Thermal Behavior and Stress Response of Steel-concrete Structures under Solar Radiation

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Abstract: Steel-concrete structures are widely used because of their large space and strong plasticity, but the long construction period, complex splicing process and other factors will make the main body of the structure directly exposed to solar radiation, resulting in temperature changes on the surface of steel structure and concrete structure. In order to obtain the stress changes of steel-concrete structures under solar radiation, two kinds of steel-concrete structures with different support forms were simulated. Under three temperature gradients, the thermal behavior and mechanical properties of two kinds of steel-concrete structures composed of upper steel roof and lower concrete support were analyzed. The results show that there is a linear relationship between the thermal behavior and stress response of steel-concrete structure and the daily temperature difference caused by solar radiation. Under the action of thermal effect, the stress difference between the lower steel frame of the full support structure and the lower steel frame of the support structure on both sides is about 10.7%.

1. Introduction

In recent years, steel-concrete structures are widely used in large-span and large space buildings such as airports, exhibition centers, stadiums and so on. Their basic form is concrete structure in the lower part and steel structure in the upper part, which not only combines the good fire resistance and durability of concrete structure with the excellent plasticity of steel structure, but also meets the use requirements of large bay structure.

The construction period of the steel-concrete structure is very long, especially the erection of the upper steel structure, which may take several seasons to complete. Therefore, the main body of steel-concrete structure may be exposed to solar radiation without auxiliary structure (such as curtain wall and roof panel), which will directly transfer heat with the surrounding environment, resulting in temperature change, thus causing its own thermal behavior stress response.

In recent years, many scholars have done research on the optimization of construction design, innovation of construction technology and safety monitoring of steel-concrete structure and steel structure [1-8]. In the process of construction design optimization, the structural stress form, building materials, external load and other factors are mainly considered, but the structure deformation caused by the temperature difference caused by solar radiation will also cause permanent damage to the structure [9-15]. However, there are few studies on the thermal behavior of steel-concrete structures.

In this paper, the thermal response of steel-concrete structure is analyzed by numerical simulation, and...
the results are discussed.

2. Engineering situation

The airport terminal is located in Handan City, Hebei Province, China, with a construction area of 18000m². The building is a two-story structure (no basement), with reinforced concrete frame structure on the first floor and steel frame structure on the second floor. The whole structure is divided into three parts, axis 1-axis 7 (named as structure A) and axis 22-axis 28 (named as structure B). The steel roof is a symmetrical structure, with a length of 52.5 m, a width of 45 m and a vector height of 17.4 m. The main components of A and B steel roof are 10 orthogonal two-way plane trusses and 2 intersecting roof trusses. Ring beams are set at the intersection of roof trusses to stabilize the structure. The ring beam of A structure is smaller than that of B structure. Similarly, a ring beam is set outside the steel roof to connect and constrain the plane truss, as shown in Figure 1. Figure 2 shows the lower support system of A and B steel concrete structures. The concrete grade is C40. The support forms of the two structures are different. The steel frame support of A structure is mainly concentrated on both sides, and the B structure is fully covered. It is worth noting that the connection mode between the two structures' concrete columns and the upper steel roof is the same, with two-way sliding support in the middle and fixed support on both sides.

![Figure 1. Main section of truss (unit: mm)](image1)

![Figure 2. A and B steel concrete structure support of terminal building](image2)

The shapes of A and B structures are similar to Chinese pavilions, and the intersecting roof trusses are similar to Chinese traditional roof ridges. The change of stress response of steel roof under solar radiation and the influence of stress response on the lower support are the factors that can’t be ignored.
in the process of structure erection. Therefore, it is necessary to simulate the thermal behavior of A and B structures to overcome the construction difficulties.

3. Numerical simulation method
From the 1990s, many scholars began to combine solar radiation with buildings to study the light movement on the surface of roof and curtain wall. The ESRA model uses solar satellite images to estimate the solar radiation received from the ground [16]. ASHRAE clear-sky model proposes a clear sky adjustment factor to calculate the variation of solar radiation on horizontal surface [17]. Liu [18] combined ASHRAE clear-sky model with spatial structure and innovated the calculation method of spatial structure temperature distribution. Through the construction monitoring of Shenzhen Bay Stadium project and Yujiapu railway station building project, this paper analyzes the variation of surface temperature of steel structure affected by environmental temperature and seasonal wind. The variation of surface temperature of steel structure is realized by convective heat exchange with air [19-20].

