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DESIGN STRATEGIES AND MODELING VERIFICATION FOR STEEL STAIRS WITH DRIFT-COMPATIBLE CONNECTIONS

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Abstract

Providing the primary means of egress in and out of a building, stair systems are an essential feature in buildings and other structures. However, previous earthquakes and experiments have shown that stairs with fixed flight-to-landing connections are prone to damage. To address this issue, stair systems with drift-release connections, capable of accommodating interstory drifts, have been proposed and tested. Recent editions of ASCE 7 require stair systems that are not part of the lateral force-resisting system to be detailed such that they can accommodate interstory drift demands. To investigate the resulting force and displacement distribution in real buildings considering these requirements, a nine-story stair system with varied drift-release connections and configurations at each level were incorporated into a recently tested 10-story cold-formed steel building at UC San Diego. All stories of the stair system were detailed to facilitate creation of a fully fixed configuration as well. This paper presents the design strategies utilized to detail these drift-release connections in this test program. It further describes the development of a practice-oriented, simplified finite element model of stair systems with drift-release connections using the general-purpose FE platform (ETABS). Linear pushover analyses were performed to determine the story stiffness of the stair system with drift-release connections and to compare them with stairs having fixed connections. The results were then incorporated in a phenomenological FE model (FEM) of the building, where zero-length shear spring elements were employed to incorporate stair stiffness. In the present paper, the influence of the stair system flexibility on the building's vibration periods is discussed.

Introduction

Seismic resilience defines a buildings capacity to resist earthquake load and return to functionality post event. When evaluating seismic resilience, although the response of the structural system plays a key role, the performance of the stair systems is equally important as it provides the primary means of egress in and out of a building during and after an earthquake event. Previous earthquake events and experimental studies have documented significant damage to stair systems under lateral load. For instance, Li and Mosalam (2013) reported significant damage to reinforced concrete stairs and their supporting structural members during the 2008 Wenchuan earthquake. In addition, Bull (2011) showed damage to steel and concrete stairs in the 2011 Christchurch earthquake.

Commonly stairs are detailed with flight-to-landing connections fixed. Investigating the performance of stairs with fixed connections experimentally showed that stairs are prone to damage. For instance, Simmons and Bull (2000) tested full-scale precast concrete stairs with fixed boundary conditions under quasi-static loading, and they reported concrete crushing and bar fracture below 2% drifts. Higgins (2009) tested full scale steel stairs under reverse cyclic loading, and they reached a maximum drift ratio of 2.5%. However, significant yielding of the flight to landing attachment was observed. Subsequently, Wang et al. (2015) studied the performance of prefabricated scissor configured steel stairs as part of a five-story full-scale reinforced concrete building. In these tests, weld fractures were reported at the flight-to-landing connection prior to the building reaching its design drift limit (2.0-2.5%).

Since stairs are attached to multiple floors, they are exposed to multiple support excitations during a seismic event. As noted earlier and discussed in more depth in a state-of-the-art review by Hutchinson et al. (2025), both reconnaissance studies and experimental investigations have shown that stairs with fixed connections are highly vulnerable to damage. To address this issue, ASCE 7-16 and ASCE 7-22 (2016, 2022) mandate that egress systems not part of the lateral force-resisting system be detailed to accommodate interstory drift without losing gravity support. Building on this requirement, Black et al. (2017, 2020) investigated the performance of prefabricated steel stairs with various drift-release connections at the subsystem scale (i.e., story-level). Their results demonstrated promising behavior, but system-level validation remained necessary. To address this gap, Sorosh et al. (2025) performed full-scale shake table testing of a 10-story stair tower integrated within the mass timber rocking-wall braced TallWood building (Pei et al., 2024). This study confirmed that drift-release connections effectively mitigated severe stair damage across a wide range of earthquake intensities. Even under risk-targeted Maximum Considered Earthquake (MCE_R) motions, which resulted in interstory drifts larger than 2%, no major stair damage was observed. Minor damage in the form of handrail detachment, fracture of handrail, and gap opening between shaft walls surrounding the stair tower were reported, though these did not compromise the intended function of the stair system.

To further refine connection detailing, especially for drift-release and handrail systems, a nine-story prefabricated steel stair system with various connection configurations is incorporated into the recently tested 10-story cold-formed steel (CFS10) building on the six-degree-of-freedom Large High-Performance Outdoor Shake Table (LHPOST6) at UC San Diego. This paper discusses the design strategies used in detailing the drift-release and handrail connections. In addition, modeling techniques used to determine story stiffness of a single-story stair system is elaborated. Story stiffness from these analysis results is used to model the stairs as part of the larger system level model of the whole building. Eigen value analysis is conducted to determine the impact of stairs on the vibration period of the supporting structure.

Cold-Formed Steel 10 (CFS10) Building

The CFS-NHERI project is a multi-university-industry collaborative project that intends to advance the understanding of the seismic performance of the mid-rise CFS buildings beyond the current height limitation of 19.8 m set by ASCE 7-22 (2022). The shake table test of a full-scale 10-story CFS building (CFS10) was part of this project. CFS10, with a total height of 30.5 m and typical floor plan of 6.86×11.58 m, was built and tested on top the six-degree-of-freedom large high performance outdoor shake table (LHPOST6) at UC San Diego (Figure 1A). The primary lateral force resisting system for the building was steel sheet sheathed shear walls along with chord studs for the lower six stories designed of hot-rolled steel sections (HSS). Various nonstructural components and systems were integrated into this building, some of which include a 9-story stair tower with various drift-release connections and configurations. In addition, the building was outfitted with windows, fire sprinklers and risers, gas pipes, and roof top units. Uniquely, all stories of the stair system integrated in this building were detailed to facilitate creation of a fully fixed configuration as well. The current paper focuses on the design techniques used to detail drift-release connections within stair systems, with an emphasis on investigating the contrast in behavior should these connections be fixed. In this regard, development of a simplified finite element model of the stairs to assess the story stiffness is discussed. For more information on the overall scope of the shake table test program and the response of the building under earthquake loading refer to Hutchinson et al. (2026).

