

Numerical analysis of axial compressive behavior of RC short columns subjected to non-uniform fire: A meso-scale study

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Abstract: The bearing capacity and durability of reinforced concrete (RC) structures can be affected by fire. In this study, a three-dimensional (3D) meso-scale simulation model for RC short column subjected to axial compression after exposure to fire was established. The degradation effect of mechanical properties of steel bars and concrete materials after high temperature was taken into account. The bond-slip behavior between longitudinal steel bars and concrete was also considered in the model. Based on the present simulation method, the failure mode and failure mechanism of the RC short columns were investigated. Moreover, the effects of fire scenario and fire duration on the axial compression performance of RC short columns were further investigated. It is found that the meso-scale numerical model can effectively simulate the mechanical behavior of RC short columns under axial load. Moreover, with the increase of fired surfaces and fire duration, the peak bearing capacity, axial compression stiffness and ductility decrease. The mechanical properties of short columns decrease more quickly under non-uniform fire. By comparing the theoretical value with the numerical simulation value of N_{ut}/N_u , it is found that the theoretical value is conservative.

1 Introduction

As the main load-bearing components, reinforced concrete (RC) columns may experience local or even overall damage due to the high temperature, thus losing a portion of its bearing capacity and affecting the service life of buildings. It is of great engineering significance to study the mechanical behavior evolution and damage mechanism of RC columns after elevated temperature.

Abduraheem and Kadhum [1] found that the initial stiffness and secant stiffness of the columns decreased significantly through the experiments. Martins and Rodrigues [2] found that the fire resistance of columns increased with the cross-section dimensions by experiments. The experimental results of Huo et al. [3] have indicated that with the increase of temperature, the axial compression stiffness and ductility coefficient of columns decreased continuously. In addition, the influence of load, section size, concrete strength and other parameters on the fire resistance of RC columns were analyzed by numerical model [4, 5]. On the basis of some assumptions, Nguyen et al. [6] developed a simplified theoretical analysis model for calculating temperature induced restraint force.

It can be seen through the abovementioned work, a lot of efforts have been devoted and promoted to the understanding of the failure mode and damage mechanism of RC columns under the action of fire or high temperature. However, there are still some issues left open to be studied and discussed. For example, most of the physical tests set

the fire scenarios as uniform fire on four sides. The available numerical models are usually macroscopic models, which cannot reveal the failure mechanism of components in depth. Moreover, the interaction between steel bars and concrete is always supposed as perfect bond, neglecting the relative slip between them [4]. Therefore, in this study, a three-dimensional (3D) meso-scale finite element (FE) numerical models for RC short column considering bond-slip behavior were established to investigate the axial compression behavior after exposure to fire.

2 Mesoscopic model for RC short columns

2.1 Geometric model

From a viewpoint of meso-scale, the concrete was considered as a heterogeneous three-phase material consisting of aggregate, mortar matrix and interface transition zone (ITZs) connected the former two phases [7]. The 3D numerical model and rebar arrangement of RC short column can be seen in figure 1. Moreover, the "concrete-steel bond-link element" proposed in [8] was used to describe the nonlinear bond-slip behavior between longitudinal reinforcement and concrete.

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(a) Axial loads N

Plate
 Mortar matrix
 Aggregate
 ITZ
 Longitudinal rebar
 Stirrups

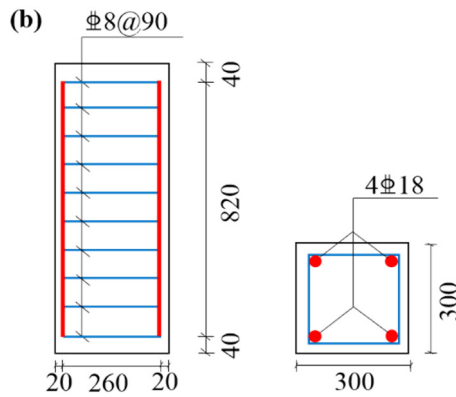


Figure 1. Numerical model of the RC short column. (a) Loading mode; (b) Cross-section size and rebar arrangement.

2.2 Constitutive model and parameters

2.2.1 Heat transfer analysis. The influence of temperature on thermal parameters of concrete is considered in the present work [9], as shown in figure 2. The thermal parameters of concrete at room temperature were listed in Table 1 [10-12]. The density, thermal conductivity and specific heat of steel bar was regarded as constant value of 7850 kg/m³, 45 W/(m·°C) and 600 J/(kg·°C), respectively [13].

