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Influence of Stair System Flexibility on Building Vibration Period: Insights from Full-Scale Building Shake Table Tests at Low-Amplitude Excitation

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Abstract. Stair systems, which provide the primary means of egress in and out of a building during and after an earthquake, play a critical role in seismic resiliency. Often, these systems are detailed with fixed flight-to-landing connections. However, previous experimental studies and field reconnaissance have shown that such configurations are prone to severe damage. To mitigate this damage to both the stair systems and the supporting structural members, as well as to avoid the ensuing potential to stiffen the lateral force resisting system of the building, stair connections are often detailed to release drift demands. Referred to as drift-release, these approaches generally focus on releasing inter-story drift at the flight-to-landing connections. Findings from a recent shake table test of a 10-story prefabricated stair system within a mass timber building showed that stair systems with drift-release connections result in a seismically resilient egress solution. However, due to the free movement of stair flights, handrail connections received damage at multiple levels. In a complementary follow-on study, a 9-story stair system with refined connection details was integrated into a 10-story cold-formed steel (CFS10) building recently tested at NHERI@UC San Diego. Numerical analyses have indicated that stair systems with fixed flight-to-landing connections can influence the dynamic characteristics of the supporting structure due to strut action. As such, stairs in the CFS10 building system were designed to allow for easy modification between fixed and drift-release connections by installing or removing locking bolts at the flight to mid-landing interfaces. In the CFS10 building, white noise tests were conducted in each orthogonal direction under two configurations: first, with the stair connections fixed, and then with the locking bolts removed. This study aims to determine the impact of stair connection detailing on the modal characteristics of the building. In addition, complementary numerical simulations were carried out for both fixed and drift-release stair configurations. Based on both experimental and numerical studies, it is found that, under low-amplitude excitation, the impact of stair flexibility on the building vibration period is not significant because the drift-release connection is not appreciably engaged under small lateral loading. However, the impact of stair strut action under large-amplitude excitation still needs to be investigated.

Keywords: Modal analysis, System identification, Stairs, Dynamic characteristics, Shake table test.

1. INTRODUCTION

Stairs are among the most critical nonstructural systems, serving as the primary means of egress during and after an earthquake. Ensuring their functionality is crucial for occupant safety and building usability after an event. Past earthquakes [Li and Mosalam, 2013; Bull, 2011] and experimental studies [Higgins, 2009; Wang et al., 2015] have reported significant damage to stairs, particularly those with rigid flight-to-landing connections (see also [Hutchinson et al., 2025]). To mitigate the damage to stairs and supporting structural members and to avoid the bracing effects of stairs, recent editions of ASCE [ASCE 7-16, 2016, and ASCE 7-22, 2022] require stairs which are not designed as part of the lateral force resisting system to be detailed such that they accommodate the seismic-induced interstory drift. In alignment with this requirement, Black et al. [2017, 2020] proposed and tested several drift-release connections at the story level (i.e., subsystem level). Subsequent system-level tests by Sorosh et al. [2025] considered the performance of three types of drift-release connections as part of a 10-story mass timber building [Pei et al., 2024]. This study found that drift-release connections effectively reduce damage to the stair system even under risk-targeted maximum considered earthquake (MCE_R) motions with peak interstory drift ratios exceeding 2%. However, they observed that the free movement of stair flights can lead to minor damage in the form of handrail detachment and fracture. To further refine the design of drift-release connections and to test drift-compatible handrail attachments, a 9-story prefabricated steel stair was integrated into a 10-story cold-formed steel (CFS) building, tested on the 6-DOF Large High-Performance Outdoor Shake Table (LHPOST6) at UC San Diego. This paper provides a brief discussion of this test program with an emphasis on the impact of stair flexibility on the vibration periods of the building.

