

Design and Construction of Long-Span Composite Beam Specimens for Large Structural-Fire Tests

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Abstract

A series of experiments is being conducted on five 12.8 m long composite floor beams at the newly-commissioned National Fire Research Laboratory at the National Institute of Standards and Technology. The test beams were designed according to current U.S. building codes with input and design-review provided by panel of expert practitioners. Each specimen consists of a W18x35 beam and a 1.83 m wide lightweight concrete slab cast over profiled steel deck units. Composite action between the steel beam and concrete slab is achieved using 19 mm diameter steel shear connectors spaced at 305 mm on center. One of the five specimens was tested at ambient temperature to measure its behavior and flexural strength, and to verify the purpose-built mechanical loading system. The remaining four specimens will be tested under simultaneously applied mechanical loading and an enclosure fire using a natural gas fuel delivery system. The beam-to-column connections and rotational restraint of the slab ends over the support girders were varied among those four specimens.

Introduction

Long-span steel-concrete composite floor beams are widely used in steel-frame buildings because they are a cost-effective means of spanning large open spaces. Predicting the fire behavior of composite beams, however, is challenging due to the many influencing parameters, which include the gravity connections, force-slip behavior provided by shear connectors, metal decking profiles, concrete characteristics, and steel framing of adjacent bays. For instance, in multi-bay buildings, composite floor systems are continuous over primary girders. The steel reinforcements, such as reinforcing bars or welded wire fabric, are typically placed in concrete slabs at those locations to minimize surface cracking due to a negative bending moment from prescribed floor loads. Also, thermally-induced restraints in the floor assemblies, when exposed to fire, would vary depending upon the combination of stiffness of surrounding frames and beam-to-connection types. Most of the furnace fire tests conducted in the past, however, focused on the fire-resistant ratings of unrestrained composite floor assemblies with limited sizes, and generated very limited information to be used for evaluating the effects of thermally induced restraints. The most recent test data in U.S., e.g. Selden et al. (2015), Wellman et al. (2011), and Guo et al. (2010), are available for composite beam specimens with lengths ranging from 4 m to 6 m.

Recently, the National Institute of Standards and Technology (NIST) hosted three stakeholder workshops [Almand et al. (2004); Almand (2013); Yang et al. (2015)] to prioritize the needs of structural-fire experimental research that could be conducted in the newly expanded National Fire Research Laboratory (NFRL). Based on the stakeholder's recommendations made

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from those workshops, composite floor systems were selected for the NFRL's first structural-fire test program because of their widespread use in building construction and because of modeling challenges in such systems under a building fire. The proposed NFRL test programs consist of two phases: long-span steel-concrete composite beam tests (Phase 1) and steel-concrete composite floor tests (Phase 2). Data and technical information developed by the NFRL test programs would be of "great practical import and a major impact on design methods" (Almand, 2013) for composite floor system under structurally significant fire conditions. Specifics of the test frame configuration, test fires, and details of the test matrices were proposed through a series of stakeholder meetings, hosted by NIST, with national and international researchers and industry experts in the field of structural fire engineering. This paper presents the experimental design and construction of the NFRL long-span composite beam test series. Testing is currently in progress.

A total of five 12.8 m long composite test beams are being tested under combined mechanically applied gravity loads and a structurally significant fire provided by the NFRL natural gas fuel delivery system. Specimens were designed to represent composite floor beams, commonly found in mid-rise office buildings, in accordance with U.S. design codes and standards. One specimen was recently tested at ambient temperature. The test results are presented in the authors' companion paper titled "Experimental Study on Long-Span Composite Floor Beams Subject to Fire: Baseline Data at Ambient Temperature" included in this proceeding. Other four specimens were designed to achieve a 2 hour fire rating as prescribed in building codes and will be exposed to a structurally significant fire with the maximum heat release rate of 4 MW. Thermal load is supplied using three purpose-built 1 m × 1.5 m natural gas burners. Mechanical load is applied at six loading points along the centerline of the specimen using hydraulic actuators. As for test variables, two types of beam connections were considered, including (a) bolted/welded double-angles and (b) single-plate shear connections. Slab continuity conditions are provided in two of the five specimens by rotationally restraining the steel reinforcements in concrete slab at the location of support girders.

