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# NHERI TallWood 10-story Test Nonstructural, Part 4 of 4: Prefabricated Steel Stair Subassemblies

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## ABSTRACT

During extreme events such as earthquake and fire, safe egress in and out of a building is crucial. To design seismic resilient egress systems, understanding the earthquake response of these systems is required. Previous earthquakes and physical experiments have proven that stairs with fixed connections are prone to damage and might even impact the dynamic characteristics of the supporting structure. To address this, resilient stair systems have been proposed, most suitably with drift ready connections or slotted connections. Large-scale system-level experimental studies using true-to field boundary conditions and real earthquake motions thus far have been limited. To this end, several stair configurations are planned to be tested within the Tall Wood Cross Laminated Timber (CLT) building test program planned for 2022 at the UC San Diego Large High Performance Outdoor Shake Table (LHPOST). This paper reviews previous studies investigating the seismic response of stairs and discusses the planed stair testing program within the CLT effort.

## Introduction

The design of seismically resilient structures is an active area of research as earthquake engineering practice strives to minimize the consequences of these natural hazards. Safe egress in and out of a building, during and after the extreme events like earthquakes, are necessary. In past earthquake events, extensive damages to egress systems have been reported. For instance, significant damages to concrete stairs during the 2008 Wenchuan earthquake are reported by Li and Mosalam [1]. In addition, damage to both concrete and steel stairs in the 2010 Darfield earthquake and the 2011 Christchurch earthquake were extensive, as summarized by Bull [2].

Although full-scale experimental studies on stairs have been limited, a few are worth noting. An important effort by Higgins [3] studied the response of two full-scale prefabricated steel stair assemblies with landings under quasi-static load. During these tests, although a drift of 2.5% was achieved, large local deformation demands at the stair to landing connection were observed. It was concluded that the overall response of the stair depends most significantly on the flexibility of the connections. In subsequent investigations, prefabricated stairs were incorporated within a full-scale five story reinforced concrete building tested on the shake table at UC San Diego [4]. In these shake table tests, connection and slab embed weld fractures were observed even before reaching a design target peak inter-story drift ratio (PIDR) of 2.0-2.5% [5-7]. During testing of this specimen, which was fixed at its base, the stairs became completely inoperable due to severe damage of the stair flight to slab connections at multiple levels. Based on the observations of stairs during earthquake events and testing, stairs with rigidly fixed connections are prone to damage.

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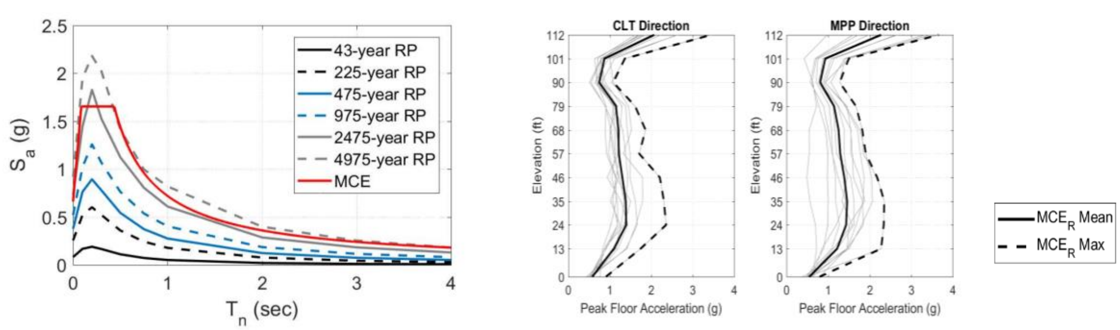
To address the paucity of data recording stair system seismic performance, in 2016 and 2018 two shake testing programs of full-scale half-story prefabricated steel stairs with a variety of connection details were conducted at the University of Nevada Reno Earthquake Engineering Laboratory [8]. As part of these programs, several strategies for connecting the stair stringers to the landings were examined. Variations included fixed at the top and free sliding at the bottom (fixed-free configuration), longitudinal slots at the top and transverse slots at the base (slotted connection), and hanger connection at the top and fixed connection at the base. This latter is known as the drift-ready (DR) connection, developed by Construction Specialties. The fixed-free configuration was damaged severely under MCE-scaled motion. Tolerances provided at the connections of stair with slots allowed the stair to move freely at lower amplitudes. Nevertheless, during tests at larger amplitudes, binding at the connection was observed. The stair with DR connection performed well under all load levels, with no damage to either the stair or the connections.

