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Temperature Effects and Calculation Method of Closure Temperatures for Concrete-filled Steel Tube Arch Rib of Dumbbell-shape Section

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Abstract: This paper has done continuous on-site experimental researches on temperature field and temperature effects that are under the influence of hydration heat of concrete during the molding process of dumb-bell CFST arch bridge. Analysis on time-history law of temperature field and temperature effects is made. Results reveal that temperature variation of hydration heat of the concrete within the steel tube is showed as follows: temperature rising—continuous high temperature—temperature dropping—equalizing. The structural temperature field, generated under the effect of hydration-heat in the process of molding arch rib, is nonlinear temperature field. Temperature field of concrete hydration heat has an obvious effect on crown section. Finally, practical methods to calculate the closure temperature of CFST arch rib and the effective measures to reduce the residual internal stress of temperature of arch rib are proposed.

Keywords: Concrete-filled steel tube (CFST), Hydration-heat, Temperature field, Effect, Calculation closure temperature.

1. INTRODUCTION

CFST arch is a stress structure composed of steel tube and concrete. Constraints of tube puts the concrete under a complex stress state and then increases the strength of concrete and mechanical performances. At the same time, it can also delay or prevent the steel tube from the premature occurrence of local buckling because of the existence of concrete, and then the full play of its material performances can be guaranteed. In addition, steel tube can be used as a template during the construction of concrete. It turns out to be faster and cheaper than the ordinary bridge construction. However, CFST arch bridge is different from steel arch bridge**,** concrete arch bridge and masonry arch bridge in various aspects, such as materials and composition of the rib, section size and construction methods etc. Thus, the emerging characteristics are different and its temperature characteristics are more complex. There have been some researches on the temperature of CFST arch bridge. Currently, researchers have made experimental and theoretical investigations on temperature of CFST respectively, including the experimental research, made by Chen Baochun *et al.* [1-4], on temperature field of 3 circular CFST, of which the diameter is less than 550 millimeters and the length 1.5 meters. The experiment lasts for 44 days within the process of empty steel tube, pouring concrete, concrete hydration heat emission and the conformation of the CFST, during which the section temperature variations are tested under the combined effects of environmental temperature and the hydration heat of cements. Feng Bin [3] conducts an experiment on hydration heat temperature field to investigate the calculation model for hydration heat of CFST with four round and square CFST of different diameters and side lengths. Applied the general program, Lin Chun Jiao and Zheng Jielian *et al*. [4] foster a calculation analysis on the temperature field affected by hydration heat of circular and arch ribs of dumbbell-shaped section respectively.

The experiments mentioned above mainly focus on the temperature field of single-tube section, however, the study of temperature effects for CFST of dumbbell-shaped section are rare.

Research shows that when concrete reaches the intensity of shaping into CFST structure, certain thermal-stress is accumulated in the structure under the influence of hydration heat, which will affect the temperature effect of molded structure. Therefore, temperature effect analysis plays an important role in the calculation of indeterminate CFST arch bridge. And the variation law of hydration heat temperature field for the arch rib section is one of the key matters.

However, since the structure of the CFST arch bridge and the arch rib section style are varied and the location and weather conditions are different, there are many factors affecting the temperature. Thus, more deep and systematical researches on temperature of CFST arch bridge are needed.

This paper conducts an investigation and analysis on dumbbell-shaped CFST arch rib bridge and observes the hydration heat temperature field and its change to test the

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distribution regularity of hydration heat temperature field and its effects of CFST arch bridge.

2. STRUCTURE DESIGN, CONSTRUCTION SEQUENCE AND INSTRUMENTS COLLOCATION OF CONTRAL SECTION

2.1. Structure Design

This research is based on the investigation of a constructing dumbbell-shape concrete-filled steel arch bridge in Nanning, Guangxi, a half-through concrete-filled steel tubular arch bridge, with a clear span L0 of 111.5m, and its arch rib adopts the constant section catenary's arch axis with an arch axis coefficient m=1.347, height -span ratio is 1/3.063 and height of arch rib is 3.0m. The two ribs are combined by transverse brace and the rib is constant-section dumbbell-shaped section, which employs Q345 spiral welded tube with a diameter of top and bottom chord tube D of 1200mm. Top and bottom chord tubes are linked by web welding and the thickness of the tube wall and web t=18mm. Tube need to perfuse micro-expansive concrete with the intensity of C50, while perfuse no concrete in peritoneal cavity but adopt the steel I63 to stiffen instead. The transverse brace is an empty steel tube, as can be seen in Fig. (**1**).

2.2. Construction Sequence

When construction is started, the steel tube should be first hoisted to arching and then pump over concrete into the tube, with the symmetry from two sides to mid-span. The sequence of pumping over concrete is as follows: first, pump over concrete to the top chord and then pump over the bottom when the intensity of the top chord reaches to a certain value. The pressure design value of pumping over concrete into the tube should be less than or equal to 2.5MPa.

2.3. Instrument Collocation of Control Section

In order to grasp the distribution regularity of hydration temperature field of concrete-filled steel composite structure and simultaneously, to control the stress in the process of construction, selected the arch foot, L/4 section and crown as the temperature measured point collocation section, and arch foot, L/8 section, L/4 section and 3L/8 section and crown as the stress measured point collocation section, of which Li is long acting steel chord strain gauge with the function of temperature testing, and Bi is long acting steel chord strain gauge. All the measured point collocation of the control sections are showed in Fig. (**2**).

After pumping over the concrete into the top and bottom chord respectively, data of the concrete-filled steel composite structure should be collected immediately. Monitoring frequency is 4 times a day when finish pumping over the concrete and later the frequency should be lowered down until the temperature in the concrete-filled steel tube is close to the air temperature.

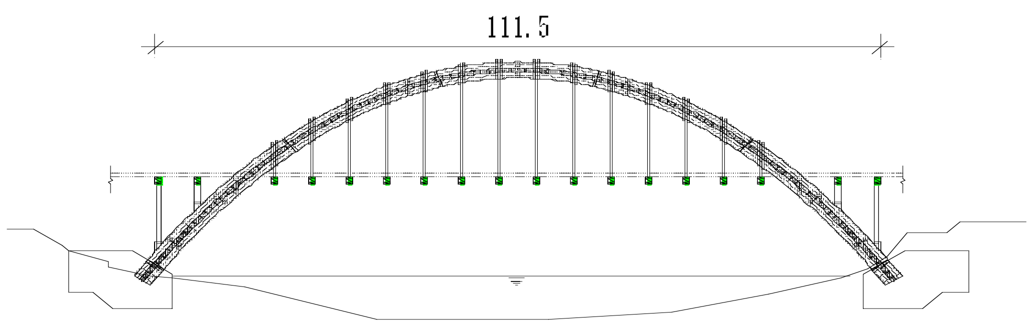

Fig. (1). Bridge elevation /m.

