Finite Element Method for Calculating Temperature Field of Main Cable of Suspension Bridge

Heng Han, Zhilei Liang, Xiangong Zhou

***Abstract*—**In this paper, the finite element method is used to study the temperature field of the main cable of the suspension bridge, and the calculation method of the average temperature of the cross-section of the main cable suitable for the construction control of the cable system is proposed. By comparing and analyzing the temperature field of the main cable with five diameters, a reasonable diameter limit for calculating the average temperature of the cross section of the main cable by finite element method is proposed. The results show that the maximum error of this method is less than 1 ℃, which meets the requirements of construction control accuracy. For the main cable with a diameter greater than 400 mm, the surface temperature measuring points combined with the finite element method shall be used to calculate the average cross-section temperature.

***Keywords*—**Suspension bridge, main cable, temperature field, finite element.

I. Introduction

THE geometry of cable system of suspension bridge is very sensitive to temperature. The accurate measurement and calculation of main cable temperature is related to the construction accuracy of cable structure. In the cable strand erection stage, the diameter of the cable strand is small, the wires are in close contact, and the heat conduction is fast. The average value of the surface temperature can be used as the average temperature of the cable strand section [1]. During the cable clamp positioning stage and the determination of the unstressed blanking length of the sling, the diameter of the main cable is large, there are certain pores between the cable strands, and the cross-sectional temperature distribution is uneven. There will be a large error if the average value of the main cable surface temperature is used to replace the average cross-sectional temperature of the main cable. To solve this problem, many scholars [1], [3], [5]-[8] have studied the temperature field of the main cable of suspension bridge, and put forward a variety of calculation methods, each of which has its own characteristics. However, for the main cable construction control stage, a method with strong practicability and high calculation accuracy is needed. At present, in the research on the cross-section temperature field of the main cable, many scholars have used different boundary conditions for heat transfer simulation calculation. Pan [2] first used the first type of boundary conditions to calculate the main cable temperature field by taking the measured temperatures of six nodes on the surface of the main cable as the boundary conditions, which can ensure sufficient calculation accuracy in a certain period of time. Zhang [3] used the measured temperature of four nodes on the main cable surface as the boundary condition, and the maximum error of the calculation results reached 2.3 ℃. Xu and Zhao [4] used the second type of boundary conditions to calculate the temperature field of the main cable, and the maximum error reached 11.9% (5.2 ℃). Huang [5] and Zhu [6] used the third kind of boundary conditions to calculate the main cable temperature field, and the maximum calculation error reached 5 ℃. Zhang [7] and Wang [8] calculated the temperature field of the main cable by using the mixed method of the second and third boundary conditions. Considering the solar radiation heat transfer and the convection heat transfer of the ambient air, the maximum error of the calculation was 5%, and the average error was 1.8 ℃. The cross-section temperature field of the main cable has great randomness and nonuniformity under the influence of the environment. It changes with the changes of solar radiation intensity, solar altitude angle, atmospheric temperature and wind speed. It is difficult to accurately grasp the convection heat transfer coefficient and heat flow density on the surface of the main cable by using the second and third boundary conditions in the finite element calculation. Therefore, the calculation error is relatively large. For the first type of boundary condition, the measured temperature at the measuring points on the surface of the main cable is used as the boundary condition for tracking calculation, and the solar radiation received by the main cable and the convective heat transfer of the ambient air are simplified to calculate the heat conduction between the surface and the interior of the main cable, which can ensure the accuracy of the calculation results.

Based on the data obtained from the full-scale model test of the main cable section of Xihoumen Bridge in [9], this paper uses the first kind of boundary conditions and the large-scale general finite element software ANSYS to simulate the temperature field of the main cable cross section, to find the calculation method of the average temperature of the main cable cross section suitable for the construction control of suspension bridges, and to discuss the distribution law of the temperature field of the main cables with different diameters.

