Experimental Research on Temperature Field of Large Diameter Concrete-Filled Steel Tube Section

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Abstract: In order to research the influence of solar radiation on temperature field of large diameter concrete-filled steel tube (CFST) section, the field test of temperature field of CFST section was carried out based on the reconstruction project of Huahe River Bridge in Xi County, Xinyang City, Henan Province. For the asymmetric temperature distribution of concrete-filled steel tube sections caused by sunlight, considering the environmental factors and the actual position, temperature field of CFST section under sunshine was analyzed by finite element method, and the results are compared with the field test results to verify the reliability of the model. The analysis results show that the non-uniform distribution of the CFST with large diameter appears due to the sunlight effect; the larger the size of core concrete, the slower the change of central temperature, and the greater the temperature difference between the core and the boundary. Therefore, the influence of sunshine effect should be considered in the actual engineering.

1. Preface

With the rapid development of China's economy and technology, large-span bridges and super-high-rise buildings have appeared in all parts of the country. At the same time, modern structural engineering has also achieved rapid development[1]. Since 1980s, concrete filled steel tube structures have been applied in long-span bridges and high-rise buildings. In the past 20 years, with the maturity of concrete-filled steel tube technology, concrete-filled steel tube structures have been widely used in various projects[2,3].

Due to the huge difference between the thermodynamic properties of steel tube and concrete, the temperature distribution of the section of concrete-filled steel tube member is nonlinear under the action of solar radiation. The temperature gradient of the section will generate temperature self-stress, and temperature secondary internal force may also be generated for statically indeterminate structures. Therefore, it is very necessary to research the distribution law of temperature field in concrete filled steel tube section.

Many experts and scholars at home and abroad have studied the temperature field distribution of concrete filled steel tubes. Scholars[4-12] pointed out through research that solar radiation has great influence on bridge structure, among which Peng Yousong et al[7] established the finite element model of sunshine temperature field, and pointed out that the solar radiation absorption rate on the surface of steel pipe is an important factor affecting the temperature distribution of cross section. Chen Baochun
et al\cite{8} studied the temperature field of concrete filled steel tube section under sunlight, and gave the temperature distribution and temperature gradient curve of the section.

However, there are few researches on the temperature distribution of concrete-filled steel tube section under sunlight, and the diameter of concrete-filled steel tube studied is also small, most of which is less than 500mm. In view of this, relying on the reconstruction project of Huaihe River Bridge in Xixian County, Xinyang City, Henan Province, this paper conducts tests and finite element simulation research on the temperature distribution of large diameter concrete filled steel tubular members under sunlight.

2. Brief Introduction of Test
The Huaihe River Bridge in Xixian County is designed as a single-tower cable-stayed bridge with concrete-filled steel tubes. The main tower adopts the form of double columns, and the structure adopts the form of consolidation of towers, beams and piers. The lower section of the tower adopts two cylindrical concrete-filled steel tubes with a diameter of 2.5m. However, the diameter of the temperature distribution of the concrete filled steel tube section studied in the existing data is relatively small, basically less than 0.5m, which is quite different from the actual situation of this project. Therefore, it is necessary to research the temperature distribution of large diameter concrete filled steel tube section.

Before the start of this test, the concrete-filled steel tubes with radii of 0.2m, 0.3m, 0.4m, 0.5m, 0.6m and 0.7m were first numerically simulated to analyze the temperature variation law with time at the central measuring points of the specimens with different radii. The specific analysis results are shown in Figure 1.

As can be seen from Fig. 1, as the radius of the concrete filled steel tube increases, the temperature change at its central measuring point gradually decreases. Among them, the temperature change trend of the central measuring point with radius less than 0.5m is similar, which decreases first, then increases and then decreases. The smaller the radius, the larger the change range, indicating that the smaller the radius, the greater the influence of external environmental factors on the central measuring point. The temperature change trend of the central measuring point with radius of not less than 0.5m is similar, which all increases slowly. The larger the radius, the smaller the change range, indicating that the larger the radius, the smaller the influence of the external environmental factors on the central measuring point. Therefore, the specimen radius of this field test should not be less than 0.5m.

