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A Review on Numerical Analysis of RC Flat Slabs Exposed to Fire

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ABSTRACT

This paper aims at presenting and discussing the numerical studies performed to estimate the mechanical and thermal behavior of RC flat slabs at elevated temperature and fire. The numerical analysis is carried out using finite element programs by developing models to simulate the performance of the buildings subjected to fire. The mechanical and thermal properties of the materials obtained from the experimental work are involved in the modeling that the outcomes will be more realistic. Many parameters related to fire resistance of the flat slabs have been studied and the finite element analysis results reveal that the width and thickness of the slab, the temperature gradient, the fire direction, the exposure duration and the thermal restraint are important factors that influence the vertical deflection, bending moment and force membrane of the flat slabs exposed to fire. However, the validation of the models is verified by comparing their results to the available experimental date. The finite element modeling contributes in saving cost and time consumed by experiments.

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مراجعة عن التحليل العددي للسقوف الخرسانية المسطحة والمعرضة للحريق

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الخلاصة

يهدف هذا المقال الى عرض وشرح الدراسات الخاصة بالتحليل العددي التي تم تنفيذها لتخمين التصرف الانشائي والحراري للسقوف الخرسانية المسلحة المسطحة والمعرضة لدرجات حرارة عالية وللحريق. التحليل الخطي يتم باستخدام برمجيات العناصر المحددة لمحاكاة تصرف الابنية المعرضة للحريق. خصائص المواد الحرارية والميكانيكية للمواد يتم ادخالها للبرنامج بالاعتماد على نتائج التجارب العملية لتكون النتائج اكثر واقعية. تم دراسة تأثير عوامل متعددة متعلقة بمقاومة السقوف للحرائق، ومن خلال النتائج المستحصلة من التحليل العددي تبين أن هذه العوامل هي عرض السقف، سمك السقف، مدة التعرض للحريق، اتجاه حمل الحريق والتقييد الحراري للمنشات والتي تؤثر على الانحراف العمودي، عزم الانحناء. عند مقارنة النتائج المستحصلة من تحليل العناصر المحددة مع تلك المستحصلة من التجارب العملية ، تم التوصل الى تقارب كبير بين وسيلتي البحث مما يمكن الباحثين استخدام التحليل العددي في شمول حالات متعددة وبتأثير عوامل مختلفة لتقدير التصرف الانشائي للسقوف المسطحة مما يوفر الكثير من الجهد والكلفة.

الكلمات الدالة: النمذجة باستخدام العناصر المحددة، مقاومة الحريق، سقف مسطح.

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1. Introduction

Reinforced concrete flat slabs are common structural systems widely used in buildings for their economical and effective features. However there are many concerns related to the strength and serviceability of this kind of members, especially if exposed to sever conditions. One of the most serious dangers that affects the performance of the structures is

exposure to fire due to its increased risk resulting from global warming consequences and terror attacks. Though concrete is considered a very good fire resistance material, the small thickness of flat slabs requires ensuring the safety of this floor system under fire condition. The requirements for the fire resistance of RC slabs are specified in most building codes. In addition, many experiments have been carried out to evaluate the residual strength and the serviceability of RC flat slabs exposed to fire taking into account different influencing factors. In order to include a vast number of cases related to the RC flat slabs under fire conditions besides economical purposes, the researchers have taken the advantage of the available finite element software packages to perform a nonlinear analysis for that type of structure. This article aims at reviewing the most important numerical studies and the obtained results for the flat slabs exposed to elevated temperature and fire.

2. Numerical analysis review

Linus Lima, Andrew Buchanan, Peter Mossb and Jean-Marc Franssenc, [1] performed a numerical finite element model by using program SAFIR on two-way RC slabs. A four node quadrilateral element shell element was used in the model. To verify the model, the experimental results of two way and composite steel-concrete slabs under exposure to the ISO standard fire carried out by Lim L, Wade C. [2] were used in the nonlinear analysis. The slabs were simply supported on all four edges over the furnace. The slabs were subjected to constant live load and exposed to ISO fire for 3 hours. The numerical results showed a good agreement with the experimental results which verify using SAFIR shell element to estimate the behavior of two-way reinforced concrete slabs in fire conditions. It was concluded that the tensile membrane forces developed in the slabs effectively enhance the resistance against fire. Also, if the two way slabs have a double curvature deformation, this will greatly increase the fire resistance.

