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BEHAVIOR OF RC FLAT PLATE STRUCTURE SUBJECTED TO COMPARTMENT FIRES

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ABSTRACT

Reinforced Concrete (RC) flat plates are commonly used in residential, commercial, and industrial concrete structures. As new fire design codes move towards performance-based design, fire rating of RC elements shall consider the restraint effect and the overall behavior of the structure. In this study, the behavior of a multi-story flat plate structure during fire exposure is investigated using numerical simulations conducted with ABAQUS software. A three-dimensional finite element model is then carried out on the RC flat slab structure exposed to standard ISO-834 fire at different location arrangements. The model investigates mid-span deflection, shear demand on the columns, bending moment and the membrane action of the floor slab. The latter plays a main role to increase the capability and ductility of the slab at longer fire exposure to compensate the reduction in the flexural capacity. Also, shear demand in columns becomes bigger in cases of more than one surrounding slab exposed to fire at the same time.

Keywords: Fire; Reinforced concrete; Flat plate; Flat slabs; Fire resistance; Membrane action

Nomenclature

K The ratio of the second stress invariant of the tensile meridian to that on the compressive meridian.

σ_{b0} Initial equibiaxial compressive yield stress

σ_{c0} Initial uniaxial compressive yield stress

INTRODUCTION

Concrete is widely used in construction due to its economic, strong, and durable properties [1]. However, its properties, as well as steel reinforcement, significantly degrade at elevated temperatures [2–4]. As fire events are one of the common scenarios which may occur during the service life of RC structures, their fire resistance constitutes an important aspect in the design process [5]. Currently, engineers use empirical methods to calculate the fire resistance as described in current building codes [6]. These empirical methods are not adequate because they determine the fire resistance only depending on the minimum thickness and concrete cover of the reinforced concrete elements and they don't consider the strain effect, the strength effect, the global behavior and the standard fire. Other methods include experimental testing of structural elements of sub-assemblages. Although fire testing is the most reliable process to estimate the fire endurance of a building, it is very limited because of its high cost, required safety measures, and complexity [7]. Numerical methods provide rational and accurate tools to predict the fire resistance of RC structures during fire exposure. There were different methods to analyze and design RC flat plate structure at ambient temperature. On the other hand, we can only use finite element method to analyze RC flat plate structure under fire exposure. ABAQUS will be adopted in this paper regarding finite element analysis.

Different researches studied the effect of fire exposure on flat plate structures. Moss et al. [8] investigated the fire performance and membrane effect of two way reinforced concrete slabs in multi-story and multi-bay buildings. They concluded that the membrane force effect was negligible. Huang [9] studied the behavior of reinforced concrete slab under fire in multi-bay building. He found that concrete spalling has small impact on the fire resistance of RC floor slab building in case of a fire is concentrated in central bay due to high thermal restraint provided by the adjacent cool structure. Also, he indicated that concrete spalling significantly decreases the fire resistance of floor slab in the corner panel of slabs due to the absence of thermal restraint in those locations. Sangluia [1] presented the behavior of reinforced concrete slab subjected to elevated temperatures. He summarized that mid span deflection increases with increasing longitudinal bar diameter or decreasing the slab thickness.

The current paper presents modeling of a multi-story multi-bay flat plate building to evaluate the behavior of the structure with four fire scenarios. Within this paper, many aspects are investigated such as vertical deformation, applied shear forces due to slab expansion, bending moment capacity of the field strips and column strips, stresses on slabs and the membrane forces.

MATERIAL PROPERTIES AND MODELLING

The material properties for both concrete and steel at elevated temperature were taken according to Eurocode part 1.2 [10].The concrete was assumed to be siliceous aggregate, with a constant density 2400 kg/m3, the compressive strength was 30 MPa and the modulus of elasticity was 24000 MPa. The steel reinforcement was assumed to have yield strength of 400 MPa. The steel is assumed to be elastic perfectly plastic under tension and compression according to [1]. Steel reinforcement was modeled as a one-dimensional rebar layer within a shell element slab. Also, it was modelled as truss element T3D2 (2-node linear 3-D trusses) within a solid element slab. The concrete slab was modelled utilizing concrete damage plasticity with five parameters from [11] as obtained in table (1). The stress-strain curve of concrete under compression behaves linearly until reaching 0.45fc’. Once the strength (ultimate or peak stress) is reached, strain softening is started according to Eurocode [10].

