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Pre-Test High-Fidelity Numerical Modeling of a Ten-Story Cold-Formed Steel Framed Building under Seismic Loading

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ABSTRACT

In the United States, current seismic code provisions restrict cold-formed steel (CFS) framed buildings to a maximum of six stories. To assess the potential for constructing taller buildings and to address the increasing demand for resilient, efficient, and non-combustible urban housing, a ten-story CFS-framed archetype building was designed using component-level test data utilizing strength capacities exceeding current code-based values. This archetype was the subject of a seismic testing program performed in June 2025 at the University of California San Diego's Large High-Performance Outdoor Shake Table (LHPOST6), as part of an NSF-funded research project focused on advancing the use of CFS in mid-rise buildings in moderate-high seismic zones. In preparation for the full-scale dynamic tests, a high-fidelity nonlinear finite element model of the ten-story building was created using OpenSeesPy. The model incorporates detailed representations of the structural components and connections, capturing both material and geometric nonlinearities. The development of the model is grounded in experimental results from prior studies of CFS-framed wall lines. Focus is placed on accurately modeling the in-plane behavior of all aspects of wall lines, including chord studs, field studs, gravity studs, top and bottom tracks, rim tracks, steel sheets, finishes, and story-to-story connections. The model considers the effects of geometric nonlinearities (either implicitly or explicitly), including buckling of steel sheet sheathing; local, distortional, and global buckling of CFS members; and member and story-level (P - δ and P - Δ) effects. This paper presents pre-test simulation results that characterize the expected dynamic response of the building under earthquake excitation. The findings helped inform expectations during the experimental program and provide preliminary indicators of system-level performance trends in taller CFS-framed buildings.

INTRODUCTION

The utilization of cold-formed steel (CFS) framed structural systems has experienced substantial growth within North American building construction, especially for structures of low to moderate height. Present seismic provisions in building standards (ASCE/SEI 2016, 2022) restrict CFS-framed buildings to a maximum height of 19.8 m when located in regions classified as Seismic Design Categories C and D. Despite extensive investigations into the behavior of individual CFS elements, which have contributed to significant improvements in design specifications including AISI S100 (2016), S240 (2015a), and S400 (2015b), research examining the seismic response of

complete CFS structural systems has been sparse. North American research efforts have produced two comprehensive experimental programs that investigated full CFS building systems through large-scale shake table testing utilizing the National Science Foundation (NSF) funded Network for Earthquake Engineering Simulation (NEES) and the Natural Hazards Engineering Research Infrastructure (NHERI). The initial program, designated as the CFS-NEES project, featured experimental testing of a two-story, full-scale CFS structure with OSB sheathed shear walls conducted by Peterman et al. (2016) utilizing the NEES@Buffalo testing facility. This investigation represented the pioneering North American study to evaluate comprehensive system-level seismic behavior of CFS construction. The test specimen consisted of a two-story structure with plan dimensions of 15.2 m by 7 m. Subsequently, the CFS- HUD (Housing and Urban Development) program was executed by Hutchinson et al. (2021) at the NEES@ UC (University of California) San Diego testing facility. This experimental program included both seismic performance testing and subsequent fire testing on a six-story, full-scale CFS-framed building utilizing steel sheet sheathed shear walls. The test structure had a floor area of 10.4 m by 7.3 m and maintained a typical story height of 3.1 m.

A collaborative research program involving multiple universities and industry partners, under the project name: Seismic Resiliency of Repetitively Framed Mid-Rise Cold-Formed Steel Buildings (or CFS-NHERI for short), was established with principal support from the NSF. This initiative aims to advance the understanding of how mid-rise CFS structural systems respond to seismic forces and to translate these findings into enhanced seismic design provisions for these structures. Within the scope of the CFS-NHERI program, extensive experimental investigations have been performed to characterize the inelastic response characteristics of structural components and connections. Significant research outputs from this program include the work of Singh et al. (2022b, 2022c), who examined steel sheet sheathed shear walls; Z. Zhang et al. (2021, 2022b), who focused on computational modeling of connections and shear wall systems; and Castaneda (2022), who investigated floor system and diaphragm performance.

In June 2025, seismic testing of a ten-story CFS building was successfully completed utilizing the recently upgraded 6-degree-of-freedom Large High-Performance Outdoor Shake Table Facility (LHPOST6) located at the NHERI@UC San Diego research center (Van Den Eijnde et al. 2021). This capstone experimental investigation (commonly referred to as CFS10 – see cfs10.ucsd.edu) presents a significant opportunity to evaluate both structural and non-structural seismic response characteristics for this distinctive building category, and concluded with full-scale fire compartment tests. Notable aspects of this tall test specimen include the incorporation of fully detailed non-structural components and a structural height that exceeded existing limitations specified in current U.S. seismic provisions (ASCE/SEI 2016, 2022). These experiments generated essential full-scale, system-level validation data for an advanced CFS structure exposed to three-dimensional earthquake excitations, thereby facilitating improvements in both structural and non-structural seismic design specifications as well as performance-based engineering guidelines. Furthermore, supplementary fire exposure experiments performed in July 2025 yielded important data regarding thermal response and smoke propagation characteristics in seismically damaged building compartments. A more detailed description of the CFS10 building and its design is provided later in this paper. An overview of the specimen and preliminary seismic test phase findings are also presented in the current conference (Hutchinson et al., 2026).

A high-fidelity numerical model was developed to simulate the anticipated behavior of the test building prior to the shake table experiments. This pre-test model, implemented in the open source software OpenSees (McKenna et al. 2000; Zhu et al. 2018), represents one of the most

comprehensive CFS structural models created to date, capturing the complete ten-story system with detail. This modeling approach utilizes discrete elements to capture each individual structural component, including studs, tracks, sheathing panels, hold-down assemblies, and tension tie-rod systems. The model accounts for a wide range of geometric nonlinearities, in some cases employing phenomenological models including for steel sheet sheathing panel buckling and CFS member local and distortional buckling, and in other cases explicitly accounting for member and frame global buckling in the overall formulation and solver. Material nonlinearity is incorporated through phenomenological hysteretic models that capture the cyclic strength and stiffness degradation as well as pinching behavior typical of CFS-framed shear wall assemblies (with different models for the shear wall itself, the story-to-story connections, etc.) and some elements modeled with traditional metal material nonlinearity such as the elastic-plastic model for the tie rods.

Model development was validated through comparison with experimental results obtained from component-level testing. This validated high-fidelity model in parallel with a practice-oriented computational model (J. Zhang et al. 2024, Singh et al. 2024b) served multiple critical purposes: providing pre-test predictions and establishing baseline expectations for structural response, guiding the selection and scaling of ground motions applied during the experimental program, and enabling future comparison studies with the actual test data. In this paper, only the pre-test predictions by the high-fidelity model are presented, focusing on the model development methodology and the simulated seismic response of the ten-story CFS structure. Comparison with CFS10 experimental measurements is not included in the current study, as the test data from the recently completed shake table tests were still undergoing processing and analysis during the completion of this paper.

