Steel Structures Research Update

Steel Diaphragm Innovation Initiative

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INTRODUCTION

A multiyear academic-industry partnership to advance the seismic performance of steel floor and roof diaphragms in steel buildings is highlighted. Lead investigators for the Steel Diaphragm Innovation Initiative (SDII) are Samuel Easterling, Matthew Eatherton, and Cristopher Moen (Year 1), Virginia Tech; Jerome Hajjar, Northeastern University; and Rafael Sabelli, Walter P. Moore, and Benjamin Schafer, Johns Hopkins University. The team includes AISC T.R. Higgins Lectureship Award and AISC Milek Fellowship Award winners for topics ranging from developments in long-span composite slabs to buckling-restrained braced frames to continuity plate detailing for steel moment-resisting connections.

SDII has been made possible through a collaboration between the American Iron and Steel Institute (AISI) and the American Institute of Steel Construction (AISC) with contributions from the Steel Deck Institute (SDI), the Metal Building Manufacturers Association (MBMA), and the Steel Joist Institute (SJI). Additional support is provided by the National Science Foundation (NSF). SDII is managed by the Cold-Formed Steel Research Consortium (CFSRC).

The team's motivations for creating SDII stemmed from issues with respect to the knowledge base for steel diaphragm performance, codes and standards, as well as missed opportunities for advancements in seismic performance–based design. The available research on steel diaphragms was primarily focused on the strength of isolated systems; little was known about ductility or whole-building performance. Code changes were being made to increase design diaphragm forces to be commensurate with elastic load levels, despite research supporting economical design of the diaphragm considering overstrength or ductility in steel deck diaphragms (O'Brien et al., 2016). Stiffness and redundancy in steel diaphragms and their connections to the vertical system were not being utilized to their full advantage and presented opportunities for advancements and innovations in steel building systems.

The team developed a five-year case and plan to "advance the seismic performance of steel floor and roof diaphragms utilized in steel buildings through better understanding of diaphragm-structure interaction, new design approaches, and new three-dimensional modeling tools that provide enhanced capabilities to designers utilizing steel diaphragms in their building systems" (SDII, 2017). The work includes providing research support for much-needed revisions to proposed seismic codes and standards for steel diaphragms. SDII is also working on innovative steel diaphragm solutions for efficient, robust and resilient steel building systems.

The Steel Diaphragm Innovation Initiative is more than halfway through its five-year effort and recently held a workshop with key stakeholders. The workshop included presentations from the research team and a brainstorming session, soliciting feedback for future research, standards development, and outreach to the engineering community (www.steeli.org). Some of the accomplishments from the third year of the initiative are highlighted here.

RESEARCH OBJECTIVES

With the overarching goal of advancing the seismic performance of steel floor and roof diaphragms utilized in steel buildings, SDII has organized its efforts into three primary thrust areas: Innovation and Practice, Experiments, and Modeling (Figure 1). Innovation and Practice tasks range from evaluation of existing design methods and technologies to seismic standards work to development and validation of new designs and technologies. The Experiments tasks include developing databases of available steel diaphragm testing and conducting new experiments to fill knowledge gaps. Modeling tasks include modeling to support the experiments as well as development of high-fidelity diaphragm models and whole-building models for exploration of various factors for diaphragm and whole-building performance. "The objective is to move the practice forward through the adoption of new design specifications for diaphragms and the creation and use of tools that allow engineers to understand and optimize in their designs of steel diaphragms for steel buildings" (SDII, 2017).

EXPERIMENTS

The team is making good progress in the Experiments thrust area. Available data on fastener tests, shear connector

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pushout tests, and full-scale diaphragm tests has been collected into databases. Within the Experiments area, the data have been used to identify testing needs. In the other thrust areas, the data are being used in development of new analysis and design methods. Testing technologies, such as photogrammetry, are being explored and developed for monitoring cracking in the concrete-filled diaphragm tests and for use in other tests. Cyclic deck sidelap and structural framing connector tests have been conducted. Diaphragm-style tests are being conducted on standing seam roof panel assemblies. The team is collaborating with investigators studying chords and collectors.

