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FIRE PERFORMANCE OF STEEL SHEAR CONNECTIONS IN A COMPOSITE FLOOR

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Abstract. *The objective of this paper is to investigate the fire performance of a concrete slab with reinforcing steel mesh, the effect of the edge (perimeter) beams and secondary beams to the slab's performance and the resilience of the steel shear connections, which connect the secondary beams to the edge beams. In this study, a 28-story tall steel building is modeled in Abaqus finite element software that allows the analysis of thermo-mechanical problems. The finite element models show that the load carrying mechanism of the reinforced concrete slab significantly differs at ambient and fire temperatures. As long as the edge supports are fire protected, the reinforced concrete slab survives the fire but the single plate connection does not provide sufficient resistance to the excessive rotations. Further, the secondary beams have limited contribution to the reinforced concrete slab fire performance.*

1 INTRODUCTION

Recent fire experiments in steel buildings with composite floor compartment have shown that the compartments resisted collapse because the concrete slab acted like a tensile membrane supported by the fire-protected perimeter beams and columns [1,2,3,4]. The most frequently encountered problem in composite floor systems is to accurately simulate the force and moment equilibrium between the concrete slab and the steel member [5]. Another difficulty based on the fire performance of the steel connections is the effect of the concrete slab to the rotation capacity of connections and the internal forces and moment equilibrium of the steel beam section [6,7,8].

Although the concrete slab has proved to be resilient against the fire exposure and sustain large deflections through tensile membrane forces, it is questionable if the steel shear connections, which connect the secondary beams to the perimeter beams, can sustain large rotation and tensile force [9]. Inadequate connection strength or ductility against the fire-induced forces could trigger a collapse. Another question arises as to whether or not the secondary beams affect the fire performance of compartments at such large deflections during fire [10].

This paper investigates the fire performance of a composite floor compartment by utilizing a full-scale finite element model in Abaqus [11]. The model considers the interaction between the reinforced concrete slab, the steel member and the shear connection components at ambient and fire conditions. The aim is to quantify the effect of the secondary beams to the reinforced concrete slab and the resilience of the shear connection at large deflections.

2 PROBLEM DESCRIPTION

2.1 Case study: Floor compartment of tall steel building

As a case study, a compartment by 9.5 m and 6 m from a steel tall building in Istanbul, Turkey is modeled using the finite element (FE) software Abaqus (see Figure 1a). The steel building is 28 stories tall and currently used as a hotel. The compartment consists of the concrete slab with steel mesh reinforcement, four HE400A edge beams and two IPE330 secondary beams, which are connected to HE400A with single plate bolted shear connections as shown in Figure 1b.

The performance of the reinforced concrete (RC) slab is investigated both at ambient and elevated temperatures. Three FE models with increasing complexity are created in Abaqus and a total of six analyses are run as described in Table 1. The behavior of the single plate connection in M3 and M3f models are also investigated. For the fire condition, ISO-curve for 2 hours is subjected to the structure.

The RC slab is divided by 200x200 mm finite elements of 4-node doubly curved thick shells with reduced integration and large strain formulation (S4R). For simplicity, the ribbed section is modeled as a flat slab with an effective thickness of 95 mm as illustrated in Figure 1c. For the reinforcement, A142 steel mesh is modeled using *Rebar Layer command in both x- and y- directions at 40 mm below the concrete top surface.

For HE400A and IPE330 beams, and the components of single plate connection, the reduced integration continuum elements (C3D8R) are employed. The beams are tied to the concrete shells using *Surface Tie command and the single plate connection components are assigned with contact configurations using penalty enforcement algorithm to the rest of the structural system. The boundary conditions along the RC slab edges are horizontally free but vertically restrained (roller) for M1 and M1f models whereas the RC slab edges are tied to the HE400A beams in M2, M2f, M3 and M3f models.

