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Fire resilience of shear connections in a composite floor: Numerical investigation

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ABSTRACT

Large-scale tests and accidental fires have demonstrated that the composite steel-framed buildings have significant load-bearing capacities and are more resilient to fire conditions compared to fire resistance tests performed on the isolated elements. Understanding the beneficial effect of the tensile membrane action will enable minimization of the amount of fire protection measures, which will increase the competitiveness of the use of steel–concrete composite floors in buildings. The fire resilience of floors is dependent on the connection behavior since the failure of the connection might lead to partial collapse of the interior beams. This paper presents a numerical investigation on the performance of a composite steel-framed floor system and the beam-to-beam shear connection at elevated temperatures. The paper also investigates the effect of the interior beams on the concrete slab in terms of vertical deflection, composite action and stress levels in the steel reinforcement. The results show that the single plate shear connection buckles and excessively deforms during the early phases of the fire. The out-of-plane distortion of the plate causes bolts to load in the tension. The connection reaches its rotational and axial capacity during the cooling phase of the fire resulting the bolts to fail with combined shear and tension.

1. Introduction

Large-scale tests and accidental fires have shown that the composite steel-framed buildings have significant load-bearing capacity and are more resilient to fire conditions compared to the results of fire resistance tests on the isolated elements [1–5]. The improved fire performance of the composite steel-framed buildings is due to tensile membrane action of the concrete slab, which is triggered by large deflections [6–8]. Large deflections are primarily the result of thermal expansion and thermal gradient through the member cross-section [9]. Tensile membrane action (TMA) is a mechanism that enhances the load-bearing capacity in slabs, in which the radial tension in the central area of a slab induces an equilibrating peripheral ring of compression [10,11]. The applied load is mainly supported thereafter by membrane action in the composite slab, effectively transferring the load from the interior beams to the edge beams [12]. The most frequently encountered problem in composite floor systems is to simulate the force and moment interaction between the concrete slab and the steel member accurately [13]. The axially restrained steel beam may buckle under large compressive forces during heating and cause large slab deflections and instability to the floor system [14]. Another challenge in the analysis of composite steel-framed buildings is the fire performance of steel connections. Large deflections of the concrete slab will cause significant rotations over the edge beams, which may be greater than the rotational capacity of shear connections [15].

Although the concrete slab has been demonstrated to be resilient against fire exposure and to sustain large deflections through tensile membrane forces, it is questionable if the steel shear connections, which connect the interior beams to the edge beams, can sustain such a large tensile force [16–18]. Inadequate connection strength or ductility against the fire-induced forces could trigger a collapse, especially when the concrete slab does not have sufficient shear resistance to carry the gravity loads [19]. The edge beams must survive the fire, and the concrete slab should sustain the hogging moments along these beams to allow the TMA mechanism to form [20–22]. Another question arises as to whether the interior beams affect the fire performance of the floor system at such large deflections during a fire [23,24].

Previous observations on fire experiments confirmed that the load-bearing mechanism of the steel-framed composite floors under fire conditions is enhanced via tensile membrane action and that there is no need to fire-protect the interior beams to improve the resistance of the floor system [25]. Understanding the beneficial effect of tensile membrane action will allow for minimization of the amount of fire protection measures, which will increase the

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competitiveness of the use of steel–concrete composite floors in buildings. Several attempts have been made to develop theoretical models for the estimation of the concrete slab deflection limit-state considering TMA, but these attempts do not include the effect of the interior beams and the behavior of the connections in the calculations [21,26]. There is a significant knowledge gap in detailed numerical finite element simulations that model the reinforcement stresses, the composite interaction between the interior beams and the slab and the effect of the steel connections during a fire.

This paper presents an investigation of the fire performance of a composite floor system with shear connections by utilizing a sub-assembly finite element model in Abaqus [27]. The aim is to quantify the effect of the interior beams to the reinforced concrete slab and the resilience of shear connections at large deflections.

2. Problem description

2.1. Case study: composite floor of a tall steel building

As a case study, a floor system of dimensions of 9.5 m by 6 m from an existing tall steel building in Istanbul, Turkey is modeled using the finite element software Abaqus (see Fig. 1a). The 28-story tall steel building has a slender design. The structure is designed using the Allowable Stress Design building code. The building is designed as a hotel. The floor system consists of a concrete slab with steel mesh reinforcement, four HE400A edge beams, and two IPE330 secondary beams that are connected to the edge beams with single plate bolted shear connections, as shown in Fig. 1b. For gravity loading at ambient conditions, the utilization factor of the secondary beams is below 0.2. The edge beams are connected to each other by end-plate moment connections. The end-plate moment connection behavior is modeled by using coupling constraints to restrain the rotational and translational degrees of freedom at beam ends of HEA400 edge beams.

