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CFS-NEES: Advancing Cold-Formed Steel Earthquake Engineering

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Abstract: The objective of this brief paper is to introduce a newly funded research project: NEESR-CR: Enabling Performance-Based Seismic Design of Multi-Story Cold-Formed Steel Structures. The project focuses on lightweight steel framing using repetitive members. The project will provide (a) new modeling capabilities that incorporate cross-section limit states (local and distortional buckling) into frame analysis engines such as OpenSees to enable more accurate incremental dynamic analysis, and (b) new knowledge in the behavior of these structures developed through component and full-scale experimental testing. The project will provide a means to understand the full system response of a lightweight steel framed building under lateral demands.

1. Introduction: Superficially similar to wood construction, lightweight cold-formed steel framing utilizes repetitive members in a manner as shown in Figure 1. The example, which utilizes platform construction and in-line framing, requires details that are by necessity significantly different from wood. For example, in wood construction direct bearing may often be utilized as a stiff load path, while in cold-formed steel framing, fastener deformations and local bending of the thin steel components must be taken into account. Differences in load path, the mechanics involved in energy dissipation, and governing limit states (e.g. local buckling) all require that cold-formed steel framing be uniquely treated and understood.

Common lateral force resisting systems (LFRS) for cold-formed steel construction consist of specifically detailed sheathed walls, strap bracing, and other systems. The two system-level load paths into the LFRS are: (1) the floor diaphragm, and (2) the load bearing wall along the same framing line as the LFRS. Conventionally one assumes the diaphragm and wall simply deliver forces to the shear wall, and collector elements are designed to enable this force transfer. However, the distribution of forces in an actual building (even ignoring non-structural components) can deviate from this idealization a great deal.

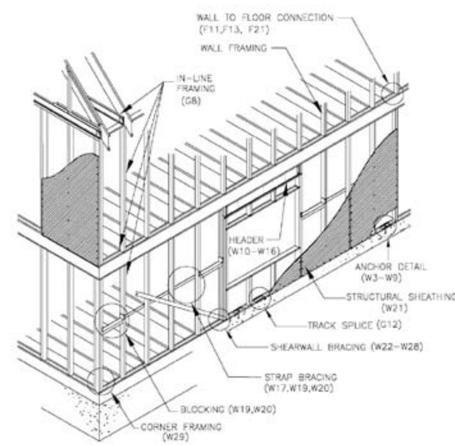


Figure 1 Typical framing details for two-story cold-formed steel framed building [1]

To date, research has focused on single-story LFRS (without gravity loads) in complete isolation from the larger system). Advancing seismic structural safety of lightweight cold-formed steel construction requires that the secondary systems, repetitively framed floors and walls, which are directly in the load path for the LFRS be understood in far greater detail. This understanding and the ability to include such understanding in numerical models of the building are the primary focus of this research.

2. Existing Research: This project leverages significant recent efforts of the first author in cold-formed steel research. Recently, it has been shown that cross-section stability analysis of thin-walled cold-formed sections may be utilized to develop unique strength relationships in P-M space, Figure 2 [2]. Thus, it is now possible to develop cross-section specific failure surfaces that incorporate local and distortional buckling limit states into frame elements. This effort will be an important part of the research.

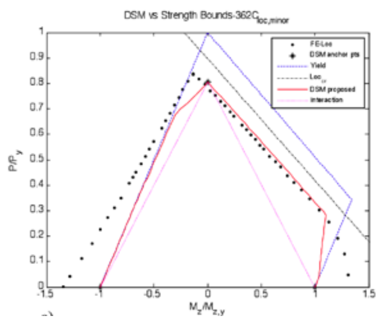


Figure 2: P-M interaction diagram for a cold-formed section subject to multiple limit states

In addition recent effort on the behavior of sheathed walls has provided a significant amount of information on the performance of these systems under gravity load, and the interaction of the studs, track, and sheathing [3]. Figure 3 shows typical limit states in a gypsum sheathed wall tested at Johns Hopkins. This knowledge will be extended through further experimentation in this research project.

a) Wall after test

b) Distortional buckling

c) Closer view of screw tearing out the board

d) Bubble forming on the board due to the stud buckling

e) Buckled flanges tearing the board

Figure 3: Response of gypsum sheathed walls [3]

While this research makes the case that cold-formed steel requires separate treatment, this is not to say that related wood research has no bearing on the work proposed herein. In particular the CUREE-Cal Tech Woodframe project[1] and the recently completed NEESWood project[2] are important contributors to the overall state of knowledge for low-rise repetitively framed construction. In particular, the NEESWood shake table tests at UB-NEES [4] form the basis for the whole building tests proposed herein and the related 3D modeling [5] demonstrates the current state of the art for modeling wood-framed construction.