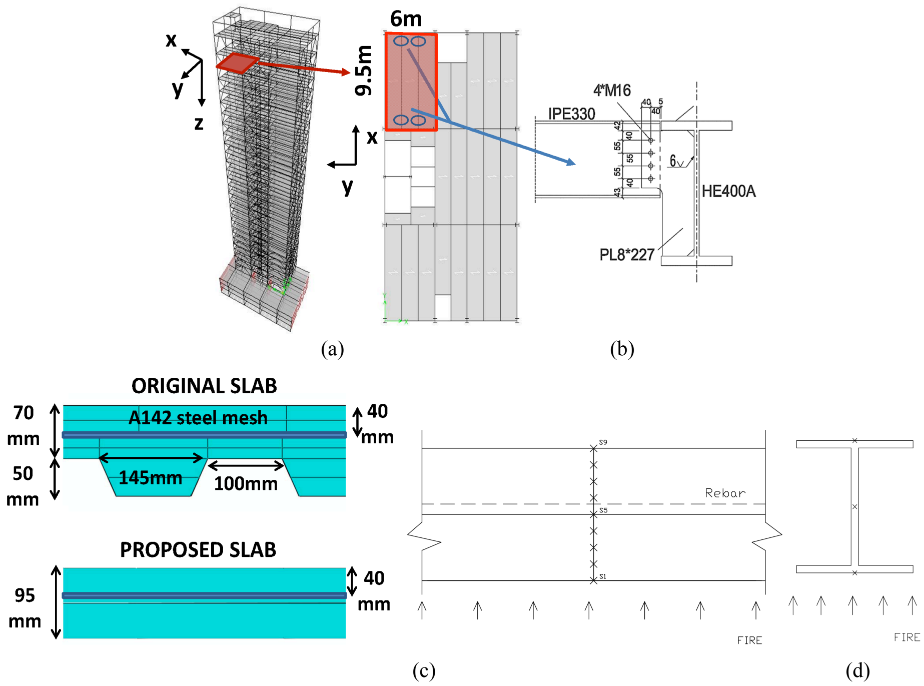


Figure 1. (a) Case study: The geometry of the compartment from 28- storey tall steel building, (b) the bolted single plate shear connection detail, (c) the RC slab geometry and temperature points and (d) IPE330 temperature points.

Table 1. FE model descriptions

FE Models	Description
M1	RC slab only at ambient temperature
M1f	RC slab at fire
M2	RC slab + HE400A at ambient temperature
M2f	RC slab + HE400A at fire
M3	RC slab + HE400A + IPE330 + single plate connection at ambient temperature
M3f	RC slab + HE400A + IPE330 + single plate connection at fire

2.2 Material Properties

The mechanical and thermal properties for the reinforcing steel mesh and the siliceous concrete material are shown in Table 2 and Table 3, respectively. For elevated temperatures, Eurocode provisions are used [12,13]. The stress-strain relationship of concrete is adopted from Youssef and Moftah [14]. For the concrete material, both compression softening and tension stiffening ratios are also taken from Youssef and Moftah [14]. The tensile and compressive concrete ultimate strength are taken as 35 MPa and 3.5 MPa, respectively. The concrete damaged plasticity in Abaqus is employed to model the plastic behaviour of the concrete material [11]. The yield strength of the steel reinforcement is 500 MPa without strain hardening. The yield strength of the IPE330 beams and the single plate is 345 MPa with strain hardening. Grade 8.8 bolts with the yield strength of 640 MPa with strain hardening.

Table 2. Mechanical and thermal properties of steel

Steel Reinforcement	Type	Size of mesh (mm)	Longitudinal wires area (mm^2/m)	Transverse wires area (mm^2/m)	Smeared layer thickness (mm)
	A142	200x200	142	142	0.1414

Steel Properties				
Mechanical (20 °C)	*E* (GPa)	Yield stress steel reinforcement (MPa)	Yield stress IPE 330 and the single plate (MPa)	Yield stress Grade 8.8 bolts (MPa)
	210	500	345	640
Thermal (20 °C)	Density (kg/m3)	Conductivity (W/m K)	Specific Heat (J/kg K)	Expansion (1/°C)
	7850	53.3	440	1.23e-5

Table 3. Mechanical and thermal properties of C35 siliceous concrete

Concrete Properties					
Mechanical (20 °C)	*E* (GPa)	Yield stress in compression (MPa)		Cracking stress in tension (MPa)	Dilation angle in yielding (°)
	21	35		3.5	12
Thermal (20 °C)	Density (kg/m^3)	Conductivity (W/m K)	Specific Heat (J/kg K)	Expansion (1/°C)	
	2300	1.95	900	0.91e-5	

