INVESTIGATION OF SEISMIC PERFORMANCE OF COLLECTORS IN STEEL BUILDING STRUCTURES

Anshul Agarwal¹, Daniel Lizarraga¹, Max Beedle², Chao-Hsien Li³, Robert Fleischman⁴, Richard Sause⁵, James Ricles⁵, and Chia-Ming Uang⁶

ABSTRACT

This paper presents an overview of a newly-initiated research program on seismic collectors in steel building structures. Seismic collectors are 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. 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. This paper presents the plans of a research program that will use nonlinear analysis of steel collector elements in steel composite floor systems, supported by: (1) large-scale testing of isolated collector elements and connections at the NHERI Lehigh Experimental Facility; and (2) shake table testing of a single-story steel composite floor system at the NHERI UCSD Experimental Facility. The research attempts to: (1) advance knowledge on the seismic performance of collectors in steel composite floor systems under the existing practice; and (2) develop innovative collector concepts that limit earthquake forces in the structure. Specific objectives are to determine collector properties (strength, stiffness and ductility), characteristics (load paths, limit states, damage accumulation) for different details (collector connections, deck orientation, slab details, etc.) and to quantify the role of composite floor in bracing the collector.

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This paper presents an overview of a newly-initiated research program on seismic collectors in steel building structures. Seismic collectors are 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. 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. This paper presents the plans of a research program that will use nonlinear analysis of steel collector elements in steel composite floor systems, supported by: (1) large-scale testing of isolated collector elements and connections at the NHERI Lehigh Experimental Facility; and (2) shake table testing of a single-story steel composite floor system at the NHERI UCSD Experimental Facility. The research attempts to: (1) advance knowledge on the seismic performance of collectors in steel composite floor systems under the existing practice; and (2) develop innovative collector concepts that limit the earthquake forces in the structure. Specific objectives are to determine collector properties (strength, stiffness and ductility), characteristics (load paths, limit states, damage accumulation) for different details (collector connections, deck orientation, slab details, etc.) and to quantify the role of composite floor in bracing the collector.

1. Introduction

Seismic collectors are key elements of a building’s Seismic Force Resisting System (SFRS). In an earthquake, the seismic collectors gather the inertial forces that develop in the floor or roof

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diaphragm and transfer them to the primary elements of the SFRS. Current design code provisions for collectors recognize their critical role through special load combinations [1] that include the System Overstrength Factor $\Omega_o$, resulting in large design forces. This design approach is an attempt to ensure that the critical collector elements remain elastic. Loss of collector elements can be catastrophic, as has been shown by failures of collectors in concrete structures, including collapses in the 2011 Christchurch earthquake [2], and the 1994 Northridge earthquake [3] in which shear or core walls were undamaged, while the floor system detached, resulting in collapse of the Gravity Load Resisting System (GLRS).

In steel structures, the collector is provided by beams in the floor or roof system. Due to the reversing nature of earthquakes, these elements must alternately carry tension and compression. Thus both collector connection strength and collector element stability are key aspects of collector design. Further, in the steel composite floor system, the collector load path involves complicated indeterminate assemblages of different materials and geometries, acting at different elevations, and connected to elements not intended for collector action, and occurs in a system also transferring gravity load, and possibly unintended lateral load resistance.

This paper presents the plans of an integrated analytical/experimental research program involving analytical modeling of collectors supported by large scale testing at the NHERI Lehigh Experimental Facility (EF), and shake table testing at NHERI UCSD EF. The objectives of the research program is to: (1) advance knowledge on the seismic performance of collectors under the existing practice; and (2) develop innovative collector concepts that limit seismic forces in the structure. This paper provides: background on steel seismic collectors (Sec. 2); a description of the overall research plan (Sec. 3); descriptions of the individual research thrusts focusing on collector connections, elements, and load paths (Sec. 4), ending with the research schedule (Sec. 5).

2. Seismic Collectors in Steel Structures

The SFRS of a steel structure has three primary components, which, acting in series, provide a complete load path between the seismic mass and the foundation: (1) the composite floor diaphragms, in which inertial forces from the floor mass and attached elements are transferred through the in-plane shear stiffness of the floor deck/slab system; (2) the vertical-plane elements that provide a laterally stiff vertical load path for these forces to the foundation; and (3) the seismic collectors, which serve as the critical link between these other two components.