Design Basis of Composite Beam Specimens

Specimens were designed to represent composite floor beams in a 12.8 m long bay of a mid-rise steel frame building. For structural design, it was assumed that a steel beam was spaced at 3.05 m. A steel beam was made composite with a lightweight concrete slab casted on 76 mm deep profiled steel deck units via 19 mm headed steel shear studs. The spacing of shear studs was 305 mm on center (i.e., every flute of deck units). A 2 hour fire rating of the composite floor assemblies was considered as prescribed in the building codes. The factored (design) floor loads were determined by the gravity load combinations prescribed in ASCE/SEI 7-10 (ASCE, 2010) and using inputs provided by the panel of expert practitioners such as construction live loads. The size and proportion of the prototype composite beam which is assumed to be framing into a 12.8 m by 6.1 m bay and the beam-to-column shear connections were designed in accordance with ANSI/AISC 360-16 (AISC, 2016), AISC Design Guide 3 (West et al., 2003), and SDI C-2011 (SDI, 2011). For Phase 1 test program, the test beams consisted of a 12.8 m long steel beam and a 12.8 m by 1.83 m slab.

Design Loads

The unit weight of a lightweight, lightly reinforced concrete slab used in the test was 18.9 kN/m^3 . The calculated self-weight of the concrete slab casted on profiled steel decking was 2.20 kN/m^2 . The self-weight of the steel beam was 0.51 kN/m . Other ASCE/SEI 7-10 design loads, including a construction live load of 0.96 kN/m^2 , super imposed dead load of 0.48 kN/m^2 , and a live load of 3.35 kN/m^2 , were used to design the composite test beam. The calculated moment and shear demand at ambient temperature was 548 kN-m and 171 kN , respectively. For extreme fire events, the moment and shear demand was reduced to 326 kN-m and 99.4 kN , respectively, in accordance with ASCE/SEI 7-10 load combination ($1.2 \times \text{dead load} + 0.5 \times \text{live load}$).

Design of Composite Beam

Figure 1 illustrates a cross-section of the test beam. A 20-gauge galvanized 7.62 cm deep fluted steel deck (with dimensions similar to Vulcraft 3VLI20) with 27.6 MPa lightweight concrete was used. The thickness of the concrete slab above the steel deck was 8.26 cm to provide a 2 hour fire rating without additional fire protection coating on the deck. The ribs of the steel deck were oriented perpendicular to the floor beams and spaced at 30.5 cm. A 6x6 W1.4xW1.4 welded wire fabric was placed in the mid height of the concrete above the steel deck as the minimum required shrinkage and temperature control reinforcement. For two specimens with slab continuity, four no. 4 reinforcing bars were placed at the spacing of 45.7 cm on center at the beam ends, which were primarily designed for a crack control of the slab over the support girders. They were placed at the top of the welded wire fabric and their embedded length from the slab end was 76.2 cm.

The W18x35 beam steel beam was designed to support the ASCE 7 construction loads, including the self-weight of a steel beam, a wet concrete slab and construction live loads, and to meet the serviceability requirement (displacement limit) for a non-composite section. The composite action between the beam and slab was provided using 19 mm diameter steel headed studs spaced at 305 mm on center. The total shear connection strength (composite action) was 82 % of the yield strength of the steel beam cross section at ambient temperature. The calculated flexural capacity of the composite section (with the AISC strength reduction factor of 0.9) per ANSI/AISC 360-16 was 695 kN-m which is about 1.27 times the moment demand at ambient temperature. The governing failure mode was fracture of steel shear studs.

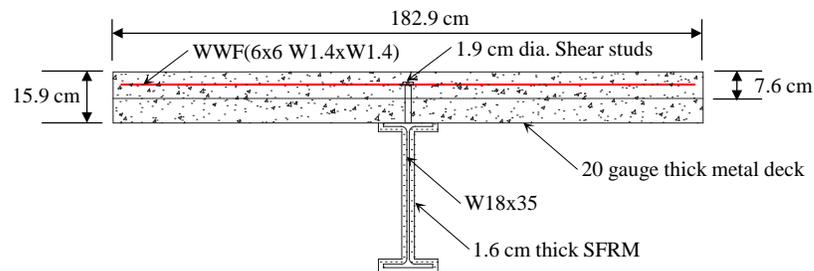


Figure 1. Cross-section of the composite beam specimen.

