Seismically-Resilient Stair Systems for Buildings

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Abstract

There is an increasing understanding that structures and communities need to be resilient. For structures in seismically active areas resiliency is strongly correlated with how buildings perform during and following an earthquake. Safe egress for occupants and ingress for emergency personnel is a critical component of a building's performance and is a matter of life safety during, and after a seismic event.

For multistory buildings, stairs are essential for safe egress. Several recent earthquakes have highlighted the vulnerability of stairs and recent experimental testing has revealed that safe egress from buildings can be compromised even when the building drift demands are much lower than the design level performance target of the building. This paper presents engineered solutions for seismically resilient stairs that have been recently developed and tested. Full-scale shake table testing of several different stair systems has been conducted and the systems all shown to perform well. This paper discusses the results of testing and solutions that may be integrated to limit damage and provide safe building egress after significant earthquake events.

1. Introduction

There is limited work in the literature which focuses specifically on the seismic performance of stairs. Roha et al. (1982) conducted an extensive review of stair damage sustained in earthquakes dating back to the 1906 San Francisco earthquake with accounts of "wrecked" stairways. The study presented both observed damage to stairs as well as damage of the primary structure which could be attributed to the stairs themselves. In the 1933 Long Beach earthquake, for example, it was observed that stairs acted like diagonal bracing between floors causing localized overloading of the structure. More recent accounts include Li and Mosalam (2013) who reported on failures of concrete stairs observed during the 2008 Wenchuan earthquake as well as numerous reports documenting damage to stairs in Christchurch during the 2010 Darfield and 2011 Lyttleton (Christchurch) earthquakes. A report to the New Zealand Royal Commission by Bull (2011) stated that the performance of stairs was less than desirable as stairs collapsed in at least four multi-story buildings and numerous others were seriously damaged. Beca (2011) presented the findings of a thorough investigation of the Forsyth Barr Building stair collapse which resulted from inadequate allowance for movement in the gap-and-ledge stair detail designed to allow the stairs to slide in order to accommodate movement associated with interstory drift. In response to concerns about stair collapses in the Christchurch central business district the New Zealand Department of Building and Housing issued Practice Advisory 13. The advisory focuses on existing buildings that had been designed with details similar to the Forsyth Barr Building. The advisory recommends that new buildings use details which allow stair flights to slide on landings without restriction and be capable of sustaining at least twice the Ultimate Limit State level inter-story displacements after allowing for construction tolerances.

Recent experimental testing has also demonstrated the potential vulnerability of stairs in seismic events. Higgins (2009) performed quasi-static testing on two full-sized prefabricated steel stair assemblies with landings to assess their response when subjected to interstory drift in both directions while supporting gravity load. Although both assemblies completed the loading protocol up to 2.5% drift, it was concluded that the imposed lateral drift placed high deformation demands on the stair-to-landing connections and that the overall performance of the stairs is dependent on the deformability and 'endurance' of these connections. For that reason, the paper recommends that careful detailing, fabrication, and inspection of the stair-to-landing connections be required to ensure desired system performance.

Shake table testing of a full-scale, five-story reinforced concrete building was conducted at UCSD in 2013 with one objective being to study the response of non-structural components including piping, HVAC, sprinklers, a passenger elevator and stairs (Chen et al. 2012). Wang et al. (2013) summarize the extensive shake table test program and reports that severe failure of the stair flight to floor slab connections at multiple levels occurred during the design event. In Wang et al. (2015), which focuses specifically on the response of the stairs in the UCSD testing, it is reported that safe egress from the building was compromised even when the associated drift demands were much lower than the design performance target of the building (with damage at 0.74% and 1.41%, compared to the design target of 2.5%). Connection plate yielding was observed at the landing and weld fractures were observed in several locations with complete detachment observed at the bottom of the 2nd floor landing (see Figure 1). A photo very similar to Figure 1 d) which shows yielding at the connection plate is also presented in Higgins (2009). Wang et al. state that, consistent with the findings of previous studies, the seismic performance of stair systems is highly dependent on the deformability of their connections.