Testing to Characterize Behavior across Scales

The third year saw a continuation of the coordinated testing effort to characterize the behavior from the individual fasteners to the diaphragm panel to the full composite slab and steel framing systems. The experimental investigations highlighted here are isolated fastener tests; tests to explore the sensitivity of fastener behavior to installation details; shear connector pushout tests; composite deck cantilever diaphragm tests; and full-scale, beam-style composite deck diaphragm tests. These investigations aim to fill gaps in knowledge needed for the design of bare deck for roof diaphragms and for concrete-filled floor deck diaphragms common in multistory steel building construction.

Isolated Fastener Tests

A series of 80 tests were conducted on isolated sidelap and structural framing fasteners with flat sheets of steel deck. The fasteners were tested in this manner in order to separate fastener behavior from the effects of deck geometry, such as bends, embossments, and edge distances. The sidelap fasteners tested were #10 and #12 screws. Structural framing fasteners included powder-actuated fasteners, pneumatic power-actuated fasteners, arc seam welds, and #12 screws.

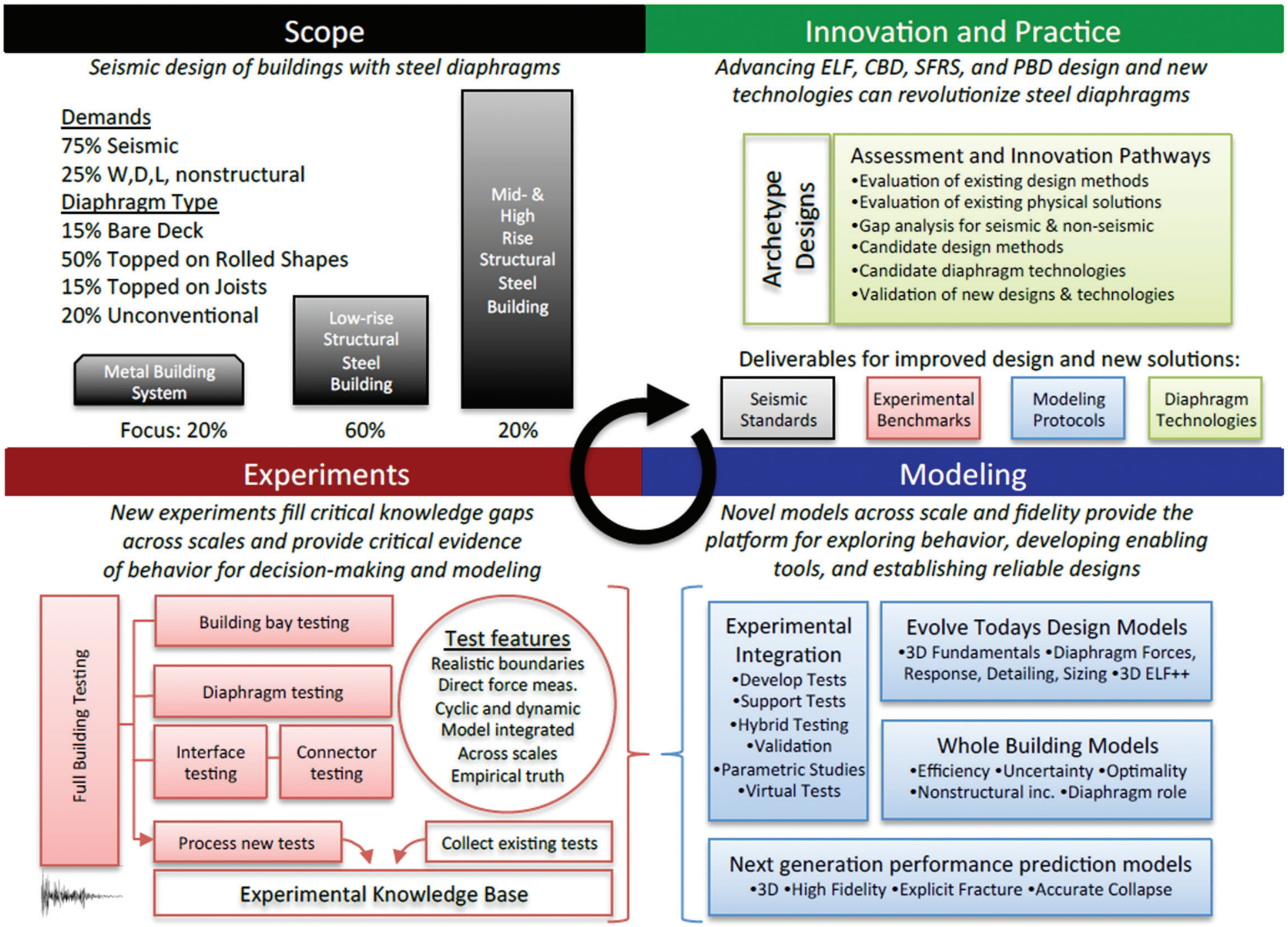


