DETAILING FOR SEISMICALLY RESILIENT STEEL STAIR SYSTEMS: VALIDATION IN THE MASS TIMBER (10 AND 6-STORY) PROGRAMS

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Abstract

A series of shake table tests were recently conducted on full-scale 10-story and 6-story mass timber buildings at the 6-DOF Large High-Performance Outdoor Shaking Table facility at the University of California San Diego. Stairs, providing the primary egress in and out of a building during and after an earthquake event, were incorporated in each of these building test programs. To ensure they support the immediate recovery of building function, a variety of drift-release details were incorporated. Previous earthquake events and experimental studies have shown that stairs are among the most drift-sensitive nonstructural systems and are prone to damage, therefore relieving interstory drifts is paramount to improving their performance. To this end, the designed drift-release connections within the stairs considered the test buildings response during earthquake motions scaled at various hazard levels with expected minor and repairable damage under large earthquake loading. This paper provides an overview of the shake table test programs from the perspective of the design and performance of resilient steel stairs.

Introduction

The robust performance of a building during an earthquake and its recovery to functionality after the event strongly depend on its nonstructural systems, particularly the egress system. Previous earthquake events have documented the significant damage and often total collapse of stair systems. For example, Li and Mosalam (2013) summarized the damage to reinforced concrete stairs during the 2008 Wenchuan earthquake. Bull (2011) reported damage to both concrete and steel stairs during the 2011 Christchurch earthquake. Both studies highlighted the poor performance of stairs with fixed connections. In addition, experimental investigations of the seismic response of stair systems, such as Simmons and Bull (2000), Higgins (2009), and Wang et al. (2015), have also revealed that the performance of these systems under lateral load strongly depends on the flexibility of their connections. Indeed, it has been consistently reported that stairs fixed at each floor-to-floor connection results in damage to both the stair system and potentially the supporting structure. To this end, ASCE 7 (2016 and 2022) requires that egress systems, when not part of the lateral force resisting system, be designed such that they accommodate interstory drift without loss of gravity support. Therefore, Black et al. (2017, 2020) studied the performance of several types of drift-release connections incorporated into a full-scale single-story straight-run stair under quasi-static and dynamic loadings. The drift release connections in these studies included slotted connections with a single degree of freedom, free connections with multiple degrees of freedom (DOF), and drift-compatible (*DriftReady*^{TM}) connections with three DOF. The stair system with a fixed-free configuration received significant damage to its connection plate. The stair system with slotted connections performed well under small to medium levels of shaking, but experienced binding when subjected to very large earthquake loading. On the other hand, stairs with drift-compatible connections showed superior performance. Nevertheless, the performance of these drift-release connections at a system level was still untested. Ultimately, the promise of such connections (as well as other types to facilitate drift-release) is best validated courtesy of full-scale testing. To this end, 10-story and 6-story prefabricated steel stair towers were incorporated into the shake table testing of three different full-scale mass timber buildings. This paper provides a brief overview of these programs, summarizes key building responses with respect to the seismic demands imposed on the stair system; and, ultimately, aims to shed light on the performance of stair systems.

Shake Table Test Programs

Mass Timber Buildings. In 2023 and 2024, a series of mass timber building shake table test programs were conducted at UC San Diego. Initially, a 10-story mass timber building was constructed and tested as part of the NHERI TallWood project (Figure 1a, Pei et al., 2024). In this project, a pair of post-tensioned rocking walls made of Cross Laminated Timber (CLT) and Mass Ply Panel (MPP) were used as the lateral load-resisting system in the east-west (X direction) and the north-south (Y Direction) directions, respectively. The building, which had a height of 34.1 m, floor plan of 10.5×10.4 m, and total weight of approximately 328 metric tons, including 51 metric tons of foundation, was built on top of the 6-DOF Large High-Performance Outdoor Shake Table (LHPOST6). In this project, U-shaped Flexural Plates (UFPs) were used to dissipate rocking-induced energy. For more details on the design of the structural system, refer to Busch (2023), Huang (2023), Wichman (2023), and Pei et al. (2024). Vertically distributed nonstructural systems were also incorporated into the 10-story building. These included a full-scale operable 10-story stair tower with various drift-release connections (Sorosh et al., 2022a, 2024), exterior and interior cold-formed steel wall subassemblies (Ji et al., 2024 and Roser et al., 2024), and a two-story fire-rated curtain wall subassembly (Wynn et al., 2024). Subsequently, as part of the NHERI Converging Design project, the bottom 6 stories of the TallWood building were preserved and tested in multiple phases (Figure 1b). The 6-story building had a height of 20.7 m and a total weight of approximately 224 metric tons, including 51 metric tons of foundation. In the first phase of the Converging Design project, the UFPs and PT bars and tensioning force were replaced to return the lateral-force resisting system closer to an undamaged state after testing of the 10-story building. In the second phase, the MPP walls (Y-direction) were replaced with new MPP walls detailed to receive buckling restrained boundary elements (referred to as BRBE in this paper) at the base of the rocking walls. In addition, during this phase, the nonstructural walls were removed. For more detail on the design and performance of the two phases of the 6-story building refer to Barbosa et al. (2024), and McBain et al. (2024).

