Fire Safety Journal 89 (2017) 63–76

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Experimental investigation on thermal and mechanical behaviour of composite floors exposed to standard fire

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ARTICLE INFO

Keywords:
Fire resistance
Experimental investigation
Composite floor
Unprotected secondary beam
Direction of rib
Location of reinforcement
EC4

ABSTRACT

This paper presents experimental investigations on the thermal and mechanical behavior of composite floors subjected to ISO standard fire. Four 5.2 m×3.7 m composite slabs are tested with different combinations of the presence of one unprotected secondary beam, direction of ribs, and location of the reinforcement. The experimental results show that the highest temperature in the reinforcements occurs during the cooling phase (30–50 °C increment after 10-min cooling). The temperature at the unexposed side of the slabs is below 100 °C up to 100-min heating, compared to the predicted fire resistance close to 90 mins from EC4. For the slabs without secondary beams, the cracks first occur around the boundaries of the slab, while for the slabs supported by one unprotected secondary beam, concrete cracks first occur on the top of the slab above the beam due to the negative bending moment, and later on develop around boundaries. Debonding is observed between the steel deck and concrete slab. The secondary beam significantly impacts the deformation shape of tested slabs. Although a large deflection, 1/20 of the span length, is reached in the tests, the composite slabs can still provide sufficient load-bearing capacity due to membrane action. The occurrence of tensile membrane action is confirmed by the measured tensile stress in the reinforcement and compressive stress in the concrete. A comparison between measured and predicted fire resistance of the slabs indicates that EC4 calculations might be used for the composite slabs beyond the specified geometry limit, and the prediction is conservative.

1. Introduction

Composite floor systems are commonly used in modern steel-framed buildings. They consist of steel beams, steel decks, concrete slabs, shear studs and reinforcement, as shown in Fig. 1. The composite action between the steel beams and concrete slabs is achieved by embedded shear studs. In the composite floor systems, the steel deck can be taken as the bottom reinforcement when calculating the load resistance at ambient temperature. In this way, the concrete can be barely reinforced by a light anti-crack rebar or steel mesh. Another advantage of composite slabs is that they allow to save construction time since the steel deck is a permanent formwork. However, the economy of composite floor systems is challenged by prescriptive fire-resistant design provisions in the current building codes, which require fire protection of the steel secondary beam. According to the observations in the large-scaled fire tests and in the real building fires, it is found that the composite slab systems can bear the dead and live load during the fire by "membrane action" mechanism, in which a "tensile membrane" is formed at the center of the slab, and is supported by a "compressive ring" at the boundary of the slab. Therefore, it is possible to remove the fire protection on the secondary beams due to the enhancement of the fire resistance by the membrane action.

Many experimental studies have been conducted to investigate the performance of composite floor systems in fire and the influencing factors, as shown in Table 1. In 1989, an ECSC research project was initiated at TNO (Netherland), in which 25 tests were performed to study the thermal and structural behavior of composite slabs [15,6]. Twelve tests on two-dimensional thermal responses showed that the geometry of the profiled steel deck greatly influence the temperature distribution in the composite slab. Ten full-scale tests were performed on simply supported, cantilever, and continuous slabs with a span of 3.2 m and different reinforcement ratios. The results showed that the failure of composite slabs was controlled by the rupture of the reinforcement. A low reinforcement ratio (typically 0.18%) led to an early failure due to the insufficient bending capacity.

Motivated by the Broadgate Phase 8 fire and Churchill Plaza fire occurred in UK in the early 1990s a total of 7 tests (Tests 1–6 in 1996 and Test 7 in 2003) were carried out on a full-scale eight-story steel-

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http://dx.doi.org/10.1016/j.firesaf.2017.02.009
Received 20 August 2015; Received in revised form 21 February 2017; Accepted 26 February 2017
0379-7112/

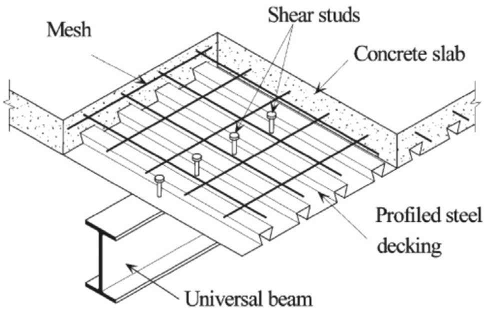

Fig. 1. Typical composite floor systems [3].

framed building at Cardington [1,18]. Different test configurations, such as restrained beams, plane frames and corner compartments at different locations of the building, were tested, and all the secondary beams were unprotected. The highest fire temperature in the tests exceeded 1000 °C. The composite floors sustained the load without any collapse even if its deflection reached 1/20 span length. The membrane action in the composite floor played an important role in the survival of the frame. Extensive computer models were also built to simulate the behavior of steel-framed buildings and the tensile membrane action of the slabs exposed to fire [16,8,24,25,19,17,11].