DESCRIPTION AND VALIDATION OF THE DEVELOPED MODEL

Earlier research on the dynamic modeling of CFS-framed buildings has generally employed simplified approaches to minimize computational expense. Typical modeling strategies involve representing lateral force-resisting walls through either single nonlinear spring elements or pairs of diagonal nonlinear truss members (Shamim and Rogers 2012). Gravity-load-carrying components are frequently omitted from these models, with the exception of incorporating leaning P- Δ columns, while floor systems are conventionally treated as infinitely rigid diaphragms represented by single-node constraints. Leng et al. (2017) developed high-fidelity numerical models of the two-story CFS-NEES experimental structure, which facilitated enhanced accuracy in simulating the response of discrete CFS structural elements subjected to earthquake excitation. This modeling approach permitted comprehensive evaluation of force redistribution mechanisms among various components including boundary studs, top and bottom tracks, and sheathing materials that form the lateral resistance system.

Extending these developments, Z. Zhang et al. (2022c) created a high-fidelity model to investigate the lateral response characteristics of CFS wall lines, explicitly modeling steel sheet-sheathed shear walls, gravity walls, and effects from non-structural finishes. In contrast to conventional simplified modeling techniques, the detailed modeling methodologies presented by Leng et al. (2017) and Z. Zhang et al. (2022c) exhibited substantial improvements in their ability to accurately simulate the earthquake response of CFS structures and wall systems, respectively. The current investigation employs the high-fidelity modeling techniques established by Leng et al. (2017) and Z. Zhang et al. (2022c). This high-fidelity modeling approach provides enhanced

understanding of force transfer mechanisms within wall assemblies and among individual elements of both shear walls (SW) and gravity walls (GW).

Model Description

Utilizing the OpenSeesPy framework, a high-fidelity numerical model is constructed. To explain the modeling technique, the numerical model of the test specimen SGGs-1HD from the wall-line dynamic tests by Singh et al. (2022b, 2022c) is used as an example (see Figure 1a). The modeling framework employs displacement-based beam-column line elements to simulate all structural framing components, including studs and track sections, as illustrated in Figure 1b. The "section aggregator" command is implemented to independently specify the axial and flexural behavior of these beam-column elements.

The nonlinear axial and flexural response of tracks and studs is represented through an elastic-perfectly plastic (EPP) material formulation, scaled to match nominal capacity values. Element strength limits are determined following AISI S100-16 (AISI 2016) provisions, which consider local buckling, distortional buckling, and material yielding (detailed further in the following subsection).

While the majority of framing elements employ centerline modeling conventions, ledger (rim) tracks and end joists are modeled to capture their complete web depth through the inclusion of supplementary beam elements, which are positioned orthogonally and connected with rigid constraints to the primary horizontal beam-column elements that represent the ledger tracks or end-joists. This modeling strategy enables the distribution of moments throughout the full depth of the ledger or end-joist components, rather than concentration at a single nodal connection, thereby providing enhanced accuracy in simulating the moment transfer characteristics (typically ignored in design) at stud-to-ledger-track and stud-to-end-joist interfaces.

The steel sheet sheathing, illustrated in Figure 1a, is modeled through a pair of diagonal truss elements (Figure 1b), incorporating a Pinching4 (P4) material formulation (Figure 2). This P4 constitutive model employs a four-point linear segment backbone curve and simulates cyclic degradation phenomena including unloading stiffness deterioration, modified reloading paths, and strength degradation, following the requirements outlined in Section 9.8 of ASCE 41-17 (ASCE/SEI 2017). As shown in Figure 2, the backbone curve is defined by four positive envelope points (ePd_1 , $ePfi$) through (ePd_4 , $ePfi_4$) and four negative points (eNd_1 , $eNfi$) through (eNd_4 , $eNfi_4$), where ePd_i and eNd_i represent deformations while $ePfi$ and $eNfi$ represent forces at each point i . The reloading path creates the pinching effect through four control factors: $rDispP$ and $rForceP$ define the positive reloading pinch point as fractions of the maximum deformation and force, while $rDispN$ and $rForceN$ define the negative reloading pinch point as fractions of the minimum values. The unloading path is controlled by $uForceP$ and $uForceN$. Calibration of the P4 model parameters was performed based on cyclic experimental data from steel-sheathed CFS shear wall tests, particularly specimen CW2 tested by Rizk and Rogers (2017).

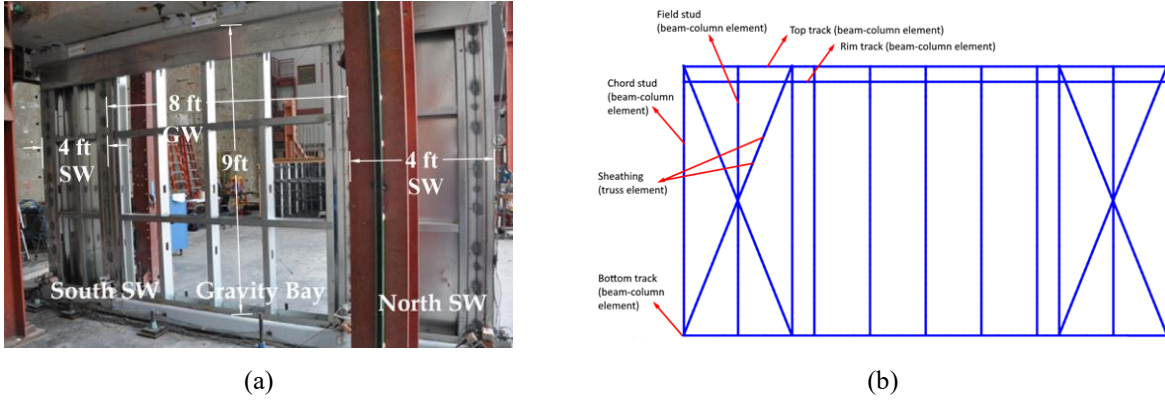


Figure 1. (a) Test specimen SGGS-1HD tested by Singh et al. (2022b, 2022c); (b) OpenSeesPy numerical model of SGGS-1HD wall-line specimen.

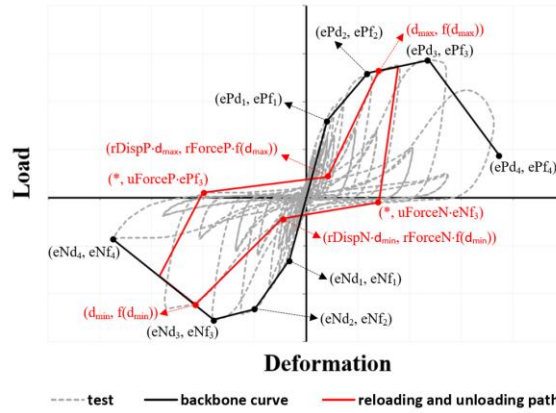


Figure 2. Equivalent energy Pinching 4 fit to an experimental response.

