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ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF SEISMIC FLOOR AND ROOF COLLECTORS IN STEEL BUILDING STRUCTURES

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Abstract

This paper presents the results of a U.S. National Science Foundation (NSF) Engineering for Natural Hazard (ENH) research project studying seismic floor and roof collectors in steel building structures. The integrated experimental and analytical research program makes use of the NSF Natural Hazard Engineering Research Infrastructure (NHERI) Facilities. Seismic collectors are critical elements that bring inertial forces to the primary vertical-plane elements of the Seismic Force-Resisting System. Due to the reversing nature of earthquake loads, collectors must alternately carry tension and compression, while under the presence of effects from gravity load and frame lateral drift. Collector failure is potentially catastrophic, yet little research has focused on collectors, and both the seismic behavior and demands on these elements are not well understood. Instead, current design code provisions rely on amplified collector design forces and simplifying design approximations. This paper presents the research program methods and results from this project, including: (1) nonlinear static and dynamic analysis of steel seismic collectors in steel composite floor systems and unfilled deck roof systems; (2) large-scale testing of collector elements and collector connections at the NHERI Lehigh Experimental Facility; and, (3) shake table testing of a two-story structure, possessing seismic collectors in a steel composite floor system and an unfilled roof deck, at the NHERI@UCSD Experimental Facility. The research is providing new knowledge on: (1) the collector seismic load path, including in the horizontal floor plane and the vertical force profile; (2) collector limit states, including collector connection failure and collector member stability modes; (3) the role of the composite slab and deck in strut mechanisms and inherent bracing; and (4) collector properties (strength, stiffness and deformation capacity) in the presence of other actions (gravity load, frame lateral drift). The research team is working together with industry partner, the American Institute of Steel Construction (AISC) and a research advisory panel composed of experts from seismic design consultants and regulatory agencies to evaluate seismic collector details, from code minimum to best practice designs, and to develop relevant and impactful design recommendations.

Keywords: Seismic Collectors; Steel Composite Structures; Shake Table Testing; Nonlinear Finite Element Analysis

1. Introduction

This paper presents the results to date of a U.S. National Science Foundation (NSF) Engineering for Natural Hazard (ENH) research project studying seismic floor and roof collectors in steel building structures. The integrated experimental and analytical research program makes use of the NSF Natural Hazard Engineering Research Infrastructure (NHERI) Facilities.

The paper describes the research program, including: (1) nonlinear static and dynamic analysis of steel seismic collectors in steel composite floor systems and unfilled deck roof systems; (2) large-scale testing of collector elements and collector connections at the NHERI Lehigh Experimental Facility; and (3) shake table testing of a two-story structure, possessing seismic collectors in a steel composite floor system and an unfilled roof deck, at the NHERI@UCSD Experimental Facility.

The research is providing new knowledge on: (1) the collector seismic load path, including in the horizontal floor plane and the vertical force profile; (2) collector limit states, including collector connection failure and collector member stability modes; (3) the role of the composite slab and deck in strut mechanisms and inherent bracing; and (4) collector properties (strength, stiffness and deformation capacity) in the presence of other actions (gravity load, frame lateral drift).

The research team is working together with industry partner, the American Institute of Steel Construction (AISC) and a research advisory panel composed of experts from seismic design consultants and regulatory agencies to evaluate seismic collector details, from code minimum to best practice designs, and to develop relevant and impactful design recommendations.

2. Background

Seismic collectors are critical elements that bring inertial forces to the primary vertical-plane elements of the Seismic Force-Resisting System (SFRS). In an earthquake, the seismic collectors gather the inertial forces that develop in the floor or roof diaphragm and transfer them to the primary elements of the SFRS. Due to the reversing nature of earthquake loads, collectors must alternately carry tension and compression, while under the presence of effects from gravity load and frame lateral drift.

Loss of collector elements is potentially catastrophic, as has been shown by failures of collectors in concrete structures, including collapses in the 2011 Christchurch earthquake [1], and the 1994 Northridge earthquake [2] in which shear or core walls were undamaged, while the floor system detached, resulting in collapse of the Gravity Load Resisting System (GLRS).Yet little research has focused on collectors, and both the seismic behavior and demands on these elements are not well understood. Instead, current design code provisions rely on amplified collector design forces and simplifying design approximations.

2.1 Steel Seismic Collector Design

Current design code provisions for collectors recognize their critical role through special load combinations [3] that include the System Overstrength Factor Ω_o, resulting in large design forces. This design approach is an attempt to ensure that the critical collector elements remain elastic. Likewise, seismic collectors are typically designed for direct axial force actions and gravity load for idealized conditions without full consideration of actual boundary conditions or the effects of frame drift.

In steel structures, the collector is provided by beams in the floor or roof system. Since elements alternately carry tension and compression, they must be designed both as tension members and compression members. Thus, both collector connection strength and collector element stability are key aspects of collector design. Tension design focuses on the collector connections [4], e.g., top flange welded (TFW), etc. (Fig. 2b). The collector element itself is designed as a beam-column, since the member is under combined flexure (due to gravity load) and axial load (due to collector action). The controlling compression limit state for a steel collector member depends on the bracing condition of the floor or roof system [4], including strong-axis or weak axis flexural buckling, torsional or constrained axis flexural torsional buckling (CAFTB) [5]. The latter mode, with center of rotation about the top flange braced by the deck or slab, is particular to collectors.

