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Resilience Through **Community Engagement** and **Technology**

Performance of Continuous Tie-Rod Systems within a 10-Story Cold-Formed Steel Shake Table Tested Building

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ABSTRACT

A full-scale 10-story cold-formed steel (CFS) framed building, coined CFS10, was tested in the summer of 2025 at UC San Diego's 6-degree-of-freedom Large High-Performance Outdoor Shake Table. A total of 18 earthquake excitations with increasing targeted hazard levels were applied during the seismic test program. Continuous tie-rod systems that create a load-path to resist uplift and overturning were employed at the ends of steel sheet sheathed CFS-framed shear walls in one primary direction (N-S) of the lateral force resisting system. This paper summarizes the overall performance of these systems and investigates an all-thread rod (ATR) detachment that occurred during the final seismic excitation.

Introduction

Tie-down systems, consisting of continuous rods with couplers and bearing plates, are widely used in multi-story timber and cold-formed steel (CFS)-framed buildings to create a continuous hold-down load path to resist uplift and overturning loads [1]. An alternative to the continuous tie-rod system, the conventional hold-down, which consists of a steel body and its connection through fasteners, bolts or welds to shear wall chord stud members is also widely used. Both assemblies were employed in a full-scale 10-story CFS framed building, referred to as CFS10, which was tested atop the 6-degree-of-freedom Large High-Performance Outdoor Shake Table (LHPOST6) [2] at NHERI@UC San Diego.

CFS10 Capstone Building

The landmark CFS10 building specimen was designed above-code height limits with 10-stories and a total height of 30.5 m and a floor plan measuring 6.86 m × 11.58 m. The primary goal of this test program was to evaluate the seismic performance of a tall CFS building with steel-sheet-sheathed shear walls exceeding the ASCE 7-22 [3] height limit of 19.8 m, or 6 stories. A total of 18 multi-directional earthquake ground motions, scaled to increasing hazard levels [4], were applied to the specimen. A detailed discussion on the seismic performance of the building is provided in Hutchinson et al. [5,6]. A summary of the design details of the

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structural system of this building is provided in Singh et al. [7]. In addition, this building was outfitted with various nonstructural components and systems, including a resilient stair system [8,9], a fire riser and sprinkler system, suspended ceiling [10], gas piping system, windows, and rooftop equipment [11].

Design of Continuous Tie-Rod Systems

When designing continuous tie-rod systems for CFS shear walls, AISI S400-200 [12] requires these elements to be designed as capacity protected components, as they are not part of the designated energy dissipating system, which is the sheathing and fasteners for a CFS steel sheet shear wall. Therefore, they need to be designed to resist amplified seismic loads including overstrength (i.e. Ω_o). In contrast, ASCE 7-22 [3] exempts wood light-frame shear walls from the requirement of resisting amplified seismic loads for the same tie-rod systems. As a result, a combination of larger diameter rods and higher yield strength steel materials are needed to resist the larger seismic demands at the lower levels of a CFS-framed building. Fig. 1 presents an illustrative elevation view of the continuous tie-rod systems used in the CFS10 building, where increasing all-thread rod (ATR) diameter and grade were detailed with decreasing building height. The CFS10 building was constructed using a combination of panelized and modular construction [13], wherein the tie-rods had to be aligned and then connected with a coupler at each story level as indicated in Fig. 1.

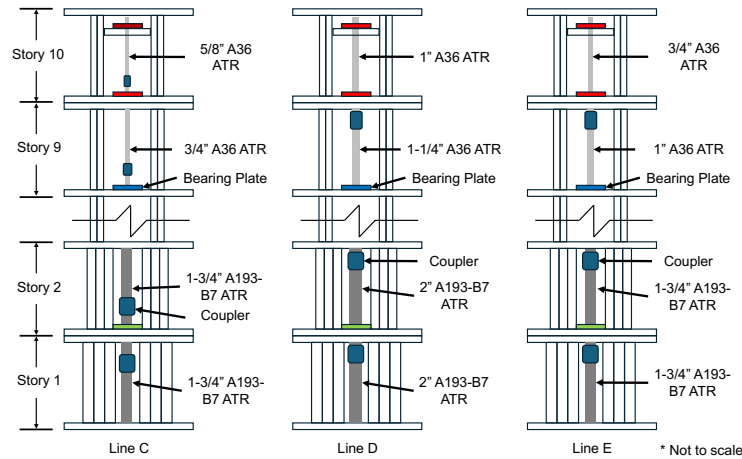


Figure 1. Schematic elevation view of the variation of continuous tie-rod systems for shear wall lines within the CFS10 building (for illustration purposes only, not to scale).

