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Numerical Simulation of Prefabricated Steel Stairs to be Implemented in the NHERI TallWood Building

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Abstract. During extreme events such as earthquakes, stairs are the primary means of egress in and out of buildings. Therefore, understanding the seismic response of this non-structural system is essential. Past earthquake events have shown that stairs with a flight to landing fixed connection are prone to damage due to the large interstory drift demand they are subjected to. To address this, resilient stair systems with drift-compatible connections have been proposed. These stair systems include stairs with fixed-free connections, sliding-slotted connections, and related drift-compatible detailing. Despite the availability of such details in design practice, they have yet to be implemented into full-scale, multi-floor building test programs. To conduct a system-level experimental study using true-to-field boundary conditions of these stair systems, several stair configurations are planned for integration within the NHERI TallWood 10-story mass timber building test program. The building is currently under construction at the UC San Diego 6-DOF Large High-Performance Outdoor Shake Table (LHPOST6). To facilitate pre-test investigation of the installed stair systems a comprehensive finite element model of stairs with various boundary conditions has been proposed and validated via comparison with experimental data available on like-detailed single-story specimens tested at the University of Nevada, Reno (UNR). The proposed modelling approach was used to develop the finite element model of a single-story, scissor-type, stair system with drift-compatible connections to be implemented in the NHERI TallWood building. This paper provides an overview, and pre-test numerical evaluation of the planned stair testing program within the mass timber shake table testing effort.

Keywords: Steel stairs, non-structural components, and systems, finite element analysis, dynamic analysis, seismic response

1. INTRODUCTION

Stairs, spanning floor-to-floor and subject to seismic interstory drift demands, are displacement-sensitive non-structural systems. Previous earthquakes and experimental studies consistently document the significant damage, including total failure possible for these non-structural systems. For example, Li and Mosalam [2013] reported significant damage to concrete stairs during the 2008 Wenchuan earthquake. In addition, Bull [2011] summarized damage to both concrete and steel stairs during the 2011 Christchurch earthquake.

Previous experimental studies showed that the overall response of the stair system significantly depends on the flexibility of the connection. Notably, Higgins [2009] studied the behavior of steel stairs under quasi-static load, achieving a drift of 2.5%. However, at this design targeted drift, large local deformations of stair to landing connection were observed. In subsequent studies, prefabricated steel stairs were tested as part of a full-scale five-story reinforced concrete building at UC San Diego [Hutchinson *et al.*, 2013]. In these shake table tests, connection and slab-embedded weld fractures were seen even before reaching the design target peak inter-story drift ratio (PIDR) of 2.0-2.5 % [Wang *et al.* 2013, 2015; Pantoli *et al.* 2013].

Observing the performance of stairs during past earthquake events and experimental studies, it is understood that stairs with fixed flight-to-landing connections are understood to be prone to damage. Therefore, ASCE 7-16 [2017], Section 13.5.10 requires that egress stairs not part of a seismic force-resisting system be detailed to accommodate the relative displacement between two levels without loss of gravity support. To this end, two shake table testing programs of full-scale prefabricated steel stairs with a variety of connection details were conducted at the University of Nevada Reno Earthquake Engineering Laboratory [Black *et al.*, 2017, 2020]. In these testing programs, the stair flight to landing connection was detailed using several strategies, notably, 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), an industry-designed drift-compatible connection at the top and fixed connection at the base (fixed-drift compatible configuration). The stair system with a fixed-drift compatible configuration performed well and sustained no damage when subjected to a target MCE-scaled earthquake. However, the stair systems with fixed-free configurations sustained significant damage under MCE-level earthquake. The stairs with slotted connections performed well under earthquakes with smaller amplitudes, but sustained binding at the connection during earthquake tests with larger amplitudes.

To further investigate the seismic performance of stairs with drift-compatible connections, at a system level, a 10-story operable steel stair system with various connection details is being planned to be tested as part of the NHERI Tallwood 10-story mass timber building at the UC San Diego 6-DOF Large High-Performance Outdoor Shake Table (LHPOST6). The NHERI Tallwood project is a multidisciplinary industry-university research program, which aims to advance the use of a new seismic resilient lateral system using post-tensioned mass timber rocking walls along with U-shaped flexural plates (UFP) as a means to dissipate energy. The design methodology was validated through testing a full-scale 2-story mass timber building in 2017 [Pei *et al.*, 2019]. The 10-story mass timber building is the centrepiece of this project. Seismic resiliency of both the structural and non-structural systems is considered in this 10-story building.

