STUDY ON HYDRATION HEAT OF CONCRETE CHANNEL-BOX GIRDER

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Temperature is one of the important reasons causing the cracks on the bridge structure during the construction and operation. In this paper, the temperature field produced by hydration heat and early thermal stress of a 64m simply supported channel-box girder are simulated during casting process, considering the time-varying characteristics of concrete shrinkage and creep, elastic modulus and tensile strength. Then, various parameters influencing the temperature field are analyzed, and the corresponding measures of controlling temperature cracks are proposed.

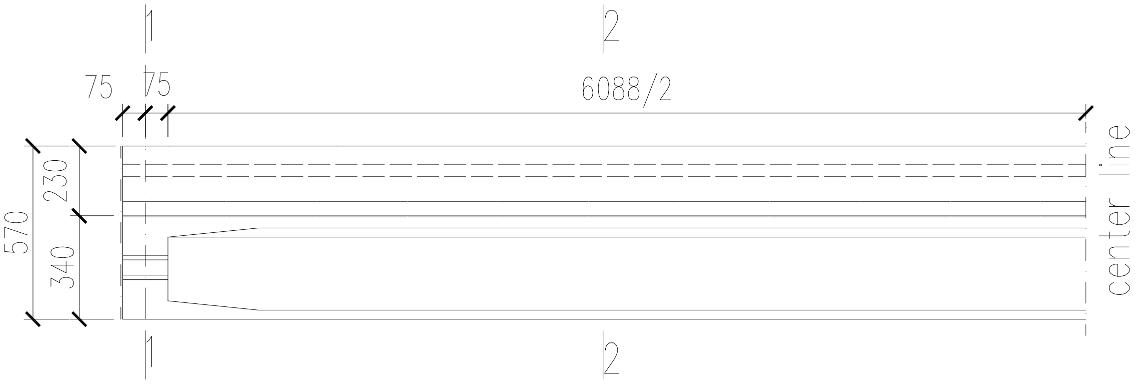
Key words*: Channel-box girder, temperature field, hydration heat, thermal stress*

1. Introduction

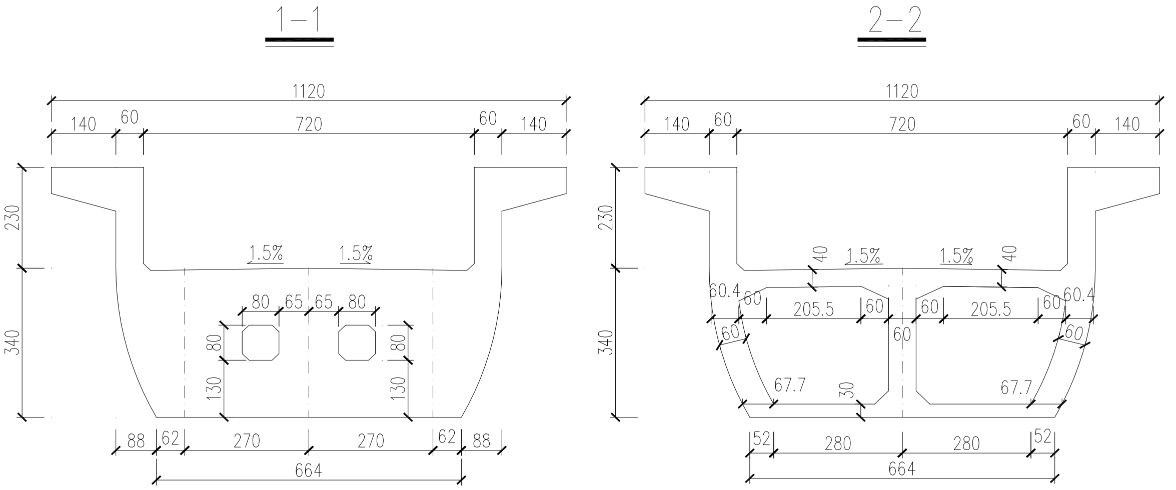
The research of the cracks caused by hydration heat in concrete structures, is mainly concentrated in the dam, bridge anchor, foundation and other large-volume structures[1][2]. However, as China's bridge construction is constantly developing and bridge span is increasing, the box girder section size is also increasing, and higher strength concrete materials are used, which will produce more hydration heat, the adverse effects of cement hydration heat in the casting process of the box girder have become more and more apparent. The local high temperature caused by hydration heat in the box girder may produce large self-induced and constraint stress, resulting in early temperature cracks, Hence, the temperature cracks[3][4] when casting can not be ignored, and it is necessary to prevent the cracks in the concrete structure.

