Steel Structures Research Update

Steel-Concrete Composite Beams at Ambient and Elevated Temperatures

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INTRODUCTION

Ongoing and recently completed research on steel-concrete composite beams and floor systems at ambient and elevated temperatures is presented. The research highlighted here includes investigations into shear connector slip, composite beams with high-strength steel, and tests of real-scale composite floor systems subjected to fire and structural loading.

A parametric study incorporating effects of shear connector slip into fiber-based models of composite beams was conducted at Purdue University. This research was part of an investigation on behavior and design of composite beams subjected to fire. The researchers identified significant factors affecting the flexural capacity of partially composite beams and produced design recommendations. The research team, led by Dr. Kristi Selden, now an Associate at Wiss, Janney, Elstner Associates Inc., included Dr. Amit Varma, project Principal Investigator and Professor at Purdue University, and Dr. J.R. Mujagic, Structural Engineering Consultant.

Composite beams with different materials and components are being investigated at the University of New South Wales. Deconstructable steel-concrete composite beams and steel-timber composite beams are topics of study, but the focus for this research update is the work on composite beams with high-strength steel and concrete. The researchers have developed a validated finite element model, quantified the available rotation capacity of composite beams with high-strength materials, and produced an empirical equation to predict this capacity. The research is a collaboration among Dr. Huiyong Ban, Research Associate, Department of Civil Engineering, Tsinghua University; Dr. Mark Bradford, Laureate Professor in the School of Civil and Environmental Engineering and Research Director in the Centre for Infrastructure Engineering and Safety (CIES) at the University of New South Wales (UNSW); and Dr. Brian Uy, Professor in Civil and Environmental Engineering at UNSW and Director in CIES.

Tests of real-scale composite floor systems subjected to fire and structural loading will be conducted at the National Fire Research Laboratory (NFRL) at the National Institute of Standards and Technology (NIST). This series of tests will take advantage of the unique capabilities of the recently expanded and renovated NFRL with two-story, multi-bay specimens. The experiments will be used to investigate behavior of composite floor systems in fire with respect to factors such as symmetry in framing (i.e., orientation of secondary beams in adjacent bays), concrete slab/metal deck geometry as it affects the development of a compression ring, restraint of thermal expansion provided by connections, and fire exposure. Dr. John Gross and Dr. Lisa Choe, Research Structural Engineers, lead this experimental research at NIST.

SHEAR STUD SLIP IN PARTIALLY COMPOSITE BEAMS

Steel-concrete composite beams are designed using a strength-based approach outlined by the AISC *Specification for Structural Steel Buildings* (2010). However, the load-slip behavior of headed stud anchors can affect the flexural capacity of partially composite beams. A benchmarked fiber-based model was utilized in a parametric study to evaluate effects of beam length, percent composite action, and other properties. Observations on shear connector ductility and strength by Oehlers and Sved (1995) and Mujagic and Easterling (2009) were incorporated into the design of the study. Results of the parametric study were synthesized into recommendations for design of composite beams (Selden et al., 2015).

Composite Beam Model

A fiber-based model was developed for use in the parametric study. This model was capable of capturing the section-level moment-curvature behavior of a composite beam. The two-dimensional cross section was divided into individual fibers with appropriate geometry and material stress-strain relationships. At the steel-concrete interface, a slip strain was used to account for slip of the shear stud and was based on

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the load-slip relationship by Zhao and Kruppa (1997). The shear connector slip was assumed to be evenly distributed along the length of the beam. It should be noted that shear studs used in decks oriented perpendicular to the beam span have less stud slip capacity as compared to studs in a flat slab (Selden et al., 2015).

The fiber-based model was benchmarked against results from experiments and analyses of three-dimensional finite models. Details can be found in Selden (2014). For the fiber model and a three-dimensional finite element model (FEM) of a simply supported composite beam, Figure 1a shows comparisons of shear stud slip to stud location along the length of a beam with 80% composite action. Figure 1b shows these same comparisons for a beam with 40% composite action. The figures demonstrate the validity of the fiber-based model as well as the increase in stud slip with a decrease in composite action.

Parametric Study

Various geometric and material properties and their effects on the maximum moment capacity of the composite beam were investigated. The study included flat concrete slabs and concrete on steel corrugated deck with the deck oriented perpendicular to the beam span. The full range of composite action, from 0 to 100% composite, was considered in order to fully evaluate any trends in behavior. Additional parameters included maximum allowable slip of the shear studs, steel material properties, and beam length. Sample composite beam details for the results presented here are W12×19 steel sections; 5½ in-thick normal weight concrete slab or 3-in. metal deck with 2½-in. normal weight concrete topping; ¾-in.-diameter shear studs; and beam lengths of 13, 25 and 35 ft. Full ranges and details can be found in Selden (2014).