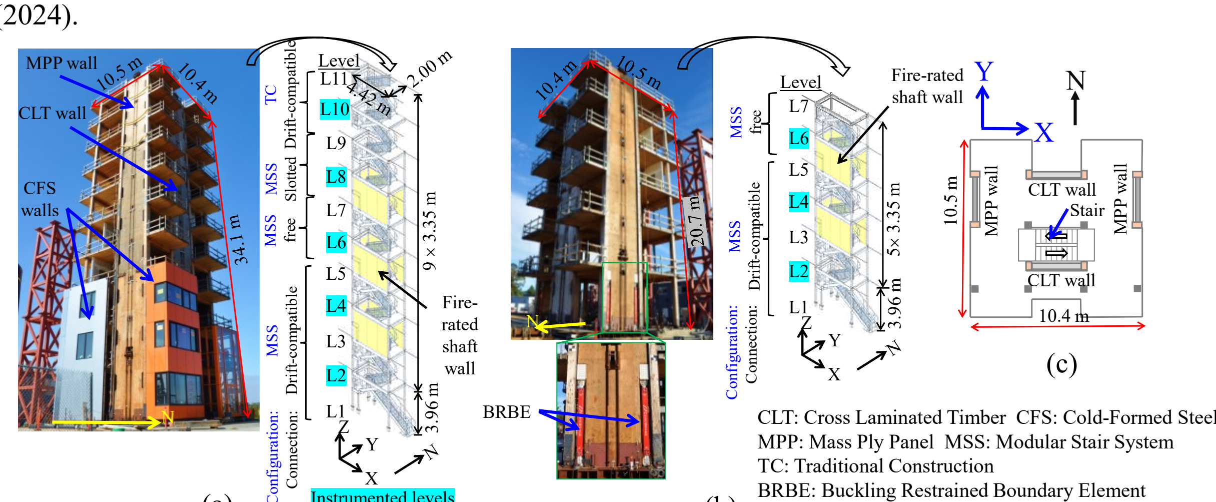

Figure 1. (a) NHERI TallWood building and the 10-story stair tower, (b) NHERI Converging Design building (phase 2: BRBE in Y-direction) and the 6-story stair tower rendering, and (c) floor plan

Stair Systems. The stair tower was placed within the central region of the floor plan such that its strong axis (longitudinal) was in the east-west direction (X Direction), and its weak axis (transverse) spanned in the north-south direction (Y Direction). The stair system incorporated into the 10-story building included the bottom eight stories of the Modular Stair System (MSS) and the top two stories of stairs built with Traditional Construction (TC), see Figure 1a. This test program featured three types of drift-release connections, namely, *drift-compatible (DC)* connections with three translation degrees of freedom (DOF), and one rotational DOF, *free connection (FC)* with three DOFs, and *slotted connections (SC)* with one DOF. Each of these drift-release connections was placed such that they were subjected to 50% of the interstory drift. Figure 2 depicts various connections details, featured in these test programs, with degrees of freedom shown in green arrows. Sorosh et al. (2022b and 2024) provides a detailed discussion of the design details of the stairs in this test program. Subsequently, as shown in Figure 1b, in the two phases of the 6-story building configuration shake table test programs, the bottom 6 stories of stairs were preserved with no modifications to their configuration. It is notable that the fundamental period of the 10-story building was 1.84 sec in the X-direction and 2.03 sec in the Y-direction; while that of the 6-story (in phase 1) was 1.14 and 1.04 sec, in X- and Y-directions, respectively.