Design of Shear Connections

Figure 2 shows the shear connections for the test beams which were designed using either double angles or shear tab in accordance with ANSI/AISC 360-16. For double angle connection (Figure 2a), L5×3×3/8 angles made of Gr. 36 steel were used. The angle legs were bolted to the beam web using three 19 mm diameter A325 bolts with the spacing of 76 mm. The top bolt was located at 114 mm from the top of the steel beam. The bolt holes in the web were drilled at 76 mm from the column face. The bottom flange of the steel beam was coped. The other legs of angles were shop-welded to a sacrificial plate on columns. The size of fillet weld was 8 mm. The design of the double angle connection was governed by the weld strength in shear, and the corresponding calculated shear capacity was 267 kN (including the AISC strength reduction factor of 0.75).

For the shear tab connection (Figure 2b), a 11 mm thick plate (Gr. 36) was bolted to the web of the steel beam and welded to a sacrificial plate of the support column. The same bolts were placed at 76 mm spacing as used in the angle connection. The location of bolt holes was also remained unchanged. The size of fillet weld was 8 mm fillet weld. The calculated shear capacity was 242 kN (including the AISC strength reduction factor of 0.75).

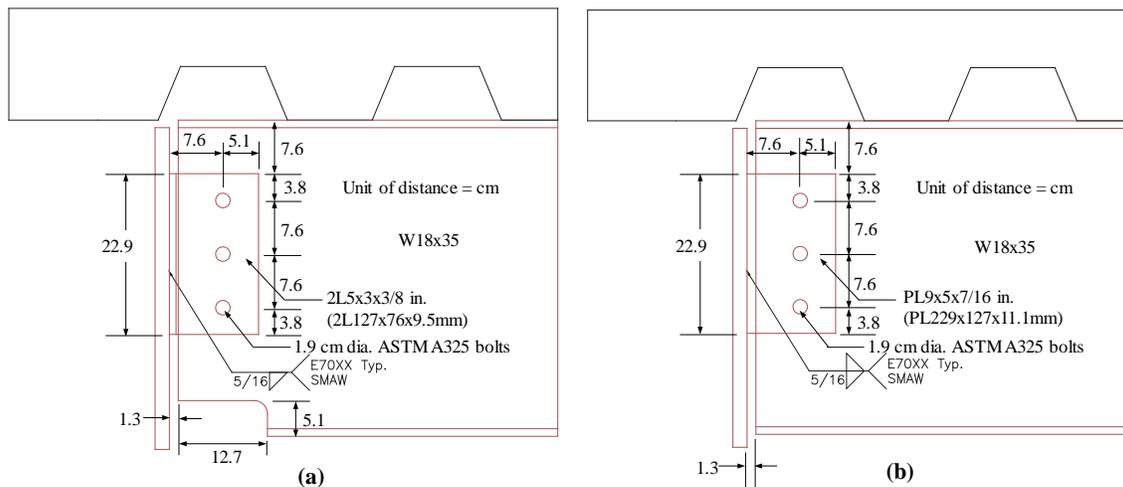


Figure 2. Shear connections at the end of specimens (a) double angle and (b) single plate. (weld dimension in inches; 1 in. = 2.54 cm)

Passive Fire Protection

The steel beam and connections were coated with sprayed fire resistive materials (SFRM) to meet the 2 hour fire rating as prescribed in the buildings code. In the connection regions, SFRM was sprayed to achieve the 3 hour fire rating which was required for primary members (i.e. columns). Since the thickness of a topping concrete was 8.26 cm (3.25 in.) for the 2 hour fire rating, no additional fire protection was necessary at underside of steel decking. The SFRM product used in this test program was the Southwest Type 5MD, a cementitious gypsum based material manufactured by Carboline. The required thicknesses of this product for the W18x35 steel beam and the connections was 16 mm and 27 mm, respectively, in accordance with the Underwriter Laboratory (UL) directory.

Test Matrix

Table 1 shows the test matrix for this test program. Test variables included shear connection type (i.e., bolted/welded double-angles versus single-plate shear connections) that are

extensively used in the U.S. construction practice and the presence or absence of slab continuity at the beam ends as shown in Figure 3. The testing is currently ongoing. Specimen 1 was recently tested at ambient temperature to measure the behavior and strength of the test beam as a baseline information that will be used to compare with the fire test results. For the ambient temperature test, the test beam was subjected to a monotonically increasing moment until failure. The maximum moment capacity (M_{max}) was measured at $695 \text{ kN-m} \pm 2 \%$ where the value after \pm symbol is the standard uncertainty with coverage factor of 1. Specimens 2 through 5 will be tested under combined mechanical and fire loads. For those specimens, the applied load is equivalent to a bending moment of 326 kN-m that was computed using the ASCE 7 load combination for fire condition (i.e., $1.2 \times \text{dead load} + 0.5 \times \text{live load}$). This gives the applied load ratio approximately equal to $0.5M_{max}$. All four specimens will be exposed to a structurally significant fire with the maximum heat release rate of 4 MW until incipient failure occurs.