This test is located at the site of Huaihe River Bridge Reconstruction Project in Xixian County, Xinyang City, Henan Province. The test piece to be tested is a scaled model simulating the main tower section of Huaihe River Bridge. Considering the actual engineering and economic factors, the scale model is a Φ φ1m×28mm×2m steel pipe, which is made of Q345qD steel. The concrete is C50 self-
compacting micro-expansion concrete, and the surface is painted red. The test piece is vertically placed in an open field that can fully receive solar radiation.

Because this article is to analyze the temperature field of the cross section of the component, in order to reduce the influence of the heat transfer along the length direction of the component on the test section, the two ends of the component to be tested are covered with white heat insulating plastic foam, and in order to reduce the influence of the ground surface on the test result, the cross section of the component which is 1.2m from the ground is selected as the test section. In order to research the cross-sectional temperature field of the specimen, 14 temperature measuring points were arranged in this test, of which 13 measuring points (1~13) were arranged in the concrete in the pipe, and one ambient temperature measuring point (t1) was arranged at the shady place near the specimen. The arrangement of all measuring points of the specimen is shown in Fig. 2.

This test uses XHS-DS18W temperature sensor to measure temperature. The sensor is a new type of digital sensor with high accuracy, high stability and high reliability. Its measurement accuracy is 0.5℃, resolution is 0.25℃, and measuring range is -55℃ ~ 125℃, which can meet the test requirements.

3. Analysis of test data

The test was conducted in early November 2018. The daily temperature difference between day and night was above 10℃ and the sunrise time was after 6 am. Considering the actual conditions of the test site, data are collected every hour from 6:00 to 23:00. Since there was no solar radiation and the ambient temperature changed little from 23 pm that day to 6 am the next day, the measurement work was simplified and the data during this period were not collected. Data collection will be conducted for 10 days from November 1, 2018 to November 10, 2018.

Table 1. Ambient temperature measurements

| Measuring time | November 8 6:00-23:00 | November 9 6:00-23:00 |
|---------------|-----------------------|-----------------------|
| Maximum ambient temperature and occurrence time | 19 ℃, 15:00 | 22 ℃, 15:00 |
| Minimum ambient temperature and occurrence time | 7 ℃, 6:00 | 8 ℃, 6:00 |
| Daily average ambient temperature (℃) | 13 | 15 |
| Daily maximum ambient temperature difference (℃) | 12 | 14 |

Preliminary analysis of test data shows that the weather on November 8 and 9 is representative, and the ambient temperature is shown in Table 1. The weather on the 8th was sunny and cloudy, and the weather on the 9th was sunny and sunny in partly cloudy. Therefore, the data of these two days are selected for analysis, and the typical data of measuring points are shown in Fig. 3.
From the curve of ambient temperature (T1) in Figure 3(a), it can be seen that since the weather on the 8th and 9th is sunny with clouds and sunny partly cloudy respectively, the ambient temperature is relatively high and reaches the highest temperature of the day at 2 pm, which is 19°C and 22°C respectively, the lowest temperature is 7°C and 8°C respectively, and the maximum ambient temperature difference of the day is 12°C and 14°C respectively. On the 8th and 9th, the cross-section temperature field of the specimen is affected by sunshine. The ambient temperature in the daytime and the temperature at the boundary measuring point of the specimen are significantly higher than the corresponding temperature in the absence of sunshine at night. The temperature of each measuring point at the boundary of the test piece also changes obviously with the duration of sunshine. When the south side of the test piece is exposed to sunshine for a long time, it is larger than the north side of the test piece, and its temperature change is also much larger than the north side. The ambient temperature reached its peak from 14 to 15 o’clock. The boundary temperature of the specimen reached its peak at about 17 o’clock under the influence of sunlight, and lagged the ambient temperature for more than 2 hours. The temperature at the central measuring point of the specimen, as it is not directly affected by sunshine, slowly rises and reaches a peak value after 0 pm and is higher than the boundary temperature and the ambient temperature at that time.
As it is cloudy all day on November 7, the ambient temperature is basically the same from the 7th to the 8th morning before the sun rises, as shown in Fig. 3(b), at 6:00 a.m. on November 8, the temperature field of the specimen section is basically the same, the center temperature is slightly higher than the boundary temperature and the ambient temperature, the overall temperature difference of the section is within 1℃, and the boundary temperature and the ambient temperature are basically the same. On the 8th and 9th, the cross-sectional temperature field of the specimen was affected by solar radiation, which resulted in obvious temperature difference. Because of sunny partly cloudy on the 9th, the change of the cross-sectional temperature field of the specimen was more obvious. The maximum temperature difference between the boundary measuring point and the central measuring point in these two days is 10.75℃ and 14.75℃ respectively.