II. Calculation Theory of Temperature Field

A. Basic Concept of Temperature Field

At a certain time, the temperature state of each point inside

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and outside the structure is the temperature field. The temperature field can be divided into steady-state temperature field and transient temperature field according to its response to time [1]. The transient temperature field changes with time, while the steady-state temperature field does not change with time. The temperature field of the main cable studied in this paper mainly refers to the temperature distribution on the cross section of the main cable. It is approximately considered that there is no heat transfer along the axial direction of the main cable. Therefore, the temperature field studied in this paper is a transient plane temperature field.

B. Basic Theory of Heat Transfer

Heat Transfer Mode

(1) Heat Conduction

Heat conduction refers to the exchange of internal energy caused by temperature gradient between contacting objects or within the same object. The heat conduction follows the Fourier law of equation (1):

$$q = K_n \frac{\partial T}{\partial n} \tag{1}$$

where: q = the heat flux density; $\partial T/\partial n$ = the temperature gradient along the heat conduction direction; K_n = the thermal conductivity, as shown in Fig. 1.

(2) Thermal Convection

Thermal convection refers to the exchange of heat between the solid surface and the fluid in contact. The heat convection is expressed by (2):

$$q = h_f (T_b - T_l) \tag{2}$$

where: h_f = the convective heat transfer coefficient; T_b = the temperature of the solid surface; T_l = the temperature of the surrounding fluid, as shown in Fig. 1.

(3) Thermal Radiation

Thermal radiation refers to the process of energy exchange between an object or two objects through electromagnetic waves, as shown in Fig. 3.

Heat Conduction Differential Equation

Based on the Fourier law, the governing differential equation of heat conduction at each point in the object is established as [10]:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + q_n = \rho c \frac{dT}{dt} \tag{3}$$

where:

$$\frac{dT}{dt} = \frac{\partial T}{\partial t} + C_x \frac{\partial T}{\partial x} + C_y \frac{\partial T}{\partial y} + C_z \frac{\partial T}{\partial z} \tag{4}$$

where: k_x、 k_y and k_z are the thermal conductivity of the object in three directions; q_n = the internal heat generation of the object (J); ρ = the density of the object (kg/m^3); c = the specific heat capacity of the object (J/kg·°C); C_x、 C_y and C_z are media conduction rates.

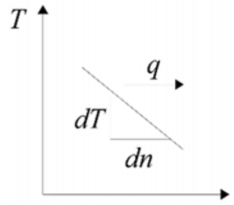


Fig. 1 Heat conduction diagram

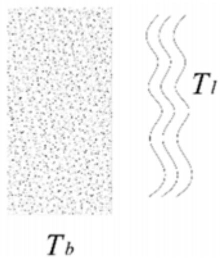


Fig. 2 Heat convection diagram

Fig. 3 Heat radiation diagram

Definite Solution Condition of Heat Conduction Problem

In engineering practice, it is necessary to solve the temperature field of the structure under certain initial and boundary conditions. For the cross section of the main cable, the initial condition is generally the section temperature distribution condition when the surface temperature of the main cable is close to the center temperature. Boundary conditions can be divided into the following three categories:

The first type of boundary condition is expressed by (5) as the temperature function on the object boundary.

$$T_w = f_1(t、\phi) \tag{5}$$

The second type of boundary condition is to use (6) to express the heat flux value on the boundary of the known object.

$$-k \left.\frac{\partial T}{\partial n}\right|_s = q_w \tag{6}$$

where: q_w = the heat flux through the boundary surface-s, and for the transient heat conduction process, q_w is a function of time.

The third type of boundary condition specifies the heat transfer coefficient HF and temperature ts of the surrounding fluid on the boundary, which can be expressed as:

$$k\frac{\partial T}{\partial n}\bigg|_s = h_f(T_s - T) \tag{7}$$

III. Analysis and Calculation of Average Cross Section Temperature of Main Cable

At present, the calculation methods for the average temperature of the cross-section of the main cable include the surface average temperature method, the weighted average temperature method and the finite element calculation method. Compared with the first two methods, the finite element method has a high degree of automation. According to the temperature values of the on-site surface measurement points, the tracking monitoring calculation can obtain results close to the actual situation.

