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Study on Thermal Response of Building Steel Structure Components in Fire

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To analyze the thermal response of building steel structure components in fire. The study stimulates indoor fire scene by the finite element software application, and designs the correlative parameters according to the possible steel structure reaction in the actual fire scene, and analyzes the thermal response of the steel structure members combined with the simulation results. The study found that steel structure components may be deformed or displaced because of fire heating, which will affect the overall performance and stability of building steel structure. The simulation of thermal response of building steel structure components does favor to prevent fire, so the study has applied research value.

1. Introduction

Steel structure is a common building material in the construction industry, which has a wide application value in civil architecture, industrial building and so on. The steel structure components can be easily installed, and with less weight load, it has a relatively high strength, so it is often used in green building structure design. Fire is a common disaster in nature, which poses a great threat to people's safety of life and property. Today, the building functional structure has become more and more perfect, the fire problem is becoming increasingly obvious, and it has attracted a widely concerns. Every year, China suffers death and economic losses result from fire, so we must consider the possible fire when applying the steer structure components. From the view of building construction structure, the steel structure itself has a poor fire resistance, so when there is fire, steel structural components may be damaged, which will affect the stability of building. Especially, high temperature will change the properties of many building steel components. Therefore, the construction department should highlight the research on the thermal response of steel structure components, and take stimulation analysis to explore the influencing factors of steel structure components.
The paper takes indoor fire stimulation as the main research method, determines the impact factors according to analysis of steer structure properties and determines the feasibility of research method.

2. Literature review

The reaction process of steel structures under indoor fire is very complicated. It is affected by many factors, such as the development process of indoor fires, the law of the spread of hot smoke gas, the distribution of temperature field in indoor space, the heating curve of indoor fire, the transient temperature field distribution of structural members, and the mutual restraint effect of thermal expansion between components, the thermophysical and mechanical properties of steel at high temperature, and so on (Kenisarin and Mahkamov, 2016). At present, the research on the fire resistance of steel structures at home and abroad is mainly focused on two aspects: the study of the fire model in the building and the research on the thermal structural response characteristics of the steel structure.
Sharma et al. pointed out that the fire in a building is usually caused by the ignition of flammable materials in a confined space (Sharma et al., 2015). Compared with outdoor fires, there are two significant differences in indoor fires. First, the heat generated by the combustion of combustibles accumulates in the room, enhancing the heat transfer to the surface of the material. Second, indoor air is limited, which has an important impact on the development of combustion. With the development of indoor fire, the temperature of fire components

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increases, which leads to the decrease of strength and the increase of deformation. The overall stability of the structure is affected. The in-depth analysis of the development law of the fire in the building is the premise of the research on the fire response characteristics of the steel structure. Therefore, it is necessary to analyze it.

Kylili et al. (2014) pointed out that in general, the development process of indoor fires will experience three stages: initial growth, overall development, and extinction. In the immediate aftermath of a fire, the heat generated by combustion continuously accumulates in the room, causing pyrolysis of combustibles. When the flammable volatiles accumulate to a certain extent, flashover will occur. However, since this phenomenon occurs in a moment, it is generally not analyzed as an independent stage. Subsequently, indoor combustibles were ignited, burning rapidly and violently, and the room temperature increased sharply, which was at the prime stage of fire burning. Until the flammable substances are gradually burned out, or the oxygen is exhausted, or after the firefighters have saved, the room temperature gradually decreases and the fire eventually fades to extinguishment.

Bikas pointed out that there are many influencing factors in the development process of building interior fires, and domestic and foreign researchers have proposed various indoor fire research models (Bikas et al., 2016). There are three types of indoor fire temperature-time curves commonly used in current research:

In the study of structural fire resistance, various countries have adopted different fire heating curve models. However, in order to solve the connection between different models, the International Standards Organization has established the ISO834 standard temperature rise curve. It is a standard fire curve used to measure and compare the fire resistance of various structural components during the temperature rise process in the room. At present, China adopts this curve in its research, but it does not consider factors such as fire load, fire source location, and ventilation coefficient in a fire room. However, these factors have a major impact on the bearing capacity of structures and components.

The standard heating curve provides convenience for structural fire resistance design. There is a certain gap between the standard heating curve and the actual fire. To link the two, the researchers proposed the concept of equivalent exposure time. This can not only better reflect the degree of structural damage in the actual fire, but also can maintain the standard warming curve of the simple and practical.