Prefabricated steel stairs incorporated into the 10-story mass timber building consist of eight stories of Modular Stair Systems (MSS), and two stories representing Traditional Construction (TC) [Sorosh *et al.*, 2022] (see Figure 1). Considering the flight to landing connections, six stories will have drift-compatible connections installed at the flight to mid-landing connections, with the other end of the flights fixed. Two stories will have longitudinal slots at the bottom connections of each flight and transverse slots at the top connections of each flight. Two stories will have fixed-free configurations with the bottom connections of each flight free and the top connections fixed. The details of each connection are shown in Figure 1. With exception of story 1, which is 13', all story heights are 11'.

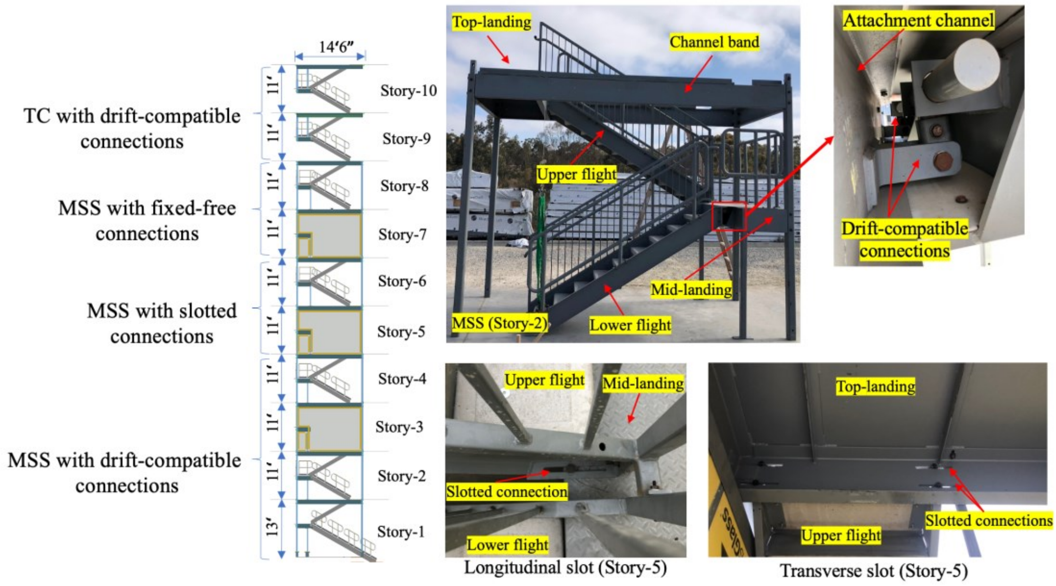

Figure 1. 10-story stair tower (Left), and a sample of stair connection details (Right)

1.1 SCOPE OF PRESENT PAPER

In an effort to prepare for the 10-story testing program, a high-fidelity finite element model of steel stairs with various boundary conditions has been proposed and validated through comparison with the aforementioned experimental studies at UNR [Sorosh *et al.*, 2022] The proposed modelling approach is used to develop the finite element model of steel stairs with drift-compatible connections to be tested as part of the 10-story building. This paper discusses the development of the finite element model and the dynamic characteristics of these stair systems.

2. FINITE ELEMENT MODEL DESCRIPTION

Using Abaqus [2020], the finite element model of the prefabricated steel stairs with various flight-to-landing connection details was developed and validated through comparison with test data. The same procedure is followed to develop the finite element model of modular stair systems with drift-compatible connections to be incorporated in the NHERI Tallwood mass timber building. To obtain the dynamic characteristics of these stair systems, a modal analysis is conducted. In addition, to determine the load capacity of each stair unit, a pushover analysis is performed.

2.1 GEOMETRY AND MESH GENERATION

Figure 2 shows the dimensions, element types, and approximate global mesh size (AGMS) of each stair component. Note that both solid and shell elements are used in this finite element model. The components that have complex geometry such as columns with bolt holes, drift-compatible connections, and bolts are modelled using solid elements. Components with simple geometry and smaller thickness-to-width ratio such as landings, risers, and stringers are modelled using shell elements. Table 1 summarizes the steel section, material, element type, and mesh size of each component. Abaqus provides many types of shell and solid elements with various formulations, integration points, and accuracy levels. Sun [2006] discusses the performance of different finite elements in this commercial software. As listed in Table 2, stairs components are modelled using various finite elements. The selection of the finite element types noted in Table 1 is based on Sun [2006] and the FEM previously developed and validated through experimental data.