G. Wang [3] carried out a nonlinear FE analysis using SAFIR software to study the behavior of fire resistance of one way RC slabs. The thermal model used in the analysis is 3D shell four-node quadrilateral solid element. From the thermal analysis, it was found that the fire effect can reach the top surface of the slab of a 20 cm thickness after 4hrs exposure. The slabs were simplified modeled in SAFIR because the affected region around the fire boundaries is small, equals the thickness of the slab. By using simplified thermal models, a comparison was made regarding the distribution of the temperature in the slab considering the presence of the steel reinforcement. It was found that the effect of reinforcement at the bottom slab can be neglected and not included in the model because the results showed that the time temperature relationship curves are identical for the two cases.

It was concluded from the analysis that along the cross section of the slab the bending moment is nonlinear distributed near the supports and linearly distributed at the midspan. Using different values of slab width affects the behavior of the slab. The wider slab experiences larger vertical deflection at mid span and nonlinearity in the bending moment distribution along the cross section in addition to a larger value of tensile force membrane lag.

It was obtained that the most important factor in the design of a slab restrained in the X-direction at the supports is the top reinforcing bars in the slab. Also, it was found that a plastic hinges are formed in the slabs exposed to fire with a decay face because of the dramatic increase in the bending moment.

Abdul-Razzak. A. [4] has adopted Mindlin/Reissner thick plate theory to perform a geometric nonlinear analysis to investigate the behavior of flat plates under fire loading. The FE model was built as eight nodes thick shell element, the slab was divided into layers including concrete and reinforcing steel. The mechanical and thermal properties were assembled to the element. The temperature varied along the cross section, but it was constant within the same layer. As the temperature increased with time, the stiffness and internal forces were computed while applying load. An iteration was made until the equilibrium is achieved between the external load and the internal forces, at that time, the deformation of the element is determined due to fire exposure.

The model was verified by its application on the slab specimens tested by Brost and Peeters [5] and on full scale slabs tests carried out by Nizamuddin and Bresler [6], on comparison the tests results with that obtained from the nonlinear analysis, a good agreement was showed especially at failure stage. Therefore, using geometric nonlinear analysis can estimate the maximum load carrying capacity of slab at elevated temperatures.

A.Y. Al-Saati, Z. Kh. Awad and Kh. I. Mohmmad [7] studied the non-linear behavior of RC slabs subjected to high temperature at service loads. The model was represented as layered shell element to predict the thermal and mechanical properties of the structural element at elevated temperature condition. The developed F.E model assumes a linear distribution of temperature along the slab thickness. As the temperature increases, the developed membrane tension contributes to carry the applied load. It was found that the section is fully cracked after one hour exposure to high temperature. The obtained results from this FE analysis were compared to the available experimental results by Lim and Wade [2] and Nechnech, Meftah and Reynouard [8] and a good agreement was shown.

Huang, Z.H. [9], carried out a numerical analysis to estimate the mechanical and thermal behavior of a uniformly loaded RC slab subjected to fire, taking into account the concrete cover spalling as a result of fire exposure. The study includes several cases regarding the position of localized fire and degree of cover spalling. The analysis results revealed that the concrete cover spalling significantly affect the thermal behavior of slabs. For the effect of the cover spalling on the structural behavior of slabs, it was found that it is associated with the thermal restraint provided to the slabs. The fire resistance of the slabs in the corner bay

of the building decreases with the increase of the cover spalling degree the cover spalling because of the insufficient thermal restraint in that region, while there is no significant effect of the cover spalling on the fire capacity of the internal bays of the building due to high thermal restraint.

