Title

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Resilience Through Community Engagement and Technology

Full-Scale 10-Story Cold-Formed Steel Building Shake Table Test: Protocol Development and Shake Table Performance

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ABSTRACT

As a capstone to the CFS-NHERI project, a full-scale 10-story cold-formed steel building, coined CFS10, was tested in the summer of 2025 at the 6-degree-of-freedom Large High-Performance Outdoor Shake Table (LHPOST6) at the University of California San Diego. A total of 18 earthquake motions, scaled to increasing hazard levels, were applied during the seismic test program. This paper describes the development of the test protocol for this unique capstone program: from the motion iteration phase, i.e. prior to building construction, to the execution of the protocol in the testing phase, concluding with an evaluation of the shake table performance towards achieving the target demands.

Introduction

Large-scale shake table tests often require sophisticated planning and coordination between the testing facility and research team. Often testing facilities have specific procedures and steps to be implemented even prior to the construction of test specimens. This paper documents the test protocol development of a full-scale 10-story cold-formed steel (CFS) framed building, referred to as CFS10, which was tested atop the 6-degree-of-freedom Large High-Performance Outdoor Shake Table (LHPOST6) [1] 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 × 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 [2] height limit of 19.8 m, or 6-stories. A total of 18 multi-directional earthquake ground motions, scaled to increasing hazard levels, were applied to the specimen. A detailed discussion on the seismic performance of the building is provided in Hutchinson et al. [3,4]. A summary of the design details of the structural system of this building is provided in Singh et al. [5]. In addition, this building was outfitted with various nonstructural components and systems, including a resilient stair system [6,7], a fire riser and sprinkler system, suspended ceiling [8], gas piping system, windows, and rooftop equipment [9].

Candidate Motions

A suite of candidate motions was developed first with consideration of the same soil condition and seismic setting as the building design basis, as well as subduction zone and near-field records to incorporate features such as long duration and pulse-like characteristics, which included four subsets [10]: (a) a "historical" suite with motions successfully utilized in past large-scale shake table tests, such as the 2-story CFS-NEES [11] and 6-story CFS-HUD [12] projects, (b) the FEMA P695 Far-Field set [13], (c) a site-specific motion suite provided courtesy of a practicing engineering team, and (d) subset from the 2023 Türkiye-Syria Earthquake Sequence.

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Test Protocol Development

Fig. 1 presents a flow chart illustrating the development of the test protocol procedure for the CFS10 program. A detailed description of this procedure is provided in the subsequent sections.

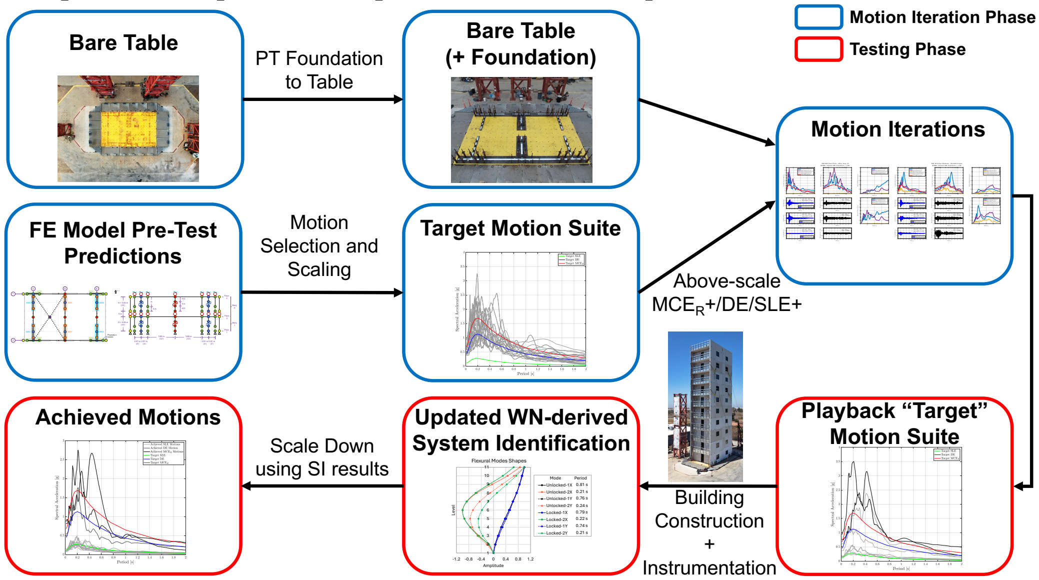

Figure 1. Flow chart adopted for the development of the CFS10 seismic test protocol.