The main structure of the steel roof truss of the terminal is completed in June 2020. The structure is under construction in summer. The temperature difference between day and night varies greatly. The difference between the average daily maximum temperature and the average daily minimum temperature in July exceeds 7°C, as shown in Figure 3. For the main structure that has been erected, the thermal effect caused by the temperature difference will destroy the installation of the subsidiary structure, and even more serious, it will lead to the overall instability of the structure and the loss of bearing capacity. According to the local temperature change of the structure, the numerical simulation of structure A and structure B is carried out. Through the temperature data in Figure 3, the value of simulated temperature gradient is obtained, as shown in Table 1.

![Figure 3. Temperature data of July 2020](image)

| Gradient   | 1      | 2      | 3      |
|------------|--------|--------|--------|
| Daily temp (°C) | 22     | 22     | 22     |
| Truss test temp (°C) | 30     | 32     | 34     |
| Temp diff (°C)   | 8      | 10     | 12     |

In order to better express the thermal behavior and stress response of steel-concrete structure, four components are selected in the upper steel roof of A and B structures respectively, and one component is selected in the lower steel frame support of the structure. The simulation results under three temperature gradients are taken. The distribution of selected components of the structure is shown in
Figure 4 (some members have been hidden for convenience).

Figure 4. Distribution of value taking parts

4. Results and discussions

By observing the simulation results, the selected components (1, 2, 3, 5, 6, 7) will produce large deformation. Comparing the deformation of the six components, Figure 5 shows that the changes of components in the same position of A and B steel roof tend to be the same, and the deformation at the peripheral ring beam of the steel roof is much larger than that at the joint of the roof truss. It is considered that the roof truss enhances the overall stiffness of the structure. In the three kinds of gradient temperature difference, the deformation increment of each component tends to a fixed value, so the stress increment of each component also tends to a fixed value. It can be concluded that there is a linear relationship between temperature increment and temperature stress.

In Figure 6, the selected parts (4, 8, 9, 10) do not have large deformation, but the stress generated by the parts is relatively large. Component 4 and component 8 are two places where two-way sliding bearings are connected. The stress of steel column and concrete column at the connection is inconsistent. The stress value of two parts is divided into two parts: steel and concrete. Figure 6 shows that the stresses of component 4 (steel, concrete) and component 8 (steel, concrete) are basically the same under three temperature gradients. It is worth noting that, because of the different supporting modes of the lower part of structure A and B, the stress of component 9 is greater than that of component 10 under the three temperature gradients, and the difference between the two stresses increases gradually.
According to the above discussion, it can be concluded that different support methods have little effect on the stress response of the upper steel roof of the steel-concrete structure under the thermal effect, but have great influence on the stress response of the lower support steel frame. Under the same temperature gradient, the stress response of concrete column is larger than that of steel column. However, considering the influence of self weight of structure, it can’t show that concrete structure is more sensitive to the change of daily temperature difference than steel structure.

5. Conclusions

(1) The finite element models of different supporting structures A and B are established under different temperature gradients. By applying different gradients of temperature difference, the linear relationship between the thermal behavior stress response of steel-concrete structure and the temperature difference caused by solar radiation is obtained.

(2) Under the action of thermal effect, the stress produced by the full support steel frame is 10.7% lower than that produced by the two side support steel frame. For the steel frame structure under the high temperature difference environment, the deformation caused by the thermal effect can be reduced by different support arrangements.

(3) The stress change of the lower supporting structure of steel-concrete structure under different temperature difference is more obvious than that of the upper steel roof.

(4) The results do not consider the uneven distribution of temperature caused by the shelter between different parts of the structure, but simulate the temperature difference from the perspective of the temperature change caused by the heat exchange between the structure and the environment. If the local temperature difference between the sunny side and the shady side of the structure is too large, the thermal behavior of the structure will be more obvious due to the temperature effect.

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