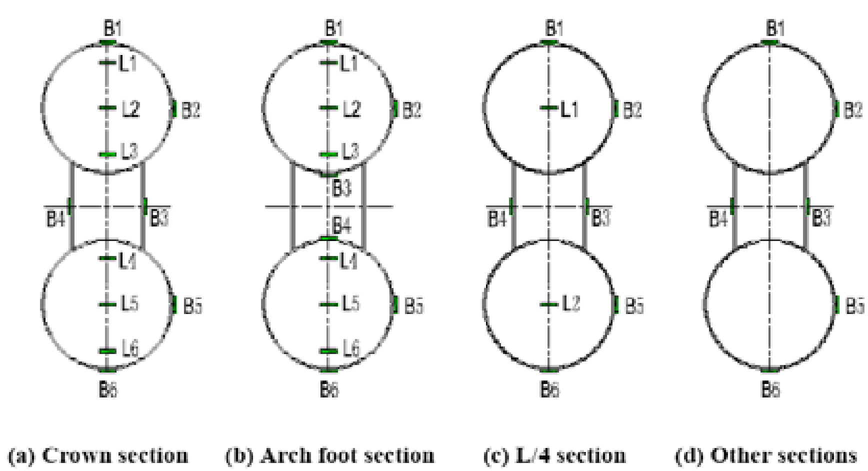

Fig. (2). Temperature and stress measured point collocation.

3. ANALYSIS ON THE EXPERIMENTAL RESULTS OF HYDRATION-HEAT TEMPERATURE FIELD AND ITS EFFECT FOR THE CONCRETE-FILLED STEEL TUBE ARCH RIB SECTION

3.1. The Temperature Field Variation Law of Arch Rib Section

Fig. (**3-6**) are the time-history curves for temperature variation of each control section after the perfusion of concrete; the completion time of concrete perfusion in top chord is adopted as the zero of time.

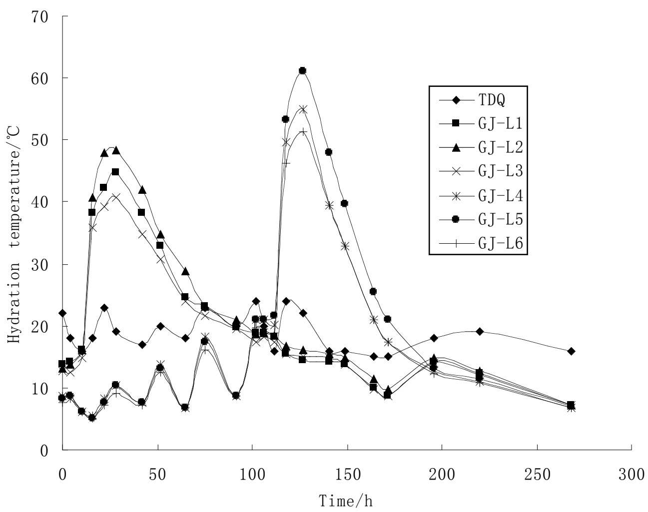

Fig. (3). Time-history curve for temperature variation of arch rib section.

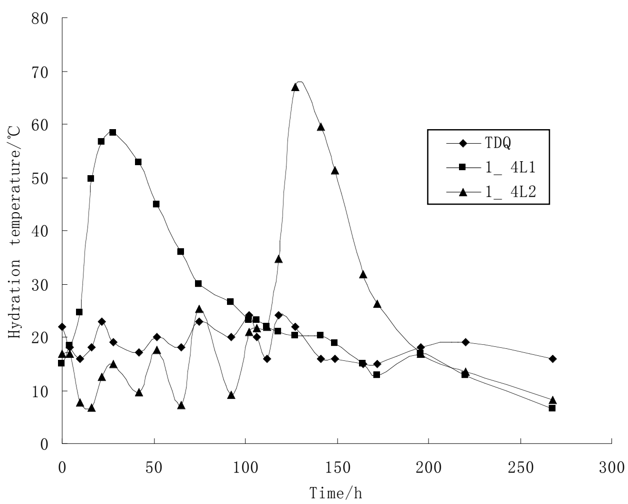

Fig. (4). Time-history curve for temperature variation of L/4 section.

From Fig. (**3-6**), it can be seen that temperature in the empty tube almost changes with air temperature simultaneously, but temperature in steel tube cavity is slightly lower than air temperature; after the concrete perfusion in the tubes, the temperature variation of arch rib structure is showed as follows: first, the temperature increases sharply in reaching the maximum temperature (where the maximum

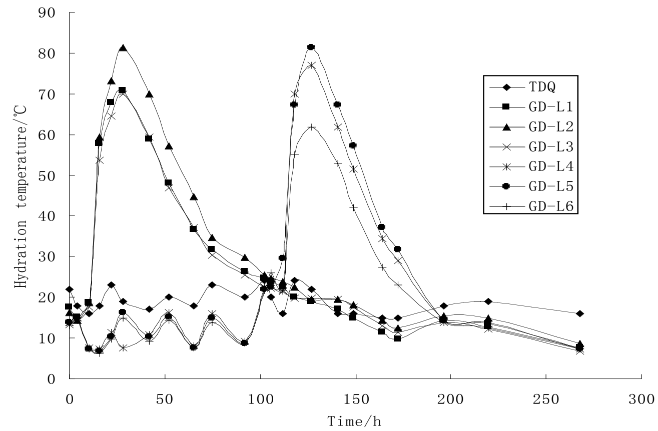

Fig. (5). Time-history curve for temperature variation in crown.