A. Example Analysis

Based on the full-scale model test data of the main cable of a long-span suspension bridge in [9], the average cross-section temperature of the main cable is calculated and compared according to the above three methods. See Fig. 4 for the layout of measuring points on the test section. There are 80 measuring points in total.

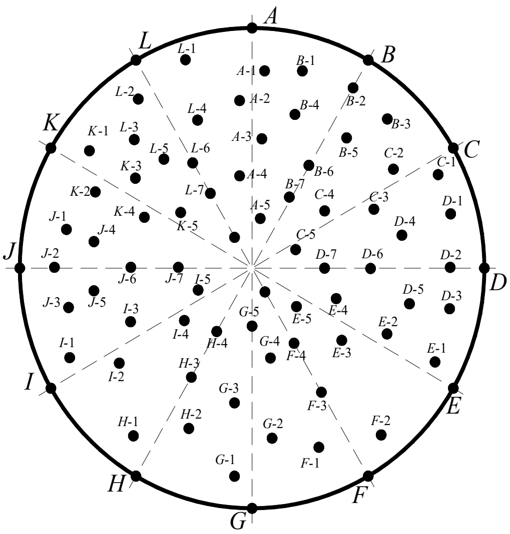


Fig. 4 Layout of measuring points of test section

According to the surface measurement point data, ansys-plane55 unit is used to simulate the model test cross section, as shown in Fig. 5. It is assumed that the cross-section material of the main cable is uniform and there is no slip between the steel wires. The diameter of the main cable is 845 mm, and the thermophysical parameters of the main cable material are taken from the test results of the main cable model test in literature [9] and [11], as shown in Table I.

The test data are the temperature data of the test site from 10:00 a.m. on one day to 10:00 a.m. on the next day in summer, with an interval of 1 h. Through the analysis of the data, the time when the average surface temperature of the main cable is equal to the average cross-section temperature of the main cable is selected as the initial time, and the steady-state thermal analysis is carried out to obtain the initial cross-section temperature. The continuous measured temperature values of eight test points on the surface are taken as the boundary conditions of the finite element model, The temperature values at the measuring points between hours are linear and continuous. The continuous analysis is carried out for 24 h in steps of 1 h. The cross-sectional temperature distribution of the main cable at each typical time is shown in Fig. 6. The comparison between the measured value and the calculated value is shown in Fig. 7. During the night temperature stabilization period of 23:00-7:00, the difference between the apparent average temperature of the main cable, the calculated average temperature and the weighted average temperature is shown in Table II.

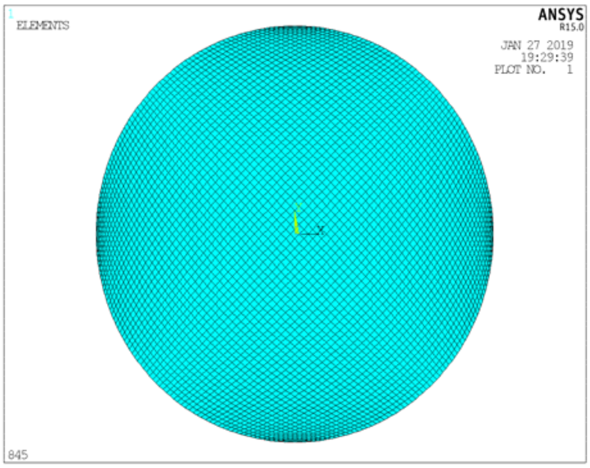


Fig. 5 Cross-section model of main cable

TABLE I
THERMOPHYSICAL PARAMETERS OF MAIN CABLE

Project	Symbol	Unit	Value
Apparent thermal conductivity	K	W/(m·°C)	1.2
Density	ρ	kg/m^3	6140.14
Specific heat capacity	C	J/(kg·°C)	508
Thermal diffusivity	D	cm^2/h	13.85

