Finite element simulation analysis of reinforced concrete large haunched slab under fire

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Abstract: The finite element software ABAQUS is used to set up the model of large haunched slab. By using the sequential thermal stress coupling calculation method, the validity of the data model is proved by comparing with the experimental results. On the basis of this, the fire resistance of large haunched slab is analyzed. The fire resistance limit of large haunched slab with different thickness of protective layer is obtained, which provides reference for the fire resistance design of large haunched slab.

1. Introduction
In recent years, in the design of underground garages and basements, in order to save space, facilitate construction, reduce expenditures, the structure of the haunched slab roof has been widely used. However, at present, scholars have only studied the design method of the slab [1], and there is no relevant literature about the research on the fire resistance performance of the slab.

2. Fire resistance finite element model of haunched slab
In this paper, ABAQUS finite element software is used to analyze the thermal coupling of two-way haunched concrete slabs with fired bottom. When the reinforced concrete structure is exposed to fire, the physical and chemical parameters inside the steel and concrete materials change with the increase of temperature, which shows the mechanical properties different from normal temperature. In order to analyze the fire resistance of reinforced concrete structures, the thermal performance and high temperature constitutive model parameters of steel and concrete materials at high temperatures must be determined.

2.1. Temperature field analysis
In the analysis of temperature field, the bottom of the slab is heated. The temperature is raised according to the ISO 843 international standard heating curve. The convection coefficient and the radiation coefficient are taken from the literature [2]. The convective heat transfer coefficient is 25W/(m²·K) on the fire surface and 10W/(m²·K) on the backfire surface. The radiation coefficient is 0.5 on the fire surface and 0 on the backfire surface.

2.1.1. Thermal properties of concrete materials
The density of concrete is constant, set to 2350kg/m³. The internal heat transfer theory of concrete adopts Fourier heat transfer theory, and the value of thermal conductivity (k, W/(m·°C)) is taken from...
the literature[3][4].

\[ k_\ell = \begin{cases} 
1.355, & 0°C \leq T \leq 293°C \\
-0.001241T + 1.7162, & T > 293°C 
\end{cases} \]  

(1)

The specific heat of concrete(Cc,J/(kg·°C)) uses the European standard EC 2[5]:

\[ C_c = \begin{cases} 
900(J/(kg·°C)), & 20°C \leq T \leq 100°C \\
900 + (\theta - 100)(J/(kg·°C)), & 100°C < T \leq 200°C \\
1000 + (\theta - 200)(2J/(kg·°C)), & 200°C < T \leq 400°C \\
1100(J/(kg·°C)), & 400°C \leq T \leq 1200°C 
\end{cases} \]  

(2)

Considering the effect of water loss on temperature distribution, the concrete specific heat is increased by 30%.

2.1.2. Thermal performance of steel bars

The density of steel bars is 7850kg/m3, and the value of thermal conductivity(λS,W/(m·°C)) is taken from the literature[3][4]:

\[ \lambda_S = \begin{cases} 
282 W/(m·°C), & 0°C \leq T \leq 900°C \\
900(W/(m·°C)), & T > 900°C 
\end{cases} \]  

(3)

The value of specific heat(Cs,kJ/(kg·°C)) is taken from the literature[3][4]:

\[ C_s = 38.1 \times 10^4T^2 + 20.1 \times 10^5T + 0.473 \]  

(4)

2.2. High temperature constitutive parameters of materials

2.2.1. Mechanical properties of concrete at high temperature

The total strain produced by concrete under high temperature, including thermal stress—strain, thermal expansion strain, transient thermal strain, and high temperature creep. The elastic modulus, compressive strength and stress-strain curve of concrete at high temperature are directly taken from the literature[5]. The stress-strain curve proposed in literature[5] implies high temperature creep and transient thermal strain[8]. The coefficient of thermal expansion α is taken from the literature[9]:

\[ \alpha = 10 \times 10^{-6}, \quad 20°C < T \leq 300°C \]  

\[ \alpha = (0.025T + 2.5) \times 10^{-6}, \quad 300°C < T \leq 700°C \]  

(5)

\[ \alpha = 20 \times 10^{-6}, \quad T > 700°C \]

2.2.2. Mechanical properties of steel bars at high temperatures

The total strain of the steel bar at high temperatures includes the thermal stress strain of the steel bar, the high temperature creep and the thermal expansion strain. The elastic modulus, yield strength and stress-strain curve of steel bars at high temperature are taken from the literature[5]. The expansion coefficient of steel bars under high temperature is taken from the literature[10]:

\[ \alpha_t = \begin{cases} 
(0.004T + 12) \times 10^{-6}, & T < 1000°C \\
16 \times 10^{-6}, & T \geq 1000°C 
\end{cases} \]  

(6)

3. Test verification of finite element model at high temperature

In order to verify the applicability of the simulation analysis of the haunched slab model at high temperature, the fire test of the fixed support slab and the simply supported slab from the literature[12] was selected as the object for verification.