Table 1. Test matrix for the laboratory experiments

Specimen	End connection	Slab Continuity Provided	Mechanical loading	Fire loading
Specimen 1	double-angle	No	Load to failure (M_{max})	Ambient Test
Specimen 2	double-angle	No	$0.5M_{max}$	4 MW fire
Specimen 3	double-angle	Yes	$0.5M_{max}$	4 MW fire
Specimen 4	Single plate	No	$0.5M_{max}$	4 MW fire
Specimen 5	Single plate	Yes	$0.5M_{max}$	4 MW fire

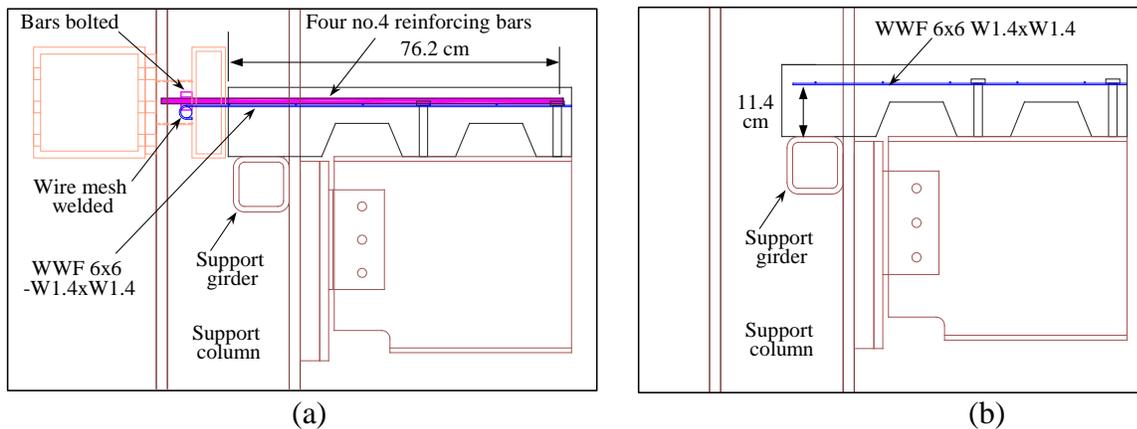


Figure 3. Slab end support conditions (a) specimen with slab continuity and (b) specimen without slab continuity.

Construction of Specimens and Test Setup

Materials

The measured and code specified minimum material properties of the steel beam, shear studs, wire mesh, reinforcing bar, and the connection materials such as shear tab, angle, and bolts are listed in Table 2. The elastic modulus (E), yield strength at 0.2 % offset ($\sigma_{y0.2}$), ultimate strength (σ_u), and the percent elongation at the ultimate strength (e_u) were measured from tensile coupon

tests that were conducted in accordance with the relevant ASTM standards (such as ASTM E8, 2016).

The concrete mix design is provided in Table 3. The guiding principle behind the concrete mix was to have a hardened concrete with mechanical properties typical of what is used in current practice, but with a low propensity for fire-induced spalling; which would add undesired variability to the experiments. To reduce the likelihood of spalling, 2.37 kg/m³ of monofilament polypropylene microfibers (FRC MONO-150) were used in the mix. To further reduce the chance of fire-induced spalling, expanded slate lightweight aggregate with a low water-retention characteristics and high desorption was selected (Pour-Ghaz, 2012) to help expedite the reduction of moisture in the slabs during curing. A large slump was required because sensitive optical fibers were embedded in the concrete to measure strain and temperature in the slab that limited the use of mechanical vibration during casting.

Fabrication of specimen

Figure 4 shows a photograph of the steel beam with metal deck, rebar chair, and shear studs. The flutes of metal deck units were oriented perpendicular to the steel beam and attached to the steel beam using power actuated fasteners. The shear studs that were 13.2 cm in original length were welded to the steel beam through the holes in the metal deck. The height of the shear studs after installation was 12.7 cm. As shown in the figure, shear studs were off centered by 2.5 cm from the center of the valleys of the metal deck toward each end of the specimen (in the ‘strong direction’ for shear). 3.8 cm high bar chairs were placed on top of the metal deck and 6x6 W1.4xW1.4 welded wire mesh was placed above the reinforcing bar chairs.