Effects of Degree of Composite Action, Beam Length, Allowable Stud Slip

Fiber model results were normalized with respect to the nominal moment capacity calculated following the AISC *Specification* (AISC, 2010); the normalized value is denoted as $M/M_{n,AISC.}$ Normalized moment values were evaluated for varying degree of composite action, η, with 1.0 corresponding to 100% composite action. Comparisons were also made with parameters such as beam length and maximum allowable stud slip.

The moment capacity is sensitive to the degree of composite action and the beam length. As the degree of composite action decreases, so does the effect of slip at the steel-concrete interface and the deviation of the moment capacity from the nominal moment capacity. The partially composite beams are unable to reach the nominal moment capacity due to slip of the shear studs. Increasing the length of the beam further reduces the moment capacities for the partially composite beams. Figure 2a shows trends in normalized moment for degree of composite action and beam length for flat slab cases. Figure 2b shows these trends for cases with perpendicular deck.

The moment capacity is also sensitive to the ductility of the shear connectors or the maximum allowable stud slip. An initial 0.20 in. was used for maximum allowable stud slip for the flat slab case; this corresponded to the deformation at the peak shear force. Without modifying the initial load-slip model, the maximum allowable stud slip was increased to 0.35 in., and a constant shear force was assumed for 0.20 in. to 0.35 in. of slip. For the perpendicular deck case, the initial and increased allowable stud slip values were 0.13 in. and 0.25 in. The comparisons for normalized moment, degree of composite action, and allowable stud slip are shown in Figure 3a for the flat slab cases and Figure 3b for the

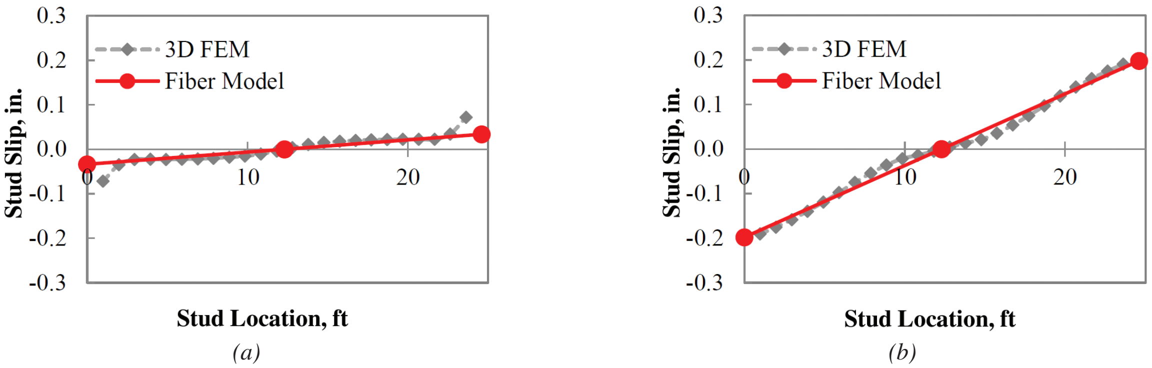


Fig. 1. Comparison of stud slip to stud location for (a) 80% composite action and (b) 40% composite action.

perpendicular deck cases. The increases in allowable slip increase the moment capacities achieved before reaching the shear slip capacity.

Summary and Recommendations

A parametric study utilizing fiber-based models of composite beams and considering the load-slip behavior of the shear studs demonstrated reductions in moment capacity due primarily to three factors: degree of composite action, beam length, and maximum allowable slip of the shear connector. The results summarized here and presented in Selden (2014) led the researchers to recommend that composite beams be designed with a minimum of 50% composite action (Selden et al., 2015).

A complementary study has investigated shear connector slip and implications for design of composite beams and girders in the United States and has provided additional recommendations (Mujagic et al., 2015). The researchers created a database of "practically occurring composite beams and girders" that satisfy AISC *Specification* requirements (AISC, 2010), 2015 IBC (ICC, 2015) loading criteria, and common detailing and fabrication requirements. Within that database, they investigated the ductility of shear connectors, making observations of configurations that exhibited significant deviations between the available and required ductility of those shear connectors. Their observations and design recommendations can be found in Mujagic et al. (2015).

