Steel Structures Research

Design for Deconstruction with Demountable Composite Beams and Floor Systems

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INTRODUCTION

Sustainable design, or building "green," includes consideration of resources (e.g., energy, raw materials) but also construction and demolition waste. The statistics on waste are motivating shifts in structural design. "Current estimates in Australia have determined that approximately 40% of landfill waste is directly attributed to building and construction … Current Australian practice in steel building construction encourage steps that structural designers can take to maximize the potential for re-using steel buildings including using bolted connections … and ensuring easy access to connections" (Uy et al., 2015). This general approach is Design for Deconstruction (DfD). "Contrary to the conventional linear material flow, which starts with the extraction of raw materials and ends with the disposal of debris in landfills, DfD could help close this loop by reducing the cost of recovering and reusing resources" (Wang et al., 2015a).

Ongoing and recently completed research on deconstructable steel-concrete composite beams and floor systems for steel frame buildings is presented. This research includes demountable beam-slab connectors, deconstructable composite floor systems with precast concrete planks, and lightweight modular two-way steel flooring systems.

An extensive study on connectors to enable reuse of steel and composite building components has been undertaken. Demountable beam-to-girder connections, column splices for concrete-filled tube (CFT) columns and beam-to-slab connectors for steel-concrete composite beams were investigated through detailed finite element analyses and full-scale experiments. The bolted beam-to-girder connections were analyzed to determine details (e.g., geometry of the cope) and load limits that would prevent large, plastic deformations and allow the connections to be easily demounted and reused. A blind-bolted sleeve plate CFT column splice was designed and analyzed to determine effects of sleeve length, bolt position and reinforcement ratio on tensile strength of the splice. Research on bolt connectors for composite beams, highlighted here, has shown improved performance relative to beams with welded connectors (Uy et al., 2015). This research is led by Dr. Brian Uy, Professor and Director of the Centre for Infrastructure Engineering & Safety at the University of New South Wales, Australia.

A deconstructable composite floor system with steel framing, precast concrete planks, and bolted clamp connectors has been developed. A comprehensive investigation on design and behavior of the proposed system includes detailed finite element analyses, parametric studies, and validation testing. The full-scale pushout tests, composite beam tests, and in-plane diaphragm tests are in progress. Selected results for the pushout tests and diaphragm analyses are presented here. The principal investigator (PI) for this research is Dr. Jerome Hajjar, CDM Smith Professor and Department Chair of Civil and Environmental Engineering at Northeastern University, with co-PI Mark D. Webster, a structural engineer with Simpson Gumpertz & Heger Inc.

A new, modular sandwich panel system is envisioned as another alternative to steel deck composite floors. Typical steel-concrete composite floors are designed with slabs supported by beams spanning in one direction. Reinforced concrete and post-tensioned flat slab construction are able to take advantage of two-way bending behavior to increase capacity and span lengths, resulting in low floor-to-floor heights, but lack modularity. Research is under way on a new lightweight modular steel flooring system that takes advantage of two-way bending behavior and rapid-construction/deconstruction inherent in modular systems. The principal investigator for this research is Dr. Matthew Fadden, AISC Milek Fellow and an Assistant Professor at The University of Kansas.

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DEMOUNTABLE BEAM-SLAB CONNECTORS

Bolt connectors can be used in place of welded shear connectors for composite beams that are deconstructable, or demountable, as shown in Figure 1 for a beam with metal deck. Limited studies on bolted connectors for composite beams were conducted by Lam and Saveri (2012) and others. Additionally, post-installable bolted connectors were investigated by Kwon et al. (2009) for retrofit of noncomposite bridge girders. Meanwhile, pushout tests on bolted connectors conducted by Mirza et al. (2010) demonstrated shear capacity comparable to that of welded headed connectors. More recent research has considered bolted connectors as potential retrofit, or strengthening, options for existing beams. This work has expanded upon prior research and has also demonstrated the viability of bolted connectors for demountable composite beams (Pathirana et al., 2015). The connectors used were the same as those studied by Mirza et al. (2010) and included welded, headed shear connectors (WS) and two different types of M20–grade 8.8 blind bolts. One type of blind bolt has a collar (BB1), and the other type of blind bolt is secured with a washer and nut cast into the concrete (BB2) (Figure 2). When used for retrofitting existing noncomposite beams, connectors are bolted through holes created in the concrete and steel beam flanges. The holes are then filled with nonshrink structural grout (Figure 3) (Pathirana et al., 2015).