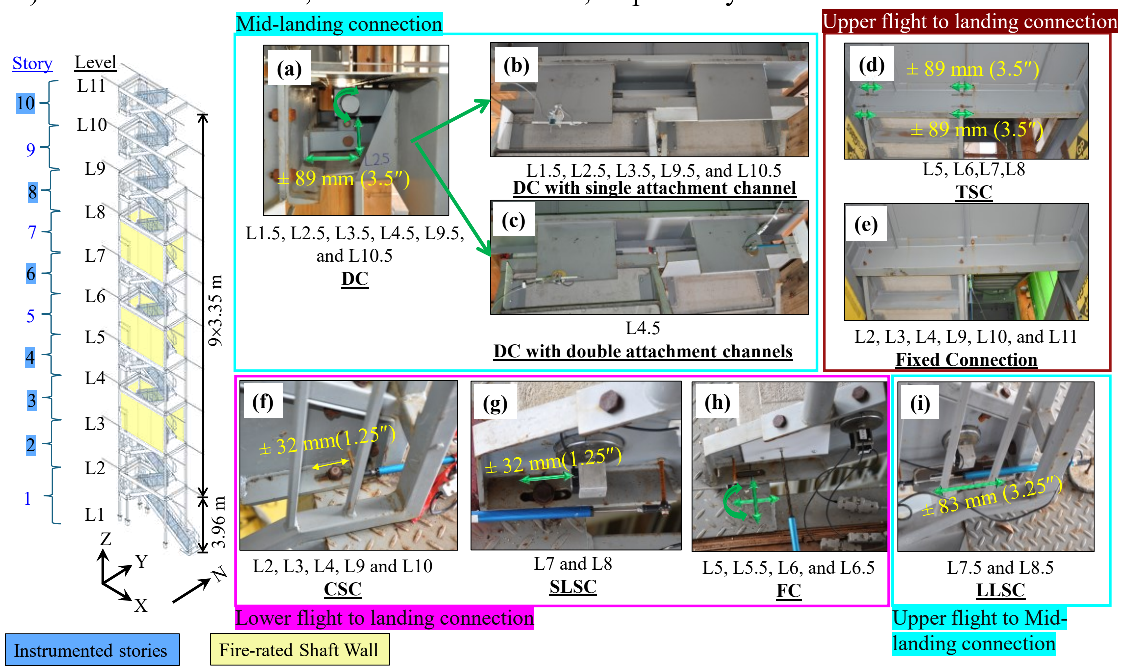

Figure 2. 10-story stair connection variations (a), (b), and (c) drift-compatible (DC), (d) transverse slotted connection (TSC), (e) fixed connection, (f) construction slotted connection (CSC), (g) short longitudinal slotted connection (SLSC), (h) free connection (FC) and (i) long longitudinal slotted connection (LLSC). [note that (1) details for L1-L7 were preserved when the building was in its 6-story configuration and (2) instrumented stories are highlighted in blue in the stair tower rendering].

Selected Input Motions. The TallWood (10-story) building was subjected to 88 earthquake motions scaled to various risk-targeted levels of intensity. These ground motions were scaled for site class C, risk category 2 with a selected site in downtown Seattle, WA. These motions were selected from past earthquake events representing distinct seismic sources. The selected motions were amplitude-scaled to risk-targeted events with return periods (RP) of 43 years, 225 years, 475 years, 975 years, and a risk-targeted maximum credible earthquake (MCE_R). Refer to Wichman (2023) for a detailed discussion on ground motion selection and scaling method for the 10-story building program. Similarly, for the shake table tests of the 6-story building, ground motions were selected for a site class C and a different location from that of the 10-story building. The selected motions in this test program also represented various seismic sources. For the 6-story building, the motions were also amplitude-scaled to various risk-targeted levels of intensity consistent with those selected in the 10-story building test (Barbosa et al., 2024). For the BRBE configured 6-story building, four ground motion records corresponding to crustal and subduction earthquakes were selected. The selected motions were then scaled to the MCE_R design spectrum. Subsequently, the selected motions were down-scaled to represent service level earthquake (SLE) and design earthquake (DE) targets (Simpson et al., 2024). The 475 year RP motions of the 10-

story program are equivalent to DE motions. This paper focuses on the response of the building and stair system during DE motions, as this offers a common design scenario across all three programs, see Figure 3. In this figure dashed vertical lines show periods corresponding to the first three translational modes in each orthogonal direction of the buildings at their initial (pre-test) state. To determine the modal properties of the building, the response of the building was represented using the Frequency Response Function (FRF), which acts as a transfer function between the input signal on the shake table platen and the output signal on the test specimen.