The concrete was batched at a local ready-mix concrete plant and trucked to NIST for casting. Because approximately 2.8 m³ of concrete was required per specimen and the trucks held 7.6 m³, two trucks (batches) were required to cast the five specimens. Two of the four specimens to be tested with fire loading were cast from each batch of concrete, with a mix of concrete from the two batches (half the length cast from Batch 1 and half from Batch 2) being used to cast the ambient temperature specimen. Although the mix design was the same for both batches, a larger amount of high-range water reducer (BASF Glenium 7920) was needed in Batch 2 to achieve the target slump; which influence the hardened concrete strength and had consequences for the ambient specimen discussed in a separate paper. Mechanical vibration of the concrete was only performed around edge embed plate and on the slab formwork. The concrete was screed out, but no floating or ‘hard troweling’ was performed.

Table 2. Measured and minimum specified material properties.

Material	Material Spec.	Min. specified		Measured material properties			
		σ_y (Mpa)	σ_u (Mpa)	E (GPa)	$\sigma_{y0.2}$ (Mpa)	σ_u (Mpa)	ϵ_u
Steel beam-Flange	ASTM A992	345	450	210	350	470	19%
Steel beam-Web	ASTM A992	345	450	200	370	470	19%
Shear stud	ASTM A29	350	450	210	410	510	5%
Wire mesh	ASTM A185	450	520	200	730	760	1%
No.4 rebar	ASTM A615 Gr 60	410	620	190	470	710	11%
Shear tab plate	ASTM A36	250	400	210	350	490	20%
Double angle	ASTM A36	250	400	200	380	510	17%
19 mm dia. Bolt	ASTM A325	630	830	210	900	960	6%

Table 3. Concrete mix design.

		w/cm: 0.46	Slump: 8.5±1.0 inch
		Surface Saturated	
Material		Dry (SSD), lb	Volume, ft ³
Cement:	ASTM C-150: Type I/II Lehigh	520	2.65
Fly Ash:	ASTM C-618: Separation Technologies Class F	130	0.88
Aggregate:	ASTM C-33: Carolina Stalite LTWT	890	9.51
Sand:	ASTM C-33: Howlin Sand	1370	8.41
Air:	2.5%		0.67
Water:	ASTM C-1602; ASTM C-1603	300	4.81
Admixture:	See Below	10	0.07
Total		3220	27.00
Unit Weight (pcf)		119.2	
Calculated Equilibrium Dry Density (pcf)		113.6	

Admixtures

- FRC MONO-150-4 lb/cy
- BASF Glenium 7920-3 ± 3 oz/cwt
- BASF Pozzoloth 322N - 4 ± 2 oz/cwt
- BASF DELVO Stabilizer- 2 ± 2 oz/cwt
- BASF Rheo TEC Z-60 - 4 ± 2 oz/cwt

The specimens were cast indoors in a test hall. Immediately after casting, the specimens were covered with wet burlap and then plastic to maintain a wet concrete surface. The burlap was re-wet, as required, for the first 7-days of curing, after which the plastic and burlap was removed. Within the next 7 days, the four specimens to be fire tested were moved to a large underground curing room where the temperature was maintained at 30 °C ± 2 °C (standard uncertainty) and the target relative humidity of the air was 50 %. Due to problems with the humidity control in the curing room, the achieved relative humidity of the air was around 30 % ± 10 %. The ambient specimen was cured in the testing hall where the temperature was 22 °C ± 2 °C (standard uncertainty) and the relative humidity of the air was not measured (typically less than 30 % during the first 3 months after casting; winter). The mean 28-day concrete cylinder strengths were 42.1 ± 0.9 MPa and 48.7 ± 1.6 MPa for Batch 1 and Batch 2 concretes, respectively.

After the fire test specimens were cured for about 6 months, the specimens were moved to the laboratory floor and the fire resistive material (SFRM) was sprayed to the steel beam and the connections of the specimens. Figure 5 shows the photographs of specimens after the SFRM was sprayed. The thickness of the SFRM was measured at various locations. Either the SFRM was scraped off or more SFRM was sprayed to maintain a uniform thickness of 16 mm with a tolerance of ± 25% of the required thickness as prescribed in building codes.