Table 1: Concrete damage plasticity parameters

Dilation Angle	***Eccentricity***	σ_{b0}/σ_{c0}	K	***Viscosity***
49^o	0.1	1.16	2/3	0

VALIDATION CASE

Lim and Wade [12] investigated the behavior of two way reinforced concrete flat slab under fire exposure. Six slabs were tested, involving three reinforced concrete flat slabs, and three composite steel concrete slabs. Fig. 1 obtained the layout of the tested specimens. The temperature of top surface slab was increased slowly to 520^{o}C at 3hrs., while the temperature of the bottom reinforcement was increased from the initial temperature 20^{o}C to 850^{o}C at 3hrs. Thermal analysis is submitted using ABAQUS to mimic the investigated specimens by Lim and Wade [12]. Fig. 2 represents the temperature distribution at different levels of slab thickness compared with the experimental results.

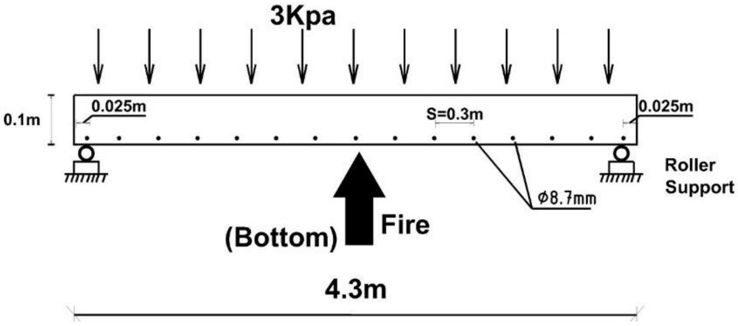


Fig. 1: layout of the test specimen

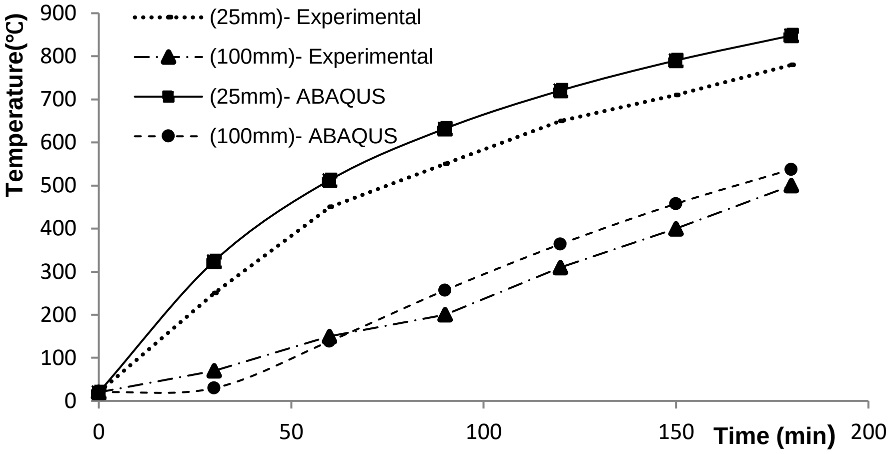


Fig. 2: Temperature distribution with time at 25mm and 100mm from the bottom surface of the tested slab (from experimental test and from finite element model using ABAQUS).

Fig. (3) obtained a comparison between the measured mid span vertical deflections of the flat slab during the fire tests by Lim and Wade [12] and that simulated by using 3-dimensional solid element (ABAQUS) as well as which developed by S4R shell element with the same finite element software. It can be seen from fig.3 that the connection between the predicted vertical deflections of the flat slab using the 3-dimensional solid element and S4R shell element (ABAQUS) are fine accuracy. Also, there is a good agreement between the numerical and the experimental results.

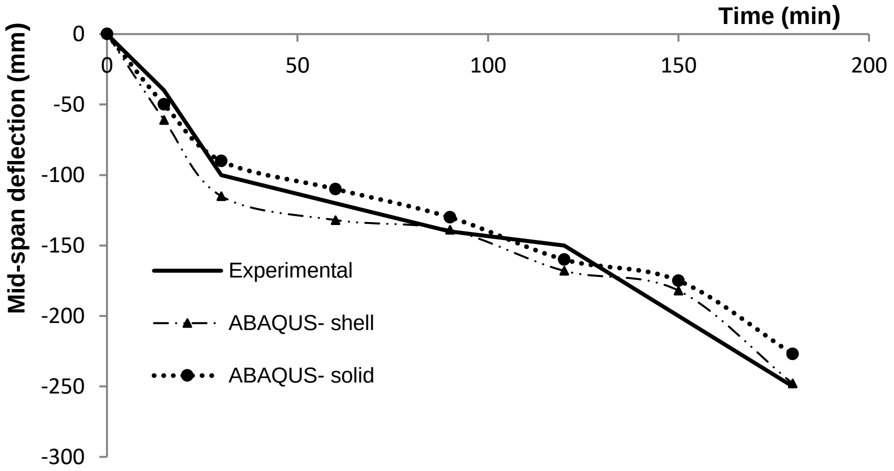


Fig. 3: Relation between mid-span deflection and fire time for experimental and analytical specimen using shell and solid elements.