TABLE II
CALCULATED TEMPERATURE DIFFERENCE DURING TEMPERATURE STABILIZATION PERIOD

Time	Weighted average/°C	Apparent average/°C	Difference /°C	Calculated average/°C	Difference /°C
23:00	31.55	28.82	-2.73	32.16	0.61
0:00	31.40	28.56	-2.84	32.07	0.67
1:00	31.25	28.36	-2.89	31.98	0.73
2:00	31.16	28.18	-2.98	31.89	0.74
3:00	30.98	28.07	-2.91	31.81	0.83
4:00	30.87	28.01	-2.86	31.73	0.86
5:00	30.76	27.96	-2.80	31.65	0.90
6:00	30.65	27.93	-2.72	31.58	0.93
7:00	30.56	27.93	-2.63	31.51	0.95

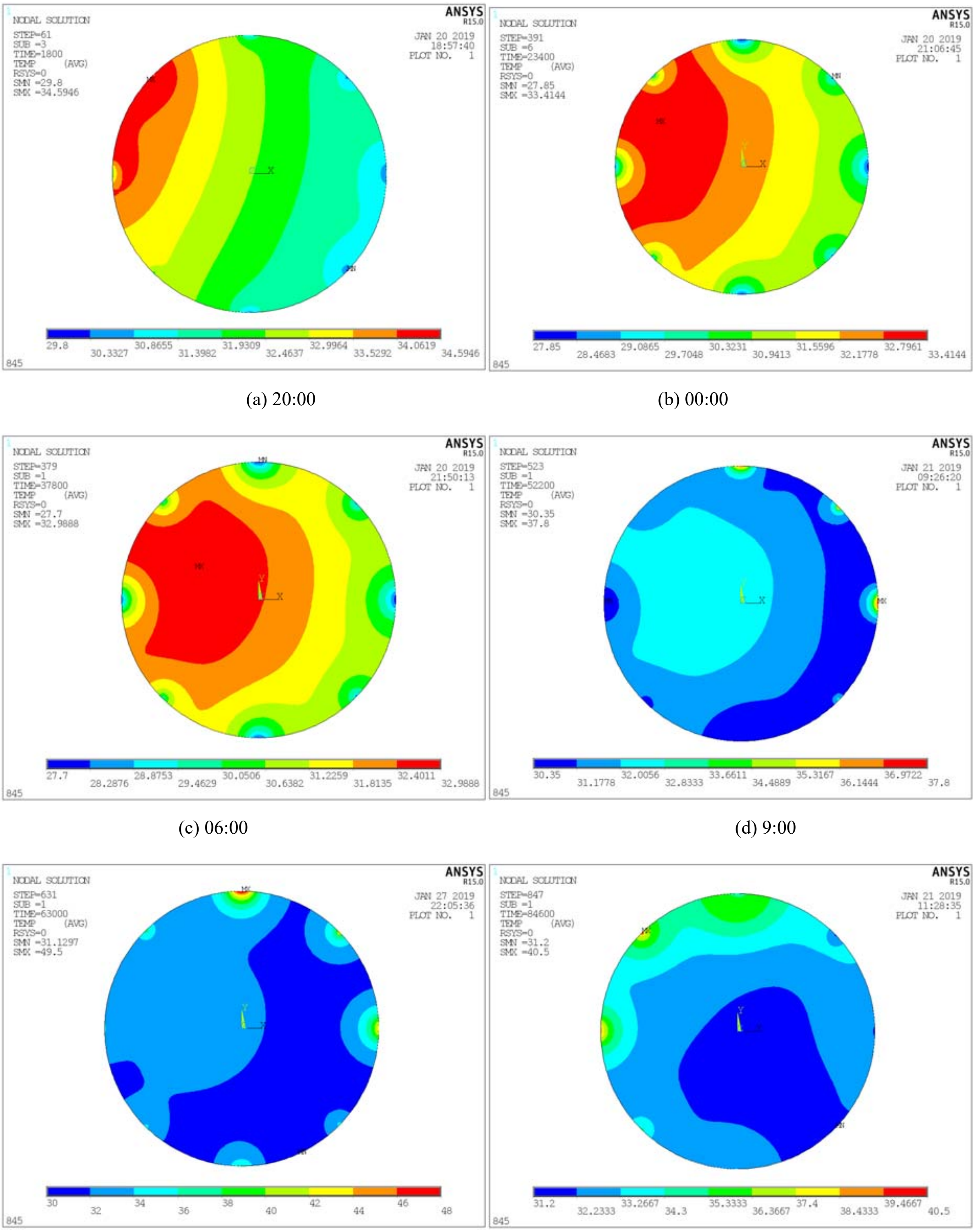


Fig. 6 Cross-section temperature distribution of main cable at each typical time

By analyzing Fig. 7 and Table II, the following conclusions can be drawn:

(1) There is a large difference between the apparent average temperature of the main cable and the average temperature of the cross section of the test model. The maximum temperature difference in the daytime is about 15:00, which is 7.8 ℃, and the average temperature difference at night is 2.8 ℃. Therefore, it is infeasible to replace the average temperature of the cross section of the main cable with the apparent average temperature of the main cable.

(2) The average temperature of the main cable section calculated by the finite element method is close to the weighted average temperature. The calculation error in the daytime is small, and the error at night is slightly larger. The average error at night is 0.8 ℃, the maximum error is 0.97 ℃, and the error is less than 1 ℃. Therefore, the finite element calculation of the average temperature of the main cable section can ensure a certain accuracy, and there is no need to set up too many temperature measuring points, which can be used for the construction control calculation of the cable system.

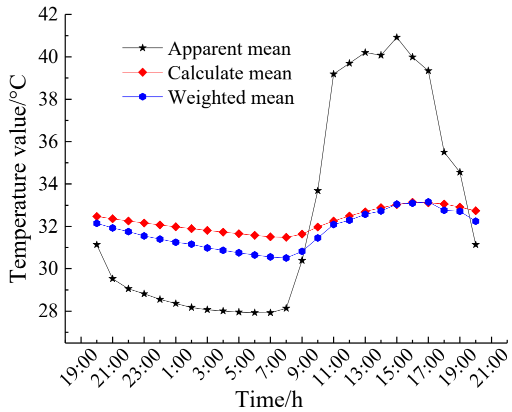


Fig. 7 Comparison of calculation results of three methods for section average temperature