Patrick Bamonte and Roberto Felicetti [10] studied the fire behavior of a typical underground garage roof consisting of a flat concrete slab supported by slender columns. To investigate the structural behavior, the RC flat slab was modeled by using ABAQUS software program. In this study, the car fires were considered as localized fires applied to the slab. The columns were modeled as point supports which means neglecting the bending stiffness and thermal expansion of the columns. Depending on the model analysis results, it was found that the axial loads applied to the columns increase by two to four times their values at the ambient temperature when exposed to localized fire which leads to increase the risk of punching shear of the slabs.

Sara J. George and Ying Tian [11] performed a nonlinear analysis to simulate the performance of flat plate buildings exposed to fire. ABAQUS finite element software was used in the analysis. The mechanical and thermal properties of materials obtained from experimental work done by Elstner and Hognestad [12] for the tensile strength of concrete and Lim and Wade (2002) for the concrete thermal properties, thermal conductivity and heat transfer, specified in ASCE (1992) [13] Manual No. 78 and EC2 (1992) [14], were used in the analysis.

On comparison with the test results obtained by Lim and Wade [2] related to the slab vertical deflection with time up to (180 min.), it was found that the ASCE (1992) [13] concrete thermal properties definitions are more accurate to represent the deflection response of slabs. The analysis predicts the residual strength of the flat plate under elevated temperature by examining the slab vertical deflection, in-plane slab expansion, membrane force, bending moment redistribution, and slab rotational deformation near the supporting columns. It also studies the effect of elevated temperature on punching shear failure at the slab-column connections of a flat plate.

For the finite element analysis, the RC slabs were simulated using thin shell elements, the mesh size equals the slab thickness, the boundary conditions of the element are restrained in three dimensions along two edges of the slab and unrestrained along the other two edges as a quarter of the slab was modeled to reduce the computations cost.

Depending on the heat transfer analysis, it was found that the flexural capacity of the slab in the mid span is reduced significantly after exposure to fire for 1.5 hr. as the bottom reinforcement experiences decrease in its yield strength by 22%. For vertical deflection, it was obtained that the deflection at the center of the heated panel is three times the value at the panel edge and reaches a maximum value after exposure to fire by 1.5 hr.

Bending moment redistributions at mid span occur after four minutes of heating that changes the positive into negative. At 30 min., all the regions of heated panel resist only negative moment. However, the change in bending moment between 30 and 90 min of heating is small. The slab rotation increases with the increase of the heating exposure time, the large value of slab rotation affects the shear strength of the slab column connection since it causes to increase the inclined cracks. From the FE analysis, it was found that the punching shear strength of the heated slab at 90 min. is much less than the design punching strength caused by the large cracks associated with the slab rotation and hence more attention should be paid to the actual capacity of flat plates exposed to fire.

C Sangluaia , M K Haridharan, C Natarajan, A. Rajaraman [15] studied the behavior of RC slab exposed to fire. A nonlinear analysis was performed using FE package ABAQUS in the modeling. The main factors considered in the model are slab thickness, reinforcement percentage, slab width and different boundary conditions under fire loading. Depending on the analysis results, it was found that the displacement decreases with the increase of the slab thickness and with the decrease of the slab width. For the reinforcement percentage, the deflection is reduced when using larger amount of reinforcement. Finally, the fire resistance is the largest when the boundary condition is fixed-fixed, then it is less if the support are pinned-pinned, followed by fixed-roller boundary condition and the smallest fire resistance was observed when the boundary condition is pinned-roller.

Mengzhu Diao,Lanping Qian, Yi Li, Xinzheng Lu and Hong Guan [16], have investigated the progressive collapse of a multi story building exposed to fire numerically, a fiber beam model and layered shell model were used to simulate the behavior of beams and columns and two way RC slabs, respectively. The boundary conditions are simply supported at all four edges and the fire loading is subjected at the bottom of the slab. The analysis results showed that the exposure to fire causes an increase in the axial load applied to columns which leads to the damage of the most affected columns, however, the building remains stable and does not collapse because of the redistribution of the internal forces. As the duration of fire exposure increases, the structure cannot resist any more loads because of the large deformations of the structural members. Eventually the structure will fall as a result of progressive collapse.

