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Tracking Multiple-Mode Frequency Changes in a 10-Story Cold-Formed Steel Building to Assess Damage

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ABSTRACT

We report frequency-domain observations from a full-scale, 10-story, cold-formed steel building tested on the 6-degrees-of-freedom Large High-Performance Outdoor Shake Table at UC San Diego where 76 triaxial Community Seismic Network accelerometers recorded continuous waveforms prior to, during, and after increasing-intensity earthquake tests. Spectrograms of the continuous ambient data reveal persistent, elevation-dependent bands of high energy at both fundamental and higher building modes. During a representative earthquake input (*MID*16, 1989 M_W 6.9 Loma Prieta motion scaled at Design Earthquake level), the data from a sensor at Level 7, for example, shows that the fundamental mode frequencies decrease at the onset by ~0.60 Hz (X direction, EW) and ~0.55 Hz (Y direction, NS), and recover within ~50 s to final residual reductions of about 0.1 Hz. The third mode shows a larger permanent decrease (~0.2 Hz). These results are consistent with transient softening and frictional slip during the test followed by small but measurable residual stiffness changes afterward. Stiffness loss is confirmed by observed physical damage, most notably rotation and pull-through of fasteners attaching gypsum sheathing to CFS-framing.

Introduction

A capstone 10-story, cold-formed steel building (CFS10) was constructed and tested at the Large High-Performance Outdoor Shake Table at UC San Diego during summer 2025 [1, 2]. This unique building specimen was designed beyond current code height limits [3], with advances in steel sheathed shearwalls and heavy chord stud details (Fig. 1a). Cold-formed steel construction is lower-cost because of the lighter-weight materials, construction methods, and design. The test program included two phases: seismic testing with increasing-intensity, multi-directional earthquake excitations, and two internal live fire compartment tests. Seismic data recorded continuously on 76 triaxial Community Seismic Network (CSN) [4] accelerometer sensors prior to, during, and after both test phases, provide the potential to characterize the evolution of dynamic properties of a full-scale building both under local seismic demands as well as during ambient vibration periods. The goal of the overall project is to improve seismic provisions in building codes and seismic design practices by correlating physical damage with measured response of the building's dynamic properties.

The data used in this study are from the 76 triaxial CSN accelerometers deployed in partnership with the California Geological Survey (CGS) through the California Strong Motion Instrumentation Program (CSMIP).

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The CSN sensors were deployed on all building levels in the corners of the floor diaphragms, in the midlandings of stair systems, and on some balconies and non-structural component systems, for a total of 228 channels (Fig. 1b). Hereafter, we denote east–west and north–south directions as X and Y, respectively.

Here we present results using the continuous accelerometer data to quantify high-spatial-resolution frequency domain response of the building specimen before, during, and after one of the larger-amplitude shakes, namely a multi-directional (XY) DE-level-scaled Loma Prieta earthquake (*MID*16) that was input to the shake table on June 23, 2025 [5]. Analysis of several long segments of continuous ambient vibration data recorded by the CSN sensors during the full testing period shows clear signals of ongoing environmental and anthropogenic noise sources in and around the structural specimen, which allow measurement of resonant frequencies long before and after each shake test.