In building design practice, typically, stair systems are often ignored in the structural model. However, numerical simulations of building-stair systems have shown that incorporating the stairs into a building's finite element model (FEM) can increase story stiffness and reduce both floor relative displacements and the building's vibration period, especially in stair systems with fixed flight-to-landing connections. For instance, Tegos et al. [2013] used SAP2000 to perform multi-modal response spectrum analysis on a reinforced concrete building with various stair configurations. They found that including stairs in the building's FEM increased the building's stiffness and reduced floor displacements. Similarly, Noorifard and Tabeshpoor [2018] investigated the interaction between stair systems and a supporting five-story reinforced concrete building. This study found that including stairs in the buildings' FEM not only increased stiffness and reduced the fundamental period but also altered the internal force distribution in structural members. More recently, Wen et al. [2022] conducted a numerical investigation on frame structures with beam-type staircases. Their study found that including stairs as part of a building's FEM, whether with fixed or sliding connections, significantly influenced both the staircase and overall building response. Notably, they found that sliding connections, as compared to fixed connections, reduced seismic demands on both the stair components and the supporting structural system. However, none of these results have yet to be experimentally confirmed - though they elevate the need to experimentally investigate the impact of stair stiffness on the modal characteristics of the supporting structure. In this regard, to evaluate the impact of stair stiffness on vibration periods of the supporting structure, the stair systems in the CFS10 building were designed to allow for reconfiguration between fixed and drift-release connections. This was achieved by installing or removing bolts at the flight-to-mid-landing connections. White noise tests were conducted in each orthogonal direction under two configurations, namely 1) with the stair connections fixed, and subsequently, 2) with the locking bolts removed to allow the stair flights at their mid-landings to move freely. This paper discusses the impact of stair stiffness on the modal characteristics of the supporting structure numerically and experimentally, as elicited from these unique test configurations.

2. SHAKE TABLE TEST PROGRAM

2.1 TEST SPECIMEN

2.1.1 CFS10 Building

The CFS-NHERI project is a multi-university-industry collaborative project that aims to advance the understanding of the seismic performance of mid-rise CFS buildings beyond the current height limitation of 19.8 m set by ASCE 7-22 [2022]. As part of this project, a capstone 10-story CFS-framed test building, coined CFS10, with a total height of 30.5 m and a floor plan of 6.86 m × 11.58 m, shown in Figures 1A and 1B, was built and tested on top of the 6-DOF Large High-Performance Outdoor Shake Table (LHPOST6) at UC San Diego. The primary lateral force resisting system of this building consists of steel sheet sheathed shear walls, along with, in one direction, chord studs detailed with both a continuous tie-rod system and outer CFS compression packs, and in the other direction, a mix of CFS compression packs and hollow structural sections (HSSs) to resist high overturning moments of such a tall building. Hutchinson et al. [2026] provides a detailed discussion of the test program, design narratives, and preliminary seismic response results of the CFS10 test building. Specifics of the design details are also provided in greater detail in the compilation by Singh et al. [2022, with extensions to the design in 2024]. Various nonstructural components and systems, including a 9-story stair system with various drift-release connections, windows, fire sprinklers and risers, and gas pipes, were incorporated into this building.

2.1.2 9-story Stair System

A 9-story stair tower, shown in Figure 1C, was integrated into the CFS10 building. The scissor-style prefabricated steel stair system was oriented such that its strong (longitudinal) axis aligned with the building's Y-axis, while its weak (transverse) axis aligned with the X-axis of the building. This shake table test program featured a modular stair system (MSS), in which stair units were preassembled off-site and installed as complete story-level units. Each story unit was designed to carry the gravity load of the entire stair tower, while lateral loads were transferred to the floor diaphragm through shear straps installed at each level. The use of a modular design in the stair system offers advantages such as reduced construction time and improved control over stair-to-diaphragm construction tolerances (Rivera et al., 2026).