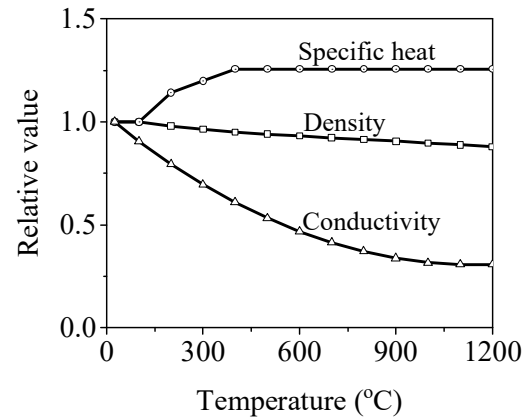


Figure 2. Evolution of density, thermal conductivity and specific heat capacity for concrete with temperature.

Table 1. Thermal parameters for the concrete components at room temperature.

Material parameters	Aggregate	Mortar matrix	ITZ
Heat conductivity k [W/(m·K)]	3.15 [10]	1.9 [10]	0.7
Special heat capacity c [J/(kg·K)]	798 [11]	813 [12]	906
Mass density ρ [kg/m ³]	2750	2400	2200

2.2.2 Constitutive model and mechanical parameters. The mortar matrix and the ITZs were described by the damage plastic model [14]. The aggregate phase was assumed to be elastic [15]. The bilinear elastoplastic model was used to describe the mechanical behavior of

steel bars. The bond stress-slip relationship between concrete and steel bars was used to describe their interaction behavior [16]. In this work, the mechanical performance degradation rule established by Ref. [17-19] for concrete and rebar after high temperature was used, as plotted in figure 3. The mechanical parameters of different components at room temperature are listed in Table 2.

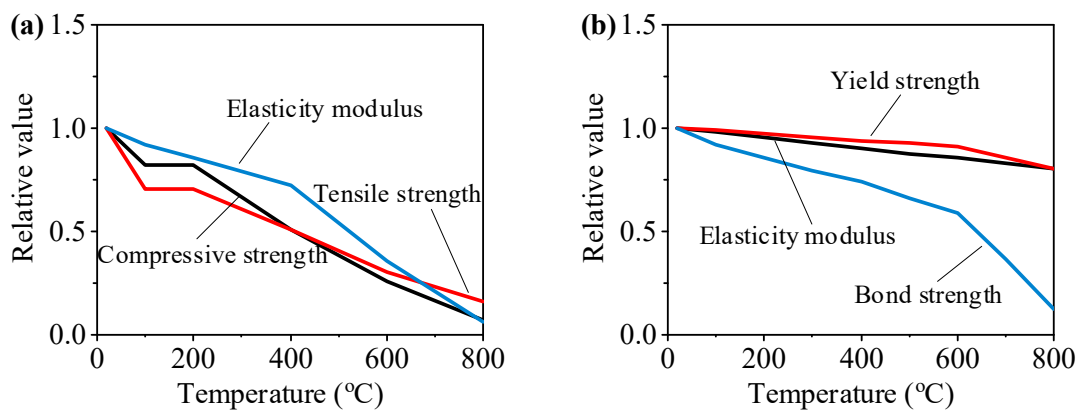


Figure 3. Degradation of mechanical performance after high temperature. (a) Concrete; (b) rebar.

Table 2. Mechanical parameters of concrete components and steel bar at room temperature.

Material parameters	Aggregate	Mortar matrix	ITZ	Stirrups	Longitudinal rebars
Compressive strength f_c (MPa)	-	50	36	-	-
Tensile strength f_t (MPa)	-	5.0	3.6	-	-
Elastic modulus E_c (GPa)	70	32.5	30.5	200	200
Poisson's ratio ν	0.2	0.2	0.2	-	-
Yield stress f_y (MPa)	-	-	-	512	520

2.3 Loading and boundary conditions

ISO 834 curve [20] was adopted to describe the heating regime of RC short columns in fire accidents. In the analysis of mechanical behavior, a displacement-controlled loading was employed while the displacement growth rate was 0.4 mm/min.