The actual fire process is very complicated and it involves many factors. In order to obtain the temperature rise curve in indoor natural fire, the computer simulation method is an important research method. At present, the indoor natural fires are simulated by three methods: empirical simulation, regional simulation and field simulation. The field simulation is to discretize the research space and use numerical methods to solve a group of partial differential equations that control the fire process, so as to obtain the distribution of each state parameter in the indoor space during the fire. The fire dynamics software FDS was used to simulate the entire process of an indoor fire. The response characteristics of steel structures were analyzed under the conditions of natural indoor fires (Bourada et al., 2015).

The domestic study of the fire resistance of steel structures began in the 1980s. Although it was relatively late to start, it also achieved some phased results. Tang et al. performed a series of fire-resistance performance tests with different types of steel components and steel frames as a whole, and obtained many important results (Tang et al., 2015). Ma et al. analyzed the axial forces of the constrained steel girder in the heating and cooling sections. The results showed that the axial force was complex and this was very unfavorable to the end nodes of the beam. Therefore, in the design of flame-resisting steel beams, the checking of nodes should be strengthened (Ma et al., 2015). Shao et al. performed fire resistance tests on a single-span steel frame. On the frame, different horizontal loads were applied to obtain the response of the steel frame under fire conditions. The fire resistance test was carried out on a three-planar portal steel frame. The damage accumulation was considered in the experiment. The effect on the stress and deformation of the structure was studied, and the deformation and ultimate bearing capacity of the structure after the fire were analyzed (Shao et al., 2016).

In summary, researchers at home and abroad have done a lot of research work on the temperature field of steel structures, which has promoted the development of research on fire resistance of steel structures. However, the analysis of the temperature field distribution pattern, the type and thickness of fire protection layer is relatively insufficient. In addition, many studies use the standard heating curve as an assumption for temperature field analysis. The analysis and calculation results have certain limitations, which are quite different from the actual fire development process. Therefore, a method combining structural performance-based fire resistance design with finite element analysis was used to investigate the thermal structural response of steel frames under indoor fire. In this way, intuitive and accurate fire analysis parameters and response status of the steel structure throughout the fire can be obtained.

3. Method

3.1 Analysis of Mechanical Properties of Steel under High Temperature

The Poisson ratio of steel is basically between 0.27~0.3 at room temperature, and it is almost unaffected with the change of temperature, so the Poisson ratio in this paper is v_s=0.3. One of the major purposes of steel mechanical properties analysis is to study the stress-strain relationship at high temperature. For the variety of models the foreign scholars proposed, the paper will select them according to specific analysis and requirement. EC3 takes the modulus got by multiplying the elastic modulus at room temperature and the reduction coefficient at the corresponding temperature. The initial elastic modulus reduction coefficient at different temperature is shown in table 1.

Table 1: The initial elastic modulus of ordinary steel at EC3 high temperature reduction coefficient

Temperature (℃)	20	100	200	300	400	500	600	700	800	900	1000
E^T/E	1.00	1.00	0.90	0.80	0.70	0.60	0.31	0.13	0.09	0.07	0.05

3.2 Analysis of Indoor Temperature When Fire Occurs in Local Areas

Fire combustion is always in a turbulent process, and there are two major numerical methods for simulating turbulence: one is direct numerical simulation and another is large eddy simulation. Direct numerical simulation takes the direct solution to the control equation of turbulence to accurately describe the convection field, temperature field and concentration field at all the time and space. Results of this method is more accurate and without introducing any turbulence model, but it's calculation is quite large, and it can only be used to solve the turbulent flow in laminar and lower Reynolds number under the current calculation conditions. The large eddy simulation decomposes the instantaneous motion of turbulence, which includes pulsation, into large scale motion and small scale motion by some filtering method. The large scale quantity is calculated directly by numerical solving differential equation, and the influence of small scale motion on large scale motion is simulated by establishing the sub grid model. In such way, it greatly simplifies the computational workload and the need for computer memory, which has been widely used in recent studies. The paper researches on steel frame structure. Assuming that there is a fire in a local location in a room, and the paper models and analyzes it. The room is 6.0m in width, 6.0m in depth and 4.0m in height. The steel column is H - shaped with a size of 350 mm× 350 mm× 8 mm× 14 mm, and the steel beam is H- shaped with a size of 600 mm× 300 mm× 10 mm× 18 mm. (the fire model diagram of indoor steel frame is as shown in figure 1).