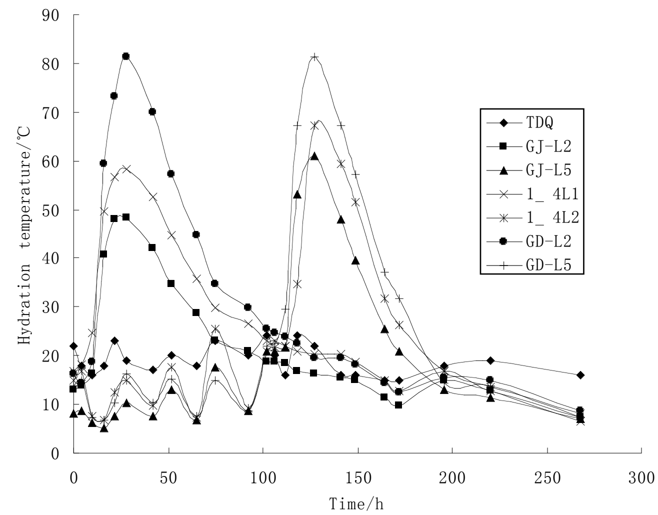

Fig. (6). Time-history curve for temperature variation in core of the concrete of each arch rib section.

temperature of the dome center section is 81.3°C) and then declines rapidly till reduces to close to ambient temperature, namely, hydration temperature changes by the rule of "Temperature raises-continuous high temperature-temperature drops down-equalization of temperature" for the reason that hydration-heat of cement begins to release shortly after the concrete casting and increases rapidly. when the hydration rate is greater than the heat dissipation rate of arch rib outer-wall, the temperature of arch structure is in a sharp rise; when the hydration rate and heat dissipation rate attain equilibration, temperature of the structure reaches the peak value; when the heat dissipation rate is greater than hydration rate, the temperature decreases continuously; after the hydration releasing, the temperature can be only affected by ambient temperature.

When bulk temperature of the structure is in the process of fall after rise, temperature in arch rib cross-section appears to be high inside and low outside; temperature difference between tested section and exterior margin is relatively large and gradually increases in the phase of temperature rise, while gradually declines in the temperature fall period.

Fig. (**6**) shows that temperature of the whole concrete-filled steel tube arch rib gradually rises from arch foot to crown; temperature of arch foot is lower than that of the other sections, of which the temperature peak value of crown is 33.0°C higher than that of arch foot and 23.0°C higher than that of L/4 section. From the above mentioned analysis on hydration temperature of the concrete-filled steel tube arch rib, conclusion can be made that the structure temperature field caused by hydration-heat in the process of molding concrete-filled steel tube is nonlinear temperature field.

From the experimental results, it can be also showed that the structure temperature variation caused by hydration-heat of concrete-filled steel tube lasts for a longer time, namely, 120 hours, mainly because of a larger arch rib section size of the bridge and larger number of concrete and slower reaction speed of the arch rib to ambient temperature.

Obviously, section temperature of concrete-filled steel arch rib is higher than that of ambient temperature under the effect of hydration-heat and has a temperature difference of high inside and low outside in the section (the highest temperature peak value of the arch rib section center exceeds 81.3°C, the average temperature peak value of the section is close to 74°C, 55°C higher than ambient temperature). Therefore, arch rib section temperature field of concrete-fill steel tube has possessed the characteristics of massive concrete temperature field and it should be attached great importance in the effect of hydration-heat.

3.2. Experimental Analysis on Hydration-Heat Temperature Effect of Concrete-filled Steel Arch Rib Section

The structure temperature field caused by hydration-heat in the process of molding concrete-filled steel tube is nonlinear temperature field, namely, besides the whole temperature variation, the structure also brings about section temperature difference. The previous will make indeterminate concrete-filled steel arch rib yield secondary internal force, while the later will make the structure generate temperature self-stress in the section. The self-stress will vanish as the temperature continuously decline, however, there exist some certain self-stress in the molded-arch-rib structure. Fig. (**7-14**) are the strain time-history curves for concrete of crown section.

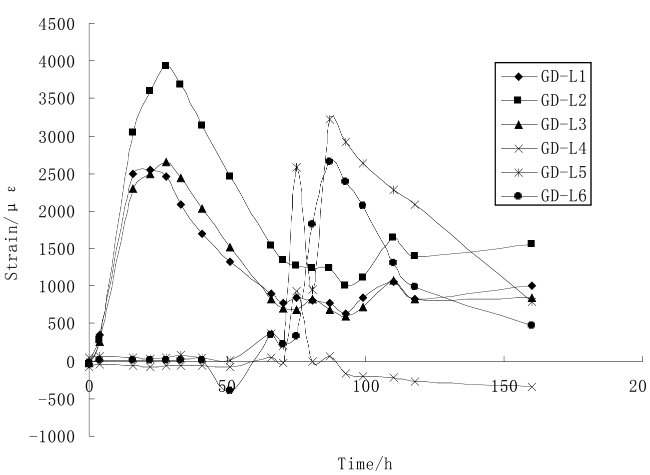

Fig. (7). Concrete strain time-history curves for crown section.

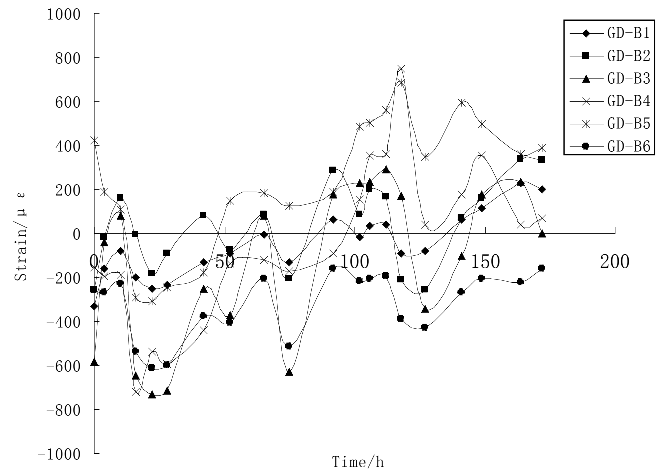

Fig. (8). Steel tube's surface strain time-history for crown section curves.

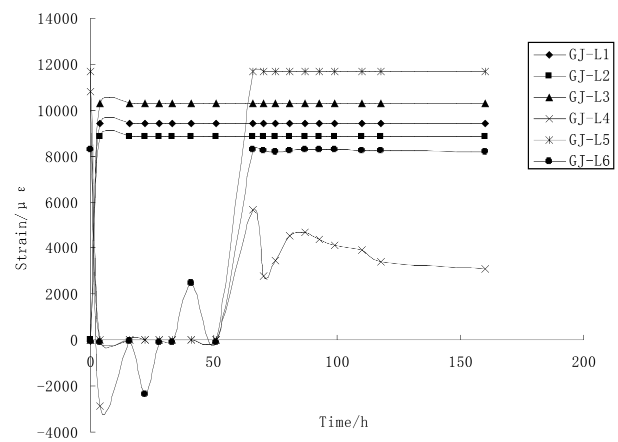

Fig. (9). Concrete strain time-history curves for arch foot section.