COMPOSITE BEAMS WITH HIGH-STRENGTH MATERIALS

Use of high-strength (HS) steel in composite beams increases loading capacity and reduces self-weight. Additional benefits may be realized by pairing HS steel with HS concrete. However, the post-yield performance (e.g., ultimate strain capacity) of HS steel is not as good as for conventional

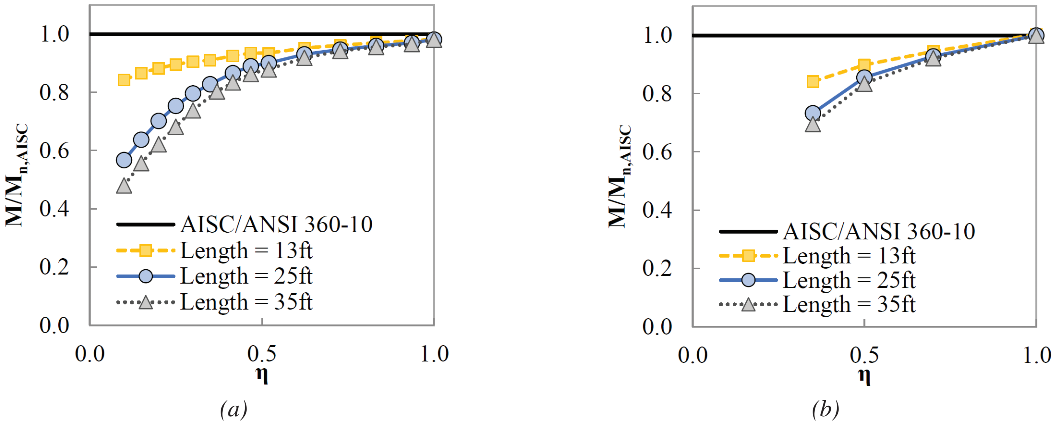


Fig. 2. Normalized moment, degree of composite action, and beam length for (a) flat slab and (b) perpendicular deck.

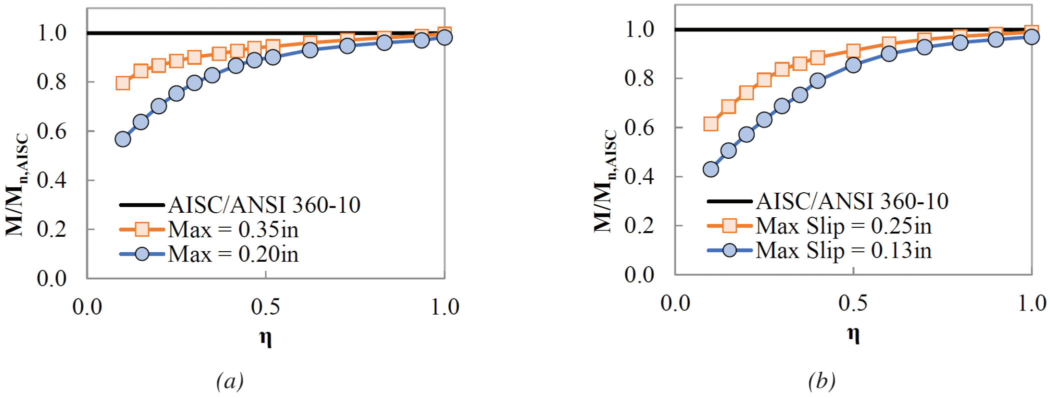


Fig. 3. Normalized moment, degree of composite action, and allowable stud slip for (a) flat slab and (b) perpendicular deck.

steels, and there is limited research on the structural behavior of composite beams with HS steel (Ban et al., 2016). Ban and colleagues note that "the plastic deformation and loading capacities of composite beams incorporating HS materials would logically have different features to those with conventional materials. As a result, relevant knowledge that provides an understanding of the structural performance of such members is much needed."

Research Objectives and Methods

Ban et al. (2016) worked to quantify the ductility of composite beams with HS steel and HS concrete using a validated three-dimensional finite element model. Specifically, the rotation capacities of numerous models of composite beams with HS materials in positive bending were measured. Rotation capacity was defined as the ratio of the ultimate rotation, θ_u, at the maximum moment, M_u, to the yield rotation, θ_y, at the yield moment, M_y. Effects of parameters such as steel strength, concrete strength, degree of shear connection, presence of profiled steel decking, and beam span-to-depth ratio were explored. Results were used to develop a nonlinear empirical equation for prediction of rotation capacity of composite beams with HS materials, as well as recommendations for ductility of shear connectors.

Finite Element Model

The finite element model used in this study was based on prior work in ABAQUS by Ban and Bradford (2013). Shell elements (S4R) were used for the steel beam. Connector elements (CONN3D2) were used for the shear connectors. For models with profiled steel decking, solid elements (C3D8) were used for the concrete, shell elements (S4R) were used for the metal deck, and truss elements (T3D2) were used for the reinforcing steel. Figure 4 shows the steel beam, reinforcing steel, and concrete for a flat slab composite beam model.

Material models included a multilinear isotropic hardening model for the steel beam and an elastic-perfectly plastic model for the reinforcing steel. A damage-plasticity model was used for the concrete. For the shear connectors, the load-slip relationship by Ollgaard et al. (1971) was used. Large slip capacities were deliberately assigned so as to avoid shear interaction failure in the analyses. Additional details for the finite element model can be found in Ban et al. (2016).

