Journal of Constructional Steel Research 129 (2017) 28–41

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Behaviour of composite floors with different sizes of edge beams in fire

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ARTICLE INFO

Article history:
Received 19 June 2016
Received in revised form 22 October 2016
Accepted 26 October 2016
Available online 5 November 2016

Keywords:
Tensile membrane action
Steel
Composite
Floor assemblies
Bending stiffness
Fire

ABSTRACT

Novel experimental results and extensive numerical studies on three one-quarter scale composite floor assemblies tested in fire are presented. The purpose is to investigate the effect of bending stiffness of protected edge beams on the fire behaviour of the assemblies. The focus of the paper is on the behaviour of interior panels with both rotational and inplane restraints along the four edges. Test results showed that tensile membrane action was mobilised at a deflection equal to about 1.0 of the slab thickness irrespective of the bending stiffness of the edge beams. An increase of the edge beam bending stiffness could help to reduce the slab deflection initially. However, as temperature increased cracks in the slab over the protected main or secondary edge beams developed, the composite slab-beam action was weakened and the benefit associated with a greater stiffness of the edge beams was lost. Subsequent part of the paper describes the distribution and development of membrane stresses in the slab and the steel beams in fire. It is noteworthy that due to composite action of protected edge beams and slab, the neutral axis across a section rises and falls within the steel web during the fire duration. However, at the slab centre above the unprotected intermediate secondary beams, no clear tensile region can be found.

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1. Introduction

The development of membrane forces in a slab at large deformation significantly enhances the load-bearing capacity of the slab above the conventional yield-line capacity. This inherent load-bearing capacity is known as tensile membrane action, which can be mobilised in steel beam – composite slab floor systems at large deformation under fire conditions. Undoubtedly, the significant contribution to the fundamental understanding of tensile membrane action came from the full-scale Cardington fire test [1]. Subsequently, extensive studies on tensile membrane action have been conducted [2–5]. The concept has also been adopted and applied in the UK practice [6].

Recently, a number of fire tests on integrated floor assemblies have been conducted to study tensile membrane behaviour in fire [7–10]. Those fire tests were necessary to understand interaction between structural components, and had provided a better understanding on the matter.

It is recognized that there are no experimental tests on the effect of stiffness of protected edge beams on the tensile membrane stage in fire, except one numerical study [11]. The authors therefore, conducted an experimental study to investigate the effect of stiffness of protected edge beams on the membrane behaviour of composite floor assemblies in fire. The effect of stiffness of protected secondary edge beams had been presented in Nguyen et al. [10]. In this paper, the effect of stiffness of protected main beams and an in-depth numerical investigation are presented.

2. Test arrangement

2.1. Test specimens

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 250 mm long M24 bolts with half of these bolt lengths cast into the slabs, while the other half were attached to an in-plane restraint system described in Fig. 2. The purpose of these bolts was to simulate accurately the boundary conditions of interior slab panels. The interior slab panels should be rotationally restrained and should only have horizontal straight movement along the four edges as explained in Section 2.2.

This test series included three one-quarter scale beam-slab assemblies, which were denoted as P215-M1099, P215-M1356 and P215-M2110. 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 protected main edge beam (I_{yMB}). P215-M1099 was chosen as the control specimen. I_{yMB} of P215-M1356 and P215-M2110 were respectively increased to 1.23 and 1.92 times that of P215-M1099. The protected edge and unprotected interior secondary beams were similar for all specimens. The effect of two unprotected interior beams on

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http://dx.doi.org/10.1016/j.jcsr.2016.10.018
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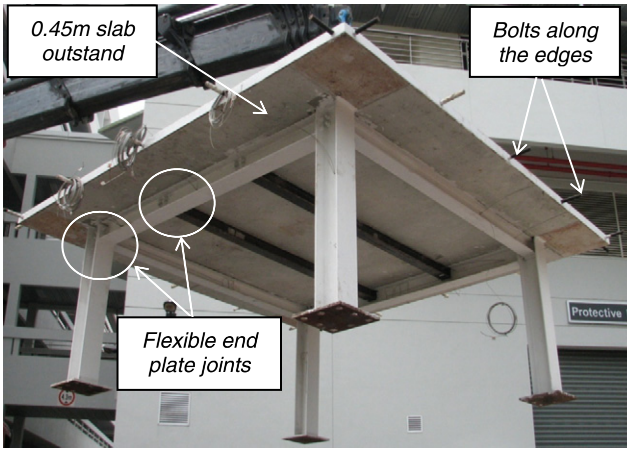

Fig. 1. Typical specimen.

tensile membrane behaviour of beam-slab systems had been investigated separately [10].

All the edge beams and columns were protected to a prescriptive fire-protection rating of 60 min using the fire protection strategy for members in the SCI Publication P288 [6]. No fire-proofing material was applied to the interior beams and the underside of the profile decking.