PARAMETRIC STUDY AND FINITE ELEMENT MODEL

A six story RC flat plate building is considered in this parametric study. This building has a 4 m story height and five bays in each direction spanning 6 m between column centers. The design of this building is conducted using the direct design method per the Egyptian code [13]. The flat-plate is designed and reinforced assuming cover weight of 2 kN/m^2 in addition to a live load of 4 kN/m^2 (i.e. a total of 11 kN/m^2) During fire exposure, a load combination of full dead load plus 25% of the live load is considered in the analysis [14].
The thickness of the slab is chosen as 200 mm and the clear cover of reinforcement is 30 mm. The steel reinforcement is distributed based on the flexural design of column and middle strips as shown in Fig. 4. The columns cross-sections are 400x400mm.The yield strength of hot-rolled steel reinforcement equals 400 MPa and the compressive strength of concrete is 30 MPa.

The same validated finite element model variables are used in the parametric study. The concrete flat slab and the steel reinforcement are modelled using master concrete shell elements with embedded slave reinforcement later with mesh size of 0.5 m The columns are connected to the slab using tie constraint [11]. Column top ends can move vertically and rotate in all directions (X, Y, and Z) while the bottom ends can rotate only. All columns are modelled as an elastic material with flexural stiffness E_c=24000 MPa.

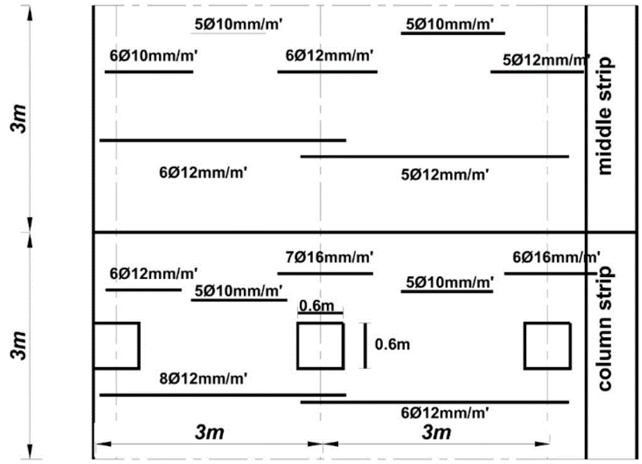
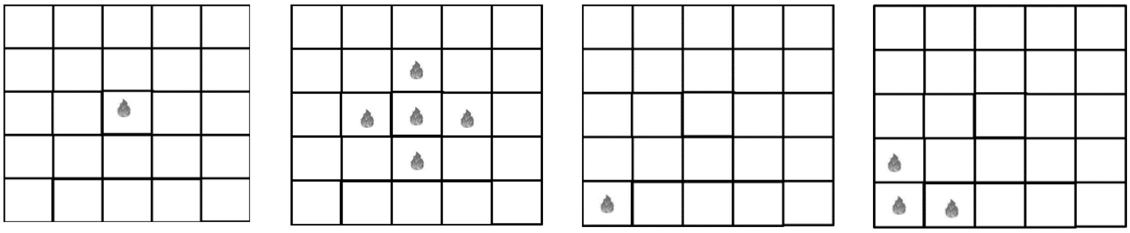


Fig. 4: Slab reinforcement layout of prototype structure

Fire Scenarios

An ISO834 standard fire is assumed to occur at the lower floor [15]. The concrete thermal properties were calculated according to Eurocode 2 [10]. Fig. 5 shows a plan view of an intermediate story with the different studied fire scenarios. These four scenarios are:

- Scenario 1 (R-C) represents a fire exposure in the central panel/compartment.
- Scenario 2 (C-I) is the same as (R-C) in addition to the four adjacent panels/compartments.
- Scenario 3 (C-II) represents a fire exposure in the external panel/compartment.
- Scenario 4 (C-III) is the same as (C-II) in addition to two adjacent panels/compartments.



a) scenario 1(R-C) **b) scenario 2 (C-I)** **c) scenario 3 (C-II)** **d) scenario 4 (C-III)**

Fig. 5: Parametric Study Fire Scenarios

Analysis Results and Discussion

Elevated Temperatures

The conductivity and the specific heat of steel are not comprised in heat transfer analysis because the absence of steel in the analyses has negligible impacts on temperature field in slabs. The steel reinforcement temperature is considered like the concrete temperature at the same location. Fig. 6 shows the elevated temperature across the thickness of the heated panel at different fire durations. The temperature of the bottom surface increases from the ambient temperature to 1090 °C while the temperature in the upper surface reaches slowly to 107 °C only during 3 hrs. of fire exposure.