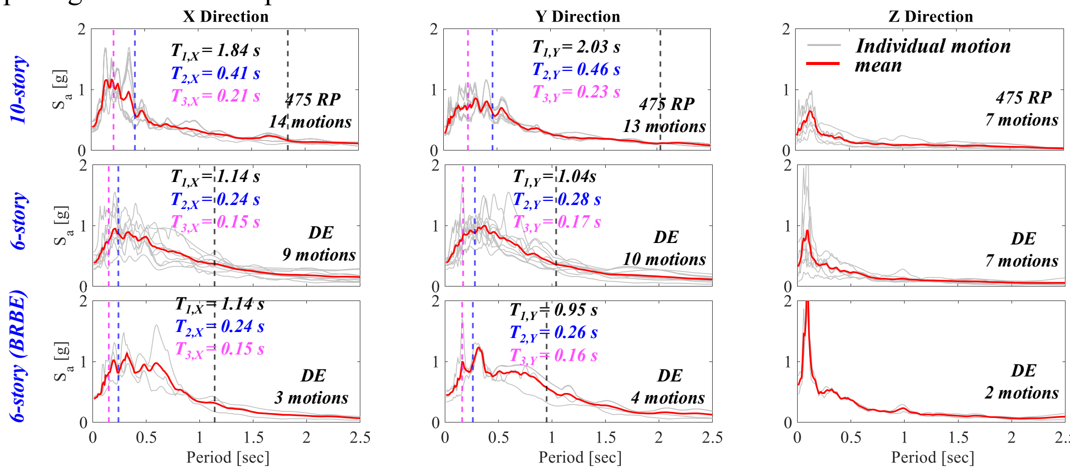

Figure 3. Elastic spectral acceleration (S_a) of select input motion (damping, ζ =5%)

Building Response

The peak floor acceleration (PFA) and peak interstory drift ratio (PIDR) profiles of each building specimen during the suite of DE motions are shown in Figures 4 and 5, respectively. The acceleration data are filtered using a 4th-order Butterworth bandpass filter with cutoff frequencies of 0.1 and 50 Hz. The floor displacements, that are used to determine PIDR, are obtained by double integrating the acceleration data using the 4th-order Runge-Kutta method. Table 1 summarizes the mean (μ) and standard deviation (σ) of |PIDR| and |PFA| based on Figures 4 and 5. On average, under DE motions, the mean of |PFAs| are between 0.25g to 0.87g with the maximum floor acceleration generally occurring at the roof. However, due to the participation of higher modes, PFAs at levels 4 and 7 of the 10-story building are larger than those at other levels except the roof. This effect is also observed at level 3 of the 6-story buildings. Observing the PIDR profiles of the 10-story building, the lower stories have a smaller PIDR, while stories at mid-height (i.e., stories 6 and 8) have a larger PIDR. However, the PIDR profile of the 6-story building is more uniform with the height of the building.

Table 1. Mean (μ) and standard deviation (σ) of PIDR and PFA

Building	Mean |PIDR| [%]		Average standard deviation of |PIDR| [%]		Mean |PFA| [g]		Average standard deviation of |PFA| [g]	
	X Dir.	Y Dir.	X Dir.	Y Dir.	X Dir.	Y Dir.	X Dir.	Y Dir.
10-story	0.38-0.99	0.38-0.94	0.15	0.11	0.33-0.75	0.25-0.71	0.11	0.09
6-story	0.69-1.23	0.91-1.20	0.28	0.50	0.34-0.67	0.34-0.65	0.09	0.10
6-story (BRBE)	0.50-0.84	0.70-1.15	0.28	0.24	0.33-0.63	0.29-0.87	0.09	0.06