Motion Iteration Phase

Utilizing a phenomenological, practice-oriented numerical model [14], which was developed and validated with prior CFS full-scale building shake table tests [12,15], motions from the candidate suites were scaled based on eigenvalue vibration analysis. These motions were initially scaled over the range of periods of interest, $[0.2 \cdot \min(T_{x1}, T_{y1}), 2 \cdot \max(T_{x1}, T_{y1})]$, to three hazard levels: Service-Level Earthquake (SLE), Design-Level Earthquake (DE), and risk-targeted Maximum Considered Earthquake (MCE_R), as prescribed in ASCE 7-22 [2]. Subsequently, select motions were scaled to typically 30% above these targets to provide flexibility during the testing phase, since for stability and safety of the control system, the LHPOST6 facility can only comfortably accommodate playback of actual test motions that are scaled down. These above-scale ground motion records were then iterated with the bare table condition, with the complete foundation installed, namely a hot-rolled steel transfer plate post-tensioned to the shake table and bottom CFS track, within a two-week duration, which was intended to achieve optimal transfer functions for shake table control system. In total, 33 ground motions were successfully iterated, including 13 that were scaled at or above MCE_R levels.

Testing Phase

Amongst the available candidate motions, the 1989 Loma Prieta (Gilroy Array #3) recording was selected as the carry-through motion for the testing program, as predictions from the numerical model indicated satisfactory global responses under the MCE_R-scaled excitation and stable damage accumulation under the SLE-DE-MCE_R sequential excitation scenario. The Loma Prieta Gilroy Array #3 recording is representative of a California shallow crustal earthquake and is present in both the FEMA P695 Far-Field set and the site-specific ground motion suite. In addition, the Northridge LA City Terrace and Cape Mendocino Rio Dell Overpass recordings were selected to investigate directional effects by swapping the two translational components and to assess the building responses under uni-directional versus multi-directional excitations. In addition, motions with nominally shorter significant durations (indicative of seismological settings present on the West Coast of the US), longer-duration motions from the 2023 Türkiye-Syria Sequence and the 2010 Maule Chile earthquake were also incorporated to examine the building's response considering non-California crustal events. It is worth noting that the building was initially tested in a "stairs locked" configuration, with bolts restricting the movement of the stair mid-landing connections and subsequently tested in a "stairs unlocked" configuration with these bolts removed for the remainder [7]. Low-amplitude white noise (WN) tests were conducted between select motions to characterize the evolution of the buildings' dynamic characteristics. Motion scale factors were only updated based on WN-derived system identification results (WN before 1st seismic excitation) to reflect the actual fundamental periods of the building in its "virgin" state. No additional updates to the scale factors were applied, even though the building periods increased as damage accumulated.

Table 1 presents the final testing protocol that was executed for the seismic testing phase of the CFS10 program. It is worth noting that MID11 was targeted to 75% SLE because the displacement prediction of the shake table was unchanged with the original scaling factor out of precaution. MID18 was initially targeted to 90% MCE_R as a precaution against the predicted displacement overshooting from the shake table, although the achieved motion was later estimated as 109% MCE_R.

Table 1. Seismic test protocol.