In many modern structures, SFRS elements have become isolated within the floor plan, resulting in significant collector runs. Composite action is attained in floor systems primarily through the shear studs. In general, the magnitude of collector force increases with area tributary to the collector line. The assumed uniform transfer of inertial force into the collector leads to a linear collector axial force diagram [6]. Thus, collector forces are larger in the bays nearer to the primary vertical plane SFRS members (See Fig. 1).

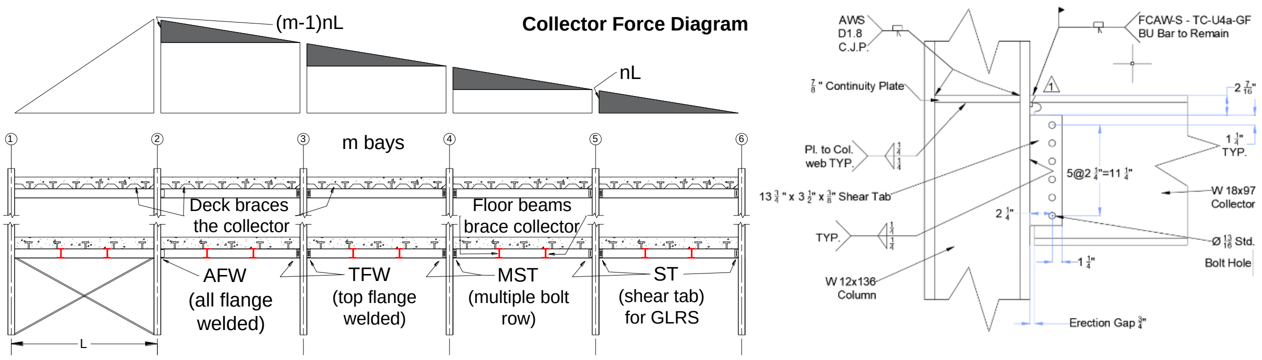


Fig. 1 – Steel Seismic Collectors: (a) Collector Line and Forces; (b) Typical Collector Connection.

2.2 Seismic Collector Connections

The connections used to transmit the collector forces across the gravity load resisting columns or to the primary vertical plane SFRS members vary depending on the magnitude of the collector force. For lower level collector forces, the conventional shear tab connection used for gravity load can be designed to carry combined shear and tension. These connections can also be supplemented by collector reinforcing bars in the slab that are properly anchored in the slab [7], as described in the design example in [4]. As collector forces grow, a modified version of the shear tab connection employing multiple bolt rows is often employed. As the collector forces increase further, typical design involves connecting the top flange. The typical detail in the US involves welding the top flange (See Fig. 1b). Finally, collector axial force levels can become sufficiently large that the top flange connection is not adequate, and at this point a connection involves both flanges.

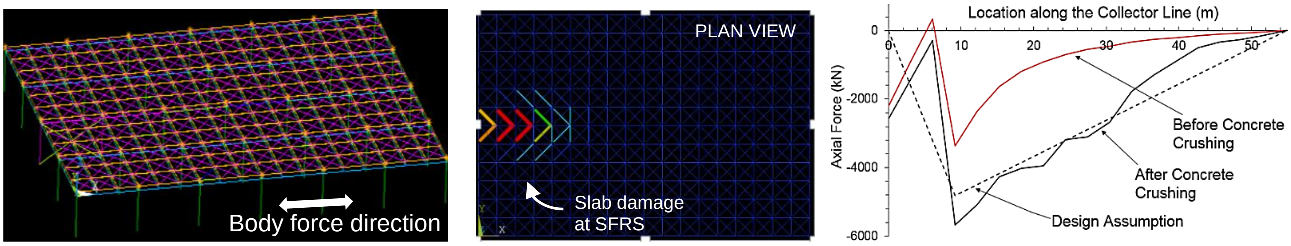
3. Analytical Research Program

The analytical research program on has four main thrusts: (1) Determining the steel seismic collector load path; (2) Determining the behavior and performance of steel seismic collector connections; (3) Determining the cyclic performance of the collector elements, including collector member stability modes, inherent bracing; (4) Determining the demands acting on the collector, including the interaction of collector forces with effects due to building lateral drift.

3.1 Analysis of Load Path

The analytical modeling of the collector load path involves a two dimensional (2D) truss model in the (horizontal) plane of the floor in order to capture the strut action provided by the floor slab (See Fig. 2a). The 2D horizontal truss model for the slab is connected to the underlying frame at the shear stud locations along the collector and gravity framing. This model captures both concrete cracking due to inertial forces causing tension in the slab (See Fig. 2b), shown here occurring in the slab regions surrounding the SFRS, as well as the diagonal strut action due to inertial forces causing compression, including local crushing.

The load path analysis permits the evaluation of the inertial load transfer along the collector line at different stages of the response (See Fig. 2c). As noted, when the concrete slab is intact (shown here for a collector line with the slab flute parallel to the collector and under inertial force creating compression, for a SFRS located at the center of the left edge of the floor). Note that before the inertial forces create damage in the slab, the transfer of collector force is highly nonlinear, leading a concentration of force in the shear studs transferring the inertial forces to the collector nearer to the SFRS. As seen in Fig. 2c, this highly nonlinear distribution begins to resemble the linear pattern assumed in design as the slab takes on damage.