The finite element model was validated through modeling of 27 steel-concrete composite beams (from four different studies) and comparisons against reported test results for those beams. Reported yield strengths for the steel

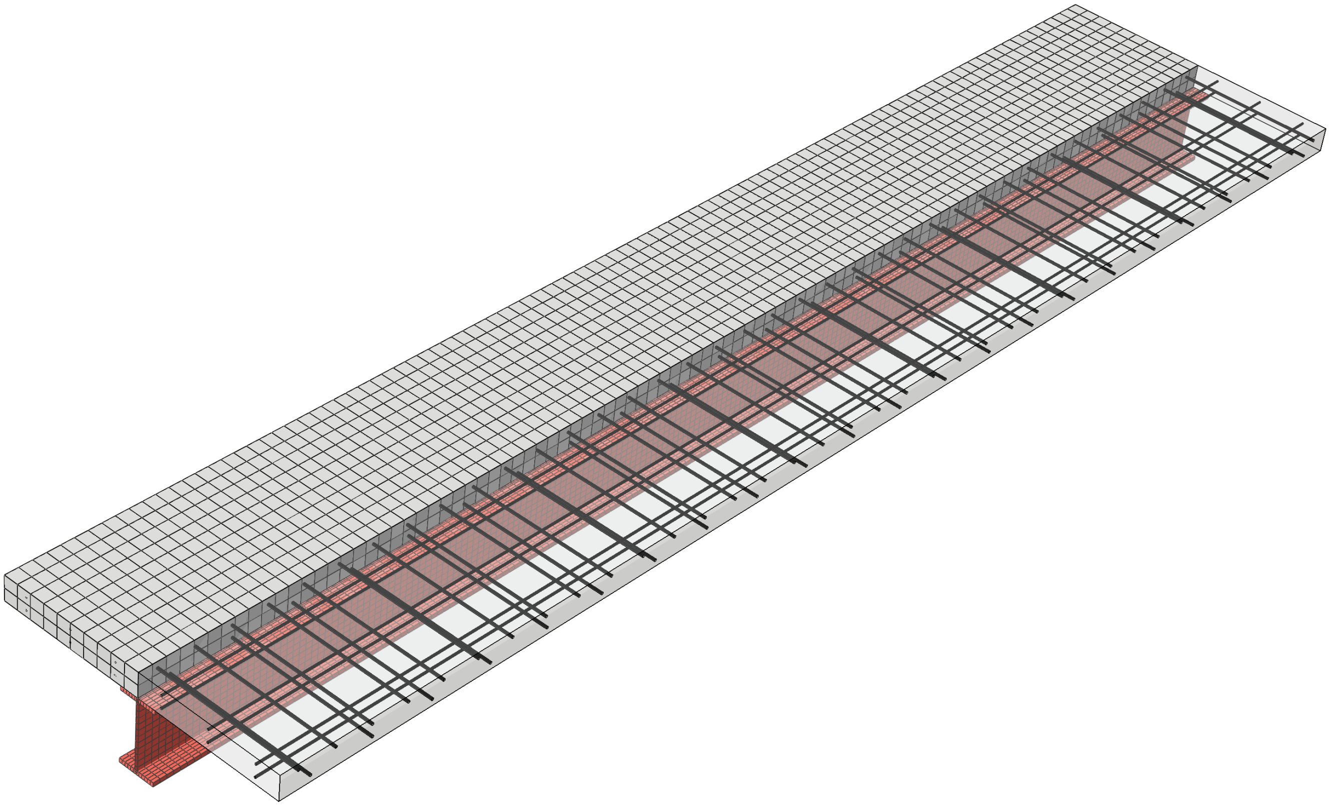


Fig. 4. Finite element model of a flat slab composite beam.

beams ranged from 31 to 109 ksi, and concrete compressive strengths ranged from 2.90 to 11.1 ksi. The experimental results were from one-point, two-point, and uniformly distributed load tests on composite beams. The finite element model was able to predict the ultimate moment capacities of the composite beams to within ±5%. Comparisons of load or moment versus mid-span deflection also showed good agreement between the finite element model and test results for initial stiffness and failure modes (Ban et al., 2016).

Parametric Study

A total of 1,380 composite beams were modeled for a parametric study that considered effects of the material properties, the shear connections, section geometry, and initial imperfections. Ten grades of steel, with yield strengths ranging from 34 to 139 ksi, were included. Concrete compressive strengths ranged from 2.90 to 14.5 ksi. Nine different degrees of shear connection and three distribution patterns (e.g., uniform, concentrated toward supports) were modeled. Five different cross sections, solid slabs and slabs with profiled steel decking, and seven ratios of beam span (L) to total depth (D) were studied, with L/D ranging from 13.75 to 45.0. Initial imperfections included initial geometric imperfections and residual stresses in the steel beam. Details can be found in Ban et al. (2016).