The selection of this specimen was based on its similarity to the SGGS-1HD wall-line configuration, sharing equivalent framing dimensions, sheathing thickness, and fastener patterns. The constitutive model additionally considers the height variation between the CW2 test specimen (2.44 m) and the SGGS-1HD wall assembly (2.74 m). In cases where architectural finishes are present, supplementary diagonal truss elements are also included, similarly utilizing the P4 hysteretic material. Gypsum finish parameters were established from cyclic experimental results of CFS-framed walls with gypsum boards, as reported by Z. Zhang (2024). This modeling technique provides more accurate representation of both sheathing and non-structural finish response characteristics during reversed cyclic loading.

Stability Assumptions

Recent experimental investigations involving CFS shear walls, wall lines, and complete structural systems have frequently documented buckling in CFS framing elements (Schafer et al. 2016; Brière & Rogers 2018; Rizk & Rogers 2018; Santos & Rogers 2018; Singh et al. 2021). Therefore, accounting for the mechanisms associated with buckling in the capacity of framing components is crucial when modeling CFS structures and their subsystems. The present investigation (as previously noted) employs displacement-based beam-column elements with displacement-based formulations to model studs and track members (Mazzoni et al. 2006).

Global flexural buckling effects are captured at the member level by subdividing each framing element into several beam-column segments ($P-\delta$) and at the frame-level ($P-\Delta$) by conducting analyses that incorporate geometric nonlinearity through the corotational coordinate transformation. The section aggregator command (Mazzoni et al. 2006) facilitates the integration of separate uniaxial material formulations representing axial, bending, and torsional responses into a single beam-column element cross-section. These individual uniaxial material models operate independently from one another.

The 3D beam-column elements within the model incorporate axial, in-plane flexural, and out-of-plane flexural responses. The nominal member strength, which considers limitations from yielding and multiple buckling modes, is used in place of the yield strength for both axial and bending material models. This methodology guarantees that all elements remain within their nominal capacity limits and insures the model implicitly accounts for local and distortional buckling of the cross-sections as well as material yielding. Member global flexural buckling is captured explicitly through the finite element model formulation. Additional information on this modeling strategy is available in Z. Zhang's numerical work (Zhang 2023 and Zhang 2025).

Model Validation

The validation of the established finite element modeling approach is conducted through comparison of model predictions against experimental results from the SGGS-1HD wall-line test (Singh et al. 2021). Figure 3 illustrates good correlation between simulated and measured cyclic behavior. Additional details on the model validation could be found in Eladly et al. (2025).

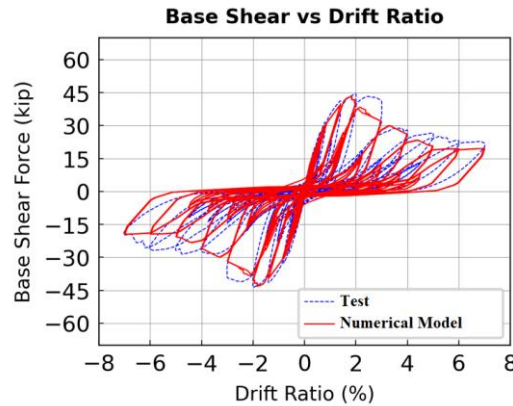


Figure 3. Experimental and FE base-shear vs. drift ratio response (specimen SGGS-1HD). Tests described in Singh et al. (2021) (1 kip = 4.48 kN).

CFS10 BUILDING DESCRIPTION and DESIGN

The ten-story test building is shown in Figure 4. It was designed as a CFS-framed building positioned at a theoretical location within a high-seismicity zone adjacent to Irvine, California, featuring Site Class C soil conditions (characterized by very dense soil and soft rock formations) as documented by Singh et al. (2022a). This test specimen incorporates CFS steel stud framing, lateral force-resisting walls with single-face steel sheet sheathing, and gravity walls. The tested building is taken as a slice from a larger building archetype motivated by the work of Torabian et al. (2016). Consequently, the northern elevation constitutes an exterior facade incorporating an EIFS (Exterior Insulation and Finish Systems) system, while the remaining three exterior elevations feature interior finishing systems. The floor construction employed a dry assembly

system (no poured concrete), utilizing ledger-framed CFS floor joists overlaid with cementitious structural panels configured within panelized or modular construction (Rivera et al. 2026).

Lateral seismic resistance was achieved through three Y-direction wall lines, each incorporating a pair of steel sheet-sheathed lateral walls, along with two X-direction wall lines that similarly featured two steel sheet-sheathed lateral walls per line. Numerous design aspects of these shear wall extend beyond the scope of current AISI S400 specifications, notably incorporating HSS members as chord studs in the lower levels, Power-Actuated Fasteners (PAFs) for steel sheet attachment to HSS chord studs, and steel sheet fastener patterns (whether PAFs or screws) that fall outside standard AISI S400 design tables. Tension forces in shear wall chord studs are accommodated through tie-rod systems in one principal building direction and direct chord stud connections employing splice plates in the perpendicular direction. The building overall height is 30.5 m, exceeding the 19.8 m restriction established in ASCE 7-16 (ASCE/SEI 2016) and ASCE 7-22 (ASCE/SEI 2022). The calculated effective seismic weight, W , equals 1575.0 kN, with the corresponding design seismic base shear, V_b , determined to be 173.2 kN for both principal directions, based on an assumed $R = 6.5$ and the selected Irvine, California site conditions. Comprehensive structural design documentation is available in Singh et al. (2022a), with subsequent design modifications detailed in Singh et al. (2024a), including the incorporation of an operable (stair) egress assembly featuring drift-release connections, shake table interface details, and an expansion of construction methods (modular and panelized construction details). The stair system was designed to be seismically resilient, with drift release connections to avoid introduction of excessive lateral stiffness (Sorosh et al., 2025).



Figure 4. Northeast view of the CFS10 specimen with annotations (Hutchinson et al. 2026).

CFS10 BUILDING HIGH-FIDELITY MODEL

The high-fidelity model of the CFS10 building is (to the team's knowledge) the largest OpenSees model ever developed for CFS-framed structures. With above 17,000 nodes and 21,000 elements, the model simulates the behavior of all studs, tracks, SW sheathing, finishes, hold-downs, tie rods, shear anchors, and wall openings. Studs, tracks, SW sheathing, and finishes are modeled the same

way described earlier in the wall line model description section. Connections between perpendicular wall lines and story-to-story shear anchors are both modeled using a combination of zeroLength elements and equalDOF constraints. In the CFS10 building, there are four shear walls in the X (E-W) direction with holddowns and splice connected end posts. In the Y (N-S) direction, 6 shear walls are employed with continuous tie-rods sandwiched between end posts. ZeroLength elements are utilized to model holddowns and tie-rods. The lateral resistance of wall nonstructural finishes is modeled using diagonal truss elements with Pinching4 material. The masses of these finishes are assigned to mass nodes. For other nonstructural components that do not provide significant lateral resistance, only their mass is considered, and any contribution to lateral stiffness or strength is neglected. A 3D rendering of the high-fidelity OpenSeesPy model of the CFS10 test building is shown in Figure 5. Detailed description of the model will be provided in the PhD thesis of the first author and additional details in the model development are in Eladly et al. (2025).