3 Numerical analysis model verification

The C0 and CR2 specimen in Zhang et al.'s [21] experiment was selected as a reference to verify the numerical simulation model. C0 is the specimen at room temperature and CR2 is the specimen with initial load after being exposed to fire on four sides. In the simulation, all the dimensions, thermal and mechanical properties of

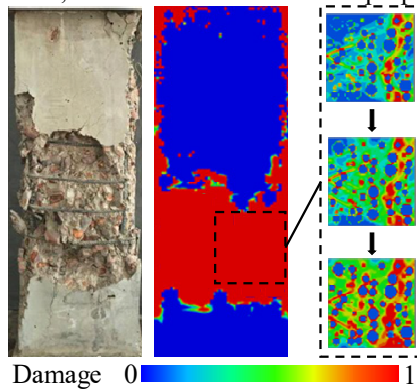


Figure 4. Failure mode of the numerical and experimental [21] at 20 °C.

4 Parametric studies

4.1 Effect of fire scenarios

The five fire exposure scenarios (namely, fired by single side, opposite two sides, adjacent two sides, three sides, and four sides) with a fire duration of 60 min, the failure mode of RC short column can be noted in figure 6. The failure mode of short column is axisymmetric under uniform fire. In the case of non-uniform fire, the deterioration of concrete directly exposed to fire is faster than that of concrete subjected to indirect fire. This can be

materials as well as boundary and loading conditions were kept as the same as their counterparts in the test.

It can be seen in figure 4 that the failure mode of numerical simulation is similar to that of the test at room temperature. Due to the slip between the longitudinal reinforcement and concrete, the concrete is damaged along the direction of the longitudinal reinforcement cover, which is also consistent with the actual physical test results. Moreover, the concrete failure process can be clearly observed in the mesoscopic model. The cracks first appear within the ITZ phase. Then, the cracks gradually propagated into the mortar matrix, bypassing the aggregates with the load increases, leading to the formation of macro cracks. The load - axial strain curves of the numerical model are in line with the experiment results, as shown in figure 5.

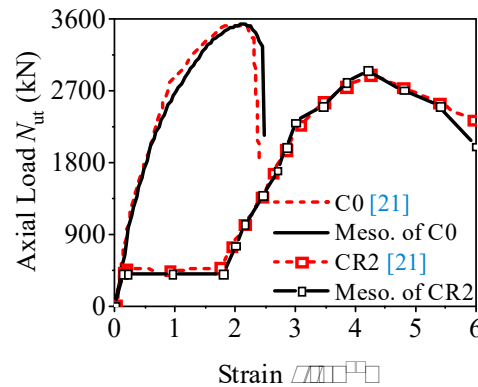


Figure 5. Load (N_{ut}) - Axial strain (ϵ) curve of RC short columns.

attributed to the fact that the properties of concrete were degraded by the high temperature, generating more serious damage on the fired surfaces.

It can be noted that with the increasing fired surfaces, the falling section of the curve is gentler due to the softening of the concrete materials caused by elevated temperatures, as plotted in figure 7. Moreover, the peak load carrying capacity of the columns on the adjacent two sides decreases more than that of the short columns after exposure to fire on the opposite two sides. This shows that the non-uniform fire makes the bearing capacity of the column further reduced.

A decrease in the axial compression stiffness and ductility coefficient can be easily noticed with the increase

of the fire surfaces due to the reduced strength and Young's modulus of concrete and steel bars after high temperature, as listed in Table 3. It should be noted that the ductility of the adjacent two sides is less than that of the three sides and four sides. It can be explained by the

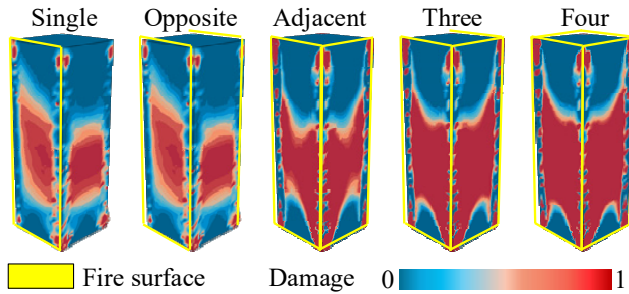


Figure 6. Failure mode of RC short columns after fire for 60 min at different scenarios.

fact that when adjacent two sides of RC short column are exposed to fire, RC short column undergoes eccentric compression under the axial load, dramatically reducing the ductility [3], which further indicates that non-uniform fire has a greater impact on the ductility of columns.