Stair Response

Connection Displacement Response. Stair connections were detailed to accommodate a drift of up to 2.5% at the MCE_R target scale, thus it is anticipated that during a DE scaled event lower displacement demands will occur. Note that each connection was placed such that they are subjected to 50% of the interstory drift. Therefore, Figure 6 shows a scatter plot of peak connection displacement versus 50% of the peak interstory drift. It is important to note that these responses are uncorrelated. In general, it is observed that irrespective of the building configuration, the stair connections accommodated the interstory drifts effectively. The standard deviation in PIDR of the 6-story building is larger than that of the 10-story building. Therefore, since stairs are drift-sensitive systems, a larger deviation in the stair connection response in the 6-story building is observed as well. Free connection (FC) shows larger displacement responses compared to the drift-compatible (DC) connections. Differential movements between stair components due to having drift-release connections result in minor damage to the stair components, such as the handrails, that were continuous through these interfaces. Sorosh et al. (2024) discuss the observed damage to the stair system during the shake table test of the 10-story stair system. During the test of the 6-story and 6-story (BRBE) buildings, no new damage instances were reported.

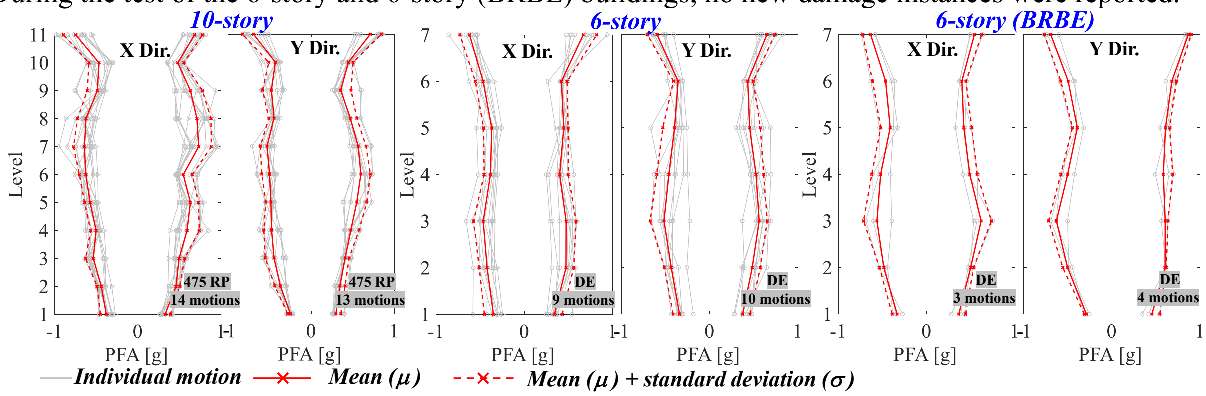

Figure 4. Peak floor acceleration (PFA)

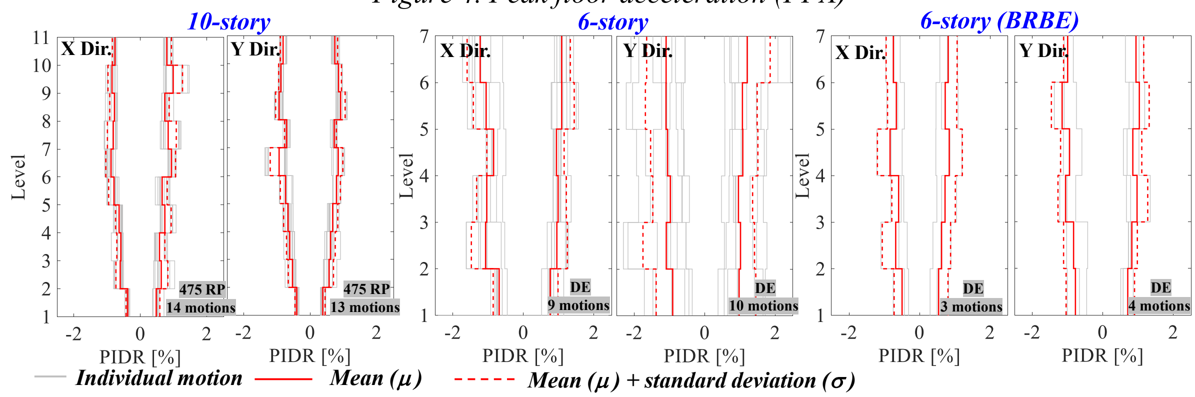

Figure 5. Peak interstory drift ratio (PIDR)