Through the ABAQUS finite element software analysis and calculation, the temperature-time curve of the fixed support slab and the displacement of each measuring point with the refractory time are compared with the test results and is shown in Fig.1 and Fig.2. The displacement-time curve of the simple support slab is compared with the test as shown in Fig.3. It can be seen from the figure that the simulation results are in good agreement with the experimental results and can be used for analysis of fire behaviors of the slabs.
Fig. 1 Test plate temperature-time curve

(a) Vertical displacement distribution map of fixed plate

(b) Measurement point 15 displacement-time curve

(c) Measurement point 4 displacement-time curve

(d) Measurement point 28 displacement-time curve

(e) Measurement point 30 displacement-time curve

Fig. 2 Comparison between the results of the fixed plate test and the finite element method
4. Analysis of fire resistance performance of reinforced concrete reinforced large slab

In this paper, the slab structure with a column spacing of 8.4×8.4m is used, the slab thickness is 0.25m, the haunching thickness is 0.2m, the haunching length is 1.2m, and the thickness of protective layer is 0.02m. In this paper, the load of the covering soil and the weight of the roof are considered. The top slab of the basement has 1.5m thick covering soil with a density of 19kN/m3 and a live load of 5kN/m2. Fire load is not considered at this time. Using C30 concrete, using YJK software haunching module design calculation, the lower force rib X&YC12@200, the support negative rib C12@200, the upper distribution rib A10@200, the initial boundary condition four sides fixed, using ABAQUS software to establish the finite element model.
4.1. temperature field of large haunched slab
The heat transfer analysis of the above model is carried out, and the temperature distribution curve of the slab is obtained, and the temperature-time curve of the 1/2 model map and the measurement points of the slab side and the span is shown in Fig. 4. It can be seen from the figure that the large-scale slab has a large temperature gradient from the bottom and the inside of the fire, and the temperature difference of the different thicknesses is also relatively large.

4.2. deformation of the large slab under fire
The heat transfer result was introduced into the above model. A static analysis was performed to obtain a displacement-time curve of the large haunched slab, as shown in Fig. 5. In Figure 5, the deformation of the haunched slab with a 0.02m-thick protective layer is divided into three stages: In the first stage, the deformation rate is very slow, and the vertical displacement increases a little. In the second stage, the deformation rate increases sharply. In a short time, the vertical deformation increases sharply. The deformation rate in the third stage is about 1/2 of that in the second stage. The deformation of large haunched slabs of different protective layer thickness also conforms to this feature.
4.3. Fire resistance endurance of haunched slabs with different protective layer thickness under fire
The fire endurance is an important index for the fireproof design of building structures. As shown in Fig. 5, four types of large haunched slabs with different protective layer thicknesses were selected for fire endurance analysis. The results are shown in Table 1. It can be seen from the table that the fire resistance endurance of the protective layer thickness of 0.03m and 0.04m is obviously greater than the fire endurance of 0.015m and 0.02m. The fire resistance endurance of the protective layer thickness of 0.03m and 0.04m meets the requirements of 1.5h of the Code for Fire Protection of Building Design.

| Table.1 Fire resistance limits of different thickness of protective layer |
|------------------|-----|-----|-----|-----|
| thickness of the protective layer/m | 0.015 | 0.02 | 0.03 | 0.04 |
| fire endurance/min | 73 | 71 | 116 | 114 |

5. Conclusion
(1) The data model of this paper can be used to analyze the deformation characteristics of simulated reinforced concrete slabs at high temperature. The obtained temperature field and deformation curve agree well with the experimental results, indicating that the sequential thermal stress coupling analysis model established in this paper is effective.
(2) Under high temperature, there is a nonlinear temperature field along the section of the large reinforced haunched concrete slab. The heat of the temperature field transmits very slow inside the concrete, and there is a large temperature gradient along the thickness direction.
(3) The finite element analysis of the slabs under fire is carried out, and the three-stage deformation characteristics of reinforced haunched concrete slabs under fire are obtained. Compared with the three-stage deformation characteristics of ordinary reinforced concrete slabs proposed in literature[9], there is a big difference.
(4) The thickness of the concrete protective layer has a significant influence on the fire resistance endurance of the haunched slab. Appropriately increase the thickness of the concrete protective layer, the fire resistance endurance will be strengthened, and the thickness of the conventional protective layer cannot meet the requirement of the fire resistance endurance. This paper provides a reference for the refractory design of the haunched slab.

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