The slab thickness was 57 mm, 58 mm, and 59 mm for P215-M1099, P215-M1356, and P215-M2110, respectively. The actual thickness of the specimens slightly differed from the design value of 55 mm due to casting error. Shrinkage reinforcing mesh with a grid size of 80 × 80 mm and a diameter of 3 mm (reinforcement ratio of 0.16%) was placed in the middle of the slab. The mesh had yield strength of 689 MPa, ultimate strength of 806 MPa, ultimate strain of 14.8%, and elastic modulus of 203.4 GPa. The specimens were cast using ready-mixed chipping concrete with aggregate size ranging from 5 to 10 mm. Six cylinders of 150 mm diameter and 300 mm long were tested at 28 days giving a mean compressive strength f_{cm} of 31.3 MPa, 32.9 MPa and 28.9 MPa for P215-M1099, P215-M1356, and P215-M2110, respectively.

All the steel beams were Class 1 sections according to EN 1993-1-1 [12]. 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. Beam-to-beam and beam-to-column connections were pinned connections with flexible end plate joints, and fully fire-protected. The protected columns were selected to be very stiff (UC 152 × 152 × 30) to avoid any instability failure.

Four tensile coupons tests for each type of I-section used were conducted at ambient temperature, two from the web and two from the flanges. The material properties at elevated temperatures were assumed to vary according to EN 1994-1-2 [13]. Table 1 summarises the average results from the tensile tests and measured geometrical properties of the protected main beams (MB), protected secondary beams (PSB), and unprotected secondary beams (USB). All specimens had two interior USB consisting of fabricated I-sections of 80 × 80 × 17.3 kg/m.

2.2. Test setup

2.2.1. Test rig

An electric furnace of dimensions 3 m long by 3 m wide by 0.75 m high was setup. The furnace could not simulate the ISO 834 fire curve due to limitation of power supply. In the initial trial tests, a heating rate of about 20 °C/min could be achieved. This value was within the practical heating rate (5 to 20 °C/min) for steel sections as prescribed in BS 5950-8 [14].

The slab was placed on top of the furnace with the supporting beams totally enclosed within the furnace. The beam-slab system was supported by four protected I-section columns, which were rigidly connected to four protected circular columns. The circular columns were located outside the furnace, and were connected to the strong floor by hinged connections allowing the specimen to sway horizontally without any restraint.

To simulate uniformly distributed load, a 12 point loading system with 12 points in contact with the slab through M24 bolts was used. The system consisted of three rectangular hollow section (RHS) beams and four triangular steel plates. When the slab deformed, verticality of the loading system was ensured by the ball-and-socket joints placed in between the steel plates and RHS beams.

The specimens were set up with two restraint beam systems (Fig. 2), rotational and in-plane restraint systems. The rotational restraint system consisted of four 160 × 100 × 6 RHS beams placed on top of the specimen and fixed to the reaction frame. The 'so-called' in-plane restraint system, including another set of four 160 × 100 × 6 RHS beams, was directly fixed to the four slab edges via five M24 bolts along each edge at a spacing of 750 mm (Fig. 1).

These two systems aimed to simulate accurately the boundary conditions of interior slab panels. The in-plane restraint system allowed the slab edges to translate inwards or outwards in straight edges, while the rotational restraint system applied flexural restraint on the slab edges. It should be noted that that there was a 20 mm gap between the in-plane restraint system and the furnace walls to avoid transferring the load to the latter.

In this experiment, the authors aimed to model accurately structural response of an interior slab panel in the common fire scenario where a fire spreads throughout the whole soffit of the floor. In this scenario, the heated slab would initially move outwards due to thermal expansion. It then moves inwards resulting from tensile membrane action mobilised at large deflections. However, the common boundary between any two interior slab panels must translate in straight edges to ensure displacement compatibility. Therefore, in this case the slab can only move inplane outwards and then inwards in straight edges.

Due to the two restraint beam systems, all the specimens can be considered as interior slab panels which are restrained rotationally. Besides, the slab edges will translate in straight lines. Test results shown in Section 3 indicate that this objective was indeed achieved.

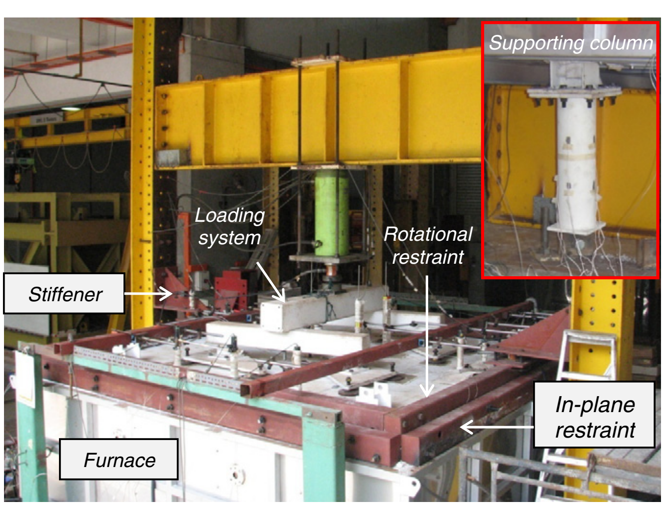

Fig. 2. Test setup.

2.2.2. Instrumentation

Temperatures and displacements of the beams and the slab were measured by K-type thermocouples and linear variable differential transducers (LVDT). Temperature of the slab was measured at

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