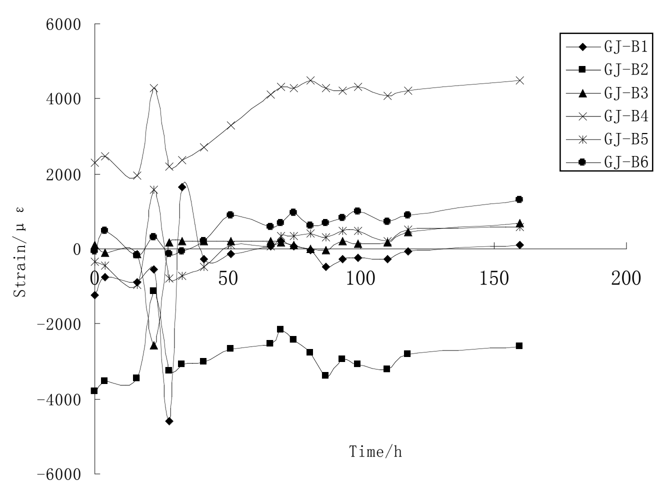

Fig. (10). Steel tube's surface strain time-history curves for arch foot section.

From Fig. (**7-14**), it can be seen that concrete hydration-heat temperature effect of the crown section basically changes with temperature field simultaneously, which has

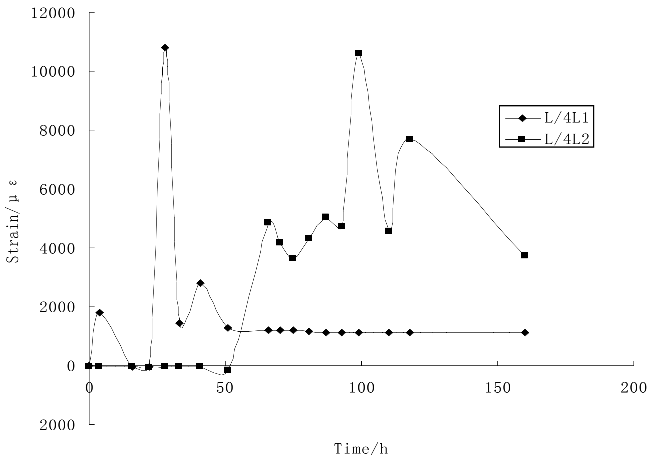

Fig. (11). Concrete strain time-history curves for L/4 section.

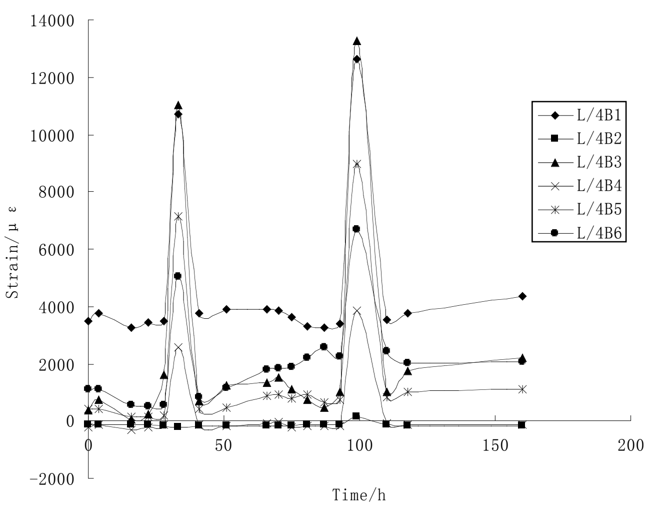

Fig. (12). Steel tube's surface strain time-history curves for L/4 section.

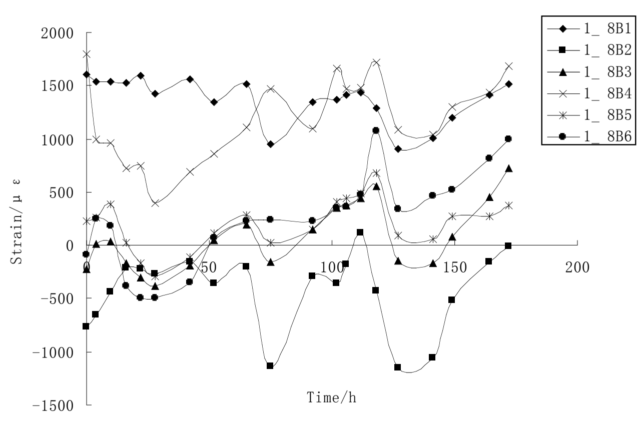

Fig. (13). Steel tube's surface strain time-history curves for 3L/8 section.

gone through the concrete casting of the upper and lower chords. The generated temperature effect has a corresponding peak value; and hydration temperature effect of arch foot section, affected by the perfusion of concrete, has a greater effect and relatively large residual strain; hydration temperature effect of L/4 Section generates peak fluctuation in the process of concrete perfusion, and the fluctuation effect varies within wide limits and finally levels off.

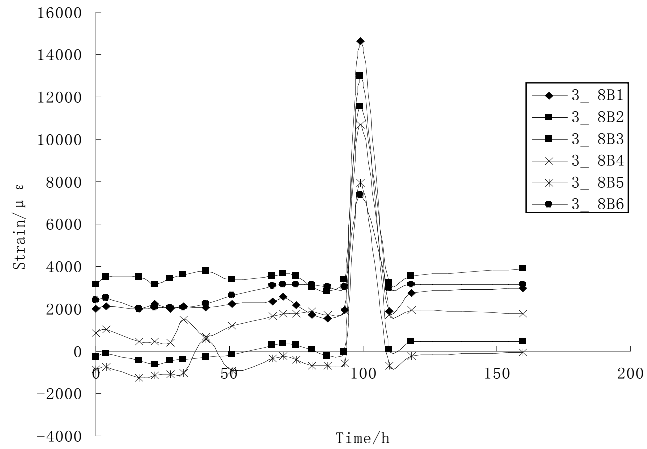

Fig. (14). Steel tube's surface strain time-history curves for L/8 section.

From the strain time-history curve of steel tube's surface, results can be viewed that hydration temperature field of concrete has a great effect on crown section, which makes the steel tube continuously withstand the tension and compression alternatively, but the poured concrete of top chord is mainly caused by the effects of tension while concrete of bottom chord is mainly caused by the effects of compression. The effect caused by concrete perfusion of top chord on steel tube of arch foot section fluctuates slightly, but the concrete perfusion of bottom chord has little influence on the tube, namely, temperature effect on the steel tube of arch foot is not obvious. From the strain time-history curves of L/8, L/4, 3L/8 sections of steel tube, it can be known that surface strain transits from single-wave peak to dual-wave peak and finally turns into a single wave peak. In the L/4 section, strain of concrete perfusion of top chord on steel tube's surface changes greatly and tend to be leveled off in the end, namely, strain effect in this section changes sharply.