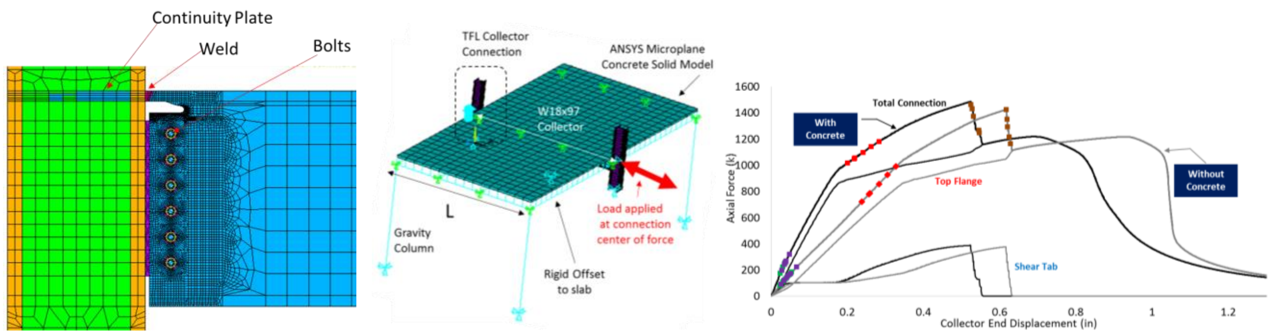
(a) (b) (c)

Fig. 2 – Collector Load Path: (a) Truss Model; (b) Damage Pattern @SFRS; (c) Collector Force Distribution.

3.2 Analysis of Collector Connections

The analytical modeling of the collector connections involves 2D plane stress models, as well as three dimensional (3D) solid models to examine the state of tri-axial stress in welds and the contribution of the concrete slab.

A 2D plane stress model for a top-flange welded collector connection is shown in Fig. 3a. The model captures the material nonlinearity of the beam, column and shear tab; and the projection geometry of the weld, as well as the slip and nonlinear shear response of the bolt and the inelastic bearing deformations at the bolt hole. The 3D model is shown in Fig. 3b. The resulting load-deformation response of this collector connection under axial tension is shown in Fig. 3c. The plots show the total collector force, as well as the distribution of this force in the top flange and the shear tab for two cases: (i) bare steel (without concrete) and with a concrete slab. As is seen in the Fig. 3c plot: (i) the shear tab, intended for gravity load transfer, participated in the collector force transfer; and (ii) the concrete slab can provide a non-negligible contribution in carrying the collector forces.



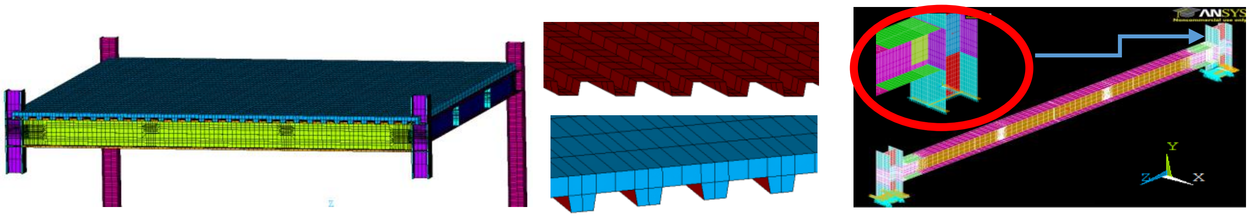
(a) (b) (c)

Fig. 3 –TFL Connection: (a) 2D Plane Stress Model; (b) 3D Model with Slab (b) Nonlinear Load-Deflection.

3.3 Analysis of Collector Stability

The analytical modeling of the collector member under compression load involves 3D nonlinear geometric and material modeling of the collector member. Key aspects of the investigations of collector stability include the determination of the inherent bracing of the floor system, the participation of the slab in compression transfer, and the effect of the connection boundary conditions, in particular during cyclic loading.

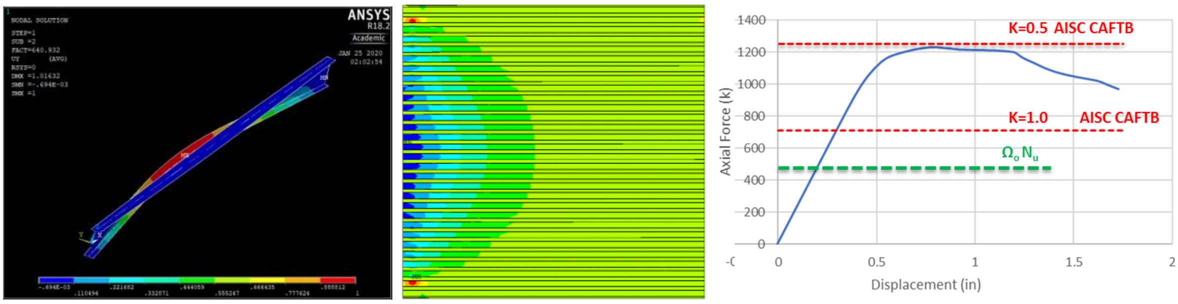
The models use for examining collector nonlinear cyclic response for composite floors and unfilled roof decks are shown in Fig. 4. In order to approximate the actual conditions, the model encompasses the bay adjacent to the collector (See Fig. 4a), including: (i) the intermediate framing; (ii) the deck and/or the slab (See Fig. 4b); and uses three dimensional representations using shell elements for the collector and the collector connections (See Fig. 4c).