This paper takes a completed bridge of the 64m simply supported channel-box girder as an example. The bridge has a great span, withstanding large live load ,which the weight of the molten iron tanker is about 2 times than the UIC load; It is of stress characteristics with combination structure to use the section form of the lower curved box girder poured in section of a lot and upper wing wall. The full length of the bridge is 64m with a calculated span 62.38m. The height of the box girder is 3.4m, the thickness of mid-span web is 0.6m, the girder-ends side web plane became thicker to 1m, and the mid-web plane became thicker to 0.8m. The height of its wing-wall is 2.3m, the thickness is 0.6m, and 1.5m cross beam was separately set at the girder-ends. The layout is shown in Fig. 1.

This paper uses simulation technology to do numerical analysis of temperature field and thermal stress of channel-box girder under the action of hydration heat. The calculation methods and conclusions in this paper will be of reference for the bridge designs of the same kind in the future.



(a) Layout of the longitudinal section



(b) Layout of the cross section

Fig. 1 Layout of the bridge (unit: cm)

2. Calculation model description

The hydration heat analysis includes two processes: Heat Transfer Analysis and Thermal Stress Analysis. The heat transfer analysis is to calculate the change of the node temperature caused by heat release, convection and conduction occurring during cement hydration process. The thermal stress analysis is to calculate concrete stress of each construction stage with the node temperature distribution obtained by heat transfer analysis, considering material time-varying characteristics, shrinkage and creep of the concrete, etc,.

2.1. Finite element model

When carrying out numerical calculations of the temperature field for established full-bridge model, it was found that apart from the nonuniform temperature field in local area at the girder-ends, the temperature distributions of the other sections were almost uniform at the longitudinal bridge. Hence, in the analysis of the temperature field produced by the hydration heat, may be simplified to take only 1m girder segment to be analyzed. As the bridge span was 64m, it could significantly reduce the calculation amount. The traditional methods does not consider the heat transfer between the inner walls of box girder due to the parameters were not easy to determine. Regarding the air inside the box and concrete as a whole heat balance exchange system, the paper believes the good heat contact between the air inside the box and girder, so as to avoid being difficult to obtain the heat convection parameters. Since the beam at the girder-ends of box girder prevents the heat transfer between the air inside the box and the outside world, the overall model is more realistic. A finite element model used by Midas software[5][6] is shown in Fig.2.

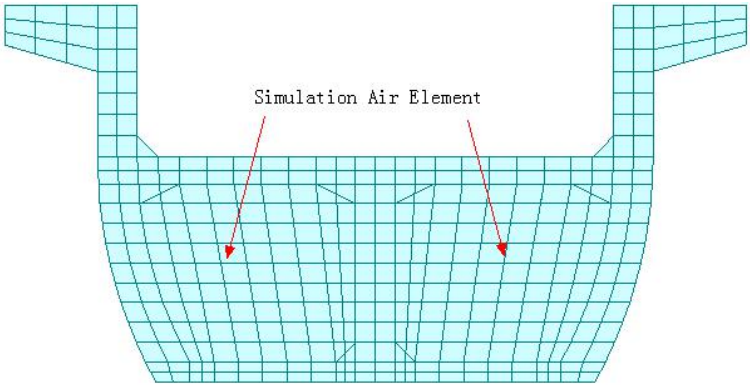


Fig. 2 Finite Element Model

2.2. Heat function of hydration

When calculating the temperature field of the concrete caused by hydration, assume that the concrete is in an insulation state. This bridge uses high strength concrete, and uses sandstone as aggregate and high strength silicate cement. The cement consumption is 500kg/m3, cement hydration heat is 350kJ/kg. Due to lack of measured information, the various obtained heat parameters of concrete come from document[1] research results: Thermal conductivity $\lambda = 3W/(m \cdot °C)$, specific heat $c = 0.96kJ/(kg \cdot$ ℃), density $\rho = 2.5 \times 10^3 kg/m^3$, the hydration heat curve of adiabatic temperature rise[7] uses exponential form, such as Formula 1.

$$\theta_c(t) = 72.9(1 - e^{-1.2t}) \quad (1)$$

Where $\theta_c(t)$ is the hydration temperature rise over time, t – the time.