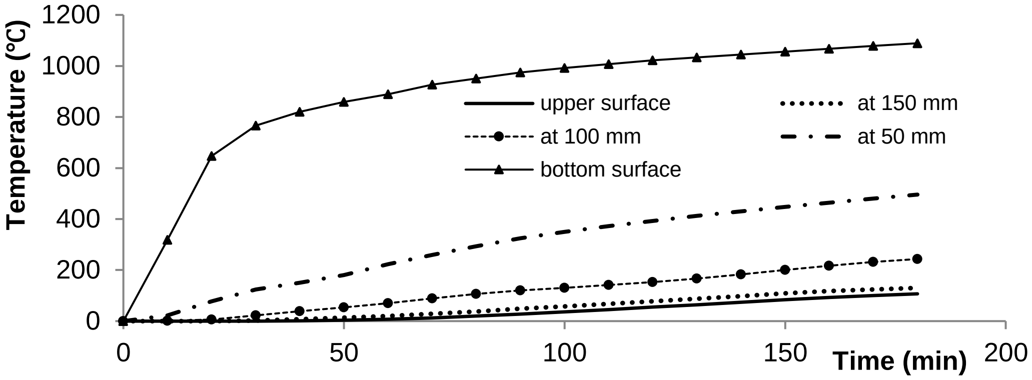


Fig. 6: Predicted temperature inside heated panel

Slab Vertical Deflection

Fig. 7 shows the vertical displacement of the heated panel of floor slab at point A. The initial deflection due to gravity load causes a deflection of 4.8 mm. During fire exposure, the deflection at (A) increases to higher values. After 3 hrs. of fire exposure, the slab displacement at (A) has reached 580 mm.

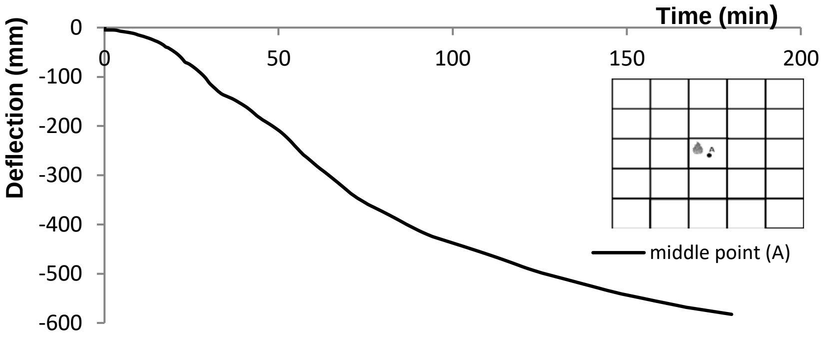


Fig. 7: Vertical deflection of the heated panel at point A

Punching Shear Forces

As shown in fig. 8, during fire exposure, the column reactions or slab punching force for any of the four columns supporting the fire exposed central panel do not change. This is because there is no other adequate load path to transfer the gravity loads.

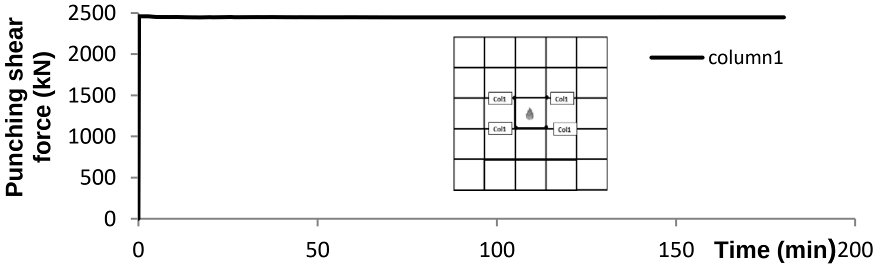


Fig. 8: Punching shear force on columns

Slab Flexural Moment

Fig. 9 shows the variation of the slab flexural moments with fire duration. The initially applied gravity load causes positive bending moment at the middle point of the slab and negative moment at the column regions. During the first 20 min, the positive moment is reduced because the heated bottom steel reinforcement losses its strength causing early yielding. The negative moment at the columns increases due to the moment redistribution. After 20 minutes of fire exposure, both the negative and positive moments decrease due to the membrane action.

