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Fire Resilience in Steel-Concrete Structures Part II: Advanced Solutions

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1. Introduction

1.1. Background

Steel-concrete composite floors are widely used in modern steel buildings because of their cost effectiveness for spanning large open spaces. However, passive fire protection design of composite floors, regardless of their size and geometry, is mainly based on prescriptive fire-resistance rating of small-scale assemblies tested following the century-old fire testing standard. Even though this prescriptive approach provides the advantage of lower design cost as well as well-known construction cost, it (1) incurs high fire protection costs, (2) seldom provides a technical basis for risk-informed design decisions, and (3) can hinder industry innovation in fire protection and structural design of multistory complex buildings.

Over the last few decades, significant research efforts have been made to better understand the integrity of full-scale composite floor systems under fire loading. The Cardington test program [1, 2] in Europe, which was performed in an eight-story steel-framed building, demonstrated that the fire resilience of composite floor systems was superior to that observed in standard fire tests on isolated composite beams. Membrane action of the composite slabs was observed as secondary load-carrying mechanism after the support beams lost their flexural capacity at extremely high temperature. These findings led to the possibility of eliminating fire protection of the secondary (filler) beams and the development of simplified design methods [3–5] accounting for the load-displacement relationship of composite floor assemblies in tensile membrane action at elevated temperatures. Both the FRACOF [6] and COSSFIRE projects [7] further examined the benefit from membrane action by conducting standard fire tests on full-scale composite floor assemblies with the bare steel secondary beams. These tests indicated that the increased amount of steel reinforcement in composite slabs can significantly enhance their fire resistance beyond a specified rating period. Adequate lap splices of steel reinforcement in the concrete slab were recommended to develop tensile membrane action at large vertical displacement and to provide a load path to the surrounding structure.

The fire performance of reinforced concrete slabs and their failure characteristics associated with the amount of steel reinforcement were further investigated by conducting furnace testing of small-scale floor specimens with simply supported slab edges. Lim and Wade [8] tested two-way concrete slabs subjected to an imposed gravity load of 3 kPa and ISO 834 [9] standard fire exposure. The 3.3 m × 4.3 m flat slab specimens varied with the steel reinforcement area ranging from 198 mm^2/m to 565 mm^2/m. This study showed that the specimen with high reinforcement ratio exhibited only the surface cracks while the slab with smaller reinforcement ratio showed full-depth cracks at the same fire exposure time. Bailey and Toh [10] tested 20 mm thick flat slabs with two different sizes (1.2 m × 1.2 m versus 1.8 m × 1.2 m) to verify the applicability of a simple design method used to predict the displacement of heated concrete slabs undergoing tensile membrane action. The slab specimens were reinforced with mild steel mesh providing a ductility ranging from 1 % to 10 % and with stainless steel with a ductility of 31 % to 56 %. The reinforcement area varied from 45 mm^2/m to 155 mm^2/m. The study showed that (1) the aspect ratio of the slab affected the location of the concrete fracture lines in the slab: rectangular slabs failed by transverse concrete fracture at mid panel, whereas the square slabs exhibited concrete fracture either along the transverse or longitudinal spans, (2) the larger reinforcement area helped to increase failure time at elevated temperatures, and (3) the slab including steel reinforcement with low ductility developed a sudden (brittle) failure mechanism. These small-scale tests demonstrated that the steel reinforcement scheme allowing tensile membrane action of the heated slabs played a significant role in preventing or delaying a collapse mechanism following the substantial reduction in flexural strength at high temperature.