2.3. Boundary conditions

2.3.1 Surface initial temperature

The surface temperature of the concrete is always the same as the atmospheric temperature, the atmosphere temperature[8] is changing in a day. At the bridge site, according to the meteorological data released from relevant department, it is usually the highest temperature at about 3 o'clock p.m. and achieves the lowest temperature at around 3 o'clock early in the morning, the maximum temperature was 19.62℃ and minimum was 9.94℃in one day.The circadian process of atmospheric temperature is determined by Formula (2):

$$T_a(t) = 14.78 + 4.84\, sin\frac{(t-9)\pi}{12} \quad (2)$$

where $T_a(t)$ is the atmospheric temperature change over time.

2.3.2 Heat transfer coefficient

The surface convection coefficient h_c of solid is not related to the material properties itself, but determined by the roughness of the surface, the viscosity coefficient of fluid etc. The value of the convection coefficient is closely related to the wind speed, determined by Formula (3):

$$h_c = 5.6 + 4.0v \quad (3)$$

where h_c is the solid convection coefficient, v – wind speed.

Commonly, the radiation exchange coefficient of the solid[9][10] is desirable at $h_k = 4W/m^2$, hence, the total heat exchange coefficient can be calculated according to the following formula(4):

$$h = h_c + h_k \quad (4)$$

The average wind speed was 1.5m/s in March at the area where bridge is, therefore, the heat exchange coefficient on the external surface of the bridge: $h = 15.6 \quad w/(m^2 \cdot ℃)$.

The air heat parameters[11] under closed state are: thermal conductivity $\lambda = 0.024W/(m \cdot °C)$, specific heat $c = 1.0kJ/(kg \cdot ℃)$, density $\rho = 1.29kg/m^3$.

3. Result and discussion

3.1. Temperature field results

Concrete initial temperature takes 15℃. The adiabatic boundary conditions are imposed on bilateral symmetrical sections. Based on the actual construction process, it is calculated in two stages. As a result of high-strength concrete, all hydration heat had basically released in 4 days. Hence, loading steps could take smaller steps in 1-4 days. The computation time of the first phase is 7 days, the second phase is 8 days, and a total of time is 15 days.

In order to get the course curve of key parts over time, do elect such cross sections (Fig.3) as a few selected locations. Fig.4 indicates the temperature distribution of the whole section at different times. Fig.5 indicates the temperature distribution curves for both the different cross sections and different times.

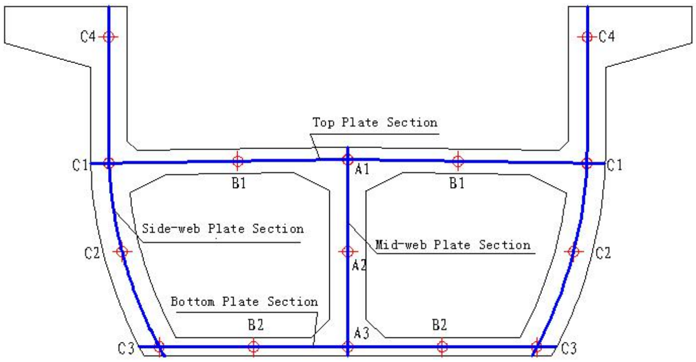
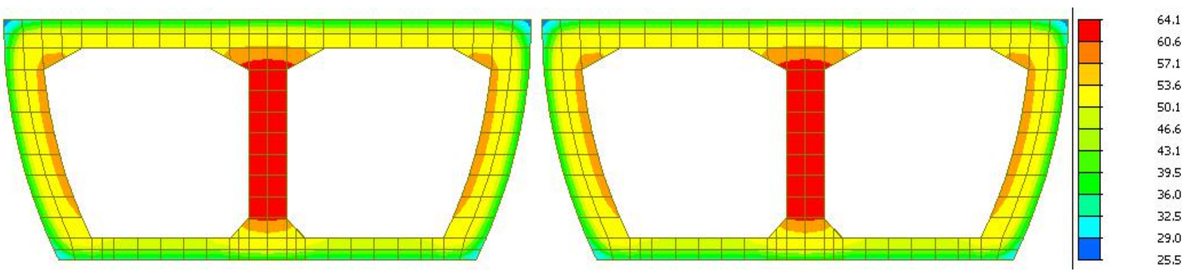
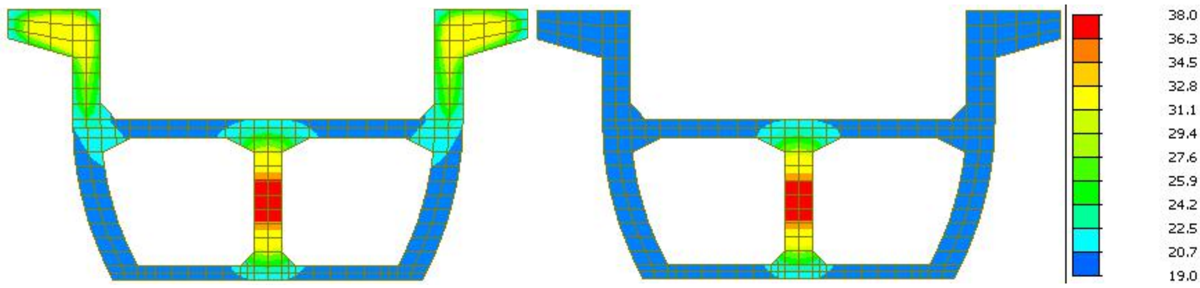