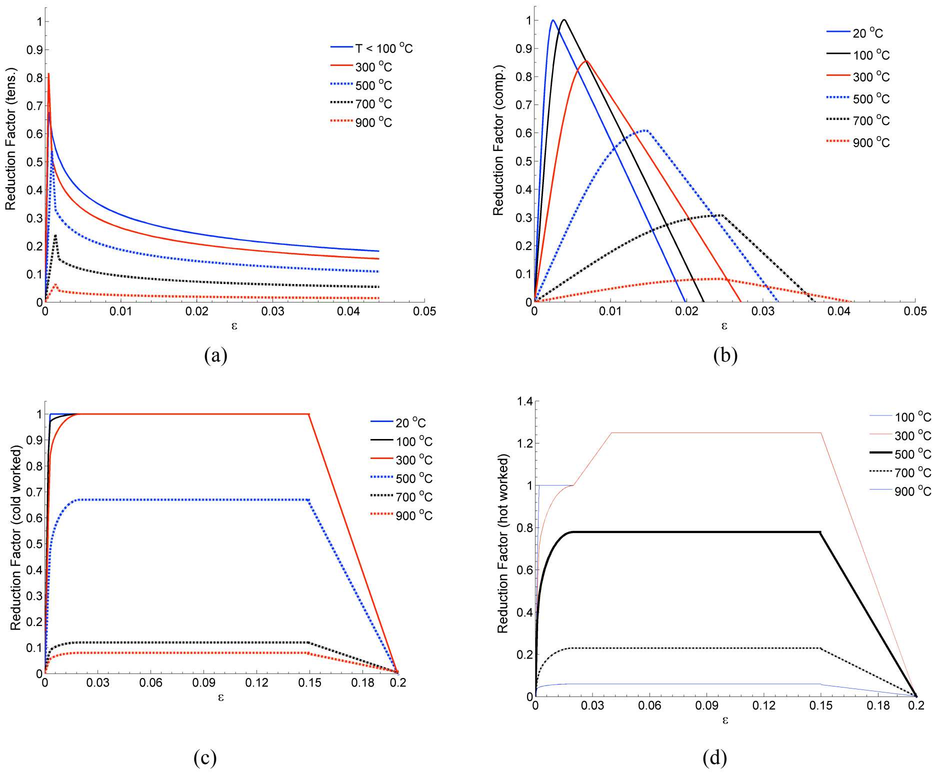


Figure 2. The reduction factors of (a) concrete material in tension, (b) concrete material in compression, (c) the steel reinforcement (cold-worked), and (d) other steel members (hot-worked) in both compression and tension.

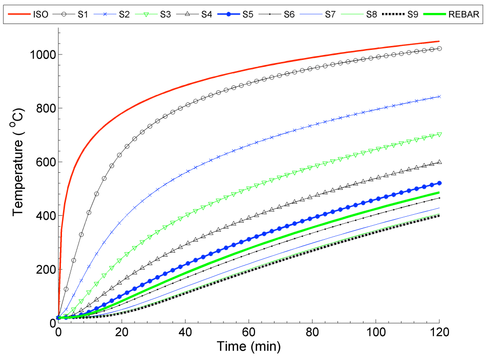
3 ANALYSIS AND RESULTS

The solution method is an uncoupled thermal-stress analysis, where the nodal temperatures calculated from the heat transfer analysis are transferred to the structural analysis. The analysis method is dynamic-explicit with Abaqus/Explicit package [11]. A dynamic analysis is favorable because of the concrete material model complexity and the slab collapse behavior. By utilizing mass scaling by a factor of 10 and scaling up the time scale to 1 second for each step, the kinetic energy levels due to inertial forces were within 10% throughout the analyses.

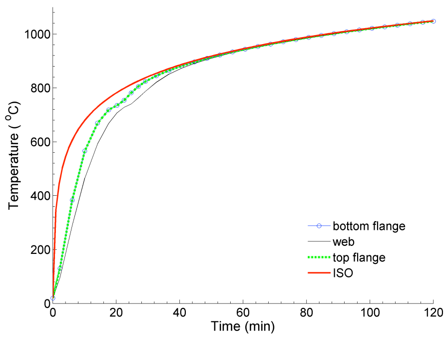
For all the FE models, the compartment is initially (quasi-statically) loaded with 5 kN/m^2 distributed (gravity) load. In the first step, the RC slab is loaded approximately 40% of the ultimate load capacity of the M1 and M1f models. In the second step, two separate analyses are conducted by: (a) increasing the (gravity) loading until 20 kN/m^2 at ambient temperature and (b) subjecting the structure to the ISO-834 fire curve for two hours. M1, M2 and M3 models are at ambient temperature whereas M1f, M2f and M3f models are heated with ISO fire curve for 2 hours.