Design Considerations to Detail Stair System

As shown in Figures 1B and 1C, a nine-story stair tower was integrated within the west compartment of the building. The stair's longitudinal axis, oriented parallel to the stair run, was aligned with the Y-axis (north–south direction), while its transverse axis, perpendicular to the stair run, was aligned with the X-axis (east–west direction). The stair system was designed following a modular concept, where each story-level module functioned as an independent unit capable of carrying the gravity load of the entire tower. However, the shear forces of the stair tower are transferred to the supporting floor diaphragm through shear straps. This modular approach facilitated constructability, ensured redundancy, and allowed for efficient load transfer.

To investigate the various drift-release connections and refine the connections discussed in Sorosh et al. (2025), three different drift-release connections, namely drift-compatible connections, modified drift-compatible connections, and sliding connections, were incorporated into different levels of the stair tower (Figure 1C). The intention here is to reduce the seismic demands on stair members and supporting structural members, to mitigate seismic damage to stair connections and components during a seismic event and to validate alternative detailing methods to provide drift-release connection options for stair systems. In addition, the bottom three modules of the stair tower were enclosed with fire-rated shaft walls to satisfy egress and fire-safety requirements, creating a realistic representation of building stair construction. It should be noted in the TallWood stair test program, damage to handrail elements were observed distributed throughout the mid-level locations (Sorosh et al., 2025); therefore, in the CFS10 program a variety of handrail details with the aim of mitigating this damage, were also explored. The subsequent subsections elaborate on the design techniques to detail these connections.

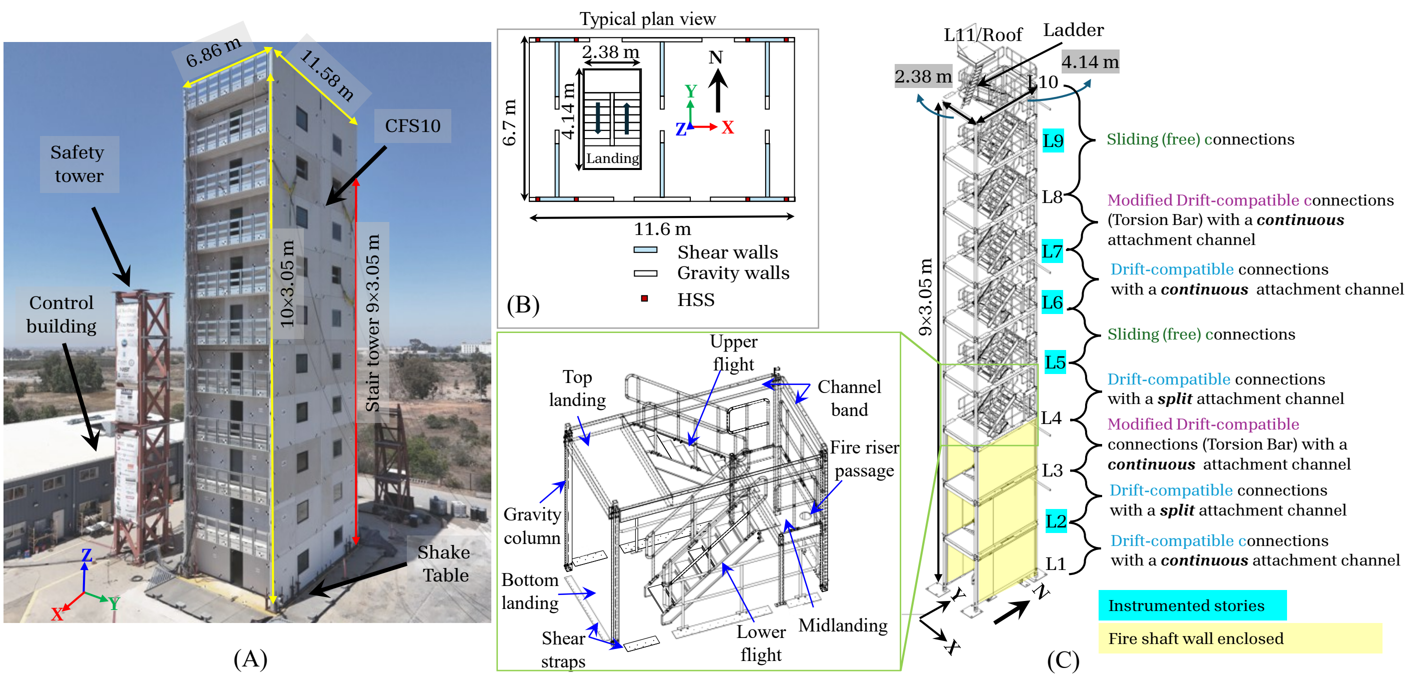

Figure 1. (A) CFS10 isometric view, (B) typical plan view and (C) stair tower and configuration (note: various connection types are color coded.