However, a system-level assembly considering direct comparison with various connection types albeit using drift-compatibility in mind, has yet to be investigated. To this end, a multi-story operable steel stair system with different connection schemes is being planned for testing within the full-scale shake table test program of a10-story mass timber building at the UC San Diego Large High Performance Outdoor Shake Table (LHPOST). These tests will be conducted in 2022, upon reopening of the upgraded 6 DOF LHPOST facility. This paper presents a pretest overview of stairs at this program.

## 10-story CLT Tall Wood Building

The 10-story CLT building is a full-scale 112 ft tall mass timber building planned for testing at the UC San Diego LHPOST facility. The building consists of three different floor plans, with mixed-use commercial, office and residential occupancies. The main goal of the NHERI Tall Wood project is to advance the use of a new seismic resilient lateral system using post-tensioned (PT) mass timber rocking walls along with U-shaped flexural plates (UFP) as means to dissipate energy. Several different mass timber components are used for floor diaphragms including CLT, glue-laminated timber (GLT), nail-laminated timber (NLT), and dowel-laminated timber (DLT). The 10-story CLT building is the culmination and centerpiece of the NHERI Tall Wood multidisciplinary industry-university research program [9]. The location of the 10-story CLT building is assumed to be downtown Seattle, WA founded on a site class C soil and a seismic risk category II. The building is designed such that no collision of the rocking walls and no yielding of the PT tendons are expected under earthquake motions with 975 years return period. Moreover, no fracture of the PT tendons and UFPs is anticipated at earthquake motions with 4975 year return period. For the specified location of the building, the spectral acceleration is shown in Fig. 1(a). Using Nonlinear Response Time History Analysis (NLRHA) of the preliminary building model, expected peak floor accelerations of the building in the east-west direction (CLT rocking walls) and north-south direction (mass plywood panel or MPP rocking walls), under 11 $MCE_R$ scaled ground motions, are shown in Fig. 1(b). Refer to the companion papers [10-12] for additional information about the NHERI TallWood project and nonstructural scope.




(a) (b)

Figure 1. (a) Spectral acceleration and (b) peak floor accelerations: east-west direction (CLT wall direction) and north-south direction (MPP wall direction)