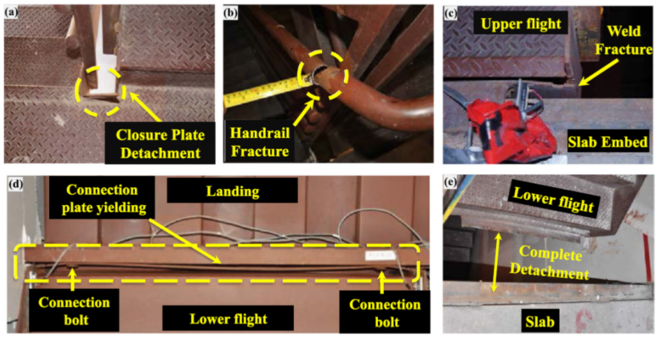

Figure 1: Damage to stairs observed in full-scale testing at UCSD (from Wang et al. 2015)

There is a growing number of analytical studies which attempt to quantify the effect of stairs on the building itself. One of the conclusions of Cosenza et al. (2008) was that in the transverse building direction, RC stairs contributed to 50 percent of the building stiffness in that direction. Observed failures of reinforced concrete stairs in the 2008 Wenchuan and 2010 Yushu earthquakes led to several additional analytical studies. Xu and Li (2012), Fallahi and Alirezai (2014) and others have studied the analytical response of RC frame structures with and without stairs and conclude that the presence of stairs may significantly alter the dynamic characteristics of a structure with undesirable consequences. Jiang et. al (2012) reached a similar conclusion in their study focusing on the potentially damaging effect of staircases on the building RC frame and Tegos et al. (2013) studied the response of different stair configurations including an external staircase on global and local building behavior.

2. Code Requirements and Project Specifications

The design of stairways is governed by codes, which generally reference ASCE 7 (ASCE, 2010) and is also addressed by multiple industry publications, design guidelines and recommendations. The code requirements and breadth of other information requires significant judgment by the design professional. Design responsibility is often delegated to an engineer other than the building structural engineer of record either through the project construction specifications or, as is often done, the stairways are defined to be a deferred submittal item. As a deferred submittal item, their design is not included in the building structural design developed by the structural engineer of record, rather it must be developed later, often by an engineer for a supplier, and submitted in a separate package for plan check review.

Construction specification documents for stairs vary widely from project to project. Even in areas of high seismicity the stair specification may make no mention of seismic performance. If there is an explicit seismic performance requirement it is often stated that stair systems should be capable of withstanding the effects of earthquake motions determined according to ASCE 7. Some specifications state that the design of the stairs should be completed by a qualified engineer while others go so far as to say that the design of the stairs should include comprehensive engineering analysis by a qualified professional engineer.

Code requirements for stairs are found in the International Building Code which in turn makes reference to ASCE 7. The International Building Code is concerned primarily with the dimensional requirements for egress stairways such as riser height, tread width and depth. ASCE 7, Chapter 13 *Seismic Design Requirements for Nonstructural Components* requires that systems that are required for life-safety purposes after an earthquake, including egress stairways, be classified as designated seismic systems and be assigned a component importance factor, I_p, of 1.5. Section 13.3.1 specifies the seismic design force and Section 13.3.2 requires that the effects of relative displacements between the ends of the component be considered. A methodology to calculate the relative displacement for components with two connection points is given. In the context of stairs, the relative displacement given by Eqn. 13.3-6 is the interstory drift from one floor to the next and includes the building importance factor, I_e.

The guideline document, FEMA E-74, *Reducing the Risks of Nonstructural Earthquake Damage – A Practical Guide* (FEMA, 2015) provides guidance in Section *6.3.8 Stairways* which includes a discussion on typical stair damage and suggested mitigation techniques. It is recommended that in order to prevent stairs from acting like diagonal struts between floors, the design should provide a fixed connection at one floor and a sliding connection at the other floor that "allows movement parallel to the direction of the stair".

Additional guidance for the design of stair systems can be found in the Metal Stairs Manual (NAAMM, 1992). Section 5 provides engineering data and design examples for metal stair systems. This manual is often specified under the heading Quality Control in construction specification documents but makes no mention of seismic considerations nor developments since the time of its original publication such as the use of slotted connections or single end attachments to accommodate interstory drift.

A stairway design that meets the requirements of ASCE 7 including the explicit requirement that interstory drift be considered and follows the recommendations of documents such as FEMA E-74 is a significant challenge for the design engineer.

3. Full-Scale Dynamic Testing of Stair Systems

Based on the failure of stairs in past earthquakes and the poor performance observed in recent experimental testing, it is clear that stairs which are rigidly fixed at the top and bottom landing are vulnerable in earthquakes and there is an obvious need for a solution which will accommodate interstory drift within the stair system. To that end, an experimental testing program was undertaken as a first step in the development a fully-tested and engineered solution for stairways.