Fig. 1. SDII summary figure: Scope and three thrust areas.

Other parameters included number of deck plies for the structural fasteners (1, 2 and 4 ply to the support), deck thickness (22, 20 and 18 gage), and loading (monotonic and cyclic). For the structural framing connection tests, a 3⁄16-in.-thick plate represented the structural support steel.

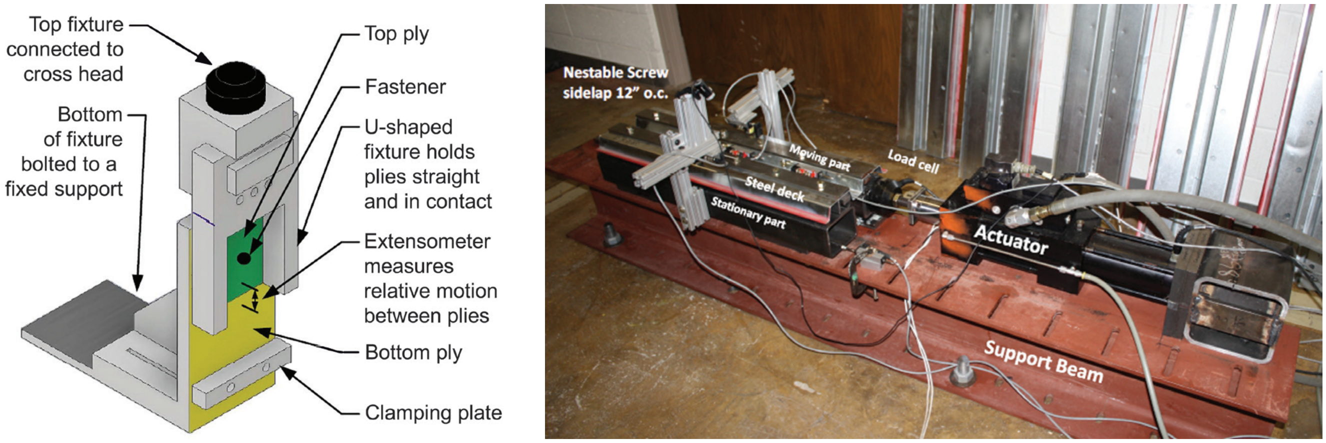
Each test specimen consisted of a single fastener and overlapping sheets of steel. The test setup for the isolated fastener tests used aluminum U-shaped fixtures to keep the deck plies flat and in contact while the specimen was loaded axially [Figure 2(a)]. Load, cross-head displacement, and relative displacement between plies were measured. Observed failure modes included sidelap screw tilting and pullout, shear failure of structural screws, bearing failure at power-actuated fasteners, tearing of the sheet around the weld, and shear failure of the weld. Cyclic loading generally resulted in lower strength, with some exceptions. Arc seam welds were generally stronger than the other fasteners but also more variable in strength and failure mode. Meanwhile, comparison to companion tests showed that the presence of corrugations and realistic boundary conditions resulted in an increase in strength, 14% on average (Shi et al., 2018).