Component Acceleration Response. Peak component accelerations (PCA) normalized by peak floor acceleration (PFA), namely the component acceleration amplification factor, are used to predict the seismic design force of non-structural components and systems. In ASCE 7-22 (2022), the acceleration amplification of nonstructural components and systems is considered in a single coefficient defined as the resonance ductility factor (C_{AR}). In ASCE 7-22 (2022), a C_{AR} of 2.2 is proposed for egress stair and ramp fasteners and attachments, while a value of 1.0 for stairs not part of the building seismic force resisting system is required. Figure 7 shows the PCA/PFA of stair systems at levels 2, 4 and 6, compared to these codified values. During the shake table test of the 10-story building, the acceleration amplifications at the midlandings, more often in the weak axis of stair system (Y Direction), exceeded the code proposed value (C_{AR} = 2.2). The accelerations recorded at stair flights, mostly, were within the range of code-based predicted values. However, during the test of 6-story and 6-story (BRBE) buildings, the acceleration amplification in the majority of stair components, particularly in the direction parallel to the stair's stiffer axis (X Direction) exceeded the code proposed value. Stair systems with free connections, more often, showed acceleration amplification exceeding the proposed code value of 2.2 in both X and Y directions. The acceleration amplification in the stair system at level 2 that features the drift-compatible connections with a single attachment channel had a lower acceleration amplification, compared to other levels. The stair system at level 4 featuring the drift-compatible connections with double attachment channels, throughout the tests of three buildings, observes consistent acceleration amplification response in the Y direction. However, the acceleration amplification in the X direction during the test of 6-story buildings is significantly higher than that of the 10-story building. It is evident that drift-release connections aid in avoiding extensive damage to the stair systems. These connections allow free movement of stair components that eventually increase the acceleration response of components.

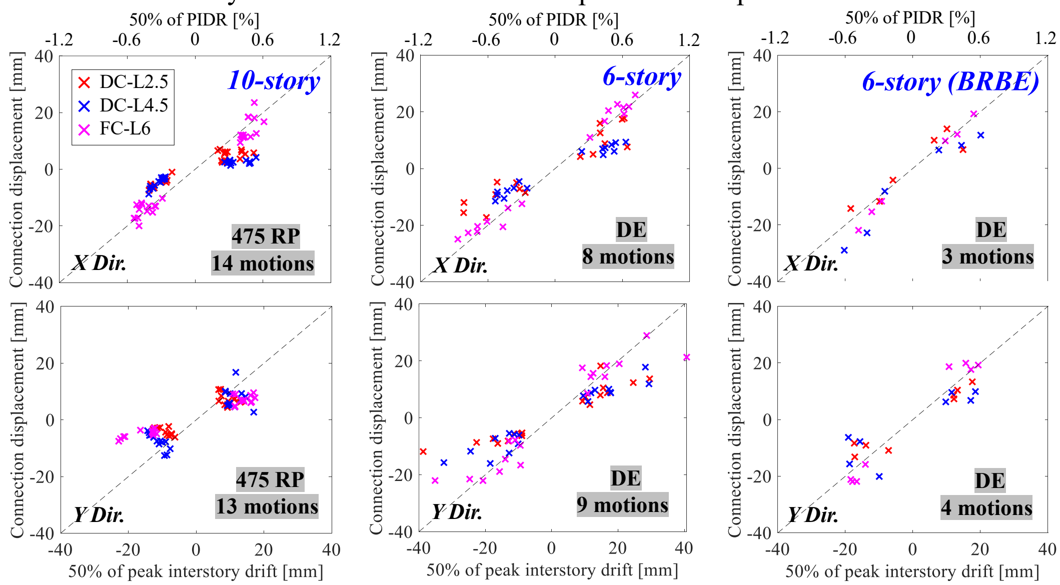

Figure 6. Peak connection displacement vs 50% of peak interstory drift (DC: Drift-compatible, FC: Free connection)