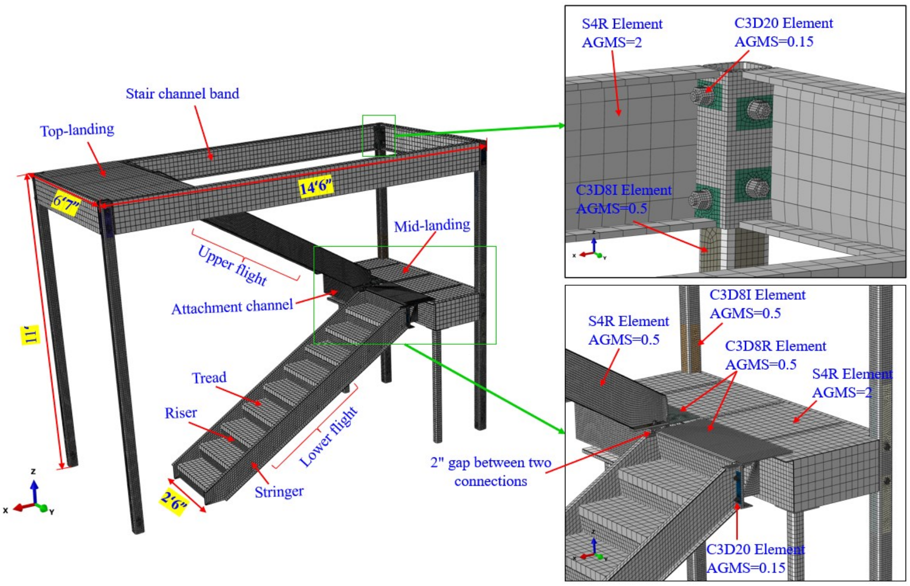

Figure 2. Geometry and mesh details of the finite element model

Table 1. Material, element type and mesh size

Component	Section	Material	Element	Mesh Size (AGMS)
Stair channel band	C12×30	A36	S4R Linear Quadrilateral	2
Column	HSS4×4×3/8	A500 Grade B	C3D8I Linear Hexahedron	0.5
Stringer	MC10×8.4	A36	S4R Linear Quadrilateral	1
Drift-compatible connection	Various	A36	C3D8R Linear Hexahedron	0.2 - 0.5
Aluminum plate	PL5'-10"×13-3/4"×3/16"	Aluminum	C3D8R Linear Hexahedron	0.5
Riser	PL2'-6"×5-7/16"×1/16"	A36	C3D8R Linear Hexahedron	1
Tread	2'-6"×12"×2-1/4"	Concrete	C3D8R Linear Hexahedron	1
Bolt	Various	A325	C3D20 Quadratic Hexahedron	0.15
Mid-landing	PL6'-7"×2'-6"×1/4"	A36	S4R Linear Quadrilateral	2
Top-landing	PL6'-6 1/2"×3'-1 1/2"×1/4"	A36	S4R Linear Quadrilateral	2

2.2 Materials

As listed in Table 1, the stair components are made of various materials. Based on the preliminary analysis, bolts and concrete do not experience inelastic deformations. Therefore, a linear material model is assigned for concrete treads and bolts. The stair components made of A36 and A500 Grade B steel have nonlinear material models. In Abaqus, a plastic material model with combined cyclic hardening rules is used to model the sections with A36 and A500 Grade B steel materials. Ramberg-Osgood's material model [1943] is used to define the stress-strain relation of A36 and A500 Grade B steel materials. Figure 3 shows the response of a single shell element with A36 and A500 Grade B steel material models under uniaxial displacement controlled monotonic and cyclic loads.

2.3 Boundary Conditions and Contact Elements

In this FEM, the column bases, and bottom connection of lower-flight have fixed (Encastre) boundary conditions, in which all rotation and translation degrees of freedom are constrained. In modal analysis, to represent a rigid diaphragm around the stair channel band, the movement of the stair channel band is restrained.