Shake table testing was conducted at the University of Nevada Reno on a bi-axial shake table in the Earthquake Engineering Laboratory. The main objective of the testing was to demonstrate that flexible stair connections at the top and/or bottom of the stair assembly can be used to accommodate building interstory drift. A second objective was to investigate the performance of the "fixed-free" configuration where the stairs are fixed at the top and free to move at the bottom landing, as this configuration has been used and some variant of it is recommended for new structures in New Zealand via the Practice Advisory 13 and by FEMA E-74 in the United States. Finally, the third objective of the testing was to experimentally evaluate how much force a fixed-fixed stair system might impart on its surrounding building structure.

3.1 Test Configuration

The test setup comprised a stiff upper landing attached to a reaction block on the shake table with the lower landing fixed to the laboratory strong floor. In this configuration, movement of the table resulted in relative movement between the two landings simulating interstory drift. The stair specimen itself was designed so that each end could be replaced allowing multiple configurations and combinations of top and bottom connections to be tested using the same central portion of the stairs. To achieve this, the top and bottom stair and their connection portions were bolted to the center nine-step section comprising the stringers, risers and treads. The overall setup and the stair specimen with removable ends is shown in Figure 2. Many different configurations were tested and six are described in the results summary of Section 3.4.

The stairs were tested with steel plates attached to the treads to simulate 100 psf live load, as per ASCE 7-10. In addition, some configurations were tested with 50 psf live load or no live load to investigate the effect of the load on the response.

Figure 2: Testing Setup at the University of Nevada, Reno

3.2 Instrumentation

Instrumentation included two wire potentiometers at each of the top and bottom landings to measure longitudinal displacement and rotation of the stairs as well as one wire potentiometer to measure the transverse direction at the top and bottom of the stairs. Tri-axial accelerometers were placed on the shake table and at the top, mid-height and bottom of the stairs (Figure 3). Force and displacement of the table are obtained directly from the shake-table control system.

3.3 Loading Protocol

The loading protocol included quasi-static, dynamic and earthquake simulation tests over a range of different amplitudes. The design interstory drift was assumed to be 2.5% which, for a 10 foot story height, corresponded to 3 in. of shake table displacement relative to the strong floor. The MCE drift was assumed to correspond to 4.0% interstory drift or 4.8 in. of shake table displacement.

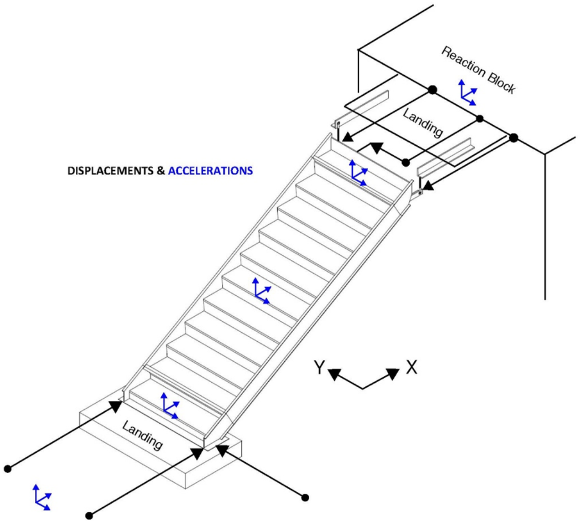

Figure 3: Instrumentation Schematic

For each setup configuration, testing was initially conducted quasi-statically (0.25 in./s) in the longitudinal (X) direction followed by the transverse (Y) direction to confirm that the configurations functioned kinematically before conducting dynamic testing. The tests included three cycles in each direction at 0.6 in. and 3.0 in. amplitudes. Following the uni-directional tests, circular tests were conducted, again at 0.6 in. and 3.0 in. amplitudes. The test sequence was repeated dynamically (0.5 Hz) with the number of cycles increased to five at each amplitude. An additional dynamic circular test with an amplitude of 4.8 in. was conducted to represent the MCE demand.

In order to investigate the response of the stairs to motion more representative of earthquake shaking a simulated interstory drift displacement time-history was developed. A simple bilinear single degree of freedom building model was assumed with an elastic period of 0.35 second. The yield strength was chosen so that there was moderate yielding (ductility of about 5) experienced in both directions for several seconds of shaking. After investigating the response of a number of bi-directional earthquake motions, the Newhall record from the Northridge earthquake was chosen since the response showed several desirable traits. Namely, the relatively strong shaking in both directions for 8-10 seconds, the good representation of cycles with the stairs moving in the same and opposite directions, several instances when there is a reversal in one direction without a corresponding reversal in the other and the fact that the pulse in the Newhall record creates a relatively strong forward-and-back displacement pulse (Makris and Black 2003) as shown in Figure 4. A summary of the test protocol is given in Table 1 below.