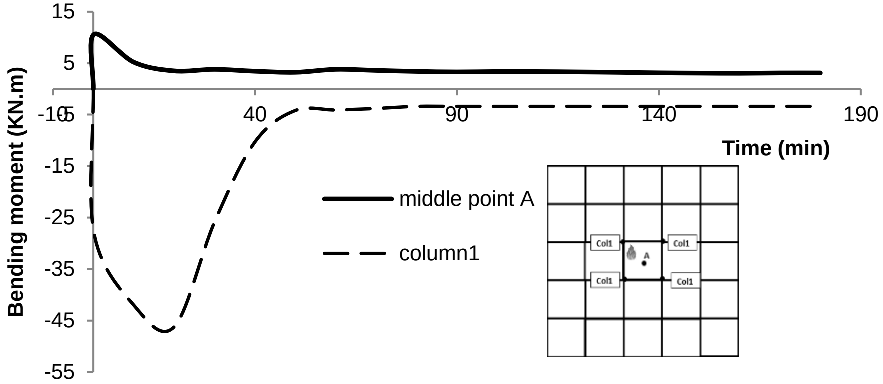


Fig. 9: Effect of fire exposure on slab bending moment at columns and at mid-span

Slab Membrane Forces

Fig. 10 shows the slab membrane forces, along X or Y axes, during fire exposure at the mid-span. Membrane forces are negligible at ambient temperature as the mid-span deflection is small compared to the slab planar dimensions. However, the large deflection during fire exposure promotes the membrane effect to resist the gravity loads through tensile forces by steel in the slab.

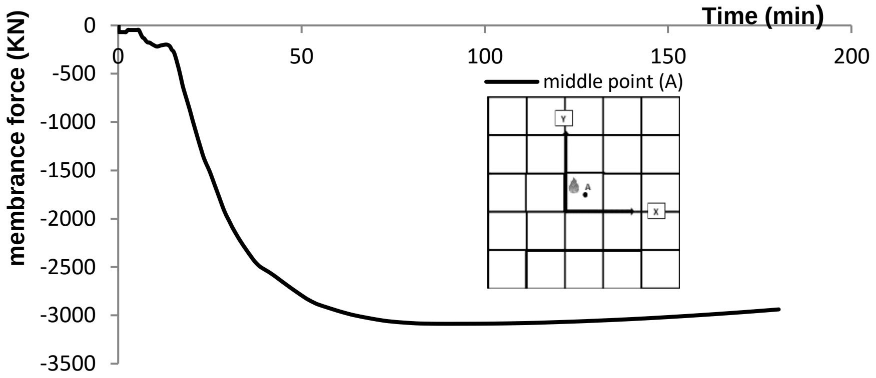


Fig. 10: Slab membrane forces at X-direction induced by fire loading

Expansion Force induced on Columns by Fire

As shown in fig. 11, the expansion forces induced on columns at Y-axis is defined by the summation of RT2 (Top) and RT2 (Bottom). The lateral forces on columns were rising during the first 20 min of fire exposure. This is because of the thermal elongation of the slab which pushes the columns outwards. Subsequently after 20 minutes of fire exposure, the lateral forces begin to reduce as shown in fig. 12. This can be due to the large mid-span deflections which pulls the supporting columns towards the geometric center of the fire exposed slab. Thus, the effect of expansion forces induced on columns should be considered when checking the shear resistance of the columns during fire exposure.

