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Fire Resilience in Steel-Concrete Structures Part I: Insights from Full-Scale Testing

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1. Introduction

The multi-year experimental research project is being conducted at the NIST National Fire Research Laboratory to study the behavior of full-scale composite floor systems exposed to large enclosure fires. The present test program is aimed to generate technical information and data essential for the development and validation of predictive tools that can be used for performance-based design and assessment for steel-framed buildings in structurally significant fires.

1.1. Background

Structural steel framing constitutes over 40 percent of the United States construction market for multi-story buildings, creating roughly 44000 new projects (valued at nearly $680 billion) between 2014 and 2019 (AISC 2020). The majority of steel-framed buildings typically require passive fire protection to meet the code-prescribed fire-resistance rating in the range of 1 hour to 3 hours. Given that an approximate cost of installing passive fire protection typically ranges from 12 % to 15 % of the overall construction cost (NFPA 2017), annual expenditure on passive fire protection for steel-framed buildings is estimated up to $20 billion. In particular, the steel composite floor construction, which is commonly used for spanning large open spaces, can incur high costs of passive fire protection because of a significant use of structural steel requiring fireproofing insulation (e.g., SFRM or intumescent paint).

For composite floor systems, the prescriptive compliance of passive fire protection is aimed to minimize the possibility of a fire that spreads beyond its compartment of origin and to provide means of occupant egress routes and safe paths for first responders. The process of prescriptive design is straightforward. The mandatory fire-resistance rating of a building is determined based on combination of several factors, such as occupancy and use, construction materials, building configurations (area and height), and the presence of active fire protection systems (smoke detectors, sprinklers, etc.), as specified in building codes, e.g., IBC (ICC 2018) or NFPA 5000 (NFPA 2021). In most cases, architects then choose an appropriate fireproofing scheme that has been qualified by the fire testing methods in accordance with ASTM E119 (2020) or standard calculation methods, e.g., ASCE 29 (2005).

The intent of standard fire testing is to provide a consensus-based method for evaluating the duration for which a single floor assembly maintains its structural integrity under prescribed furnace heating conditions. This testing method usually requires a test assembly that is representative of the structural details used in construction, however, the size and support conditions of a test assembly are limited by available furnaces in testing facilities. According to the ASTM E119 standard, the minimum required area of a test floor assembly placed on top of a furnace chamber is 16.7 m^2 with a minimum length of 3.7 m on each side. While subjected to furnace heating with a prescribed time-temperature relationship, a test assembly is required to resist its maximum load condition permitted in the national structural design standard. The fire-resistance rating of a test floor assembly, typically expressed in hours of the thermal endurance time, can be determined using the following criteria (AISC 2003):

- A test assembly fails to resist a maximum load as specified,
- A cotton waste on the unexposed (top) surface of a test floor is ignited,

- An average temperature of the unexposed surface of a test floor exceeds 139 °C above its initial temperature, or
- For test specimens employing steel structural members spaced more than 1.2 m on center, the temperature of the steel structural members shall not have exceeded 704 °C at any location during the classification period nor shall the average temperature recorded by four thermocouples at any section have exceeded 593 °C for a specified duration. The duration during which this average temperature shall not be exceeded varies depending on whether a restrained or unrestrained approval is sought. For specimens employing steel structural members spaced 1.2 m or less on centers, the single location temperature limit does not apply.

Fire-resistance rating values of various test assemblies detailed with commercial fireproofing materials are available through public databases (e.g., https://iq.ulprospector.com/) and manufacturer's websites. These values vary with concrete slab properties (including compressive strength, unit weight, and thickness of concrete), steel deck properties (including deck profile, thickness and finish coating of sheet steel, and attachment to steel beams), and the thickness of fireproofing materials applied to floor beams. However, the actual test results, such as thermal gradients developed within tested assemblies, temperature-dependent thermal properties of fireproofing materials, structural responses (forces, displacements, and failure modes) of tested assemblies, and the governing criterion used for termination of testing, are not required to be reported and mostly remain proprietary. More importantly, the fire-resistance rating itself seldom provides useful insight into the overall fire resilience of a building (as a whole system) exposed to uncontrolled fires which may be vastly different from prescribed furnace heating conditions.

With inherent limitations in prescriptive approaches, there has been renewed interest in development of performance-based approaches which can improve both fire resilience and cost effectiveness of building construction in the United States. Alternative engineering approaches have been established along with guidance and design references, e.g., Appendix 4 *Structural Design for Fire Conditions* of AISC 360 (AISC 2016) and the ASCE *Structural Fire Engineering* manual of practice (ASCE 2018). However, most of the suggested methods rely heavily on numerical models of assemblies or members limited in sizes or tested under idealized support conditions. Large knowledge gaps still exist including (1) temperature dependence of composite interactions between a concrete slab and steel floor beams used in long-span floor systems under realistic fire exposure and (2) the effects of thermal restraints from the surrounding structures and steel framing connections. This knowledge cannot be readily achieved by standard furnace testing of a single floor assembly limited by its small size and support conditions. Research-quality data from large-scale testing of structural systems (including connections) will be needed to quantify the complex structure-fire interaction and vulnerabilities (limit states) from realistic fires and to benchmark or validate computational models used for performance-based fire protection design of buildings.