Fig. 3 Temperature Sketch in Different Points of Box Girder

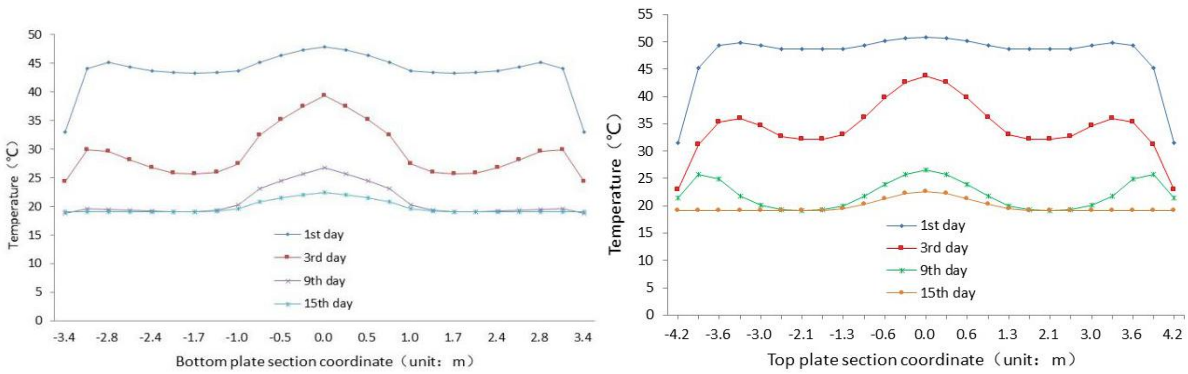


(a)Temperature distribution on 1st day **(b)Temperature distribution on 3st day**



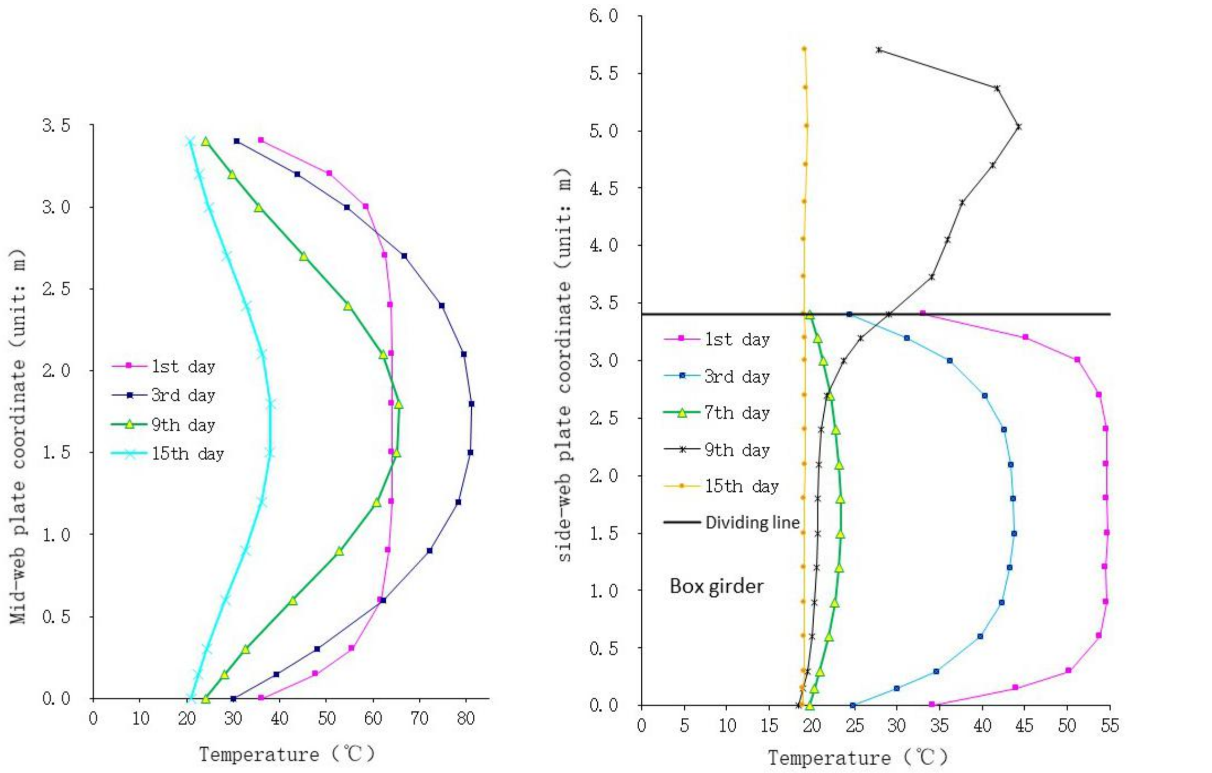
(c)Temperature distribution on 9st day **(d)Temperature distribution on 15st day**

