EFFECT OF UNPROTECTED INTERIOR BEAMS ON
Membrane Behaviour of Composite Floor Systems in Fire. I: Experimental Investigation

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Abstract

A number of previous studies on tensile membrane action have been conducted and they are very valuable towards understanding the behaviour of isolated slabs as well as of floor assemblies. However, the role of unprotected interior beams in the development of TMA still has not clearly determined. This paper presents an experimental study on the effect of unprotected interior beams on the behaviour of composite floor assemblies in fire. The experimental observations and results of two one-fourth scale composite slab-beam systems, 3.15 m by 3.15 m in plan, subjected to transient-heating test are presented.

The test results show that the presence of interior beams can reduce the slab deflection and greatly enhance the slab load-bearing capacity. The interior beams have a major role in helping the slab in passing through the 'transition' stage, and thus the slab can mobilize more tensile membrane forces. Without the interior beams, the compressive ring failure may occur resulting in a little contribution from TMA in the slab load-bearing capacity.

Keywords: tensile membrane action, slab-beam systems, composite slabs, fire

INTRODUCTION

Composite slabs, which are commonly used in steel-framed buildings, have shown very good load-bearing capacities under fire conditions because of the mobilisation of tensile membrane action at large-deflection stage. Interior secondary beams can be left unprotected in fire without affecting the stability of the slabs. Recent years, interest in the tensile membrane behaviour of the overall floor assemblies in fire has increased (Vassart et al., 2010; Zhao and Roosefid, 2010; Stadler et al., 2011; Wellman et al., 2011). These studies are very valuable towards understanding the membrane behaviour of the floor assemblies. To investigate the influence of interior supporting beams between two slab panels, Stadler *et al.* (2011) conducted two medium-scale tests on composite beam-slab systems in fire. They found that tensile membrane forces changed considerably when the interior beams were taken into account. However, more research is still needed on the effect of unprotected interior beams on the development of tensile membrane action.

Therefore, part of a research project conducted in Singapore aims to investigate the effect of unprotected interior beams on membrane behaviour of the column-beam-slab systems in fire. This paper presents the test results and observations from two specimens, namely, one with two unprotected interior beams and one without any interior beams at all.

1 TEST ARRANGMENT

1.1 Specimen Design

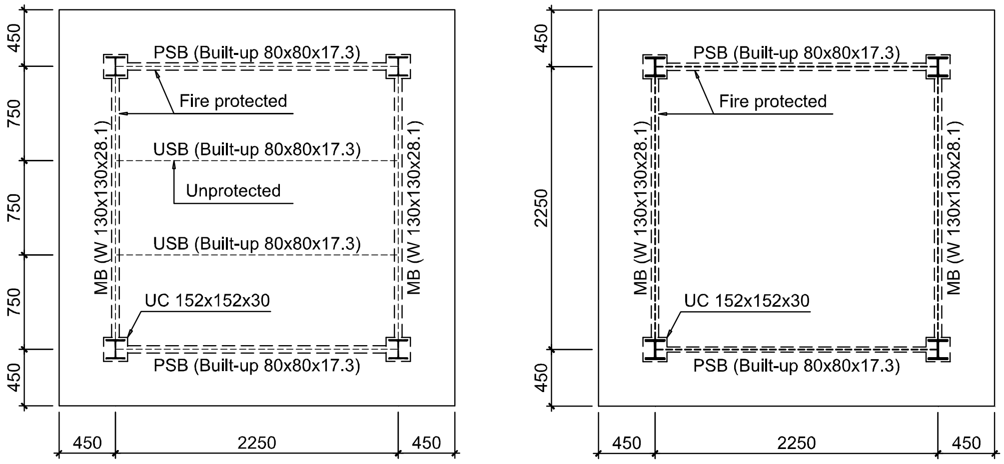
The dimensions of two specimens were 2.25m long by 2.25m wide, giving an aspect ratio of 1.0. To simulate interior slab panels, the specimens were designed with a 0.45m outstand beyond the edge beams in both directions. The specimens were denoted S2-FR-IB and S3-FR. Specimen S3-FR were designed without interior beams (IB), while S2-FR-IB (denoted as S2 in a previous conference paper (Nguyen and Tan, 2012)) had two unprotected interior beams as shown in Fig. 1. In this figure, the notation MB, PSB, and USB denote the protected main beam, protected secondary beam, and unprotected secondary (interior) beam, respectively. The concrete slabs were supported by I-beams and four I-section steel columns. All the edge beams were protected with intumescent coating to a prescriptive fire-protection rating of 60 minutes.