All in all, there remains some certain temperature stress in the structure after the molding of concrete-filled steel tube arch rib and the residual temperature strain is large when the placing temperature of concrete is high in the same ambient temperature. In addition, dimension of internal force also relates to joint temperature of empty steel tube of the arch rib, the average air temperature in the stage of molding arch rib and the tube diameter and strength of the concrete etc.

4. DETERMINATION METHOD FOR THE CALCULATION CLOSURE TEMPERATURE OF THE CONCRETE-FILLED STEEL TUBE ARCH BRIDGE

According to the "General Code for Design of Highway Bridges and Culverts (JTG D60-2004 China)" [5], when calculating the imposed deformation or constrained deformation caused by the effect of even temperature, we should start from the structure temperature when it is constrained (generally it refers to the status when the whole bridge is closed), and we should take the effect of the minimum and maximum temperature into consideration. "The structure temperature under constraint" is the datum temperature of the bridge.

As for the common steel-reinforced concrete and concrete arch bridge, it's formation process is as below: to finish the constraint of the structure by the closure of the arch rib (arch ring), when the internal stress of temperature at the closure of the arch rib (arch ring) reaches 0, its datum temperature is the structure temperature at the closure of the he arch rib (arch ring).

Due to its particularity in the structure construction technology and material, the closing process of the concrete-filled steel tube arch bridge is different from that of the ordinary bridges and steel arch bridges. The construction sequence of the concrete-filled steel tube arch rib is: first close the empty steel pipe, and then pour concrete into the pipe; the concrete will form the concrete-filled steel tube arch rib when it is hardened. The structure system will subject to two times of closures, and it's intensity will form 28 days later after the closure of empty pipe and closure of concrete within the steel pipe. Therefore, whether it is the closure temperature of the empty steel pipe or the temperature of the arch rib 28 days after the pouring of concrete, it cannot give a true description about the pressure under the concrete arch rib structure.

4.1. Calculation Idea

Calculation closure temperature is the key problem for the analysis of the internal stress of temperature of the static indeterminate the concrete-filled steel tube arch rid. Although we can decide the calculation closure temperature of the specific bridge through the experiment and analysis of numerical method such as finite element method, it is not practical. Therefore, to find an easy yet practical computation for the engineering design and construction has great significance. Manual calculation for the internal stress of temperature of the non-hinge arch is an easy and traditional method for engineering personnel to grasp and use [6].

As for the concrete-filled steel tube arch in the forming process, we can use the general idea that is used to calculate the internal stress of temperature of the arch bridge, but we should aware that: as soon as the empty steel pipe is closed, the steel pipe is under constraint. Therefore, the internal stress of temperature produced in the steel pipe should be based on the closure temperature of the empty steel pipe; while the concrete inside the pipe is under constraint as soon as it obtains intensity. Therefore, the internal stress of temperature produced by the concrete changes from the temperature when the concrete obtains intensity and the concrete varies with the change of the temperature and the elastic modulus. When the concrete in the steel pipe forms integrity, both the steel pipe and concrete still remains internal stress of temperature. By deciding the residual internal stress of temperature existing in the concrete arch rib of the steel pipe, we can obtain the calculation closure temperature (datum temperature).

The main process to create internal stress of temperature during the forming process of the arch rib on the concrete-filled steel tube arch bridge includes the following: the stage from the closure of the empty steel pipe to the pouring of concrete, the completion of the concrete pouring to the forming of the concrete arch rib in the steel pipe (the internal stress of temperature during the hydrate temperature rising and decreasing period). This article adopts the force-method to analyze the variation of the internal stress of temperature during the forming process of the arch rib.

4.2. The General Stress of Temperature Produced in the Forming Process of the Concrete-Filled Steel Tube Arch Rid

4.2.1. The Stage from the Closure of the Empty Steel Pipe to the Concrete Pouring

When the empty steel pipe is closed, the arch rib of the steel pipe begins to be constrained and it produces internal stress of temperature under the effect of temperature. Set the closure temperature of the empty steel pipe as $T_{0,}$ if the structure temperature (the pouring temperature of concrete) is T_1 when pouring the concrete, then the horizontal stress H_{1T} (also known as redundant stress) produced at the elastic center of the arch rib is

$$H_{1T} = \frac{\alpha \cdot (T_1 - T_0) \cdot L}{\int_S \frac{y^2 ds}{EI}} \tag{1}$$

Where, α and EI are respectively the linear expansion coefficient and bending rigidity of the arch rib.

Because the arch rib in this stage is steel structure, we can directly take the linear expansion coefficient and bending rigidity of the steel pipe for α and EI, that is $\alpha = \alpha_s$, $EI = E_S I_S$

As for the uniform section arch, Formula (1) is written as

$$H_{1T} = \frac{\alpha_S \cdot (T_1 - T_0) \cdot L}{\int_S \frac{y^2 ds}{E_S I_S}} = \frac{\alpha_S \cdot (T_1 - T_0) \cdot E_S I_S \cdot L}{\int_S y^2\, ds} \tag{2}$$

4.2.2. The Stage from the Completion of the Concrete Pouring in the pipe to the Formation of the Concrete-Filled Steel Tube Arch Rid

After pouring concrete is completed, the concrete starts to harden and gradually release its hydrate-heat. The temperature firstly goes up then turns down.

(1) The Internal Stress of Temperature of the Arch Rib in Hydrate-Heat Temperature Rising Period

According to the test on the temperature field, the temperature rising process keeps for over 10 hours to several ten hours. The process is not long. In the temperature rising stage, the elastic modulus and intensity of the concrete is low, which is not able to afford various effects including temperature. Therefore, in this period, the steel pipe still undertakes the structure stress.

If the maximum temperature of the structure under the influence of the hydrate-heat is T_2, the temperature variation of the structure is T_2 -T_1 during the process from the completion of the concrete pouring to the maximum temperature, and the horizontal stress produced at the elastic center of the arch rib changes to H_{2T} due to the variation of temperature,

$$H_{2T} = \frac{\alpha \cdot (T_2 - T_1) \cdot L}{\int_S \frac{y^2 ds}{EI}} \tag{3}$$

According to the analysis above, α and EI in Formula (3) still take the value as below $\alpha = \alpha_s$, $EI = E_S I_S$

As for the uniform section arch, Formula (3) is written as:

$$H_{2T} = \frac{\alpha_S \cdot (T_2 - T_1) \cdot L}{\int_S \frac{y^2 ds}{E_S I_S}} = \frac{\alpha_S \cdot (T_2 - T_1) \cdot E_S I_S \cdot L}{\int_S y^2\, ds} \tag{4}$$

(2) The Internal Stress during Hydrate-heat Temperature Reducing Period

When the concrete-filled steel tube arch rid reaches the maximum temperature through hydrate-heat, its temperature will gradually reduce to be close to the environment temperature and be mainly influenced by the environment temperature. During the temperature reducing period, the elastic modulus and intensity of the concrete will gradually increase. When the hydrate-heat is completely released, the elastic modulus and intensity of the concrete will have greater increase.