Seismic Relative Displacement

Section 13.5.10 of ASCE 7-16 (2016) and ASCE 7-22 (2022) are used to determine the displacement demand of stair connections. To account for the seismic drift, the stair system is not considered as part of the seismic force resistance system. Therefore, according to these standards, stair connections are required to accommodate the minimum displacement suggested by the design code or the expected maximum displacement of the building under MCE_R demand. This standard suggests use of a sliding connection with slotted or oversized holes, sliding bearing supports with end stoppers for safety concerns, or other types of connections that allow movement via deformation of the metal attachment. These connections shall accommodate a displacement of D_{PI} (Equation 1) but no less than 13 mm (0.5 in) without loss of vertical support. D_{PI} is the design seismic relative displacement, computed as:

$$D_{PI}=(\Delta_{xA} - \Delta_{yA})\times I_e \tag{1}$$

Where Δ_{xA}, and Δ_{yA} are the building displacements at the height of h_x and h_y (equation 13.3-8 of ASCE 7–22 (2022)), and I_e is the importance factor based on section 11.5.1 of this standard. For stair system, the importance factor of 1.5 was considered. The expected peak interstory drift ratio (PIDR) of CFS10 under MCE_R motion was 1.5%. Considering PIDR of 1.5% and story height of 3.05 m, D_{PI} is 69 mm. Since each of drift-release connections are placed at the mid-landing level, they are exposed to approximately 50% of interstory drifts. This seismic drift demand was experimentally verified by Sorosh et al. (2025) for various drift-release connections. Considering a safety factor of 1.5, a minimum drift of 52 mm shall be accommodated at the stair connections in CFS10 building.

Detailing Drift-release Connections

Stair systems within the CFS10 building featured three types of drift-release connections: a sliding (free) connection, a drift-compatible connection, and a modified drift-compatible connection. As shown in Figure 2A, with degree of freedom (DOF) indicated in green arrows, sliding connection has two translational DoF (Δ_X, Δ_Y) along with a rotation DoF about Z axis (θ_Z). This connection is detailed based on the recommendations in ASCE 7-22 (2022). As shown in Figure 2A, two HSS tubes are designed to serve as stoppers that engage under extreme drift demand. The drift capacity of this connection is 89 mm in the positive Y direction, and 108 mm in the negative Y direction. Drift-compatible connections, shown in Figure 2B, provide two translational DOFs (Δ_X, Δ_Y), one rotational DOF (θ_X), and a nominal vertical DOF (Δ_Z). The drift capacity of this connection is 194 mm in the positive Y direction and 155 mm in the negative Y direction. Figure 2C illustrates the third type of drift-release connection, the modified drift-compatible connection. In addition to the characteristics of the drift-compatible connection, this configuration allows free rotation of the stair flight about the Z-axis. This rotation is enabled by an additional translational DOF, indicated by the blue arrow in Figure 2C. It is worth noting that each of these connections are detailed with gravity support below each stair flight. To study the response of stairs with rigid (fixed) connections and compare their response to the stairs with drift-compatible connections under similar geometrical conditions, each of these connections were detailed with locking bolts to assure complete restraint in all DoF of the otherwise drift-released connections. This allows investigation of the response of the stair system with a fully fixed connection and its impact on the dynamic characteristics of the building (Figure 2). These bolts are detailed such that they can easily be removed and subsequently converted to a stair system with fully drift-release connections.

As shown in Figure 2, flights in stair systems with free connections rest directly on the gravity supports without any additional attachment detailing. In contrast, stair systems with drift-compatible and modified drift-compatible connections use an attachment channel to connect the stair flights to the drift-release connections. As illustrated in Figure 3, two strategies were employed: a continuous (single) attachment channel and split (two) attachment channels. In the continuous channel configuration (Figure 3A), both stair flights share the same channel, which is connected to the flights on one side and to the drift-release connection on the other. In the split channel configuration (Figure 3B), each stair flight is supported by its own attachment channel, thereby isolating the movement of the two flights. As shown in Figure 3C, the stair flights are connected to the attachment channels through bolted connections. Numerical studies on similar stair systems showed that stairs with continuous attachment channels are relatively stiffer than those with independent split channels (Sorosh et al. (2022). It should be noted that in total, 56 locking bolts were distributed throughout the 9-story stair system within the CFS10 building to facilitate locking of each of these connections, see Figure 4.

