Fire Safety Journal 78 (2015) 31–43

Contents lists available at ScienceDirect

Fire Safety Journal

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

The effects of protected beams and their connections on the fire resistance of composite buildings

Shuyuan Lin, Zhaohui Huang*, Mizi Fan

Department of Mechanical, Aerospace and Civil Engineering, Brunel University London, Uxbridge UB8 3 PH, UK

ARTICLE INFO

Article history:
Received 5 November 2014
Received in revised form
6 August 2015
Accepted 15 August 2015
Available online 15 September 2015

Keywords:
Steel connection
Fire resistance
Composite floor
Finite element modelling
Tensile membrane action

ABSTRACT

According to full-scale fire tests, it is noticed that tensile membrane action within the concrete floor slabs plays an important role in affecting the fire resistance of composite buildings. It is well known that the development of tensile membrane actions relies on the vertical support along the edges of the slab panel. However, there is at present a lack of research into the influence of vertical supports on the tensile membrane actions of the floor slabs. In this paper, the performances of a generic three dimensional 45 m × 45 m composite floor subjected to ISO834 Fire and Natural Fire are investigated. Different vertical support conditions and three steel meshes are applied in order to assess the impact of vertical supports on tensile membrane action of floor slabs. Unlike other existing large scale modelling which assumes the connections behave as pinned or rigid for simplicity, two robust 2-node connection element models developed by the authors are used to model the behaviour of end-plate and partial end-plate connections of composite structures under fire conditions. The impact of connections on the 3D behaviour of composite floor is taken into consideration. The load-transfer mechanisms of composite floor when connections fail due to axial tension, vertical shear and bending are investigated. Based on the results obtained, some design recommendations are proposed to enhance the fire resistance of composite buildings.

1. Introduction

Significant progress has been made in analysing the performance of steel framed composite buildings under fire conditions over the last decades. The most common and conventional way of retaining the strength and stiffness of steel-framed buildings under fire conditions, is to provide fire protection to all exposed steel members. However, observations from a series of full-scale Cardington fire tests have shown that steel framed composite structures can provide a significantly greater fire resistance than is suggested by standard fire tests on isolated structural members [1]. This appeared to be due to an interaction between the heated members within the fire compartment, the concrete floor slabs and the connected steel frame structure. If steel members within the structures loss strength and stiffness rapidly due to high temperatures, alternative load paths would be adopted to transfer load for the remaining part of the structures. Experimental and analytical investigations involving full-scale fire tests indicated that tensile membrane action within the concrete floor slabs plays an important role in enhancing the fire resistance of composite buildings. The load carrying capacity of slab due to tensile membrane action is significantly higher than the slab under pure bending [2]. Tensile membrane action can occur when the slabs undergoes large vertical displacements. As shown in Fig.1, the induced radial tension in the centre of the slab is balanced by a peripheral ring of compression [3]. The occurrence of tensile membrane action mainly relies on the conditions of vertical support maintained around the edges of the slab panel. To utilise the tensile membrane action, the composite floors need to be divided into slab panels, consisting of an array of steel beams. The beams around the perimeter of the slab panels are protected, while the internal secondary beams can be left unprotected.

Up to now, research has focused on the influence of the tensile membrane actions on the fire resistance of composite floors, with the assumption that the fully vertical supports along the perimeter of the slab panel are provided by protected beams. Different design methods have been developed to simulate the behaviour of composite slab at elevated temperatures incorporating tensile membrane action [4–12]. However, there is as yet a lack of detail research into the influence of the vertical deflections of protected beams during fire on the tensile membrane actions of the slab panel. For the majority of previous research on modelling composite floor subjected to fire, the beam-to-column and beam-to-

* Corresponding author.
E-mail addresses: Shuyuan.Lin@brunel.ac.uk (S. Lin), Zhaohui.Huang@brunel.ac.uk (Z. Huang), Mizi.Fan@brunel.ac.uk (M. Fan).

http://dx.doi.org/10.1016/j.firesaf.2015.08.003

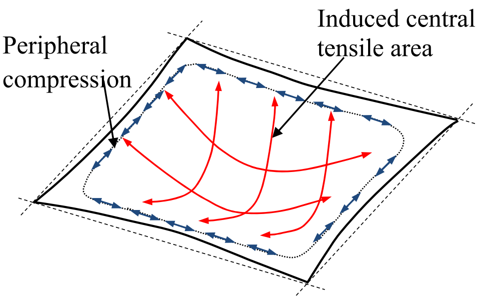

Fig. 1. Tensile membrane action within floor slabs.