Finally, in addition to the NEESWood project the NEES nonstructural project[3] involves cold-formed steel in much of the planned testing, and provides a general framework for the integration of testing and modeling of secondary systems in OpenSees[4] and their use in whole building models; a task that this project also shares in many respects.

3. Building archetype: A key feature of the research is the development of a cold-formed steel building archetype. A two-story commercial cold-formed steel framed building located in southern California is the preliminary specifications for this structure. This structure will be used as the motivation for component-level, and later full-scale testing. The fourth author (Madsen) is a practicing engineer with experience in seismic design of load bearing cold-formed steel buildings and will be leading this effort.

4. Experimental Program: The experimental program will involve component-scale testing at Johns Hopkins as summarized in Figure 4 and full-scale shake table tests at the University of Buffalo NEES site as summarized in Table 1. The component-scale testing serves the dual purpose of (a) providing information necessary for developing computational models, both high fidelity and reduced-order models appropriate for time history analysis and (b) provides direct experimental information on components and sub-systems that comprise the full-scale building thus enabling improved system identification.

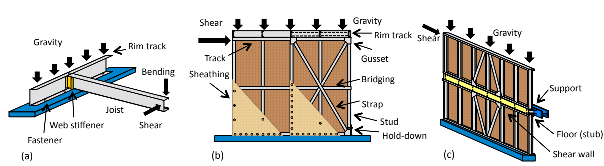


Figure 4: Planned testing at JHU laboratories (a) stud-to-track and joist-to-rim track sub-system tests (b) a

1 www.curee.org/projects/woodframe

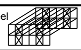
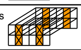
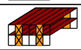
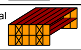
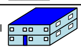
2 jwv.eng.ua.edu/neeswood_reports.html

3 www.nees-nonstructural.org

4 opensees.berkeley.edu

wall line with gravity and shear walls, and (c) a shear wall with floor detailing included

Table 1: Planned testing at UB-NEES facility

	System Identification	Seismic Performance Evaluation		
Configuration	Random Excitation	Small-Level Earthquake	Design Earthquake	Max Considered Earthquake
Bare Cold-Formed Steel Frame (CFSF) 	System ID, Model validation	-	-	-
CFSF with Shear Walls 	Contribution of shear walls	C. Rogers @McGill's Research		
CFSF with Floor and Roof Diaphragms 	Contribution of diaphragms	Interaction effects of diaphragms	Model validation for EQ loadings, Strength/Ductility	Collapse margin *Specimen #1*
CFSF with All Structural Members Sheathed 	Contribution of gravity walls	Interaction effects of gravity wall	Strength/Ductility with gravity wall	Collapse margin *Specimen #2*
Complete CFSF including Nonstructural Members 	Contribution of nonstructural members	Interaction effects of nonstructural members	Strength/Ductility	Collapse margin *Specimen #3*

5. Computational Program: Advancing seismic structural safety and enabling performance-based design for lightweight cold-formed steel framed buildings requires that significant progress is made in computational modeling. The modeling research builds from the component scale up to the whole building and are divided into two classes: high fidelity, and reduced order models. The high fidelity models directly support the experimental program allowing local details (fastener demands, developed cross-section failure mechanisms, etc.) to be explored, and also providing the opportunity to extrapolate results. The reduced order modeling includes element development in OpenSees, encapsulates the key features from the experimental testing in phenomenological hysteretic elements, and enables efficient inelastic time history analysis.

The proposed development work in OpenSees encompasses (a) the inclusion of a 14 DOF frame element appropriate for thin-walled members which are unsymmetric and primarily resist torsion through warping, (b) the inclusion of finite strip analysis as a cross-section analysis engine, (c) the development of a bounding surface plasticity model for the 14 DOF element which is driven by cross-section finite strip analysis, and (d) the development of reduction parameters for the elastic stiffness to reflect cross-section deformation under loading. With these modifications cold-formed steel members may be modeled separately from the sheathing, and the limit states appropriate to the members (local, distortional, and global buckling) captured directly in the analysis. This research will provide a critical enabling tool for inelastic time history analysis of cold-formed steel structures.