1.2. Previous Fire Experiments

Over the last few decades, there have been active research efforts in Europe to better understand the fire resilience of steel-concrete composite floors (Bisby et al. 2013). Of particular interest for the present study are the experimental investigations on the full-scale composite floor assemblies with steel framing connections, especially those spanning in excess of 6 m.

The Cardington test program (British Steel 1999; Wald et al 2006) utilizing the eight-story steel framed building demonstrated membrane action of composite floors as the secondary load-carrying mechanism in fire and the possibility of eliminating fire protection of the secondary (filler) beams. These findings led to the development of simplified desktop design methods (Bailey 2000; 2001; 2003) accounting for tensile membrane action of composite floor assemblies at elevated temperatures. Both FRACOF (Zhao et al. 2008) and COSSFIRE projects (Zhao et al. 2011) further examined the benefit from Bailey's method by conducting standard fire tests on large-scale composite floor assemblies. Table 1-1 presents a summary of key features of the test floor assemblies used in those studies. A comparison of experimental features as well as important observations and conclusions from these studies are presented in the following subsections.

Table 1-1. Summary of experimental features used in previous fire experiments on composite floor systems

Reference	Test Name	Fire compartment	Test fire	Approx. test load	Topping concrete thickness (total slab thickness)	Steel mesh	Beam-to-column connection	Beam-to-beam connection
British Steel (1999)	Cardington Test 3	Corner bay 10 m x 7.6 m (Floor) 6.6 m x 1.8 m (Opening)	Wood cribs (45 kg/m^2)	5.5 kN/m^2	70 mm (130 mm)	142 mm^2/m	Flexible endplate	Fin plate (Shear tab)
British Steel (1999)	Cardington Test 4	Corner bay 9 m x 6 m (Floor)	Wood cribs (40 kg/m^2)	5.5 kN/m^2	70 mm (130 mm)	142 mm^2/m	Flexible endplate	Fin plate (Shear tab)
Wald et al. (2006)	Cardington Test 7	Edge bay 11 m x 7 m (Floor) 9 m x 1.3 m (Opening)	Wood cribs (40 kg/m^2)	6 kN/m^2	70 mm (130 mm)	142 mm^2/m	Flexible endplate	Fin plate (Shear tab)
Zhao et al. (2008)	FRACOF	Furnace 8.7 m x 6.7 m (Floor)	ISO 834 (2 hr)	5 kN/m^2	97 mm (155 mm)	256 mm^2/m	Flexible endplate (column flange) & Double angle web cleat (column web)	Double angle
Zhao et al. (2011)	COSSFIRE	Furnace 9 m by 6.7 m (Floor)	ISO 834 (2 hr)	4 kN/m^2	77 mm (135 mm)	256 mm^2/m	Flexible endplate (column flange) & Double angle web cleat (column web)	Double angle

1.2.1. Fire Compartment

The floor area of the fire compartments used in the Cardington tests varied from 54 m^2 to 77 m^2. Both Test 3 and Test 4 were conducted in the 9 m × 6 m corner bay of the test building on different floors, whereas Test 7 was situated in the edge bay enclosing the same size column grid. In Test 3, the compartment walls were constructed with non-load bearing CMU (Concrete Masonry Unit). In Test 4 and Test 7, the interior walls were replaced with steel stud partitions with fire-rated plasterboards. All three Cardington tests used a single opening (with an approximate area of 12 m^2) on the exterior wall. On the other hand, both FRACOF and COSSFIRE tests were conducted using a 9 m × 6.7 m furnace chamber that simulated standard fire conditions.

1.2.2. Test Floor Assembly

All tested floor specimens in Table 1 consisted of concrete slabs cast in-situ on light gauge steel decking with a trapezoidal profile, acting compositely with steel beams (weighing 40 kg/m to 51 kg/m) via headed stud anchors. The deck flute used in those studies was approximately 60 mm deep, whereas the depth of concrete topping (above the deck flute) varied from 70 mm to 97 mm. In the Cardington tests, anti-crack steel mesh with an area of 142 mm^2/m was used based on the British construction practice in 1990s. However, the area of steel mesh used in FRACOF and COSSFIRE was 256 mm^2/m, designed based on Bailey's method.

The primary beams were supported by steel columns using either flexible endplate or all bolted double angle connections. The ends of the secondary beam(s) had fin-plate connections to the primary beams. Among these five experiments, fire protection scheme (e.g., insulation type and thickness) of the primary beams and member connections varied. However, all columns were protected with SFRM, whereas the secondary beams left unprotected.