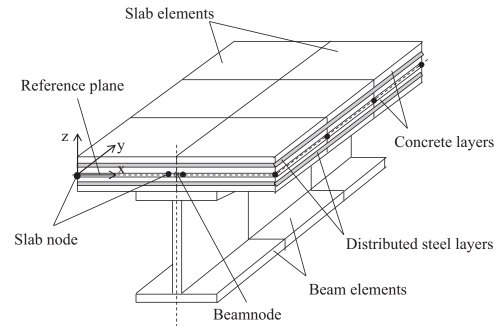

Fig. 2. Division of composite structures into beam, slab elements.

beam connections were assumed to behave either as pinned or rigid for simplicity, and the vertical shear and axial tension failures of the connection were not taken into account [13,14]. However, under fire conditions due to the loads transferred from unprotected beams to the protected beams, the vertical loads acting on the connections of the protected beams may increase to beyond the design capacity of vertical shear resistance of the connections. Hence, a proper connection model is needed to predict the failure of the connections due to vertical shear loads.

This paper presents a comprehensive study conducted on a generic three dimensional 45 m × 45 m composite building, with realistic loading conditions and structural layout, under different fire conditions. A series of analyses has been carried out using different support conditions on floor slab panels and slab reinforcement details. In this research, it is assumed that the beam-to-column and beam-to-beam connections behave as semi-rigid. The end-plate connections are used to connect primary beams to columns. The partial end-plate connections are adopted to connect secondary beams to columns, and primary beams to secondary beams, respectively. These two types of the connections are modelled using the simplified connection models developed by the authors [15,16]. The proposed two connection models have good numerical stability under a static solver condition, and can be used for large scale modelling of composite buildings in fire. The main objectives of this study are:

- To systematically investigate the impact of the connections for protected beams on the tensile membrane actions of supported floor slabs, in which the failure of the connections due to axial tension, vertical shear or bending is considered.
- To understand the influence of the vertical deflections of protected beams on the tensile membrane action of the floor slabs.
- To analyse the effects of different reinforcement details of the floor slabs on the performance of composite floor under different fire conditions.

2. Theoretical background of the software VULCAN

In this study, the finite element software VULCAN is employed, which is capable to model the three dimensional performance of composite and steel-framed buildings under fire conditions [17–19]. The software VULCAN has been developed through long term research, and has been extensively validated against available experimental results. VULCAN has also been used in many real projects for structural fire engineering design. As shown in Fig. 2, in this programme the steel-framed composite buildings are modelled as an assembly of finite beam–column, connection and slab elements. It is assumed that the nodes of these different types of element are defined in a common reference plane that is assumed to coincide with the mid-surface of the concrete slab element, whose location is fixed throughout the analysis.

The beam–columns are modelled using 3-node line elements [19]. The cross-section of each element is divided into a number of segments to allow the required variation of the distributions of temperature, stress, and strain. Both geometric and material nonlinearities are included. The reinforced concrete slabs are represented using 9-node nonlinear layered elements, in which the membrane action of the floor slabs is considered [17,18]. The slab elements are divided into a number of plain concrete and reinforcing steel layers. The temperature and material properties for each layer can be specified independently. An effective stiffness model was developed to model the ribbed nature of typical composite slabs [20]. For modelling composite steel decking concrete floor slabs, a maximum-strain failure criterion is applied for plain concrete layers, and the concrete layers are considered to be orthotropic after the initiation of cracking.

Recently, two robust simplified connection models have been developed by the authors [15,16] for modelling the end-plate and partial end-plate connections between steel beams and columns in fire. The proposed models are based on the two-node connection element framework developed by Huang [21]. In order to assess the influence of the axial ductility of connection on the connection's axial forces and deflection of the connected beam, five different levels of axial stiffness of connection were used to represent pinned and rigid connections for modelling of steel frame at elevated temperatures [21]. The numerical analyses indicated that axial stiffness of the connection has a very limited influence on the deflection of the connected beam and negligible influence on the axial tensile forces of the connection [21]. Hence, in Huang's model the axial deformability of the connection is ignored. This assumption is retained in the current two connection models used in this study.

These models have been incorporated into software Vulcan. The brief descriptions of the connection models are given in the following.

2.1. *Simplified major-axis connection models*

For modelling the behaviour of connections which connect beam to flange of column (major-axis) at elevated temperatures, two simplified connection models were developed [15,16] and incorporated into software VULCAN. As described in Ref. [15], a simplified model has been proposed to predict the performance of flush and extended end-plate beam-to-column flange (major-axis) connections in fire. The connections failure due to bending, axial tension, compression and vertical shear are all taken into account, as well as the impact of axial tensile force of the connected beam on the connection. Validation results showed that the proposed model is capable of predicting the performances of flush and extended end-plate connections under fire conditions with reasonable accuracy.

Another simplified 2-node connection element model for