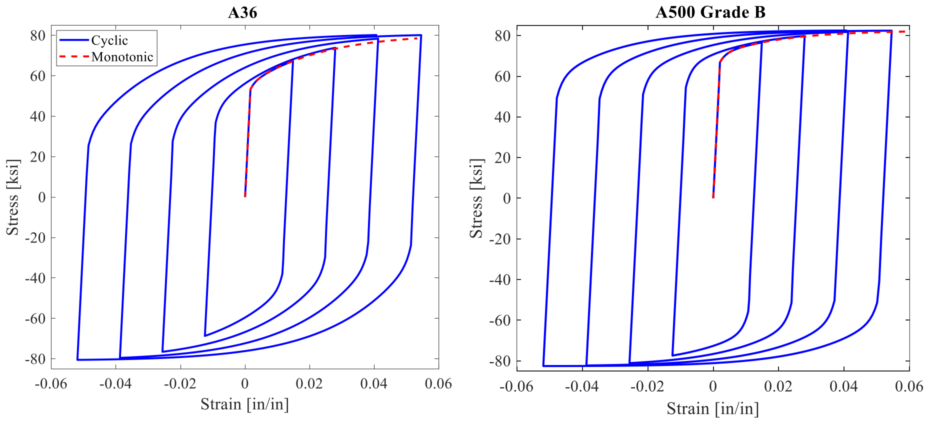

Figure 3. Stress-strain relation of A36 steel (Left) and A500 Grade B steel (Right) adopted for the FEs used herein

Welded connections are not modelled explicitly. Instead, a tie constraint is defined in all welded sections. The interaction between stair components such as the bolted connections and the drift-compatible connections are modelled using surface-to-surface contact elements with a friction model. The ideal friction model results in a convergence issue. Therefore, in this FEM, the penalty formulation with isotropic directionality, and 0.005-unit elastic slip is used to model the frictions in all surfaces in contact. Figure 4 shows the shear stress-slip relation in penalty and ideal friction models. In addition, for better illustration purposes, meshed drift-compatible connections and surfaces with contact elements highlighted are shown in Figure 4.

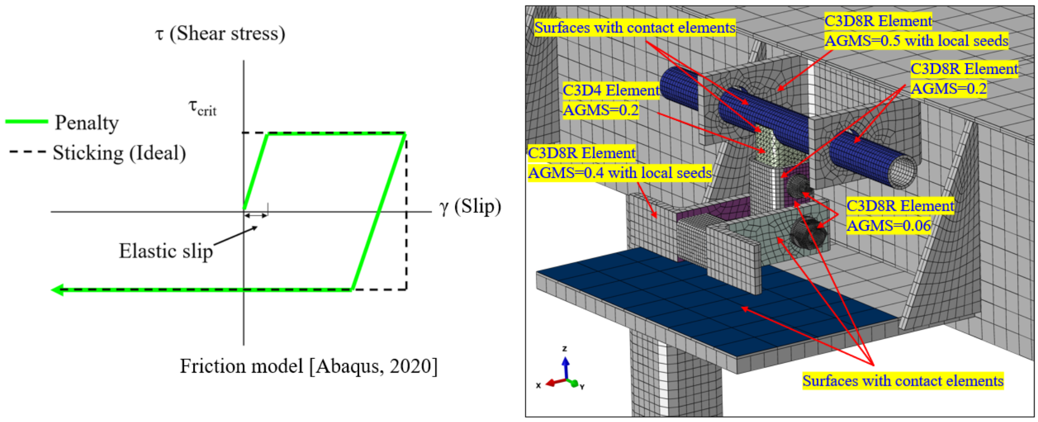

Figure 4. Friction model (Left), and meshed drift-compatible connection with contact elements highlighted (Right)

3. DYNAMIC CHARACTERISTICS OF STAIR SYSTEMS

This paper discusses the dynamic characteristics of modular stair systems (MSS) with drift-compatible connections. In the 10-story mass timber building, two types of MSS with drift-compatible connections will be tested. In the first three stories, at the mid-landing level, two drift-compatible connections are attached to a single attachment channel (see Figure 1). The lower flight is bolted to this channel using four 1/2"-diameter ASTM A325 tension control bolts. The upper flight is bolted to the same channel using two 1/2"-diameter ASTM A325 tension control bolts. In the fourth story, to allow free movement of each stair flight and corresponding drift-compatible connection, two attachment channels are installed. There is a two-inch gap between attachment channels (see Figure 2).

In the dynamic response of the stair system, both the local and global vibration modes are essential to fully characterize the stair subsystem. The local vibration modes manifest within each stair largely along the flights, see Figure 5. To determine the local mode in Abaqus modal analysis is conducted on each stair unit separately. The global mode of the stair system consists of the vibration modes of the stair tower at the system level. The structural non-structural interaction primarily depends on the global modes of the stair tower. The global modes of stair systems are calculated based on a simplified shear-frame model of a 10-story stair tower. The story stiffness is based on the pushover analysis of the proposed FEM.