![Steel Deck Diaphragms: (a) Bare Metal-Deck [4]; (b) Composite Steel Deck [5].](image-url)
2.1 Steel Composite Floor Systems

Steel composite deck is the typical construction for floor systems in steel building structures. In this floor system, a concrete-filled metal deck is placed on top of the underlying steel gravity framing: girders span the columns; floor beams span the girders; and the metal deck (thin-gage cold-formed corrugated sheets) spans the floor beams (Fig. 1a). The concrete floor slab is cast-in-place using the deck as formwork, and may be reinforced with bars or welded wire fabric. In composite floor systems, steel shear studs are welded to the underlying framing and project into the slab (Fig. 1b). Composite action is attained in floor systems primarily through the shear studs.

2.2 Steel Collector Design

Seismic collectors bring the inertial forces that develop in the floor system during earthquakes to the vertical plane SFRS elements, e.g. braced frames (Fig. 2a). Collector demands depend on seismic hazard [1] and collector length. In many modern structures, SFRS elements have become isolated within the floor plan, resulting in significant collector runs. Due to the reversing nature of earthquake loads, collectors must be designed both as tension and compression members. Tension design focuses on the collector connections [6], e.g., top flange welded (TFW), etc. (Fig. 2b). The collector element itself is designed a beam-column, since the member is under combined flexure (due to gravity load) and axial load (due to collector action).

![Steel Collector Design Forces](image)

**Figure 2.** Steel Collector Design Forces [7]: (a) Plan View; (b) Collector Profile.

![Collector Details](image)

**Figure 3.** Collector Details: (a) MST; (b) TFW; (c) Constrained Flange FTB [8].

Under low seismic demands, collector forces are often sufficiently small that existing floor system elements serving as part of the GLRS can also count as collectors, e.g. shear tabs (ST) with fully-pretensioned bolted connections [7]. In cases for wind or more modest seismic loads, the collector may be provided by reinforcing bars placed within the concrete slab [7]. For moderate seismic demand, gravity system details may be modified to carry the loads, e.g., adding extra rows
of bolts, MST (Fig. 3a). For high seismic collector demands, however, the outcome of current code provisions is that expensive special elements must be introduced into the floor system specifically to carry the amplified forces. Members significantly larger than the surrounding gravity system elements are required to prevent instability under compressive collector forces; expensive full-penetration welded connections are often required for tension transfer, applied to only the TFW if possible (Fig. 3b) to minimize moment, but also to both flanges (AFW) when necessary. Due to the way collector forces build up (Fig. 2b), different collector connection types may be used along a single collector run. Depending on the gravity framing layout, collectors in one direction might act through the column weak axis (e.g. Fig. 3a).

Collector member limit states in compression include flexural, torsional, flexural torsional, and lateral torsional buckling [8]. The lateral and torsional bracing inherent in the floor framing and deck is an important consideration in design. Deck orientation (both are shown in Fig. 2b), level of composite action, and the presence of openings all can have a significant effect [8]. In general, lateral bracing is ignored for parallel deck ribs. Torsional bracing, often ignored for a bare steel deck, is considered continuous for a composite steel deck [8]. The unique boundary conditions for collectors, in comparison to most beam-column situations, leads to a constrained-flange flexural torsional buckling (FTB) mode about the top flange, where shear studs anchor the member (See Fig. 3c). Designers are permitted to follow approximate methods based on design equations for other conditions [9], as modified using simplified assumptions [8]. Collectors are treated in several technical documents [10], including for new construction [11] and retrofit [12].

New diaphragm seismic design forces are being adopted in the code [13] in recognition of large peak inertial forces that can develop during a seismic event. These forces can be substantially larger than the prescribed current code [1] equivalent lateral forces (ELF). Fig. 4b compares the current and newly proposed ASCE 7 diaphragm design forces. Collector overstrength factors are also treated differently in the new design procedures [13]. These changes impact collector design.

![Figure 4. Seismic design forces: (a) ELF; (b) F_{px} Comparison.](image)

2.3 Discussion: Seismic Collector Action in Composite Steel Floors

Seismic collectors must be able to transfer the seismic forces as axial load into the SFRS through a dependable, stiff load path. The collector forces are accumulated through shear studs on the elements, or to a lesser extent transverse framing members. Cowie, et. al. [14] emphasized the need for sufficient shear strength in the composite slab along a collector to ensure inertial force transfer. Codes do not formally address these conditions, with exceptions, e.g., shear strength design equations in [15] based on rib orientation.