Material and geometrical properties of the I-section steel beams are given in Tab. 1. The beams were designed for full-shear composite action using 40mm long, 13mm diameter headed shear studs at a spacing of 80mm to avoid premature failure at the studs. A common type of steel joints, i.e. flexible end plates, was used for beam-to-beam and beam-to-column connections.

Tab. 1 Properties of I-beams

Specimen		Depth	Width	Thickness		Yield stress	Ultimate stress	Elastic modulus
		h (mm)	b_f (mm)	Web t_w (mm)	Flange t_f (mm)	f_y (MPa)	f_u (MPa)	E_s (MPa)
S2-FR-IB	MB	131	128	6.96	10.77	302	437	197500
	PSB & USB	80	80	9.01	9.14	435	533	206900
S3-FR	MB	131	128	6.97	11.03	307	462	211364
	PSB & USB	80	80	10.26	10.02	467	588	210645

The concrete slab thickness was 55mm and 58mm for S2-FR-IB and S3-FR, respectively. Shrinkage reinforcement mesh with a grid size of 80mm x 80mm and a diameter of 3mm was placed within the slabs and 18mm from the top. The mesh of S2-FR-IB had a yield strength of 543MPa and a ultimate strength of 771MPa, while the corresponding values of S3-FR were 648MPa and 806MPa. The characteristic cylinder strengths of concrete were 36.3MPa and 31.3MPa for S2-FR-IB and S3-FR, respectively.



a) S2-FR-IB b) S3-FR

Fig. 1 Structural layout of the specimens

1.2 Test Setup

The test setup is shown in Fig. 2. The concentrated force from a 50-ton hydraulic jack was distributed equally to twelve-point loads by means of a loading system designed to simulate uniformly distributed loads. Slabs S2-FR-IB and S3-FR are considered as rotationally restrained by the additional beam system on top of the outstand part which were fixed to the reaction frame via two plate stiffeners.

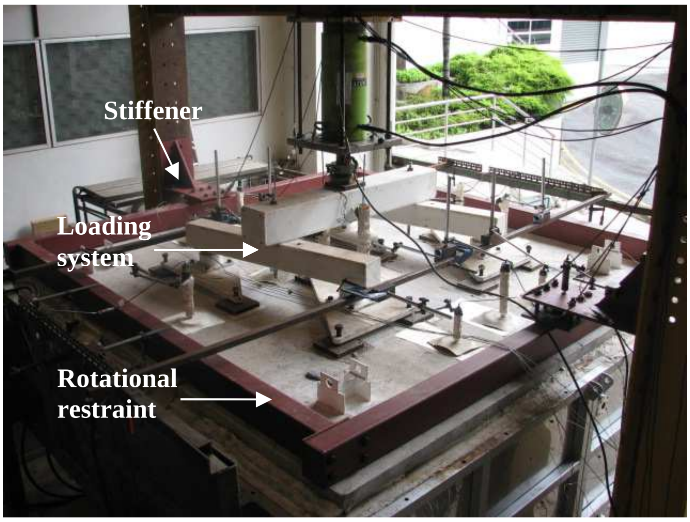


Fig. 2 Test setup

Fig. 3 Supporting columns

The edge and interior beams, which were totally enclosed inside the furnace, were able to deform freely. The specimens were connected to four supporting circular columns which were located outside the furnace and connected to the strong floor by pinned connections (Fig. 3). These pin-ended columns allow the specimens to move horizontally without any degree of restraint.

An electric furnace, of length 3m, width 3m and height 0.75m, was used to simulate fire conditions. Because of limitations on the power supply, the furnace could not simulate the ISO 834 standard fire curve. However, the furnace temperature could reach 1000^{o}C within 50min, a heating rate of about 20^{o}C/min which is within the practical range stipulated by BS 5950-8 for steel sections.

Transient-state heating was applied. The specimens were first loaded to a value of 15.8kN/m^2, corresponding to a load ratio of 0.43 for S2-FR-IB, and 1.97 for S3-FR. The furnace temperature was then increased while the load was manually maintained constant. After failure had been identified, the test was ended.

Linear variable differential transducers (LVDT) were used to measure the vertical displacements of the slabs and beams. Temperatures at various locations of the slab and beams were captured with 21 K-type thermocouples. The furnace air temperature was also recorded by four thermocouples.

The load from the hydraulic jack was measured by a 300-kN load cell which was placed between the jack and the loading system.

2 TEST RESULTS AND OBSERVATIONS

2.1 Slab Deflection

Fig. 4 shows the relationships between the mid-span vertical deflections and temperature, plotted against time, together with the corresponding failure points of the slabs. ‘Failure’ was considered to have occurred when there was a significant drop in the mechanical resistance, and the hydraulic jack could no longer maintain the load level (violating criterion “R”). S2-FR-IB failed at a deflection of 177mm when the mesh temperature had reached 512^{o}C, while S3 failed earlier at a deflection of 115mm when the mesh temperature was only 150^{o}C.