3.1 STAIR SYSTEM WITH DRIFT-COMPATIBLE CONNECTIONS

In Abaqus, linear perturbation analysis is conducted to obtain the modal properties of the modular stair systems with drift-compatible connections. During linear perturbation analysis, the model's response is defined by its linear elastic stiffness at the base state. The mode shapes and corresponding vibration frequencies of the stair system with a single attachment channel are shown in Figure 5. The first mode of this stair system corresponds to the vibration of stair flights transverse to the stair run direction (in Y-direction). The second local mode of the stair system corresponds to the buckling of stringers because of the single attachment channel.

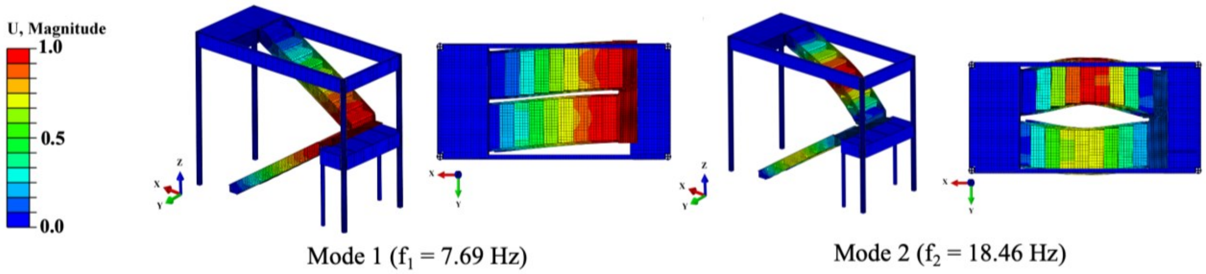

Figure 5. First two local modes of stair system with a single attachment channel

In the stair system with two attachment channels at the mid-landing level, the movement of the lower flight is independent of that of the upper flight. Therefore, as is seen in Figure 6, the vibration modes of the stair flight are not continuous throughout the stair height, rather each flight vibrates in distinct vibration modes. The first vibration mode of this stair unit corresponded to the vibration of upper flight in the gravity direction. The vibration of lower flight in transverse to the stair run direction (in Y-direction) corresponds to the second mode of the stair unit. The stair system with two attachment channels at the mid-landing connections is more flexible than the one with a single attachment channel. The natural periods corresponding to the local modes of the stair systems are much lower than the building period. However, as discussed in Section 3.2.3, the natural periods corresponding to the global vibration modes of the stair tower are closer to the building vibration period.

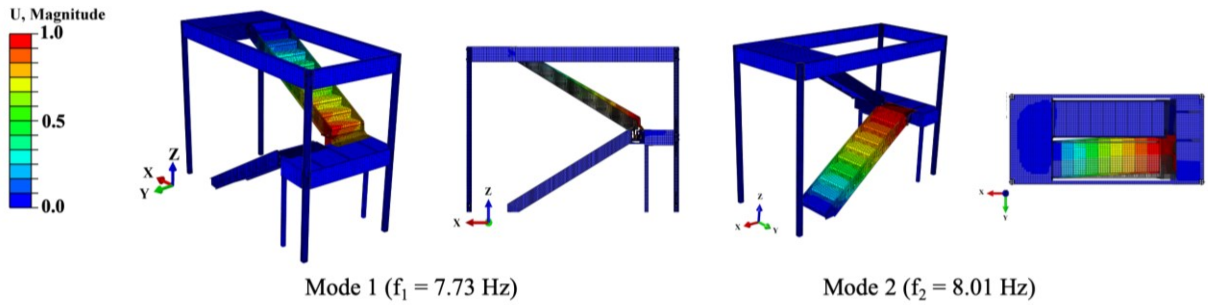

Figure 6. First two local modes of stair system with two attachment channels

3.2 GLOBAL MODAL PROPERTIES OF 10-STORY STAIR TOWER

To determine the global modes of the stair tower, a 10-story shear frame is assumed for characterizing the 10-story stair tower. Specifically, a lumped mass model of the shear frame is developed. The stair mass is distributed throughout the stair tower height such that mass at each level accounts for 50% of the story mass above and below the specific level. The stiffness of the lumped mass model is based on the initial stiffness of the pushover analysis of the developed FEM.