Performance of Continuous Tie-Rod Systems in the Past Large-Scale System-Level Experiments

Continuous tie-rod systems have shown robust performance in past large-scale system-level experiments for both wood [14] and CFS [15] shear walls. Van de Lindt et al. [14] was amongst the earliest to test a continuous tie-down system in a multi-story configuration, with the execution of the NEESWood full-scale six-story light-frame wood building program at E-Defense. This building performed well with maximum interstory drifts around 2%. The high maximum measured uplift force indicated a need for a high strength tie-down system for MCE-level earthquakes. Rods in wood shear walls might yield at DE or MCE_R levels, while the yielding of rods in CFS shear walls is not expected since CFS shear walls are designed for overstrength. Hutchinson et al. [15] tested a full-scale six-story CFS-framed building with continuous tie-rods sandwiched between compression stud packs at NEES@UC San Diego as part of the CFS-HUD program. The largest peak interstory drift in this program was about 1.5% during a pre-fire MCE-scaled motion. A single coupler detachment was observed during the later phase of the program, however, it should be noted that the coupler was not in the primary lateral force-resisting system, and the high level of redundancy in distributed continuous tie-rods resulted in stable global performance and load redistribution.

Overall Performance of All-Thread Rods

Selected ATRs in the N–S shaking direction were instrumented with uniaxial strain gauges to capture transient strain amplitudes. A sample of the measured strain histories during MID18 (Cape Mendocino Earthquake Rio

Dell Overpass recording scaled to Risk-Targeted Maximum Considered Earthquake (MCE_R), the second MCE_R -scaled and final motion in the seismic test program) is shown in Fig. 2. A pronounced difference was observed between ATRs. For instance, the ATR at Level 1 (SF01-01Z) exhibited a peak strain of approximately 20% of the yield strain, while the ATR at Level 10 (SF10-01Z) maintained strains below 2% of the yield strain. A synthesis of maximum strain amplitudes across all 18 motions is presented in Fig. 2b. The maximum measured strains remained below 20% yield strains of individual rods, demonstrating an anticipated and satisfactory outcome for capacity-protected elements.

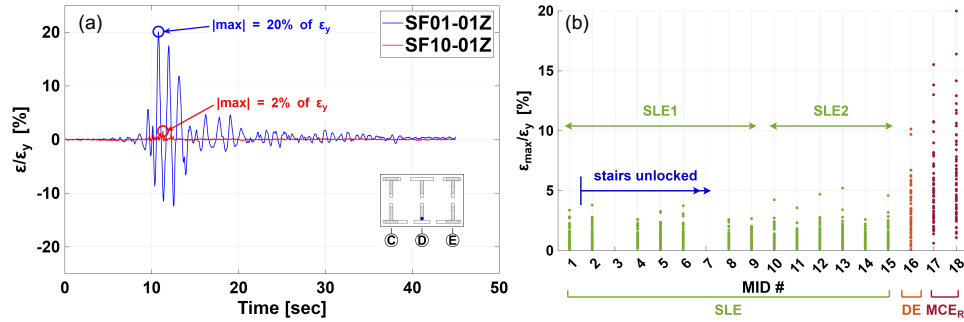


Figure 2. Measured strain in tie-rods at the end of shear walls: (a) time history during MID18, and (b) synthesis of all maximum (transient) strain measured across all tests, normalized by individual tie-rod yield strain.

Performance of ATR under Final MCE_R -Scaled Test

During MID18, the ATR in the northwest corner of the building observed detachment at the first level, see Fig. 3. Notably, this detachment can be identified by observing acceleration and interstory drift ratio time histories attained near this location, see Fig. 4. As shown in Figs. 4b and 4c, the detachment is determined to have occurred at approximately 6.16 s into the strong duration of the input motion. It is noted that the ATR which incurred detachment was not instrumented with strain gauges. Since the nuts were spot-welded to couplers, a nearby camera offered audio evidence of the fractured weld coinciding with this approximate time. It should be noted that nuts and spot welds were present solely for experimental purposes, as an additional measure aimed at ensuring continued attachment during repeated low amplitude white noise and multiple earthquake tests. They do not reflect typical design and construction practice. The interstory drift reached a negative peak, i.e. the upper floor was moving towards south, subjecting the northmost ATR along this wall line to high tensile force, see Fig. 3c. The detachment of the ATR resulted in a sudden energy release, resulting in large Z-direction pulses observed both through the shake table controller and platen accelerometers (Fig. 4b) as well as through the distributed pulses captured by sensors located at upper floors (Fig. 4d). It is noted that vertical accelerations were not input for this test (rather it was a bi-axial XY input motion); and as such, the center of mass did not realize similar pulse-like vertical accelerations. Figs. 3a and 3b show the approximate 25.4 mm (1 in.) uplift observed consistently throughout the entire height along that continuous tie-rod. Threads along the detached region of the ATR at L1 were visibly stretched and marred with surface damage at the location of immediate detachment with the coupler.

