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PERFORMANCE OF PREFABRICATED STEEL STAIR ASSEMBLIES UNDER SEISMIC AND GRAVITY LOADS

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ABSTRACT

Experimental tests were performed on full-size prefabricated steel stair assemblies. Seismic interstory drift responses combined with factored gravity loads were assessed. The stair assemblies were production-run units of a standard stair system and were designed for a typical steel frame building. Two different stair assembly units were tested: one with checker plate and one with concrete filled pans. A testing protocol was developed to evaluate the seismic performance using seismic and gravity load combinations. Lateral drifts were imposed followed by factored live and dead loads. Lateral drifts were imposed in both orthogonal directions as separate tests. Imposed lateral drift placed high deformation demands on the stair-to-landing connections. Overall performance is dependent on these connections. Careful detailing, fabrication, and inspection of welds joining the landing connection plates are required to ensure desired performance.

Introduction

Stairs serve as a primary means of egress from a structure after an earthquake or other disaster and thus their role in a building achieving life-safety performance is critical. As a result of newly adopted performance-based design provisions for buildings in the US, the lateral drift performance of prefabricated stair assemblies during seismic events has become of interest to designers. No standardized testing methods or loading protocols are currently available for evaluating the seismic performance of stair assemblies. Further, data on the structural performance of stair assemblies under lateral and combined lateral and gravity loading are lacking. Research was undertaken to develop a testing protocol to evaluate the anticipated seismic performance of production-run prefabricated steel stair assemblies. Laboratory tests of two full-size stair assemblies were conducted in the Structural Engineering Research Laboratory at Oregon State University to assess seismic performance and the results of this study are reported here.

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Specimen Description

Two full-size stair assemblies were fabricated. The stairs were production-run units designed for a typical steel frame building with 3.6 m story heights, a common design used in the United States. Each stair set consisted of two flights, a single intermediate landing, and 4 support columns as illustrated in Fig. 1. The two stair assemblies were similar except for the stair tread and landing surface. One set was fabricated with 14 gauge diamond or checker plate (called Checker in this paper). The other was fabricated with 14 gauge steel pans that were filled with concrete (called Infill in this paper). Each of the two flights of stairs consisted of 10 treads with each tread having a 166 mm rise and 279 mm run. Stringers consisted of ASTM-A36 6x254 mm plate. Stair tread plates were fillet welded to the stringers. The landing area was 1.2x2.39 m and supported by ASTM-A36 channel framing. Vertical support to the landing was provided by four ASTM-A36 63x63x6 angle columns bolted to each corner of the landing. Connections at the base of each flight of stairs consisted of ASTM-A36 127x76x6 angle fillet welded to the stringers. Connections at the top of each flight of stairs consisted of ASTM-A36 6x101 mm plate fillet welded to the stringers. The top and bottom connections to the flight were made with two 16 mm diameter A325 tension-controlled (TC) bolts. The Infill test specimen required placement of concrete in the tread form pans and landing. The landing consisted of 20 gauge 'BR' decking with the ribs oriented in the short landing dimension. Minimum height of the concrete overfill in the decking and treads was 16mm. Concrete consisted of 9.5 mm maximum size aggregate with an average compressive strength on the first day of testing (7 day strength) of 13.8 MPa.

After assembly of the components in the laboratory, instruments were applied. The sensors were used to measure specimen deformations and internal stresses as well as applied lateral force. Sensor locations are illustrated schematically in Fig. 1. Sensor data were acquired using 16-bit PC-based data acquisition system with commercially available software used to control acquisition and data storage.