Fig. 4 Temperature Distribution at Different Time



(a) Bottom Plane Temperature Distribution at Different Time

(b) Top Plane Temperature Distribution at Different Time



(c) Mid-web Temperature Distribution at Different Time

(d) Side-web Temperature Distribution at Different Time

Fig. 5 Different Sections Temperature Distribution at Different Time

According to Fig.4 and Fig.5, after box girder casting was completed in the first construction phase, the internal temperature of the box girder started to rise rapidly. From the 2nd to the 3rd day, all observations basically reached the highest values, which was consistent with the law that heat productivity of the hydration heat was great in early days. On the 7th day, except very high temperature of internal mid-web, the temperature of the other parts was gradually reduced to atmospheric temperature.

On the 3rd day, the maximum temperature of internal mid-span web reached 82°C, and on the 15th day the high temperature still reached 40°C, which is mainly due to blocking ventilation inside the box, so as to affect heat evacuation in this area. Since the web girder-ends direct contacted with the atmosphere, the most temperature got 50°C on the 2nd day, and quickly dropped to atmospheric temperature. Hence, the temperature difference about 50°C formed along the section height of mid-web on the 3rd day (see Fig. 5c), which would very easily lead to the cracks of concrete surface.

On the 8th day, the maximum temperature of wing walls was 55°C, and quickly dropped to atmospheric temperature. The hydration heat produced by the wing walls had little effect on the lower box girder, which only made local temperature rise by about 10°C within the range of 0.6m width at the junction of the box girder and the wing wall.

3.2. Thermal stress result

When the temperature results of the heat analysis were transformed as a load and were applied to the structure. The material properties of the concrete were: elastic modulus3.55×10^4Mpa, Poisson's ratio 0.2, coefficient of linear expansion1.0×10^{-5}. As steel formwork was thin, and formwork removal time was comparatively early, its role on elastic constraint of the concrete could be ignored. Internal air unit does not participate in the stress calculation, hence this paper make its elastic modulus be 0 in order to eliminate impact on the total rigidity of the structure.

During the hydration heat, concrete was prone to produce early surface cracks, so a few key surface position are selected (see Fig. 6) to obtain the principal tensile stress change curve with time (see Fig. 7).