The expense of testing will only allow for exploration of essentially one prototype building. The impact of modified openings, differing hold-down details, different means of connecting the multi-story shear walls, etc. will remain unexplored. Even fully instrumented, the amount of information available from a brief series of shake table tests is by its nature limited. A high fidelity whole building model will be used to help determine the best instrumentation scheme before testing, to help insure desired behavior and limit states during the test, and once improved and validated against the full-scale testing, these models will be utilized to explore important variations in the prototype structure.

An important component of the research is the application of incremental dynamic analysis (IDA) to cold-formed steel buildings; specifically the prototype building. IDA, following the FEMA-P695 protocol, will be applied with progressive sophistication on the prototype cold-formed steel building throughout the duration of the project. The baseline IDA models will be 2D and focus on the shear wall in isolation (assuming rigid diaphragms). The models will then progress, along with the research herein, through system-level additions: (i) in-line gravity walls with the shear walls, (ii) flexible diaphragms – themselves modeled with varying degrees of sophistication, (iii) all load bearing structural components, and finally (iv) addition of nonstructural walls to arrive at complete 3D building models. The suite of IDA models will provide for sensitivity of the FEMA-P695 procedure and developed response modification coefficient (R), system over-strength factor (Ω_o), and deflection amplification factor (C_d) for the prototype building as a function of modeling sophistication, an important step for enabling true, building-specific, performance-based design of cold-formed steel structures.

6. Education and Outreach: The project has a comprehensive education and outreach program lead by the third author, Buonopane. Of specific note, he will lead in developing and implementing earthquake engineering teaching modules, with elements appropriate for both the undergraduate and K-12 levels. The modules will demonstrate seismic response of structures using repetitive framing such as cold-formed steel and will be centered around a small-scale physical model for use with the UCIST shake table system[5] which currently does not provide any educational materials that address these systems, in particular the technical issues of shear walls, floor diaphragms, and hold-downs. The developed physical model will demonstrate the fundamental structural behavior associated with this type of construction through both visible motion and data acquired from instrumentation. Plans and specifications for the model and educational

[5] mase.wustl.edu/wusceel/ucist

materials will be contributed to the UCIST web site for distribution.

7. Industry Involvement: The American Iron and Steel Institute have committed to assisting in the experimental research and have provided significant staff time to insure that the research is connected with ongoing codes and standards development. An Industrial Advisory Board is currently under formation, and being coordinated with the American Iron and Steel Institute.

8. Project website: In addition to the project information available at NEEShub[6] the project team maintains its own web site with all activities summarized at www.ce.jhu.edu/cfsnees. Interested parties are encouraged to visit the site and provide feedback to the team. The project team has also created a logo for the effort, Figure 5, which is utilized on all materials created by the team.

Figure 5: Logo developed for the CFS-NEES project

10. Acknowledgments: This material is based in part upon work supported by the National Science Foundation under Grant No. 1041578. The authors would also like to gratefully acknowledge the support of the American Iron and Steel Institute. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

11. References:

[1] SFA (2000). Low-rise residential construction details. Publication NT6-00, *Steel Framing Alliance*. Washington, D.C.

[2] Shifferaw[†], Y., Schafer, B.W. (2010). "Towards a direct strength method for cold-formed steel beam-columns." *Proceedings of the Structural Stability Research Council - Annual Stability Conference*, Orlando, FL. 613-630.

[3] Vieira[†] Jr., L.C.M., Schafer, B.W. (2010). "Full-scale testing of sheathed cold-formed steel wall stud systems in axial compression." *Proceedings of the Structural Stability Research Council - Annual Stability Conference*, Orlando, FL. 533-552.

[4] Filiatrault, A., Christovasilis, I.P., Wanitkorkul, A., van de Lindt, J. (2010). "Experimental Seismic Response of a Full-Scale Light-Frame Wood Building." ASCE, Journal of Structural Engineering, 136 (3) 246-254.

[5] van de Lindt, J.W., Peui, S., Liu, H., Filiatrault, A. (2010). "Three-Dimensional Seismic Response of a Full-Scale Light-Frame Wood Building: Numerical Study." ASCE, Journal of Structural Engineering, 136 (1) 56-65.

6 www.nees.org