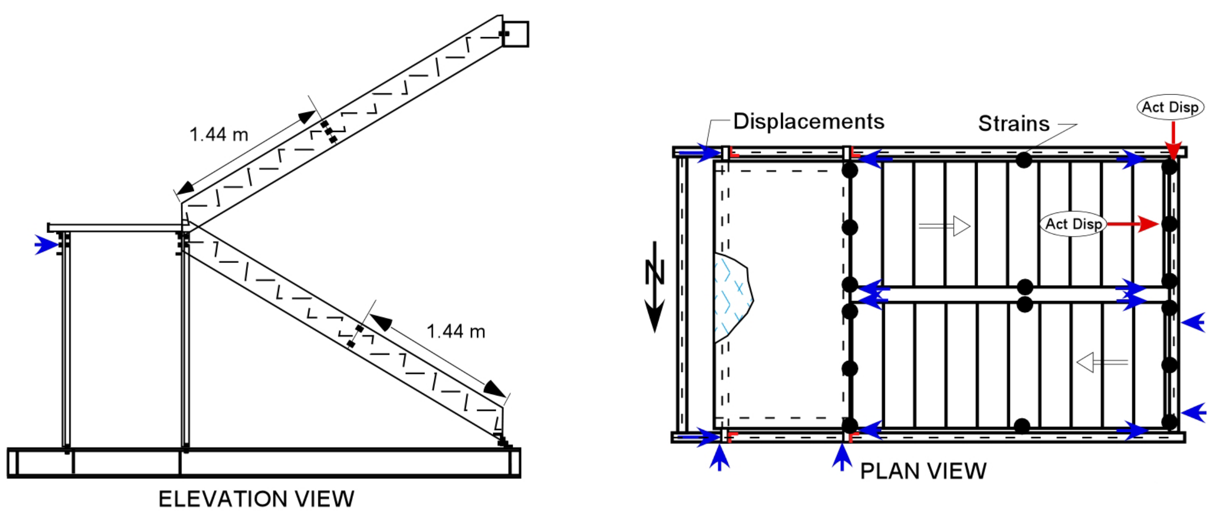

Figure 1. Prefabricated stair assembly instrumentation.

Test Setup and Methdology

The stair assemblies were placed in a loading frame as shown in Fig. 2. A base frame consisting of beam sections was welded to 19 mm thick steel plates that were bolted to the structural laboratory strong-floor. An ASTM-A36 76x76x6 angle was fillet welded to the flange of the beams to permit connection of the first stair flight to the base frame. Stiffeners were added to the angle to minimize distortion during tests. The landing posts were bolted through the top flange of the base frame with a single A325 TC bolt. Single-sided 6 mm web stiffeners were located near each of the column post connections.

Figure 2. Test setup on laboratory floor.

The top landing was attached to an ASTM A600 152x152x6 mm tube. The tube dimensions were selected to approximate the concrete landing slab dimensions. It further replicates the force transfer mechanism for an actual stair assembly in a building. A unique guiding system was developed to permit only in-plane deformations at the top landing attachment location as shown in Fig. 3. This was necessary to prevent uplift and out-of-plane deformations during lateral tests that are not possible when the stairs are located in an actual building subjected to lateral drift. Special radial and axial bearings were mounted to the steel tube and guided by special profile rails to restrict deformations to the in-plane directions. Stair tests were performed in each direction separately and the guide assembly had to be reconfigured for each of the test directions. The steel tube landing was displaced during testing using a hydraulic actuator that was operated under displacement control using a closed-loop servo-hydraulic system.

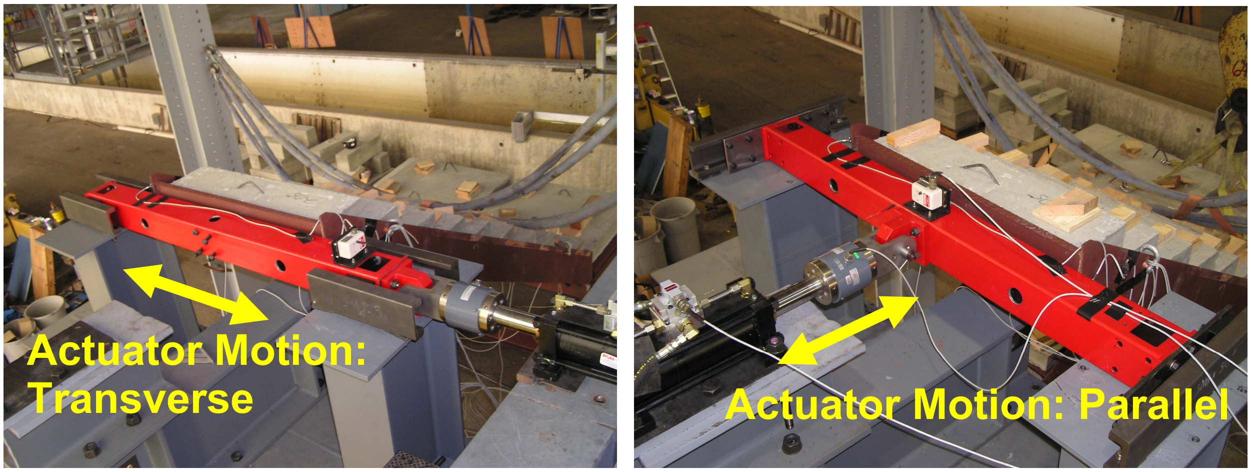

Figure 3. Top landing loading and guide assembly for each of the two orthogonal directions.