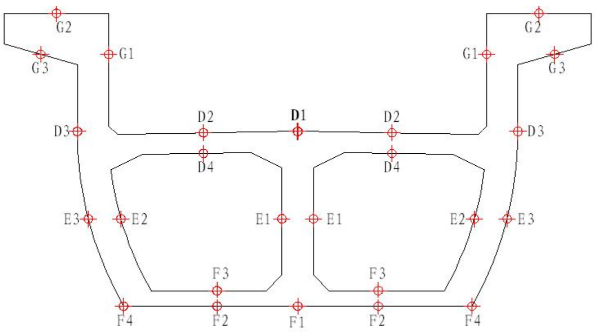
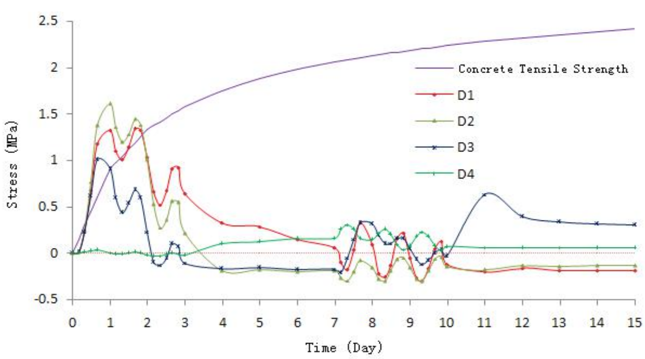
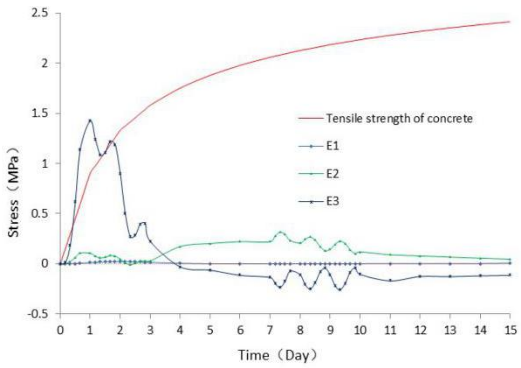


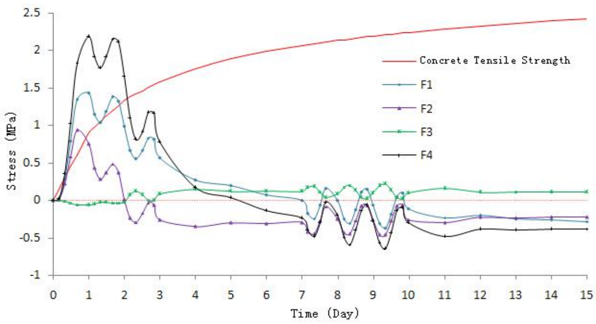
Fig. 6 Sketch of Principal Tensile Stress at Different Points



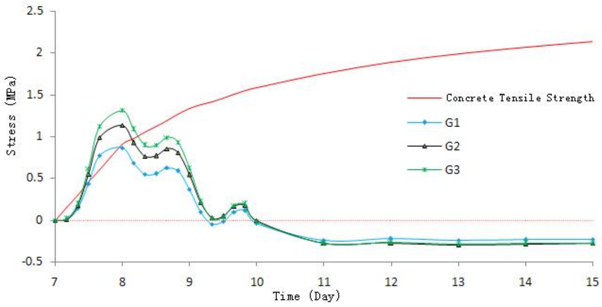
(a) Diagram of Principal Tensile Stress on Top Plan



(b) Diagram of Principal Tensile Stress on Web Plan



(c) Diagram of Principal Tensile Stress on Top Plan



(d) Diagram of Principal Tensile Stress on Wing Wall Plan

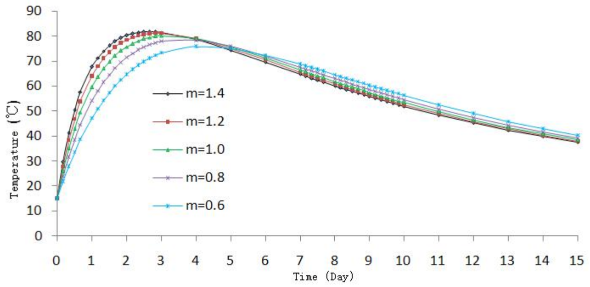
Fig. 7 Diagram of Principal Tensile Stress on Different Surfaces

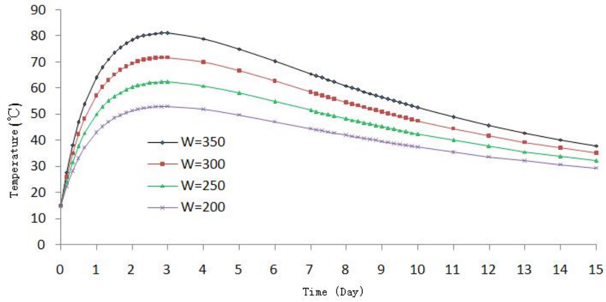
Stress analysis results show: overall, the maximum temperature effect of heat hydration basically appeared between the 1st day and the 2nd day after cast-in-place and in the area of the intersection between planes, for example, in the area of the intersection between web and roof plane and bottom plane. Even if the lead angle was set, a larger principal tensile stress would appear. The principal stress presented sandwich distribution in the thickness direction for almost all the planes. While the temperature of hydration heat was rising, "outside sandwich" quickly dissipated heat to the external environment. However, "intermediate sandwich" was difficult to dissipate hydration heat, making the plane inside expand and outside shrink, so as to result in surface cracks.