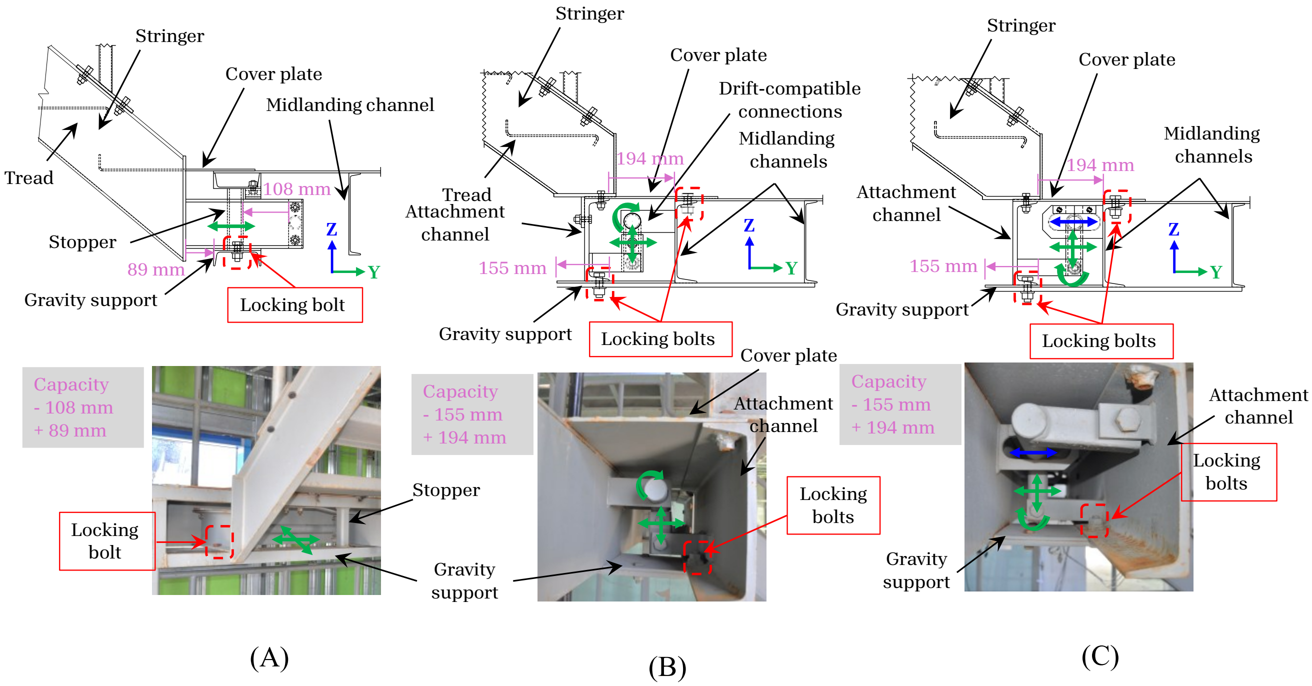

Figure 2. Stair flights to midlanding connection details and configurations (A) sliding (free) connections, (B) drift-compatible connections, (C) modified drift-compatible connections.

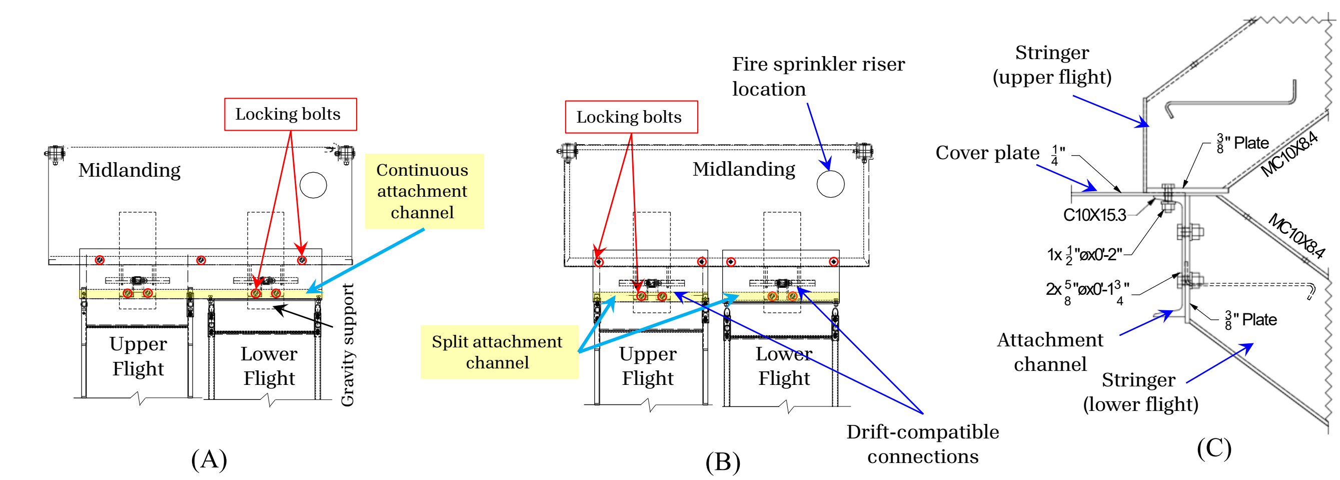

Figure 3. Two flights to drift-compatible connection attachment techniques (A) continuous (single) attachment channel and (B) split (two) attachment channels, and (C) bolted connections at the stringer to the attachment channel interface.