Currently, no standardized seismic testing protocols for prefabricated stair assemblies exist. However, ATC-24 (1992) provides guidelines for cyclic seismic testing of components of steel structures. In general, these procedures are based on the yield level of the component, which may not be appropriate for a stair assembly. The stair assembly within a building, does not provide significant lateral stiffness or force resistance, but is instead compliant with the building deformations. The production-run stair assemblies were considered for a typical application in a steel moment resisting frame (MRF). For a typical steel MRF, the interstory drift angle considered for the 2/3 MCE event was 2.5%, which corresponds to a peak lateral displacement (Δbm) of +/-91 mm. Using Δbm as the maximum cyclic displacement to be imposed on the stair specimen, the cycle amplitudes for three previous sequences of displacement cycles were scaled in proportion as ¾, ½, and ¼ of Δbm. Four cycles were imposed at these amplitudes as compared to the two or three cycles used in the ATC24 protocol for cycles imposed after yielding. At the start of testing, two sets of small amplitude cyclic displacements (2 cycles at 3 mm and 2 cycles at 6 mm) were applied to ensure data sensors were seated and data acquisition was properly functioning. Following these small amplitude initial cycles, six cycles were imposed at +/-13 mm. The complete lateral loading history is shown in Fig. 4. Because the stairs are compliant with the building deformations, and steel MRFs tend to be more flexible than many other types of lateral force resisting structural systems, the test displacement history would likely impose higher demands on the stair assembly than those required for many other building types.

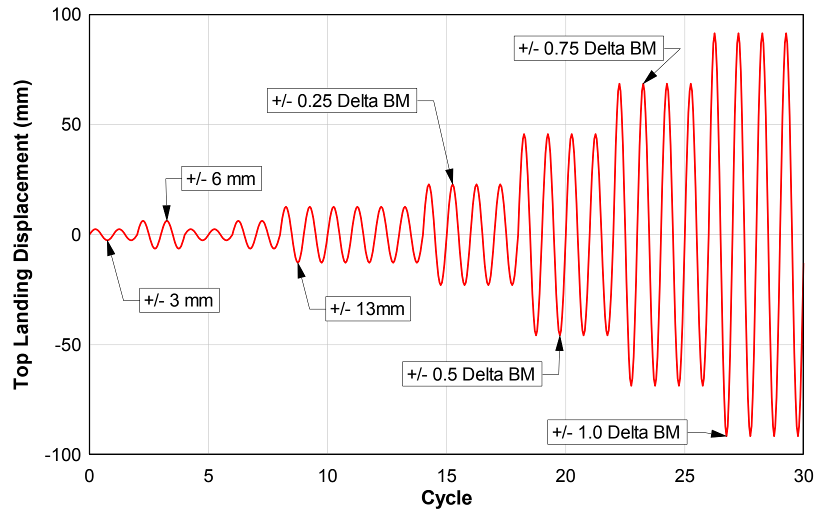

Figure 4. Imposed lateral displacement history.

Current AISC LRFD (2003) specification load combinations require consideration of live and dead loads with earthquake loading. The specified load combination is:

$$U = 1.2D + 0.5L + 1.0E \tag{1}$$

where U is the factored load combination, D is the dead load, L is the service live load, and E is the earthquake load. The applied lateral load was considered to be at the load factor of 1.0 and the in-place stair assembly represented 1.0D, however additional gravity load was required to account for the additional 20% dead load and 50% service live load. For stairs, the specified service live load is 4.8 kPa. The dead load of the stairs was provided by the manufacturer as 6.5 kN and 5.6 kN for the checker plate and infill concrete treads (without concrete), respectively. The total dead load of the concrete in-fill stair including the weight of concrete was approximately 14.7 kN assuming normal weight concrete. Individual concrete blocks weighing approximately 0.9 kN were cast for each step and two large blocks weighing 7.4 kN total were cast for the landing. The total weight of the blocks applied to the stair specimen was 25.4 kN and exceeded the load factor combination in Eq. 1 for both specimens. The blocks were placed on the specimen prior application of the lateral load and remained in place during lateral displacement testing (as seen in Fig. 2).