The first goal of this study is to investigate the load bearing capacity of the reinforced concrete slab at elevated temperatures. This will be essential to identify when and how TMA is triggered in the concrete slab. The second goal is to understand the influence of the interior (secondary) beams and the shear connection on the fire performance of the floor system.

Since the floor section is on the perimeter of the building (see Fig. 1), no continuity with the adjacent floors is considered [7]. Eq. (1) shows the Eurocode (EC0) load combination in a fire situation for office buildings [28]. Assuming a 2.5 kN/m^2 live load (Q) and a dead load (G) of 1.25 kN/m^2 (partition load), a uniformly distributed surface load (w) of 2.5 kN/m^2 is initially applied to the concrete slab. The applied live load is in agreement of the suggested live load for an office building according to Eurocode 1 [29]. The self-weight of the subassembly is automatically activated in the model.

$$w = G + 0.5Q \tag{1}$$

The subassembly is subjected to ISO834 fire curve from the bottom surface for 90 min with 90 min of cooling (decay). The decay rate is taken from furnace test measurements where the furnace gas burners are immediately shut down, and the furnace temperature decreases via air-cooling.

2.2. Fire performance validation using simple design method

In order to validate the accuracy of the model, the load carrying capacity as well as the ultimate deflection of the composite floor subassembly are calculated using the tensile membrane action method developed by Bailey [1,2]. The design method does not consider the thermal and mechanical effects during the cooling phase. Hence, only the first 90 min is comparable with the model.

According to P288 Design Guide [5], Eq. (2) estimates the bearing capacity (q_c) of the concrete with the contribution of the interior beams. Here, M_s is the moment resistance of the slab section only; M_b is the moment resistance of each composite beam; L and l are the long and short length of the slab, respectively; e is the enhancement factor due to membrane action; n is the geometric factor; a is the aspect ratio of the slab and n_{ub} is the number of interior beams. The concrete slab capacity and the unprotected IPE330 interior beam capacity is calculated as 4.1 kN/m^2 and 17.1 kN/m^2 at room temperature. After 90 min, the beam capacity drops to 0.7 kN/m^2 whereas the slab capacity increases to 4.4 kN/m^2 due to tensile membrane action at large deflections. The design code suggests that the composite floor subassembly barely survives 90-min ISO fire with the total capacity of

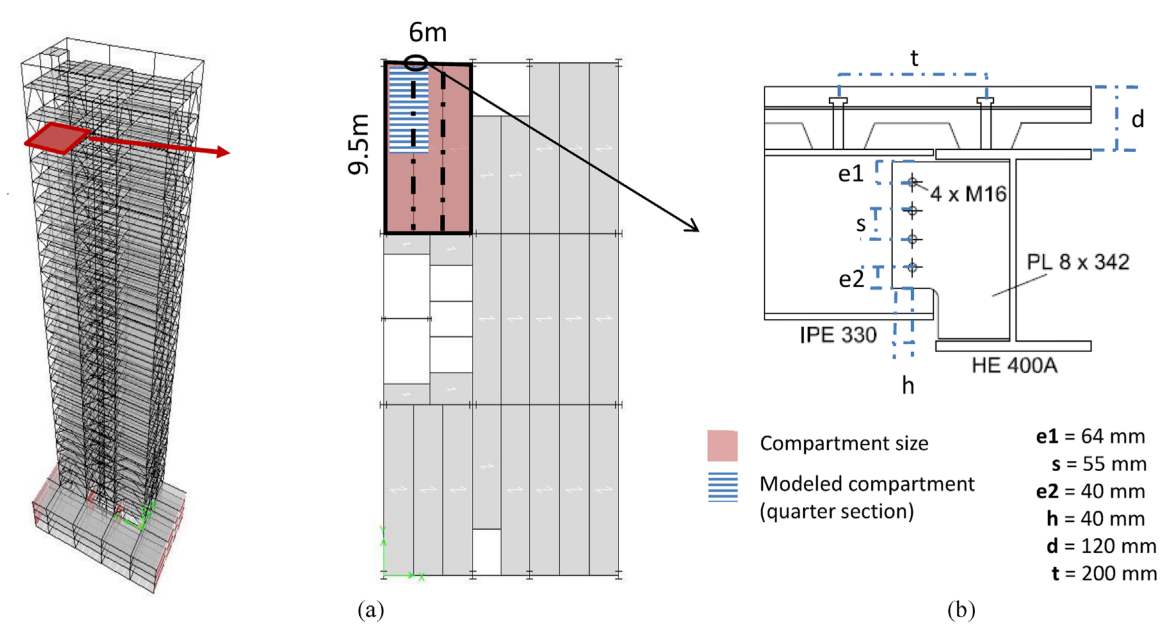

Fig. 1. Case study: 28-story tall steel building: (a) the floor layout, and (b) the bolted single plate shear connection detail.