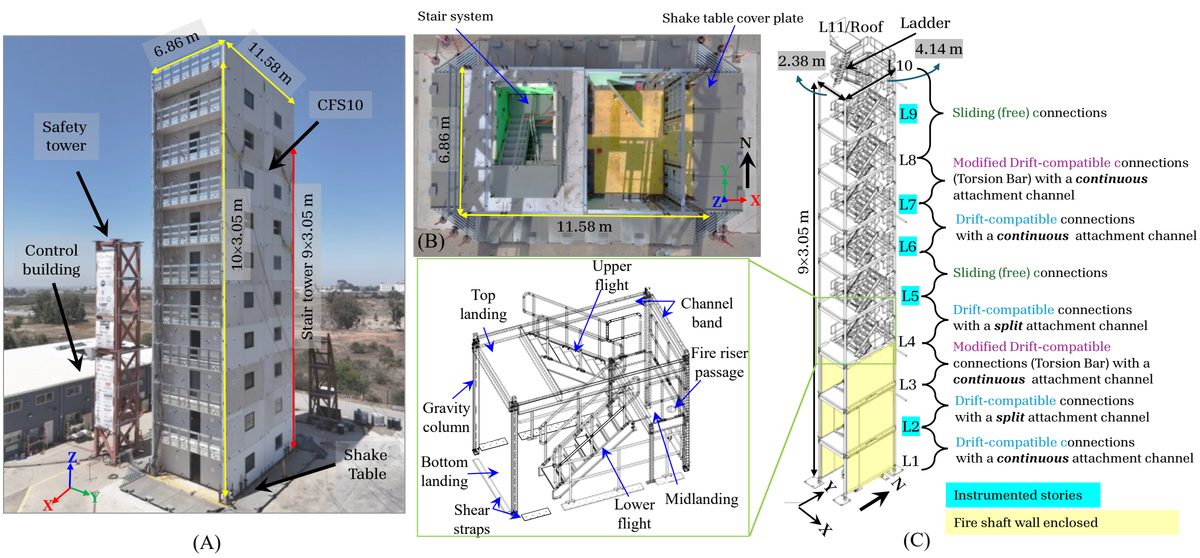

Figure 1. (A) CFS10 building isometric view, (B) CFS10 building plan view, and (C) stair tower isometric view (various connection types are color-coded)

As shown in Figure 1C, stairs with various configurations and midlanding connection details were incorporated in the CFS10 building. Three types of drift-release connections that were integrated into this building (1) sliding or free connections (Figure 2A) with two translational degrees of freedom (DOFs) (Δ_X, Δ_Y) along with a rotational DOF about Z axis (θ_Z), and (2) drift-compatible connections (Figure 2B) with two translational DOFs (Δ_X, Δ_Y), one rotational DOF (θ_X), and a nominal vertical DOF (Δ_Z), and (3) a modified drift-compatible connection (Figure 2C) with two translational DOFs (Δ_X, Δ_Y) and two rotational DOF (θ_X, θ_Z). Figure 2 presents details of these connections, where translational and rotational DOFs are indicated by green arrows. Notably, in the modified drift-compatible connection (Figure 2C), the rotational DOF about the Z-axis (θ_Z) is coupled with translational motion, as shown by the blue arrow at the connection interface. In stair systems with a free connection, as depicted in Figure 2A, both lower flight (LF) and upper flight (UF) stairs are resting on the gravity support at midlaning (ML). As shown in Figure 2D, in stair systems with drift-compatible connections, two attachment strategies are used: (1) at levels 2 and 4, each stair flight is attached to an attachment channel, and the movement of each flight is isolated from the others; however, (2) at levels 1 and 6, both stair flights are connected to the drift-compatible connection using a single attachment channel. Likewise, stair systems with modified drift-compatible connections utilize a continuous or single attachment channel. Note that despite the variation in details, all connection configurations comply with the requirements of ASCE 7-22 [2022]. Sorosh et al. [2025b] provide a thorough discussion of the design details of these stair systems. To lock the drift-release connections, temporary locking bolts were integrated at the midlanding levels, as shown in Figure 2. These locking bolts were installed during the first phase of the shake table test program to study the impact of stairs with fixed connections on the dynamic response of the building.

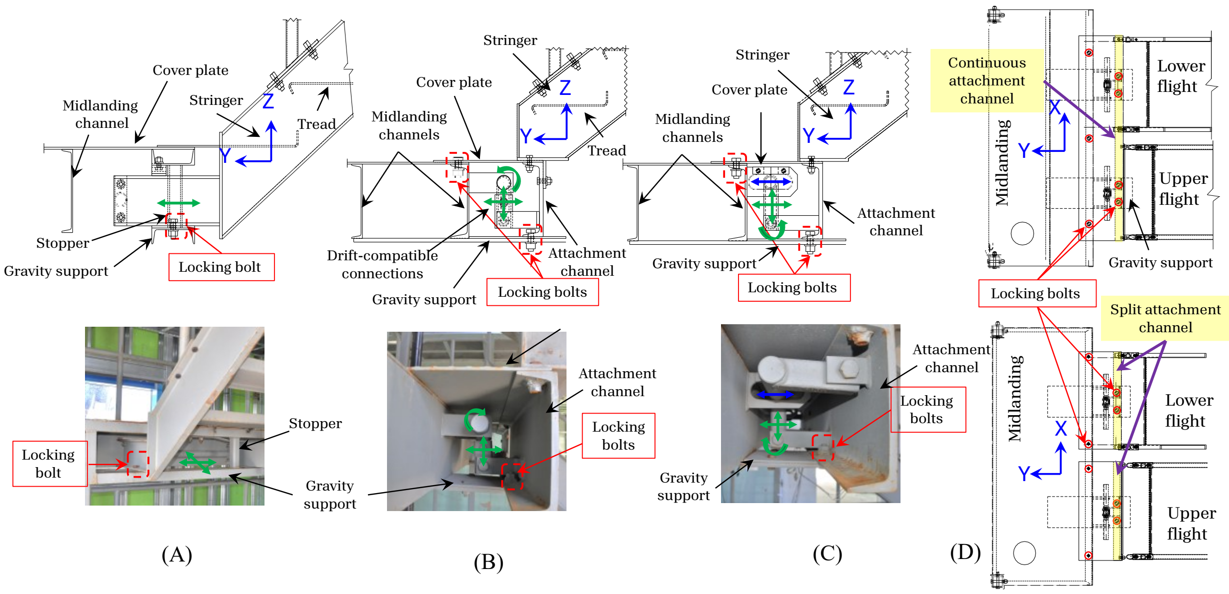

Figure 2. Stair flight to midlanding connection details and configurations (A) sliding (free) connection, (B) drift-compatible connection, (C) modified drift-compatible connection, and (D) continuous and split attachment channel details (note: DOFs are highlighted in green and blue arrows)