Behavior of Demountable Beam-Slab Connectors

Seven full-scale beam specimens were tested statically under four point bending (Pathirana et al., 2015). Beam span was 19.6 ft, with an 18-in.-deep steel I-beam. The 6-in.-thick, 3.28-ft-wide concrete slab was reinforced with N12 (0.5-in. diameter) longitudinal and transverse bars at 9.45-in. spacing. One beam was noncomposite, and three composite beams were constructed with each of the three connectors; specimens CWS-ST, CBB1-ST and CBB2-ST used connectors WS, BB1 and BB2, respectively. Three specimens (CWS-RT, CBB1-RT and CBB2-RT) were constructed originally as noncomposite beams and then retrofitted with each of the connectors. Beam specimens all used 27 shear connectors in a staggered pattern. For the welded connector specimen, this would correspond to a partially composite beam design, with approximately 50% of the connectors required for fully composite beams (i.e., a shear connection ratio of 0.5). The grout hole sizes in the retrofitted specimens corresponded to the geometry and installation requirements of the connector: 3.94-in., 2.95-in. and 1.97-in. hole diameters for the WS, BB1 and BB2 connectors, respectively.

Six pushout tests were also conducted to investigate the

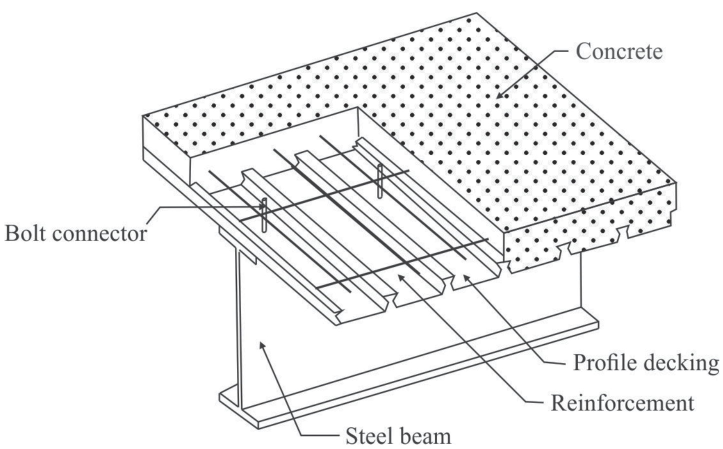


Fig. 1. Demountable composite beam with concrete on metal deck.

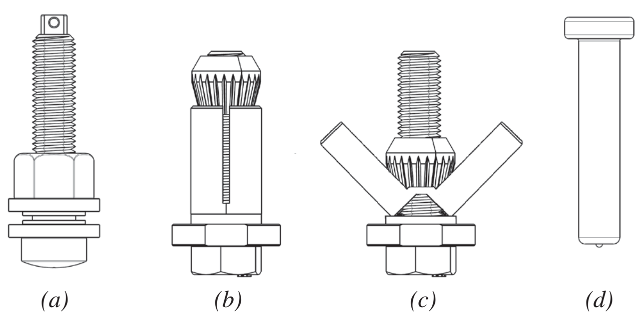


Fig. 2. (a) BB2 connector; (b) BB1 closed collar; (c) BB1 open collar; (d) WS connector.

load-slip behavior of the connectors. Each of the pushout test specimens corresponded to one of the standard (ST) composite beam specimens or one of the retrofitted (RT) composite beam specimens. Concrete or grout failure and welded stud failures were observed for the WS specimens (PWS-ST and PWS-RT). Concrete or grout failure was the limit state for the BB1 specimens, while the BB2 connectors failed in shear. The slip responses of the BB1 and BB2 specimens were variable; this was attributed to bolt hole clearances as well as deformations of the bolted connector components. Comparisons of the load-slip behavior of the connectors (Figure 4) revealed higher stiffnesses for the WS and BB1 connectors in the standard and retrofitted specimens. The strengths of the BB1 and BB2 connectors were comparable and, for the retrofitted specimens, were higher than that for the WS connectors. The BB2 connectors were noted to be the most ductile, and the WS connectors were noted as having the most slip after yielding (Pathirana et al., 2015).

The load-slip behavior from the pushout tests was reflected in the composite beam tests. The retrofitted beam with the BB2 connectors was much less stiff than the other retrofitted beams. Both beams retrofitted with bolted connectors exhibited higher ultimate load capacity than the retrofitted beam with the welded connector. The load capacity of a noncomposite beam was increased by 40% with the BB2 connectors. At the serviceability deflection limit of approximately 1 in., the load capacities of all retrofitted beams were 50% higher than predicted (Pathirana et al., 2015). Overall, the research confirmed the viability of bolted connectors for both retrofit and new construction of composite beams.

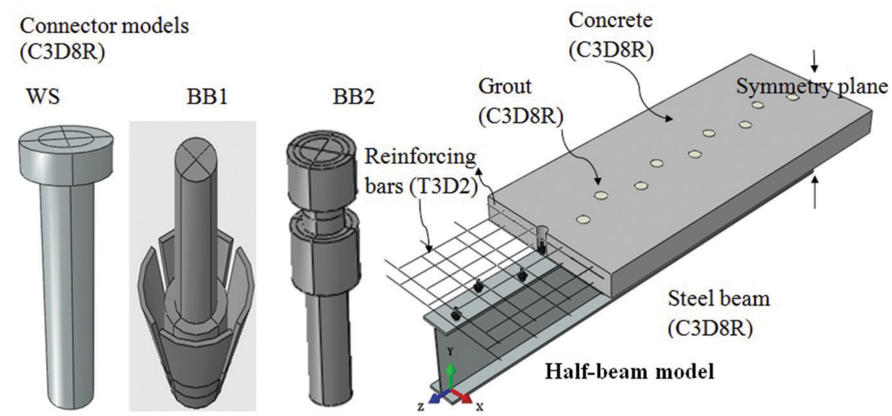


Fig. 3. Finite element model components and element types.

