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Experimental and numerical evaluation of composite floor systems under fire conditions

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ABSTRACT

This paper presents novel experimental results and observations from three one-quarter scale tests on two-way concrete slabs supported by protected steel edge beams under fire conditions. The sizes of the protected secondary edge beams were varied to study the effect of beam stiffness on the fire behaviour of the assemblies. Test results showed that as the stiffness of the protected secondary edge beams increased, the slab central deflection decreased and failure of the slab occurred later. However, composite action between the edge beams and the concrete slab plays a key role in mobilising this beneficial effect. Once the composite slab-beam action is weakened by cracks in the slab over the main or secondary edge beams, the benefit associated with a greater stiffness of the edge beams is lost. Tensile membrane action was mobilised at a deflection equal to 0.9 to 1.0 of the slab thickness irrespective of the bending stiffness of the edge beams. The commencement of tensile membrane stage was marked by one of three indicators: (a) concrete cracks which formed a peripheral compressive ring in the slab; (b) horizontal in-plane displacements along the slab edges; and (c) horizontal and vertical displacements of four corner protected steel columns. The test results were used to validate a finite element model developed using Abaqus/Explicit. Good correlation between the predicted and experimental results was obtained.

1. Introduction

It has been experimentally observed that the ultimate load of composite slabs in steel-framed buildings under fire conditions is significantly greater compared to the load-carrying capacity predicted by the conventional yield-line theory. The increase in the ultimate load is due to the contribution of tensile membrane action (TMA) which develops in the composite slabs at large deflections. This beneficial effect allows secondary interior steel beams to be unprotected, providing savings of fire protection materials for steel-framed composite buildings.

The Cardington fire tests performed by the British Research Establishment and British Steel between 1995 and 2003 [1] triggered the first research wave on tensile membrane behaviour of composite slabs in fire. Numerous research works have been conducted and only a few key references are mentioned here [2–7]. Although these works have been very valuable in providing a great understanding of membrane behaviour of composite floors in fire, most of these studies focused on isolated concrete slabs, rather than on composite slab-beam systems.

Recently, there has been a renewed wave of interest in the membrane behaviour of integrated floor assemblies in fire, which consist of protected edge beams and supporting columns, unprotected interior beams, and a composite slab. Most of these tests demonstrated very good fire performance of floor assemblies which relied on TMA in the slab mobilised at large deformation stage. Zhao et al. [8] conducted a full scale test on a single composite floor slab panel, 6.66 m × 8.74 m, representative of a corner compartment. The slab panel, which consisted of protected edge beams with two-hour fire rating and two unprotected secondary beams, was tested under exposure to a two-hour ISO 834 standard fire. The fire resistance was over two hours. The floor system did not collapse although the failure was due to poor welding between two steel reinforcing meshes.

Zhang et al. [9] tested four 5.23 m × 3.72 m composite slabs subjected to ISO 834 standard fire. Two tests had one unprotected interior beam and another two without interior beams. The authors observed that no structural collapse was found and membrane action was mobilised to carry the applied load. They concluded that interior secondary beams were not needed to support the slab under fire conditions and could be left unprotected. However, in all their tests, the edge beams were outside the furnace and were not heated directly.

Wellman et al. [10] conducted three tests to study the behaviour of composite floor assemblies subjected to standard and non-standard fire conditions with uncontrolled or controlled cooling phase. The specimens were designed with two different connection configurations and two different fire protection scenarios (interior beams with or without fire protection). The authors observed that both protected connection types (shear tab and double angle) did not fail during the heating or cooling stage. They concluded that the interior secondary beams could be left unprotected provided that a better load-transfer mechanism

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from the secondary to primary beams is available, for example, by increasing the slab thickness.

Some studies on membrane behaviour of composite slabs incorporating cellular steel beams have also been conducted [11,12]. Nadjai et al. [11] conducted a large-scale natural compartment fire test on a 9.6 m × 15.6 m composite floor slab supported by long-span cellular beams. The tested slab was supported on a steel frame spanning 9 m by 15 m between four columns. All the columns and the edge beams were protected, while the interior cellular beams were unprotected. It is found that the reinforcement in the central region of the slab was under tensile force and a concrete compressive ring was formed around the perimeter of the slab. They concluded that the interior secondary beams can be left unprotected due to mobilisation of tensile membrane action.

Although previous studies offer valuable insight into the fire behaviour of composite slab-beam systems, there has not been any reported experimental study on the effect of stiffness of protected edge beams. In literature, there was only a numerical study on this issue. Lim [13] conducted a numerical study on the fire behaviour of the slab-beam systems with different sizes of supporting edge beams. He concluded that as the beam size decreased, failure of the slab occurred earlier with greater deflections. However, the positive effect of the beam size on the slab behaviour was only confirmed by numerical studies in which concrete cracking and crushing could not be accurately modelled.

To bridge this gap, a series of tests have been conducted at Nanyang Technological University, Singapore in 2012. This paper first presents the experimental behaviour of three one-quarter scale composite beam-slab floor systems in fire. The test results were then used to validate a numerical model developed in Abaqus/Explicit. The main parameter was the bending stiffness of protected secondary edge beams.