When installed properly, the minimum engaged length for a 44.5 mm (1-3/4 in.) diameter B7 [16] ATR is 38.1 mm (1-1/2 in.). Post- MCE_R forensics revealed that about 3-4 threads failed and only a fraction of the intended length was fully engaged, see Fig. 3a, indicating a likely inadequate installation during construction. It should be noted that this detachment is not a rod fracture and failure via detachment at the coupler is the anticipated failure mode when designing such systems. According to AISI S400-20 [12], end-posts, hold-downs and connections must be designed as capacity-protected components, requiring design demands for these elements to be amplified by the system overstrength factor (Ω_o). The reduced thread engagement significantly offset the required overstrength amplification. These observations suggest that these details need greater attention during design and quality control during construction inspection.

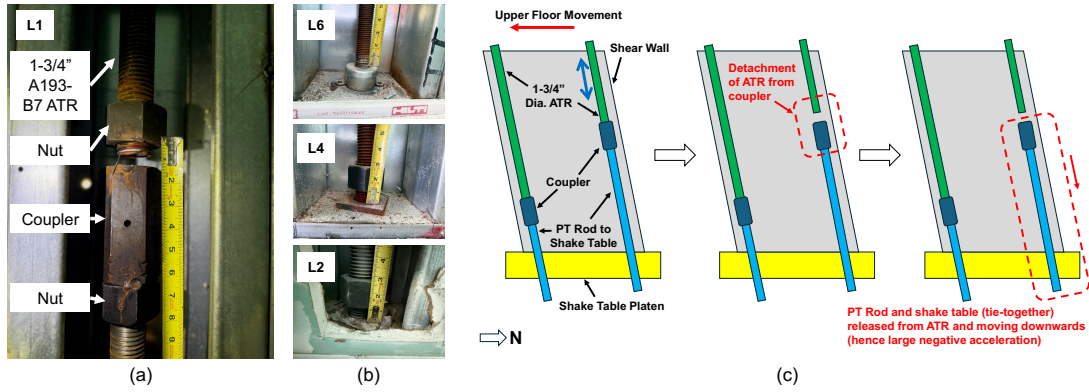


Figure 3. Post-test observed (a) ATR detachment from coupler at Level 1 (L1), and (b) approximately 2.5 cm (1 in.) uplift consistently along the height, and (c) a cartoon explaining the instance when detachment occurred.

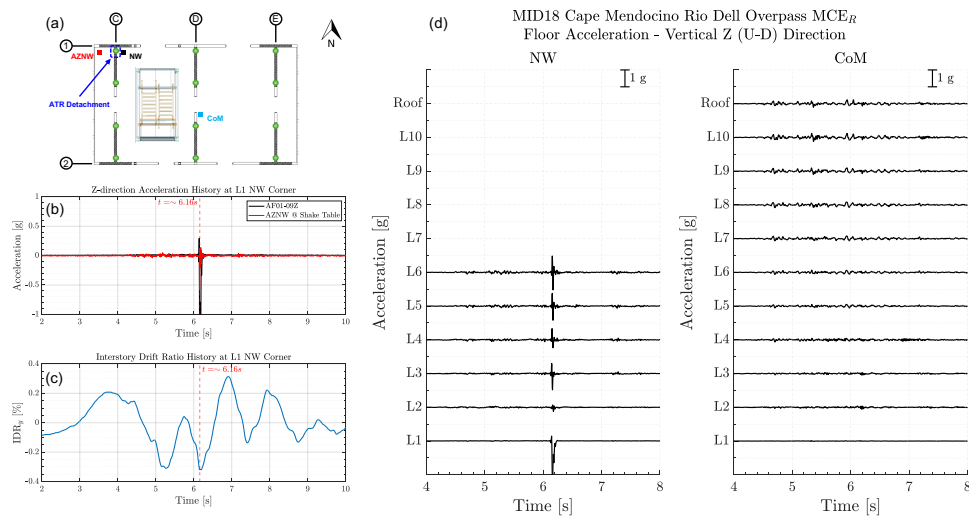


Figure 4. (a) Plan view of sensors with detached ATR boxed; (b) Z-direction acceleration time history at L1 northwest corner; (c) Z-direction interstory drift ratio history at L1 northwest corner; and (d) Z-direction floor acceleration histories with sudden impulses along the entire elevation at north-west (NW) corner and center of mass (CoM).

Concluding Remarks

This paper summarizes the overall performance of the continuous tie-rod systems in a full-scale 10-story CFS building with steel-sheet-sheathed shear walls under seismic loading. In general, the tie-rod systems deliver satisfactory performance, with peak measured strains at approximately 20% of the yield strains, which is anticipated for elements designed as capacity-protected components. However, during the final motion of the seismic test program, one ATR detachment from its coupler was observed, likely due to inadequate installation during construction. Post-test forensics indicated that only about 40% or less of the expected threads were likely engaged at the detachment location, which significantly offset the overstrength factor required by design for these components.

Acknowledgments

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