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Journal of Constructional Steel Research 62 (2006) 1282–1289
JOURNAL OF CONSTRUCTIONAL STEEL RESEARCH
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Structural behaviour of composite slim floor frames in fire conditions

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Received 5 April 2006; accepted 28 April 2006

Abstract

The structural behaviour of the composite slim floor frame as a whole in fire conditions has been investigated. Both the deformation behaviour of the structural members and the mechanical interaction between the members were studied. The additional lateral deformation of the side-column caused by the thermal expansion and the catenary action in the beam in the different fire phase was highlighted. The moment variation in the head of the columns during fire and the variation of the axial force in the heated beam were also investigated. A comparison between the deformation behaviour of the heated beam in the plane frame and the spatial frame indicated the excellent effects of the composite floor slab on the stability of the frame structures in fire.
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Keywords: Fire resistance; Composite frame; Slim floor structure; Numerical modelling

1. Introduction

When subjected to fire, the steel and composite structures will lose their loading capacity and stiffness. To ensure the safety of the life and properties of the public, the indispensable fire resistance of the building is required by the authority [1]. Traditionally, the fire resistance ability of the structural members was tested using the isolated element heated by the ISO standard fire. In this methodology, the buildings were treated as a series of individual members, and the continuities and interaction between these members were assumed to be negligible. Consequently, most of the structural steel members need to be protected by the insulation materials, such as intumescent paints and fire protection boards, in order to achieve the required fire resistance.

Throughout the 1990s, following the investigation of the fire event in Broadgate (1991, UK), fire tests in William Street (1992, Australia), and full-scale fire tests on a 8-storey composite steel-framed building in Cardington (1995, 1996, UK) [2,3], it was found that the structural member in the frame had a significantly better behavior in fire than that in the standard fire resistance test. The standard fire test was very conservative by disregarding the interaction between members. The fire event and tests also highlighted that the current Codes, although conservative, were not addressing the true behavior of building structure in fire, since the building was not acting as a series of individual members [4–7].

In recent years, increasing interest has also shown throughout Europe in developing and designing shallow floor systems in steel-framed buildings [8–11]. In the shallow floor system, the steel beam is contained within the depth of the pre-cast concrete floor or composite slab with profiled steel decks. Recently, interest has been concentrated on the asymmetric hot-rolled steel in UK [9] and on the asymmetric welded steel beam in Finland [10,11].

The analysed steel-framed building in the present study was designed to resemble a part of the typical office or apartment, constructed with the typical composite slim floor frame. The layout of the frame building is shown in Fig. 1. The building has 4 storeys with an overall height of 12 m. There are 5 equally spaced bays along the length of the building. Across the width there are 2 bays spaced 6 m, connected by the slim floor beam. The steel beam was designed as simply-supported, acting compositely with the floor slab. Between rows of the single frame, the tie members are employed to link them together. The applied uniform load on the floor is 2.5 kN/m^2, and four equally spaced concentrated loads (110 kN for each) was applied on the beam. The fire region is also shown in Fig. 1.

The Finnish asymmetric slim floor beam was employed and the section shape is shown in Fig. 2. The steel column was

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doi:10.1016/j.jcsr.2006.04.026

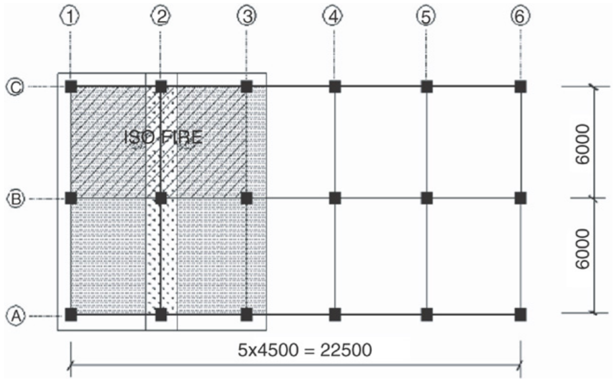

Fig. 1. Layout of the analyzed frame building.