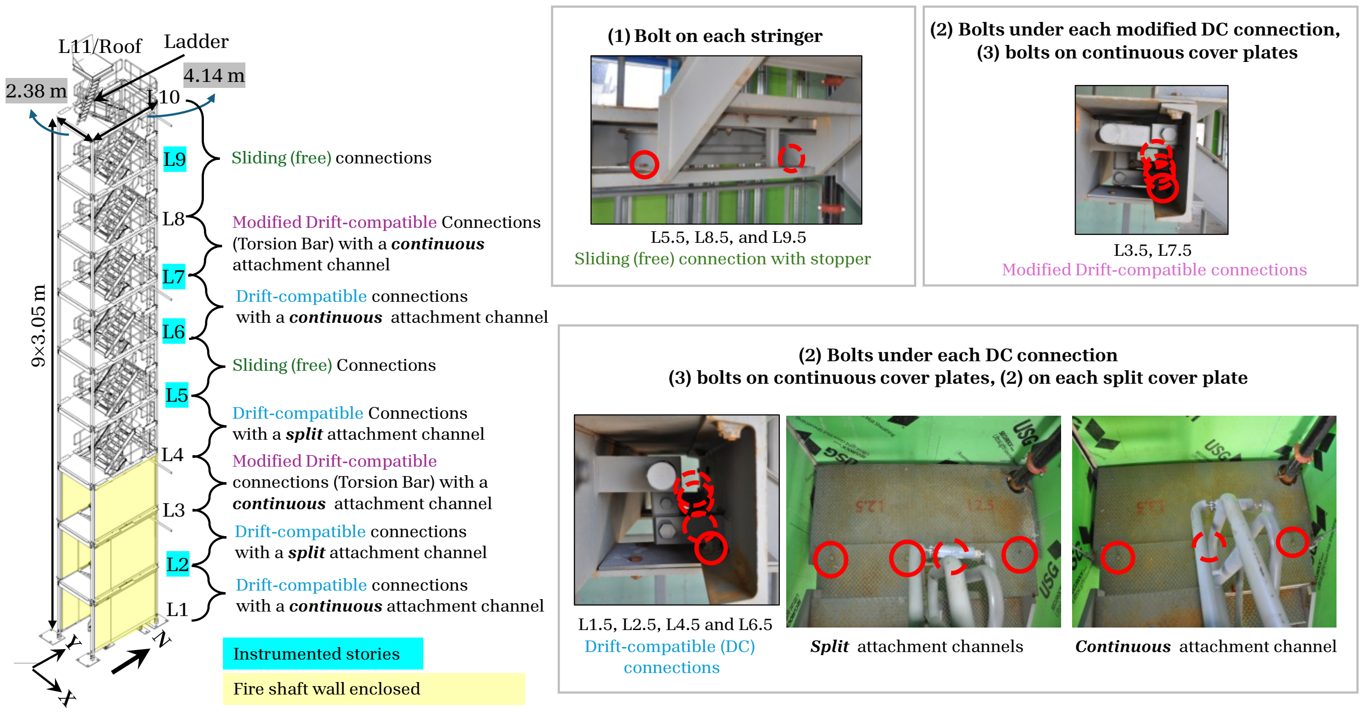

Figure 4. Locking bolts configuration of stair system with various drift-release connections (locking bolts locations are annotated using red circles).

Flight to Landings Connections

In stair systems with sliding connections at the mid-landing level, the lower flight is detailed with a fixed-type connection, as shown in Figure 5A. In this configuration, each stringer of the lower flight is bolted to the face of the bottom landing channel, and no relative movement of the stair flight across this interface is expected. In stair systems with drift-compatible and modified drift-compatible connections at the mid-landing level, the lower flight is attached to the bottom landing through a bolted connection with oversized holes to accommodate construction tolerances (Figure 5B). In this case, small relative movement of the stair flight across the joint is expected during earthquakes of large intensity. Figure 4C shows the bolted (fixed) connection between the upper flight and the top landing, which is applied consistently at all levels.

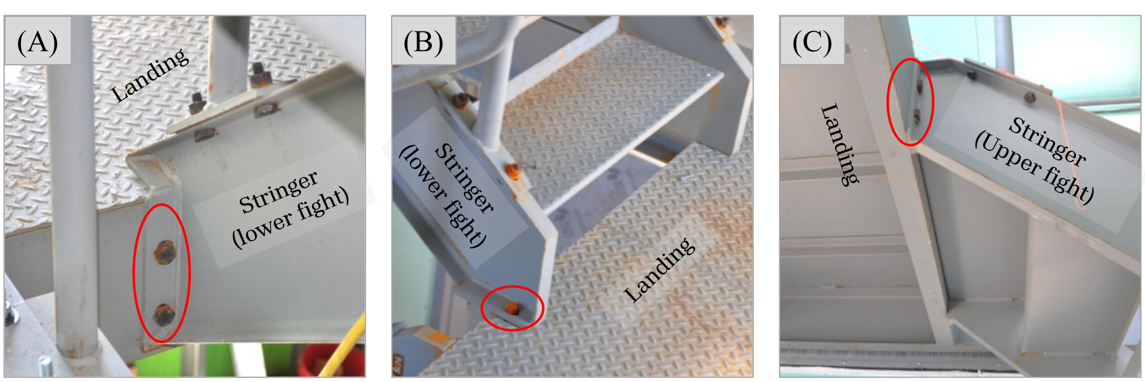

Figure 5. Stair flight to landing connections (A) fixed connection between the lower flight to bottom landing (B) fixed connection with construction tolerance between the lower flight and the bottom landing, and (C) fixed connection between the upper flight and the top landing.

Handrail Connection Details

In previous experimental studies, Sorosh et al. (2025) demonstrated that drift-release connections can effectively accommodate interstory drift and mitigate severe damage or failure of stair systems during seismic events. However, the free movement of stair flights can lead to handrail damage, and in the aforementioned study manifest in the form of detachment or fracture. With the aim of mitigating this type of seismic damage in the CFS10 building specimen, three different handrail connection details were tested. The main objective of each design was to allow movement of the handrail in a controlled manner while preventing complete detachment. Figure 6A shows the slip-fit handrail connection, in which one section of the handrail is designed to slide in and out under lateral movement of the stair flight. Figure 6B shows the double-hinged handrail connection, which accommodates the relative movement between adjacent handrails through rotation at the hinge. Figure 6C shows the hinged-and-sliding handrail connection, which utilizes hinge rotation with sliding of one section into another to accommodate both rotational and translational demands at the handrail connection.

