B, Filiatrault A. (2001). Cyclic analysis of wood shear walls. *Journal of Structural Engineering* 2001; 127(4): 433-441.
18. K.D. Peterman, B.W. Schafer (2013). "Hysteretic shear response of fasteners connecting sheathing to cold-formed steel studs" Research Report, CFS-NEES, RR04, January 2013, access at www.ce.jhu.edu/cfsnees
19. K.D. Peterman, N. Nakata, B.W. Schafer (2012) "Cyclic Behavior of Cold-Formed Steel Stud-to-Sheathing Connections" 15th World Conference on Earthquake Engineering, September 24-28, Lisbon, Portugal.
20. Buonopane SG, Tun TH, Schafer BW. (2014). Fastener-based computational models for prediction of seismic behavior of CFS shear walls. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK.
21. Padilla, D., Moen, C.D., Eatherton, M.R. (2013). Energy dissipation of cold-formed steel connections. Final Report, American Iron and Steel Institute, Washington, D.C.
22. Leng, J., Schafer, B.W., Buonopane, S.G. (2013). "Modeling the seismic response of cold-formed steel framed buildings: model development for the CFS-NEES building." Proc. of the Annual Stability Conference - Structural Stability Research Council, St. Louis, MO, April 16-20, 2013, 17pp.
23. Leng, J., Schafer, B.W., Buonopane, S.G. (2012). "Seismic Computational Analysis of CFS-NEES Building." Proc. of the 21st Int'l. Spec. Conf. on Cold-Formed Steel Structures, 24-25 October 2012, St. Louis, MO, 801-820.
24. C.A. Ganea, B.W. Schafer (2013). "Challenges with Analysis-Based Design for Light Steel Framing: Modeling the CFS-NEES Building in Commercial Structural Analysis Software." Research Report, CFS-NEES, RR05, (forthcoming as of November 2013).
25. Shamim, I. and C. A. Rogers. (2013). "Steel sheathed/CFS Framed Shear Walls Under Dynamic Loading: Numerical Modelling and Calibration." Thin-Walled Structures 71: 57-71
26 Buonopane SG, Burkhart K, Puleo J, Li X, Earley T, Schafer BW. (2014). Educational shake table models of CFS shear walls. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK.