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Experimental and numerical investigation on the non-uniform temperature distribution of thin-walled steel members under solar radiation

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ABSTRACT

The temperature effect often significantly affects the performance of large-span spatial structure and even becomes one of the controlling loads. To obtain the non-uniform temperature field distribution of the thin-walled steel members under solar radiation and the influence rules of various factors, in this paper, experimental studies are carried out with three groups of specimens including rectangular steel tube, I-shaped steel and circular steel tube. Based on the test data, the non-uniform temperature field distributions considering the influence of solar radiation intensity, member size and surface coating are analyzed in detail. Then, numerical methods for the temperature field of steel members are studied considering multiple environmental factors. The validity of the numerical method is evaluated with test results. Finally, based on the parametrical studies of the major influence factors, a simplified calculation approach is presented for practical engineering applications. The experimental study demonstrates that the non-uniform temperature distribution of steel members truly exists and cannot be overlooked. The numerical method for the temperature field in this paper is effective, and the simplified calculation approach can meet the required engineering precision. The research methods and conclusions of this work can provide valuable references for thermal design, monitoring and control of steel structures.

1. Introduction

Because of their large scale, numerous components and higher-order indetermination, large-span spatial steel structures are usually sensitive to the temperature effect. The seasonal temperature effect is usually slow, uniform and easy to calculate in a conventional structural design. However, the daily variable temperature field is quite complex for an open-air steel structure due to each individual member being exposed to a time-dependent thermal environment [1,2]. Under solar radiation and ambient temperature effect, as the structural deformation is prevented by redundant constraints, the temperature effect can sometimes become one of the key design loads. In particular, the construction errors caused by the temperature effect seriously affect the component assembly efficiency and structure closure [3]. Therefore, the accurate determination of the non-uniform temperature field distribution is of great significance.

Previous studies on the non-uniform temperature field mainly focused on the temperature effect of bridge, dam or radio telescope [4–6]. Many studies were also carried out to evaluate the fire performance of various structures [7,8]. Only a few studies analyzed the non-uniform temperature field of steel structures by experiment and numerical simulations. Alinia [9–11] has conducted some studies on the thermal behavior of double layer space truss domes under uniform thermal load, gradient and partial thermal loading. Liu [12] investigated the temperature distribution of H-shaped steel members through an experimental and theoretical study in the case of solar radiation. Liu [13] also carried out an in-site test on the large-span steel structures under solar irradiation, covered by a glass roof and light roof, to gain insight into the temperature distribution of steel members under a glass roof or light roof. Our research team experimentally explored the daily non-uniform temperature field of the reflectors of a 3-m aperture radio telescope. The distribution rule and time-varying regularity of the daily temperature field are summarized in this study. A numerical simulation for the non-uniform temperature field of the reflectors is also studied considering self-shadows [14–16]. In most numerical simulations, some simplifications and assumptions are used without the validation of the corresponding test data. No published papers refer to the monitoring of various thermal boundary conditions and influence factors for the temperature field of steel members. Therefore, to fill in this gap in the experimental work, we conducted systematic measurements of the

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Nomenclature

Acronyms

FEM	finite element model

Greek letters

λ	solar radiation absorptance
θ	angle of circumference (degree)

Small letters

x_i	sensitivity coefficient of the ith parameter
Δx_i	variations of the ith parameter
$x_i{}^*$	standard value of the ith parameter
k_i	undetermined coefficients
n_i	undetermined coefficients
t	peak value of air temperature (°C)
h_f	coefficient of convective heat transfer
h	wall thickness of tube (m)

Capital letters

L	length of specimen (m)
ΔT	variation of tube temperature
T^*	standard values of tube temperature
T_{max}	maximum temperature (°C)
T_{min}	minimum temperature (°C)
J_{max}	maximum heat flux density (J/m^2 s)
J_{min}	minimum heat flux density (J/m^2 s)
G_θ	intensity of direct radiation (W/m^2)
G_d	intensity of diffuse radiation (W/m^2)
G_R	intensity of reflection radiation (W/m^2)
D	tube diameter (m)

temperature field of steel members.

In this paper, the temperature field of common steel members is investigated by experimental and numerical methods considering various influence factors. The non-uniform distribution and time-varying regularities are obtained from the analysis of test results. From the contrastive analysis, the validity of the numerical methods is also evaluated using the test data. Moreover, based on the parametrical studies of the major influence factors, a simplified calculation approach is presented for practical engineering application.

2. Experimental programs

2.1. Test specimens

Test specimens consist of commonly used steel shapes including rectangular tube, I-shaped steel and circular tube, and all use Q235B steel. They can be divided into three groups. For the first group, the temperature field distributions of the different shaped steels are measured and contrastively analyzed. The second group explores the impact of sectional dimension on the temperature field, as well as the influence of environmental factors such as solar radiation, wind speed and others. In the third group, different surface coatings are considered. The detailed data of all specimens are listed in Table 1. For each test condition, temperature measurement continues 24 h a day. All tests were carried out during a July to September time period.

To obtain reliable results, an open and flat venue with adequate ventilation, strong sunlight and without surrounding buildings and trees is selected as the test site. Experimental platform is design as a triangle self-balanced supporting frame. This experimental platform is suitable for temperature tests of multiple components under various test conditions. The overall layout of the experiment is shown in Fig. 1. The masks connected with the beams are used to prevent the thermal effect of the frame.

2.2. Test equipment and test point layout

The test scheme includes the measurements of temperature and ambient environmental parameters such as air temperature, wind speed and solar radiation. Solar radiation intensity is the main part of radiant heat transfer. The ambient air temperature is a key factor affecting changes in the entire temperature field. Wind speed is a major parameter in the calculation of the convective heat transfer coefficient. The test equipment chosen according to the complex test requirements is presented in Table 2. The sampling frequency of various testing data is every half an hour.

Fig. 2 gives the layout of the test points. Along the length direction, test points of the specimens are arranged in each one-fourth location as Fig. 2a). For every cross-section, the temperature sensors are set and numbered as in Fig. 2b). For example, the top flange, web and bottom flange of I-shaped steel are, respectively, numbered G_A, G_B, and G_C. The test points are named G_1 to G_7. The four plates of the rectangular tube are numbered J_A, J_B, J_C and J_D, while the test points are named J_1 to J_8. The four test points of the circular tube are named Y_1 to Y_4.

3. Test results analysis of the temperature field

3.1. Temperature variation along the length and thickness direction

Taking plate A of the rectangular tube, plate A of the I-shaped steel and test point 1 of the circular tube as an example to analyze and contrast the temperature distribution along the length direction. The representative test results are given in Fig. 3. The temperature of these three components shows almost no change along the length direction. Moreover, temperature sensors are arranged on both sides of each plate of the I-shaped steel to study the temperature variation along the thickness direction, and the test results are given in Fig. 4. The temperature change along the thickness direction can also be ignored. In the subsequent test conditions, the temperature test points can only be arranged on one side of the mid-span section.

Table 1
Detailed parameters of all specimens.

Groups	First			Second			Third		
Type	Circular tube	Rectangular tube	I-shaped steel	Circular tube	Circular tube	Circular tube	Circular tube	Circular tube	Circular tube
Size (mm)	76 × 3	100 × 150 × 3	100 × 100 × 6 × 8	76 × 3	130 × 4	219 × 4	130 × 4	130 × 4	130 × 4
Surface coating	Silvery gray	Silvery gray	Silvery gray	Silvery gray	Silvery gray	Silvery gray	White	Silvery gray	Rust