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Behaviour of composite slab-beam systems at elevated temperatures: Experimental and numerical investigation

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ABSTRACT

This paper presents the experimental observations and results of three one-quarter scale composite slab-beam systems, 3.15 m by 3.15 m in plan, and tested in fire conditions. The tests aimed to examine the effects of unprotected interior secondary beams and edge rotational restraint on the behaviour of floor assemblies. The test results show that continuity of reinforcement in the slab over the supporting beams, and the presence of interior beams, can reduce the slab deflection and enhance its load-bearing capacity. Interior beams can be left unprotected without leading to a structural failure. The interior beams play a major role in helping the slab to move from biaxial bending stage to membrane behaviour, enabling the slab to mobilize higher tensile membrane forces. Rotational restraint along the protected edge beams induces intense stress concentration above these beams, resulting in more severe concrete crushing at the four corners and wide cracks over the edge beams. In addition to the experimental study, a numerical model using ABAQUS has been developed to simulate the tests. The numerical predictions agree well with the experimental results, showing that the proposed model is reliable. A shortcoming of the study is that the fire resistance performance of the specimens cannot be compared with those in practical design because a real furnace fire and small-scale fire tests were used due to limits of the furnace. However, the experimental results do provide basic information on the membrane behaviour in fire and also allow analytical methods and numerical models to be validated.

1. Introduction

Large-scale fire tests, as well as well-publicised accidental building fires over the past two decades, have shown that under fire conditions composite-steel-framed floor systems possess a significant load-bearing capacity, which can be well above that predicted by conventional yield line theory. It is now accepted that this enhanced capacity is due to tensile membrane action (TMA), which can be mobilized in the composite slabs at large displacements, irrespective of whether they are restrained or unrestrained horizontally.

A number of studies on tensile membrane behaviour of composite slabs in fire have been conducted, mainly from 1995 to 2003 [1–10], including experimental, numerical, analytical, and design-related research investigations. A design guidance document, SCI publication P288 [11], for steel-framed buildings using composite construction was subsequently developed and applied in the UK. This has allowed structural engineers to take advantage of TMA to minimize the fire protection to interior steel beams and thus to optimize the cost of fire protection. Although previous studies have been very valuable in developing a greater understanding of structural behaviour in fire, most of those from 1995 to 2003 only focused on isolated slab behaviour, rather than on the behaviour of connected floor assemblies.

Recognizing this shortcoming, there has been a recent interest in membrane behaviour of integrated floor assemblies. In 2008, a single composite floor slab panel with two unprotected secondary beams was tested in France [12] as part of the FRACOF project, under exposure to a 120-min ISO 834 standard fire. The main aim of the test was to assess the fire resistance of a full-scale partially protected floor against the SCI P288 design guidance. All the edge beams were fire-protected, but the two interior secondary beams and the composite slab itself were left unprotected. The results showed a fire resistance, according to the criterion “R” (structural capacity) of over 120 min. Also, to assess the suitability of the P288 design rules for use in Germany, Stadler et al. [13] conducted two medium-scale tests on composite beam-slab systems in fire with the aim of investigating the influence of interior

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supporting beams between two slab panels. They found that tensile membrane forces changed considerably when interior beams were present. Zhang et al. [14] conducted furnace tests on four 5.23 m × 3.72 m composite slabs under ISO 834 standard fire heating, with applied load ratios between 0.6 and 0.65. No structural collapse was seen in these tests. Their observation was that, due to the mobilization of TMA, secondary beams were not needed in supporting the slabs under fire conditions, and therefore these beams could be left unprotected. However, this was not confirmed by the results of a series of tests on composite floor assemblies under fire loading, presented in 2010 by Wellman et al. [15]. These were conducted as part of a study intended to consider the elimination of fire protection to interior secondary composite beams in the USA. Partial composite action was achieved in both the main and secondary beams by using headed shear studs. The failure of the edge and interior composite beams was defined as excessive deflection, or excessive deflection rate, according to BS 476 requirements. Based on BS 476 criteria, the observed failure mechanism of the tested specimens was identified as failure of the interior beams, followed by failure of the edge beams. Therefore, the conclusion of the study was not to recommend removal of fire protection from the interior beams of lightweight composite slabs in the context of current construction practice in the USA. This conclusion did not agree with the pre-mentioned tests. This was possibly because the slabs used in these tests were rather thick compared to the span, 101.6 mm depth over the shorter span of 2.13 m, leading to premature of the protected edge beams.