Parameters that had little to no influence on the available rotation capacity, or ductility, of the composite beams were the degree of shear connection, distribution patterns for the shear connectors, cross-sectional dimensions, solid slabs or slabs with profiled steel decking, initial geometric imperfections, and residual stresses.

Rotation capacities generally increased as the steel yield strength decreased. Conversely, the rotation capacities tended to increase as the concrete strength increased, although this trend was not as pronounced as the trend with steel strength. The combined steel and concrete strength effect can be described using the depth ratio of the plastic neutral axis, x_{pl}, defined as the distance between the plastic neutral axis and the extreme fiber of the concrete slab in compression divided by the overall depth (D). The available rotation capacity increases as x_{pl} decreases.

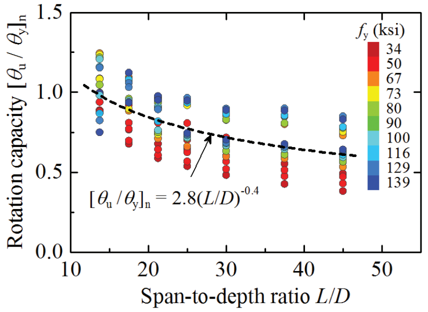


Fig. 5. Rotation capacity relationship to span-to-depth ratio.

The span-to-depth ratio was another significant parameter. The available rotation capacity decreases with an increase in L/D, as shown in Figure 5. This is because "higher levels of development of the curvature and of the steel plasticity are demanded for composite beams with larger L/D values" but are limited by "the nearly constant ultimate strain for different concrete strengths" (Ban et al., 2016).

Empirical Equation and Recommendations

Based on the results of the parametric study, an empirical equation for available rotation of composite beams was developed. This equation (Equation 1) considers steel yield strength (f_y), depth ratio of the plastic neutral axis (x_{pl}), and span-to-depth ratio (L/D). The predicted rotation capacities from the empirical equation compare favorably to those from the finite element analysis results, within ±15% (Figure 6). As with the finite element model, the empirical equation can be used for predictions for composite beams with conventional strength or HS materials. Given the available rotation capacities for composite beams, the researchers are currently investigating the required rotation capacities in composite beams and frames with HS materials (Ban et al., 2016).

$$\frac{\theta_u}{\theta_y} = \frac{507.6(e)^{-1.7x_{pl}}}{f_y\left(L/D\right)^{0.4}} + 1 \tag{1}$$

As noted earlier for the shear connectors, large slip capacities were deliberately assigned so as to avoid shear interaction failure in the analyses. In the parametric study, for steel yield strengths less than 67 ksi or concrete compressive strengths greater than 10 ksi, slip was less than 0.24 in. However, results also showed increasing maximum slip of

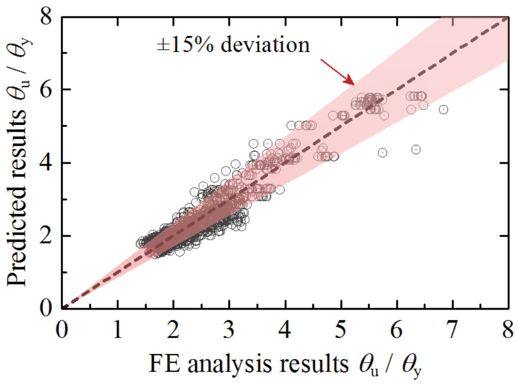


Fig. 6. Predicted rotation capacities for equation and finite element analysis.

the connectors with increase in steel yield strength. Ban et al. (2016) recommend slip capacities of 0.35 or 0.47 in. for different combinations of steel yield and concrete compressive strength.

FIRE-STRUCTURE INTERACTION

The National Institute of Standards and Technology (NIST) is planning a series of real-scale experiments at the recently renovated National Fire Research Laboratory (NFRL). This series focuses on the performance of steel-concrete composite floor systems in fire, with the aim to provide technical information, through experimental tests, for advancing performance-based design for fire conditions. The motivation for the investigation dates back to NIST research on the fire-induced collapse of the World Trade Center (WTC) 7 building. The WTC investigation identified potential vulnerabilities of composite floor systems in uncontrolled fires with issues related to structural layout, sources of thermal restraint, and connections. Meanwhile, two recent stakeholder workshops at NIST (Almand, 2012; Yang et al., 2015) presented the large-scale structural-fire testing capabilities of the NFRL and unprecedented opportunities for research. Among the priorities defined at the workshops: conduct three-dimensional full-scale tests on structural systems and contribute to the "generation of a database of large-scale experiments documenting the performance of structural connections, components, subassemblies, and systems under realistic fire and loading conditions for validation of analytical models" (Yang et al., 2015). Also, as stated in Almand (2012), "a focus on large scale experiments related to the many unanswered questions about composite floor system performance would have great practical import and a major impact on design methods."