Sensitivity of Fastener Behavior to Installation Details

The sensitivity of sidelap fastener behavior to screw installation details was also investigated. This testing expanded upon the study of cyclic performance of steel deck sidelap and structural framing connections (Torabian et al., 2018a). Parameters for this study included screw edge distances (0.25, 0.375 and 0.5 in.), deck thicknesses (22, 20 and 18 gage), screw size (#10, #12), and loading (cyclic, monotonic). Note that the 0.5-in. edge distance placed the screw at a bend in the deck, and results from those tests were not available at the time of this article. In the test setup, the sidelap connected the stationary side of the deck to the moving part of the specimen, which was connected to a dynamic actuator [Figure 2(b)]. As in the other fastener tests, screw tilting and pullout was observed. For monotonic and cyclic tests, a larger edge distance resulted in a higher shear strength. The effect of edge distance on the sidelap stiffness is being analyzed (Torabian et al., 2018b).

Shear Connector Tests

Monotonic and cyclic composite shear connector tests, also referred to as "pushout" tests, are under way. The shear connector test specimens are correlated to the cyclic concrete-filled steel deck cantilever tests described later in this section. For the monotonic pushout tests, each side of the symmetric specimen has two shear studs that are welded to the flange of a WT and embedded in a 36-in. × 36-in. slab. A hydraulic jack applies load to the ends of the WTs [Figure 3(a)]. Parameters for the 41 monotonic tests include type of concrete (lightweight or normal weight), thickness of slab (4, 6.25 or 7.5 in.), and position of the stud in the rib (strong or weak). Cyclic pushout tests are conducted using a new testing rig developed for the purpose [Figure 3(b)]. Monotonic pushout tests will also be conducted with the new testing rig. The concrete portion of specimen is restrained at each side. Steel roller guides underneath the steel beam allow the steel portion of the specimen to move as load is applied in line with the top beam flange, thereby imposing realistic demands on the shear connectors. In the 16 monotonic and cyclic tests, effects of stud position, deck rib orientation, slab thickness, and lightweight or normal-weight concrete will again be investigated. Behavior for a deck oriented parallel to an edge beam will also be studied. Stud number and spacing will include 1 @ 12 in. and 2 @ 12 in. on center.



(a) isolated fastener test specimen

(b) deck sidelap test setup

Fig. 2. Test setup.

Cantilever Composite Deck Diaphragm Tests

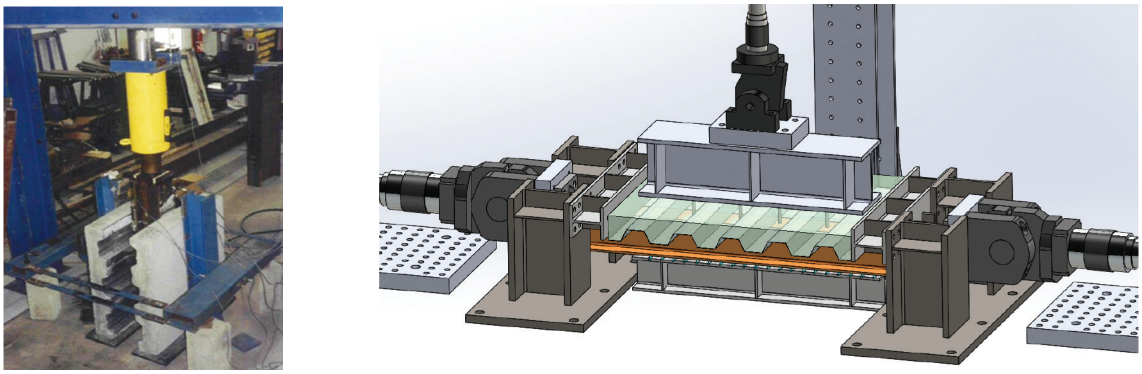
Cantilever composite deck diaphragm tests are also under way [Figure 4(a)]. In these specimens, the composite deck is connected with perimeter studs to a steel frame, with the frame restrained at one side and cyclic displacements applied at the other side [Figure 4(b)]. A total of six specimens will be tested to investigate effects deck depth, slab thickness, perimeter stud configuration, and lightweight vs. normal-weight concrete. Four specimens have been designed to fail from diagonal concrete cracking; two will be limited by the strength of the perimeter shear stud anchors.