TIME HISTORY ANALYSIS RESULTS FOR THE CFS10 BUILDING

This section presents pre-test time history analysis predictions generated by the high-fidelity model for the CFS10 test building. The numerical results presented herein examine the test building's response under bi-directional (XY) design earthquake (DE)-level ground motion from the 1994 Northridge earthquake, specifically the Canoga Park – Topanga Can record (with the 106° component of the input ground motion applied at the X direction of the CFS10 building and the 196° component of the input ground motion applied in the Y direction of the building). DE denotes the design earthquake intensity level for which the ground excitation is scaled. Additionally, analyses using three different ground motions scaled to service-level earthquake (SLE) intensity and to DE intensity are included at the conclusion of this section. These motions were selected from a suite of candidates used in prior large shake table tests, from within the Federal Emergency Management Agency (FEMA) P695 record set (FEMA 2009), and a site-specific record set developed for a nearby site in Irvine, California (Zhang, J. et al., 2024). During the recent shake table test program, a subset of these records were identified and scaled to target hazard levels of service, design, and risk-targeted maximum considered earthquake (SLE, DE, and MCER; see Zhang, J. et al., 2026).

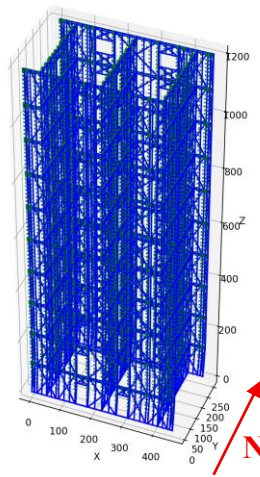


Figure 5. 3D rendering of the high-fidelity numerical model of CFS10 building (units: inch, 1 inch = 0.0254 m).

Figures 6 and 7 illustrate the roof acceleration time history in the X (E-W) and Y (N-S) directions, respectively, of the CFS10 building as predicted by the high-fidelity model for the DE-level 1994 Northridge - Canoga Park - Topanga Can excitation. As observed in the figures, the peak roof acceleration in the Y direction approaches 1g, which is approximately 20% higher than the peak roof acceleration in the X direction. Figure 8 presents the total roof drift ratio time history in both directions, also predicted by the high-fidelity model. The Y direction (N-S) experienced a higher peak roof total drift ratio compared to the X direction (E-W), reaching a maximum of 0.37% compared to 0.23% in X direction. The base-shear versus drift ratio response predicted by the model in both directions, as shown in Figure 9, reveals characteristic pinched behavior typical of CFS systems. From the figure, it can also be seen that the high-fidelity model predicts significant overstrength capacity beyond the design demand levels. Analysis of the base shear response reveals a peak value of around 400 kN in both directions under the DE-level ground motion, which represents an overstrength factor of approximately 2.3 when compared to the design base shear demand of 173.2 kN. This observed overstrength is notably lower than the code-prescribed system overstrength factor (Ω_0) of 3.0 specified in ASCE 7-22 (ASCE/SEI 2022) for cold-formed steel light-frame shear wall systems with steel sheets. It is important to note that this ratio represents only the overstrength developed during the DE-level event, not the ultimate overstrength capacity of the system.

Figures 10-15 present the numerical Peak Interstory Drift Ratio (PIDR) profiles and Peak Floor Acceleration (PFA) profiles for the CFS10 test building subjected to three different ground motion records scaled to two different scales: SLE and DE. The three ground motions investigated include:

- 1994 Northridge - Canoga Park - Topanga Can record (with the 106° component of the input ground motion applied at the X direction of the CFS10 building and the 196° component of the input ground motion applied in the Y direction of the building);
- 1994 Northridge - LA - City Terrace (with the 90° component of the input ground motion applied at the X direction of the CFS10 building and the 180° component of the input ground motion applied in the Y direction of the building);
- 1989 Loma Prieta - Gilroy Array #3 record (with the 90° component of the input ground motion applied at the X direction of the CFS10 building and the 0° component of the input ground motion applied in the Y direction of the building).

It should be noted that all analyses presented in the current paper consider single ground motion records; cumulative damage from sequential ground motions is not considered..

The results indicate that the finite element model predicts peak interstory drift ratios below 0.2% for SLE-level excitations, with values approaching 0.5% under DE-level motions. Correspondingly, peak floor accelerations remain within 0.3g for SLE-level motions, but increase to approximately 1.22g under DE-level seismic demands.

Based on these numerical predictions, the ten-story CFS test building demonstrates adequate structural performance with interstory drifts remaining below 0.5% even under DE-level excitations—well below typical permanent damage thresholds for CFS systems. The predicted response indicates that the structural system maintains sufficient lateral stiffness and strength to control deformations within acceptable limits at SLE and DE levels.

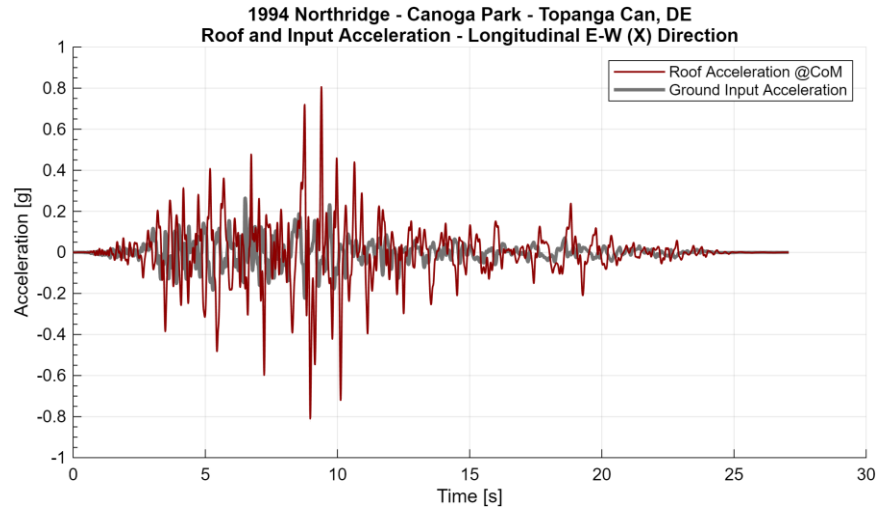


Figure 6. Roof Acceleration Time History at center of mass (CoM) -predicted by the high-fidelity model- and input acceleration in X direction (1994 Northridge - Canoga Park - Topanga Can, DE). Note: the input accelerations used for analyses presented in the current study are achieved input motions during “bare” shake table tests.