Collector compression forces may be strongly carried through the concrete slab (See Fig.
5a). Little evidence exists to distinguish strut action [16] in the composite slab relative to the transfer of the underlying frame. Experiments with composite steel decks show the slab contributing to frame action [17] and laterally bracing members, except when early cracking of concrete ribs occurs [18]. Easterling & Porter [19] identified controlling limit states in composite decks, including slab X-cracking and longitudinal cracking in thin slabs; with higher strength for loading perpendicular to ribs. A compression collector reverses and becomes a tension collector with each earthquake oscillation. Tension collector action depends on relative stiffness of the steel frame, deck and slab, the fixity of collector connections, and deck orientation [14]. Relative stiffness will change during the seismic event as elements soften, yield, slip, crack, or crush.

The floor system profile also involves significant vertical eccentricity (See Fig. 5b). Moment in a collector due to the eccentricity of the slab inertial force transfer is assumed to be completely compensated by vertical end shear force, and is ignored in design [14]. The same elements providing collector action also provide gravity load resistance [10]. These interactions are typically ignored [14] as is gravity load interaction on shear studs [22].

The collector load path must cross gravity columns, including the panel zones. Collector connections at the columns are often detailed to minimize moment (e.g. Fig. 3b). The slab detail at the column affects the collector force developing [20] via force transfer between the slab and column face through bearing or strut and tie mechanisms [21]. At the building perimeter, gravity load transfer induces torsion into the collector, requiring proper spandrel beam slab reinforcement [23]. Ubiquitous slab openings (e.g. Fig. 5a), can create torsion and an unbraced collector condition. The research program will address these issues as described in the next sections.

![Figure 5. Composite Diaphragms Load Paths: (a) Horizontal-Plane; (b) Vertical Profile.](image)

3. Research Program

The research program, which involves integrated analytical and experimental work, consists of two phases: (1) evaluation of the current practice for steel seismic collectors; and, (2) development of the innovative concepts for steel seismic collectors. The second phase is future work that will depend on knowledge developed in the first phase and is not to be presented in this paper.

The first phase has three main thrusts, involving characterizing the: (1) collector connections (stiffness, strength, deformation capacity); (2) collector elements (strength, stiffness, slab effects, stability limit states, inherent bracing of the slab); and (3) collector load path in the composite steel deck floor system. The first two thrusts are aligned with large-scale experimental work at the NHERI Lehigh EF. The third is aligned with shake table testing at the NHERI UCSD EF.

3.1 Evaluation Structure
An evaluation structure, a 4-story office building representing typical construction, has been designed to guide the research (See Fig. 6a). The building footprint is 110m x 73m. The initial analytical research focuses on a quadrant of the floor plan (See Fig. 6b). The SFRS is a Special Concentric Braced Frame (SCBF). A baseline design for the evaluation structure is performed for the current code [1] SDC E (R=6, $C_2=5$, $\Omega_0=2.0$) and typical live loads (2.4kN/m²) [24]. Details of the design are found in [24]. The 4th floor baseline design is indicated in the Fig. 6b floor plan.

Figure 6. Evaluation Structure: (a) collector connections; (b) 2nd Floor plan (baseline design).

3.2 Integrated Analytical Experimental Research

The integrated analytical experimental research program involves: (1) construction of initial models using existing data from tests of composite floor system elements (mostly related to other research, e.g., gravity systems, composite frames, progressive collapse, etc.); (2) sensitivity studies will be performed on the initial models to determine general behavior, and to plan experiments; (3) the physical experiments will be conducted, with test results directly providing new information, but also used to calibrate the models; (4) the calibrated models will be used in extensive parametric studies; (5) design recommendations and new concepts will be proposed.

3.3 Parameter Studies

Parameters considered in the research include: (1) collector connection detail; (2) beam depth; (3) slab thickness; (4) deck depth and orientation; (5) column orientation; and (6) shear stud layout; (7) live load level. The analytical models presented here are created using the general purpose finite element program ANSYS\(^1\), however other tools may be used.

4. Research Thrusts

The program involves three research thrusts, involving characterizing the collector: (1) connections; (2) elements; and, (3) load paths. These research thrusts are described in this section:

4.1. Collector Connections

This thrust involves determination of the properties (strength, stiffness and ductility) for different

\(^1\) ANSYS Inc., Canonsburg, PA.
steel collector connections. The collector connection models (See Fig. 7a) encompasses the joint region (local column, collector member, connection). 2D plane stress models, calibrated with experiments, are used to rapidly determine the general stress state and limit state sequence for various design parameters. These findings are then verified using 3D models. The models capture weld stress state (See Fig. 7b), bolt shear (See Fig.7c) and bolt bearing (See Fig.7d). Analyses are initially nonlinear increasing-amplitude tension, followed by cyclic protocols.