Table 1: Summary of Loading Protocol

	Direction	Amplitude (in)	Drift (%)	Rate
Quasi-static Cyclic Tests (3 cycles)	X	0.6	0.5	0.25 in/s
	X	3.0	2.5	
	Y	0.6	0.5	
	Y	3.0	2.5	
	X+Y	0.6	0.5	
	X+Y	3.0	2.5	
Dynamic Cyclic Tests (5 cycles)	X	0.6	0.5	0.5 Hz sine
	X	3.0	2.5	
	Y	0.6	0.5	
	Y	3.0	2.5	
	X+Y	0.6	0.5	
	X+Y	3.0	2.5	
	X+Y	4.8	4.0	
Earthquake Tests	X+Y	Approx. 3”	“DBE”	
	X+Y	Approx. 4.8”	“MCE”	

3.4 Summary of Results

Twelve different mass and end conditions were considered as part of the test program. The testing looked at three basic configurations: 1) stairs hanging from the upper landing with different lower landing configurations; 2) stairs supported on a track at the upper landing; and 3) stairs fixed at the top landing and free to move at the lower landing. In addition, the testing also included a fixed-fixed case, although this proved to be difficult to test as discussed later.

The following sections provide a brief summary of the different configurations and the results of the testing. Specific comparisons between the different configurations are made for the MCE test. In that test, the landing (shake table) moved approximately 4 in. in the Y direction and 2.5 in. in the X direction. This is less than the target of 4.8 in. in the Y direction at the MCE level. For a number of the configurations the input signal was increased to 4.8 in. although the comparisons presented in the following sections are based on the response to the original MCE input (4 in. maximum landing movement in Y) as that test was run for every stair system configuration.

3.4a Hanger-Spring Configuration

In this configuration, rod end bearings, or heim joints, were used on either end of a threaded rod to suspend the stairs from the top landing (Figure 5). These hanger assemblies were supported by two cantilevers extending from the landing to provide clearance for the stairs to move towards the landing. The bottom of the stairs rested on a high-density polyethylene (HDPE) sliding surface with spring assemblies installed to provide restoring force in the transverse direction (Figure 6). This configuration was designed to have unrestricted movement at the top landing with the bottom connection allowing rotation and movement with a transverse restoring force.

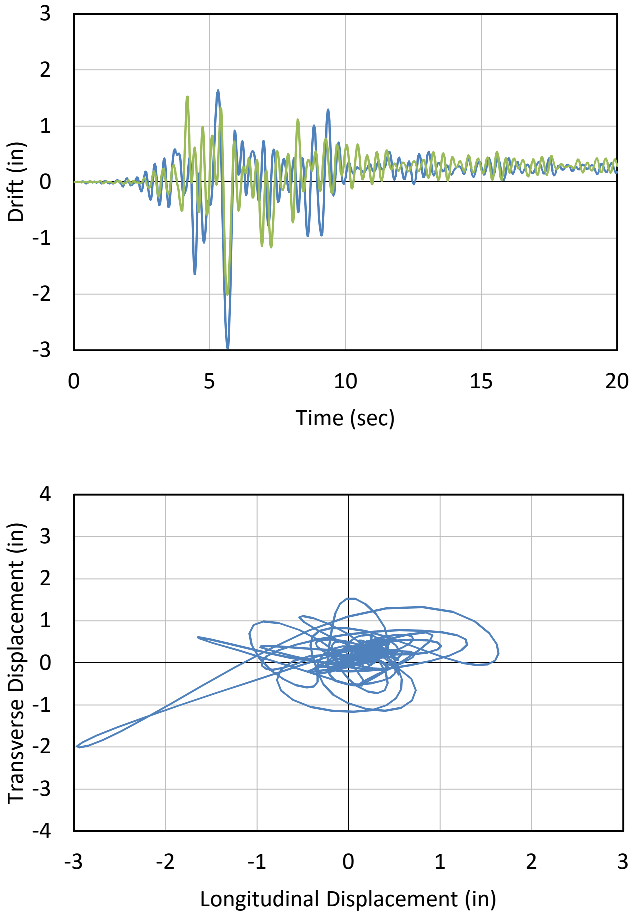

Figure 4: DBE Input Time-Histories (Top) and X-Y Displacement Plot (Bottom)

In the quasi-static and low amplitude dynamic tests, the movement was primarily focused at the top of the stair assembly with little movement noticeable at the bottom landing. For the larger amplitude dynamic testing the stairs rotated approximately 2 degrees around the vertical axis. Figure 7 shows the relative displacement between the top of the stairs and the landing. The displacement pulse in the MCE record moved the top of the stairs 2 in. in the longitudinal direction relative to the landing and 5 in. in the transverse direction.