2.2 TEST MATRIX

The CFS10 building was tested under 18 simulated earthquake motions scaled to three distinct targeted seismic hazard levels, namely, 15 service-level earthquakes (SLE), one design earthquake (DE), and two risk-targeted maximum considered earthquakes (MCE_R). To monitor the dynamic characteristics of the building, low-amplitude unidirectional white noise tests in each orthogonal direction were conducted after earthquake motions. It is worth noting that at the beginning of each locked and unlocked stairs phase, to tune the shake table with the presence of the building, one white noise test in each orthogonal direction with a target root mean square (RMS) of 4%g and duration of 160 seconds was conducted. All other WN tests, except WN3 and WN4, were conducted with a target RMS of 4%g and a duration of 64 seconds. WN3 and WN4 were intentionally conducted with a target RMS of 3%g and a duration of 64 seconds to investigate the frequency response function of the building at smaller amplitude excitation. It is expected that larger amplitude WN tests will result in larger periods of the building at a given state. Table 1 lists the subset of tests discussed in this paper. The vibration period of the building under WN1 through WN12, with two configurations of stairs locked and unlocked, will be discussed. In addition, briefly, the response of the stairs and CFS10 building under MID1 and MID2 will be included.

Table 1. Subset of tests discussed in this paper (Note: for brevity, MID3 and MID4 are excluded from this paper. RMS: root mean square, WN: white noise, and SLE: service level earthquake).

Test Day, *Configuration*	Test	Description
Test Day 1, ***Stairs Locked***	WN1	WN_X 4.0%g RMS for a duration of 160 sec
	WN2	WN_Y 4.0%g RMS for a duration of 160 sec
	WN3	WN_Z 10.0%g RMS for a duration of 160 sec
Test Day 2, ***Stairs Locked***	WN4	WN_X 3.0%g RMS for a duration of 64 sec
	WN5	WN_Y 3.0%g RMS for a duration of 64 sec
	MID1	1989 Loma Prieta XYZ SLE (station: Gilroy Array #3)
	WN6	WN_X 4.0%g RMS for a duration of 64 sec
Stairs were unlocked after WN7	WN7	WN_Y4.0%g RMS for a duration of 64 sec
Test Day 3, ***Stairs Unlocked***	WN8	WN_X 4.0%g RMS for a duration of 160 sec
	WN9	WN_Y 4.0%g RMS for a duration of 160 sec
	WN10	WN_Z 10.0%g RMS for a duration of 160 sec
	MID2	1989 Loma Prieta XYZ SLE (station: Gilroy Array #3)
	MID3	1989 Loma Prieta X SLE (station: Gilroy Array #3)
	MID4	1989 Loma Prieta Y SLE (station: Gilroy Array #3)
	WN11	WN_X 4.0%g RMS for a duration of 64 sec
	WN12	WN_Y 4.0%g RMS for a duration of 64 sec

3.EXPERIMENTAL RESULTS

3.1 STAIR SYSTEM DISPLACEMENT RESPONSE

The response of the CFS10 building and its nonstuctural components and systems during the shake table test program was monitored using more than 1000 analog sensors. Pertinent to the analyses herein, the accelerations at each level of the building and stair components were measured using accelerometers. In addition, relative displacements across stair flights to story-level landings and midlanding interfaces were measured using linear potentiometers. Note that not all levels were instrumented; refer to Figure 1C for those stories with detailed stair instrumentation. Figure 3 shows the displacements of the stair flight with respect to the midlanding in both X and Y directions under MID1 (locked phase) and MID2 (unlocked phase) at Levels 2.5 and 5.5 (midlanding locations). Locking the stair connection, which was achieved by bolting the connection, was efficient, and small displacements across the joints were recorded during MID1. MID2 was conducted with all stair midlandings unlocked, and despite this being a service-level earthquake, small relative movements across the stair's drift-release connections were measured. As seen in Figure 3, these movements across drift-compatible connections at L2.2 and free connections at L5.5 were in the range of 0.1 to 1 mm.