Full-Scale, Beam-Style Composite Deck Diaphragm Tests

A test program of full-scale, beam-style composite deck diaphragm tests with realistic floor framing is in development. The primary objective for these tests is to provide information on the response of the complete floor system. The test setup will be designed to follow the load path during seismic excitation of a building, from the inertia force in the concrete floor, through the shear studs into the framing system of chords and collectors, and then to the vertical lateral-force-resisting system. The test program will investigate typical floor framing as well as integration of energy dissipating fuses in the chords and collectors.

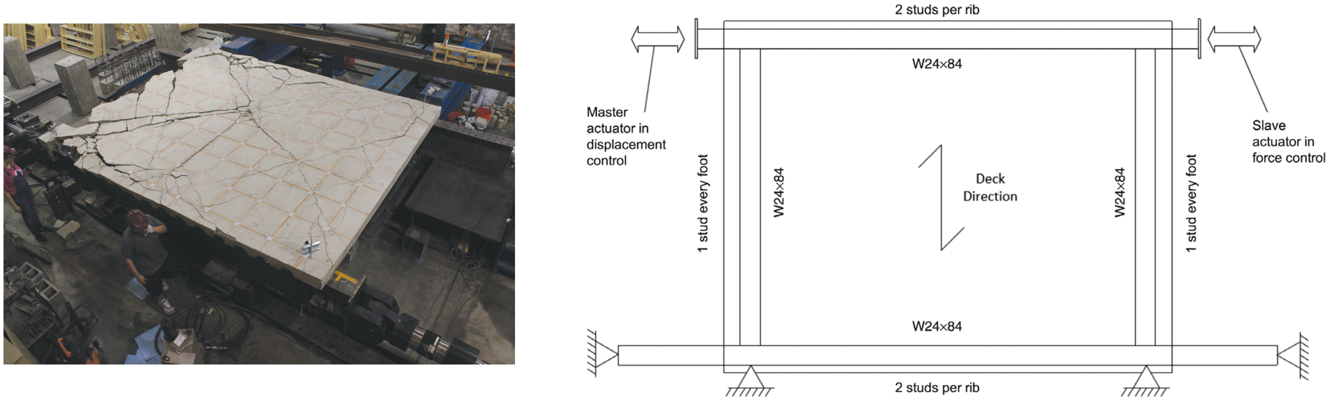
MODELING

The Modeling area has been critical for achieving objectives in the Experiments as well as the Innovation and Practice thrust areas. The team is developing and using models to support and supplement the testing programs, to assess current seismic codes and standards, and to explore potential innovations in design. Improved simplified models have been developed for conventional and new design. High-fidelity models with new capabilities (e.g., predicting fracture) are also being developed. The team is actively working on whole-building models, validated with experimental data and useful for validation of proposed designs and technologies. Some recent progress on the whole building models is highlighted.



(a) test setup *(b) new testing rig for cyclic and monotonic pushout tests*

Fig. 3. Monotonic pushout test.



(a) cantilever composite deck specimen after testing *(b) schematic of test setup*

Fig. 4. Cantilever composite desk diaphragm testing.