A number of sandbags were used to load the test assemblies during test fires. The total gravity load (including the self-weight of a test floor assembly) ranged from 4 kPa to 6 kPa. This load level provided the demand-to-capacity ratio of the secondary composite beam approximately equal to 0.5.

1.2.3. Fire Development

The Cardington test series employed wood cribs (40 kg/m^2 to 45 kg/m^2) as fuel to simulate a real compartment fire in typical office buildings. On the other hand, both FRACOF and COSSFIRE tests incorporated the furnace fire conditions simulating the ISO 834 temperature-time curve up to 2 hr.

The test fires used in these studies created the upper layer gas temperatures reaching near or beyond 1000 °C within the compartment enclosure or a furnace chamber. In the Cardington tests, however, the fire development was highly influenced by thermal boundary conditions of the compartment walls and opening schemes, resulting in dissimilar gas temperature-time relations among tests. The fire growth was much slower than that predicted using the EC parametric curve as outlined in the Annex of EC1-1-2 (2004). In Test 3 and Test 7, a peak value of the gas temperature reached to 900 °C and 1100 °C, respectively, at about 1 hr after ignition, followed by the decay stage that took another 1 hr. However, in Test 4, a flashover was not developed until 100 min due to the lack of oxygen within the compartment, thereby a window glazing system was manually removed for air intake. A peak value of the recorded gas temperature was 1050 °C at 102 min, but it sharply decreased afterward.

1.2.4. Specimen Response

The actual response of the heated floor assemblies varied by fire intensity and duration as well as the fire protection scheme of exposed steel. In all five experiments, temperatures of unprotected steel beams reached nearly 1000 °C. The maximum vertical displacement measured at the center of the floor assemblies was in the range of 27 cm (Test 4) to 120 cm (Test 7), equivalent to the ratio of $L/30$ to $L/8$ where L is the length of the secondary beam(s). Bare steel beams also exhibited local buckling toward the ends due to the restraint to thermal elongation. The beam-end connections exhibited minor damage except for the flexible endplates used in Test 7. Temperatures of these connections were in excess of 700 °C during fire.

Despite these high-temperature effects, the test assemblies in Table 1-1 did not reach the collapse mechanism. However, both the Cardington Test 7 and FRACOF test reported concrete cracks resulted from inadequate splice detailing of steel mesh mat. Temperatures of the top (unexposed) surface of the concrete slab, measured using discrete thermocouples away from locations of concrete cracks, did not exceed 140 °C during the heating phase. None of the tests reported the extent of damage in steel deck exposed to fire.

1.2.5. Conclusions from Previous Studies

The Cardington test series demonstrated that the fire performance of composite floor systems was markedly superior compared to that observed in standard fire tests on isolated composite beams with the simply supported boundary conditions. The aforementioned experiments showed that temperatures of exposed steel and deflections of floors exceeded the conventional limiting criteria specified in standard testing methods. Also, both FRACOF and COSSFIRE projects proved that the increased amount of steel reinforcement in composite slabs can significantly enhance their fire resistance for a longer duration of a fire. Adequate details of the steel reinforcement in concrete slabs in combination with robust end supports would be required for activating tensile membrane action in the composite floor assemblies enduring extremely high compartment temperatures (>1000 °C).

These large-scale experiments led to the development of simplified design tools that can be used for the optimized fire-resistance design of composite floor systems, e.g., TSLAB by SCI P288 (Newman et al. 2006), Slab Panel Method (SPM) by SCNZ (Clifton et al. 2010) and MACS+ (Vassart et al. 2014).

1.3. Research Motivation

To date, there is lack of data describing the actual fire performance of full-scale steel-concrete composite systems designed and constructed in compliance with the United States building codes and standards. The large-scale experiments discussed in Sect. 1.2 have provided useful insights into realistic fire performance of composite floor systems; however, the data and findings from those studies are more applicable to structures constructed following the European standard practice. In addition, none of these experimental studies accurately characterized fire loading in terms of *measured* heat energy (heat release rate) that would be essential for developing design-basis fires used for performance-based fire protection design. Furthermore, simple design tools exclude the influence of thermal restraints from the adjacent structures and connections as well as thermally induced buckling of steel members in estimating the load bearing capacity of composite floor systems in fire. Although computational modeling techniques have evolved, they still need to be validated against comprehensive test data with quantified uncertainty in measurements and qualitative evidence describing a full course of fire-induced structural damage during and after fire exposure.

Motivated by such research needs, NIST has proposed the experimental research project on full-scale structural steel frames with composite floor assemblies to measure fire behavior and structural failure modes under structurally significant fire conditions. The goal of this project is aligned with several recommendations from NIST's WTC Disaster Study