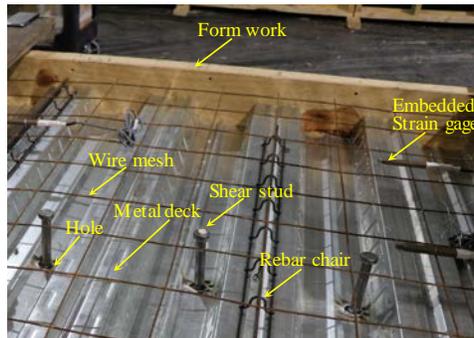


Figure 4. Placement of metal deck, shear stud, wire mesh.

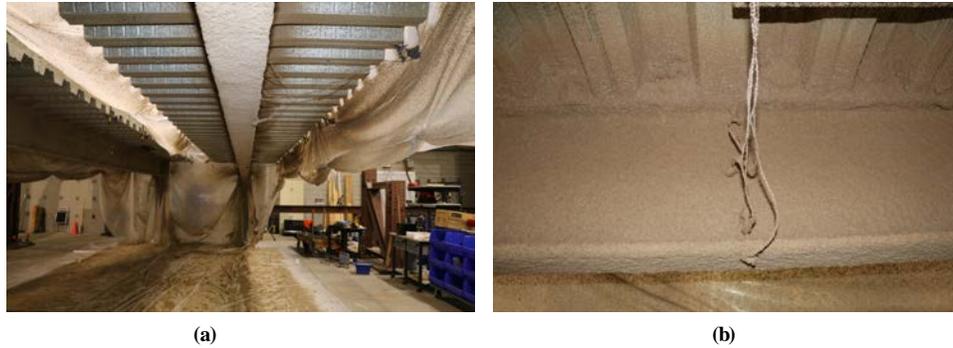


Figure 5. Specimens after spraying fire resistive materials (a) front view (b) side view.

Test Setup

The test setup is shown in Figures 6(a) and (b). The composite beam specimens were attached to the support columns at the ends using either a double angle connection or a single plate shear connection. The top of the slab, top of the steel beam, and the bottom of the steel beam were at elevations of 3.93 m, 3.77 m, and 3.32 m from the strong floor, respectively. Mechanical load was applied to the specimen at six load points simulating a uniform floor load. Three loading beams were used to apply the load as shown in Fig 7. The hollow steel section (HSS) loading beams were guided such that they can only move down vertically as the specimen deforms. Each loading beam was pulled down by two actuators at its ends. Actuators were placed underneath the basement and high-strength bars were used to transfer the forces from the actuators to the loading beam. As shown in Figures 6 and 7, a loading truss was used to transfer the force from each loading beam to two load points on the specimen.

The support columns were braced using a brace module (Figure 6) to provide lateral stiffness simulating the stiffness provided by the surrounding steel framing to the column in a building. The columns and the brace modules were anchored to the strong floor using post-tensioned high strength bars to prevent slip. The length of the steel beams was 12.3 m. The center-to-center distance between the bolt lines was 12.2 m. The steel beams that had double-angle connections at the end were coped at the lower flange. The flanges of the steel beams with single plate shear connection were not coped. The slab extended to the centerlines of the support columns and was supported on a HSS 5x5x1/2 girder to simulate typical construction conditions. For the specimens with slab continuity (Specimens 3 and 5), the wire mesh and the no.4 crack control reinforcing bars were extended beyond the slab edge and anchored as shown in Figure 3.

The longitudinal sides of the slab were laterally braced at the locations of the loading beams to simulate the restraints provided by the adjacent concrete slab. Figures 8(a) and 8(b) show a schematic and a photograph of the lateral-torsional restraint used in this test, respectively. The actuators that pulled down the loading beam were programmed such that the loading beam is horizontally leveled while it vertically moves up or down along with the specimen during the test. The axial displacement of the loading beam is restrained at its ends using laterally braced columns. Frictionless bearings were used between the HSS tube attached to the specimen and the lateral-torsional restraining system to minimize any force transfer to the edge of the slab.

For the specimens tested under fire conditions, a compartment (total area of 110 m²) constructed surrounding the specimens with a ventilation area of 4.93 m² is used to confine the fire below the composite beam specimen. Figure 9 shows the layout of the compartment wall and the locations of the burners. The enclosure walls were constructed with stiffened sheet steel (18 gauge) protected with 50 mm thick ceramic blanket. Thermal load will be applied using three 1 m × 1.5 m natural gas burners. A heat release rate of 1.33 MW will be maintained for each burner for 3.5 hours followed by a controlled cooling for 30 minutes. The layout of the compartment wall, the locations of the burners, and the heat release rate of the fire applied during the test were designed to develop a structurally significant fire during the fire test. Computational fluid dynamics (CFD) models were developed using the NIST Fire Dynamics Simulator (FDS) software to estimate the required heat release rate of the fire. Expected temperature time histories of the upper hot gas layer and the lower flange developed using the CFD models are shown in Figure 10. As shown, the lower flange is expected to reach a maximum temperature of 990 °C in about 3 hours 10 minutes of fire exposure.