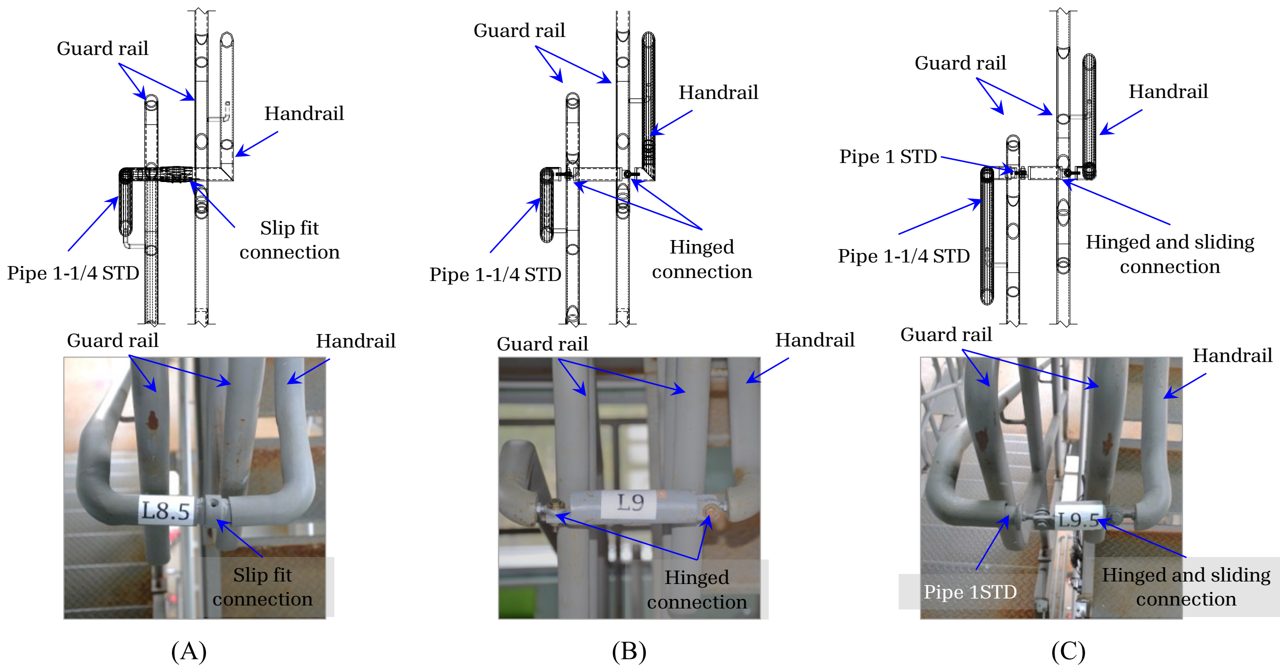

Figure 6. Handrail connection details (A) slip-fit connection, (B) hinged connection, and (C) hinged and sliding connection.

Finite Element Model

A simplified model of the stair system was developed using the general-purpose finite element software ETABS (2018). As shown in Figure 7A, all columns, attachment channels, channel bands, and treads were modeled using beam elements, while stair landings were modeled using thin shell elements. To represent the various stair configurations shown in Figure 1, two base models were created: one with two attachment channels (Figure 7B) and another with continuous attachment channels (Figure 7C). Two assumptions were made in the construction of these models: (1) when unlocked, the drift-release connections move freely in two orthogonal directions with a minimum elastic stiffness of 35 kN/m, and (2) when locked, no movement occurs across the drift-release connections, and the shear stiffness of the locking bolts governs the stiffness of the stair connections at these interfaces. Due to the variety of story-level stair drift-release connections, the total number of locking bolts varies from floor to floor. The third column of Table 1 lists the total shear stiffness expected at the drift-release connections. In ETABS, these connections are modeled using link elements with bi-directional stiffness. In addition, to model the fully free and fully fixed (bolt-shear stiffness) cases, an additional scenario with all DoFs of link elements constrained was analyzed. Since the stair column bases were neither perfectly fixed nor perfectly pinned, two different boundary conditions of pinned and fixed column bases are considered in this analysis. To determine the story stiffness displacement-based linear pushover analysis was performed. Table 1 summarizes the story stiffness results for stairs with various connection types, configurations, and boundary conditions as estimated using the aforementioned assumptions.

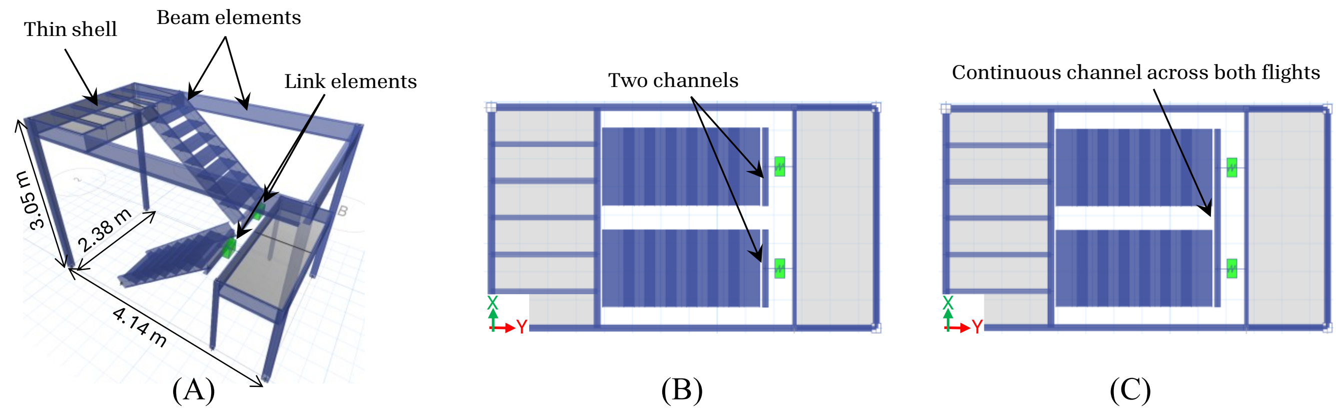

Figure 7. Details of the developed FEM (A) isometric view, (B) plan view of the stair FEM with a split (two) attachment channels, and (C) plan view of the stair FEM with a continuous (single) attachment channel.

Table 1. Stair story stiffness during locked (L) and unlocked (UL) cases based on displacement-based linear pushover analysis.