Hazard level	MID	Earthquake event				Input DOF	Components			$D_{5\text{-}95}$ [sec]
		Name, location	Year	M_w	Station		X	Y	Z	
SLE	1	Loma Prieta, California	1989	6.9	Gilroy Array #3	XYZ	G03090	G03000	G03-UP	11.4
	2					XYZ	G03090	G03000	G03-UP	11.4
	3					X	G03090	-	-	11.4
	4					Y	-	G03000	-	6.4
	5	Northridge, California	1994	6.7	LA City Terrace	XYZ	LAC090	LAC180	LAC-UP	11.9
	6					XYZ	LAC180	LAC090	LAC-UP	11.9
	7					X	LAC180	-	-	11.9
	8					Y	-	LAC090	-	11.6
	9	Cape Mendocino, California	1992	7.0	Rio Dell Overpass	XYZ	RIO270	RIO360	RIO-UP	15.3
	10					XYZ	RIO360	RIO270	RIO-UP	15.3
	11	Kahramanmaras, Türkiye	2023	7.8	4611	XYZ	4611-E	4611-N	4611-U	43.4
	12					XYZ	4611-E	4611-N	4611-U	43.4
	13	Elbistan, Türkiye	2023	7.5	4611	XYZ	4611-E	4611-N	4611-U	35.1
	14	Maule, Chile	2010	8.8	Curico Hospital	XY	CURI-EW	CURI-NS	-	45.2
	15	Kahramanmaras, Türkiye	2023	7.8	4611	XYZ	4611-E	4611-N	4611-U	43.4
DE	16	Loma Prieta, California	1989	6.9	Gilroy Array #3	XY	G03090	G03000	-	11.4
MCE_R	17	Loma Prieta, California	1989	6.9	Gilroy Array #3	XY	G03090	G03000	-	11.4
	18	Cape Mendocino, California	1992	7.0	Rio Dell Overpass	XY	RIO360	RIO270	-	15.3

SLE = service level earthquake, DE = design earthquake, and MCE_R = risk-targeted maximum considered earthquake.

$D_{5\text{-}95}$ = significant duration of strong shaking computed as the time interval between 5% and 95% Arias Intensity per original record (max component)

Shake Table Performance

Peak Input Responses Comparison

Fig. 2 presents a one-to-one comparison between the target and achieved peak input acceleration (PIA) and peak input displacement (PID). It is noted that the achieved are those attained with the building constructed and atop the shake table. It can be observed that in terms of PIA, the shake table tends to modestly overshoot (i.e. achieved > target) in the X-direction and undershoot (i.e. achieved < target) in the Y-direction for the larger intensity motions (MID16-18). This observation generally holds for the SLE-level motions, independent of their significant duration. In terms of PID, the shake table tends to produce larger peak displacements for the SLE-level motions with longer significant durations (MID11-15) in both the X- and Y- directions, whereas for the SLE-level motions with shorter significant durations (MID1-10), the alignment between target and achieved PID is comparably improved.

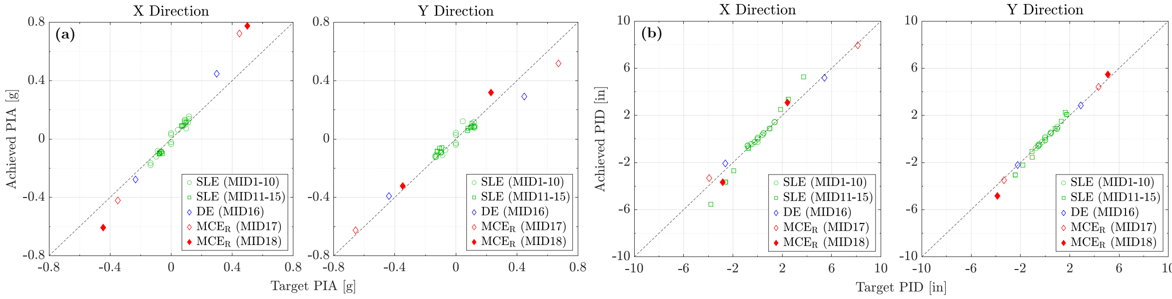

Figure 2. Comparison of target vs. achieved (a) PIA and (b) PID.