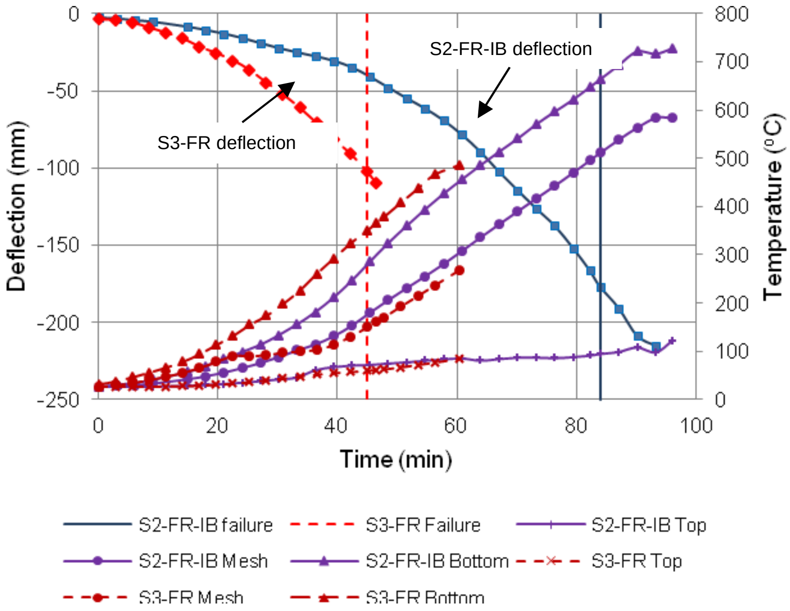


Fig. 4 Comparisons of temperatures and vertical deflection of the slabs

2.2 Behaviour of Edge Beams

Fig. 5 shows a comparison of the temperature development at the beam bottom flange and the vertical deflection against time. It can be seen that the temperature development of the beams was very close in both tests. Therefore the differences in the beam behaviour, if any, were definitely not caused by thermal effects. The limiting target temperature at 650°C of 60min for the edge beams was also observed.

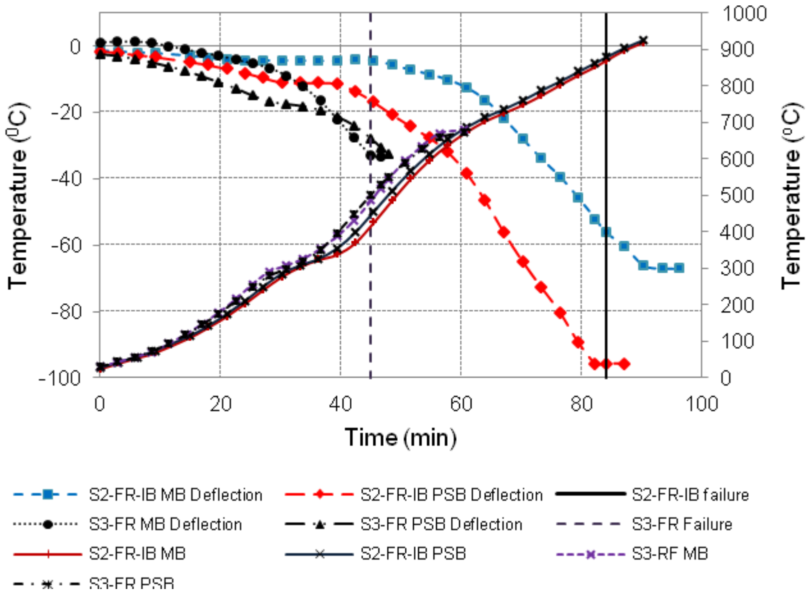


Fig. 5 Comparisons of temperatures and vertical deflection of the edge beams

At failure, the protected secondary beam (PSB) and the main beam (MB) of S2-FR-IB experienced very large deflections, 96mm and 56mm, respectively. The corresponding values of S3-FR were only 28mm and 33mm for PSB and MB, respectively. However, in S3-FR the recorded values for the main beam were not accurate. This was because severe cracks appeared at a very early stage (after only 20min of heating), directly above the main beams, as shown in Fig. 7. Thus, composite action between the main beams and the slab could not be maintained, leading to inaccurate measurement of the beam deflection. It should be noted that the beam deflection was measured from the part of the concrete slab which remained intact and directly above the beams.

After cooling, it was observed that local buckling of the beam flanges had not occurred. This is due to discontinuous nature of the specimens, allowing the beams to expand to some extent through the flexible end plate connections and overall expansion of the slab system.