(a) (b) (c)

Fig. 4 –Collector Stability Models: (a) 3D Bay; (b) Roof and Composite Deck; (b) Connections.

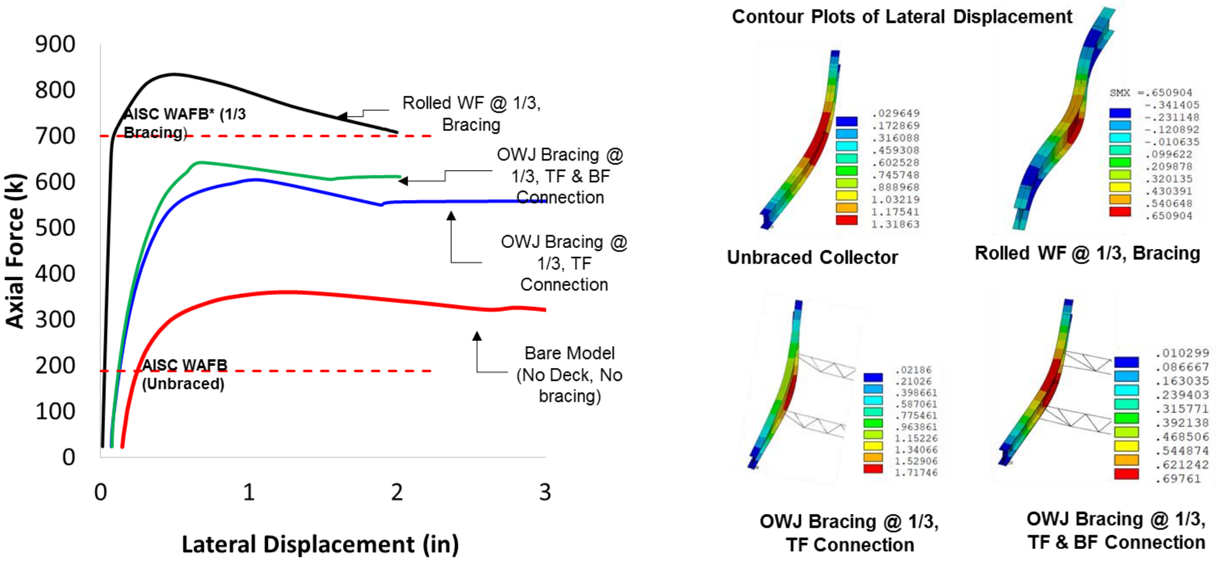
Typical results from these models are shown in Fig. 5. In Fig. 5a, a contour plot of transverse displacement for the isolated collector, indicates that the collector is undergoing CAFTB. In Fig. 5b, a plan view of the bay showing the axial stress contour, with blue indicating high compression, one can see that the slab can participate in force transfer as a collector member loses stiffness, even for deck oriented perpendicular to the collector. The collector nonlinear load deflection plot is shown in Fig. 5c, indicating that the design code prediction of collector compressive strength is well estimated in this case using the CAFTB limit state equation [4] with an effective torsional length factor of 0.5.



(a) (b) (c)

Fig. 5 –Collector Stability: (a) Constrained Axis Flexural Torsional Buckling (CAFTB); (b) Stress Contour Plan View showing axial load participation of deck/slab; (c) Nonlinear Load Deflection.

Roof collectors are also evaluated. Fig. 6a plots nonlinear load-deflection plots for roof collectors under compression for the different bracing cases shown in Fig. 6b, including: (i) unbraced; (ii) wide-flange intermediate struts at third points; (iii) open-web joists (OWJ) top-connected intermediate struts at third points; and (iv) OWJ top-and-bottom connected intermediate struts at third points. As seen, the design code prediction of collector compressive strength is well estimated in this case using the weak axis buckling limit state equation [4] with the appropriate unbraced.

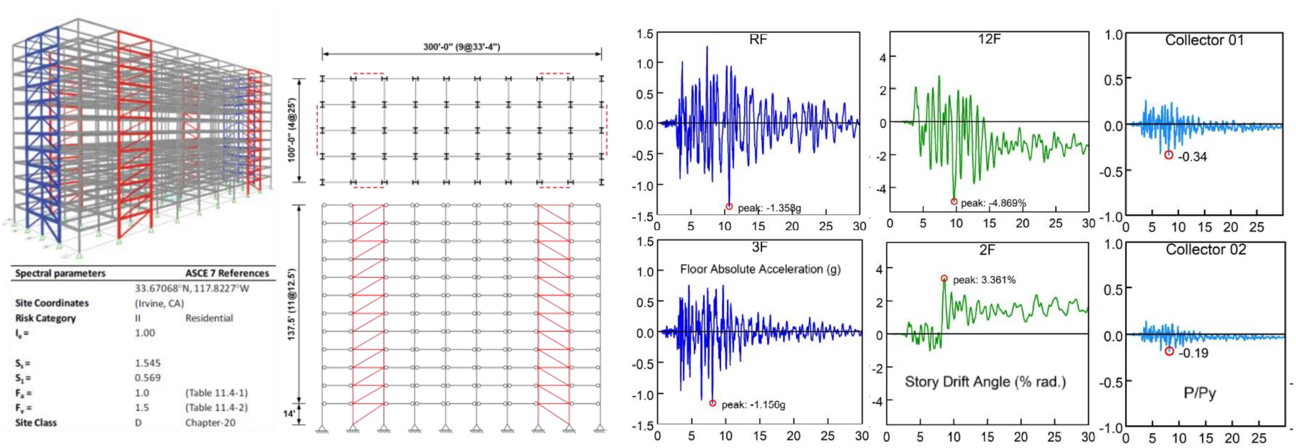


(a) (b)

Fig. 6 –Roof Collector Stability: (a) Weak Axis Flexural Buckling for different deck parallel bracing cases; (b) Different beam and joist bracing cases.