National Fire Research Laboratory (NFRL)

The National Fire Research Laboratory (NFRL) at NIST was expanded in 2015 and can "accommodate experiments on real-scale structural systems and components up to two stories in height and 2 bays × 3 bays in plan." (Bundy et al., 2016). High-bay areas include a strong floor, strong wall, overhead cranes, exhaust hoods, an emissions control system (ECS), and a hydraulic loading system, enabling testing of structures under realistic fire and structural loading. The exhaust hood above the strong floor is used for quantification of the heat release rate as a function of time, and retractable side skirts on the hood can be positioned to improve smoke capture. Hydraulic actuators can be mounted underneath the strong floor. Figure 7 shows a cross section of the NFRL and a photograph of calibration of the heat release rate measurement system with a 10-MW fire. Additional

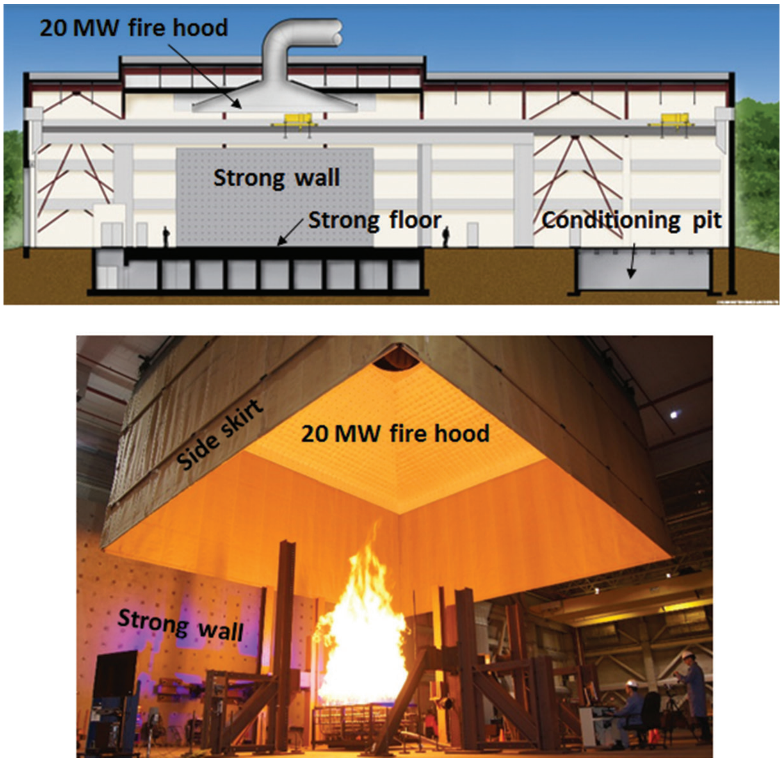


Fig. 7. Section view of the NFRL and calibration of heat release rate measurement system.

details of the NFRL and its capabilities can be found in Bundy et al. (2016).

Research Plan

Of the "unanswered questions about composite floor system performance" (Almand, 2012) in steel frame construction, NIST has focused a number of important factors for behavior in fire, as identified in the literature. The primary objectives for the experiments are to characterize behavior of the composite floor system and to improve models that can be used for performance-based design of steel frame buildings for fire.

Test Specimen and Test Parameters

A two-story, two-bay by three-bay composite floor system is to be experimentally investigated. Story heights are 11 ft, and the test bay is 20 ft by 30 ft. Figure 8 shows a plan view of the test frame shaded in gray, with the test bay in dark gray. An outline of the hood shows its placement above the test bay. Note that the test bay can be configured as an interior, edge or corner bay of a building, as illustrated by the dashed lines in Figure 8. Also shown at the East and West perimeters are bracing modules. Restraint on the East side can be varied through use of actuators. The North–South frames can also be braced at the strong wall.

Parameters to be investigated in the tests include the orientation of secondary beams in adjacent bays (i.e., "symmetry in framing" or "balanced framing"), geometry and orientation of the deck (and floor framing) with regard to formation of a compression ring, test bay location (corner, edge or interior bay), and types of beam to girder connections (bolted double-angle or single-plate shear connections). Also varied are the magnitude and location of service gravity loads using six actuators located underneath the strong floor (Figure 9).