Level	Link Stiffness [kN/m]		Stair Story Stiffness [kN/m]									
			Pinned Columns				Fixed Columns				Fixed Columns	
			X Dir.		Y Dir.		X Dir.		Y Dir.		X Dir.	Y Dir.
	UL	L	UL	L	UL	L	UL	L	UL	L	Fixed all DOFs	
1,6	35	4597	641	648	12784	18353	1979	1979	14816	16252	2347	17460
2,4	35	5254	622	629	1856	4897	2023	2023	4623	6672	2329	9299
3,7	35	4597	641	648	12784	18353	1979	1979	14816	16252	2347	17460
5,8,9	35	2627	622	627	1856	3800	2023	2023	4623	5937	2329	9299

To integrate the stair stiffness into the building model, the average stair story stiffness from the pinned- and fixed-column cases was used. Figure 8 summarizes the stair story stiffness based on this analysis. Key observations based on Figure 8 and Table 1 are:

- Results from the model in which all DoF of link elements were constrained to simulate the fixed connection align well with the results from the model in which the link stiffness were determined using the shear stiffness of the locking bolts.
- Locking the stair connections does not alter the story stiffness in the perpendicular to stair run direction (X direction). This is because the perpendicular to stair run direction is the weak axis of the stair system, and stair's story stiffness in this direction is predominantly due to the flexural response of the flights and portal frame.
- Locking the stair connection significantly changes the stiffness of the stair system in the parallel to stair run direction (Y direction). This stiffness is particularly high in stair systems with both lower and upper flights attached to the continuous (single) attachment channel. That is the story stiffness of stairs with continuous attachment channel (i.e., levels 1,3,6 and 7), in the Y direction, is significantly larger than that of stairs with split attachment channels (i.e., levels 2,4,5,8,9).

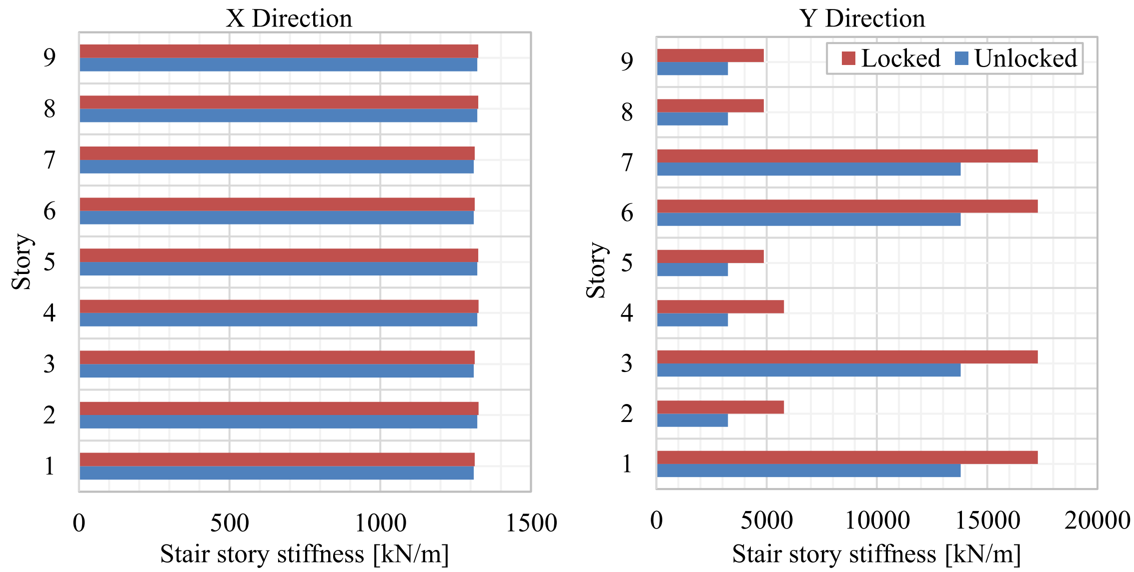

Figure 8. Stair story stiffness during locked and unlocked cases (average of the pinned and fixed gravity column analyses cases assumed).

Figure 9 presents the story stiffness of the CFS10 building alongside the stair story stiffness for both locked and unlocked configurations. For stairs with continuous attachment channels, the story stiffness in the Y direction is approximately 30–40% of the building's story stiffness in the locked state, and 20–30% in the unlocked state. On the other hand, stairs with two (split) attachment channels (i.e., levels 2,4,5,8,9) are relatively less stiff with the stiffness of the stairs in the Y direction approximately 10-15% and 5-9% of the building story stiffness in case of stair locked and unlocked, respectively. The stair story stiffness in the perpendicular to stair run direction (X direction of CFS10), is much lower, at less than 4% of the building's story stiffness.

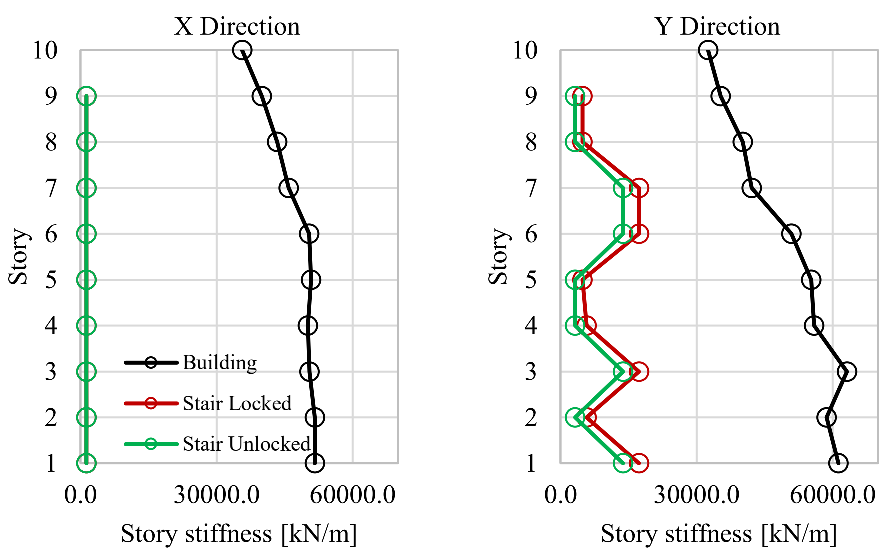

Figure 9. Stair system compared with building story stiffnesses.