3.4 Analysis of Collector Demands

The demands for the collector elements are estimated through nonlinear time history analysis of an archetype building structure [8]. The SFRS layout, elevation, plan and design parameters for the building are shown in Fig. 7a. A selection of the time history responses of the building to a spectrum compatible maximum considered earthquake (MCE) are shown in Fig. 7b. From left to right are the floor acceleration time histories, the inter-story drift and the collector forces, normalized by the collector member axial yield force. The upper acceleration and drift plots show the response of the roof/top story of the building; the lower acceleration and drift plots show the response of a lower floor/story of the building. The normalized collector forces are shown for the collector in the interior bay adjacent to the braced frame (01), and the adjacent bay farther away from the braced frame (02). Note that depending on the level of the building, the collector can be subjected to different combinations of collector force and the effects of inter-story drift.



(a) (b)

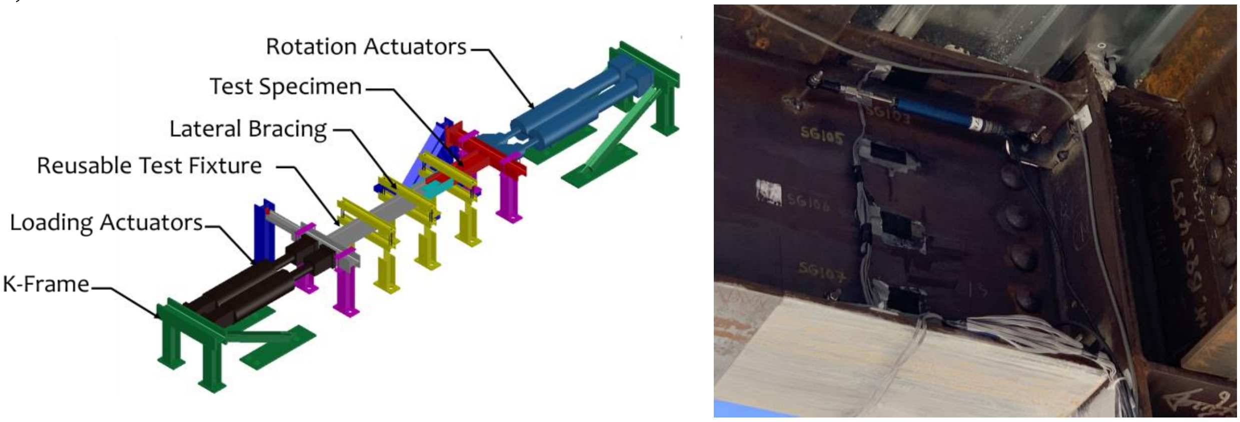
Fig. 7 –Collector Demands: (a) SDII Archetype Building [8]; (b) Seismic Demands (MCE).

4. Experimental Program

The experimental program has three main components: (1) Large-Scale Collector Connection Tests; (2) Large-Scale Collector Component Tests; and (3) Large-Scale Shake Table Test of a Building Specimen.

4.1 Large-Scale Collector Connection Tests

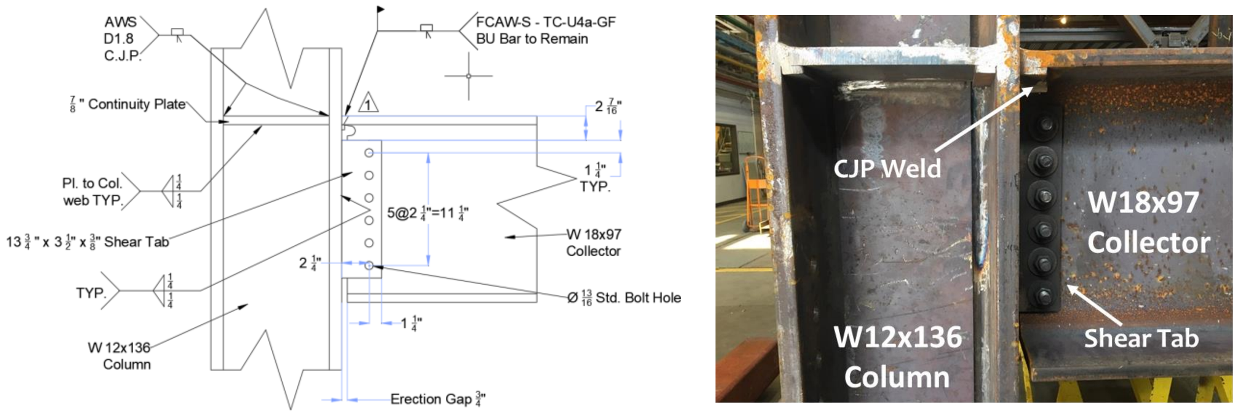
The large-scale collector connection tests are being performed at the NHERI Lehigh Facility. The test setup is shown in Fig. 8a. Note that the collector member is turned on its side. The collector connection is located within the test specimen (shown in red), while the rest of the collector is represented by a reusable test fixture (shown in gray). Loading protocols for the tests include cyclic tension/compression loading in the presence of joint rotation. In order to achieve this protocol, the test setup employs two pairs of actuators at each end of the test setup. One pair of actuators simulates inter-story drift by rotating the column of the test specimen while the other pair of actuators applies an axial force to the collector. By utilizing two actuators at each end, the location of the center of force applied to the collector is controlled. Note that this latter feature is important as the true line of action of the inertial force acts eccentrically to the centroid of the collector; likewise in some collector connections (e.g. the top flange welded connection shown in Fig. 1b) the center of resistance is eccentric to the centroid of the collector. Typical instrumentation at the collector connection is shown in Fig. 8b. This instrumentation includes linear displacement transducers to measure displacement and rotation at the collector connection, and an array of strain gages near the welded flange and along the beam web, as well as a rosette at the weld access hole.



