Experimental Research on the Temperature Field Distribution of Circular CFST Section

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Abstract. This paper aims to study the circular CFST section temperature field distribution caused by temperature variation, which is tested under outdoor environment and artificial climate simulated test chamber, measuring the temperature field of the CFST component and the plain concrete control specimen under different temperature variation conditions. The test results show that the temperature field of the CFST and the plain concrete is basically the same. The cross section temperature fields presented uniform distribution when there was no sunshine and under the action of sunshine, the temperature field of the specimen section showed a non-uniform distribution. In both conditions, the specimen section temperature field shows a phenomenon that the temperature change from outside to inside is increasingly behind, and the specimen section maximum temperature difference mainly depends on the solar radiation and the range of temperature changes.

1. Introduction
Concrete-filled steel tube (CFST) is a new type of composite structure formed by filling concrete into steel tube. It fully exerts the advantages of steel tube and concrete and makes up for the shortcomings of each other to the maximum extent, forming an optimal combination, with the advantages of high bearing capacity, good fire resistance, good ductility and excellent seismic performance [1-3]. Due to the above advantages, the CFST structure can withstand the external harsh conditions and has been widely used in various construction and bridge projects at home and abroad [1-3]. As a new type of bridge, CFST tied arch bridge has been rapidly promoted and applied in China for more than 20 years, but as an internal high-order statically indeterminate structure, its temperature change will inevitably add additional internal forces and additional stresses to the structure, changing the structural forces and causing the redistribution of internal forces [4-5]. Therefore, the research on the influence of the temperature field distribution of CFST components is the premise and basis for the temperature research on CFST tied arch bridges. The article [6] studied the temperature field of the section of CFST components under the action of sunshine, carried out the temperature field test of CFST components under sunshine, and analyzed the distribution and variation of the temperature field of the section under sunshine. In the article [7], based on the calculation of solar radiation on the surface of CFST components, the finite element method for calculating the temperature field of the section of CFST components under the action of sunlight was proposed. The article [8] analyzed various...
environmental factors that affected the temperature change of the structure surface, established a three-dimensional solid finite element model of the structure in the finite element software, and solved the temperature field of the structure at any time of one day. In the article [9], based on the finite element method and experiment, the temperature field of CFST under high temperature was studied. In the article [10], the continuous test and observation on the section temperature field of a rectangular CFST specimen under sunshine and coolness were carried out, and combined with the finite element method, the distribution law of the sectional temperature field of the rectangular CFST specimen was analyzed based on the measured temperature data. In the article [11], taking CFST tied arch bridge as an example, based on the finite element analysis method, a three-dimensional finite element model was established, and the influence of temperature on the static performance of tied arch bridge was analyzed. The article [12] established the temperature field analysis model for CFST in the hydration heat stage of cement based on the finite element software ABAQUS, and analyzed the effects of section size, steel content and ambient temperature on the temperature field of CFST sections in the hydration heat stage of cement. Previous studies more focused on experimental researches on the temperature field of CFST specimens under sunshine and lacked the comparative experimental research on temperature fields of CFST specimens and plain concrete specimens under the actions without sunshine and with sunshine. Therefore, based on the large-diameter circular CFST specimen and the plain concrete control specimen, this article respectively carried out temperature field tests in artificial climate simulation test chambers and outdoor environments, and analyzed the test results, to understand the temperature distribution of the sections, so as to facilitate its application in actual engineering.

2. Experiment

In the test, a CFST specimen with circular section and a plain concrete specimen were designed, and the temperature field tests were carried out in the outdoor environment and in the artificial climate simulation test chamber. The designed concrete was C55, with the water-to-binder ratio of 0.35, which was prepared with the cement P.O42.5, and the specific mixing ratio is shown in Table 1. The seamless steel tube Q235 was utilized. The prepared CFST specimen had a diameter × wall thickness × height of Φ 630 mm × 11 mm × 1000 mm, filled with C55 concrete; As for the plain concrete specimen, the diameter × height is Φ 608 mm × 1000 mm. In the interior of the CFST specimen, nine temperature sensors were arranged on the steel frame along the orthogonal direction of the radius at the height of 400mm and 600mm, respectively, and four sensors are arranged along the orthogonal direction of the radius at 500mm outside the steel tube wall, whose specific layout is shown in Fig. 1. For plain concrete specimen, only nine temperature sensors were arranged on the steel frame along the orthogonal direction of the radius at 500mm outside the steel tube wall, whose specific layout is shown in Fig. 1. The temperature sensor was connected to the temperature inspection instrument, and the data was recorded every 6 minutes with the temperature inspection instrument. The outdoor environment and the artificial climate simulation test chamber were utilized to carry out the temperature variation test in the experiment. There into, the temperature range of the artificial climate simulation test chamber was -20°C ~ 80°C, with the maximum heating/cooling rate ≥1°C/min, and the temperature change could realize the temperature load programming, with a temperature fluctuation ≤ ±0.5°C;The temperature uniformity was ≤2°C, as shown in Fig. 2. The core concrete was poured for more than 30 days, and the hydration heat was basically released, at this time, the temperature field of the CFST was only related to the temperature change of the outdoor environment and the artificial climate simulation test chamber.