B. Analysis of Influence of Finite Element Method on Calculation Accuracy

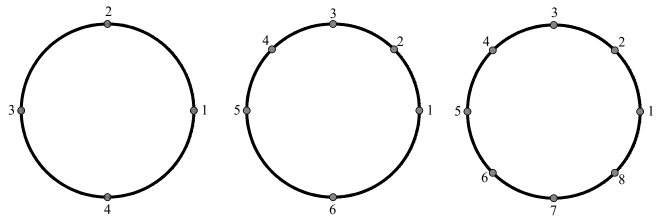
The finite element method used in this paper is based on the continuous measured values of the main cable surface temperature measurement points and the first kind of boundary conditions. The calculation accuracy is mainly related to the selection of the initial calculation time and the number of boundary measurement points.

1. Selection of Initial Conditions

To calculate the temperature field of the main cable by finite element method, first we select an initial temperature field as the initial condition for finite element calculation, and then carry out tracking calculation to obtain the average temperature of the main cable section at any time. The steady-state analysis shows that the average temperature of the cross-section of the main cable is close to the average temperature of the surface measuring points. Therefore, the temperature of the surface measuring points of the main cable at the time when the internal and external average temperatures are close to each other should be selected as the initial condition for the finite element calculation, so that the accuracy of the average temperature of the cross-section of the main cable calculated by the finite element method can be guaranteed under the measured boundary conditions [1]. According to the model test results, the temperature distribution of the main cable at 9:00 and 19:30 can be selected as the initial conditions.

2. Selection of Boundary Conditions

The difference of boundary conditions in finite element calculation is mainly reflected in the difference of measuring points on the main cable surface. The arrangement of main cable surface temperature measuring points in the project mainly includes four nodes, six nodes and eight nodes, as shown in Fig. 8. [2].