According to Fig.7, while the temperature of hydration heat was rising, the tensile stress outside the surface of channel box girder was relatively significant. Particularly on the1st day or so after cast-in-place concrete, the tensile stress had already exceeded the tensile strength of concrete (At the junction between base plane bottom flange and the outer web, the principal tensile stress had reached 2.3MPa). After such as the most unfavorable condition, the tensile stress of the outer surface began to gradually decrease. Between 3 and 4 days after cast-in-place, the stress state changed from the pull to the press. From the calculation, it confirmed the inference that surface cracks generated in the hydration heat stage could be "self-healing" for concrete structures, which was beneficial to the concrete.

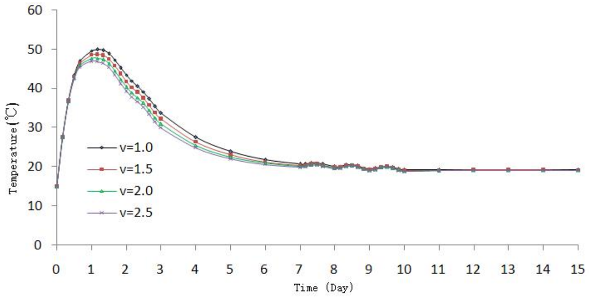
3.3. Analysis of parametric sensitivity

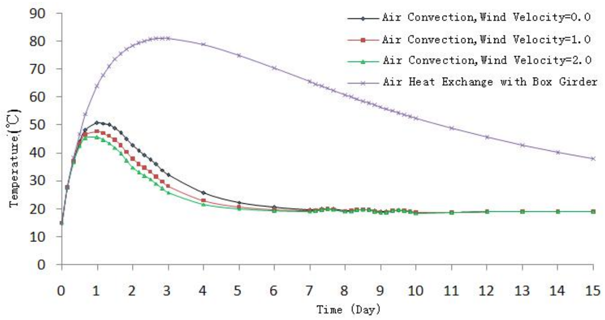
From the above analysis, it can be seen that the main factors affecting hydration heat temperature field and stress of the box girder are wind speed, the air convection inside the box and other factors[12]. The paper makes a quantitative analysis on these impact parameters, seeing Fig. 8.



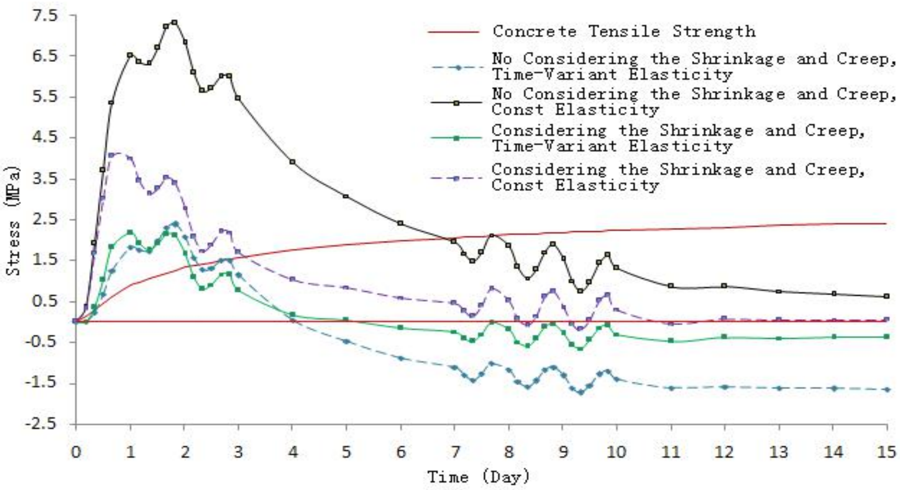


(a) Impact of Hydration Heat Rate m (A2) **(b) Impact of Cement Hydration Heat W (A2)**