3.2 BUILDING ACCELERATION RESPONSE

Figure 4 shows the acceleration time histories and corresponding 2% damped spectral acceleration recorded at the estimated center of mass (CoM) locations at levels 1, 5, and 10 in both X and Y directions. It is seen that at certain periods, for instance, at a period closer to the first flexural modes in each orthogonal direction, the power in spectral acceleration during MID1 is larger than that during MID2. This is more pronounced in the responses in the Y direction, which is anticipated as this is the strong axis of the stairs. In addition, from the acceleration response histories, it is seen that during MID1, the acceleration demand is higher than that during MID2. This may be attributed to the fixity of the stair system during MID1, as the bracing effect of the stair system during the locked phase is expected to result in larger floor accelerations. However, it is worth noting that this subtle change in acceleration demand could also be due to a change in the building's dynamic characteristics due to five white noise tests conducted between MID1 and MID2.

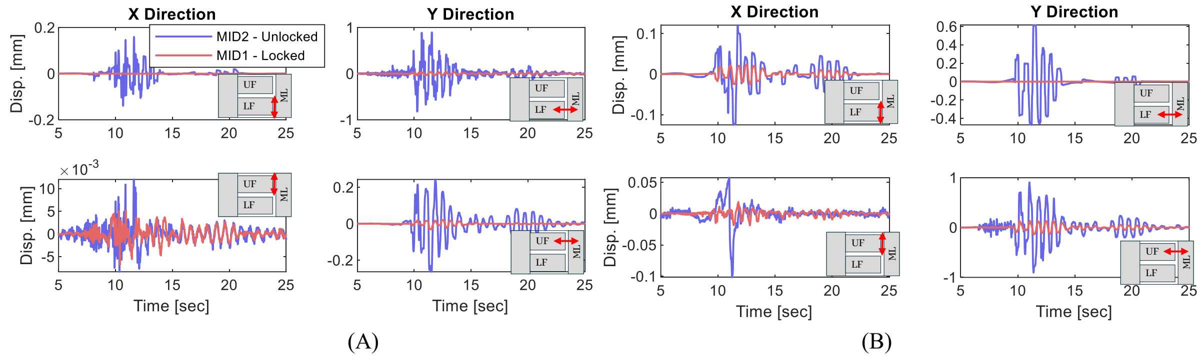

Figure 3. Stair connection displacement response during MID1 (stairs locked) vs MID2 (stairs unlocked) at (A) L2.5, and (B) L5.5

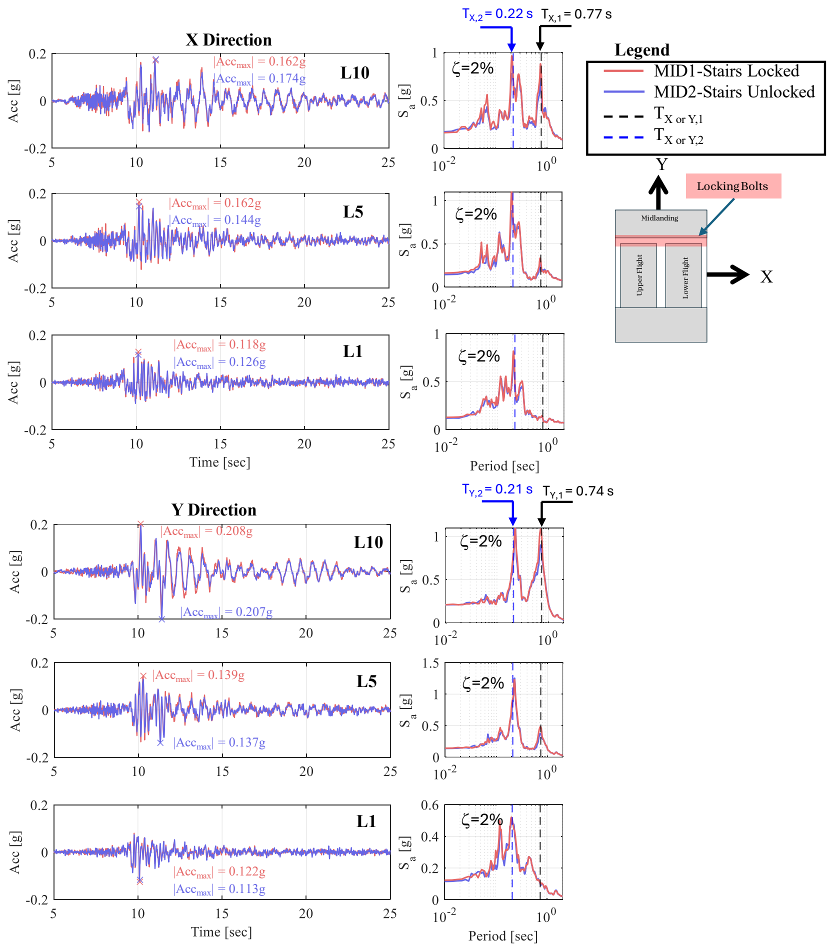

Figure 4. Acceleration time histories and corresponding 2% damped elastic spectral acceleration at Levels 1,5, and 10 during MID1 and MID2 in each of the X and Y directions