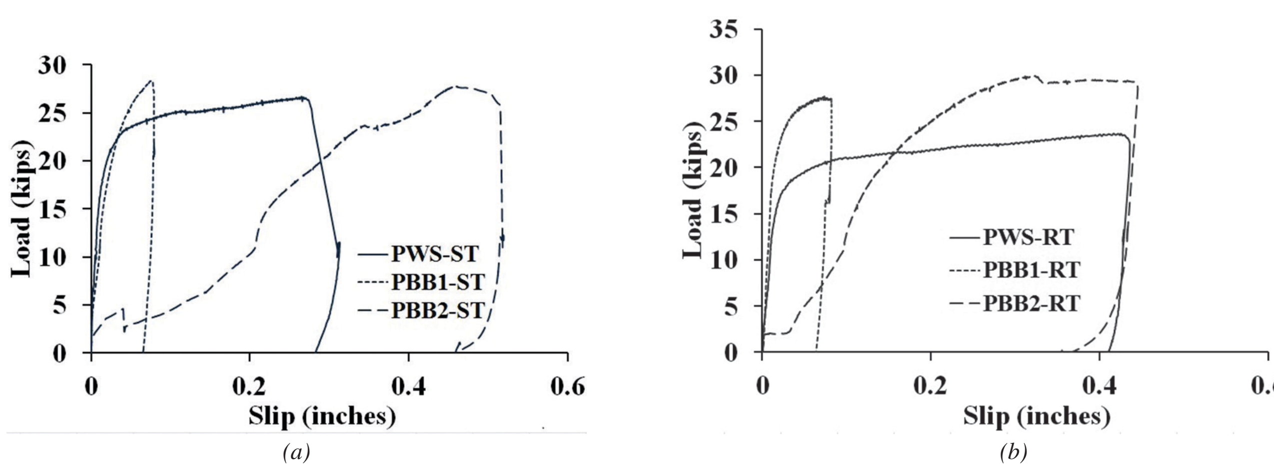


Fig. 4. Load-slip response: (a) standard condition; (b) retrofitted condition.

Finite Element Analysis of Demountable Beam-Slab Connectors

In addition to analyses for the retrofitted composite beam specimens, Uy et al. (2015) developed detailed finite element models and conducted a parametric study of composite beams. The finite element models were composed of eight-node brick (C3D8R) and quadratic brick (C3D20R) elements for the shear connectors, concrete slab and beam. Steel reinforcement was modeled with two-node, three-dimensional truss elements (T3D2). The models allowed for comparisons of flat slabs and slabs with profiled metal decking, as shown in Figure 1; the thin steel sheeting was modeled with thin shell elements (S4R). Structural steels were modeled using elastic-plastic behavior, and the concrete was modeled with an elastic-plastic stress strain relationship with strain softening. In addition to profiled decking or flat slab, parameters investigated included concrete compressive strength and headed or bolted connectors. The bolted connectors were the type with the embedded nut. The models were validated against the experiments from Mirza et al. (2010), with good agreement on the load-slip curves, including initial stiffness that was "identical up to the ultimate load" (Uy et al., 2015).

The results of the parametric study showed increases in stiffness and strength with greater concrete compressive strengths. Use of a flat slab instead of a profiled slab also increased initial stiffness and ultimate strength. The beams with the bolted connectors were stronger than beams with the welded headed connectors, primarily due to the higher yield strength of the bolted connectors. An initial 0.04-in. slip observed in beams with the bolted connectors was attributed to the oversized holes "provided to achieve demountability in composite beams" (Uy et al., 2015).

Pathirana et al. (2015) expanded on these results with finite element models that were validated against all three of the retrofitted beam specimens. The models utilized symmetry boundary conditions to represent half of the beam. As with the models described earlier, C3D8R elements were used for the concrete, grout and steel beams; C3D20R elements were used for the shear connectors; and T3D2 elements were used for the reinforcing bars (Figure 3). A concrete damage plasticity model was used to capture the behavior of the concrete and grout. The stress-strain curves for the steel materials were represented by piecewise linear curves. Properties for the steel and concrete were based on the measured values from material property tests for the materials used in the test specimens. The finite element models again demonstrated good agreement with the experimental results. Stiffness, strength, ductility and limit states such as tensile failure of the concrete at the bottom of the slab were well predicted. Additional details of the modeling can be found in Pathirana et al. (2015).