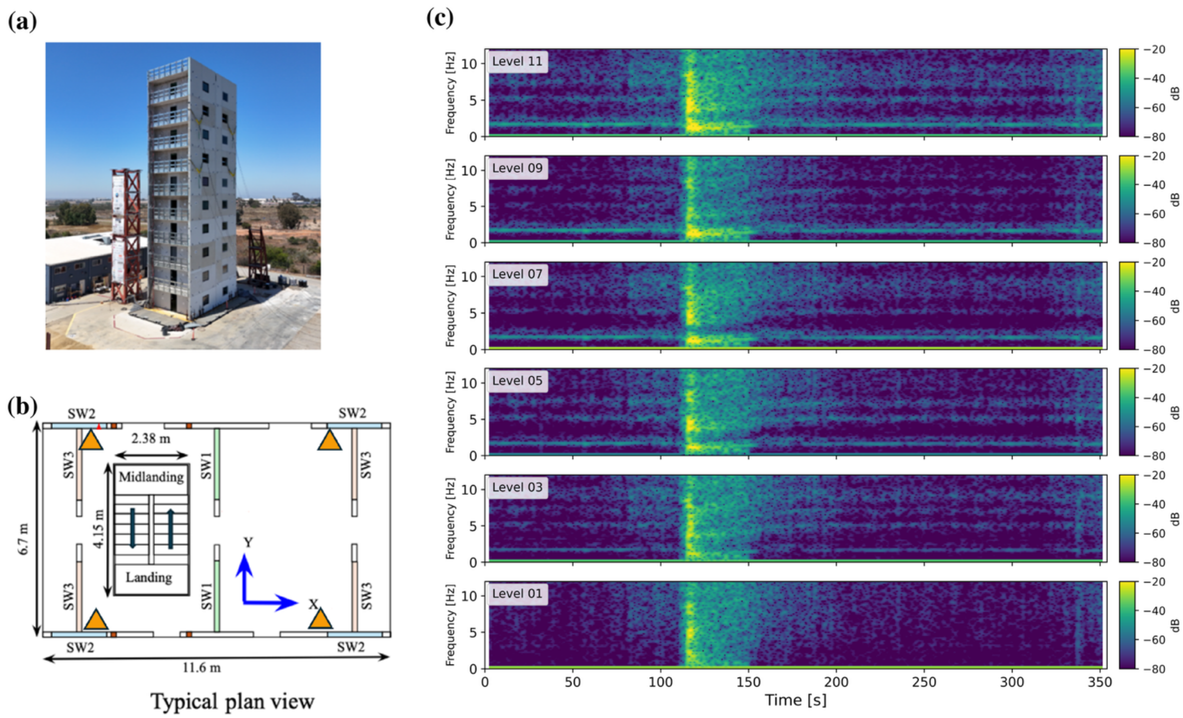

Figure 1. (a) The specimen and shake table. (b) An example of the specimen plan view where CSN sensors are annotated as orange triangles. (c) Y-direction spectrograms from six CSN sensors on every other level at the time of the DE-scaled test *MID*16 [1].

Methods

The continuous acceleration records were detrended and tapered prior to computing short-time Fourier transform spectrograms [6]. To obtain a single frequency estimate per time bin for each mode, we fit a Gaussian distribution to the spectral amplitude within narrow, pre-specified bands (Y-axis ranges in Fig. 2) and use the fitted mean as the modal pick for that bin. The resulting time-dependent modal frequencies are summarized by a two-segment analytical model that mirrors the visual behavior (white dashed lines in Fig. 2). An instantaneous step at the known test onset time captures the abrupt drop, and a normalized logistic function with a common S-shaped curve [7] captures the recovery on a finite interval, ending at the time when strong shaking subsides.

Results

Spectrograms derived from the continuous waveforms reveal stable, persistent bands aligned with the fundamental and higher modes in both the translational and torsional responses. Fig. 1c shows continuous spectrograms from the 10-story building specimen subjected to the DE-scaled test *MID*16 [1]. In the ambient intervals, narrow, nearly-stationary peaks are present at the fundamental and several higher modes on all floors, indicating persistent modal excitation from ongoing human activity inside the building. These energy concentrations enable the modes to be tracked well before and after each test to identify permanent change. The visibility of these peaks is not uniform with elevation, due to mode shape deflections; the fundamental tends to be most coherent at the upper stories and becomes harder to distinguish toward the base, whereas some higher-frequency bands are most recognizable on intermediate floors. Across the building, however, the modal pattern is robust and spatially consistent, providing a stable baseline against which test-induced changes can be assessed.