3.3 BUILDING VIBRATION PERIOD

Modal characteristics of the first three fundamental vibration modes were determined using both input-output and output-only system identification (SID) techniques. In the input-output SID, the frequency response function (FRF) of the building during the WN tests conducted in each orthogonal direction was used. In the output-only SID method, the Stochastic Subspace Identification (SSID) technique, first described by Van Overschee and De Moor (1996), was employed. All acceleration data used in the SID analysis are initially filtered using a 4^{th} order Butterworth bandpass filter [Matlab, 2022] with cut-off frequencies of [0.075 50] Hz and then baseline corrected using the mean of the first 256 data points, i.e., the first second of data.

3.3.1 Frequency Response Function

Frequency response functions define how different parts of the building amplify specific frequency components of the excitation at the base. Since white noise (WN) tests are low-amplitude broadband excitation, they excite the building modes with approximately equal energy. This characteristic of the WN test enables the estimation of modal characteristics without any significant nonlinear response of the building. In this study, the FRFs were calculated based on one acceleration either at the estimated CoM location on the shake table platen or the north-west corner of the shake table platen as the input, and the acceleration at the CoM or north-west corner at each of the other levels in the building served as the output. Considering two input signal locations, 20 output signal locations in each orthogonal direction, results in a total of 4 input and 40 output signals used in these analyses. Figure 5 shows the average FRF in the X and Y directions during WN tests listed in Table 1.

Two modal characteristic extraction methods were employed to estimate the vibration periods of the building using FRFs. In the first method, the conventional peak picking (PP) method was used to extract the vibration frequency associated with the first two flexural vibration modes and the first torsional mode based on the peaks of the FRF around these vibration modes. In addition, using FRFs, the vibration frequencies were extracted using the Least Squares Rational Function (LSRF) curve fitting algorithm with a modal order of 100 [Matlab, 2022]. Figure 6 shows the periods associated with the first three vibration modes using the methods discussed here. In general, the predicted periods using the PP and LSRF methods are in good agreement.