After completion of lateral displacement testing protocol, the top landing displacement was returned to the original neutral position. The AISC LRFD (2003) specification full design live load combination was applied to the specimen as:

$$U = 1.2D + 1.6L \tag{2}$$

Additional concrete blocks were placed on the specimen to represent the additional factored live load (5.3 kPa above the previous level in Eqn. 1). Individual concrete blocks weighing approximately 1.8 kN were placed on each step and two large blocks weighing 15.5 kN total were placed on the landing. These new blocks were placed on top of the previous sets of blocks.

The total weight of the blocks applied to the stair specimens was 75.8 kN (two sets of blocks stacked on top of each other) and exceeded the load factor combination in Eqn. 2 for both specimens.

To account for a possible aftershock event that may occur as the stairs are subjected to the full design live load, the following load combination was also considered:

$$U = 1.2D + 1.6L + 0.5E \tag{3}$$

For this test, four (4) cycles of lateral displacement of +/- 0.5Δbm (=+/-45 mm) were applied when the specimen was loaded with the concrete blocks representing the full design live load.

Each stair specimen was subjected to lateral displacements imposed in the two orthogonal directions separately. To achieve the performance requirements, the specimen was expected to sustain both events without loss of gravity load carrying capacity. The combined testing history for each specimen consisted of the following:

- Application of 0.2D+0.5L gravity load blocks
- Application of complete lateral displacement history in Fig. 4 (transverse for checker plate specimen; parallel for infill specimen) [Meets Eqn. 1]
- Application of additional 1.1L gravity load blocks [Meets Eqn. 2]
- Application of four cycles +/- 0.5Δbm [Meets Eqn. 3]
- Removal of additional 1.1L gravity load blocks
- Switch actuator direction
- Application of complete lateral displacement history in Fig. 4 (parallel for checker plate specimen; transverse for infill specimen) [Meets Eqn. 1]
- Application of additional 1.1L gravity load blocks [Meets Eqn. 2]
- Application of four cycles +/- 0.5Δbm [Meets Eqn. 3]
- Test complete for one specimen

Test Results

Test specimens were initially loaded with concrete blocks simulating gravity load. Strains gages on the stringers indicated bending along the weak-axis of the stair run under the gravity load. The internal moment determined from measured strains indicated some degree of moment restraint was provided by the landing connections (the runs are not simply supported at ends). Strains on the connection plates and angles were negligible and relative displacements between connected parts were also negligible.

The checker plate specimen was first subjected to lateral displacements in the transverse to stair run (north-south direction in Fig. 1), while the in-fill specimen was initially loaded in the parallel to stair run direction (east-west direction in Fig. 1). Overall force-deformation response for the lateral loading cases are shown in Fig. 5a and 5b and Fig. 5c and 5d for the checker and infill specimens, respectively. As seen in these figures, the specimens provided relatively little lateral stiffness and energy dissipation. The stair assemblies had higher strength and stiffness in the parallel to stair loading direction as compared to the transverse loading case.