Figure 5: Hanger Assembly

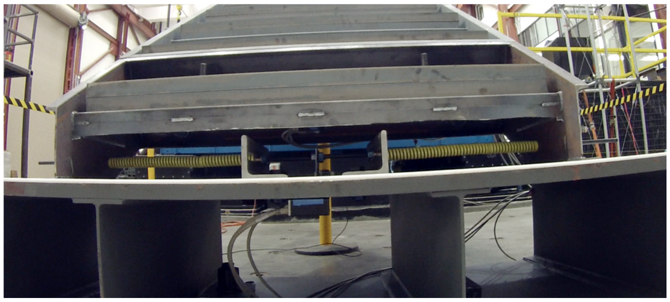

Figure 6: Transverse Spring

3.4b Hanger-Pinned Configuration

In this configuration, the top connection comprised the hanger assemblies of 3.4a while the bottom was supported on a physical pin consisting of a trailer hitch receiver attached to the underside of the stair and a hitch ball attached to the bottom landing (Figure 8). The motivation to test this configuration was to investigate the response with translation completely restrained at the base.

It was observed that translational restraint at the base did not have much effect on the response in comparison to the hanger-spring configuration, which is consistent with the observation that in the hanger-spring configuration most of the deformation at the base was rotational. During the MCE test the top of the stairs moved 5 in. transversely relative to the landing.

This configuration was also tested with half the mass and no mass. With half of the mass, the movement at the top of the stairs was slightly larger than the full mass case (5.2 in. versus 4.7 in.) with comparable rotation at the base. For the no-mass test the displacement at the top of the stairs was 4 in. with about two-thirds of the rotation compared to the full and half-mass cases.

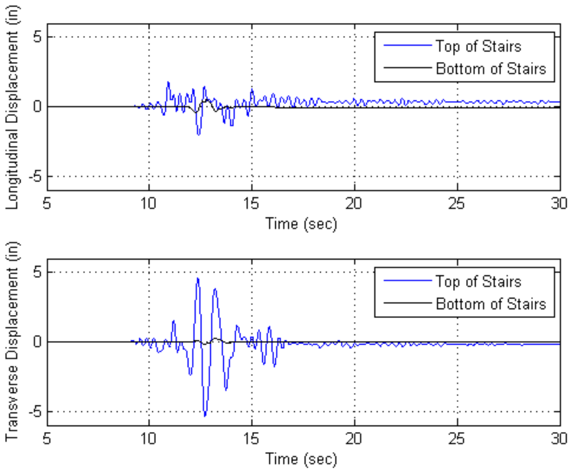

Figure 7: Relative Displacement History Between Landing and Stairs (MCE; Hanger-Spring)

Figure 8: Pin at Base

3.4c Hanger-Fixed Configuration

Finally, a hanger-fixed configuration was tested to observe the response of the stairs with no movement or rotation allowed at the base landing. The lower fixed connection comprised a ½ in. steel plate welded to the stringers with four ½ in. diameter, A325 bolts (Figure 9).

As the top landing moved, there was little or no visible movement of the stairway in the horizontal directions. During the MCE test there was less than 0.3 in. of absolute horizontal movement at the top of the stairs. Given that the hanger assembly has a fixed length, as the landing moves away from its neutral position in any direction the top of the stairs necessarily rise. For some of the larger motions, this rise was clearly visible. This vertical deformation was also present for the other cases but less visible and of less concern as the other configurations both allowed rotation at the base. For the fixed base case however, there was no visible damage caused by the imposed vertical deformation as the stairs were flexible enough to accommodate it.

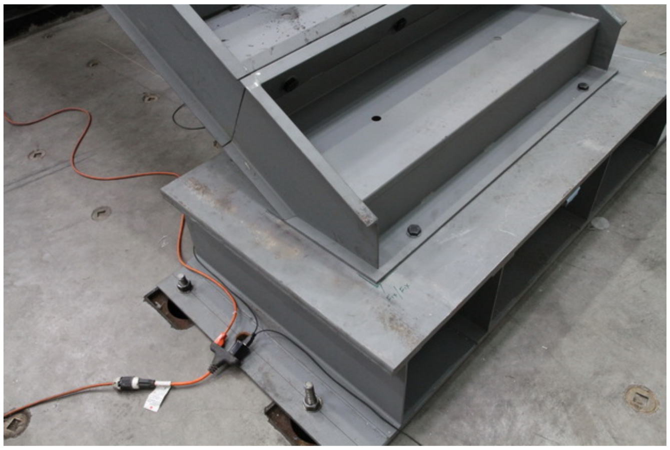

Figure 9: Fixed Base

The favorable response of the stairs in the hanger-fixed configuration suggests that it is not necessary to allow movement or rotation at the bottom landing if the stairs are able to move independently from the top landing via a hanging-type system.