Conclusions

Previous field reconnaissance studies and experimental investigations have revealed that stairs with fixed types of connections are prone to damage under earthquake loading. Therefore, modern design codes such as ASCE 7 (2016, 2022) require egress stairs to be detailed such that they accommodate the interstory drift without loss of gravity support. Recently, stair systems with various drift-release connections were integrated as part of three full-scale mass timber buildings, offering a unique opportunity to characterize their response in a variety of (height and detailed) buildings. In total, over 150 earthquake motions were utilized throughout the three shaking table test programs. This paper provides a brief overview of these test programs, the global response of the buildings, and the seismic design and response of the stairs under the design earthquakes. It was found that drift-release connections consistently avoided extensive damage to the stair systems. However, the movement of stair flights relative to the landings may result in minor damage to continuous members such as handrails. In addition, the free movement of stair flight increases the acceleration response of the stair system. In the shake table test program of the 10-story mass timber building, only the mid-landing of the stair system observed acceleration that exceeded the ASCE 7 (2022) design amplification value. However, testing of both 6-story building configurations presented herein, the acceleration amplification in the majority of stair components in all levels measured exceeded the ASCE 7 (2022) proposed value. Although minimal damage was observed and complete return to functionality was preserved courtesy of the various drift-release connections explored; the observed acceleration amplification in excess of codified values requires further study to ensure that essential connections within the gravity support of a stair are not compromised.

Future Investigations: CFS10

Findings from the stair system investigations conducted during the tall and mid-rise mass timber building programs document very good performance, including continued functionality post-earthquake, of a variety of drift-release connections within stair systems. To expand understanding of these details and continue to improve their robustness, particularly for a wider range of building lateral force-resisting systems, the authors have implemented a similar modular stair system with drift release details, and enrichments to select features (notably flexible handrail details, locking mechanisms, and improvements to stair shaft details) into an upcoming 10-story cold-formed steel building shake table program, also at the UC San Diego outdoor shake table. At the time of preparation of the current article, construction of this specimen, coined CFS10, was underway. Interested readers are encouraged to note progress and findings to be presented on the project website as they become available: cfs10.ucsd.edu.

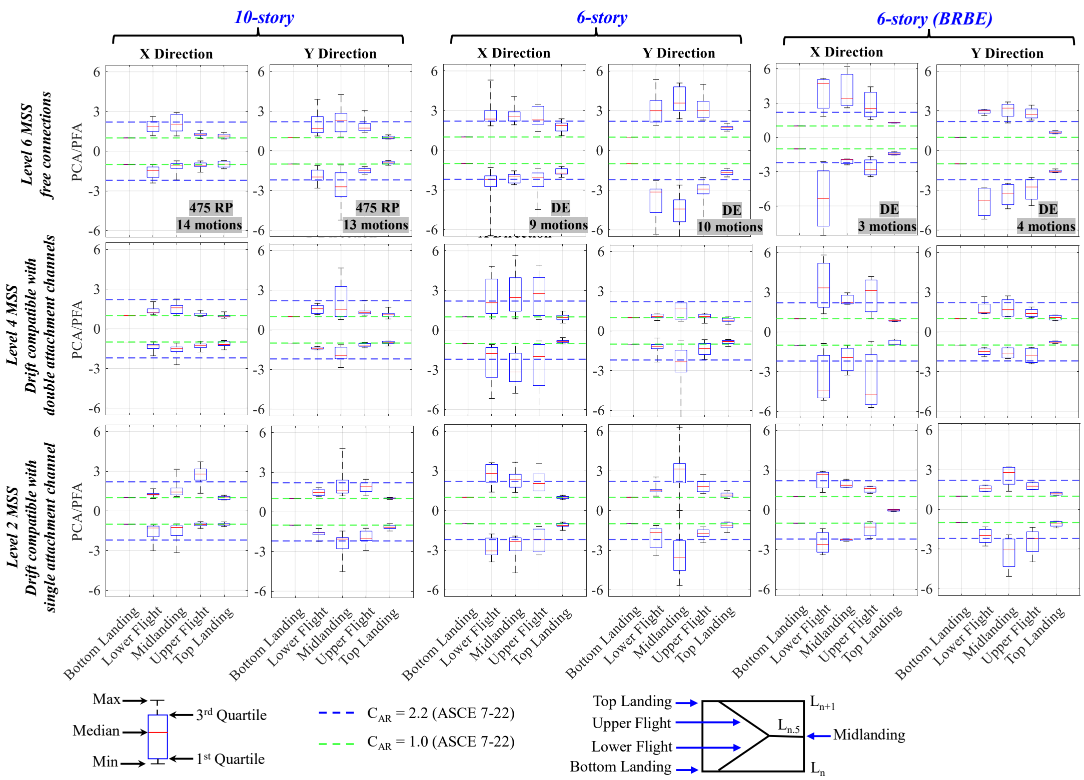

Figure 7. Peak component acceleration (PCA) normalized by peak floor acceleration (PFA)

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