Gouda Ghanem, Tarek Ali, Mohamed Nooman, and Mohamed Kadry [17] carried out an experimental and numerical nonlinear FE analysis to study the behavior of RC flat slab exposed to fire. The analysis was performed by using ANSYS to simulate the experimental specimens which were divided into two groups, in the first group (A), the concrete cover is fixed and equal to 25mm while the fire duration varies from one to three hours. In the second group (B), three values of concrete cover were selected as (30, 35 and 40mm), while the fire duration is constant at four hours. The structural behavior of the members depends on the concrete cover thickness and fire duration. The numerical results are consistent with the tests results. The main conclusions obtained from the present work

are: as the concrete cover decreases, the slab fire resistance decreases for the same value of fire duration. Also, with the increase of the fire exposure time, the slab fire resistance decreases at a constant value of concrete cover thickness.

Hamed Sadaghian and Masood Farzam [18] predicted the punching shear strength of reinforced concrete slabs subjected to fire. The study includes the effect of different parameters which are the fire direction, flexural reinforcement ratio, shear reinforcement, load levels, and compressive strength of concrete. The analysis results revealed that when fire is subjected from the top it causes the slab to deflect upward, with the decrease of the applied load value, the deflection changes to be in the direction of the gravity load. When the fire is subjected from the bottom surface, it will increase the vertical displacement in the direction of the gravity load which results in slab collapse. Related to the compressive strength of concrete, there is no significant effect of concrete grade on the slab fire resistance. For the effect of shear reinforcement, it was found that it has no effect on the fire resistance for the same load value. Moreover, it was noted that the flexural reinforcement ratio affects the failure mode of the slab which becomes brittle punching when increasing the reinforcement ratio. The estimation of fire resistance enhancement by adding gypsum as an insulating material was also studied, and the numerical analysis showed that the use of gypsum layer of 10 mm and 20 mm thickness reduces the maximum heat transferred to the slab by 45.8% and 70%, respectively.

Athraa H. Gharbi, Akram S. Mahmoud and others [19-22] developed a numerical model to simulate the behavior of RC slabs exposed to fire. The thermal analysis was performed by using ANSYS package, the concrete and reinforcing steel were modeled by using SOLID70 and link 33 elements, respectively. The boundary conditions of the model is simply supported for four edges, the time of exposure to thermal loading was selected to be 2 hr. A parametric study was conducted in order to study the influence of temperature values, length to thickness ratio and concrete compressive strength. The numerical results showed that the increase of slab length/thickness ratio significantly increases the deflection under fire conditions. The deflection increases at elevated temperature by 25%, 41% and 66% of its value at ambient temperature for temperature values (600, 800 and 1000 oC), respectively. For the effect of compressive strength, it was found that increasing the concrete grads by 50% and 100% reduces the deflection value by 17.5% and 28.6%, respectively under fire condition.

3. Conclusions

The numerical analysis models results for RC flat slabs exposed to fire when compared to the available experimental results in that field have been found to be well representing the actual mechanical and thermal behavior of the structures. The results show that the flat slabs fire resistance is affected by major factors including the fire duration, fire direction, supports conditions and the concrete cover thickness. The vertical deflection decreases with the increase of the slab thickness and decrease of slab width. It was also found that the developed membrane tension contributes to carry the applied load. The fire exposure time causes to increase the slab rotation which affects the shear strength of the slab column connection since it causes to increase the inclined cracks. The Fixed-Fixed boundary condition is considered the best to increase the fire resistance. It was found that there are very limited experimental and numerical studies on the cover spalling impact which is needed to be investigated since it significantly influences the slab fire resistance depending on the localized fire position. Also, the thermal restraint of the building can reduce the risk of the fire exposure.

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