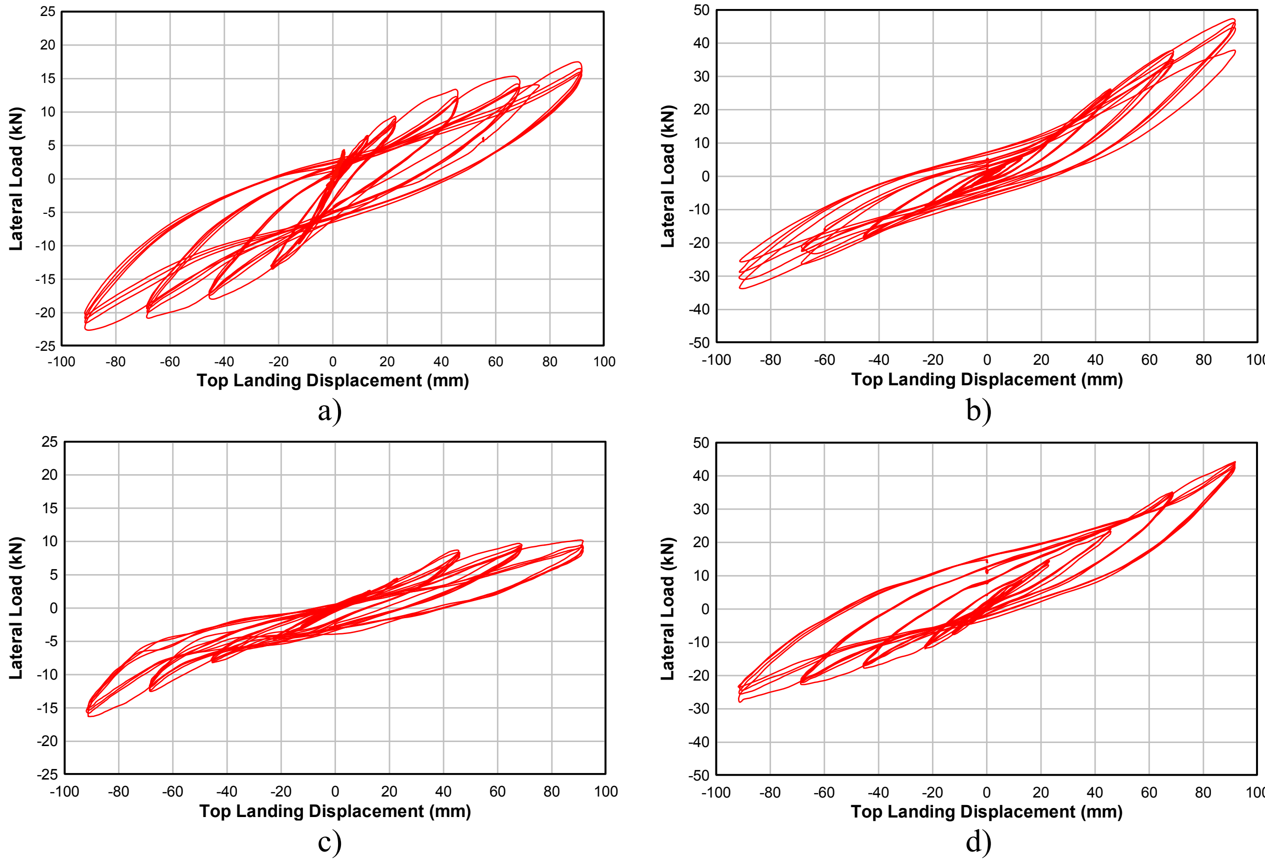

Figure 5. Overall top force- top displacement response for the Checker plate specimen (a) Transverse (b) Parallel loading and Infill concrete specimen (c) Transverse (d) Parallel loading directions.

The larger stiffness and energy dissipation seen for both stair specimens during the initial loading direction (transverse for the checker plate and parallel for the infill concrete) was due to the initial undamaged installation conditions that provided original contact between connecting stair components. After the actuator was moved to the orthogonal direction for the second sequence, specimens exhibited softer response with some stiffening and very little energy dissipation. This is because the connection parts were already yielded and residual connection gaps were produced during the previous loading history and thus the observed response for this second loading case does not correspond to that of a new undamaged specimen. Connection strains indicated initial yielding at low lateral displacements (approximately +/- 10 mm). Stringer strains indicated a relatively small amount of bending in the strong-axis of the stair run at the instrumented locations. Parallel loading produced single curvature in the stair runs, while transverse loading produced double curvature in the stair runs. Transverse loading produced higher demand at the upper landing connections. Parallel loading produced higher demands at the lower landing connection. Displaced shapes for the stair assemblies are shown in Fig. 6 in the two loading directions. The intermediate landing moved primarily in the north-south direction with relatively small displacements in the east-west direction for the transverse loading case. Indeed almost no motion of the intermediate landing was observed in the west direction for this case. For the parallel loading case, the intermediate landing exhibited relatively large motions and rotated about the bottom landing connection.