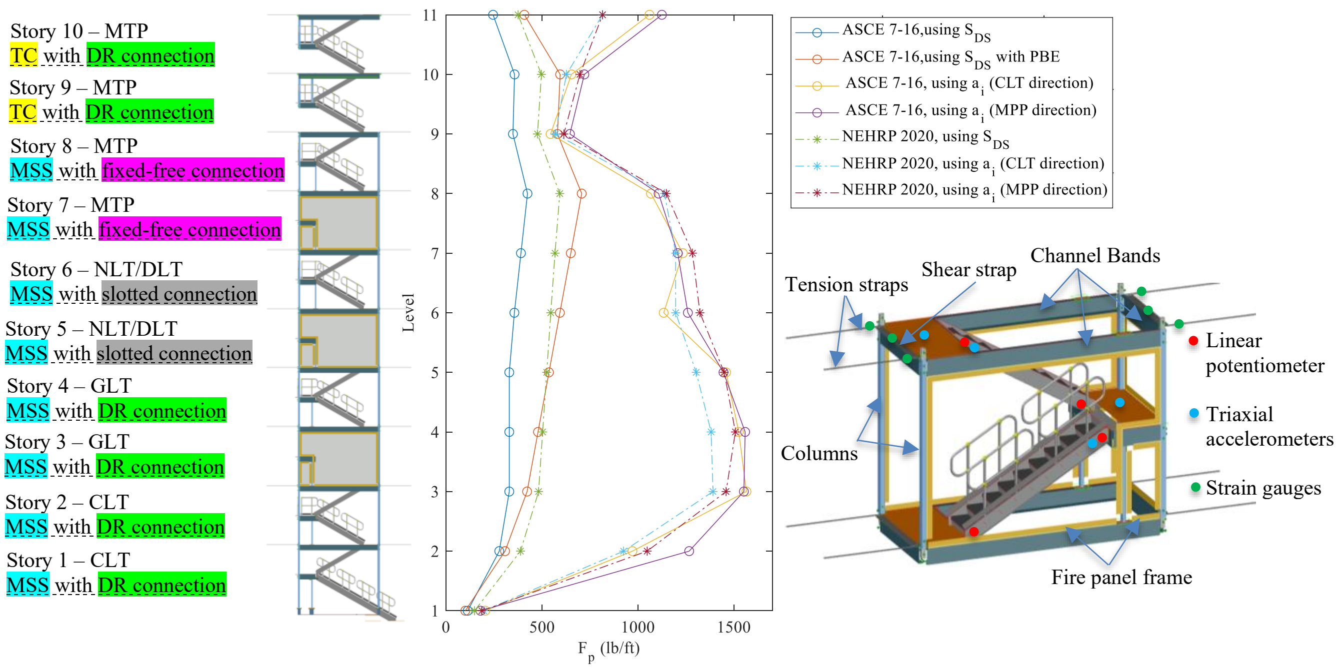
## Steel Stairs Design Parameters

Incorporated into the 10-story CLT building design will be full-scale, full-height, prefabricated steel stairs. As seen in Fig. 2(a), eight stories will be outfitted with self-supporting modular stair systems (MSS, originally proposed and developed by Construction Specialties), which are preassembled. A representative figure of the MSS with drift-ready connection is shown in Fig. 2(c). As seen in this figure, the channel band at each floor level is designed to transfer floor level loads to end columns. By means of stair columns, gravity loads of the eight stair assemblies are transferred to foundation. To monitor the response of stairs constructed in traditional construction (TC), the gravity loads of the stair assemblies at the 9th and 10th stories are transferred to the floor diaphragm. Hence, most of the stair columns in the 9th and 10th stories are removed.

Considering the stair connection schemes, three types of connections are to be tested in this shake table program. As shown in Fig. 2(a), six stories will have DR connections, two stories will have slotted connections and two stories will have fixed-free connections. In the slotted connection scheme, the longitudinal slots will be placed at the bottom connection of each flight, and the transverse slots will be placed at the top connection of each flight. Free connection will be like slotted connection, but the bolts will not be preloaded. In the drift-ready scheme, both DR connections will be installed at the mid-landing level.

Finally, as seen in Fig. 2(a), an innovative fire protection wall solution is proposed in which the fire panel frame will be installed as part of the stair assembly and the fire protection wall is installed within this frame. The fire protection wall is surrounded by flexible fire-rated filler material, which allows the wall to freely move within the frame. Three stories will be installed with fire protection walls surrounding the stairs.

Methods given in the ASCE 7-16 standard [13] and 2020 edition of NEHRP recommended provisions [14] are used to determine the seismic design forces ($F_p$) at each level of the test building. The NEHRP recommendations are based on research conducted within the Applied Technology Council ATC-120 project [14,15]. In the scope of ATC-120 project, both nonlinear analysis of archetype buildings and strong motion recordings from instrumented buildings were utilized to study the effect of various design parameters influencing the seismic force to nonstructural components, $F_p$. Since the NEHRP equations will appear in subsequent version of the ASCE-7 standard, a cross comparison with the ASCE 7-16 equations is undertaken in this work to offer a design envelope when considering the stairs seismic design inertial responses.