In this temperature reducing period, the concrete and the steel pipe will jointly undertake the effect of the temperature. The concrete-filled steel tube arch rid will reduce to normal temperature from its maximum temperature of hydrate-heat T_2 , if the structure temperate at this moment is T_3. Presume that the horizontal force at the elastic center of the arch rib changes to H_{3T} due to temperature variation T_3-T_2, considering the elastic modulus of the concrete arch rib is gradually increasing; we should use incremental method to solve H_{3T}.

To divide the temperature variation process from T_2 to T_3 into a serials of time section, where the temperature variation corresponding to section i is ΔT_i and the corresponding average elastic modulus of the concrete is E_{ci} ; if the general rigidity of the arch rib is $(EI)_i$, then the horizontal force produced at the elastic center of the arch rib changes as below due to the temperature variation:

$$\Delta H_i = \frac{\alpha \cdot \Delta T_i \cdot L}{\int_S \frac{y^2 ds}{(EI)_i}} \tag{5}$$

Where, α and $(EI)_i$ are under the influence of steel pipe and concrete, its value should take the contribution of the steel pipe and concrete into consideration.

The linear expansion coefficient of the concrete-filled steel tube arch rid calculated by the means of area weighted average when the steel pipe and concrete are deemed as an integrity, that is:

$$\alpha_{sc} = \frac{\alpha_c A_c + \alpha_s A_s}{A_c + A_s} \tag{6}$$

Where, α_{sc} represents the linear expansion coefficient of the concrete-filled steel tube.

As for the rigidity, both the steel pipe and concrete has contributions to the rigidity of the arch rib. The structure rigidity adopts the direct superposition method.

That is, $(EI)_i = (E_{sc} I_{sc})_i = E_S I_S + E_{ci} I_c$.

If we add the variation value of the horizontal force through all the process, we can get H_{3T} produced from the temperature variation from T_2-T_3, that is:

$$H_{3T} = \sum \Delta H_i = \sum \left[\frac{\alpha \cdot \Delta T_i \cdot L}{\int_S \frac{y^2 ds}{(EI)_i}} \right] = \left(\frac{\alpha_c A_c + \alpha_s A_s}{A_c + A_s}\right) \cdot L \cdot \left[\frac{\Delta T_i}{\int_S \frac{y^2 ds}{(E_S I_S + E_{ci} I_c)}} \right] \tag{7}$$

As for the uniform section arch, Formula (7) can be written as:

$$H_{3T} = \left(\frac{\alpha_c A_c + \alpha_s A_s}{A_c + A_s}\right) \cdot L \cdot \sum \left[\frac{\Delta T_i \cdot (E_S I_S + E_{ci} I_c)}{\int_S y^2\, ds} \right] = \left(\frac{\alpha_c A_c + \alpha_s A_s}{A_c + A_s}\right) \cdot L \cdot \left[\frac{(\sum \Delta T_i \cdot E_S I_S)}{\int_S y^2\, ds} + \frac{(\sum \Delta T_i \cdot E_{ci} I_c)}{\int_S y^2\, ds} \right] \tag{8}$$

From Formula (8) we can see that, the abundant stress produced in the temperature reducing process of the arch rib in made by two parts, and is only related to the linear expansion coefficient and has nothing to do with the characteristic of the material. We can deem the total abundant stress directly superposed by the abundant stress produced by steel pipe and that produced by the concrete.

Because the elastic modulus of the steel pipe does not change with the time and temperature, we can neglect the temperature variation process when calculating the temperature abundant stress produced by the steel pipe in Item 1 in Formula (8), and we can only consider the temperature difference $T_3 - T_2$ from the starting point to the ending of the time section. Therefore, we can write the Formula (8) as below:

$$H_{3T} = \left(\frac{\alpha_c A_c + \alpha_s A_s}{A_c + A_s}\right) \cdot L \cdot \left[\frac{(T_3 - T_2) \cdot E_S I_S}{\int_S y^2\, ds} + \frac{(\sum \Delta T_i \cdot E_{ci} I_c)}{\int_S y^2\, ds} \right] \tag{9}$$

According to horizontal force produced at the elastic center of the arch rib in each stage above, we can obtain the residual value H_T of the total temperature abundant stress in the forming process of the concrete arch rib of the steel pipe.

$$H_T = H_{1T} + H_{2T} + H_{3T}$$

$$= \frac{\alpha_S \cdot L \cdot (T_1 - T_0) \cdot E_S I_S}{\int_S y^2\, ds} + \frac{\alpha_S \cdot (T_2 - T_1) \cdot E_S I_S \cdot L}{\int_S y^2\, ds}$$

$$+ \left(\frac{\alpha_c A_c + \alpha_s A_s}{A_c + A_s}\right) \cdot L \cdot \left[\frac{(T_3 - T_2) \cdot E_S I_S}{\int_S y^2\, ds} + \frac{(\sum \Delta T_i \cdot E_{ci} I_c)}{\int_S y^2\, ds}\right]$$

$$= \frac{\alpha_S \cdot L \cdot (T_2 - T_0) \cdot E_S I_S}{\int_S y^2\, ds} + \left(\frac{\alpha_c A_c + \alpha_s A_s}{A_c + A_s}\right) \cdot L \cdot \left[\frac{(T_3 - T_2) \cdot E_S I_S}{\int_S y^2\, ds} + \frac{(\sum \Delta T_i \cdot E_{ci} I_c)}{\int_S y^2\, ds}\right]$$

$$= \frac{(\alpha_s A_c + \alpha_s A_s) \cdot (T_2 - T_0) + (\alpha_c A_c + \alpha_s A_s) \cdot (T_3 - T_2)}{(A_c + A_s) \cdot \int_S y^2\, ds} \cdot E_S I_S \cdot L$$

$$+ \frac{(\alpha_c A_c + \alpha_s A_s)}{(A_c + A_s) \cdot \int_S y^2\, ds} \cdot L \cdot (\sum \Delta T_i \cdot E_{ci} I_c) \quad (10)$$

From Formula(10) we can see that, the residual abundant stress of temperature in the concrete arch rib of the steel pipe is divided into two parts: the first part is the abundant stress produced by the steel pipe in the whole process which is also divided into two sub-parts; the first sub-part is produced by difference value between the closure temperature of the empty steel pipe and the maximum temperature of the structure hydrate-heat; the second sub-part is produced by the difference value between the maximum temperature of hydrate-heat and the normal structure temperature after the completion of hydrate-heat (structure temperature during the formation). The second part is the abundant stress of temperature produced by the concrete during the temperature reducing period under the action of the hydrate-heat and environment temperature. Such internal stress is mainly subject to the influence of the development mode of the maximum temperature of hydrate-heat T_2, structure temperature T_3 upon the final formation, temperature reducing track and the elastic modulus E_{ci} of the concrete.