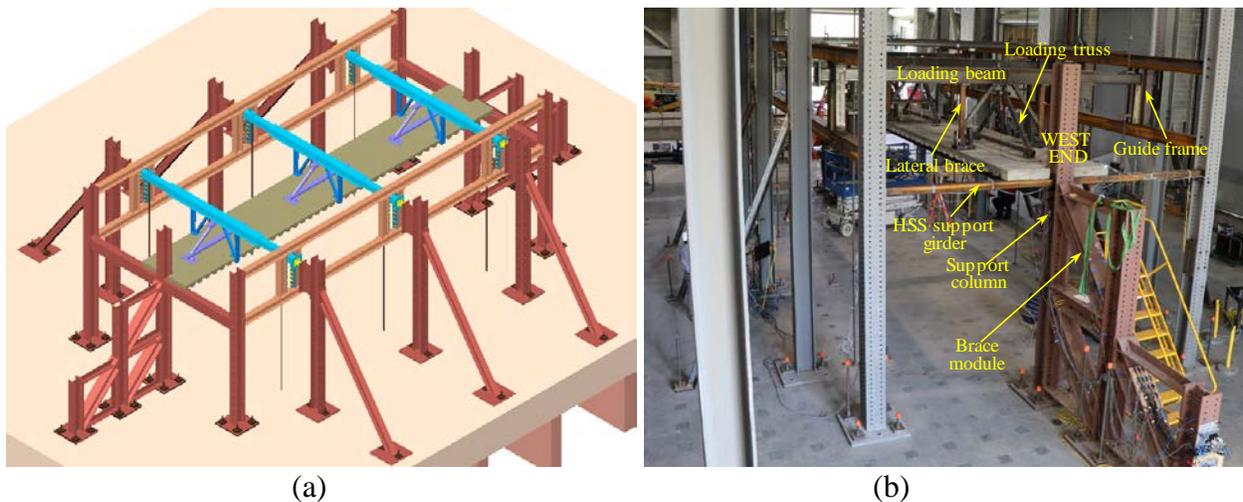


Figure 6. (a) A 3D schematic and (b) photograph of the structural test setup. Fire compartment walls and ventilation opening not shown.

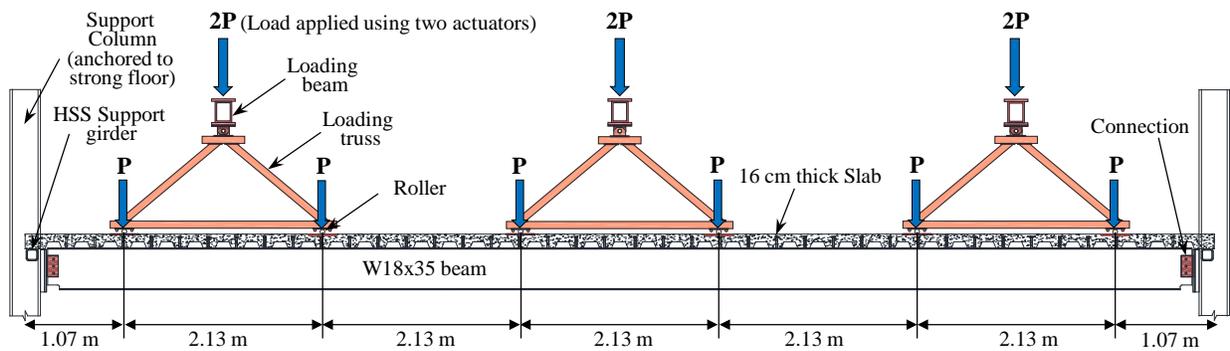


Figure 7. Mechanical loading system.