Building-Scale Simulations

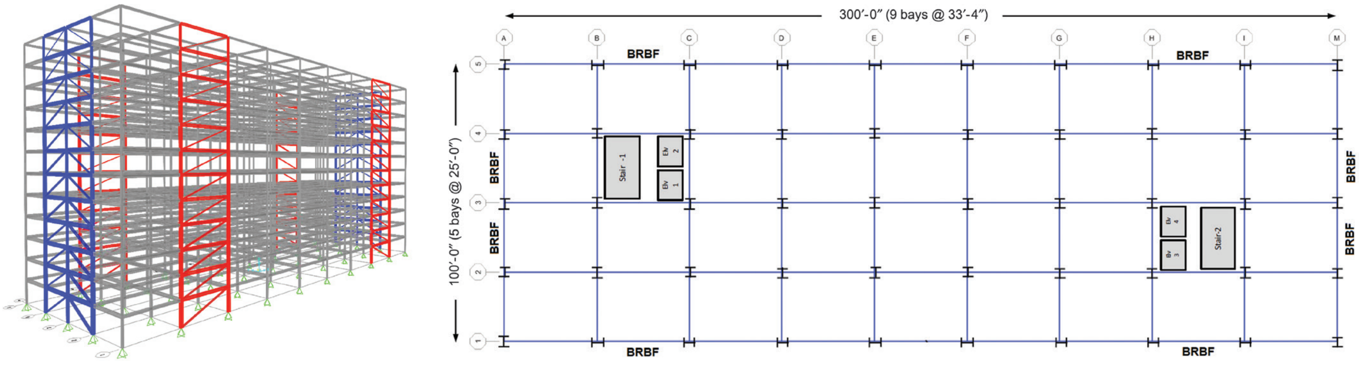
The whole-building models make use of the SDII archetype designs from the Innovation and Practice thrust area. The inventory of archetype buildings ranges from 1 to 12 stories in height and includes different lateral force-resisting systems such as special concentrically braced frames (SCBF), buckling restrained braced frames (BRBF), and moment frames. To date, 1-, 4-, 8- and 12-story buildings with SCBF and BRBF have been designed. The completed archetype buildings are 300 ft by 100 ft in plan with seismic-force-resisting systems designed for Seismic Design Category (SDC) D at an Irvine, California, site (Figure 5). At the floor levels, the composite slab has a 3-in. metal deck with either 7.5 in. total thickness of normal weight concrete or 6.25 in. of lightweight concrete. The roof diaphragm is assumed to be a bare 1.5-in. metal deck. The diaphragms have been designed following *Minimum Design Loads and Associated Criteria for Buildings and other Structures*, ASCE/SEI 7–16 (ASCE, 2016) standard and alternative design methods, providing opportunities for evaluation of different diaphragm design methods. Drawings, reference spreadsheets, and models can be found in Torabian et al. (2017).

Various options have been considered for reduced order modeling of the diaphragms in the building models. The options include rigid diaphragms, elastic or nonlinear shell elements, and nonlinear truss elements. These reduced-order models have been calibrated using experimental data obtained from cantilever diaphragm tests, as seen for development of the nonlinear truss element model. In the model, elastic beam-column elements were used for the perimeter steel members, and X-braces represented the deck or composite slab [Figure 6(b)]. The Pinching 4 material model in OpenSees was used in the X-braces to simulate the hysteretic behavior of the diaphragm. A comparison of the calibrated simulation and the experimental results shows that the hysteretic behavior was reasonably captured by the nonlinear truss element model of an 18-gauge deck with power-actuated fasteners and screws tested by Beck (2013) [Figure 6(a)]. Other reduced-order modeling options being explored include a hybrid shell-truss model, utilizing the shell element's ability to handle out-of-plane gravity demands.

Work continues on other aspects of the reduced-order modeling and analysis of the archetype buildings. Initial investigations of the one-story and four-story archetype building models with the diaphragm truss elements included nonlinear time history analysis at the design basis and maximum considered earthquake levels. Qayyum et al. (2017) evaluated force transfer, deformation and ductility demands, distribution of inelasticity, peak displacements, and residual displacements. Further modeling refinements included nonlinear beam-column elements with plastic hinging for the frame members and modifications to better represent fixity of the joints. Nonlinear pushover and time-history analyses have been conducted on these improved models, and the work has been extended to the other archetype buildings.

INNOVATION AND PRACTICE

The Innovation and Practice thrust area is focused on translation of SDII to industry, with improved seismic codes and standards, experimental benchmarks, modeling protocols, and new diaphragm technologies. Progress within this thrust area has included development of archetype designs, evaluation of existing design methods and technologies, performing gap analysis for seismic as well as nonseismic and nonstructural design, and exploring new design methods and technologies. Another important task is the team's efforts in codes and standards to improve the design of steel deck diaphragms. Some activities in the seismic standards work are briefly summarized.