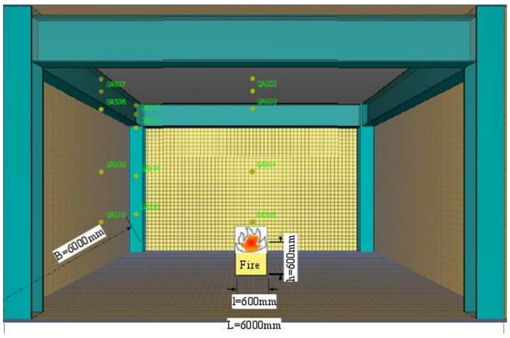

Figure 1: interior fire model of steel frame

The structure layout of the building, the location of fire source, the distribution of combustible materials and combustion characteristics will directly affect the development and spreading of indoor fires. However, it is neither realistic nor necessary to analyze and study all the fire scenes, so it is necessary to have a comprehensive analysis of judge the location of fire, the rate of heat release and the danger of fire in accordance with the function and layout of the building. Thus to determine one or more fire scenes to study and analyze the temperature field distribution of fire in building. According to relevant provision of the Shanghai Civil Building Smoke Control Technology Specification (DGJ08-88-2008) and Australia Fire Engineering Guide, the paper sets the ignition source on wooden desktop, which is 0.6m high from ground. The ignition source is solid stable fire source, the size is 0.6mx0.6m=0.36m^2. When its heat release rate is 500kw/m2, the heat release rate of the ignition source is 180kW. The chapter mainly studies the scene of fire in the indoor location, so the influence of different fire location is mainly considered. The set working condition of the scene are shown in table 2.

Table 2: Fire scene condition

Working condition	Fire source location	Thermal release rate of ignition source (kW/m^2)
Fire scene A	Room center	500
Fire scene B	Beam directly	500
Fire scene C	Column foot	500

3.3 Calculation Model of Steel Frame

The chapter takes a simplified planar steel frame structure as computational model, which is 7 layers, and the height of each layer is 4m, the beam span is 6m, and there are three spans. All pillars are consolidated. Beam-column connection uses H-beam, with steel strength of grade Q235. Section size is shown in figure 2.

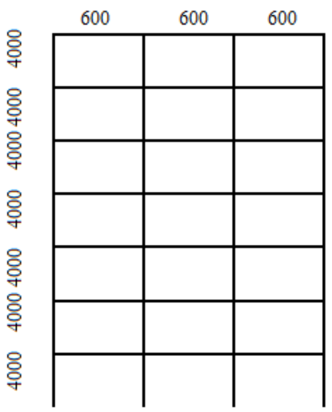

Figure 2: diagram of plane steel frame calculation

4. Results and discussion

4.1 Structural response analysis of steel frames subjected to fire at different positions

In the whole deformation of the steel frame, the displacement of fire beam is larger. As can be seen from Figure 3, the variation tendency of deflection of fire beam is different when fire occurs in different position. Within 420s after the fire occurred, the deflection value of the beam was basically the same when the side span and the middle span was subjected to fire, and it changes small, basically in a stable value about 3mm. With the spreading of fire range, the indoor temperature rises rapidly, and the deflection value also increases rapidly in the beam span. Compared with the side span fire, the middle-span fire is faster, and its deflection value is also slightly larger. 960 seconds later, the deflection value of the middle span fire is increased abruptly, and reaches the peak 52.8mm by 1320s. In the later stage of fire, with the decreasing temperature, the deflection value will gradually stabilized and decreased.

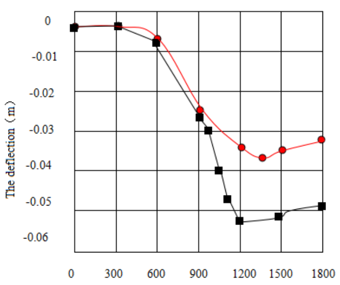

Figure 3: deflection curve of fire beam span

Before 420 seconds, the column top horizontal displacement of the side span and the middle span are basically same, and the growth is slow. Then the fire burning intensified, and the temperature rises very quickly, the column top horizontal displacement value also increases, and the side span fire is growth faster, the displacement value is also larger. When the middle span is exposed to fire, the displacement reaches the maximum value of 31.6 mm at 1020th seconds, and at the same time, the displacement value of the side span is larger and increase continuously, until it reaches the maximum value of 45.6 mm at 1200th seconds. While the fire weakening and the temperature dropping, the side-shift value of the bottom column is reduced. Because the horizontal displacement of top column is large, the column is easy to be unstable and destructive.