Table 1. Mix ratio of concrete C55 (Kg/m³)

| Materials     | Concrete | Fine aggregate | Coarse aggregate | Water | Water reducer | Coal ash |
|---------------|----------|----------------|------------------|-------|---------------|----------|
| Weight        | 480      | 691            | 995              | 168   | 26.1          | 80       |
3. Experiment results and analysis

3.1 Distribution law of the temperature field of the component section under the temperature change of outdoor environment

The temperature change in the outdoor environment is a non-uniform temperature variation due to the action of sunshine. The temperature field of the circular steel tube section exhibits a nonlinear distribution in the section and can only be simplified as a two-dimensional plane problem. In order to study the temperature field variations of CFST section and plain concrete section with the change of outdoor environment temperature, the 22d outdoor temperature change test was carried out, selecting the typical 1d to analyze, and the test results are shown in Fig. 3-6. In the figure, H is the measured temperature of the outdoor environment, N-1 is the temperature at the concrete surface in the north direction, N-2 is the temperature at the radius of the concrete in the north direction, E-1 is the temperature at the concrete surface in the east direction, and E-2 is the temperature at the radius of the concrete in the east direction, S-1 is the temperature at the concrete surface in the south direction, S-2 is the temperature at the radius of the concrete in the south direction, W-1 is the temperature at the surface of the concrete in the west direction, W-2 is the temperature at the radius of the concrete in the west direction, EN-1 is the temperature at the concrete surface of the CFST in the northeast direction, EN-2 is the temperature at the radius of the CFST in the northeast direction, ES-1 is the temperature at the concrete surface of the CFST in the southeast direction, ES-2 is the temperature at the radius of the CFST in the southeast direction, WS-1 is the temperature at the concrete surface of the CFST in the southwest direction, WS-2 is the temperature at the radius of the CFST in the southwest direction, WN-1 is the temperature at the concrete surface of the CFST in the northwest direction, WN-2 is the temperature at the radius of the concrete in the northwest direction, SC-1 is the temperature at the center of the CFST specimen, and C-1 is the temperature at the center of the plain concrete specimen. The outdoor environment has a maximum temperature of 36 °C and a minimum temperature of 19 °C.
Fig. 5 Temperature-time curves of each measuring point of the lateral section of the CFST specimen

It can be seen from Fig. 3-5 that the lowest temperature in the outdoor environment emerges at 6:30 in the morning, and the temperature fields of the sections of the CFST specimen and the plain concrete specimen experience a uniform temperature variation without sunlight at night. The temperature shows a trend of high outside and low inside. Subsequently, under the action of sunshine, the temperature gradually increases, and the temperatures outside the CFST and plain concrete specimens rise slowly with the atmospheric temperature. The inside temperature still falls due to the temperature difference between the inside and the outside. At 11:30 in the morning, the temperatures inside and outside gradually reach a state of short-term internal and external consistency from the state of outside high and low inside. After that, with the increase of the atmospheric temperature, the maximum temperature appears at 17:00 in the afternoon, reaching 36 °C. Due to direct solar radiation, the temperatures of the measuring points W-1, WN-1 and WS-1 of the CFST and the measuring point W-1 of the plain concrete specimen are higher than the ambient temperature, close to 40 °C and 38 °C, respectively. The temperature of the measuring point outside the specimen reaches the peak value, and the temperature field of the section shows a non-uniform distribution. However, the temperatures of the shady surfaces are low and relatively close to each other. The maximum differences between the temperatures of the measuring points on the section of CFST specimen and that of the plain concrete specimen reach 13 °C and 12°C, respectively. After 17:00, the atmospheric temperature gradually decreases, and the temperatures of the external measuring points of the specimen decline with the reduction of the atmospheric temperature, but the temperatures of the internal measuring points still rise slowly. The temperature at the center of the specimen reaches a peak at 21:00, which is delayed by 4 hours.