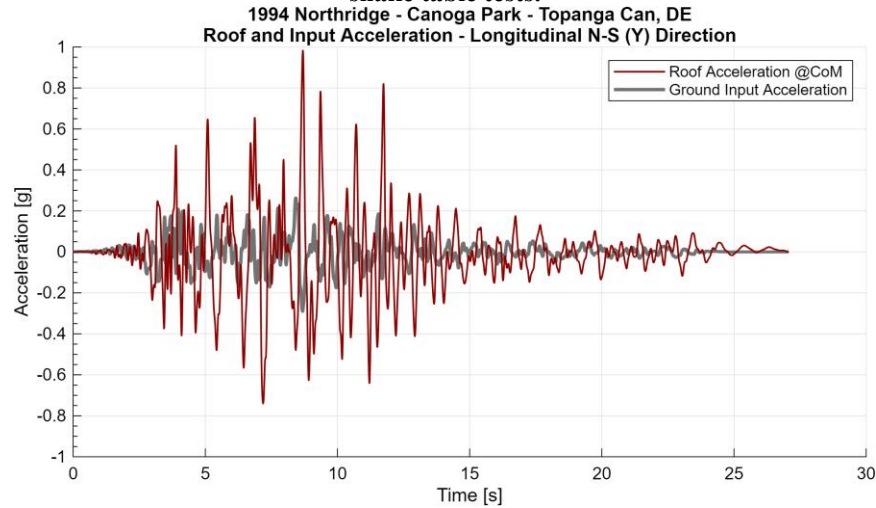


Figure 7. Roof Acceleration Time History at center of mass (CoM) -predicted by the high-fidelity model- and input acceleration in Y direction (1994 Northridge - Canoga Park - Topanga Can, DE). Note: the input accelerations used for analyses presented in the current study are achieved input motions during “bare” shake table tests.

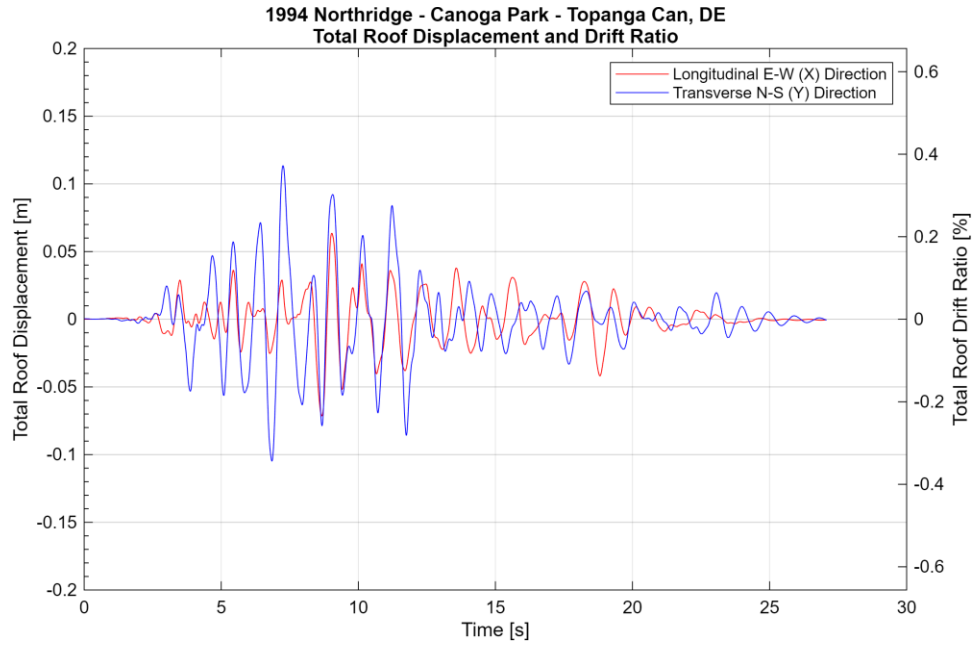


Figure 8. Total Roof Displacement and Drift Ratio Time History (predicted by the high-fidelity model) in both directions (1994 Northridge - Canoga Park - Topanga Can, DE).

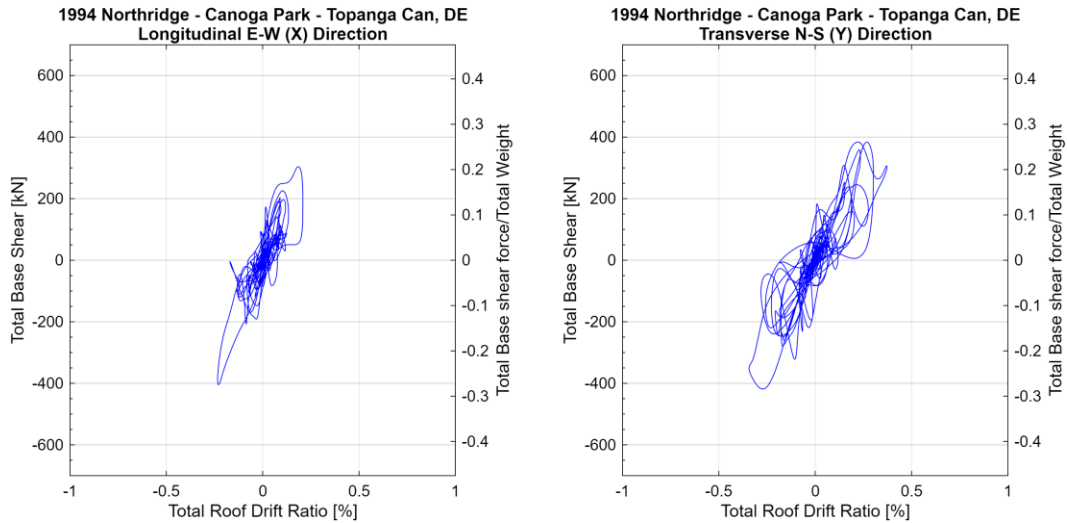


Figure 9. Comparison of Base-Shear vs. Roof Drift Ratio responses predicted by the high-fidelity model in both directions (1994 Northridge - Canoga Park - Topanga Can, DE).

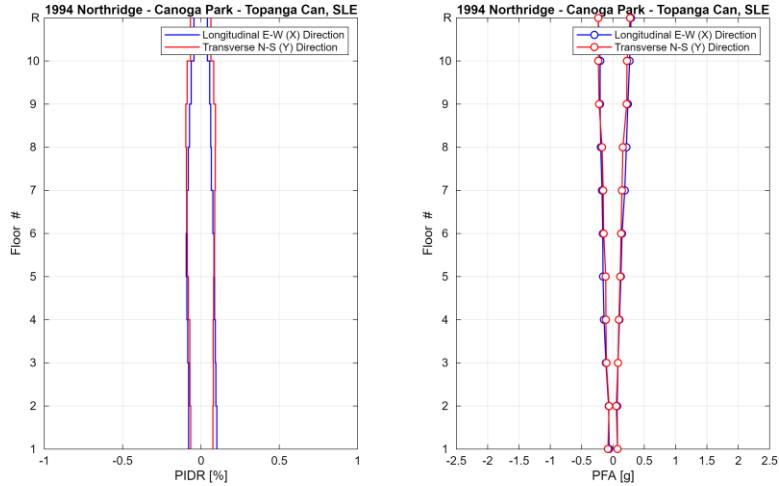


Figure 10. Comparison of Peak Interstory Drift Ratio (PIDR) and Peak Floor Acceleration (PFA) Profiles predicted by the high-fidelity model in both directions (1994 Northridge - Canoga Park - Topanga Can, SLE).