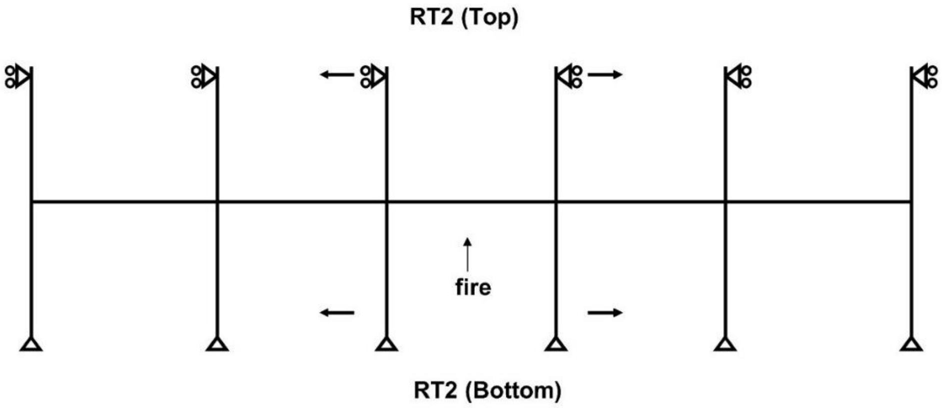


Fig. 11: Definition of Expansion Force induced on Columns by Fire

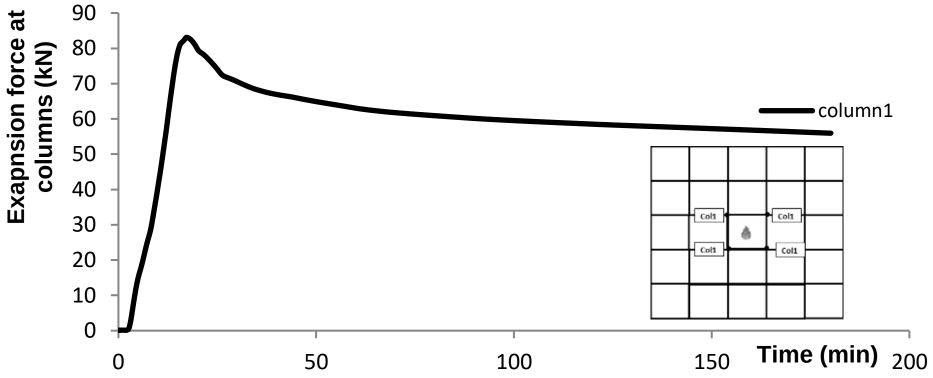


Fig. 12: Expansion shear Force induced on Columns by Fire in Y-direction

Effect of Preload Level

Fig. 13 shows the impact of varying gravity load on the vertical deflection of slab. In case of scenario 3 (C-II), it is observed that decreasing the uniform gravity load from 6KPa to 3KPa results in an increase in the time till slab collapse from 65 min to 135 min with approximately the same value of mid-span deflection. The same behavior is observed in scenarios 2 (C-I) and 4 (C-III) when uniform gravity load decreased from 6KPa to 3KPa as time till slab collapse increases from 70 min to 150 min and from 55 min to 80 min, respectively.

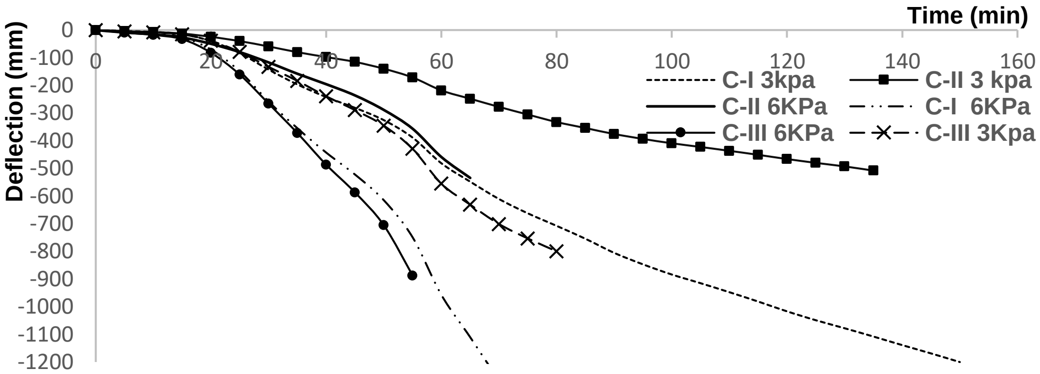


Fig. 13: Effect of gravity loads on time till slab collapse

Effect of Travelling Fires

After fire spreads from the panel where fire begins to other panels around it, deflection at middle point of slab increases at the same time of the reduction of positive mid-span bending moment as shown in fig. 14 and fig. 15, respectively as reinforcing bars lose its strength with temperature increase. As demonstrated in fig. 15, mid-span bending moment reduces in exterior and interior panels but the moment reduction rate decreases when fire spreads from the panel where fire begins to other panels around it. In addition, expansion forces induced on columns increases as presented in fig. 16. On the other hand, membrane force in slabs decreases with the fire spread as indicated in fig. 16, because the existence of adjacent cool slabs leads to the development of membrane forces. For instance, if we compare fire case scenario of (R-C) with (C-I) at inner panel and inner column at fire time of 70 min., mid-span deflection increases from 392mm to 1268mm and maximum shear forces induced on each column increases from 80 kN to 246 kN, while membrane force decreases from 3040 kN to 2187 kN. If we present two other fire case scenarios of (C-II) with (C-III) but for corner column and corner panel at fire time of 50 min as another example as shown in figures 14-17, mid-span deflection increases from 460mm to 705mm and maximum shear forces induced on each column increases from 612 kN to 942 kN, while membrane force decreases from 768 kN to 437 kN.