Through all of the testing with the hanger assembly, there was no visible sign of damage to the stairs, the hanger assembly or the base connections.

3.4d Slide Track-Base Guides Configuration

This configuration was developed to investigate the behavior of the stairs for a case where the deformation capacity in one of the horizontal directions was provided at the top landing while the deformation capacity in the other direction was provided at the bottom landing. A transverse track was designed for the top connection at the landing and longitudinal guide channels were used at the base.

At the upper connection, a hollow tube attached to the underside of the stairs and extending across the width of the stair rested on a HDPE-lined slide track. The track had a lip on the front edge and spring bolts which passed through a long slot on the back of the assembly to keep the system from disengaging from the track. The length of the slots also limited the total transverse displacement capacity to provide a safety limit as a precaution. The width of the upper track was oversized by about one inch in the longitudinal direction to accommodate rotation. The base guide channels at the bottom were also HDPE-lined and were slightly wider than the base to accommodate rotation. A schematic view and a photo of the slide track are given in Figures 10 and 11, respectively. Figure 12 shows the lower base guides.

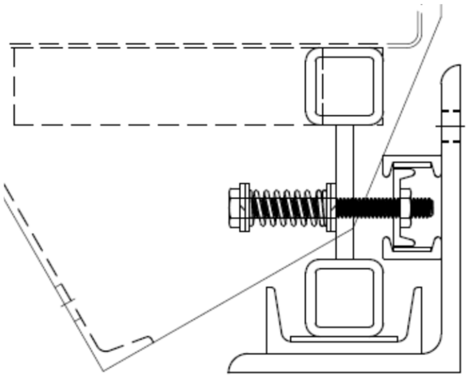

Figure 10: Slide Track Schematic

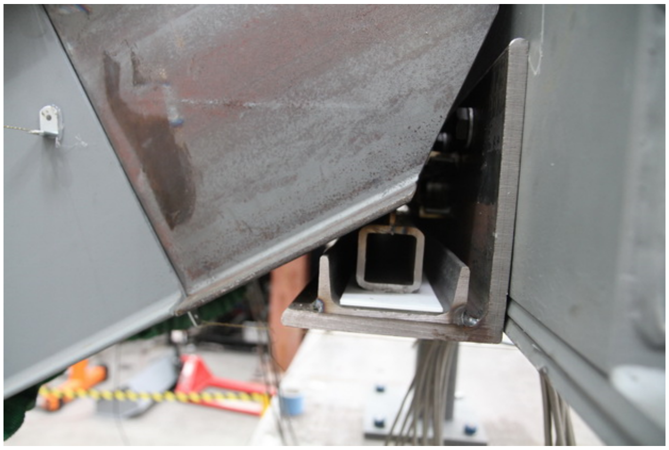

Figure 11: Photo of Slide Track

The response of the slide track-base guide configuration showed that this system was also effective in accommodating drift. It was observed that the oversized slide track and base guides allowed considerable rotation which over the length of the stairs accommodated nearly all of the imposed transverse drift, as seen in Figure 13.

3.4e Fixed-Free Configuration

In this configuration, the top of the stairs was connected to the landing using a typical bolted connection. A bolted configuration was chosen to facilitate the test setup and allow for faster installation and removal of specimens. In an attempt to represent common practice, the fixed stair connection was defined after a review of publicly available details from major industry stair manufacturers, consultation with smaller stair fabricators and various construction documents provided to Construction Specialties. Given the number of variations that were identified, it can be said that there is no standard industry detail. The final typical connection selected was one that has been used on numerous projects and is substantially similar to a standard connection used by major manufacturers. The upper connection was detailed to have a 4 in. wide ¼ in. thick steel plate welded between the stringers which was bolted to the landing with ¾ in. diameter A325 bolts.