3.2.1 Pushover Analysis of Stair System with Drift-compatible Connections

To determine the lateral load-displacement relation of the stair system, a pushover analysis is conducted. In the pushover analysis, after applying the boundary conditions as stated in Section 2.3, monotonic, slow application of displacement-controlled load is applied at the stair channel band in each of the X and Y directions. The target interstory drift ratio (IDR) for the stair system with two attachment channels is 4%. However, the target IDR for the stair system with a single attachment channel was set as 3.5% as convergence issues are observed at the large in-elastic response of the attachment channel. Figures 7 and 8 show the pushover analysis results of the stair systems with one and two attachment channels, respectively. Griffis [1993] states that the typical interstory drift ratio (IDR) corresponding to the serviceability limit state is 0.17% to 0.5%. Therefore, in this study, the initial stiffness of the stair system is calculated based on a secant line from IDR=0 to 0.5%. Both stair systems showed higher stiffness in the longitudinal direction (X-direction) compared to the lateral direction (Y-direction). It is worth noting that the stair system with two attachment channels performed well and sustained no material yielding. This high-fidelity FEM captures the interaction between each component and the friction response between each surface in contact. Therefore, the nonlinearity in the pushover curve is due to the interaction between stair components (Figure 8). However, during pushover analysis of the stair system with a single attachment channel in the X-direction, the upper flight of the stair system freely slides until an IDR of 1.25% (See Figure 7). Beyond IDR=1.2% the torsion of the attachment channel about the Y axis was observed.

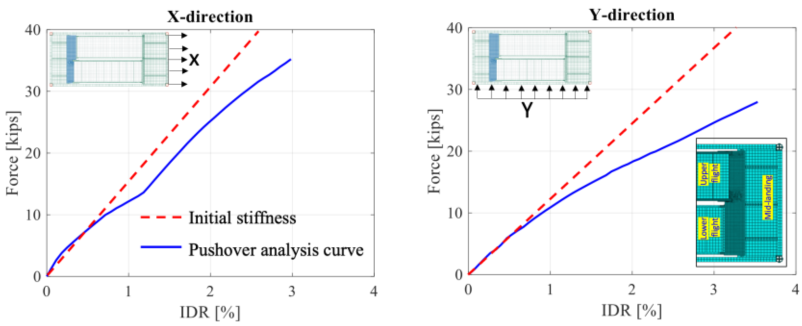

Figure 7. Pushover analysis results of stair system with single attachment channel

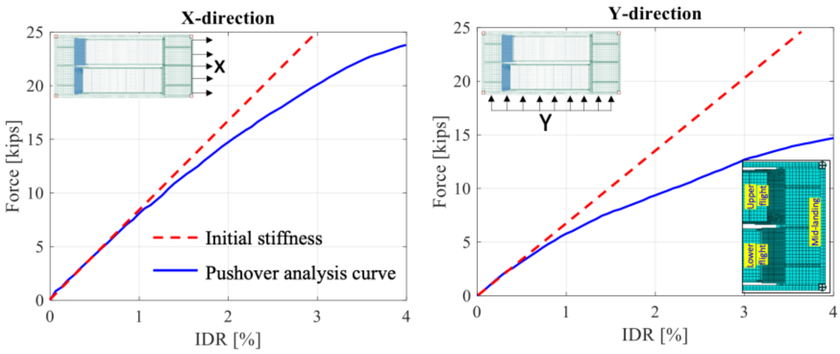

Figure 8. Pushover analysis results of stair system with two attachment channels

3.2.2 Modal Properties of the 10-story Stair Tower

Eigenvalue analysis of the lumped mass model is conducted to determine the global mode shapes and corresponding natural vibration periods of the 10-story stair tower. The developed finite element model of the stair systems represents the modular stair systems on the 2nd, 3rd, and 4th stories of the NHERI Tallwood building as shown in Figure 1. The stairs on the 1st, 9th, and 10th stories have the same connection details. However, the first story is 2 ft taller than all other stories, and the stairs on the 9th and 10th stories represent traditional construction. Therefore, the initial stiffness of the 1st, 9th and 10th stories, which are based on the 2nd and 4th stories, are adjusted to consider the change in the configuration of the stair systems. These adjustments are based on the stiffness of stair columns with fixed boundary conditions at the bottom and top connections. The initial stiffness calculated based on the pushover analysis of the stair system with a single attachment channel is applied at the 5th -8th stories. Figure 9 summarizes the lumped mass model properties and associated eigenvalue analysis results of the 10-story stair tower.