(a) isometric rendering

(b) floor plan

Fig. 5. Building archetype.

Seismic Standards Work

SDII is already influencing standards and specifications. Contributions in the third year include technical support for the AISC *Seismic Provisions for Structural Steel Buildings* (AISC, 2016) related to horizontal truss diaphragms and the alternative diaphragm design provisions in the *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE/SEI 7–16 (ASCE, 2016). Updates to the AISC *Seismic Provisions* for concrete-filled deck diaphragms are also in progress. Research team members are making use of the SDII test database to provide modeling parameters and nonlinear acceptance criteria for steel deck systems for the new AISC standard that is currently in development, *Seismic Provisions for Evaluation and Retrofit of Structural Steel Buildings*. Team members have also proposed improvements in the AISI *North American Standard for the Design of Profiled Steel Diaphragm Panels*, AISI S310–16 (AISI, 2016), for strength predictions of steel deck diaphragms and in the AISI *North American Standard for Seismic Design of Cold-Formed Steel Structural Systems*, AISI S400–15 (AISI, 2015), for diaphragm design provisions. Through the Building Seismic Safety Council and with a peer review team from the Applied Technology Council, steel deck provisions for the alternate diaphragm design method are being prepared, and the groundwork is being laid for steel deck provisions for rigid-wall flexible diaphragm systems in ASCE/SEI 7–16.

SUMMARY AND FUTURE WORK

SDII seeks to advance the seismic performance of steel floor and roof diaphragms utilized in steel buildings and is doing so in a multi-institution effort with three coordinated thrust areas: Innovation and Practice, Experiments, and Modeling. Accomplishments in the third year of their five-year plan included experimental investigations ranging from isolated fastener tests to cantilever diaphragm tests and filling gaps in knowledge for bare deck roof diaphragms and concrete-filled floor deck diaphragms; development of models to support and supplement the testing programs, to assess current seismic codes and standards, and to explore potential innovations in design; and significant efforts in codes and standards to improve the design of steel deck diaphragms.

The research team continues to improve understanding of diaphragm-structure interaction and to develop new design approaches and three-dimensional modeling tools with enhanced capabilities. Outcomes from work by the Steel Diaphragm Innovation Initiative will include much-needed revisions to proposed seismic codes and standards for steel diaphragms and innovative steel diaphragm solutions for efficient, robust and resilient steel building systems.

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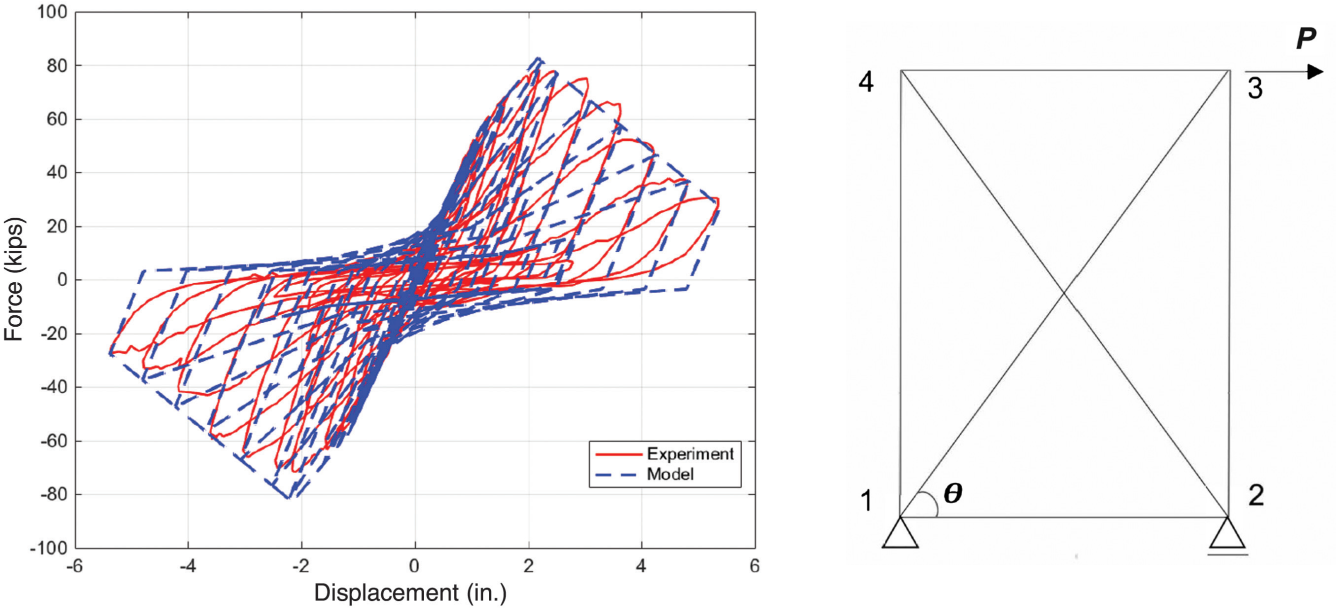