Parameters related to the fire loading are the thickness of the spray-applied fire resistive materials (SFRM), fires on

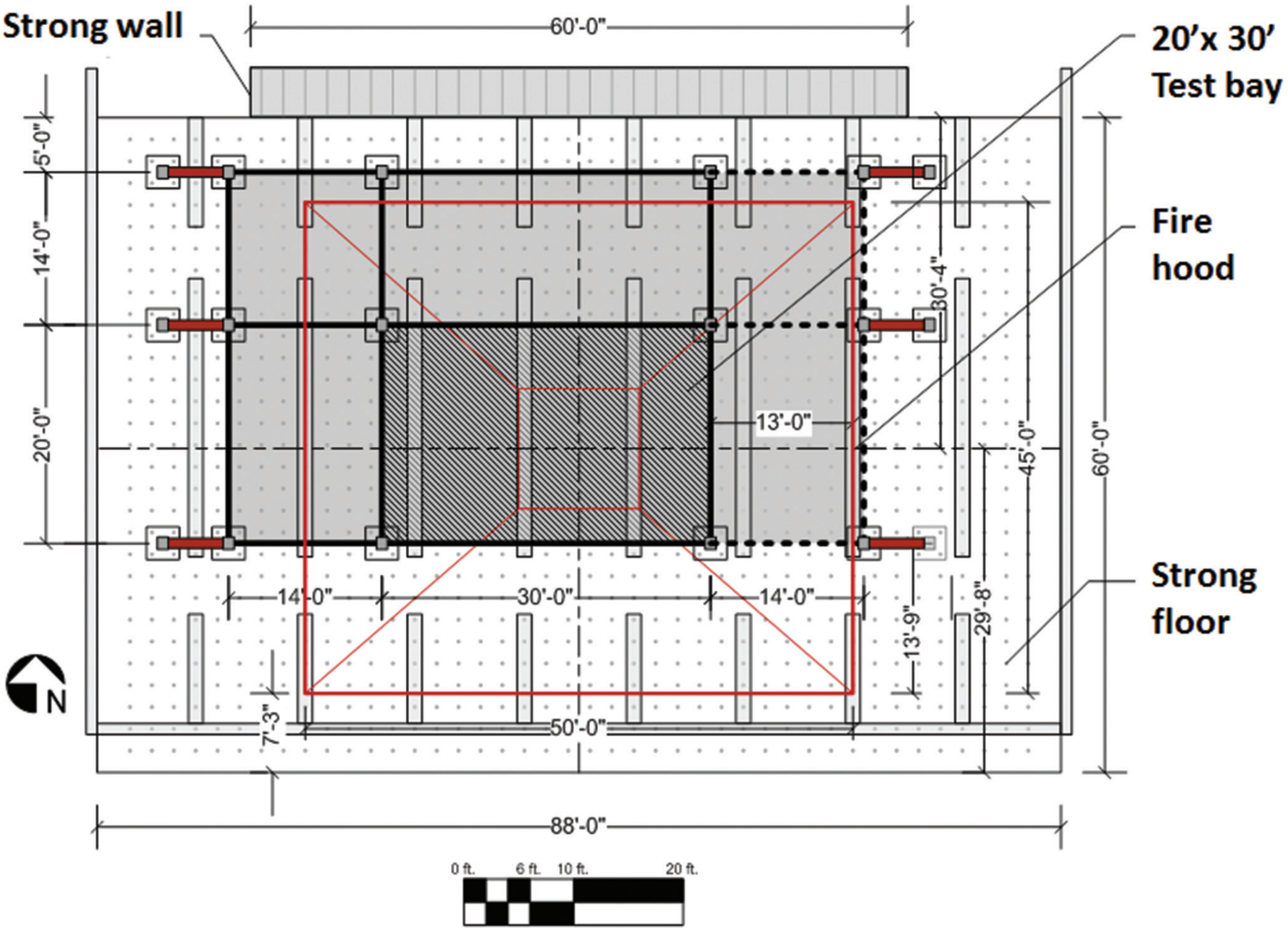
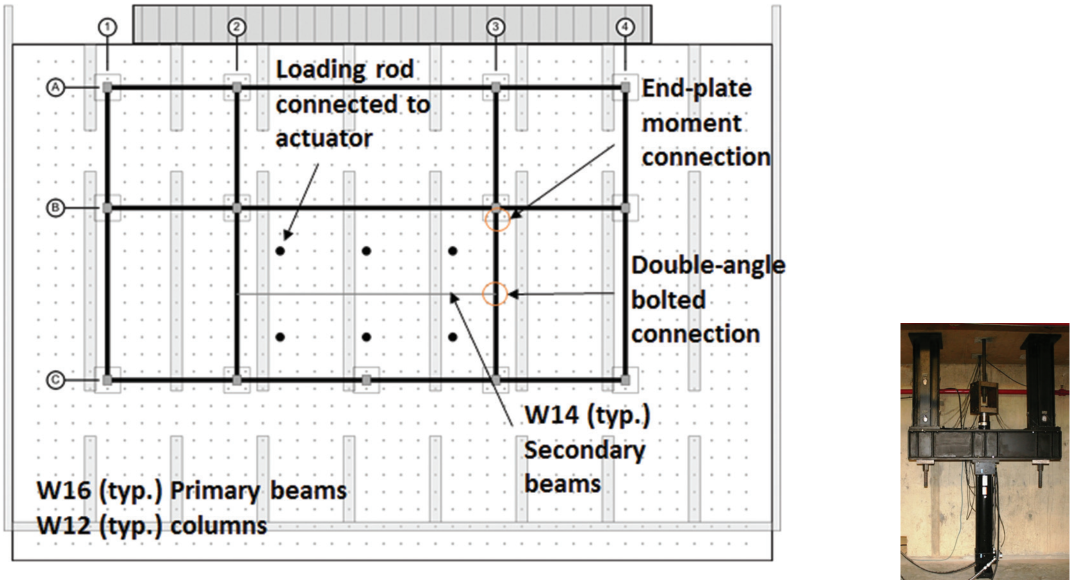