When the shake commences, the spectrograms show a brief, broadband burst of energy that rides atop the modal pattern, and all tracked bands exhibit an abrupt downward shift in frequency that is clearly visible in Fig. 1c. Following the event, the frequencies gradually recover and, within roughly 50 s, approach new steady-state values that are slightly lower than their pre-shaking levels for this test. This indicates that the shake test causes instantaneous slip along structure interfaces (in wall panels, fasteners, etc.) and, potentially, damage. Most of the slip surfaces may self-heal or revert to rigid-body behavior, while the slight but permanent change of modal frequency suggests that this recovery is incomplete and permanent fractures or element disengagement or detachments are generated. This behavior is most evident at the fundamental mode where the modal energy is strongest. The higher modes display the same pattern but with reduced coherence, making the transition less visually distinct even though the instantaneous shaking effect can be larger (seen in Fig. 1c). Taken together, the observations are consistent with a transient reduction in effective stiffness during strong motion and a small, persistent, permanent change afterward that is more pronounced at higher modes.

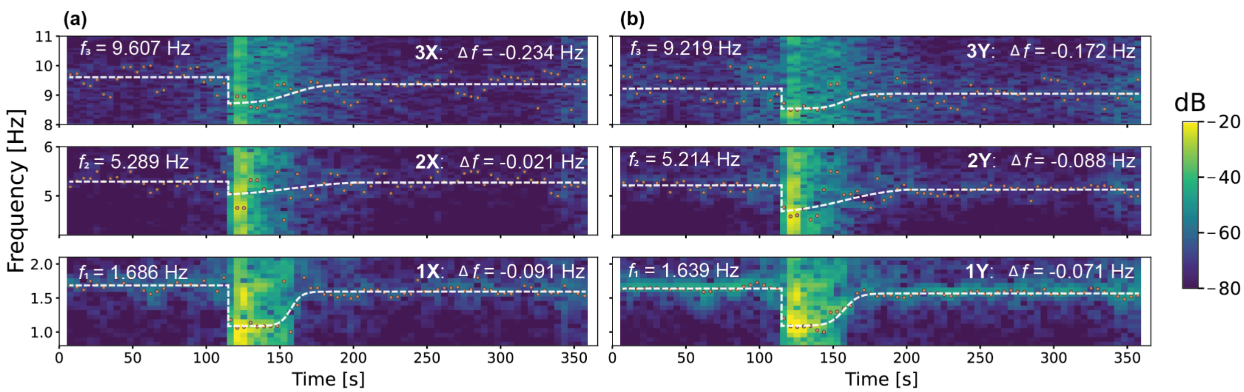

Figure 2. Zoom-in of Fig. 1 at Level 7 to show measurements of frequency drift.

For the fundamental mode, the instantaneous drop is approximately 0.60 Hz in the X direction and 0.55 Hz in the Y direction, after which the frequency recovers toward a value about 0.1 Hz below the pre-event level. The second mode exhibits similar permanent residual change, less than 0.1 Hz. In contrast, the third mode shows a larger residual of about 0.2 Hz, even though its energy peak is broader and its picks are less certain because of lower spectral energy. These differences across modes are consistent with the expectation that higher-order mode shapes, with greater curvature and different damping, are both more weakly excited under ambient conditions and more sensitive to localized changes in stiffness.

Strong shaking induces a transient reduction in effective stiffness, followed by rapid recovery of stiffness as relative motions decay. The immediate drop reflects the onset of these mechanisms under large deformation while the rapid recovery reflects re-clamping and contact re-establishment as the motion decays. The small but measurable residual suggests minor, distributed changes in stiffness that persist after the event. The larger residual seen in the third mode is compatible with its higher associated curvature and damping, which increase in sensitivity to local changes and dissipative processes. Importantly, the residuals are small in absolute terms, indicating that despite measurable effects, the structure's dominant modal behavior remains largely intact after this event. It is notable that the largest peak interstory drift ratio (PIDR) observed during *MID*16 was at the northwest corner on Level 8 in the X direction, at 0.6%. PIDRs in the Y direction were all within 0.4%, a range indicative of the quasi-linear behavior of the steel sheathed shearwalls providing lateral force resistance within the building. It should be mentioned, however, that moderate damage to sheathing finish was observable post-*MID*16 test inspection. Most notable observations included damage to fasteners at the perimeter of the gypsum sheathing, manifesting in the form of rotation and pull-through, see Fig. 3. Additional damage modes observed following this design-level earthquake test included perimeter crushing at wall intersections (Fig. 3 right) and permanent offset of gypsum board, particularly at locations where the gypsum was installed over structural steel sheathing (i.e. at the interface between shearwalls and gravity walls). These damage patterns are consistent with the moderate permanent frequency reduction observed in the spectrograms.