2.3 Failure modes

Fig. 6 Crack pattern of S2-FR-IB

Fig. 7 Crack pattern of S3-FR

In S2-FR-IB, the compression ring formed after 50min of heating. The test ended when fracture of reinforcement occurred and full-depth cracks appeared close to the edge beams, as shown in Fig. 6.

In S3-FR, the compression ring formed after 28min of heating with the appearance of curved cracks at the four corners (Fig. 7). However, at 45min three full depth cracks appeared suddenly, one at the slab corner near the column, and two above the main beams. These cracks led to ‘brittle’ failure of the compression ring and caused ‘run-away’ failure in the slab.

In conclusions both of the slabs did not fail globally, but they lost their integrity and load bearing capacities (criteria “E” and “R”).

3 DISCUSSION

In S2-FR-IB test, after 50min of heating, the compression ring began to form at a mesh temperature of 200^{o}C. The corresponding deflection was 52mm, 0.95 of the slab depth. In S3-FR test, after 30min of heating, the compression ring was observed to begin to form when the mesh temperature had reached about 100^{o}C, corresponding to a deflection of 52mm, equal to 0.95 of the depth. It can be concluded that that S2-FR-IB, which included interior beams, entered the tensile membrane action stage later than S3-FR, because the unprotected secondary beams enhanced the slab capacity during the bending stage. On the other hand, the compression ring formed at the slab deflection equal to 0.95 of the slab thickness, irrespective of the presence of interior beams.

Fig. 4 indicates clearly that S3-FR experienced larger deflection than S2-FR-IB. At failure S2-FR-IB had a greater enhancement factor, of 2.55 compared to 1.54 for S3-FR. This enhancement is defined in this paper as the ratio of the test failure load to the conventional yield-line failure load at the same mesh temperature. It is obvious that the presence of interior beams significantly reduces the slab deflection and enhances the load-bearing capacity of the slab.

As can be seen in Figs. 6 & 7, S2-FR-IB failed because of reinforcement fracture in the vicinity of edge beams which led to full-depth cracks, while S3-FR failed because of ‘brittle’ failure of compression ring. Therefore it can be concluded that the interior beams have a major role in helping the slab to transit smoothly from biaxial bending to membrane behaviour. Without the interior beams, failure of compression ring may occur, resulting in less contribution from tensile membrane action in the load-bearing capacity of the slab.

With regard to temperature distribution, the presence of interior beams did not have any effect on the temperature distributions of the edge beams as shown in Fig. 5, but they had effect on their deflection profiles. At similar temperatures, the protected secondary beams of S3-FR had greater deflection than those in S2-FR-IB, because of the difference in load path from the slabs to the beams. During the initial heating stage, in S3-FR load was transferred directly to the protected edge beams, while in S2-FR-IB the load was transferred via unprotected interior beams to the edge beams.

4 CONCLUSIONS

This paper presents the experimental results and observations of two one-quarter scale composite floor systems tested in fire, aiming to define the effect of interior beams on the membrane behaviour of the systems. The results show that the presence of interior beams greatly enhances the load-bearing capacity of the slab. Without interior beams, the slab may experience ‘brittle’ failure of the compression ring and caused ‘run-away’ failure in the slab.

This work is part of an on-going research project which shall facilitate the use of membrane action for fire design of composite slabs in Singapore.

5 ACKNOWLEGEMENT

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REFERENCES

Nguyen, T. T. and K. H. Tan, Testing of Composite Slab-beam Systems at Elevated Temperatures, 7th International Conference on Structures in Fire (SiF), Zurich, Switzerland, 2012.

Stadler, M., M. Mensinger, et al., Munich Fire Tests on Membrane Action of Composite Slabs in Fire - Test Results and Recent Findings, Application of Structural Fire Engineering, Prague, Czech Republic, 2011.

Vassart, O., C. G. Bailey, et al. (2010). Large-scale fire test of unprotected cellular beam acting in membrane action. 6th International Conference on Structures in Fire, SiF'10, June 2, 2010 - June 4, 2010, East Lansing, MI, United states, DEStech Publications Inc.

Wellman, E., A. Varma, et al., Experimental Evaluation of Thin Composite Floor Assemblies under Fire Loading. Journal of Structural EngineeringVol 137, N0. 9 (2011), 1002-1012, 2011.

Zhao, B. and M. Roosefid (2010). Experimental and numerical investigations of steel and concrete composite floors subjected to ISO fire condition. 6th International Conference on Structures in Fire, SiF'10, June 2, 2010 - June 4, 2010, East Lansing, MI, United states, DEStech Publications Inc.