In a parametric study, the effects of concrete compressive strength, grout strength, grout hole size and shear connection ratio were investigated. The results confirmed that an increase in concrete compressive strength increases the ultimate capacity of the retrofitted beam. However, doubling the grout strength produces marginal increases (less than 1%) in the flexural strength of the beam. Similarly, doubling the grout hole diameter increases the ultimate strength of the beam, but this increase was not significant (less than 4%). For shear connection ratio, an increase in this ratio resulted in an increase in the ultimate capacity of the composite beam, although the rate of increase was generally less significant at higher numbers of shear connectors. Figure 5 shows the ultimate load ratio, or ultimate load normalized to that for 42 connectors (shear connection ratio of 1), versus the number of connectors. It is worth noting that the composite beam models with the BB2 connectors (CBB2) were able to develop an ultimate load ratio close to 1 (i.e., capacity of a fully composite beam) with fewer connectors than for the CBB1 and CWS models (Pathirana et al., 2015).

Dynamic and Time-Dependent Behavior of Composite Beams with Demountable Connectors

Complementary research has been conducted on the time-dependent behavior of composite beams with blind bolts (Ban et al., 2015) and dynamic behavior of composite beams with different shear connectors (Henderson et al., 2015a, 2015b). Ban et al. (2015) conducted four full-scale tests and a computational parametric study, identifying important parameters for the long-term deflections of these composite beams, in addition to developing a finite element model capable of predicting the time-dependent behavior of composite beams with blind bolts or welded connectors. Test results from Henderson et al. (2015a) showed comparable dynamic behavior for composite beams with blind bolts and welded shear studs. The results were also used to validate a Timoshenko beam model for steel-concrete composite beams (Henderson et al., 2015b).

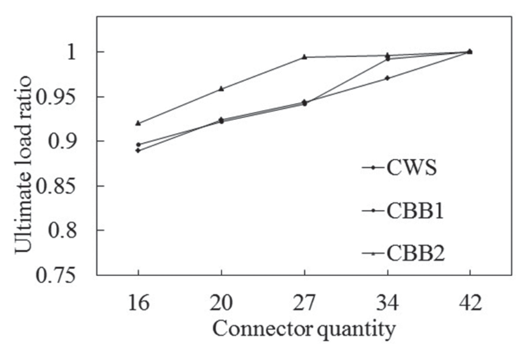


Fig. 5. Ultimate load ratio versus number of shear connectors.

DECONSTRUCTABLE COMPOSITE FLOOR SYSTEM

Similar concepts have been used in the development of a new, deconstructable composite floor system that uses precast concrete planks and clamp connectors. This research program includes pushout tests of the clamp connectors, beam tests and diaphragm simulations. Finite element models have been used to investigate behavior of the deconstructable floor system and components, to study effects of various parameters and to inform the experimental program. Details of the floor system, finite element models and selected results from the diaphragm test finite element analyses are described. Results from some of the pushout tests are also presented.

Details of the Deconstructable Composite Floor System

Wang et al. (2015a, 2015b) are studying deconstructable composite floor systems to enable reuse of all of the structural components. Precast concrete floor planks are attached to steel beams and girders with clamps and pretensioned bolts. The clamp connections are designed to provide composite action in the system. Channels that have been cast into the planks allow beams of any flange width to be attached at any location. Figure 6 shows a schematic of the deconstructable composite beam and cross-sections of the plank.

The planks themselves are envisioned to be 20 ft × 2 ft × 6 in., with tongue-and-groove side joints and connections designed to resist in-plane diaphragm forces. The plank size "is believed to be large enough to ensure structural integrity and reduce labor for construction and deconstruction but small enough to facilitate handling, transportation and reuse in new structures" (Wang et al., 2015b). Instead of the conventional procedure of grouting between the planks and topping with cast-in-place concrete to achieve diaphragm shear resistance, threaded rods are used to allow for future deconstruction. The unbonded rods connect the precast planks in a staggered pattern as shown in Figure 7 and are tensioned. In this manner, friction in the joints resists the diaphragm shear, and the horizontal clamping of the panels resists joint opening due to diaphragm flexure (Wang et al., 2015b).

Behavior of Deconstructable Clamping Connectors

To date, seven full-scale pushout tests have been conducted to investigate the strength and ductility of the clamping connectors. Prior to the pushout tests, one set of pretension tests was conducted. Several bolts were torqued until fracture to develop the relationship between the number of turns and bolt axial force and to establish pretensioning procedures for the clamps. It was determined that two complete turns of the nut provide a reliable pretension force.