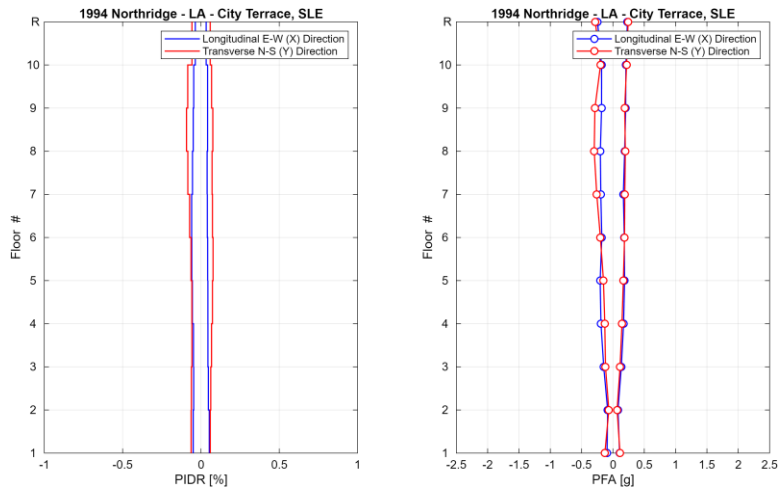


Figure 11. Comparison of Peak Interstory Drift Ratio (PIDR) and Peak Floor Acceleration (PFA) Profiles predicted by the high-fidelity model in both directions (1994 Northridge - LA - City Terrace, SLE).

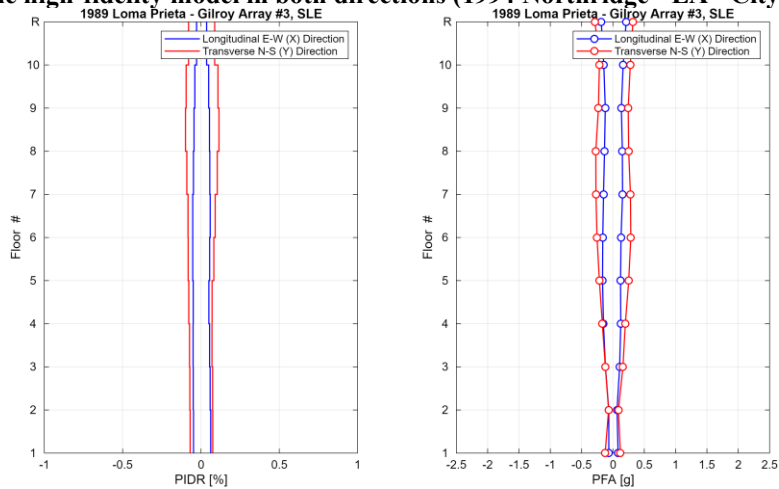


Figure 12. Comparison of Peak Interstory Drift Ratio (PIDR) and Peak Floor Acceleration (PFA) Profiles predicted by the high-fidelity model in both directions (1989 Loma Prieta - Gilroy Array #3, SLE).

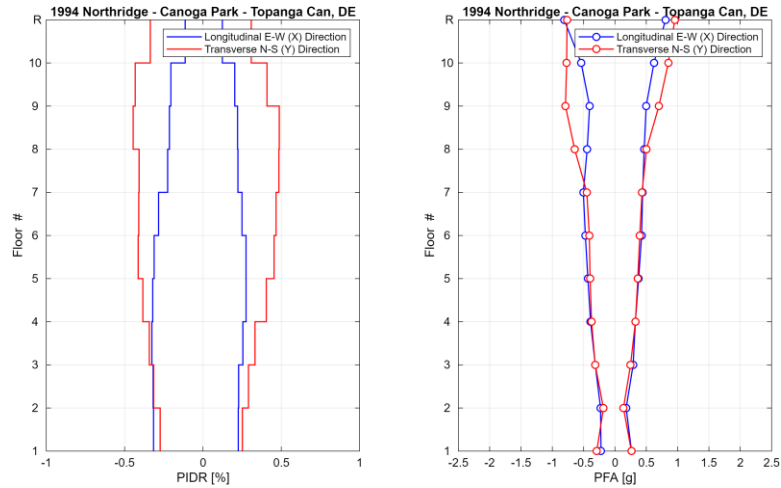


Figure 13. Comparison of Peak Interstory Drift Ratio (PIDR) and Peak Floor Acceleration (PFA) Profiles predicted by the high-fidelity model in both directions (1994 Northridge - Canoga Park - Topanga Can, DE).

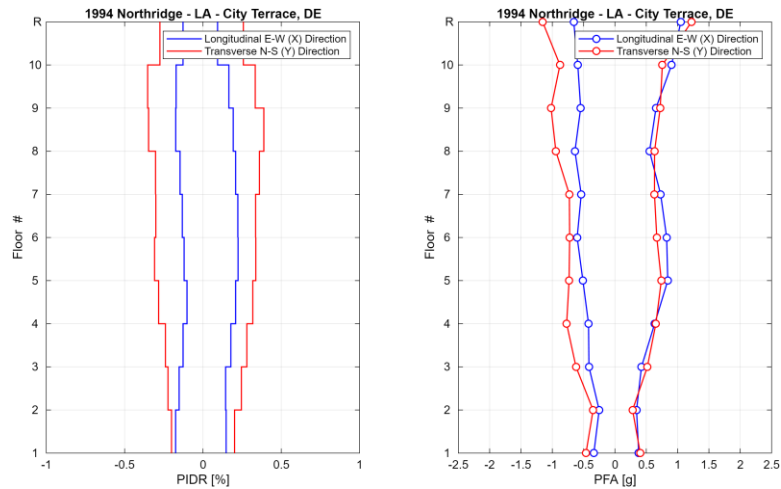


Figure 14. Comparison of Peak Interstory Drift Ratio (PIDR) and Peak Floor Acceleration (PFA) Profiles predicted by the high-fidelity model in both directions (1994 Northridge - LA - City Terrace, DE).