As can be seen in Fig. 6, the reduction of the temperatures at the section center of the CFST specimen and the plain concrete specimen are basically close before 12:00. After 12:00, the conductive heat transfer in the ascending section of the CFST specimen increases. After 17:00 pm, the temperature at the center of the CFST specimen gradually exceeds the temperature at the center of the plain concrete specimen, but the maximum temperature difference is only 1 °C, and the temperature difference between the both is gradually reduced after the peak at 21:00.

3.2 Distribution law of the temperature field of the component section under the temperature change in the artificial climate simulation test chamber

The temperature change in the artificial climate simulation test chamber was a uniform temperature variation due to the absence of sunshine. The temperature field of the circular steel tube section was only a one-dimensional temperature field related to the radial direction. In order to study the variation of temperature field of CFST section and plain concrete section with external environment temperature change, four groups of different temperature change tests were carried out, and the test results are shown in Fig.7-10. In the figure, H is the measured temperature in the artificial climate simulation test chamber, C-1 is the temperature at the center of the plain concrete specimen, C-2 is the
average temperature of the four measuring points at the radius of the plain concrete specimen, C-3 is the average temperature of the four measuring points at the surface of the plain concrete specimen, S-1 is the average temperature of the two measuring points at the center of the CFST specimen, S-2 is the average temperature of the four measuring points at the radius of the CFST specimen, S-3 is the average temperature of 4 measuring points at the surface of the core concrete in the CFST specimen, and S-4 is the average temperature of 4 measuring points at the outer surface of the CFST specimen.

In Fig. 7, the maximum temperature in the artificial climate simulation test chamber is 17 °C, and the lowest temperature is -2 °C. It can be seen from Fig. 7 that when the ambient temperature rises at 0-5h, the maximum temperature reaches 17 °C at the 5th hour, during which the temperatures of the CFST specimen and plain concrete specimen tend to rise, but the temperature climbing rates of the measuring points S-4, S-3, and C-3 are approximately similar and far greater than those of other measuring points. The ambient temperature decreases at 5-12h, but the temperatures of the measuring points S-4, S-3, and C-3 still increase during the period of 5-6h due to the temperature difference of more than 6°C from the ambient temperature, and drops down gradually and slowly after 6h; The measuring points S-1, S-2, C-1, and C-2 are always in a slowly warming state. At 12h, the temperatures of each measuring point on the section of the CFST specimen are all larger than the temperature of the measuring point on the corresponding section of the plain concrete specimen, and the core temperature of the CFST specimen is the highest. During the test, the maximum temperature difference between the section of the CFST specimen and the section of the plain concrete specimen reaches 4 °C, and the maximum temperature difference between the inside and outside of the steel tube wall is 1 °C.
In Fig. 8, the maximum temperature in the artificial climate simulation test chamber is 12 °C, and the lowest temperature is 3 °C. As can be seen in Fig. 8, when the ambient temperature rises from 0 to 2h, the maximum temperature reaches 12°C at the 2nd hour. The ambient temperature maintains a constant temperature range of 11±1°C during 2-12h, and the temperatures of each section of the CFST specimen and the plain concrete specimen always tend to be an ascending state, but the temperature rising rates of the measuring points S-4 and S-3 are approximately similar and far greater than the temperature rising rates of other measuring points. The wall temperature of the steel tube is close to the ambient temperature at 10h, mainly because the thermal conductivity of the steel tube is about 18.5 times that of the concrete [13], and the heat conduction is fast. Due to the high thermal conductivity of the steel tube wall in the CFST, the heat conduction in the CFST is fast, so that the temperature of the measuring points S-1 and S-2 in the CFST is higher than the temperature of the measuring points C-1 and C-2 in the plain concrete. During the test, the maximum temperature difference between the sections of the CFST specimens reached 5 °C, while the maximum temperature difference between the sections of the plain concrete specimens reached 2 °C, and the maximum temperature difference between the inside and outside of the steel tube wall is 3 °C.