(a) (b)

Fig.8– NHERI Lehigh Collector Connection Tests: (a) Test Set-up; (b) Instrumentation.

The detail and a photo for the ¾ scale top-flange weld (TFW) specimen is shown in Fig. 9. Test specimens representing code-minimum connections are being tested first to determine their adequacy.



(a) (b)

Fig. 9 – NHERI Lehigh Collector Connection Tests: (a) TFW Detail; (b) TFW Specimen.

4.2 Large-Scale Collector Member Tests

The large-scale collector connections test setup is modified as shown in Fig. 10 to perform the collector member testing. With the collector member turned on its side, the deck / slab is oriented vertically and braced on the strong floor. Smaller actuators are added to simulate gravity load acting on the collector.

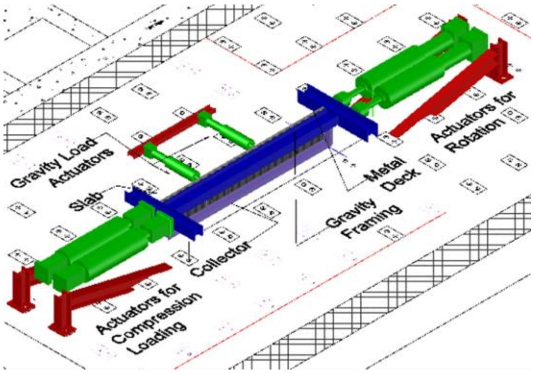


Fig. 10 – NHERI Lehigh Collector Member Test Set-up.

4.3 Shake Table Testing of a Two-Story Building

The shake table test testing for evaluating the collectors involved a test specimen with perimeter collectors aligned in the direction of the table motion direction (See Fig. 11a). The test specimen was examined in three configurations to meet the research objectives.

In Phase 1, a one-story steel composite floor deck was tested in isolated fashion. For this phase, a simulated table motion was created based on analysis to reproduce the floor acceleration response and reasonably estimate the inter-story drift of an upper level floor of the archetype building. To achieve this goal for a one-story specimen, the gravity columns were configured with a slightly shorter first story height, and provided with pinned connections at their base. The plan of the composite floor is shown in Fig. 11a, indicating that one perimeter collector was oriented in a deck perpendicular configuration, while the other was oriented in a deck parallel orientation with intermediate beams serving as the collector bracing. The collector connections for the composite floor are indicated in the insets of Fig. 11b, and are, in order moving away from the vertical plane SFRS, an all-flange welded (AFW), a top flange welded (TFW) and a shear tab (ST) connection. The SFRS was a cantilever column, in order to maximize the collector length.

The elevation shown in Fig. 11b is the Phase 2 configuration where a second story to an unfilled steel roof deck was added to the specimen. The layout and connection types for the roof collector are the same as for the composite floor, with smaller member size. The two-story structure was treated as a building, and subjected to a Northridge earthquake ground motion input, scaled to different intensities.

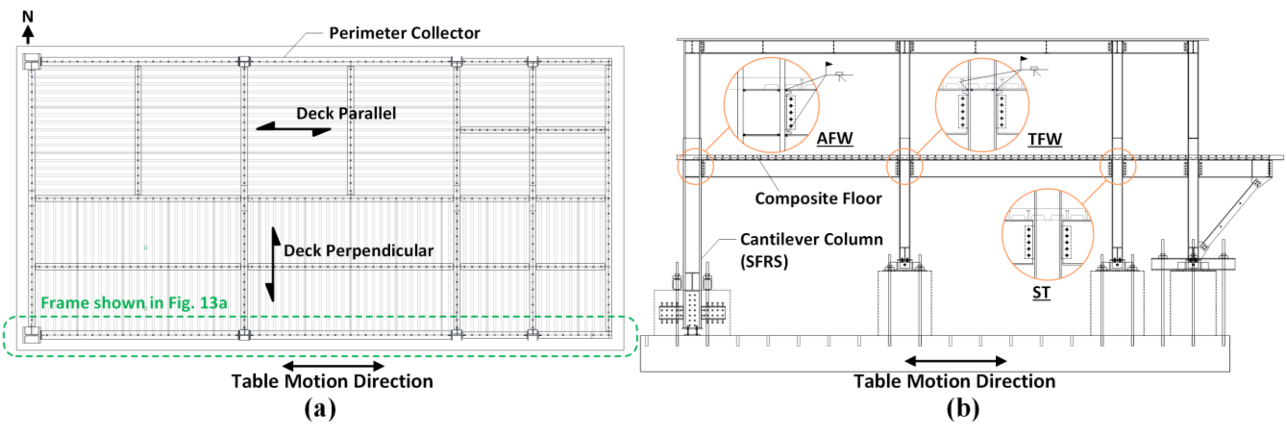


Fig. 11 – NHERI@UCSD Shake Table Specimen: (a) Plan View (Phase 1); (b) Elevation (Phase 2).