Effect of Fire Location

As shown in figures 14-17, when fire is located at the external corner panel instead of inner panel, mid-span deflection increases, and maximum expansion shear force induced on columns excessively increases, while slab membrane forces decrease. This result could be attributed to the fact that more horizontal deformation occurred at slab column connection of exterior panels due to fire rather than that of the interior panels and less resistance and restrains exists from adjacent cool slabs. For instance, at fire time of 50 min., mid-span deflection in case (R-C) is 229mm compared to 705mm in case (C-II). For the same two cases, maximum expansion shear Force induced on columns increases from 65 kN to 287 kN. On the other hand, slab membrane forces decrease from 2795 kN in the interior panels to 767 kN in the exterior panels at the same fire time. Mid-span bending moment reduction happens in exterior and interior panels as shown in fig. 15.

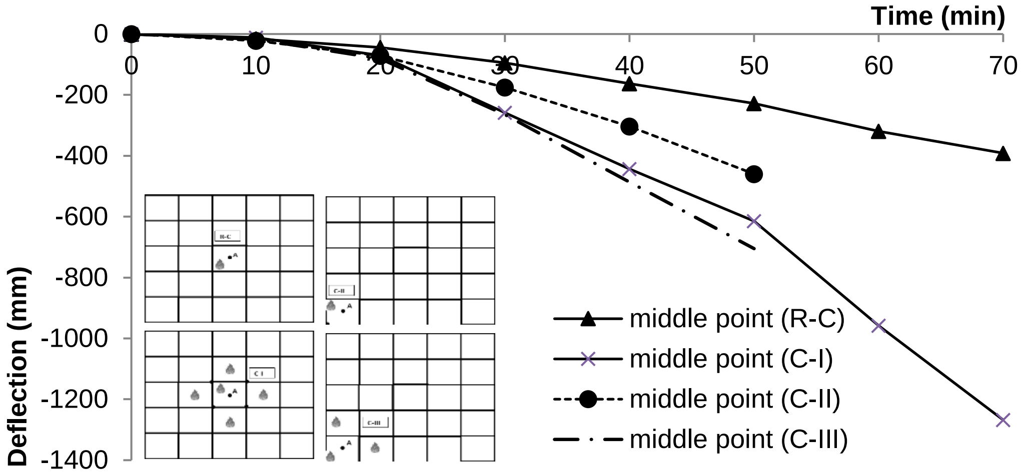


Fig. 14: Deflection at middle point A for different fire scenarios and different locations.

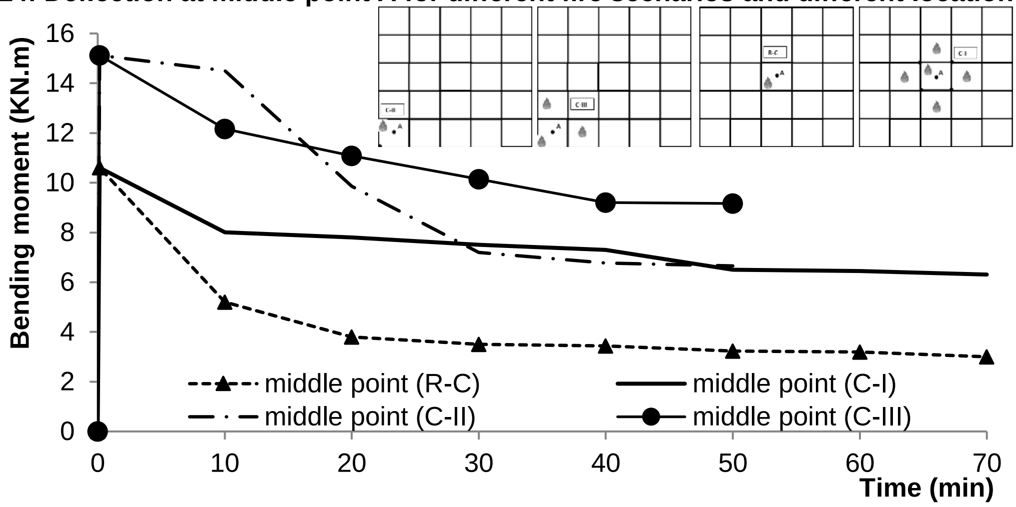


Fig. 15: Bending moment at middle point A for different fire scenarios and different locations.