The test specimens included precast concrete planks connected to WT sections representing the top portions of a W-shape beam (Figure 8a). The specimen includes a 4-ft × 2-ft × 6-in. precast concrete plank that was clamped to a WT5×30 or WT4×15.5 section. The loading was applied to the flanges of the WT sections using displacement control "to reduce eccentricity of the force application in the WT. Reaction angles are chosen to react against the concrete plank to provide realistic compressive stress distributions within the concrete" (Wang et al., 2015a). The WT4 flanges were smaller and required shims at the clamp connections. Additional parameters included the use of heavy or light reinforcement in the planks, monotonic or cyclic loading,

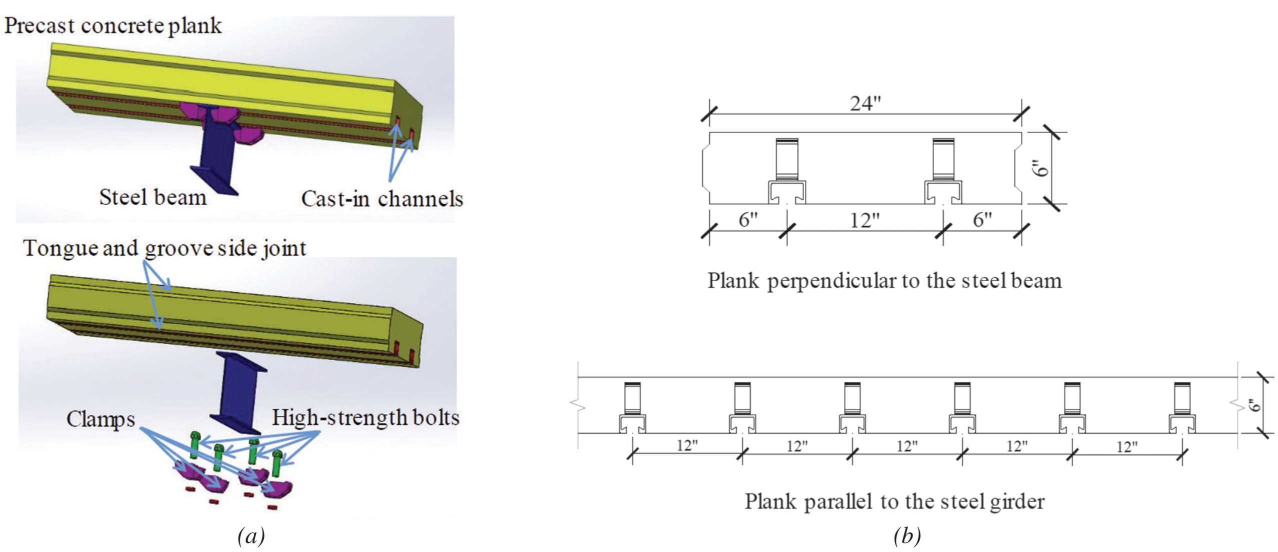


Fig. 6. (a) Deconstructable composite beam prototype; (b) precast concrete plank cross-sections.

and different bolt diameters. The light reinforcement pattern was limited to reinforcement necessary to resist gravity loading, while the heavy reinforcement pattern included additional bars to limit cracking due to concrete breakout (Wang et al., 2015a). In addition to the pushout tests, full-scale composite beam tests are designed to study the clamping connectors and the flexural strength and stiffness of the composite beams (Figure 8b).

Typical load-slip curves are depicted in Figure 9 for a monotonic pushout test and the corresponding cyclic test with two cast-in channels and four clamps attaching the WT to the plank using 1-in. bolts. In the monotonic test, the average peak load for one clamp connector was 22.1 kips, comparable to 21.5 kips for a ¾-in. shear stud embedded in a 4-ksi solid concrete slab. The connectors retained almost 80% of the peak capacity even at a slip of 10 in. Compared to the monotonic test results, the peak load was reduced in the cyclic test, and pinching behavior was observed, particularly at large slip values. This behavior was mainly attributed to the reduction of the frictional coefficient as a result of worn