![Figure 7. Collector Connection: (a) Model; (b) Weld Stress; (c) Bolt Shear; (d) Bolt Bearing.](image)

The results will be used to plan multiple large scale tests at the NHERI Lehigh EF. A typical test specimen is shown in Fig. 8, where one end of the specimen has the collector beam-to-column connection detail under investigation connected to a column stub. Two actuators will be used to impose load at the other end of the collector beam. The force through each of these actuators will be applied in a manner that the shear, moment and axial force develop in the collector beam is a representation of an actual building. The objective of the test is to evaluate the strength of the collector connection and to investigate the failure modes for different collector connection details.

![Figure 8. Test Schematics for Collector Connection at NHERI Lehigh EF.](image)

4.2. Collector Members

This thrust determines the strength, stiffness and stability of the collector elements in composite steel deck diaphragms. Key behavior to investigate include slab participation, inherent bracing provided by the composite slab, and column interaction. The analytical models include two adjacent columns, the collector member between the columns, and the tributary deck/slab system and gravity framing (See Fig. 9a). The model consists of nonlinear shell elements (steel members),

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orthotropic shells (deck), nonlinear springs (shear studs, connections), and solid elements with cracking/crushing capability (slab). Nonlinear geometry is used for the stability analyses, with models including initial imperfections at standard tolerances and residual stresses. The models are subjected to eigenvalue analysis, nonlinear 2nd order load-deflection, and cyclic load protocols. The models are initially calibrated to classical beam and column solutions (See Fig. 9c). The models are then extended to account for the realistic boundary conditions through inclusion of the collector connections (See Fig. 9b) and slab (See Fig. 9a).

![Figure 9. Collector model: (a) Isometric; (b) Close-up at connection; (c) Eigenvalue analysis.](image)

The results will be used to plan large-scale subassembly testing at the NHERI Lehigh EF. Two specimens are planned. The test specimens will consist of one-bay of the evaluation structure, as shown in Fig. 10, and includes the collector beam, floor slab with transverse gravity beams, collector connections, and columns. One end of the test specimen will be connected to a reaction block; the other to an actuator. The test specimen will be subjected to compression and cyclic load protocol. Key parameters in the testing include slab orientation and thickness and collector depth.

![Figure 10. Test Schematics for Collector Element at NHERI Lehigh EF.](image)

4.3. Collector Force Path

This research thrust examines collector force paths in composite steel deck diaphragms, including: (a) the horizontal-plane spatial distribution of collector forces; (b) the relative participation of the slab, deck, and underlying framing in the collector force transfer; and (c) the limit-state sequence of elements within the collector load path. The analytical models encompass one floor and associated vertical elements (gravity columns, SCBFs) of the evaluation structure (See Fig. 11a). The model consists of nonlinear 1D beam elements for framing members (including collectors); non-linear degrading spring elements for collector and gravity connections [25] and shear studs; 2D nonlinear orthotropic shell elements for the metal deck, and a nonlinear 2D truss model for the concrete slab [24] (See Fig. 11c). Concrete bearing is modeled with contact elements; slab-to-deck slip is modeled using interface elements as needed. The floor system is vertically offset from the
slab using rigid elements (See Fig. 11b). The models are subjected to body force analyses creating collector tension or compression, as well as cyclic load protocols.

**Figure 11**: Isolated Floor models: (a) Isometric View; (b) Elevation View; (c) Close-up at SFRS.

The results will be used to design a shake table test at the NHERI UCSD EF. The shake table test will involve a 0.4-scale specimen. The test will examine the performance of steel collectors under realistic boundary conditions and inertial force mechanisms. The specimen will have a steel composite deck floor system (Fig. 12) and may include a 2nd level with an unfilled metal roof deck.

**Figure 12.** Shake Table Test Schematics at UCSD: (a) Isometric view; (b) South Elevation.

5. **Research Schedule**

The project relies on strong industry advisory and began with a Fall 2017 kickoff meeting between the researchers, the industry advisory panel (AISC, OSHPD) and design consultants. Year 1 tasks focus first on planning for the NHERI Lehigh EF collector connection tests (and associated analytical studies). The 2nd half of Year 1 will focus on planning for the NHERI Lehigh EF collector element tests. Year 2 focuses on the NHERI UCSD EF shake table test. Year 3 will focus on calibrated model parameter studies and developing innovative collector concepts. The ultimate goal of the project is to provide new design recommendations for collectors in steel composite floor systems.

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7. References