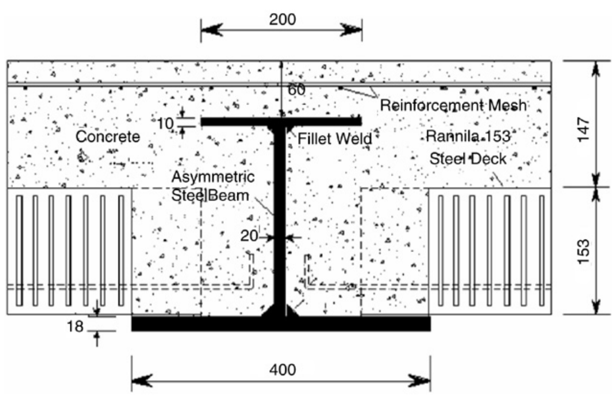

Fig. 2. Section shape of the Finnish asymmetric slim floor beam.

filled with the autoclaved aerated concrete blocks between the flanges. The width and thickness of the flange are 300 mm and 20 mm, respectively. The height of the column section is 300 mm and the web thickness is 20 mm.

The aim of this research was to investigate the structural behaviour of the composite slim floor frame as a whole in fire conditions. The deformation behaviour of the structural members and the mechanical interaction between the members were studied. Both the beneficial and the detrimental effects of the frame continuities on the structural members were explored. The influence of the concrete floor slab on the fire resistance of the whole frame building was also addressed.

2. Thermal analysis

The thermal analysis was based on the computer program, TACS-FIR (Temperature Analysis of Composite Structures exposed to FIRe) [12], which is purposely developed for the temperature analysis of composite structures in fire. The explicit forward difference method was used in this program.

The analyzed temperature distribution in the different fire phase has been reported elsewhere [12,13]. The simplified temperature distribution of the slim floor beam under 60 minutes ISO heating is shown in Fig. 3(a). The temperature distribution along the web is assumed to be parabolic. The concrete slab was divided into seven uniform layers and two regions to represent the temperature distribution. The central part of the slab has a much lower temperature in 60 min due to the encasement of the concrete between the bottom flange and the slab. The temperature variation with time of the steel beam is also shown in this figure (Fig. 3(b)).

The temperature variation with time of the blockfilled column is shown in Fig. 4. It is assumed that the column is heated from one side only. Therefore, there exists a large temperature gradient within the depth of the web.

In this context, the structural response is described against the ISO fire exposure time. Certainly, it is also reasonable for this to be given against the bottom flange temperature if the behavior of the beam is of the major concern. This transformation can be easily made according to Table 1.

Table 1
Relationship between ISO fire exposure time and temperature of bottom flange

ISO time (min)	0	15	30	45	60	75	90
Bottom flange temp. (°C)	20	220	500	650	750	830	890

Table 2
Material properties for structural modelling

Steel		Concrete	
Yield strength (N/mm^2)	Thermal expansion ($°C^{-1}$)	Cubic strength (N/mm^2)	Thermal expansion ($°C^{-1}$)
355	1.4×10^{-5}	30	1.8×10^{-5}

3. Structural analysis of the frame

3.1. General description of the FEM model and assumptions

The structural analysis was carried out by using the general finite element program, ABAQUS/Standard [14]. The composite slim floor beam was represented by combining a shell element (S8R) and a beam element (B32). The asymmetric steel beam was modeled by 3-node beam elements with 6 degrees of freedom at each node. The concrete slab was modeled using 8-node thick shell elements, also with 6 degrees of freedom at each node. The reinforcements were modeled using REBAR elements encased in the concrete shell elements. Beam elements were also used for the modeling of the columns. The following assumptions were made in this modelling:

(1) Both the ribs of the composite slab and the concrete between the bottom steel flange and concrete slab were neglected, due to significantly increased difficulties in the numerical convergence.
(2) The concrete was assumed to be an elastic–plastic material, which has a plastic plateau after reaching the compressive and tensile strength. No descending phase in compression and in tension was taken into account. The tensile strength of the concrete was taken as 10% of its compressive strength. The material properties of steel and concrete used in this modeling are listed in Table 2.
(3) There is no slip between the steel beam and the concrete.
(4) The material properties of the concrete and steel at elevated temperature were taken from Eurocode 4 Part 1.2 [15].

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