The boundary measuring point of the specimen is affected by solar radiation, and its temperature change is especially obvious in sunny days. In these two days, due to the long-term sunshine on the south side of the test piece being greater than that on the north side of the test piece, the temperature change at the positive south boundary measuring point 7 is the fastest, reaching the peak value at 19℃ and 25.5℃ (about 15:00) respectively, and its temperature peak value is not lower than the ambient temperature peak value and is obviously greater than the temperature peak value at other boundary measuring points. The temperature change rates of the other boundary measuring points 4, 10 and 13 decrease in sequence, and the temperature change rate of the positive north boundary measuring point 13 is the smallest among all the boundary measuring points, which indicates that the shorter the sunshine duration of the boundary measuring point, the slower its temperature change curve, and the lower the peak temperature, i.e. the closer to the north side, the lower the temperature field of the boundary measuring point is affected by solar radiation; The temperature change curve at measuring point 1 is the slowest among all measuring points in the section of the specimen, which indicates that the closer the temperature distribution of the section of the member is to the center of the specimen, the less the influence of solar radiation is, and the more serious the hysteresis phenomenon of temperature change is.

4. Numerical simulation

4.1. Calculation of Solar Radiation Intensity

According to relevant documents[13], the total solar radiation intensity on the surface of the structure consists of three parts, namely, direct solar radiation, sky scattering and surface reflection. The formula for calculating the total solar radiation intensity on any facing surface is as follows:

\[ G_{\alpha} = G_{na} + G_{sa} + G_{fa} \]  

Where: \( G_{\alpha} \) is the total solar radiation intensity on the surface facing any direction; \( G_{na} \) is the direct radiation intensity of the sun on the surface facing any direction; \( G_{sa} \) is the sky scattering intensity on any facing surface; \( G_{fa} \) is the surface reflection intensity received on any facing surface.

\[ G_{n} = G \left[ 1 + 0.034 \cos \left( \frac{2\pi N}{365} \right) \right] \frac{\sin H}{\sin H + C} \]  

Where: \( G_{n} \) is the direct solar radiation intensity received by the plane perpendicular to the incident light of the sun; \( G \) is the daily radiation constant, \( G = 1367 \text{W/m}^2 \); \( N \) is the date serial number; \( H \) is the solar altitude angle; \( C \) is the atmospheric transparency coefficient, which is 0.33 in sunny days.

\[ G_{na} = G_{n} \cos \theta \]  

Where: \( \theta \) is the angle of incidence of the sun.

\[ G_{sa} = \frac{(1 - P)^{(1 + \cos \alpha)}}{4(1 - 1.4 \ln P)} G_{n} \sin H \]  

Where: \( P \) is atmospheric transparency, and 0.8 is taken for better sunny days; \( m \) is the air quality, \( m = 1/\sin H \); \( \alpha \) is any inclination toward the surface.

\[ G_{fa} = \frac{\rho(1 - \cos \alpha)}{2} \left[ 1 + \frac{1 - P^{m}}{2(1 - 1.4 \ln P)} \right] G_{n} \sin H \]  

Where: \( \rho \) is the ground reflectivity, generally 0.2;
According to equation (1), the solar radiation intensity of a typical measuring point on the surface of the test piece (the azimuth angle of the surface of the test piece is taken as a point every 15 degrees, the azimuth angle in the positive south is 0 degrees, the azimuth angle in the east is negative, and the azimuth angle in the west is positive) can be calculated, as shown in Fig. 4. According to relevant data\[14\], the solar radiation absorptivity of steel pipe surface is mainly determined by the color of surface coating, and the surface of the test specimen is red coated, taking 0.6.