If we adopt the same linear expansion coefficient for the steel pipe and the concrete, the internal stress of temperature produced by the steel pipe has no relation with the concreting temperature and hydrate-heat. That is, when taking $\alpha_s = \alpha_c = \alpha_{sc}$, Formula (10) will change to:

$$H_T = \frac{\alpha_{sc}(T_3 - T_0)}{\int_S y^2\, ds} \cdot L \cdot E_S I_S + \frac{\alpha_{sc}}{\int_S y^2\, ds} \cdot L \cdot (\sum \Delta T_i \cdot E_{ci} I_c) \quad (11)$$

The first item in Formula (11) is the internal stress of temperature produced by the steel pipe, and the second item is the internal stress of temperature produced by the concrete. Formula (11) is the formula used to compute the final residual internal stress of temperature of the calculation closure temperature of the concrete-filled steel tube arch rid.

The residual internal stress of temperature obtained from Formula (11) is used to decide the calculation closure temperature of the arch rib. If T_0 is equal to T_3, the temperature at the formation of the arch rib is equal to the closure temperature of the empty steel pipe, and the internal stress of temperature produced by the steel pipe in the first item is 0. In this case, the residual internal stress of temperature used to decide the calculation closure temperature of the arch rib will be produced wholly by the concrete. Because the internal stress of temperature produced by the concrete usually makes the arch rib under tension, the calculation closure temperature obtained by the use of the residual internal stress is usually higher than T_3.

If $T_0 > T_3$, that is, the closure temperature of the empty steel pipe is higher than that of the arch rib at the formation, the internal stress of temperature produced by the steel pipe makes the arch rib under tension, whose stress direction is the same with the internal stress produced by the concrete. The calculation closure temperature obtained by superposing these two internal stress is also higher than T_3. If $T_0 < T_3$, that is, the closure temperature of the empty steel pipe is lower than that of the arch rib at the formation, whose stress direction is opposite to the internal stress produced by the concrete. Party or complete of stress is counteracted, therefore, the calculation closure temperature obtained is lower than the two circumstances above mentioned.

4.3. The Practical Method to Calculate the Closure Temperature of the Concrete-Filled Steel Tube Arch

According to the analysis made above and considering the influence of various factors, we have obtained a practical method to calculate the closure temperature (datum temperature) of the concrete-filled steel tube arch rid as below:

(1) To decide the closure temperature of the empty steel pipe T_0 and pouring concrete temperature T_1.

(2) According to the pouring concrete temperature T_1, steel pipe diameter Φ, cement volume W used for unit surface under concrete mixtures design, cement characteristic (hydrate-heat Q_0) and the environment temperature T_{air} (it mainly refers to the temperature within the pipe 7 days after the pouring of concrete) at the formation process, we can solve the closure temperature T_2 of the concrete (maximum temperature of the structure hydrate-heat), structure temperature T_3 at the formation and the time t when the maximum temperature appears. The structure formation temperature takes the environment average temperature 7 days after the pouring of concrete, that is $T_3 = T_{air}$.

This paper conducts a calculation on hydration heat temperature of CFST arch rib of the main tubes by using the finite element method. Then make a comparison with the collected measured temperature curve and experimental data of this paper and then revise them. Based on the comparison

Table 1. Hydration Heat Temperature of CFST Arch Rib

Diameter of the Tube/mm	Environmental Temperature/°C	Concreting Temperature/°C	Increased Value of Temperature/°C	Time when the Highest Temperature Appears/h	Duration Time of Cooling/h
0.5	5-10	10-15	11-13	18-21	30-60
	10-15	15-20	12-13	16-17	
	15-20	20-25	13-14	15-16	
	20-25	25-30	14-17	15-16	
	25-30	30-35	17-19	14-16	
	30-35	35-40	19-20	14-16	
1.0	5-10	10-15	23-25	28-34	80-120
	10-15	15-20	25-26	26-27	
	15-20	20-25	26-27	25-26	
	20-25	25-30	26-27	24-25	
	25-30	30-35	27-28	23-24	
	30-35	35-40	28-29	22-23	
1.5	5-10	10-15	30-33	36-38	100-150
	10-15	15-20	33-34	35-36	
	15-20	20-25	34-35	33-35	
	20-25	25-30	35-36	31-33	
	25-30	30-35	36-37	30-31	
	30-35	35-40	37-39	30-28	
2.0	5-10	10-15	35-38	42-46	120-180
	10-15	15-20	38-39	40-42	
	15-20	20-25	39-40	38-40	
	20-25	25-30	40-42	36-38	
	25-30	30-35	42-43	35-36	
	30-35	35-40	43-45	33-35	

and revision, hydration heat temperature of CFST arch rib shown in Table **1** is obtained, which can be used as the similar temperature curve under the circumstance of lacking measured data.

Basic conditions of Table **1** are shown as follows: the cement is Portland cement; the cement intensity grade is 42.5# and dosage is 450kg/m^3; wind velocity is 0.5m/s; there is no cover on the surface of steel tube. When the conditions change, data in Table **1** need to be multiplied by the modified coefficient K. All the modified coefficients K_1, K_2, K_3, K_4 are adopted according to Table **2**.

(3) To calculate the temperature difference corresponding to the residual internal stress of temperature.