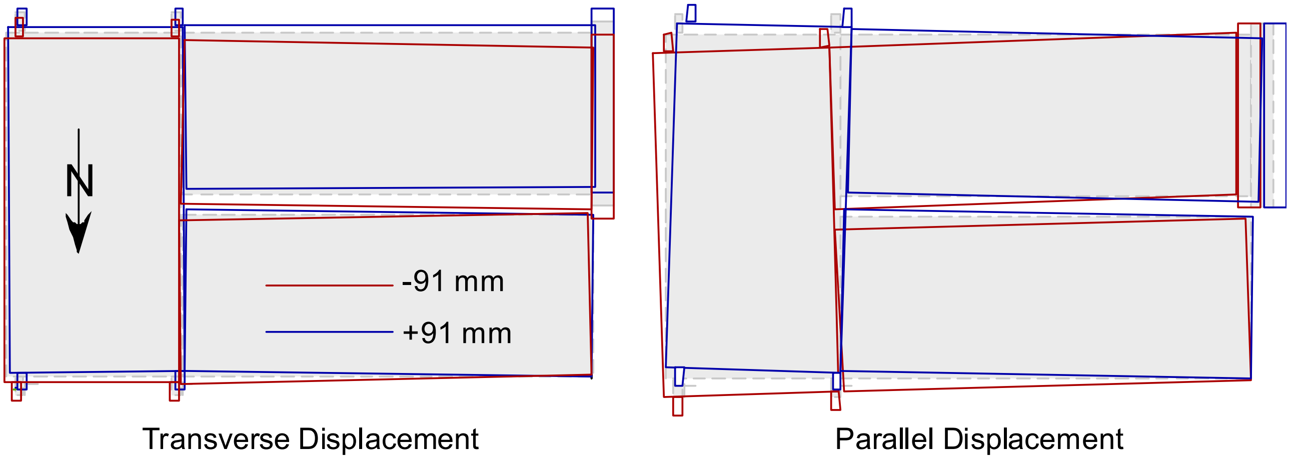

Figure 6. Displaced shape for stair assembly loaded in the transverse and parallel directions.

Relative displacements between the stringer ends and the landing connections were observed during loading. Under the imposed transverse displacements, the stringers are alternatively pulled away from and compressed against the landing connections as seen in Fig. 7. Under the imposed parallel displacements, the stringers are alternatively pulled away from and pushed against the landing connections. The deformed shape of the connection plate appeared to be fixed at the vertical weld line and primarily fixed at the bolt location as seen in Fig. 7. Due to connection plate yielding, there were residual displacements in the form of gaps that remained when the stairs were returned to the original neutral position. Displacement measurements of the base connection and laboratory floor were small and the base connection appeared to reasonably approximate that of a stiff slab connection typical of in-situ building conditions.

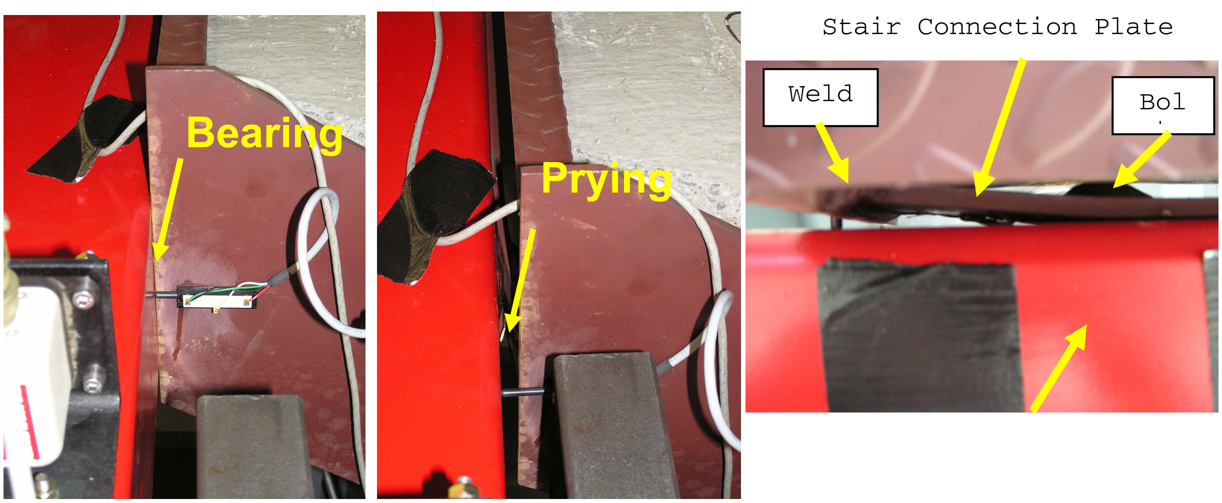

Figure 7. Alternating top landing connection bearing and prying during transverse loading.