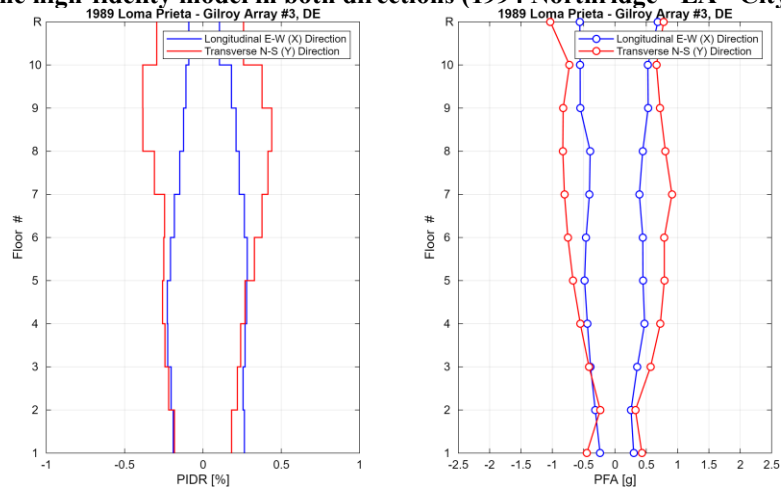


Figure 15. Comparison of Peak Interstory Drift Ratio (PIDR) and Peak Floor Acceleration (PFA) Profiles predicted by the high-fidelity model in both directions (1989 Loma Prieta - Gilroy Array #3, DE).

CONCLUSIONS

This paper presents a high-fidelity numerical model for a 10-story CFS-framed building developed using OpenSeesPy, incorporating detailed representations of structural components and capturing critical nonlinear phenomena including material degradation, cyclic pinching, and different buckling modes. The modeling approach, validated against component-level experimental data, demonstrated good correlation with measured cyclic responses. Pre-test simulations of the CFS10 full-scale test building predicted that the ten-story structure will maintain adequate seismic performance despite exceeding current 19.8 m code height limits. Peak interstory drift ratios remained below 0.2% under SLE-level and approximately 0.5% under DE-level ground motions—well below permanent damage thresholds for CFS systems. While this study focused on pre-test predictions, future correlation with data obtained from the recently completed experimental program for the CFS10 test building will further validate the modeling approach and advance performance-based design methodologies for tall CFS construction.

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REFERENCES

- AISC (2022). "Specification for Structural Steel Buildings, AISC 360-22." American Institute of Steel Construction, Chicago, IL, USA.
- AISI (2015a). "North American Specification for Cold-Formed Steel Structural Framing, AISI S240-15." American Iron and Steel Institute, Washington, D.C., USA.
- AISI (2015b). "North American Specification for Seismic Design of Cold-Formed Steel Structural Systems, AISI S400-15." American Iron and Steel Institute, Washington, D.C., USA.
- AISI (2016). "North American Specification for the Design of Cold-Formed Steel Structural Members, AISI S100-16." American Iron and Steel Institute, Washington, D.C., USA.
- AISI (2017a). "Cold-formed steel design manual." American Iron and Steel Institute (AISI).
- ASCE/SEI (2016). "Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE/SEI 7-16." American Society of Civil Engineers, Reston, VA, USA.
- ASCE/SEI (2017). "Seismic Evaluation and Retrofit of Existing Buildings, ASCE/SEI 41-17." American Society of Civil Engineers, Reston, VA, USA.
- ASCE/SEI (2022). "Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE/SEI 7-22." American Society of Civil Engineers, Reston, VA, USA.
- Brière, V., Rogers, C. A. (2018). "Higher capacity cold-formed steel sheathed and framed shear walls for mid-rise buildings: Part 2 [Research Report]." Dept. of Civil Engineering and Applied Mechanics, McGill University.
- Castaneda, H. (2022). "Seismic performance of cold-formed steel diaphragms." Ph.D. thesis. University of Massachusetts, Amherst, MA, USA.
- Eladly, M. M., Zhang, Z., Singh, A., Zhang, J., Hutchinson, T. C., Schafer, B. W. (2025). "Stability assumptions in numerical modeling of cold-formed steel-framed buildings under seismic loading." Proceedings of the Annual Stability Conference Structural Stability Research Council, Louisville, Kentucky, April 1-4, 2025.
- FEMA (2009). "Quantification of Building Seismic Performance Factors, FEMA P695." Federal Emergency Management Agency, Washington, DC, USA.
- Hutchinson, T. C., Wang, X., Hegemier, G., Kamath, P., Meacham, B. (2021). "Earthquake and post-earthquake fire testing of a midrise cold-formed steel-framed building. I: Building response and physical damage." *Journal of Structural Engineering*, 147(9): 04021125. DOI: [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.00030](https://doi.org/10.1061/(ASCE)ST.1943-541X.00030).