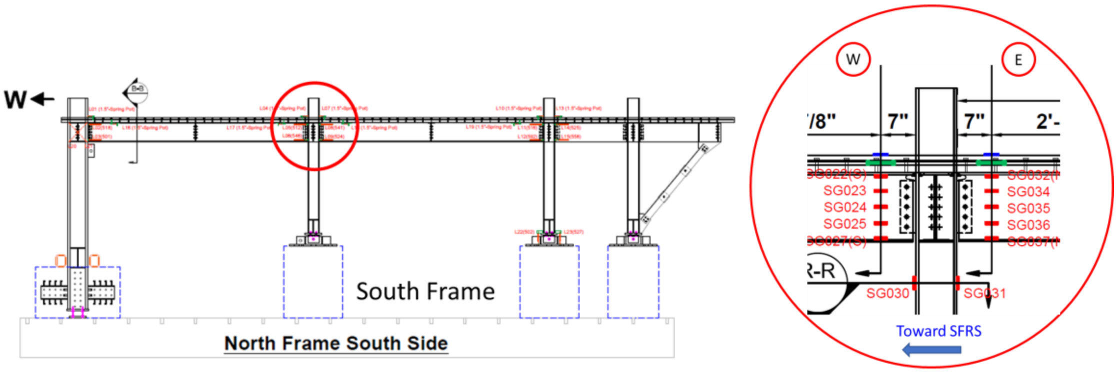
The Phase 3 specimen is shown in Fig. 12a. In this phase, a buckling-restrained brace (BRB) was added to the upper level to modify the building dynamic characteristics and the collector seismic load path. Note that the entire building is placed on concrete pedestals, used to create the cantilever column fixed base and the gravity columns pinned bases. A view from the underside of the composite floor shows the different deck orientations, the intermediate floor beams bracing the collector, and the HSS diagonal braces to provide stability to the specimen in the lateral direction orthogonal to the table motion. Table 1 provides the shake table test matrix, including phase, input motion intensity (DBE=Design Basis Earthquake) and direction.

Fig. 12 – NHERI@UCSD Shake Table: (a) Phase 3 Test Specimen; (b) Composite Floor Deck Orientation.

Table 1 – Steel Collector Shake Table Test Sequence

PHASE	TEST ID	INTENSITY LEVEL	DIRECTION	MOTION
PHASE 1	1-A	20% DBE	-	SIMULATED
	1-B	50% DBE	-	SIMULATED
	1-C	100% DBE	-	SIMULATED
PHASE 2	2-A	50% DBE	-	NORTHRIDGE
	2-B	100% DBE	-	NORTHRIDGE
	2-C	100% DBE	INVERTED	NORTHRIDGE
	2-D	100% DBE	-	NORTHRIDGE
	2-E	125% DBE	INVERTED	NORTHRIDGE
PHASE 3	3-A	50% DBE	-	NORTHRIDGE
	3-B	100% DBE	-	NORTHRIDGE
	3-C	100% DBE	INVERTED	NORTHRIDGE
	3-D	150% DBE	-	NORTHRIDGE
	3-E	150% DBE	INVERTED	NORTHRIDGE
	3-F	200% DBE	-	NORTHRIDGE
	3-G	200% DBE	INVERTED	NORTHRIDGE

The typical instrumentation along the collectors is indicated in Fig. 13a. A close-up of the strain gage layout at the collector connections is shown in Fig. 13b, here for the TFW connection. As seen, inelastic strain gages were distributed along the depth of the collector, as well as within and on top of the concrete slab. The remainder of the instrumentation includes elastic stain gages deployed on the columns to determine column moment and shear; linear displacement transducers to read collector connection rotations, and accelerometers deployed across the floor plan at each level to read floor and roof accelerations. String pots were deployed on each frame at each level to read inter-story drift. The instrumentation was used to estimate building specimen fundamental period before and after each of the input motions shown in Table 1.

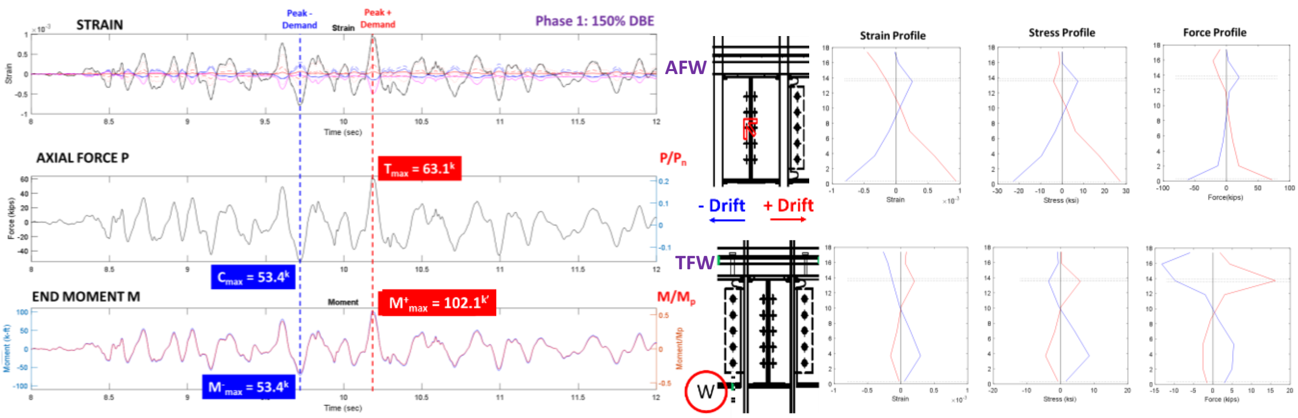


(a) (b)

Fig. 13 – Shake Table Test Instrumentation: (a) First Level; (b) Typical Connection Strain Gage Layout.