Shake Table Performance during MCE$_R$-Scaled Motions

Fig. 3 presents a time-domain comparison of the target and achieved acceleration histories for the two MCE$_R$-scaled motions (MID17-18). For MID17, the achieved PIA exceeded the target by 61% in the X-direction and fell short by 7% in the Y-direction. For MID18, the achieved PIA exceeded the target by 55% in the X-direction and fell short by 7% in the Y-direction. Despite this nominal mismatch in peak amplitudes, the salient features in time of the target motion are captured with good fidelity.

Fig. 4 presents a comparison of the target and achieved spectral accelerations for these same two motions. For MID17, the achieved spectral acceleration exceeded the target values in the high-frequency range but fell below the targets at periods between 0.5-1 s in the X-direction, while it was generally lower than the targets in the Y-direction. However, when examining the RotD100 spectra, which were used to scale the bi-directional motions to consider the maximum directional effects, improved agreement is observed. The average of the RotD100 spectral acceleration over the period range corresponded to approximately 88% of the target MCE$_R$ value. Although not shown, both MCE$_R$ (and DE) landed similar decent comparison across the period range of interest when considering RotD100.

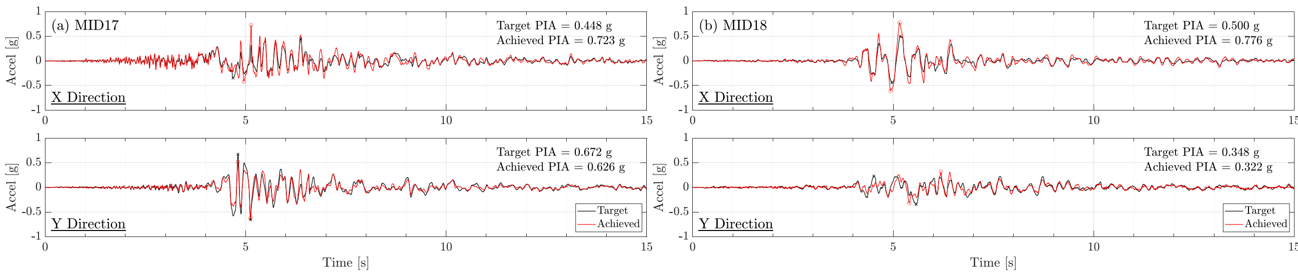

Figure 3. Time-domain comparison of target vs. achieved accelerations for (a) MID17 and (b) MID18.

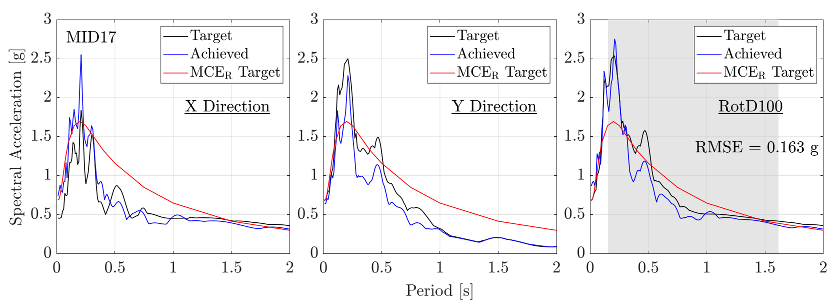

Figure 4. Comparison of target vs. achieved 5% damped elastic spectral accelerations for MID17 (MCE$_R$-scaled) (gray = period range of interest for scaling [0.15 s,1.61 s]).

Conclusions

This paper presents the development of the seismic test protocol for the CFS10 seismic test program, along with an evaluation of shake table performance. Overall, the shake table demonstrated satisfactory capability to reproduce recorded ground motion targets across the hazard range from SLE to MCE$_R$. Comparisons between target and achieved motions highlight the importance of employing RotD100 values when accounting for bi-directional earthquake inputs. Documentation of the procedure adopted in this work and the associated iteration procedure is envisioned of value to future researchers conducting large-scale testing at the unique outdoor shake table facility at UC San Diego. Interested readers may find useful the capabilities of the facility documented in [1].

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