Fig. 8. Plan view of the test frame.



(a) (b)

Fig. 9. (a) Locations of service gravity loads; (b) actuator mounted underneath the strong floor.

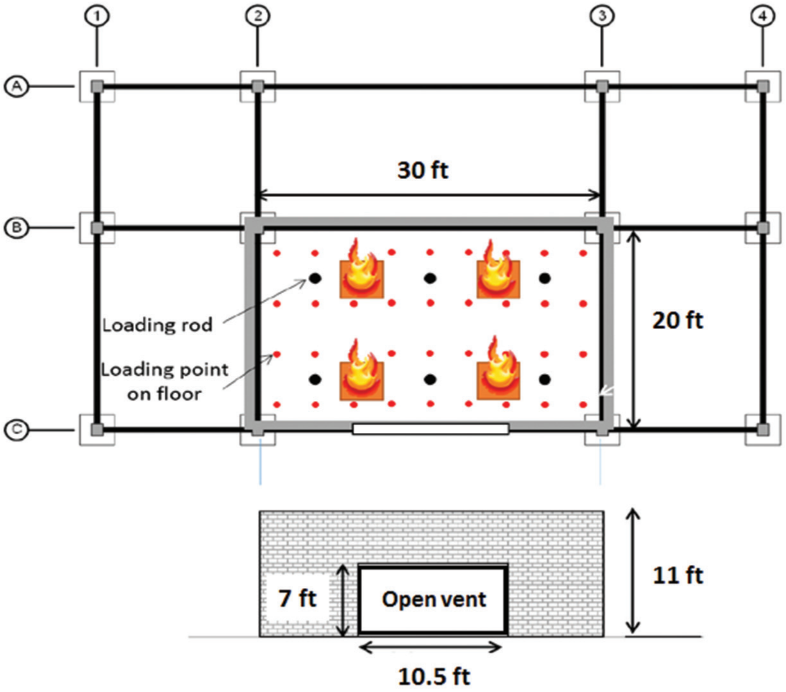


Fig. 10. Schematic of the test bay, burners, loading points, and enclosure.

multiple floors, and fire conditions (e.g., severity, duration, and location of the proposed structural fire). Figure 10 is a schematic of the test bay, showing locations of natural gas burners, locations of gravity loading points, and the outline of the enclosure with an open vent on one side as shown in the elevation drawing. The four burners can simulate a fire traveling through the room. Additional details on the test program, including development of and specifics on the fire loading, can be found in Choe et al. (2016) and Manzello and Suzuki (2015).

Expected Outcomes

The tests planned at the NFRL represent a major advance in real-scale testing of steel-concrete composite floor systems under fire and structural loading. The two story, multi-bay test specimens and test matrix capture a broad spectrum of geometric, design and loading parameters. The temperature and structural response data, through heating and cooling phases, will be extremely valuable for validation of physics-based models for prediction of structural performance under fire. As such, this research will provide important steps forward for performance-based standards for fire resistant design of steel buildings.

SUMMARY

A few studies on steel-concrete composite beams and floor systems at ambient and elevated temperatures were highlighted. A parametric study with fiber-based models incorporating effects of shear connector slip was used to identify significant factors affecting the flexural capacity of partially composite beams and produce design recommendations. A validated finite element model was used to quantify the available rotation capacity of composite beams with high-strength materials and in the development of an empirical equation to predict this capacity. Tests of real-scale composite floor systems subjected to fire and structural loading will take advantage of the unique capabilities of the NFRL and provide valuable data to help answer questions about the performance of these systems under fire.

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