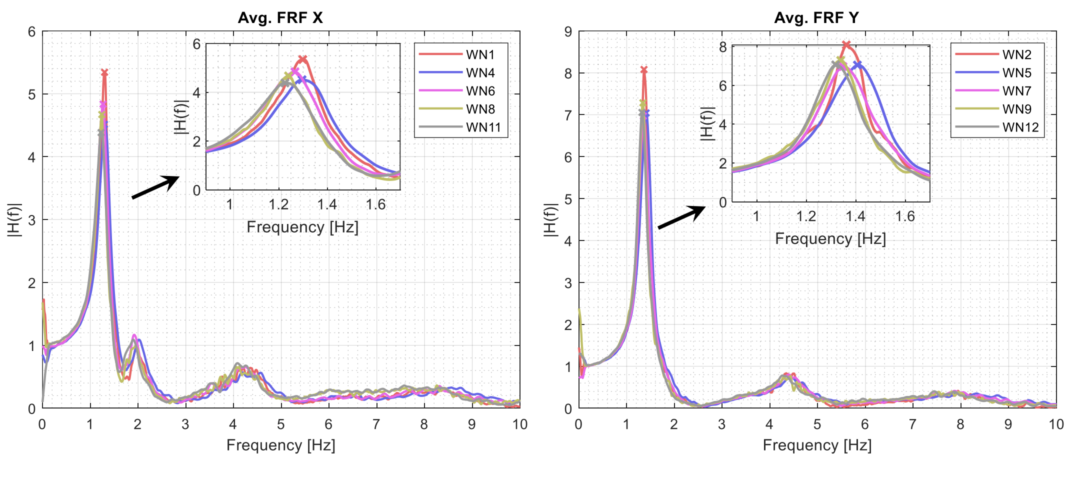

Figure 5. Averaged frequency response function

3.3.2 Stochastic Subspace Identification

Using WN test data, in addition to the two input-output methods of system identification, this study uses a time-domain output-only system identification (SID) method. In output-only SID analysis, a data-driven stochastic subspace identification (SSID) method [Van Overschee and De Moor, 1996] is used to extract the modal characteristics of the CFS10 building. SSID is a promising method for the current effort to characterize such a complex building with closely spaced modes. In this analysis, the data from 44 accelerometer channels, consisting of two accelerometer channels each at the estimated CoM on the shake table platen and the north-west corner at L1, and 40 accelerometers at the estimated CoM and north-west corner at levels 2 to L11, were used. In this analysis, the output block Hankel matrix is constructed using 100 block rows with 22 rows per block. Figure 6 and Table 2 compare the predicted period using the various SID techniques discussed in this section. The key observations from this figure are as follows:

- The predicted vibration periods based on various SID techniques match reasonably well. In general, the SSID method predicts slightly higher periods than either input-output method.
- Based on the mean of the vibration periods estimated with each method, the change in building periods corresponding to the first two flexural modes after MID1 is smaller than 2.2%. This change after MID2, MID3, and MID4 is smaller than 1.7%. However, the change in period based on the individual SID technique is as high as 3-4%.
- Observing the mean of the period estimated based on WN tests before and after unlocking the stairs, there is about 1.3% and 0.9% change in the periods corresponding to the first flexural mode in the X and Y directions, respectively. This change, based on the individual SID method, is reported as high as 2.1% and 1.8% in the periods corresponding to the first flexural mode in X and Y directions, respectively. However, it is worth noting that, as was listed in Table 1, WN8 and WN9 are 160 seconds long while WN6 and WN7 are 64 seconds long. In addition, it is noted that under such small excitation levels, the drift-release connections of stair systems are not significantly engaged, and therefore, there is a small difference between drift-release and fixed connections at low levels of shaking. However, under stronger excitation, the gap between the vibration period of a building with fixed stairs and that of a building with stairs having drift-release connections is expected to increase.

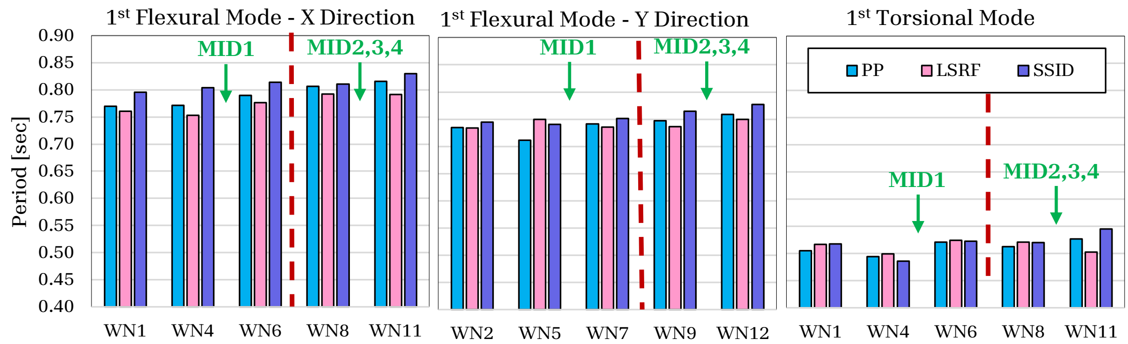

Figure 6. Building vibration periods corresponding to the first flexural modes in each orthogonal direction and the first torsional mode based on peak picking (PP), least squares rational function (LSRF), and stochastic subspace identification (SSID) methods. Note: the red vertical dashed line shows the instant of unlocking the stairs

4.NUMERICAL SIMULATION

A general-purpose finite element software [ETABS, 2018] was used to develop a simplified finite element model of individual stories of the stairs with various drift-release and fixed connections. A detailed discussion of this modeling effort is provided in Sorosh et al. [2025b]. Using these finite element models, displacement-based linear pushover analyses were conducted to estimate the story stiffness of the stairs, and these stiffnesses were incorporated into a model of the CFS10 building. Stair story stiffnesses were defined with zero-length shear springs that represent the stair tower as part of the building's finite element model previously developed by Zhang et al. [2024]. This building–stair system level simulation was used to complement the experimental modal analysis presented in the current paper. Table 3 summarizes the building vibration periods corresponding to the first three fundamental modes from eigenvalue analysis and compares them with the experimental results discussed in Section 3. Although the building model included only the minimum DOF essential to predict the building's dynamic response with low computational cost, periods from eigenvalue analysis match the experimental results reasonably well. It is seen that locking stair connections does not significantly affect the vibration periods of the building. However, based on eigenvalue analysis, excluding stairs from the building model results in a relatively larger increase in the building period, particularly in the direction parallel to the stair run (Y direction).