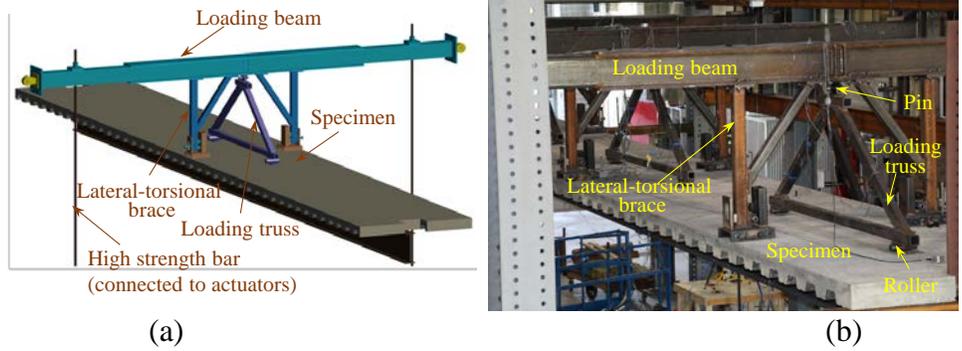


Figure 8. Loading truss and lateral brace setup (a) A 3D schematic and (b) a photograph.

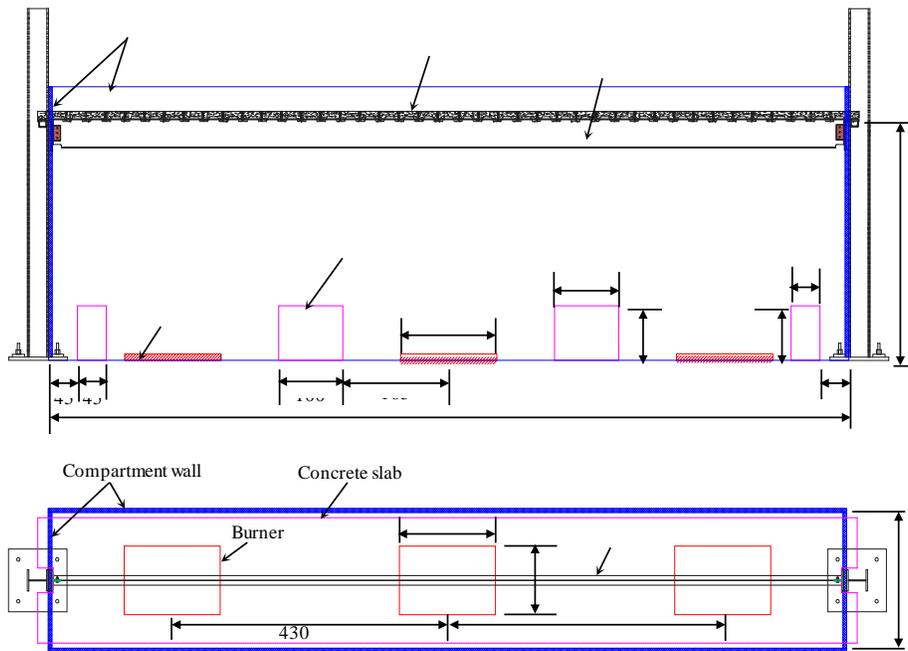


Figure 9. Locations of burners and the layout of the compartment wall (a) front view and (b) plan view. (units in cm)

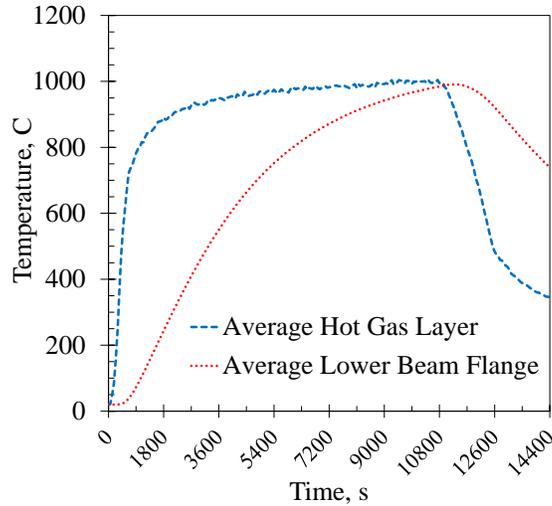


Figure 10. Expected temperature time history during the tests.

Conclusion

This paper presented the design and construction of the specimens as well as the experimental program used for the large structural-fire tests conducted at the National Fire Research Laboratory at NIST on five 12.8 m long-span composite floor beams. Test variables include the connection type at the beam ends and the slab continuity over the support girders. One specimen is tested at ambient temperature and four specimens are tested under combined structural and fire loads. The test data obtained from this research study can be used to evaluate the performance of long-span composite floor beams and to better understand the behavior of composite floor assembly under fire.

Disclaimer

Certain commercial equipment, instruments, or materials are identified in this report to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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