3.1 Thermal analysis

In M1f, M2f and M3f models, the RC slab, the secondary beams (IPE330) and the connection components are not fire-protected. The temperature distribution within RC slab cross-section (9 section points and steel reinforcement) and IPE330 cross-section (3 section points) are shown in Figures 3a and 3b, respectively. The temperature section points used in Figure 3 are shown in Figure 1c-d. In the RC slab, a significant thermal gradient was observed whereas the steel temperatures were close in the beam cross-section IPE330.



(a)



(b)

Figure 3. FE heat transfer results: The temperature distribution of (a) 10 section integration (temperature) points of RC slab and (b) 3 section integration (temperature) points of IPE330.

3.2 Structural analysis

The FE models M1, M2 and M3 were quasi-statically loaded at ambient temperature until 20kN/m^2 distributed load. The FE models M1f, M2f and M3f were quasi-statically loaded until 5kN/m^2 and then subjected to ISO-fire curve for 120 minutes.

3.2.1 RC slab

Figure 4 shows the principal membrane tractions in the RC slab for all the models. At ambient temperature, it is clearly observed that the RC slab behaved significantly different if it was isolated (Figure 4a), supported by HE400A beams around the edges (Figure 4b) or IPE330 beams in the center (Figure 4c). A small tension zone with a compression ring is formed in the RC slab for M1 and M2 models as seen in Figure 4a-b. A compression zone is formed in M3 model as seen in Figure 4c. The slab deformations were relatively small at ambient temperature. IPE 330 beams provided significant flexural stiffness to the RC slab. At fire, the fire performance of the RC slab is similar. A large tension zone is developed in the middle section with a compression ring in the outer section as seen in Figure 4d-f. The addition of the edge beams around the perimeter (Figure 4e) or the secondary beam (Figure 4f) does not affect the load carrying mechanism of the RC slab.

Figure 5a-b shows the vertical deflection at RC slab midpoint. At ambient temperature, the deflection significantly differs for each model. M1 model has larger deflection and goes into tensile zone action as seen in Figure 5a. By adding HE400A (edge) beams, the RC slab in M2 model behaves like having a rotationally fixed boundary, and hence the total deflection decreases. As the loading increases, M2 model starts with compressive zone action but later goes into the tensile zone action. M3 model exhibits much smaller deflection since IPE330 beams provide additional flexural stiffness to the structure. Therefore, the RC slab develops only the compression zone action as the distributed loading increases. At fire, the RC slab starts in compression due to the axial restraint on the edges. However, as the stiffness of the slab decreases at elevated temperatures, the vertical deflection increases and the RC slab gets into the tension zone with a compression ring around the perimeter. The secondary beams in M3f contribute to the vertical resistance of the RC slab, although the contribution is much limited compared to the contribution at ambient temperature as seen in Figure 5b.