(a) Four node (b) Six node (c) Eight node

Fig. 8 Arrangement of main cable surface temperature measuring points

In order to discuss the influence of the three boundary conditions on the accuracy of finite element calculation, nodes 4, 6 and 8 are used as boundary conditions, respectively, and the measured temperature value of the main cable surface measurement points at each time is used as the boundary condition for finite element calculation. The thermal transient analysis is carried out, the average temperature value of the main cable section at each time is tracked and calculated, and compared with the weighted average temperature value of the main cable model test. The calculation errors of the three boundary conditions are shown in Fig. 9.

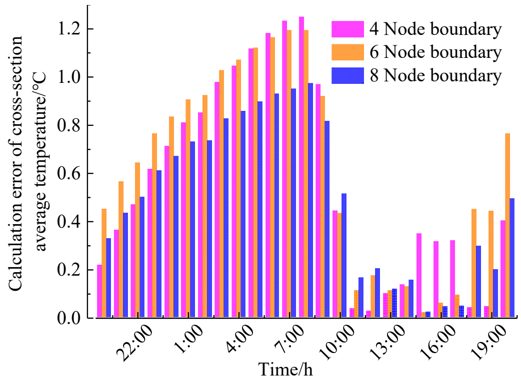


Fig. 9 Calculation error of different boundaries

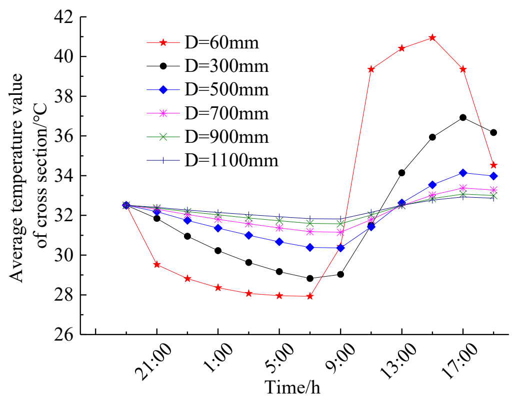


Fig. 10 Average temperature of main cables with different diameters

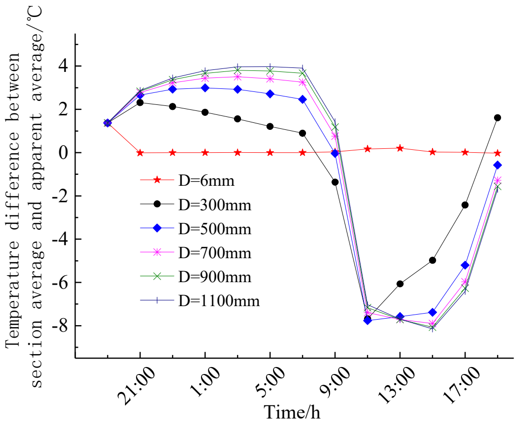


Fig. 11 Difference between sections with different diameters and apparent average temperature

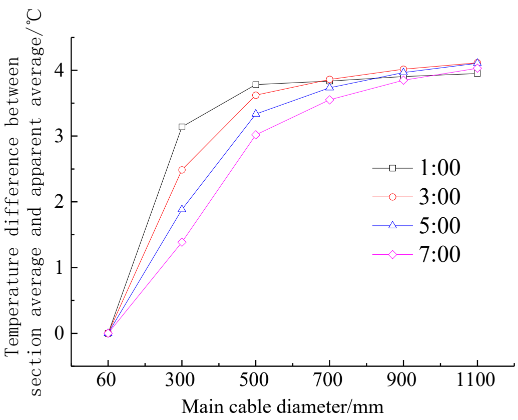


Fig. 12 Variation law of error with diameter

It can be seen from Fig. 9 that the calculation error of the 8-node boundary is significantly less than that of the 4-node and 6-node boundaries, and the maximum error of the 8-node boundary is 0.97 ℃, less than 1 ℃, which can meet the accuracy requirements of construction control. The 8-node boundary condition is recommended for the finite element calculation of the main cable temperature field.