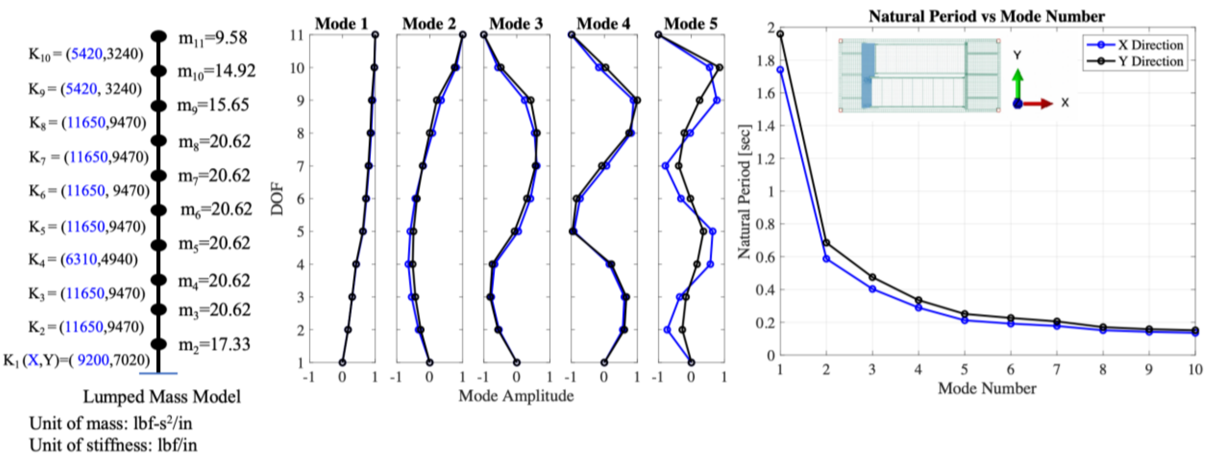

Figure 9. Global modal properties of the 10-story stair tower

The stair systems with slotted connections (stories 5 and 6) and those with fixed-free configurations (Stories 7 and 8) are stiffer than the stair system with drift-compatible connections. At this time the exact initial stiffnesses of these four stories are unknown. Figure 10 shows the natural periods corresponding to the first 10 modes and the first mode shape of the 10-story stair tower considering various stiffness values for these four stories. In this eigenvalue analysis, the stiffness of stories 5 through 8 is defined in terms of the percentage of the stiffness of the stair system at story 2. The figure illustrates that stiffness values beyond 100% do not have a significant effect on the modal properties, while stiffness values below 100% have a significant effect.

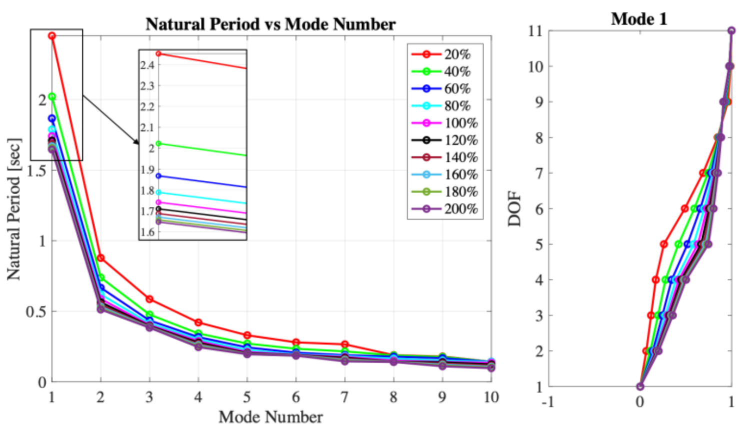

Figure 10. Global modal properties of 10-story stair tower with varying stiffness at story 5 to 8

3.2.3 Relation Between Modal Properties of the Building and the Stair Tower

The modal properties of the stair tower can be compared to the modal properties of the building acquired from the 3D non-linear OpenSees numerical model presented in Wichman *et al.* [2022a-b]. This model was initially developed and utilized to conduct non-linear response history analyses for the design of the lateral force resisting system of the test building. As a result, the model is a simplified representation of the building, including only the four post-tensioned structural walls, absent the stairs, and other non-structural building components. Figure 11 summarizes the natural periods of the building and the stair tower. The first, second, and third mode periods are shown for each of the two orthogonal directions in the building as well as the torsional response. As seen from this figure, the natural periods corresponding to the first mode of the stair tower in both the x- and y-directions are close to that of the building. Thus, it is anticipated that the stair tower will oscillate nominally with the building when this vibrational period is excited. However, the second and third modes of the stair tower are much larger than those of the building. Thus, it can be anticipated that at higher modes the two systems will be out of phase. It should be mentioned that the proposed lumped mass model of the stair tower does not capture the torsional modes of the stair tower, however, it is notable that none of the stair tower predicted translational modes are close to the first torsional mode of the building (~1.1sec), implying minimal interaction when the building is excited at this mode.