In Fig. 9, the maximum temperature in the artificial climate simulation test chamber is 10 °C, and the lowest temperature is -20 °C. It can be seen from Fig. 9 that when the ambient temperature drops from 0 to 1.5h, the temperatures of all measuring points decrease. When the ambient temperature rises during 1.5-3h, except for the increasing temperature of the measuring point S-4, the temperatures of the other measuring points is slowly decreasing. The temperature drops during 3-9h, and the temperature reaches the lowest value of -20 °C at the 9h, during which the measuring point S-4 is the most sensitive and its temperature descending slope is roughly equal to the ambient temperature descending slope. The temperatures of the measuring points S-3 and C-3 are almost the same, and the temperatures of the measuring point S-2 is approximately equal to C-2, while the temperature of the measuring point S-1 is slightly lower than that of the measuring point C-1. However, the closer the temperature field of the section to the center of the circle from the outside to the inside, the more obvious the hysteresis of temperature reduction. At 9-12h, when the ambient temperature rises, the temperature of the measuring point S-4 rises to consist with the ambient temperature finally, and the temperature of the measuring point S-3 and C-3 ascend slowly. The temperature rising slope of the measuring point C-3 is greater than that of the measuring point S-3. The temperatures of the remaining measuring points slowly decrease. These further reflect the hysteresis of the core concrete temperature field. During the test, the maximum temperature difference between the sections of the CFST specimen reaches 10 °C, and the maximum temperature difference between the sections of the plain concrete specimen reaches 7 °C, while the maximum temperature difference between the inside and outside of the steel tube wall is 4 °C.

In Fig. 10, the maximum temperature in the artificial climate simulation test chamber is 25 °C, and the lowest temperature is -15 °C. As can be seen in Fig.10, when the ambient temperature declines during 0-1h, the temperature reduction reaches 30 °C, and the lowest temperature reaches -15 °C at 1h. During this period, the temperatures of each test point tend to decrease. The closer the temperature field of the section to the center of the circle from the outside to the inside, the more obvious the hysteresis phenomenon of temperature reduction, but the temperature rising slopes of the measuring points S-4, S-3 and C-3 are almost the same. The ambient temperature raises during 1-12 h, but during the period of 1-6 h, the temperature change slopes of the measuring points S-4 and C-3 are close to 0, and during 1-7h the ambient temperature is lower than the temperatures of each measuring point of the specimen. Therefore, except for the measuring points S-4 and C-3, the temperatures of the other measuring points of the specimen trend to decrease slowly. The ambient temperature is higher than the temperatures of each measuring point of the specimen during 7-12h, but only the temperatures of the measuring points S-4, S-3 and C-3 have a rising tendency, and the temperature change slopes of other measuring points approach to 0. During the test, both the maximum temperature differences between the sections of the CFST specimen and those of the plain concrete specimen reach 7 °C, and the maximum temperature difference between the inside and outside of the steel tube wall is 4 °C.
4. Conclusions
In this paper, the temperature fields of the sections of a large-diameter CFST specimen with circular section and a plain concrete specimen were tested in the artificial climate simulation test chamber and the outdoor environment. Through a larger amount of the measured data of the temperature field distribution under the temperature variation, the distribution law of the section temperature field of the large-diameter CFST specimen with circular section was analyzed, and the following conclusions were obtained:

1. It can be seen from the test of the outdoor environment temperature change that when there was no sunshine to the CFST specimen and the plain concrete specimen in the outdoor environment, the section temperature fields basically presented uniform distribution. The section temperature curve of the specimen was consistent with the ambient temperature variation, and the curves were roughly parallel. The temperature change of the concrete in outer ring was basically synchronized with the temperature change. The closer to the core, the smaller the concrete temperature variation, and the temperature variation of the core concrete showed a significant hysteresis. The maximum temperature difference between the section of CFST specimen and that of the plain concrete specimen mainly depended on the solar radiation and the range of temperature change. In addition, under the action of sunshine, the temperature field of the specimen section showed a non-uniform distribution, and the temperature of the sunny surface was significantly higher than that of the shady surface. The temperature field variation of the section of the CFST specimen and that of the plain concrete specimen was basically consistent.

2. It can be seen from the temperature change tests in the artificial climate simulation test chamber that the temperature variations of the sections of the CFST specimen and the plain concrete control specimen were affected by the ambient temperature. The temperature variation curve of the specimen section was consistent with that of the environment, but the section temperature field significantly lagged behind the ambient temperature. The variation ranges of the temperature fields of the CFST specimen and plain concrete specimen were smaller than the variation range of ambient temperature, and the temperature variation of core concrete obviously lagged behind the variation of ambient temperature. The section temperature field closer to the center of the circle from the outside to the inside, the more obvious the hysteresis phenomenon.

3. Based on the experimental research in this paper, the degree of debonding, temperature stress and internal force of the CFST specimen and structure caused by temperature variation can be analyzed.

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