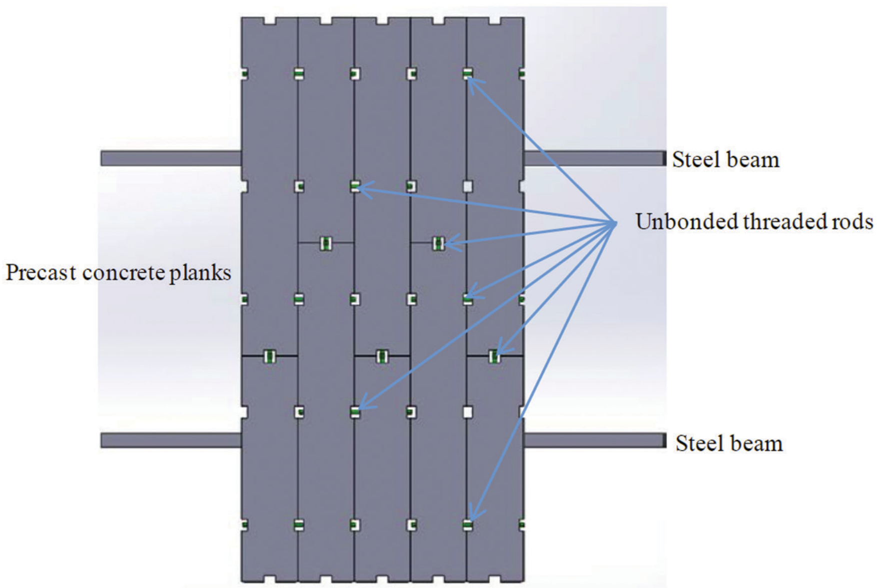
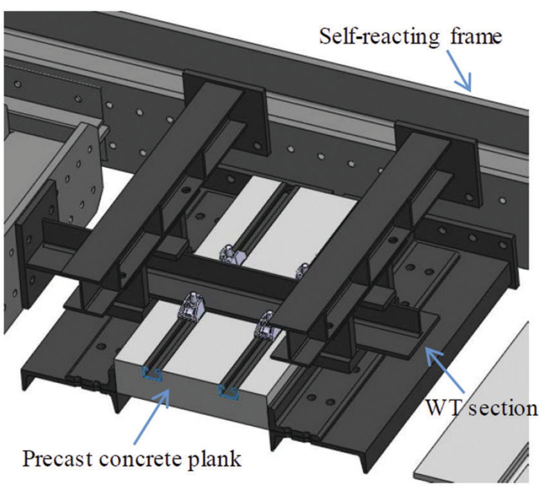
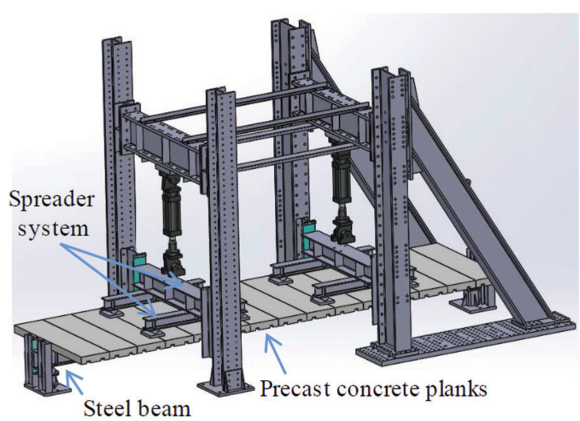


Fig. 7. Precast concrete plank layout and connections.



(a)



(b)

Fig. 8. Schematics: (a) pushout test setup; (b) composite beam test setup.

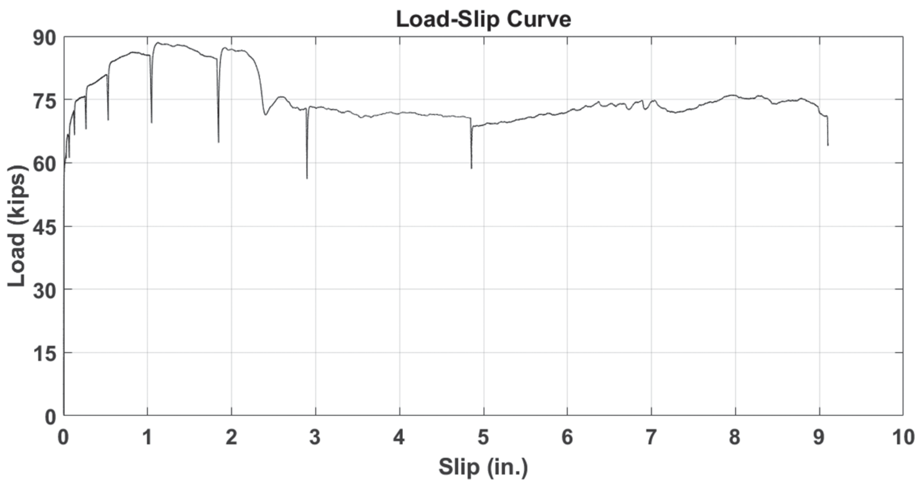
steel flanges and clamp teeth after several cycles. The tests were terminated when the linear potentiometer stroke was reached, and no specific limit states were observed.