Pre-Test Analysis

A practice-oriented phenomenological-based FEM model of the CFS10 building was developed using the OpenSeesPy framework in preparation for motion selection and predictions under selected motions to guide the development of the testing protocol (Zhang et al., 2024). The model is intended to use a low number of DoF, while also capturing the salient features anticipated to most significantly contribute to the seismic response. Thus, this model can be used to run an extensive number of nonlinear time history analyses with reasonable efficiency. As detailed in Zhang et al (2024), shear walls and gravity walls were lumped into zero-length elements with Pinching4 material properties using calibrated tested data with additional stiffness and strength contribution from the use of heavier chord studs (such as HSS sections designed within the lower chord studs at floors in the E-W direction and compression stud packs in the N-S direction) as well as finishes such as gypsum board and exterior stucco. Rigid diaphragms were employed, and seismic masses were assumed to be lumped at shear wall and gravity wall nodes. In addition to these features, zero-length shear springs that reflect the stiffness of the stairs, as tabulated in the previous section, were added at the center of the stairs to model the additional stiffness and strength contributions from the stairs. Both "locked" and "unlocked" configurations were explored, and eigenvalue analyses were performed to obtain the dynamic characteristics of the building-stair specimen numerical model. Figure 10 shows the period of the building corresponding to the first nine vibration modes consisting of three flexural modes in each of the X- and Y- directions and three torsional modes. The key observation from this figure is:

- Excluding stairs from the building's finite element model results in an approximate 5% increase in the periods of the flexural vibration modes in the Y direction (parallel to stair run). In contrast, the periods of the flexural modes in the X direction (perpendicular to stair run) and torsional modes increase by about 1%.
- The periods of the flexural modes in the Y direction and torsional modes are reduced by approximately 1% when comparing the building model with locked stairs to the model with unlocked stairs. In the X-direction, negligible change in vibrational periods is observed between these two cases.
- The most significant impact of the presence of the stairs are observed in the first and second translational Y-direction modes (Y,1 and Y,2 parallel to run) when the stairs are assumed locked.

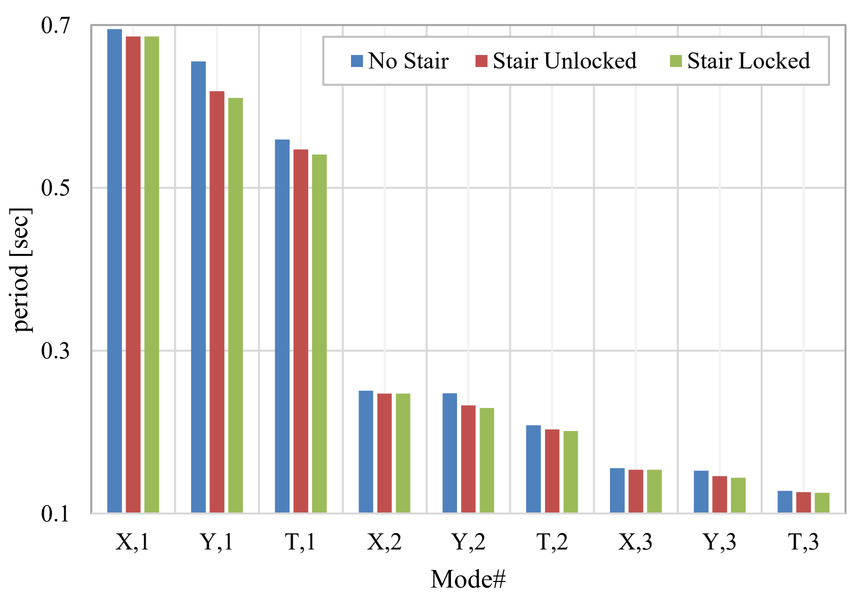

Figure 10. Period estimations for the CFS10 building model corresponding to the first three flexural modes in two orthogonal X and Y directions and three torsional (T) modes.

Concluding Remarks

Previous experimental and field reconnaissance studies have revealed that stair systems with fixed flight-to-landings connections are prone to severe damage during earthquakes with moderate to high levels of intensity. Therefore, recent editions of ASCE 7 mandate that stairs are detailed such that they accommodate seismic-induced interstory drift demands. To investigate these ramifications at a system level, several different stair connections capable of accommodating interstory drifts were recently tested as part of a full scale 10-story cold-formed steel building. This paper provides a summary of the design strategies used to detail the stair system integrated within this landmark shake table building program. In addition, development of a simplified FEM of such stairs is discussed. The contribution of stair flexibility to the vibration period of the building was investigated using an integrated building-stair system FEM. Key findings from this analysis are as follows:

- Including the stair system within the FEM of the building reduces its overall predominant periods. This reduction is more significant in the direction parallel to the stair run as this is stiff axis of the stair system. In addition, it is worth noting that in this study various drift-release connections and configurations were considered. To study the extreme case, a scenario with stairs at all levels having most rigid configurations can be considered.
- Locking the stair connection did not alter the vibration period significantly. However, this does not necessarily mean that stair systems with fixed connections do not impact the dynamic response of the building because the analysis in this paper was solely based on eigen value analysis, and for the configurations selected within the CFS10 building – which balanced the concept of varying the drift-release connections on a floor-by-floor basis. Further analysis of the two cases under earthquake motions is required to offer insight during realistic demand scenarios.
- In alignment with findings from previous studies, stair systems with drift-release connections that utilize split (two) attachment channels are significantly more flexible as compared to the ones with continuous (single) attachment channel.

Acknowledgments

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