2. Test setup

2.1. Test specimens

Numerical studies [14] showed that in terms of the four geometric properties of the protected edge beams (steel grade, torsional rigidity GI_t, bending stiffness about major axis EI_y, bending stiffness about minor axis EI_z), only the bending stiffness about the major axis EI_z has significant effect on membrane behaviour of floor assemblies. Therefore, the bending stiffness about the major axis EI_z was chosen as the main parameter in this experiment.

The experiment consisted of three one-quarter scale composite beam-slab systems tested at elevated temperature, which were denoted as P215-M1099, P368-M1099 and P486-M1099. In this nomenclature, for example, P215-M1099 indicates a specimen which has 215 cm^4 as the second moment of area about the major axis of protected secondary edge beam (I_{yPSB}), and 1099 cm^4 as that of main edge beam (I_{yMB}). P215-M1099 was chosen as the control specimen. I_{yPSB} of P368-M1099 and P486-M1099 was respectively increased to 1.71 and 2.26 times of I_{yPSB} of P215-M1099. The protected main and unprotected interior secondary beams for these specimens were kept the same. The effect of two unprotected interior beams on tensile membrane behaviour of beam-slab systems has been investigated separately [15].

This experiment applied the fire protection strategy for members recommended in the SCI Publication P288 [16]. All the edge beams and columns were protected to a prescriptive fire-protection rating of 60 min. No fire-proofing material was applied to the interior beams and the slabs.

Fig. 1 shows a typical specimen with the slab 2.25 m long by 2.25 m wide and an outstand of 0.45 m around the four edges. Along each edge were five M24 bolts with half of these bolt lengths cast into the slabs, while the other half were attached to an in-plane restraint system shown in Fig. 2. The locations of these bolts were fixed by using 8 mm thick steel plates along the four slab edges. The purpose of these bolts was to simulate accurately the boundary conditions of interior slab

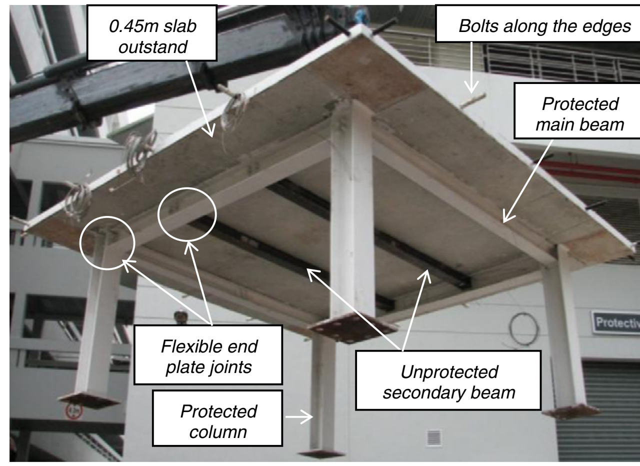

Fig. 1. Typical specimen.

panels. The interior slab panels should be rotationally restrained and could only have horizontal straight movement along the four edges as explained in Section 2.2.

The slab thickness was 57 mm, 58 mm, and 55 mm for P215-M1099, P368-M1099, and P486-M1099, respectively. Shrinkage reinforcing mesh with a grid size of 80 mm × 80 mm and a diameter of 3 mm (giving a reinforcement ratio of 0.16%) was placed within the slab, 25 mm from the top. The mesh was continuous across the whole slab with a yield strength of 689 MPa and an ultimate strength of 806 MPa. Ultimate strain of the mesh was 14.8%, and the elastic modulus was 203.4GPa. The specimens were cast using ready-mixed concrete with the aggregate size ranging from 5 to 10 mm. Six cylinders (150 mm in diameter and 300 mm long) were tested at 28 days after casting giving a mean compressive strength f_{cm} of 31.3 MPa, 32.9 MPa and 28.9 MPa for P215-M1099, P368-M1099 and P486-M1099, respectively.

All the selected steel beams were Class 1 sections according to EN 1993-1-1 [17]. Fabricated section was used for secondary beams when necessary. The beams were designed for full-shear composite action using 40 mm long, 13 mm diameter headed shear studs with a spacing of 80 mm to prevent failure due to shear. This was successful since there was no observed failure of shear studs. Flexible end plate joints were used for both beam-to-beam and beam-to-column connections. Both the beam-to-beam and beam-to-column connections were fire-protected. The protected columns were selected to be very stiff (UC 152x152x30) to avoid any instability failure.

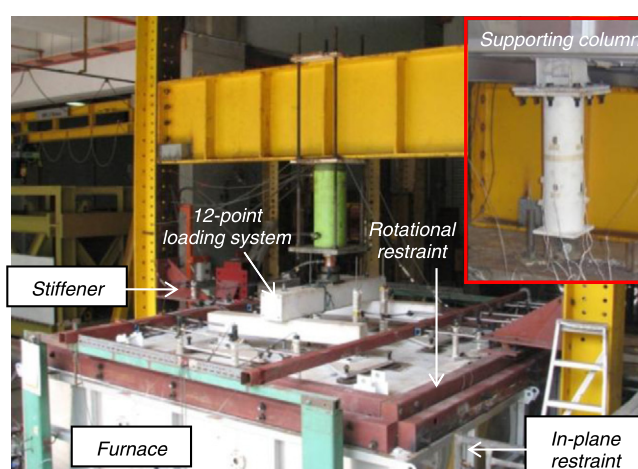

Fig. 2. Test setup.