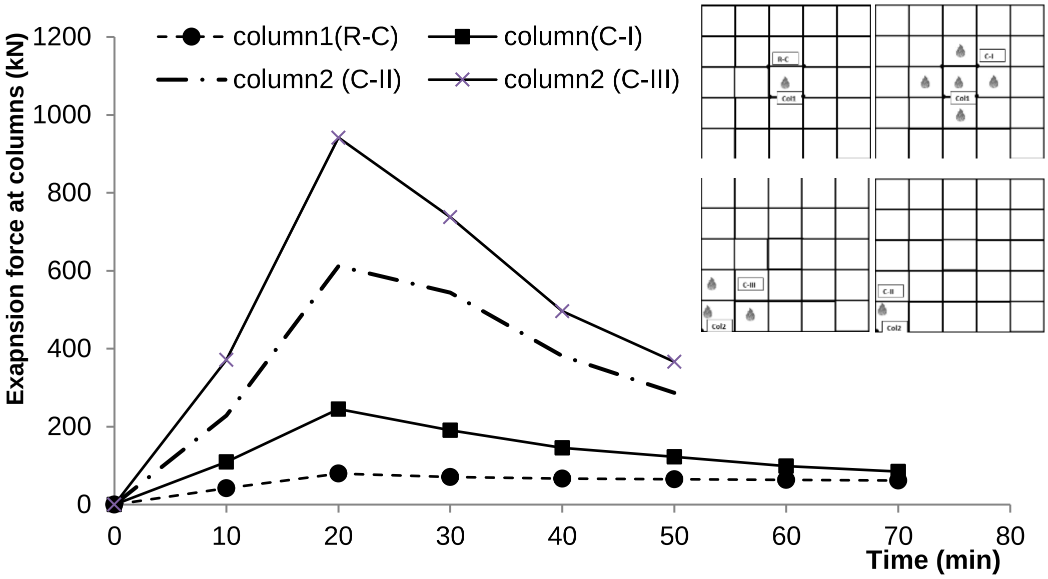


Fig. 16: Expansion Force induced on Columns by Fire for different fire scenarios and different locations.

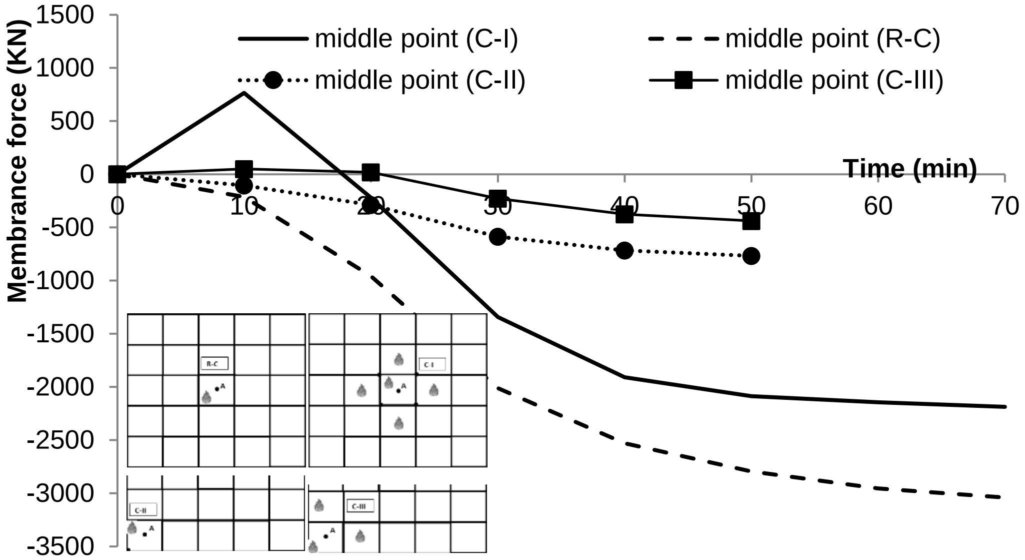


Fig. 17 Slab membrane forces at X-direction induced by fire loading for different fire scenarios and different locations.

CONCLUSION

From the carried out numerical study, the following conclusions could be drawn:

- The membrane forces developed in the slabs due to fire had a significant role in their stability especially when large deflections took place at long exposure times. Also, they remarkably affected the shear forces induced on columns.
- Uniformly distributed gravity load has a significant influence on fire resistance of slabs. As the gravity load increases, slab fire resistance decreases regardless of the occurring fire scenario.
- Travelling fire has a significant effect on slab deflection, expansion forces induced on columns, slab bending moment, and slab membrane forces. As fire spreads from one compartment to the surrounding ones, the mid-span deflection increases, moment

reduction rate decreases, expansion shear forces induced on columns increases, and membrane force in slabs decreases.

- When fire is located at the external panels instead of inner panels, mid-span deflection increases, maximum expansion shear force induced on columns excessively increases, and slab membrane forces decrease

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