A significant variation exists in steel reinforcement requirements for composite slabs with steel decking in current construction practice. Table 1 shows a summary of the minimum steel reinforcement prescribed in building design standards as well as that used in previous large-scale fire experiments which demonstrated superior fire resilience of composite floors exposed to structurally significant fires. In the United States (US), the Steel Deck Institute standard (ANSI/SDI C-2017) [11] specifies a minimum required shrinkage reinforcement ratio of 0.075 % for a composite floor slab with steel decking. The Underwriters Laboratories testing standard (UL 263) [12], essentially identical to the ASTM E119 standard [13], allows using a similar reinforcement area for standard furnace testing to determine a fire rating of small-scale composite floor or beam assemblies. The British standard, SCI-P56 [14], permitted a minimum slab reinforcement of 142 mm^2/m for the fire resistance design of composite floors with steel decking. The same amount of steel reinforcement was used in the Cardington test program. The post-Cardington large-scale experiments (e.g., FRACOF and COSSFIRE projects) used the reinforcement ratio designed using Bailey's method [3–5], ranging from 0.26 % to 0.33 %. The steel reinforcement ratio of composite slabs permitted in the US practice is considerably lower than that used in prescriptive or performance-based design of composite floors (incorporating tensile membrane action) used elsewhere. The floor integrity provision in the US fire testing standard tends to focus on the heat transfer aspect only (i.e., delaying the unexposed surface temperature by passive fire protection measures), not specifically accounting for the concrete damage associated with structural responses (i.e., excessive vertical displacements) of composite floors to fire. It is noteworthy that the fire resistance design in the US does not consider the slab reinforcement as a factor to determine fire resistance and is not always based on the displacement limit specified in the furnace testing standard.

Table 1. Steel reinforcement in concrete slabs specified in design standards and used in research.

Standard or Test Name	Reinforcement area	Reinforcement ratio*	Reinforcement details
ANSI/SDI C-2017 [11]		0.075 %	
SCI-P56 [14]	142 mm^2/m		6 mm mesh reinforcement at 200 mm spacing
Cardington Tests 3, 4, 7 [1, 2]	142 mm^2/m	0.20 %	6 mm mesh reinforcement at 200 mm spacing
FRACOF [6]	256 mm^2/m	0.26%	7 mm mesh reinforcement at 150 mm spacing
COSSFIRE [7]	256 mm^2/m	0.33%	7 mm mesh reinforcement at 150 mm spacing

*Computed as the ratio between the cross-sectional area of a steel wire to the cross-sectional area of the topping concrete above the fluted steel deck per unit slab width.

As alternatives to a prescriptive approach, the US building design standards (e.g., AISC 360 Appendix 4 [15], ASCE 7 Appendix E [16], and ASCE Manual of Practice 138 [17]) offer a variety of resources that allow engineers to adopt performance-based design of buildings in fire. However, numerical analyses used in performance-based design require validation against test data and experimental evidence of the extent of fire-induced structural damage during and after fire exposure. Previous studies mentioned above have provided useful insights into the capability of composite floors to activate membrane action in fire; however, the data and findings from those studies are more relevant to the European standard practice.

The National Institute of Standards and Technology (NIST) has launched a large-scale experimental campaign at the National Fire Research Laboratory (NFRL) to fill knowledge gaps in realistic fire-structure interaction and failure of composite floor systems. The expected outcome includes the technical data and experimental evidence necessary for benchmarking and validating predictive computational models and design tools used for performance-based design of structures in fire. Currently, the Phase II project is in progress, which involves a series of large enclosure fire experiments using the full-scale two-story steel building. In this experimental campaign, a variety of factors influencing the fire resilience of full-scale composite floor systems will be investigated, including the steel reinforcement used in composite slabs (concrete slabs with steel decking), passive fire protection scheme of steel floor framing, and structural layout (e.g., connection type, slab continuity, or floor plate geometry).

The first fire experiment (Test #1) was conducted on November 14th, 2019, to generate the baseline data for current US prescriptive approach applied to a full-scale building floor system and to compare with forthcoming experiments. Literature review, experimental design, measurement systems, and results of Test #1 are reported in Choe et al. [18]. An overview of Test #1 and key findings from this study are summarized in Sect. 1.2.

1.2. Composite Floor Test #1

The initial experiment, Test #1, investigated the structural performance and failures of the 6.1 m × 9.1 m composite floor system designed following the current US practice, incorporating prescriptive fireproofing insulation details to achieve the 2-hour fire-resistance rating and the minimum steel reinforcement (with a cross-sectional area per unit width, 60 mm^2/m) prescribed for shrinkage and temperature crack control of a composite slab (a concrete slab with fluted steel decking).