To prove the existence of the membrane action, Bailey et al. [2] performed a test on a 9.5 m×6.5 m composite floor at ambient temperature. The steel deck was removed during the test to take into account the fire effect. It showed that the failure load doubled that calculated from classic yield line theory. The BRANZ (Building Research Association of New Zealand) carried out a fire test on a two-way simply supported Hi-bond composite slab (3.3 m×4.3 m) [21,22]. The test was performed in a controlled furnace environment (ISO834) in order to compare the results with the current simple design method. The measured temperature at the bottom of the slab was substantially lower than the numerical simulation results due to the buckling of the steel deck and its debonding from the concrete slab.

Evidences of building behavior were also available in the large-scale fire tests in Australia and Germany. The purpose of the Australian tests (also known as William Street fire tests and Collins Street fire tests) conducted by BHP was to assess the reliability of the existing sprinkler system and the behavior of unprotected steel beams [7]. The temperature of unprotected steel beams and slabs remained low due to the fire barrier effect of the suspended ceiling system. The fire tests were conducted on a four-story steel-framed building in Germany. The test results showed that the composite floor reached a maximum displacement of 60 mm and retained its overall integrity. In both Australia and New Zealand, design approaches that allow the unprotected steel in multi-story steel-framed buildings have been developed.

As demonstrated in previous studies, the sizable extra load-bearing capacity exhibited by composite slabs thanks to the tensile membrane action allows to remove the fire protection of the secondary beams underneath the slab, without harms to structural safety, something that may be extended in principle to the whole structure of tall buildings. Many factors have been pointed out to influence the resistance of membrane action, such as the boundary restraints, beam-to-slab and beam-to-girder connections, cooling phase of realistic fires, etc. Bailey and Toh [4] conducted 22 small-scale fire tests on horizontally unrestrained concrete slabs. The test results were used to validate the design method proposed by Bailey [3] for predicting the membrane action under fire conditions. It was found that the fracture of the reinforcement across the shorter span governed the failure. Li et al. [20] presented a theoretical model to calculate the membrane action, in which the slab was divided into 5 parts (a center-elliptic part and four rigid parts around) at the limit state. The equilibrium equations were established by using the force and moment in discretized slab stripes. This method was further developed to include both the geometric continuity and equilibrium on the integral slab (no discretization) in the calculation of the loading resistance of membrane action [27]. In 2008, CTICM (France) tested an 8.7 m×6.6 m composite slab in an ISO 834 standard fire [12]. It was intended to provide experimental evidence about the behavior of composite steel and concrete floors exposed to the standard temperature-time curve and to promote the application of the design concept based on membrane action. In order to investigate the fire resistance of connections between concrete slab and steel members at the perimeter of the composite floor when subjected to large deflections due to membrane action, another fire test was carried out in the project of COSSFIRE [28]. Fike and Kodur [10] presented experimental and numerical studies on steel beam-concrete composite floors made of steel fiber reinforced concrete. The studies showed that the fire resistance of composite slabs can be significantly improved by the composite action of the beam-slab assembly and tensile membrane action. Wellman et al. [26] tested the behavior of thin composite floor systems (4 m×4.5 m) exposed to fire. Various shear connections, fire scenarios, and fire protection scenarios of secondary steel beams were considered. None of the shear studs and beam-to-girder shear connections failed during the heating and cooling phases of the tests. The conclusion was that removing the fire protection of the interior beams in thin lightweight composite slabs is not recommended. Guo and Bailey [13] conducted experimental studies on the behavior of composite slabs during the heating and cooling phases in real fires. The results showed that the behavior of

Table 1
Summary of previous experiments on composite floor systems.

References	Slab	Slab size (m)	Type of decking	Secondary beam	Test load (kN/m^2)	Fire	Maximum deflection (mm)
TNO tests [15]	Simply supported	3.2×0.9	Prins PSV 73	NA	5.8	ISO 834	290
	Continuous	3.2×0.9					150
Cardington tests [11,18]	BS Corner	9.5×6.5	PMF CF70	Unprotected	5.4	Wood ribs 40 kg/m^2	428
	BRE Corner	9×6					269
	Test 7	11×7			6.0		1000
BRANZ [21]	Two-way	4.3×3.3	Hibond	NA	5.5	ISO 834	253
Purdue Tests [26]	Two-way	4.6×4	Vulcraft 1.5VLR	Unprotected and protected	9	ASTM E119 with cooling	250
Manchester tests [13]	One-way rotational restrained	6.45×1.2	PMF CF60	NA	3.85–11.7	Parametric fire	33–103
FRACOF [29]	Two-way	8.7×6.7	COFRAPLUS 60	Unprotected	5.1	ISO834	460
COSSFIRE [28]	Two-way	9×6.7	COFRAPLUS 60	Unprotected	3.9	ISO834	550
CTU test [5]	Two-way	4.5×3	TR40/160	NA	1.8	ISO834	300