In-Plane Diaphragm Analysis of the Deconstructable Composite Floor System

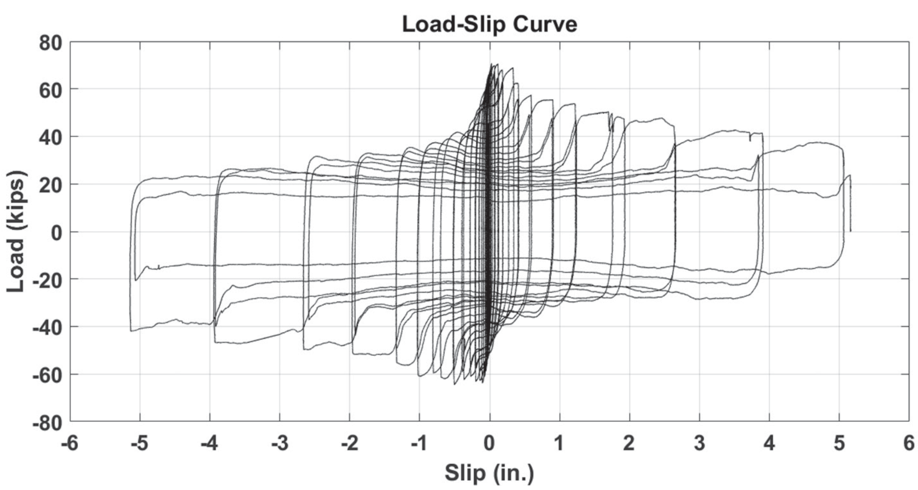
To explore the in-plane shear behavior of the proposed system, a model of half of a 30-ft × 30-ft bay was created, with symmetry boundary conditions. This model was inspired by the test setup used by Easterling and Porter (1994) to study the behavior of steel-concrete composite diaphragms. The modeled diaphragm system used a W18×40 girder, W14×30 filler beams and W12×19 beams at the column lines (Figure 10). The W18×40 girder was considered to be part of the seismic force-resisting system and was, therefore, the point of application for the loading. The quasi-static, cyclic displacement was applied after (1) compression between the planks from the threaded rods was simulated with an applied pressure and (2) bolt pretension was simulated through a change in temperature. Planks were unreinforced in the models, and they were staggered as shown in Figure 7.

The finite element analysis used a combination of eight-node reduced integration brick elements (C3D8R) and six-node reduced integration triangular prism elements (C3D6R) to represent the concrete and cast-in channels. The steel beams and concrete planks were modeled using the eight-node brick elements. The clamps and bolts were modeled using four-node tetrahedron elements (C3D4), and the steel reinforcement was represented by two-node, three-dimensional truss elements (T3D2).

Material models include a concrete damage plasticity model capable of capturing changes in stiffness with opening and closing of cracks (Wang et al., 2015b). The steel



(a)



(b)

Fig. 9. Load-slip curves for specimens under (a) monotonic loading; (b) cyclic loading.

Table 1. Diaphragm Models and Parameters (Wang et al., 2015b)		
Model Number	Compressive Stress (ksi)	Number of Shear Connectors
1	0.22	28
2	0.22	20
3	0.44	28
4	0.44	20
5	0.87	28
6	0.87	20

beam, reinforcement and channels were modeled using elastic-perfectly-plastic material in both tension and compression. The bolt material was modeled following Kulak et al. (1987). Pretension was simulated by a temperature change and the resulting thermal shrinkage in the bolts. Additional details can be found in Wang et al. (2015b).

Parameters studied included the level of the compressive stress between planks and the number of shear connectors between the steel girder and the girder plank. The applied compressive stress between the planks ranged from 0.22 ksi, equivalent to tensioned rods at 4-ft spacing, to 0.87 ksi. The number of shear connectors was either 20 connectors at 3-ft spacing, representing the minimum of 25% composite action for the girder, or 28 connectors at 2-ft spacing. In total, six models with parameters as shown in Table 1 were analyzed.

The results of the analyses showed ductile behavior for all diaphragm models, with no strength or stiffness degradation. Observed limit states included joint sliding and slip of the clamps. The diaphragm shear strength increased as the compressive stress between planks increased. Joint sliding was the limit state for models 1 through 4. Slip at the clamps was the limit state for models 5 and 6. Model 4, with fewer shear connectors, exhibited a combination of joint sliding and slip at the clamps, and was less stiff than model 3, with comparable strength. Similarly, model 6 was less strong and less stiff than model 5.

Some limit states typically observed for cast-in place concrete and conventional precast concrete diaphragms were not observed for the proposed system. No diagonal cracking was observed in the models, even though the planks were modeled with no reinforcement. The "concrete remains intact except for localized damage near the clamps" (Wang et al., 2015b). Also, the compressive stress at panel joints prevented the limit state of joint opening due to diaphragm bending.

The diaphragm parametric study, together with the push-out test results, provided valuable information for design and detailing of the proposed floor system. All of the results also showed ductile behavior at both the component and system level. Full-scale pushout, beam and diaphragm tests will further inform design guidelines and confirm the viability of this deconstructable composite floor system.