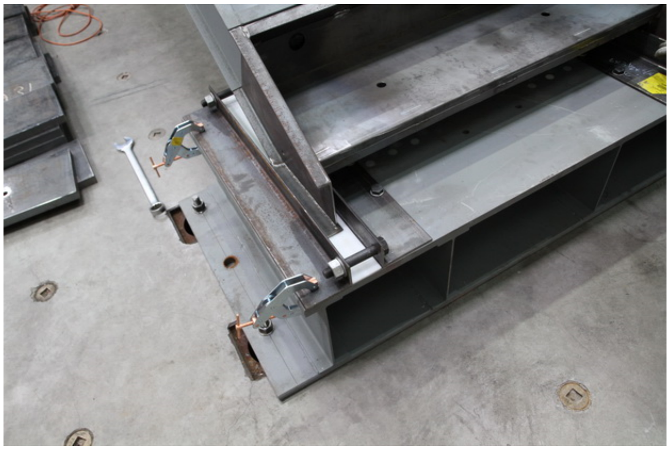

Figure 12: Sliding Base with Guides

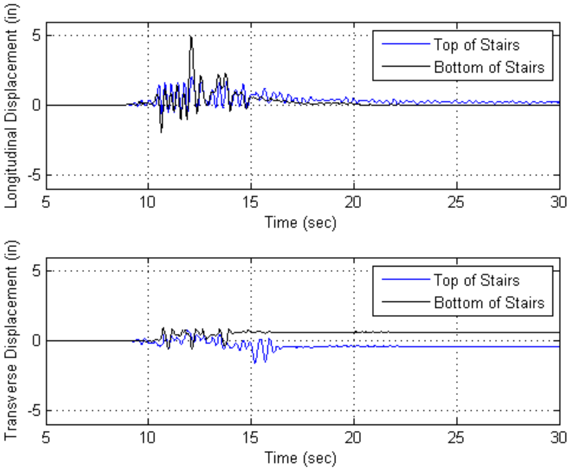

Figure 13: Relative Displacement History Between Landing and Stairs (MCE; Slide Track–Base Guides)

This configuration was first tested without any additional mass. After completion of the MCE motion the stairs were inspected and it was found that the mounting plate at the top landing had yielded and was permanently deformed (Figure 14). A similar result was reported in Higgins (2009) and by Wang et al. (2015) and shown in Figure 1(d) of this paper. From the data it can be seen that the yielding and permanent deformation at the top of the stairs occurred during the pulse at about 13 seconds (Figure 15). This configuration resulted in nearly 8 in. of displacement at the base, compared to 4 or 5 in. of relative displacement at the top landing for the hanging or sliding systems.

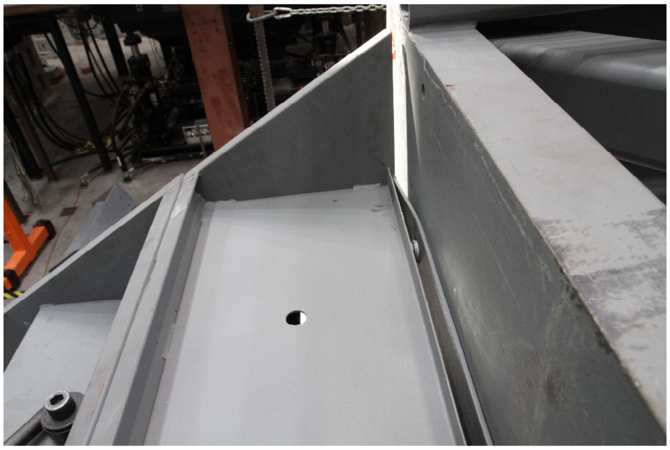

Figure 14: Yielded Mounting Plate

In order to continue testing with the additional live load, the stairs were removed, the mounting plate was straightened and additional gussets and welds were added to strengthen the connection. With the strengthened landing connection, the stairs were loaded with the full live load and re-tested. All tests completed successfully except the MCE motion which fractured the weld between the mounting plate and the stringer, despite the additional strengthening.

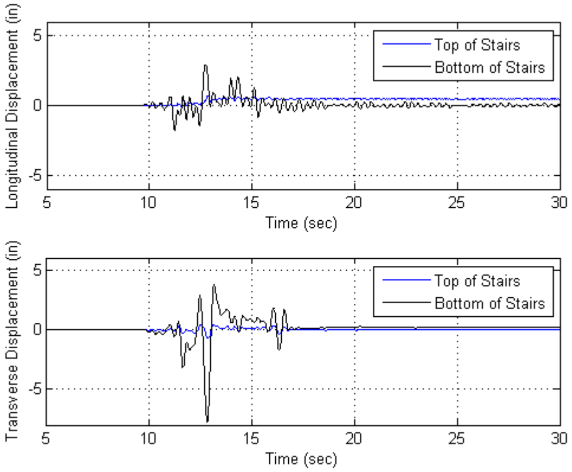

Figure 15: Relative Displacement History Between Landing and Stairs Showing Permanent Deformation (MCE; Fixed-Free)

3.4f Fixed-Fixed Configuration

The upper connection of the fixed-fixed case was the same as that described in the fixed-free case including similar strengthening. The lower fixed connection was chosen in the same manner as the upper fixed connection described in the fixed-free case and consisted of a ½ in. steel plate welded to the stringers with four ½ in. A325 bolts.