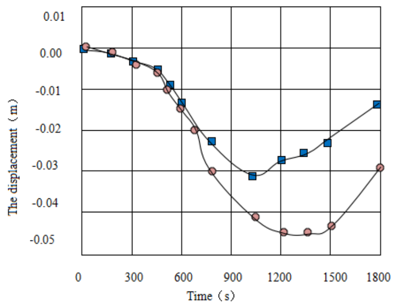

Figure 4: the horizontal displacement curve of the top end of the fire side

4.2 Structural response analysis of steel frames at different heating conditions

In the early stage of fire (first 180 second), the deflection values of beam span in two heating conditions are basically the same and small. With the development of fire, the temperature change of indoor natural fire is very different from the standard heating, and the deflection value of beam is increasing with the increase of temperature under the condition of standard heating, but the deflection value of indoor natural fire is growing slowly, when it reaches 480th seconds, the deflection growth rate is accelerated. However, the deflection value is always less than that of the standard temperature condition. In 1320th seconds, the deflection value of the indoor natural fire reaches maximum, and then the fire and temperature in the room decreases, and result in the deflection value. However, the deflection value of beam is always increasing at the standard temperature, and it will increase rapidly in 1500th seconds, and the changes trend are definitely different. Under the condition of indoor natural fire heating, at the initial stage of fire, the horizontal displacement value at the top column is growing slowly, then with the fire development, it will accelerate growth rate. Side span fire will reach maximum in the 1200th second, and middle span fire reaches maximum in the 1020th seconds, but the value still below that in standard temperature. Analysis of the structural response of steel frame under different heating conditions shows that the deformation and displacement of the structure varies greatly with different heating conditions. As the ISO834 standard heating decrease in curve, the heating rate is fast, and continuous increase, which differs greatly from the actual indoor fire development, and the displacement value of the beam and column in the fire frame is larger under such condition. In indoor natural heating, the deformation displacement of structure is relatively small, which is more in line with the reaction of structure in actual fire, and its fire resistance is longer.

4.3 Coupling field analysis

It is common to encounter two or more engineering physical fields in real physics, they interact with each other, and affect each other, which can not be ignored, and then, it needs coupling field analysis. When analyzing and solving practical problems, we should choose suitable analysis methods for different situations and complexity, there are two major methods, one is direct coupling and another is sequential coupling. The coupling field analysis can be obtained by the direct coupling method in one time, which uses the coupling field type unit, including all the necessary degrees of freedom and coupled by calculating the cell matrix or load vector containing the required physical quantities.

The sequential coupling method calculates and analyses two or more different physical fields in a certain order, and the results of the previous analysis are applied as a known loads to the subsequent analysis for the coupling of different physical fields. Such coupling can be “one-way”, or “two-way”. If subsequent analysis results affect the input of previous physical analysis, such analysis is fully coupled. Indirect method and physical environment method can be used to analyse sequential coupling. The sequential coupling analysis can divide the total load into basic physical load and coupling load.

5. Conclusion

The paper analyses the thermal response of the steel structure with the temperature simulation of local fire chamber, and explores the influence factors of the structure based on the of simulation results. Research shows that the temperatures of steel structure components cross-sections are largely different. When there is fire, the building steel structure components will emerge displacement and deformation. For example, when the top column or the beam span of the steel structure emerge a large displacement, they may affect the surrounding steel structure components, which results in deformation of the building steel structure. When the indoor natural fire occurs, the temperature values of the steel structure components are correspondingly low at any time, and the thermal responses of the steel structure has a certain similarity in indoor nature fire and in actual fire.

Because of the limited professional level, the simulated scene of the indoor fire has yet to be improved, and the thermal response of the steel structure components has some differences with that in actual fire. The relevant designers should consider possible factors to stimulate the actual fire, when they research on the model application of thermal response of model building steel structure in actual fire.

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