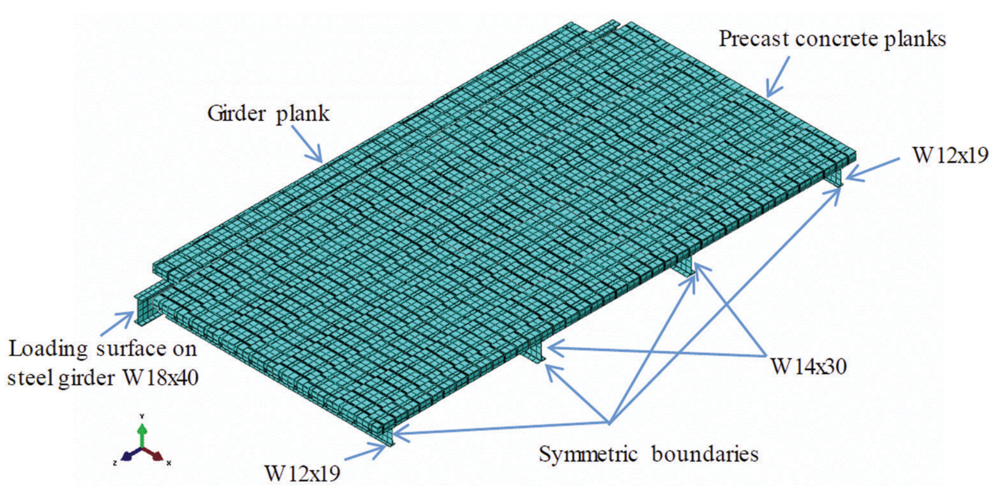


Fig. 10. Finite element model of the composite floor diaphragm.

LIGHTWEIGHT, MODULAR, TWO-WAY, STEEL FLOORING SYSTEMS

Another alternative to conventional steel deck composite floors is a new, lightweight, modular, two-way, sandwich panel system (Figure 11) that will allow for more economical steel frames designed for reduced dead loads and seismic forces. Preliminary analysis shows that 30-ft × 40-ft bays with no filler beams are attainable with modular panels. Because this project is in an early stage, the sandwiched material is currently being modeled and optimized using finite element analysis. Possible solutions include cold-formed sections, three-dimensional space trusses or lightweight cementitious materials. It is important that the sandwiched material allows space for mechanical, electrical and fire protection equipment to optimize floor-to-floor heights and structural integration.

The modularity provides this new flooring system with advantages over traditional steel-concrete composite floors, which have significant construction and curing times. Faster construction and the possibility of deconstruction given future building use changes can reduce long-term costs and waste. Additionally, modular pieces can be shipped compactly by truck, providing transportation cost savings. Each panel will be constructed on site, bolted together and lifted into place, thus avoiding any field welding. If building use changes, deconstruction can be carried out with minimal damage to the structure by removing fireproofing and unbolting the floor system. It is even possible that panels from the floor could be deconstructed and removed while other areas of the structure remain occupied. Similarly, this modular decking system can be reconstructed for future needs. Currently, connectors are being designed and developed to be able to resist required forces while maintaining a flat profile. Future work includes conducting full-scale experimental testing on the proposed system.

SUMMARY

A number of options for building "green" with deconstructable composite beams and floor systems have been presented. Steel-concrete composite beams become demountable with blind bolt connectors. A comprehensive experimental and computational study confirmed the viability of these bolt connectors for retrofit and new construction of composite beams. Precast concrete planks and clamp connectors are integral to a proposed, deconstructable composite floor system. Finite element parametric studies in combination with pushout, diaphragm and beam tests, in progress, are advancing Design for Deconstruction (DfD) with this viable composite floor system. A third option for sustainable design is envisioned as a lightweight, modular, sandwich panel system that will reduce design loads, accelerate construction and accommodate building use changes. The proposed modular panel system, in early stages of development and analysis, will be validated with full-scale experiments.

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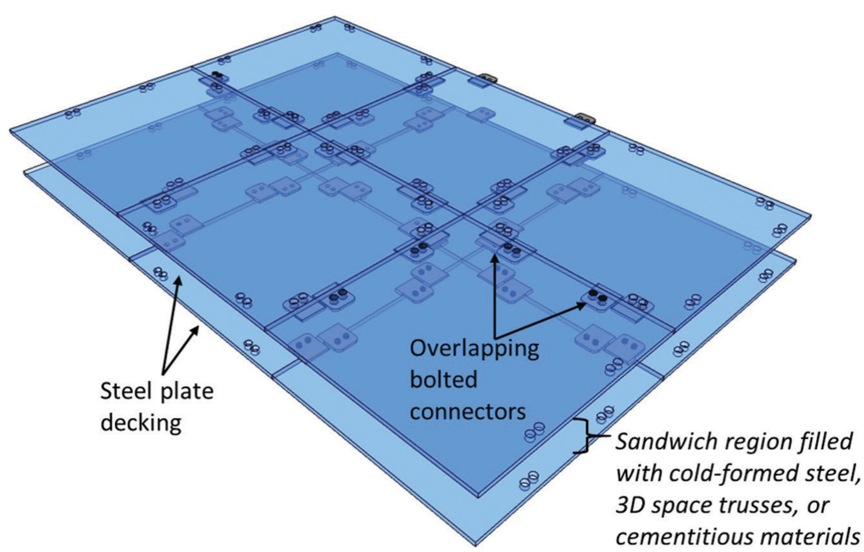

Fig. 11. Conceptual connection detail for a lightweight, modular, two-way, steel flooring system.

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