The full-scale two-story steel frame two bays by three bays in plan was used to mimic the realistic boundary conditions of composite floors when exposed to fire (Fig. 1). The fire test compartment (10 m × 6.9 m × 3.8 m) with the main opening (5.8 m × 1.5 m) on the exterior wall was situated in the south middle bay of the two-story test building. There was a 5.8 m × 0.3 m slit on the north wall designed for air intake only. Four natural gas burners (1 m × 1.5 m each in size and rated 16 MW total) distributed on the floor of the test compartment created standard fire exposure to the soffit of the composite floor in the test bay (Fig. 2). During fire exposure, the composite floor in the test bay was hydraulically loaded to 2.7 kPa which resulted in a total design gravity load of 5.2 kPa according to the ASCE 7 [16] load combination for fire conditions (1.2 × dead load + 0.5 × live load). The composite floors in the adjacent bays, which remained cool during fire loading, were loaded to 1.2 kPa (equivalent to 0.5 times live load) using water-filled drums. Over 300 data channels were used to characterize the fire testing conditions as well as thermal and structural responses of the two-story building to a test fire at a variety of locations.

(a) (b)

Fig. 1. (a) Compartment fire test in the south middle bay of the two-story building under 20 MW exhaust hood; (b) Composite floor soffit exposed to natural gas fueled compartment fire.

The natural gas fueled compartment fire produced the upper layer gas temperature (below the composite floor) closely following the temperature-time relationship used in standard fire testing. The peak gas temperature of 1060 °C was recorded when both the test fire and hydraulic loading was removed at 107 min. Temperatures of the protected steel beams in the test bay reached a peak value of 800 °C. The peak heat release rate and total heat energy was measured 10.8 MW and 63.5 GJ, respectively.

During fire, the heated composite floor (with imposed mechanical loads on top) continuously sagged, reaching the peak vertical displacement of 60 cm at 107 min. The 9.1 m long floor beams (W16×31) buckled at their ends due to large compressive forces induced by the restraint to thermal elongation. The exterior columns (W12×106) bent outward due to thermal expansion of the heated floor assembly, resulting in partial shear ruptures in some bolts connected to those columns.

Whereas temperatures of the protected steel beams were acceptable compared to the ASTM E119 [13] limiting temperatures, significant integrity failure (concrete cracks) occurred in the heated composite floor before attaining the specified fire rating period. Large concrete cracks appeared around the hogging moment region (next to the test-bay column gridline) less than 30 min into heating, and the mid-panel concrete cracks began to occur at 70 min, exposing the hot glowing steel deck beneath along the longitudinal centerline (Fig. 2).

The limited ductility of the heated composite slab was the primary cause of the integrity failure which might initiate fire spread above the compartment of fire origin and eventually lead to local collapse mechanisms during longer (uncontrolled) fires. The steel wire reinforcement (60 mm^2/m) embedded in the test floor slab ruptured in tension at critical locations as the thermally degraded composite floor sagged but before reaching the ASTM E119 displacement limit. The minimum steel reinforcement (60 mm^2/m) prescribed for concrete crack control in normal conditions and permitted in standard furnace testing may not be sufficient to maintain the integrity of a full-scale composite floor undergoing the 2-hour standard fire exposure.

Fig. 2. Still image showing top of the Test #1 composite floor developing slab breach at 106 min after burner ignition.

1.3. Scope and Objectives

This report presents the second experiment of the Phase II program (Test #2) conducted on March 10, 2021. This study is aimed to investigate the influence of the steel reinforcement on the structural performance of the full-scale composite test floor assembly subjected to combined mechanical and fire loading. The improvement in the fire resilience of the composite floor and failure characteristics associated with the slab reinforcement scheme are discussed.

The experimental measurements include:

- fire characteristics including heat release rates, gas temperatures, velocity flow of the openings, and heat fluxes from the natural gas fueled compartment fire,
- thermal (temperatures) and structural responses (displacements, forces, and strains) of the test building, and
- any noteworthy observations during the fire test and post-test inspections critical to understand the overall fire performance and failure modes of the test floor assembly.

This report offers the unique experimental results that provide insight into the effects of standard fire exposure in a real building structure and potential failure mechanisms of full-scale steel-concrete composite floor systems including steel frame connections and slab continuity. This technical information can be used to guide the development and validation of physics-based computational models of composite floor assemblies in fully developed fires as well as after fire is extinguished. This research effort also provides important steps toward the improvement of the current fire testing methods and performance-based design provisions for steel-framed buildings in fire.

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