Table 2. Building vibration period corresponding to the first three fundamental modes (note: green lines define the instance of subjecting the building to a service-level earthquake, red dashed line is the instance of unlocking the stairs)

Mode	SID Method	Period [sec]					Period Change[1] [%]				
		WN1	*WN4*	*WN6*	*WN8*	*WN11*	*WN1*	*WN4*	*WN6*	*WN8*	*WN11*
1st Flexural Mode in the X Direction	PP	0.77	0.77	0.79	0.81	0.82	0.00	0.23	2.31	2.11	1.20
	LSRF	0.76	0.75	0.78	0.79	0.79	0.00	-1.02	3.09	2.05	-0.09
	SSID	0.80	0.80	0.81	0.81	0.83	0.00	1.03	1.15	-0.30	2.38
	Average	0.78	0.78	0.79	0.80	0.81	0.00	0.08	2.19	1.29	1.16
1st Flexural Mode in the Y Direction		*WN2*	*WN5*	*WN7*	*WN9*	*WN12*	*WN2*	*WN5*	*WN7*	*WN9*	*WN12*
	Peak Picking	0.73	0.71	0.74	0.75	0.76	0.00	-3.18	4.31	0.69	1.56
	LSRF	0.73	0.75	0.74	0.74	0.75	0.00	2.17	-1.90	0.09	1.84
	SSID	0.74	0.74	0.75	0.76	0.78	0.00	-0.53	1.45	1.81	1.64
	Average	0.74	0.73	0.74	0.75	0.76	0.00	-0.51	1.29	0.87	1.68
1st Torsional Mode		*WN1*	*WN4*	*WN6*	*WN8*	*WN11*	*WN1*	*WN4*	*WN6*	*WN8*	*WN11*
	Peak Picking	0.51	0.49	0.52	0.51	0.53	0.00	-2.13	5.26	-1.59	2.79
	LSRF	0.52	0.50	0.52	0.52	0.50	0.00	-3.44	4.96	-0.65	-3.43
	SSID	0.52	0.49	0.52	0.52	0.54	0.00	-6.26	7.24	-0.25	4.69
	Average	0.51	0.49	0.52	0.52	0.52	0.00	-3.94	5.82	-0.83	1.35

PP: Peak picking
LSRF: Least square rational function
SSID: Stochastic subspace identification
[1]Period change refers to the difference in period during a WN test compared to the previous test in the same direction.

Table 3. Building vibration period corresponding to the first three fundamental modes based on experiment and eigenvalue analysis

Mode	Experiment[1]		Numerical simulation[2]		
	Stairs Locked	*Stairs Unlocked*	*Stairs Locked*	*Stairs Unlocked*	*No stair*
1st Flexural Mode in the X Direction	0.78	0.80	0.69	0.69	0.70
1st Flexural Mode in the Y Direction	0.74	0.75	0.61	0.62	0.66
1st Torsional Mode	0.51	0.52	0.54	0.55	0.56

[1]These periods are based on the average of the 3 different methods summarized in Table 2
[2]These results are per Sorosh et al. (2025b)

5.CONCLUDING REMARKS

Previous earthquake events and tests of stair systems have confirmed that stairs are prone to severe damage under lateral loads, particularly for stairs with fixed flight-to-landing connections. In addition, numerical simulations have shown that stairs with fixed connections act as braces and significantly reduce the vibration period of supporting buildings. However, in practice, stairs are usually not incorporated into the finite element model of the supporting building. To experimentally investigate the impact of stair flexibility on the vibration period of a building, a nine-story stair tower featuring various drift-release connections was recently tested as part of a full-scale ten-story CFS building. The drift-release connections in these stairs were detailed to also facilitate a fixed connection using bolted connections. Select test results from this program are discussed in the current paper, with particular attention to the impact of stair flexibility on the vibration period of the building. Three different system identification techniques were used to extract the vibration period of the building using acceleration data recorded during white noise tests. The results from all SID techniques agree well with each other, though the output-only SSID method is generally consistently higher than the traditional input-output methods considered. It was found that locking the stair connections did not significantly change the vibration period of the building. The observed minimal change in the period of the building when comparing the locked and unlocked stairs cases was due to the small-level excitation imposed. Under small-level excitations, the drift-release connections are not fully released, and therefore, the gap between the vibration period of the building with fixed stairs and that of the building with stairs having drift-release connections is not significantly large. Nonetheless, using the experimental data herein, future numerical studies should consider larger earthquake excitations with the stairs locked and unlocked to elicit their impact on building systems under more severe hazard scenarios.

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