(a) (b) (c)

Figure 2. (a) Stair tower (b) stair seismic design force $F_p$ (c) MSS (Image courtesy of Construction Specialties.)

For both ASCE 7-16 and NEHRP 2020 provisions, seismic design forces are calculated using two different sets of acceleration demands; first, the given design spectral acceleration for short period ($S_{DS}$), and second, the floor acceleration ($a_i$) obtained from NLRHA of CLT building under $MCE_R$ in both CLT and MPP rocking wall directions. Fig. 2(b) summarizes the seismic design forces of stairs in the 10-story CLT building based on these different methods. When calculating $F_p$ by ASCE 7-16 equations with predicted floor accelerations ($a_i$), the maximum floor acceleration is used, and the component amplification factor ($a_p$), component importance factor ($I_p$), and component response modification factor ($R_p$) are all taken to be 1.0. However, considering the decision made by the design and research teams and referring to Section 13.3.1 of NEHRP provisions, when calculating $F_p$ using the 2020 NEHRP provision, the mean floor acceleration is used, with component strength factor ($R_{po}$) = 1.5, component resonance factor ($C_{AR}$) = 2.2 and component importance factor ($I_p$) = 1.0. The seismic design forces by ASCE 7-16 using maximum floor acceleration in MPP rocking wall direction, have been used to design the connection between stair and floor diaphragm. As it is seen in Fig. 2(c), the shear forces in the 1st -8th floors are transferred to floor diaphragm by shear straps installed at the boundary between the floor diaphragm and the stair band at both ends of the stair assembly. However, at the 9th and 10th floors, since the gravity loads of the stairs are also transferred to floor diaphragm, forces are transferred through a steel angle. This angle will be welded to the side of stair band and bolted to the diaphragm. To transfer the tensile forces from the stair assembly to the floor diaphragm, tension straps will be installed, in all floors, at both ends of the stair band as presented in Fig.2 (c).

## Planned Instrumentation Layout

A dense array of sensors are proposed to capture the response of the stairs under earthquake loading. Namely, linear potentiometers will be used to record the displacement between the landing and lower flight, the mid-landing and lower flight, the mid-landing and upper flight, and the upper flight and landing. These potentiometers will be installed at the specific locations, as presently proposed in Fig. 2(c), on the 1st , 3rd, 5th , and 10th stories. This multistory distribution is selected to capture the global response of the stairs with different configurations and connection details. Moreover, to enrich the kinematics obtained with discrete relative linear potentiometers, triaxial accelerometers will be installed on the flights (e.g., attached to stringers) and landings. The forces transferred to diaphragm may also be recorded, as feasible using strain gauges attached to the shear and tension straps.

## Conclusions

The NHERI TallWood project is an NSF-funded research project with the main goal of developing and validating a resilient seismic design methodology for tall wood buildings. Central to this project, a shake table test program of 10-story CLT building is scheduled for 2022 at the UC San Diego LHPOST facility. The shake table test will validate design procedures for a new lateral system that utilizes post-tensioned rocking walls built from mass timber panels, along with various resilient detailing options for nonstructural components. The test building offers unique opportunity to test various nonstructural components and systems. Amongst the most critical to resilient and rapid return to function post-earthquake are the stairs, as they serve as essential egress. To this end, it is planned to test a full-scale 10 story prefabricated operable steel stairs with different configurations and connection details. Based on experimental data and physical observation, stairs with fixed connections are prone to damage. Hence, several solutions with preliminary full-scale half-story test results are proposed for inclusion in the 10-story CLT building. Shake table tests of stairs with flexible connections will pave the way to design seismic resilient and drift-compatible stairs. Moreover, the results from these shake table tests will be useful to judge the robustness of current and future $F_p$ design equations provided in the ASCE 7-16 standard and the 2020 edition of NEHRP recommended provisions.

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