When the structure temperature changes from T_0 to T_3, the abundant stress of temperature H_{sT} produced at the elastic center of the arch rib can be solved according to the design of arch axle (H_{sT} takes positive value if under pressure, and takes negative value if under tension. Below are the same)

Table 2. Modified Coefficient

Modified Coefficient of Cement Strength Grade K_1	Modified Coefficient of Cement K_2	Modified Coefficient of Cement Dosage K_3	Modified Coefficient of Wind Velocity K_4
32.5# K_1=0.86 42.5# K_1=1.00 52.5# K_1=1.13	Slag cement K_2=0.8 Portland cement K_2=1.0	K_3=W/450 W is the actual cement dosage	wind velocity 0m/s K_4=1.15 wind velocity 0.5m/s K_4=1.0 wind velocity 1m/s K_4=0.95 wind velocity 2.0m/s K_4=0.87 wind velocity 3.0m/s K_4=0.80

$$H_{sT} = \frac{\alpha_{sc}(T_3 - T_0)}{\int_x y^2 \mathrm{ds}} \cdot L \cdot E_s \cdot I_s \tag{12}$$

The process from the closure of concrete in the steel pipe to be formation of the concrete arch rib is generally a temperature reducing process. In this process (from T_2 to T_3), the temperature abundant stress produced by the concrete is H_{cT}. We can divide the temperature variation (T_3-T_2) into n time sections during the calculation, where ΔT_i is the temperature variation corresponding to Time Section i, and E_i is the average value of the elastic modulus corresponding to Time Section i.

$$H_{cT} = \frac{\alpha_{sc}}{\int_x y^2 \mathrm{ds}} \cdot L \cdot (\sum \Delta T_i \cdot E_i \cdot I_c) \tag{13}$$

In order to simplify the calculation, the calculation made above has neglected the difference of the linear expansion coefficient of the steel pipe and concrete. Here we take the weighted value of the above two as the linear expansion coefficient.

Take the summation of H_{sT} and H_{cT} as the total residual abundant stress of temperature of the structure at the formation of the concrete arch rib, and consider H_T as the abundant stress of temperature produced at the time when the temperature ΔT of the concrete-filled steel tube arch rid appears variation. Therefore, we can solve the temperature difference ΔT corresponding to the residual internal stress of temperature.

$$\Delta T = \frac{H_T \cdot \int_s \frac{y^2 ds}{(E_s I_s + E_c I_c)}}{\alpha_{sc} \cdot L} \tag{14}$$

Because $H_T = H_{sT} + H_{cT}$, substitute Formula (12) and (13) in Formula (14), we can obtain:

$$\Delta T = \frac{H_T \cdot \int_s \frac{y^2 ds}{(E_s I_s + E_c I_c)}}{\alpha_{sc} \cdot L} = \frac{(H_{sT} + H_{cT}) \cdot \int_x y^2 ds}{\alpha_{sc}(E_s I_s + E_c I_c) \cdot L}$$

$$= \frac{\alpha_{sc}(T_3 - T_0) \cdot L \cdot E_s I_s + \alpha_{sc} \cdot L \cdot (\sum \Delta T_i \cdot E_{ci} I_c)}{\alpha_{sc}(E_s I_s + E_c I_c) \cdot L}$$

$$= \frac{(T_3 - T_0) \cdot E_s I_s + I_c \sum \Delta T_i \cdot E_{ci}}{(E_s I_s + E_c I_c)}$$

That is： $$\Delta T = \frac{(T_3 - T_0) \cdot E_s I_s + I_c \sum \Delta T_i \cdot E_{ci}}{(E_s I_s + E_c I_c)} \tag{15}$$

To calculate the calculation closure temperature of the concrete-filled steel tube arch rid.

$$T_{cs} = T_3 - \Delta T \tag{16}$$

Where, if H_T is pressure, ΔT is positive; if H_T is tension, ΔT is negative.

The calculation closure temperature depends on the structure temperature and residual internal stress of temperature at the formation of the arch rib. Therefore, only to reduce the structure temperature at the formation and the internal stress of temperature in the structure will effectively drop off the calculation closure temperature of the arch rib.

Specifically speaking, we can consider the following aspects: firstly try to complete the construction of the concrete-filled steel tube arch rid so as to ensure the structure temperature keep a lower value at its formation; secondly to pour the concrete at low temperature, and use low-heat cement to reduce the hydrate-heat as soon as possible, so as to drop off the residual internal stress of temperature of the arch rib. In addition, because the internal stress of temperature of the arch rib is also related to the concrete elastic modulus in the steel pipe, required by the concrete mixtures design, we should separate the development curve of the concrete elastic modulus from the peak value of the hydrate temperature curve. We should avoid large temperature reduction to superpose with the large addition of elastic modulus. This method will also effectively reduce the residual internal stress of temperature of the arch rib.

CONCLUSIONS

Through the experimental research of temperature field and its effect of concrete-filled steel tube arch rib section and theoretically analyzed the calculation closure temperature of the concrete arch rib of the steel pipe, the conclusions can be made as follows:

(1) Temperature in the empty tube basically changes with air temperature simultaneously; after the perfusion of concrete in the tubes, the temperature variation of arch rib structure can be showed as follows: first, the temperature increases sharply in reaching the maximum temperature and then declines rapidly till reduces to close to ambient temperature, namely, hydration-heat temperature changes by the rule of "Temperature rises-continuous high temperature-temperature drops down-equalization of temperature".

(2) The structure temperature field caused by hydration-heat in the process of molding concrete-filled steel tube is nonlinear temperature field. Temperature in the arch rib cross-section appears to be high inside and low outside; temperature difference between tested section and exterior margin is relatively large and gradually increases in the phase of temperature rise, while gradually declines in the temperature fall period.

(3) hydration temperature effect of concrete of the crown section basically changes with temperature field simultaneously; concrete hydration-heat temperature effect of arch foot section, affected by the perfusion of concrete, has a g relatively large residual strain; hydration temperature effect of L / 4 Section concrete generates peak fluctuation in the process of concrete perfusion, and finally levels off.

(4) Hydration temperature field of concrete has a great effect on crown section, which makes the steel tube continuously withstand the tension and compression alternatively, The effect caused by concrete perfusion of top

chord on steel tube of arch foot section fluctuates slightly, but the concrete perfusion of bottom chord has little influence on the tube, namely, temperature effect on the steel tube of arch foot is not obvious. From the strain time-history curves of L/8, L/4, 3L/8 sections of steel tube, it can be known that surface strain transits from single-wave peak to dual-wave peak and finally turns into a single wave peak. In the L/4 section, strain of concrete perfusion of top chord on steel tube's surface changes greatly and tends to be leveled off in the end, namely, strain effect in this section changes sharply.

(5) Only to reduce the structure temperature at the formation and the internal stress of temperature in the structure will effectively drop off the calculation closure temperature of the arch rib. That is, try as far as possible to complete the construction of the concrete arch rib of the steel pipe; to pour the concrete at low temperature, and use low-heat cement to reduce the hydrate-heat as soon as possible; In addition, starting from the concrete mixtures design, we should separate the development curve of the concrete elastic modulus from the peak value of the hydrate temperature curve. We should avoid large temperature reduction to superpose with the large addition of elastic modulus.

CONFLICT OF INTEREST

None

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