Figure 3. Damage documented post-*MID*16, along wall line D at Level 8.

Conclusions

Continuous, floor-by-floor spectrograms of a 10-story building specimen reveal persistent modal peaks under ambient conditions and an evolution during a shake test in which all tracked modes undergo an abrupt frequency drop followed by a short-timescale recovery to a slightly reduced long-term plateau. Mode-resolved quantification at a representative seismic station (Level 7) shows that the fundamental mode frequencies have a temporary drop to approximately 0.60 Hz in the X component and 0.55 Hz in the Y component, recover after ~50 s, and stabilize ~0.1 Hz below their pre-event values. The third mode exhibits a larger residual of about 0.2 Hz, consistent with higher curvature, damping, and sensitivity to localized changes. These observations point to transient softening during strong motion due to motions on new or pre-existing contact surfaces or cracks, rapid rejoining of interfaces in rigid-body motion as relative motions decay, and small but measurable residual stiffness changes thereafter. The combination of spectrogram visualization and an analytical function recovery model provides an interpretable and reproducible summary of the pre-test level, instantaneous drop, recovery timescale, and post-test level. The results indicate that the building's dominant dynamic characteristics are resilient for this test. They are briefly perturbed by shaking yet re-establish an elevation-dependent pattern within minutes, while preserving quantitative signatures of both transient and residual effects that can support cross-mode, cross-floor, and cross-test comparison and operational structural health monitoring.

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References

1. Hutchinson TC, Eladly M, Ji R, Rivera D, Rukundo FC, Singh A, Sorosh S, Zhang J, Zhang X, Padgett L, Jones H, Karns J, Schafer BW. Advancing use of cold-formed steel framing systems for mid-rise residential construction in seismic zones via full-scale shake table testing. Proceedings of the 8th Residential Building Design & Construction Conference, State College, PA. 2026.

2. Hutchinson TC, Zhang J, Sorosh S, Ji R, Rivera D, Zhang X, Singh A, Cyizere Rukundo F, Eladly MM, Jones H, Karns J, Padgett L, Emberley R, Gernay T, Meacham B, Schafer BW. Overview of the CFS10 Program: Full-scale Shake Table (Earthquake and Fire) Testing of a 10-Story Cold-Formed Steel Building. Proceedings of Structures Congress 2026, Boston, MA. 2026.

3. ASCE. Minimum design loads and associated criteria for buildings and other structures. Standard ASCE/SEI 7-22. Reston, VA: Structural Engineering Institute of the American Society of Civil Engineers; 2022.

4. Kohler MD et al. The Community Seismic Network for dense, continuous monitoring of ground and structural strong motion. SMIP Seminar on Utilization of Strong Motion Data, Seminar Proceedings. 2021.

5. Zhang J, Sorosh S, Ji R, Lotfizadeh KH, Schafer BW, Hutchinson TC. Full-scale 10-story cold-formed steel building shake table test: Protocol development and shake table performance. Proceedings of the 13th National Conference on Earthquake Engineering, Earthquake Engineering Research Institute, Portland, OR. 2026.

6. Clinton JF, Bradford SC, Heaton TH, Favela J. The observed wander of the natural frequencies in a structure. *Bulletin of the Seismological Society of America* 2006; 96 (1): 237–257.

7. Berkson J. Application of the logistic function to bio-assay. *Journal of the American Statistical Association* 1944; 39 (227): 357–365.