Some studies on membrane behaviour of composite slabs incorporating cellular steel beams have also been conducted [16,17]. Nadjai et al. [16] 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.

It can be seen from these previous research studies that some important aspects of the system behaviour, such as the effects of unprotected interior beams and of different boundary conditions, on the development of TMA, are still not clearly determined. Thus further research is required to address the above issues, and this needs to include carefully monitored experimental investigations.

This paper firstly describes an experimental investigation on three one-quarter-scale composite floor assemblies, tested under fire conditions. Specimens, including steel beams, four columns and a concrete slab, were totally enclosed in an electric furnace. The objectives were to study the effects of leaving interior beams unprotected, and of rotational edge-restraint, on the behaviour of composite floor assemblies in fire. A numerical model using ABAQUS/Explicit has also been developed to simulate the tests, and detailed numerical assessments have been conducted.

Although small-scale fire tests and using a real furnace fire due to the limit to the furnace can result in unrealistic temperature distributions in the beams and slabs, the experimental results do provide basic information on the membrane behaviour in fire. They also allow analytical methods and numerical models to be validated; in future work realistic temperature distributions, appropriate to full-scale slab-beam floor systems, can then be incorporated into the validated numerical models. On the other hand, because standard fire curves cannot be followed, the fire resistance performance of the specimens cannot be compared with those in practical design. This is a shortcoming of this study.

2. Experimental programme

2.1. Heating facility

An electric furnace, of length 3 m, width 3 m and height 0.75 m, was designed at Nanyang Technological University (NTU); the dimensions were dictated by space constraints within the fire laboratory. Due to limitations on the power supply the furnace could not simulate the ISO 834 standard fire curve. However, in initial trial tests conducted without a specimen, the furnace temperature was able to reach 1000 °C within 50 min, at a heating rate of about 20 °C/min. This temperature increase rate indicates that for actual specimens the heating rate should be within the practical range (5 °C/min to 20 °C/min) specified for steel sections by BS 5950-8 [18].

2.2. Design of test specimens

The dimensions of the specimens were in turn limited by those of the furnace. Thus the slab dimensions were scaled down to one-quarter of a prototype floor which was designed for gravity loading at ULS in accordance with EN 1993-1-1 [19] and EN 1994-1-1 [20]. The other parameters, such as beam size, reinforcement ratio, and the ratio of flexural stiffness of the main and secondary beams to that of the slab, were selected so as to closely replicate the relationships typically present in conventional design of composite floors.

The three specimens were denoted as S1, S2-FR-IB, and S3-FR. In this nomenclature FR indicates a rotationally restrained system, while IB indicates the presence of interior beams. Specimens S1 and S3-FR were designed without interior beams, while S2-FR-IB (denoted as S2 in a previous conference paper [21]) had two interior beams. The dimensions of all specimens were 2.25 m long by 2.25 m wide, giving an aspect ratio of 1.0. To simulate interior slab panels, all specimens were designed with a 0.45 m outstand beyond the edge beams in both directions, as shown in Fig. 1. In this figure, the notation MB, PSB, and USB denotes a protected main beam, a protected secondary beam, and an unprotected secondary (interior) beam, respectively.

The target thickness h_s of the slabs was 55 mm. Shrinkage reinforcement 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 about 38 mm below the slab top surface. This 0.16% reinforcement ratio is well within the allowable range specified in EN 1994-1-1 (0.2% for un-propped construction and 0.4% for propped construction). The mesh was continuous across the whole slab, without any laps. The specimens were cast using ready-mixed concrete, with aggregate size ranging from 5 to 10 mm. Specimens S1 and S2-FR-IB were cast from a single concrete batch, while S3-FR was cast from a separate batch. Thus the mean compressive strengths f_{cm} of the two batches, determined by six cylinder tests 28 days after casting for each batch, differ slightly. Table 1 summarises the properties of the concrete slabs.

Because of the 1:4 scaling there was no standard steel decking suitable for the slabs. To protect the heating elements from concrete spalling, the slabs were cast on a 2.0 mm thick steel sheet with small pre-drilled holes. The contribution of this decking to the slab's load-bearing capacity could be ignored, since the unprotected sheet would de-bond from the concrete slab, as observed in previous studies.

All the beams chosen were classified as Class 1 sections according to EN 1993-1-1 [19]. The use of fabricated sections for all secondary beams was necessary, since there was no Universal Beam section suitable for the scaling required. Full-shear composite action between the slab and the downstand beams was achieved