- Hutchinson, T. C., Eladly, M., Ji, R., Rivera, D., Rukundo, F. C., Singh, A., Sorosh, S., Zhang, J., Zhang, X., Padgett, L., Jones, H., Karns, J., Schafer, B. W. (2026). "Advancing use of Cold-formed Steel Framing Systems for Mid-Rise Residential Construction in Seismic Zones via Full-Scale Shake Table Testing." *8th Residential Building Design & Construction Conference*. Pennsylvania Housing Research Center. March 18-19. In review.
- Leng, J., Peterman, K. D., Bian, G., Buonopane, S. G., Schafer, B. W. (2017). "Modeling seismic response of a full-scale cold-formed steel-framed building." *Engineering Structures*, 153: 146-165. DOI: <https://doi.org/10.1016/j.engstruct.2017.10.008>.
- Mazzoni, S., McKenna, F., Scott, M. H., Fenves, G. L. (2006). "OpenSees command language manual." Pacific Earthquake Engineering Research (PEER) Center. (pp. 137–158).
- McKenna, F., Fenves, G. L., Scott, M. H. (2000). "Open System for Earthquake Engineering Simulation." University of California, Berkeley. <http://opensees.berkeley.edu>.
- Peterman, K. D., Stehman, M. J. J., Madsen, R. L., Buonopane, S. G., Nakata, N., Schafer, B. W. (2016). "Experimental seismic response of a full-scale cold-formed steel-framed building. I: System-level response." *Journal of Structural Engineering*, 142(12): 04016127. DOI: [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001577](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001577).
- Rivera, D., Zhang, J., Singh, A., Ji, R., Sorosh, S., Eladly, M., Rukundo, F. C., Rivera, D., Ellis, M., Padgett, L., Jones, H., Karns, J., Stewart, D., Schafer, B. W., Hutchinson, T. C. (2026). "Investigating Construction Methods in a Landmark ten-story Cold-Formed Steel Residential Building Specimen Shake Table Test Program." *8th Residential Building Design & Construction Conference*. Pennsylvania Housing Research Center. March 18-19. In review.
- Rizk, R., Rogers, C. A. (2017). "Higher strength cold-formed steel framed steel shear walls for mid-rise construction." Research Report, Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, Canada.
- Rizk, R., Rogers, C. A. (2018). "Higher strength cold-formed steel framed/steel shear walls for mid-rise construction." Research Report, Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, Canada.
- Santos, V., Rogers, C. A. (2018). "Higher capacity cold-formed steel sheathed and framed shear walls for mid-rise buildings: Part 1 [Research Report]." Dept. of Civil Engineering and Applied Mechanics, McGill University.
- Schafer, B. W., Ayhan, D., Leng, J., Liu, P., Padilla-Llano, D., Peterman, K. D., Stehman, M., Buonopane, S. G., Eatherton, M., Madsen, R., Manley, B., Moen, C. D., Nakata, N., Rogers, C., Yu, C. (2016). "Seismic Response and Engineering of Cold-formed Steel Framed Buildings." *Structures*, 8, 197–212. DOI: <https://doi.org/10.1016/j.jstruc.2016.05.009>.
- Shamim, I., Rogers, C. A. (2012). "Numerical modeling and calibration of CFS framed shear walls under dynamic loading." *Proceedings of the 21st International Specialty Conference on Cold-Formed Steel Structures*, St. Louis, MO, USA.
- Singh, A. (2023). "Seismic Behavior of Cold-Formed Steel-Framed Wall-Line Systems in Mid-Rise Buildings." Doctoral dissertation. University of California San Diego, La Jolla, CA.
- Singh, A., Wang, X., Hutchinson, T. C. (2021). "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 Project Report Rep. No. SSRP-19/05)." Department of Structural Engineering, University of California San Diego.
- Singh, A., Hutchinson, T. C., Torabian, S., Schafer, B. W., Peterman, K. D., Padgett, L., Jones, H. (2022a). "Structural design narrative of the CFS-NHERI ten-story test building for multi-dimensional shake table testing." *Proceedings of the Cold-Formed Steel Research Consortium Colloquium 2022*, Baltimore, MD, USA.
- Singh, A., Hutchinson, T. C., Wang, X., Zhang, Z., Schafer, B. W., Derveni, F., Castaneda, H., Peterman, K. D. (2022b). "Steel Sheet Sheathed Cold-formed Steel Framed In-line Wall Systems. I: Impact of Structural Detailing." *Journal of Structural Engineering*, 148(12): 04022193. DOI: [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0003433](https://doi.org/10.1061/(ASCE)ST.1943-541X.0003433).
- Singh, A., Hutchinson, T. C., Wang, X., Zhang, Z., Schafer, B. W., Derveni, F., Castaneda, H., Peterman, K. D. (2022c). "Steel Sheet Sheathed Cold-Formed Steel Framed In-line Wall Systems. II: Impact of Nonstructural Detailing." *Journal of Structural Engineering*, 148(12): 04022194. DOI: [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0003434](https://doi.org/10.1061/(ASCE)ST.1943-541X.0003434).
- Singh, A., Zhang, J., Eladly, M., Jones, H., Kovac, A., Padgett, L., Rivera, D., Smith, K., Torabian, S., Peterman, K., Schafer, B., Hutchinson, T. (2024a). "CFS-NHERI ten-story Building Shake Table Test Specimen: Design Updates." *Proceedings of the 18th World Conference on Earthquake Engineering (WCEE2024)*, Milan, Italy, June 30–July 5, 2024.
- Singh, A., Zhang, Z., Wang, X., Schafer, B.W., Hutchinson, T.C. (2024b). "Practice-oriented numerical model for seismic response of cold-formed steel-framed mid-rise buildings." *Engineering Structures*, 319: 118833. DOI: <https://doi.org/10.1016/j.engstruct.2024.118833>.

- Torabian, S., Saneei Nia, Z., Schafer, B. W. (2016). "An archetype mid-rise building for novel complete cold-formed steel buildings." Missouri University of Science and Technology.
- Van Den Eijnde, L., Conte, J. P., Restrepo, J. I., Bustamante, R., Halvorson, M., Hutchinson, T. C., Lai, C.-T., Lotfizadeh, K., Luco, J. E., Morrison, M. L., Mosqueda, G., Nemeth, M., Ozcelik, O., Restrepo, S., Rodriguez, A., Shing, P. B., Thoen, B., Tsampras, G. (2021). "NHERI@UC San Diego 6-DOF large high-performance outdoor shake table facility." *Frontiers in Built Environment*, 6. DOI: <https://doi.org/10.3389/fbuil.2020.580333>.
- Zhang, J., Singh, A., Eladly, M., Schafer, B. W., Hutchinson, T. C. (2024). "Pre-Test Numerical Modeling of the CFS-NHERI ten-story Capstone Building." *Proceedings of the 18th World Conference on Earthquake Engineering (WCEE2024)*, Milan, Italy, June 30–July 5, 2024.
- Zhang, Z., Singh, A., Dervani, F., Torabian, S., Peterman, K. D., Hutchinson, T. C., Schafer, B. W. (2021). "Cyclic experiments on isolated steel sheet connections for CFS framed steel sheet sheathed shear walls with new configurations." *Engineering Structures*, 244: 112805. DOI: <https://doi.org/10.1016/j.engstruct.2021.112805>.
- Zhang, Z., Singh, A., Dervani, F., Torabian, S., Peterman, K. D., Hutchinson, T. C., Schafer, B. W. (2022b). "Cyclic experiments on steel sheet connections for standard CFS framed steel sheet sheathed shear walls." *Journal of Structural Engineering*, 148(2): 04021261. DOI: [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.000323](https://doi.org/10.1061/(ASCE)ST.1943-541X.000323).
- Zhang, Z., Speicher, M. S., Singh, A., Hutchinson, T. C., Schafer, B. W. (2022c). "Effects of Modeling Decisions on the Lateral Performance of Cold-Formed Steel Framed Walls." *Proceedings of the Cold-Formed Steel Research Consortium Colloquium 2022*, Baltimore, MD, USA.
- Zhang, Z. (2023). "Simulation and Performance of Steel Sheet Sheathed Shear Walls in CFS-Framed Building Systems." Doctoral dissertation. Johns Hopkins University, Baltimore, MD, USA.
- Zhang, Z., Eladly, M. M., Rogers, C. A., Schafer, B. W. (2024). "Cold-formed steel framed shear wall test database." *Earthquake Spectra*, 40(1), 871-884. RetryClaude can make mistakes. Please double-check responses.
- Zhang, Z., Singh, A., Speicher, M. S., Peterman, K. D., Hutchinson, T. C., Schafer, B. W. (2025). "Modeling cold-formed steel framed wall-lines with steel sheet sheathed shear walls." *Thin-Walled Structures*, 113408.
- Zhang, J. et al. (2026). Full-scale 10-story cold-formed steel building shake table test: protocol development and shake table performance. 13th National Conference on Earthquake Engineering. Portland, OR. July 13-17. In preparation.
- Zhu, M., McKenna, F., Scott, M. H. (2018). "OpenSeesPy: Python library for the OpenSees finite element framework." *Software X*, 7: 6-11. DOI: <https://doi.org/10.1016/j.softx.2017.10.009>.