(c) Impact of Wind Speed V (B1) **(d) Impact Considering Air Convection (A2)**



(e) Impact Considering Time-varying Characteristics of Concrete on Thermal stress (F4)

Fig. 8: Sensitivity Analysis of Parameters

According to Fig.8, the faster the hydration heat rate, the higher the maximum temperature inside the box and the shorter the time getting the highest temperature, but the impact is not significant; The cement hydration heat W had made a significant impact on the temperature field. While cement hydration heat lowered 50kJ/kg, the temperature could lower 10℃; Surface wind speed made a small impact on the temperature of the channel-box girder. When the wind speed changed from 1m/s to 2.5m/s, the temperature only lowered by about 3℃.

The aeration inside the box made a very big impact on the temperature field. Considering the air convection inside the box, the maximum temperature in the middle of the mid-web plate was about 50℃, which was 30℃ less than considering the overall heat of the air with the box girder. But the ventilation rate of inside the box had little effect on the temperature. Therefore, during cast-in-place concrete, keeping the convection between the air inside the box and the outside air could greatly lower the temperature field inside the box girder, thereby lowering the temperature difference between inside and outside.

Whether considering the development of concrete shrinkage creep and elastic modulus has a great impact on the results. Without considering, the principal tensile stress was as high as about 7.5MPa, and it would not change tensile stress into compressive stress in the later period. There will be a long-term tensile stress 0.9MP left in the concrete. Considering time-varying characteristics, the maximum tensile stress was only 2.5MPa. Therefore, the calculation must take the time-varying nature of concrete materials into account so as to get more real results.

4. Measures toreduce hydration heat

Making the analysis on different impact parameters of the temperature field and thermal stress of the channel-box girder, the measures reducing cement hydration heat of concrete [13][14] are as follows:

a. On the basis of ensuring the amount of concrete, select the cement of small heat release in order to reduce heat release. To be appropriate to add retarder, which can not only increase the workability, slow down the cement hydration, but also reduce the peak temperature and the temperature difference between inside and outside the structure.

b. Strictly control the concrete temperature going into the formwork, when necessary, be able to take certain pre-cooling measures; Strictly control removal time of shuttering, when the temperature difference between internal and the external surface of the concrete is less than 15℃, do strip the formwork, this can effectively eliminate the cracks generated by the thermal stress of hydration heat.

c. Reduce the concrete deformation restraints of the formwork. When carrying out cast-in-place concrete in early days and material strength has not fully developed, must strictly ensure that the contact surface between formwork and concrete is greased in order to reduce the concrete restraints as much as possible and make the deformation caused by temperature effects free to occur, thus avoiding the concrete surface cracks.

d. The construction program can be optimized for the bridge with closed cross beam at the girder ends. The general principle is to strengthen the air flow inside the box in order to quickly spread the heat inside the concrete to the external air, reducing the temperature difference between inside and outside the box. The size, layout and so on of ventilation holes can be optimized in structural design.

5. Conclusions

By the finite element calculation, this paper has analyzed the temperature field and early thermal stress during casting process on the 64m channel-box girder, and the calculations have taken into account the time-varying characteristics of contraction creep, elastic modulus and tensile strength increasing with time. The analysis results show: cement hydration heat and whether the air inside the box are circulating, will make the greatest impact on the box girder temperature field. Hence, developing low-heat cement and ensuring smooth flow between the air inside the box and the outside world in construction are the most effective methods to lower the hydration heat inside the box. In addition, the thermal stress calculation must take into account the time-varying characteristics of the concrete. Otherwise the calculation results are relatively large so that the design is too conservative.

However, the calculations carried out in this paper have not considered the impact on the prestressed and regular reinforcement. During the research course in the future, more realistic mathematical model should be established to quantitatively describe the improvements of the reinforcement property to the crack resistance of concrete in order to improve the accuracy of numerical simulation.

Acknowledgment

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Nomenclature

$\boldsymbol{c}$ –specific heat, [kJ/(kg.°C)]

v –velocity, [ms^{-1}]

T_a –atmospheric temperature over time, [°C/s]

t –time, [s]

h –heat exchange coefficient, [wm^{-2}]

Greek symbols

$\boldsymbol{\lambda}$ –thermal conductivity, [w/(m.°C)]

$\boldsymbol{\rho}$ –density, [kgm^{-3}]

θ_c –hydration temperature over time, [°C/s]

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