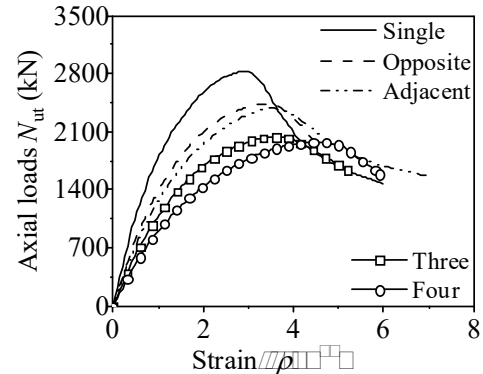


Figure 7. Load (N_{ut})-Axial strain (ϵ) curve after fire for 60 min at different fire scenarios.

Table 3. Stiffness and ductility at different fire scenarios.

Fire surfaces	Single	Opposite	Adjacent	Three	Four
Stiffness EA_t ($10^6 \cdot \text{kN}$)	2.50	1.98	1.84	1.65	1.43
Ductility μ	1.283	1.281	1.276	1.280	1.277

4.2 Effect of fire duration

It can be seen in figure 8 that the peak bearing capacity of the side columns decrease gradually with the increase of fire duration. The peak strain of side columns increases with the fire duration, which indicates that the concrete material softens after high temperature. It can be found that the peak bearing capacity shows a nonlinear downward trend as the fire duration increases.

The ratio of stiffness or ductility coefficient after different fire duration to those after 30 min is used to describe the relationship between fire duration and ductility coefficient or stiffness, as shown in figure 9. The

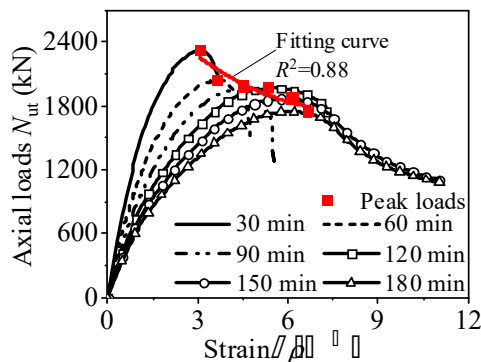


Figure 8. Load (N_{ut})-axial strain (ϵ) curve of side columns after different durations.

ductility coefficient decreases linearly with the increase of fire duration. In addition, it can be noted that for the side columns, the relationship between the axial compression stiffness and the fire duration is a nonlinear function may be adopted to describe this relationship. What's more, the curve is convex to the time axis, indicating the different variation speed of stiffness. This can be attributed to the fact that the axial load of RC short column is mainly borne by concrete. When the time of fire is short (less than 90 min), the strength of concrete drops sharply. After 120 min, the maximum temperature of the column section is above 1000°C , the concrete almost loses all its strength. Consequently, the decreasing trend of axial compression stiffness slows down.

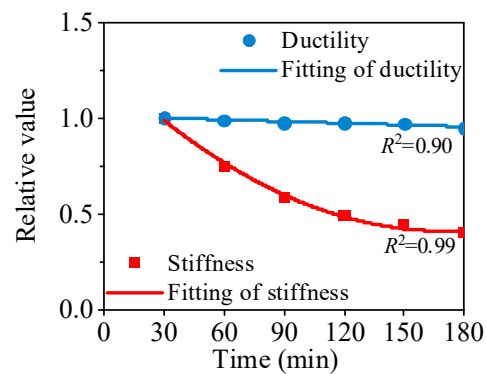


Figure 9. Relationship between the stiffness, ductility and fire durations.

5 Conclusions

In this present work, a 3D mesoscopic numerical model of axial compression of RC short columns after exposure to fire was established. On the basis of the verification of the rationality of the mesoscopic model, the effects of fire scenario and fire duration on the performance of RC short columns under axial load after fire were further discussed. Based on the analysis, the following conclusions can be drawn:

(1) The meso-scale numerical model considering the heterogeneity of concrete can effectively simulate the axial compression performance of RC short columns.

(2) The increase of fire duration and fire surface has adverse effects on the peak bearing capacity, ductility and axial compression stiffness of RC short columns.

(3) After the same fire duration, the non-uniform fire has great influence on the failure mode and the ductility of the column, but has little effect on the axial compression stiffness.

(4) With the increase of fire duration, the peak bearing capacity and stiffness of the side column show a nonlinear downward trend. The relationship between ductility coefficient and fire duration can be described by linear function.

Acknowledgements

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