(a) comparison to experimental results (b) schematic of the nonlinear truss element model

Fig. 6. Reduced-order diaphragm simulation.

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REFERENCES

AISC (2016), *Seismic Provisions for Structural Steel Buildings*, ANSI/AISC 341-16, American Institute of Steel Construction, Chicago, IL.

AISI (2015), *North American Standard for Seismic Design of Cold-Formed Steel Structural Systems*, AISI S400-15, American Iron and Steel Institute, Washington, DC.

AISI (2016), *North American Standard for the Design of Profiled Steel Diaphragm Panels*, AISI S310-16, American Iron and Steel Institute, Washington, DC.

ASCE (2016), *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE/SEI 7–16, American Society of Civil Engineers, Reston, VA.

Beck, H. (2013), "Inelastic Cyclic Diaphragm Tests with Hilti Powder-Actuated Fastener X-HSN 24," Report No. XE_13_162, Technical Center of Hilti Corporation, Liechtenstein.

O'Brien, P., Flori, S., Moen, C.D. and Eatherton, M.R. (2016), "Characterizing the Load Deformation Behavior of Steel Deck Diaphragms," International Specialty Conference on Cold-Formed Steel Structures, Baltimore, MD, November, 15 pp.

Qayyum, B., Eatherton, M.R. and Easterling, W.S. (2017), "Seismic Behavior of One-Story Steel Buildings with Inelastic Diaphragm,." *Proceedings 11th U.S. National Conference on Earthquake Engineering*, Los Angeles, CA, June 25–29.

SDII (July 20, 2017). "Steel Diaphragm Innovation Initiative Case and Research Plan," version 4.0, Steel Diaphragm Innovation Initiative (available on request).

Shi, Y., Torabian, S., Schafer, B.W., Easterling, W.S. and Eatherton, M.R. (2018), "Sidelap and Structural Fastener Tests for Steel Deck Diaphragms," *Proceedings Wei-Wen Yu International Specialty Conference: Cold-Formed Steel Structures*, November 7–8, St. Louis, MO.

Torabian, S., Easterling, W., Hajjar, J.F. and Schafer, B.W. (2017), "SDII Building Archetype Design v1.0," CFSRC Report R-2017–04, permanent link: jhir.library.jhu.edu/handle/1774.2/40638.

Torabian, S., Fratamico, D., Shannahan, K. and Schafer, B.W. (2018a), "Cyclic Performance and Behavior Characterization of Steel Deck Sidelap and Framing Connections," *Proceedings Wei-Wen Yu International Specialty Conference: Cold-Formed Steel Structures*, November 7–8, St. Louis, MO.

Torabian, S., Folk, H. and Schafer, B.W. (2018b), "Effect of Connection Details on the Cyclic Behavior of Nestable Screw Sidelaps," *Proceedings Wei-Wen Yu International Specialty Conference: Cold-Formed Steel Structures*, November 7–8, St. Louis, MO.