The initial intent for the fixed-fixed case was to slowly increase the loading amplitude until the connections fractured. At the time of testing it was decided that the stiffness of the stair assembly was too high in the longitudinal (X) direction and that testing might damage the shake table. In order to protect the shake table, it was decided that the testing would continue until a force of 50 kips was measured at which point the table would shut down. Quasi-static cycles at 0.3 in. amplitude were run in the X and Y directions followed by quasi-static cycles at 0.6 in. The table completed the 0.6 in. amplitude test in the Y direction but force-stopped in the X direction as the 50 kip limit was exceeded prior to reaching 0.6 in. The implication of this result is that the stairs had a longitudinal stiffness of at least 100 kips/in and likely closer to twice that value as relative deformation measured between the top end of the stairs and the lower landing was less than 0.3 in. The stiffness in the transverse direction was measured as 7 kip/in from the 0.6 in. amplitude test. Due to compliance in the connections between the middle and end portions of the stairs, this is a lower bound estimate and higher stiffness would likely have been observed for larger displacements.

As it was not possible to run the bi-directional earthquake motion without exceeding the 50 kip table force limit only the transverse earthquake motions were applied. The transverse DBE record completed while the transverse MCE record caused the bottom landing (tensioned to the strong floor) to shift violently on the floor which stopped the shake table.

4. Conclusions

Based on observed damage in past earthquakes and recent experimental testing there is a clear need for the development of a practical solution to better protect stairs and ensure safety for the building egress during and following an earthquake. Although treated as nonstructural components in ASCE 7, studies have shown that stairways which are rigidly attached at the top and bottom landing can significantly change the dynamic behavior of a building, increase local stiffness substantially and impart very large forces to the structure itself.

The New Zealand Department of Building and Housing Practice Advisory 13 issued after stair failures in the 2011 Lyttleton (Christchurch) earthquake and FEMA E-74 guidlines both recommend that one end of a stair system allow free movement in order to accommodate interstory drift to protect the stairs and the building itself. ASCE 7 explicitly requires that interstory drift be considered in the design of the stairs.

A full-scale shake table testing program was undertaken as a first step in the development of fully-tested and engineered solutions to protect stairs. A total of twelve different stair system and mass configurations were tested as a proof of concept investigation and to determine the best systems for further refinement and future testing.

In general, all configurations designed to accommodate interstory drift performed well, particularly at lower amplitudes. The level of force transferred to the shake table (i.e., that would be imparted to a building) was estimated to be less than 4 kips for all quasi-static tests after accounting for the internal friction in the shake table itself. The following specific conclusions can be drawn:

A hanging system, in which the stairs are free to move at the top landing, performed well during all tests. The testing identified that for this configuration, allowing rotational or translational movement at the bottom landing is not necessary. A potential obstacle to overcome for this type of system is the need to provide a lock-up mechanism to keep the stairs from swaying during normal use.

The slide-track configuration performed well and showed that transverse deformation could be accommodated at the upper landing. As a result of the oversized slide track and base guides, in this particular configuration, most of the transverse deformation was accommodated through rotation.

The fixed-free configuration performed satisfactorily for smaller amplitude DBE motions with no live load but yielded the top connection plate during the MCE motion. The landing was subsequently strengthened to test the assembly with the full 100 psf live load. Even after measures were taken to strengthen the upper landing connection the weld between the top plate and the landing fractured in the MCE motion. This configuration had the largest relative deformation between the stairs and the landing at nearly 8 in. compared to less than 5 in. for the hanging-fixed case.

The fixed-fixed stair assembly was too stiff to test safely with even small amplitudes producing high forces into the shake table. The longitudinal stiffness was calculated to be in excess of 100 kip/in. The implication of this is significant noting that an interstory drift of two inches would correspond to more than 200 kips of force being imparted on the landings, assuming that the connections don't fail.

Given the number of different stair configurations used in construction, it is recognized that developing a single method to accommodate interstory drift is not practical for widespread implementation. The goal of future work is to develop an array of fully-engineered and tested concepts that accommodate maximum interstory drift and provide a high level of safety for building occupant egress.

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