![Figure 4. Solar radiation intensity at a typical measuring point](image)

4.2. Finite Element Calculation Results

In this paper, the boundary conditions between steel tube and concrete in tube are simplified when the finite element simulation of concrete-filled steel tube specimen is carried out, i.e. the temperature and heat flux density on the contact surface between steel tube and core concrete are assumed to be continuous, and at the same time, the specimen is assumed to have no heat conduction along the axial direction, so that the two-dimensional plane temperature field can be used to research the section temperature field of the specimen.

C50 self-compacting micro-expansive concrete is used for the concrete filled in the specimen. The thermodynamic parameters used for finite element simulation in this paper are shown in Table 2.

| Material parameters | Concrete | Steel tube |
|---------------------|----------|------------|
| Density / kg/m³     | 2480     | 7850       |
| Specific heat capacity / J/(kg·K) | 1.01 | 0.48 |
| Thermal conductivity / W/(m·K) | 10.42 | 172.8 |
| Convection coefficient / W/(m²·K) | / | 139.54 |
| Ambient temperature / °C | 8 | 8 |

A two-dimensional finite element model of the test section of the specimen is established by ABAQUS, as shown in Fig. 5.
According to the relevant parameters obtained above, the boundary conditions are established in the finite element model, and the temperature field of the specimen section is simulated and calculated for 24 hours starting from 0:00 a.m. on November 9. Fig. 6 shows the temperature distribution nephogram at a typical moment of specimen section. As can be seen from Fig. 6(a), at 6:00 a.m., the temperature difference inside the test section of the specimen is within 1℃, the temperature of the core concrete gradually decreases from inside to outside until the temperature near the steel pipe increases slightly, and the temperature of the steel pipe is basically consistent with the atmospheric temperature. Since the sun has not yet risen, the temperature distribution of the section is in a symmetrical state as a whole. As can be seen from Fig. 6(b), at 9:00 a.m., the temperature of the outer boundary of the test piece began to rise due to the increase of atmospheric temperature, while the temperature of the southeast outer boundary of the test piece increased rapidly due to the influence of solar radiation. As can be seen from Fig. 6(c), at 12:00 noon, due to the change of the position of the sun, the temperature at the outer boundary on the south side of the test piece rises faster. As can be seen from Fig. 6(d), at 15:00 p.m., the cross-sectional temperature of the specimen reached the maximum temperature of 25.86℃ in the southwest outer boundary region and reached the maximum temperature difference of 14.2℃ in the same day. It can be seen from Fig. 6(e) that after 18:00 p.m., as the sun sets and the atmospheric temperature decreases, the cross-sectional temperature of the specimen decreases, and the highest point of the cross-sectional temperature of the specimen gradually moves toward the center. As can be seen from Fig. 6(f), the temperature distribution in the cross section of the test piece starts to gradually return to the equilibrium state.
As can be seen from Fig. 6, due to solar radiation, the temperature difference at the measuring points on the south side of the test section of the specimen is relatively large, and the maximum temperature of the section is always on the south side, while the temperature difference at the measuring points on the north side is relatively small and the temperature is generally low. The closer the cross-section temperature distribution of large diameter concrete filled steel tube is to the center and the north, the smaller the influence of solar radiation, the slower the temperature change, and the smaller the temperature gradient. However, the closer the cross-section temperature distribution is to the boundary and the south, the greater the influence of solar radiation, the faster the temperature change, and the greater the temperature gradient.