Selected results are shown in Fig. 14 from Test 1-C (Phase 1, 150%. Collector force time histories for the south frame collector at the west joint (AFW connection) are shown in Fig. 14a. For the one story specimen, the maximum collector force and end moment are seen to correspond, both for collector tension and collector compression. Note that the collector force and end moment tend to create components that act together, either in tension or in compression, on the bottom flange.

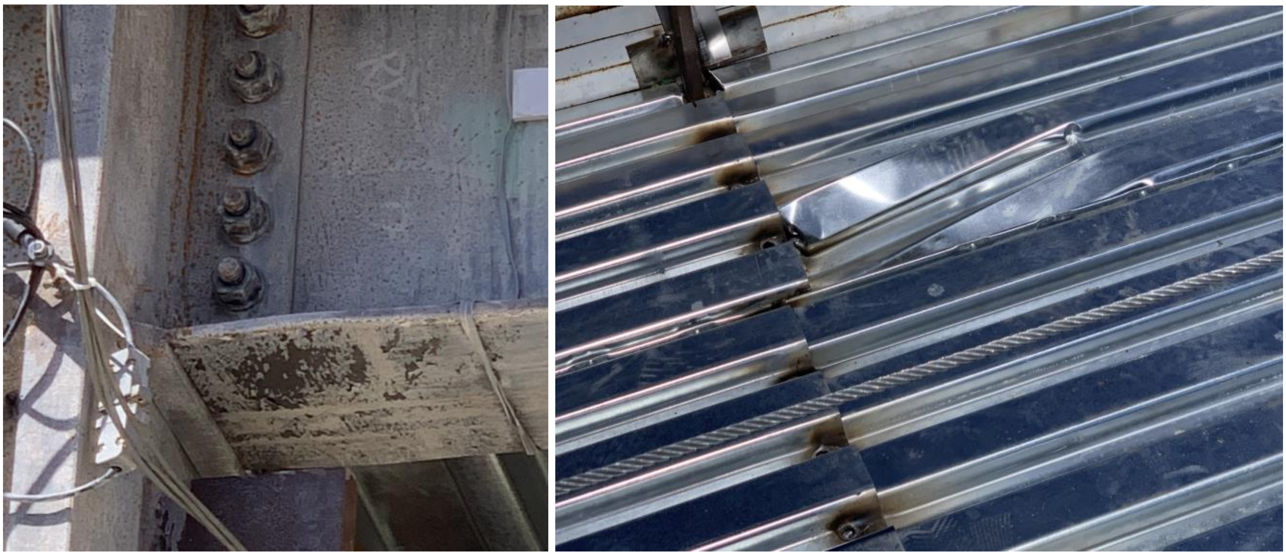
Strain, stress and force profiles are shown in Fig. 14b, both for the AFW connection and the west facing TFW connection on the same collector span, again for the south frame. The profiles are taken at the maximum positive and negative demands for Test 1-C, and include the distribution along the depth of the collector beam as well as the slab above. Examining the profiles shows that composite action can be mobilized in the collector when it is under positive moment for both the AFW and TFW; the high demands on the lower flange due to the combination of collector force and moment; the significant difference in force transfer between the AFW and TFW connections, in particular at the top flange.



(a) (b)

Fig. 14 – Shake Table Test Results: (a) Collector Force Time History; (b) Connection Strain Profiles.

Selected photos showing damage to the shake table test specimen are shown in Fig. 15. The condition of the bottom flange of the south frame AFW connection after Phase 2 is shown in Fig. 15a. As seen, the lower flange has yielded and undergone local buckling. The condition of the end lap joint for the roof deck after Test 3-F is shown in Fig. 15b. In this test, at 200% DBE intensity, the intermediate longitudinal side lap joint between perimeter frames and the floor centerline failed in shear (with the added mass anchored to the center portion of the roof plan flanking the center longitudinal beam line), resulting in loss of diaphragm force transfer, and buckling of the end of the deck as shown.



(a) (b)

Fig. 15 – Shake Table Test Specimen Damage: (a) Local Buckling of AFW Connection Bottom Flange; (b) Longitudinal Seam Failure of Roof Deck.

5. Conclusions and Recommendations

The project is ongoing, however the following preliminary conclusions and design recommendations can be drawn from the research:

- The participation of the floor slab in strut action should be considered in the load transfer of the floor inertial forces to the collector system.
- The portion of the connection intended for gravity load transfer and the local slab should be considered in the collector force transfer across the collector connection.
- The controlling stability limit states for the collector depend on the floor or roof system parameters. Design expressions for collector compression strength provide good bounds to analytically-obtained response. The role of the collector connections in the cyclic response requires further investigation.
- The interaction of collector axial force and moment due to inter-story frame drift needs to be accounted in collector design.

6. Acknowledgements

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