After applying the lateral displacements of Fig. 4, the specimens were returned to the original neutral position and loaded with additional concrete blocks simulating Eqn. 2 level gravity loads.

The specimens sustained the applied load. Strains gages on the stringers indicated additional in-plane bending of the stairs under the gravity load and again showed some moment restraint was provided by the landing connections. The specimens were then subjected to 4 cycles of lateral loading with maximum displacement amplitude of +/- 0.5Δbm while under the full factored design gravity load. The specimens exhibited stable and repeatable cyclic performance during the four cycles. After the first lateral loading position was completed, the top layer of concrete blocks was removed and the lateral loading actuator orientation was changed to permit testing of the specimen in the orthogonal direction. The resulting overall force-deformation responses for the second sequence are shown in Fig. 5b and 5c for the two specimens (the diminished performance was again due to the residual damage from the first loading orientation). After lateral displacements of Fig. 4 were imposed for the orthogonal direction, the specimens were returned to the original neutral position and loaded with additional concrete blocks simulating Eqn. 2 level gravity loads. The specimens again sustained the applied gravity load. The specimens were subjected to 4 cycles of lateral loading with maximum displacement amplitude of +/- 0.5Δbm while under the full factored design gravity load (Eqn. 3) and exhibited stable cyclic performance during the four cycles. Both the checker plate and infill concrete stair specimens satisfied the loading protocol by sustaining the factored gravity loads under the design lateral motions in the two orthogonal directions and demonstrating full design gravity load carrying capacity combined with the aftershock lateral displacements.

A final visual inspection of the specimen was performed after all the concrete blocks were removed. Cracks were observed in the wrap-around welds along the bottom of the connection plate resulted in tearing of the checker plate material. Based on dye-penetrant inspection, cracks in the wrap-around weld did not propagate into the vertical weld joining the connection plate to the stringer. To investigate the condition of the vertical weld along the stringer to landing connection plate, connections were removed from the specimen after disassembly of the stair specimen from the loading system. Cracks were visible along the weld toe at the stringer-plate boundary. Three slices of the weld were machined from the section and inspected. There was evidence of crack propagation initiating at the lack of fusion zone. One section indicated almost no weld penetration although it appeared from the surface to be similar to the adjacent areas. While the weld conditions were not sufficient to hinder the overall stair performance, welding procedures and inspection protocols for stringer to landing connections should be further emphasized to ensure desired connection strength and performance.

Conclusions

Laboratory tests were performed to assess the anticipated seismic performance of prefabricated steel stair assemblies. Two different production-run stair assembly units were tested: checker plate and concrete filled pans. The stair assemblies were subjected to combined AISC factored gravity loads with lateral displacements simulating seismic interstory drift demands. Peak lateral displacements on the stair assemblies were based on an average interstory drift angle of +/-2.5% for a steel frame building having 3.6 m story heights and displacements were imposed to the stair assemblies at the top landing location in each direction (parallel to stair run and transverse to stair run) separately. The testing apparatus constrained the top landing displacements to the plane of loading considered, thereby imposing deformations and stresses consistent with in-situ building conditions Both stair assemblies successfully completed the testing protocol by demonstrating full design gravity load capability after undergoing lateral displacements in both orthogonal directions and there were no appreciable differences between the performance of the two different stair assemblies. Parallel loading produced single curvature in the stair runs and produced the highest deformation demand in the bottom landing angle connection. Transverse loading produced double curvature in the stair runs and produced the highest deformation demands in the top stair to landing connection plate and weld. Strain measurements in stringers indicated the stairs carry gravity loads as semi-rigid beams along the horizontal projected length. The stair-landing connections provided some moment restraint that was reduced after lateral loading produced separation at the landing connections. Stringers are subject to combined stringer bending (both strong-axis from seismic and weak-axis from gravity load) and axial force from seismic loading. Stair performance was dependent on the landing connections and the vertical weld joining the connection plate to the stringer. Inspection of the weld after testing indicated lack of penetration of the weld along the stringer edge. Fabrication procedures and inspection of the welds joining the connection plate to the stringer should be further emphasized to ensure best practices and desired performance.

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