4.3. Comparison between Test Measurement Results and Numerical Simulation Results

The comparison between the measured temperature at the typical measuring point of the specimen section and the finite element numerical calculation value curve is shown in Fig. 7. The temperature curves of each measuring point in Fig. 7 are in good agreement with the numerical simulation curves, which shows the reliability of the finite element numerical simulation method. The temperature difference of each measuring point at any time throughout the day is within 2.5℃, and the temperature difference at the center point of the cross section is the most stable at any time throughout the day, all within 2℃. This is because there may be measurement errors in the field measurement, and there are also errors between the parameters of numerical simulation and the actual situation in the field. At the same time, the outer boundary of the test piece is easily affected by other external factors, while the center of the test piece is less affected by other external factors, but these factors are ignored in the numerical simulation because of their small influence, which leads to the temperature difference value of the outer boundary being larger than that of the center point of the cross section.
**5. Conclusions**

Based on the reconstruction project of Huaihe River Bridge in Xixian County, the temperature distribution of large-diameter concrete filled steel tubular members under sunlight is tested and simulated by finite element method. The following conclusions are drawn:

1. The finite element numerical simulation of the temperature field of concrete filled steel tube section is carried out. The simulation results are in good agreement with the field measured values, indicating the feasibility of using numerical simulation to calculate the temperature distribution of concrete filled steel tube section.

2. The temperature distribution law of large diameter concrete filled steel tube section is as follows: the closer to the center of the section, the less the temperature field is affected by solar radiation, and the more serious the hysteresis phenomenon of temperature change is; the closer to the boundary and south side, the greater the influence of solar radiation, the faster the temperature change and the greater the temperature gradient.

3. The temperature field of large-diameter concrete filled steel tube section presents non-uniform distribution due to the influence of sunlight. The larger the size of core concrete, the slower the change of center temperature, which is easy to produce large temperature difference with the boundary.

**References**

[1] Zhou Xuhong, Liu Jiepeng. Performance and Design of Concrete Filled Steel Tubular Columns [M]. Beijing: Science Press, 2010.

[2] Yang Fengjun, Wang Bang. Brief Discussion on Concrete Filled Steel Tubular Structure [J]. Sichuan Building Materials, 2014, 40(01): 24-26.

[3] Lu Weipeng. Overview of Concrete Filled Steel Tubular Members [J]. Guangdong Building Materials, 2016, 32(08): 76-78.

[4] Zuk W. Thermal and Shrinkage Stresses in Composite Bridges[J]. Journal of AmericanConcrete Institute, 1961, (3): 327-340.

[5] Emerson M. The Calculation of the Distribution of Temperature in Bridges[R]. 1973.

[6] Hunt B, Cooke N. Thermal Calculations for Bridge Design[J]. Journal of the structural division, 1975, 101: 1763-1781.

[7] Peng Yousong, Qiang Shizhong, Li Song.Temperature Distribution in Dumbbell Cross Section
Concrete-Filled Steel Tube Arch Due to Solar Radiation [J]. China Railway Science, 2006, 27(5): 71-75.

[8] Chen Baochun, Liu Zhenyu. Analysis on Temperature Field Tests of Members under Solar Radiation [J]. Journal of Highway and Transportation Research and Development, 2008, 25(12): 117-122.

[9] Ren Zhigang, Hu Shuguang, Ding Qingjun. Research on the Effect of Solar Radiation Model on Temperature Field of Concrete-Filled Steel Tube Pier [J]. Engineering Mechanics, 2010, 27(04): 246-250+256.

[10] Sun Guofu. Theory and Application Study of Sunshine Temperature Effects on Long-Span CFST Arch Bridge [D]. Jinan: Shandong University, 2010.

[11] Wu Qian. Experimental Study on Temperature Rise of Concrete Filled Steel Tubular Circular Section under Solar Radiation [D]. Wuhan: Wuhan University of Technology, 2014.

[12] Tian Zhijuan, Liu Yongjian, Ma Yinping, Liu Jiang. Experiment on Temperature Distribution of Rectangular CFST Cross Section in Severe Cold Areas [J]. Journal of Architectural and Civil Engineering, 2018, 35(5): 170-178.

[13] Xiang Xuejian, Dong Jun, Liu Haosu, Zhang Jinquan, Li Wanheng. Determination of Parameters of Temperature Field of Box-girder Bridge in Winter Weather of Plateau [J]. Journal of Highway and Transportation Research and Development, 2012, 29(3): 58-63.

[14] Chen Zhihua, Chen Binbin, Liu Hongbo. Experimental Research on Solar Radiation Absorptance of Commonly Used Coatings for Steel Structures [J]. Journal of Building Structures, 2014, 35(5): 81-87.