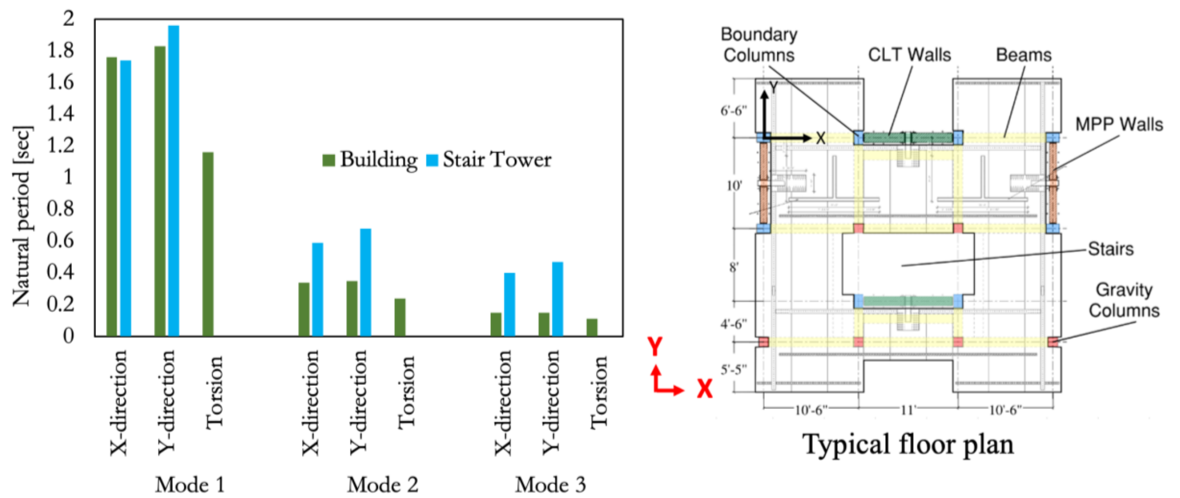

Figure 11. Natural periods of the building and the stair tower (Left), and a typical floor plan (Right (Wichman *et al.* 2022b))

At the time of writing this paper, the NHERI Tallwood 10-story mass timber building is under construction. Currently, the floor panels at level 6 are being constructed. According to the current state of knowledge, the shake table testing of this building will happen in January 2023.

4. CONCLUSIONS

This paper describes a high-fidelity finite element model of a modular stair system with drift-compatible connections to be tested as part of the NHERI Tallwood 10-story mass timber building. The modelling approach is based on a methodology previously proposed and validated through comparison with experimental data [Sorosh et al., 2022]. Of particular interest herein, are the dynamic characteristics of the modular stairs, considering drift compatible details, with two different attachment strategies. Using modal analysis and nonlinear static pushover analysis, it was shown that stair systems with two attachment channels at the flight to mid-landing connections are more flexible than those detailed with a single attachment channel. In addition, in the case of a stair system with two attachment channels, during pushover analysis with a target IDR of 4%, no damage to the stair components was observed. However, the bending of an aluminum plate and yielding of the associated attachment channel is expected on the stairs with a single attachment channel.

In stair systems, the local modes account for the vibration of stair components within each stair unit. The design and performance of stair components and connections depend on the local modes. However, the design and performance of connections between the stair system and the floor diaphragm and the interaction between the stair systems and the supporting building strongly depend on the global modes of the stairs. Therefore, in this study, a simplified lumped mass model of the 10-story stair tower was developed using data from the nonlinear static pushover analysis and the geometry of the stair system.

The NHERI Tallwood 10-story mass timber building is currently under construction. Parallel to the construction phase, each stair system is being tested under man-loaded walking excitation, wind excitation, and low amplitude impact loading. Analysis of these system identification tests is ongoing and may be available for comparison to the high-fidelity FEM discussed herein at the time of the workshop.

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