C. Temperature Field Distribution of Main Cables with Different Diameters

The temperature field distribution of the main cable of suspension bridge is very uneven. Many scholars believe that with the increase of the diameter of the main cable, the difference between the average temperature of the main cable section and the apparent average temperature will become larger and larger; Pan [2] suggested that when the diameter of the main cable is greater than 600 mm, the average cross-section temperature of the main cable should be calculated by using the finite element method combined with the measured surface temperature. Yu [1] pointed out that, in order to calculate the average temperature of the cross section of the main cable whose diameter is greater than a certain limit, it is necessary to calculate the temperature distribution of the cross section of the main cable, but it is not rigorous to obtain the limit of diameter 600 mm only through a separate calculation example. Therefore, in order to discuss the reasonable diameter limit of the calculation method for the average temperature of the cross-section of the main cable, based on the above calculation examples, under the same initial and boundary conditions, we change the diameter of the main cable (the cable strand diameter in the project is generally about 60 mm, and the main cable diameter range is 300 mm-1100 mm), and select five main cables with diameters of 60 mm, 300 mm, 500 mm, 700 mm, 900 mm and 1100 mm, of which the specific heat capacity of 60 mm cable strand is 460 j/(kg•℃). The density is 7850 kg/m^3, the thermal conductivity is 50 w/(m•℃), and the thermal physical parameters of the main cables with other diameters are the same as those in Table I. We calculate the average cross-sectional temperature of main cables with different diameters at different times, as shown in Fig. 10. See Fig. 11 for the difference between the average cross-sectional temperature of main cables with different diameters and the apparent average temperature. See Fig. 12 for the variation law of the error of replacing the average cross-sectional temperature of main cables with the apparent average temperature with the diameter.

The following conclusions can be obtained by analyzing Figs. 10-12:

(1) Under the same external environmental conditions, the variation amplitude of the average cross-section temperature of the main cable decreases with the increase of the diameter. The average cross-section temperature of the cable strand with a diameter of 60 mm changes about 13 ℃ day and night, while the average cross-section temperature of the main cable with a diameter of 1100 mm changes only 1.1 ℃ day and night. It can be seen that the cable strand temperature during cable strand erection is significantly affected by the external environment than the average cross-section temperature after the main cable is formed. Therefore, the real-time monitoring of cable strand temperature during cable strand erection is very important.

(2) Under the same boundary conditions, the difference between the average temperature of the main cable section and the apparent average temperature increases nonlinearly with the increase of the diameter at the same time. When the temperature is stable at night (23:00-7:00), the difference between the two average temperatures of the main cable is less than 0.1 ℃. The diameter of main cable ranges from 300 mm to 1100 mm. The difference between the two average temperatures increased from 1.5 ℃ to 3.8 ℃. In the range of diameter from 60 mm to 500 mm, the temperature difference increases rapidly with the increase of diameter, and the temperature difference greater than 500 mm increases slowly.

IV. Conclusion

This paper expounds the importance of the calculation of the temperature field of the main cable of suspension bridge in the construction control calculation, and studies the method of calculating the average temperature of the cross section of the main cable by using the temperature field calculation theory. The main conclusions are as follows:

(1) Through the comparison and demonstration of the three commonly used methods for the layout of the main cable surface temperature measuring points, it is found that the average error of the 8-node boundary is the smallest, which can meet the accuracy requirements of construction control. The 8-node boundary condition is recommended for the finite element calculation of the main cable temperature field.

(2) By discussing the difference between the apparent average temperature and the section average temperature of the main cables with different diameters, combined with the engineering practice, the results show that: for the main cables with diameters below 400 mm, the apparent average temperature can also meet the requirements of engineering accuracy. If the diameter is greater than 400 mm, the surface measurement point plus finite element method should be used to calculate. The reasonable limit of the diameter of the main cables using the apparent average temperature to replace the section average temperature is 400 mm.

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