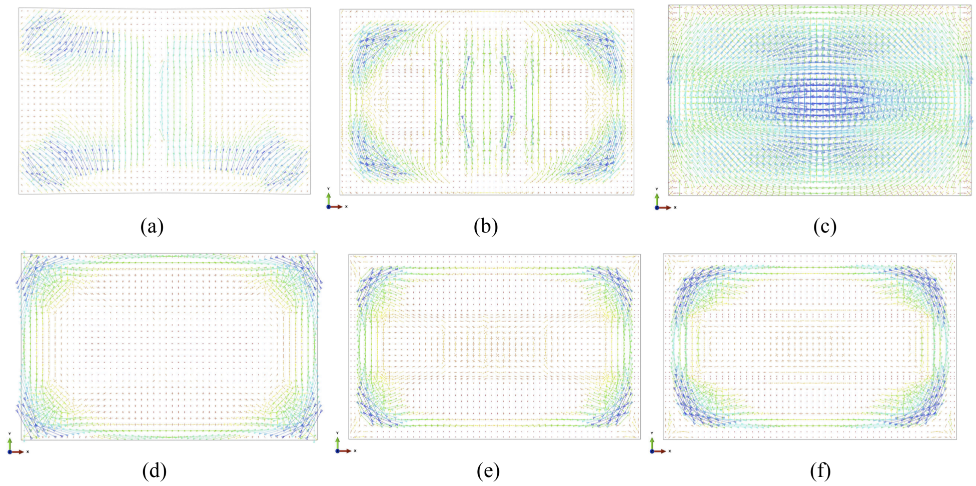


Figure 4. Principal membrane tractions (top shell surface) of the reinforced concrete slab in models (a) M1, (b) M1f, (c) M2, (d) M2f, (e) M3 and (f) M3f at the end of the analysis. The blue (darker) lines represent compression and red (lighter) lines represent tension.

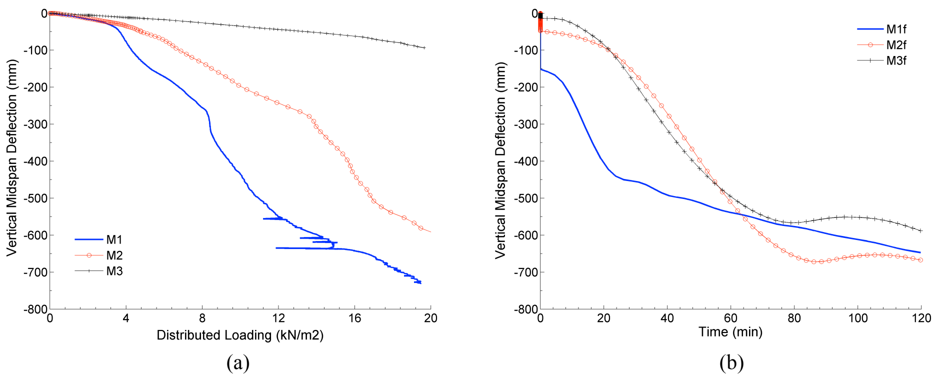
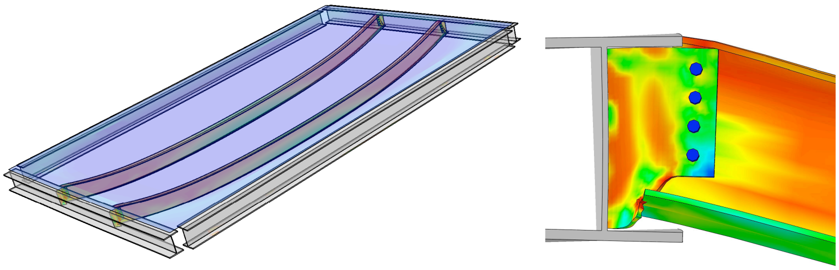


Figure 5. Vertical deflection at the RC slab midpoint for (a) ambient condition of M1, M2, M3 models and (b) fire condition of M1f, M2f, M3f models.

3.2.2 Single plate connection

The deformation of the M3f model and the single plate connection are shown in Figure 6a and b, respectively. Although the RC slab carries the gravity loading at elevated temperatures by the 'tensile inner zone-compressive outer ring' mechanism, the slab deflections become very large and the single plate shear connection deforms significantly around the bolt-hole regions in the beam web. Further, due the large connection rotation, the IPE330 flange contacts the plate and causes excessive deformations as observed in Figure 6b. The von Mises stresses confirm that the bolt shear is the governing limit state failure of this type of connection.



(a) (b)

Figure 6. The von Mises stress contours and deformations of (a) the entire structure and (b) the single plate shear connection of the M3f model.

4 CONCLUSION

In this paper, the fire performance of a large compartment with single plate shear connections is studied at ambient and fire temperatures. The finite element models show that the load carrying mechanism of the RC slab differs significantly at ambient and fire temperatures. At ambient temperature, the main mechanism is the compression zone action with relatively small vertical slab deflections. The addition of the edge beam around the perimeter and the secondary beams in the center greater increases the load carrying capacity of the slab at ambient temperature. At fire, the RC slab forms tension in the middle zone and compression in the outer ring. Therefore, the design of the steel reinforcement for tensile membrane action is necessary for a robust fire performance of the RC slabs. As long as the edge supports are fire protected, the RC slab survives the fire. However, the single plate connection does not provide sufficient resistance to excessive rotations. Further, the secondary beams have limited contribution to the RC slab fire performance.

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