Measurements and numerical simulations for cast temperature field and early-age thermal stress in zero blocks of high-strength concrete box girders

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Abstract
The measurements and simulations using finite element software are carried out on the cast temperature field as well as the related thermal stress field in zero blocks of segmental high-strength concrete box girder. The thermodynamic parameters, to some extent dominating the effectiveness of the simulation, are determined carefully in terms of the statistical data, the empirical formulas as well as the measured data in an actual project, which leads to reliable simulation results by means of the finite element software. The comparison between the calculated and measured values of temperature field shows that the maximum error among all measuring points is only 1.71%. Meanwhile, the predicted directions of principal tensile stress coincide with the actual directions of the observed cracks well. Based on the above work, the common features of the cast temperature field caused by heat of hydration are obtained for this kind of structures. The relationships of the cast temperature field, the thermal stress, and the early-age cracks are discussed quantitatively in order to provide reasonable suggestions for temperature control and crack prevention in similar projects.

Keywords
High-strength concrete box girder, heat of hydration, cast temperature field, early-age thermal stress, finite element analysis, thermal cracks

Introduction
In general, the problems resulting from heat of hydration exist in the construction of dams, the foundations of large-scale industrial equipment, the anchorages, and pile caps of bridges due to their big cast volume of concrete and the hard conditions for internal heat dissipation.1,2 Accordingly, it is necessary to consider the temperature effect caused by heat of hydration and take measures to control the thermal cracks for this kind of structures.3–5

In recent years, the cast-in-place continuous rigid frame bridges constructed using cantilever installation technique span longer, so that the section size of box girders near the piers is becoming larger and larger. Because of the heavy use of high-strength concrete, the consumption of cement per unit volume is relatively larger.6 Therefore, the temperature effect caused by heat of hydration is more pronounced.
of hydration also cannot be ignored in the construction of box girders, which is gradually attracting the attention in bridge engineering community.\textsuperscript{7–10} Compared with the commonly used mass concrete structures (e.g. the dams, the anchorages, and the pile caps of bridges), the box girders have more complex geometries and heat dissipation conditions. So far, the existing researches for this topic mainly focus on the measurements of the cast temperature field of box girders.\textsuperscript{11,12} The numerical simulations using finite element method (FEM) were also carried out to compare with the measured data,\textsuperscript{13} and the key issues affecting the cast temperature field including the ambient temperature, the temperature of concrete in cast, the water-cement ratio and the concrete mix proportion were investigated further.\textsuperscript{14–16} However, the common features of the cast temperature field for this kind of structures haven’t been clarified yet due to their complicated heat dissipation conditions resulting from the special structural geometries and construction method.\textsuperscript{17} Meanwhile, there is also a lack of quantitative analysis on the thermal stress caused by the cast temperature field, and the research on the correlation between the thermal stress field, thermomechanical behavior, and the risk of thermal cracks.\textsuperscript{18–20}

Based on a three-span prestressed continuous rigid frame bridge under the construction, the cast temperature field and the related thermal stress field of the zero block with the biggest cast volume among the segments of box girder are measured using the embedded instruments in this study. Combining with the FEM simulations using large-scale commercial software ANSYS, the common features of the high-strength concrete box girder in the process of hydration heat are obtained. The correlations between the cast temperature field, the thermal stress, and the early-age cracks are then investigated quantitatively, which aims to provide reasonable suggestions for temperature control and crack prevention in similar projects.

\textbf{Materials and methods}

\textbf{Test of cast temperature field in zero blocks of high-strength concrete box girder}

\textbf{Engineering background.} There is a three-span prestressed concrete continuous rigid frame bridge in an expressway, with the spans of 65, 110, and 65 m respectively. It is constructed using cantilever installation technique, so that the box girder is divided into several sections numbered from 0 to 11, as shown in Figure 1. The zero block of the box girder is 19 m along the axial direction; the height at root is 6.5 m; the thickness of the bottom plate is 70 cm. The height of the box girder and the thickness of the bottom plate vary along the length by the 1.8 power parabola. The thickness of the web of the box girder at root is 60 cm, and it varies linearly along the length. The thickness of the top plate is 25 cm. The cross-section size of the diaphragm is $2 \text{ m} \times 6 \text{ m}$, which is the same as the pier. According to the cantilever installation technique, the cast-in-situ box girder is constructed section by section, while the zero blocks are poured firstly on brackets (the pouring time was in early November, and the ambient temperature is about 20$^\circ$C). Although the design grade of the concrete is C60, the mix proportion of the concrete for zero block of Pier 2 is slightly different from that of Pier 1, where a part of cement is replaced by silica fume (see Table 1).

\textbf{Arrangement of measuring points and measurement method.} The cast temperature field was measured for both zero blocks in this study. The layout of measuring points in zero block of Pier 1 was shown in Figure 2.

![Figure 1. Diagram and size of segmental box girder of a three-span rigid frame bridge (unit: cm).](image-url)
The layout of measuring points of Pier 2 is exactly the same as that of Pier 1, and its number is marked with an apostrophe to distinguish. The ordinary thermistors were employed as temperature sensors in some measuring points. For the rest of measuring points, the vibrational chord strain gauges were embedded to test the strain and temperature simultaneously. The range of strain measurement is 1500 $\mu e$ in compression or 1000 $\mu e$ in tension. The range of temperature measurement is 25°C–90°C with the accuracy of $\pm 0.5$°C. The whole process of temperature measurement started from the time when the concrete was put into the mold and continues to the time when the temperature field of the box girder was finally stable. In the first 5 days, the measurements were conducted every 3 h. Then the frequency was appropriately reduced depending on circumstances. The strain of the measuring points was recorded at the same time if the vibrational chord strain gauges were embedded, and the atmospheric temperature was recorded every 2 h for 10 days.

Analysis of the measured data. The measured data of zero block of Pier 1 is employed to explain the common features of the cast temperature field caused by heat of hydration:

1. Compared with the dams, the anchorages or the pile caps of bridges, the cast volume of zero block of box girder is not very large. However, the problem caused by the heat of hydration still exist since the heavy use of high-strength concrete results in large amount of cement per cubic meter. For the parts with larger cast volume, the rate of heat generation is greater than the rate of heat loss at the initial stage of cement hydration, resulting in a significant increment in the structural temperature. It usually reaches the thermal peak in 1–3 days, which is closely related to the cast volume – the larger the cast volume, the longer the time to reach the peak, and the higher the temperature peak; vice versa. With the development of cement hydration, the rate of heat generation is going to be less than that of heat loss, and the structural temperature begins to decrease until it tends to be stable. Indeed, Figure 3(a) to (c) show that the temperature rose firstly and then dropped in most measuring points, which has the typical characteristics of hydration heat temperature field of mass concrete structures.

2. Compared with the common mass concrete structures such as anchor blocks and foundation slabs, the zero blocks of box girders have more complicated geometries and heat dissipation conditions. Hence, the temperature field of each part presents different features. For example, the temperature rising caused by the heat of hydration is prominent in the parts with relatively larger volume of concrete, such as the diaphragm and the junction of multiple parts. The thermal peak at the center of diaphragm (corresponding to measuring point 19) reached 70.8°C on the second day, while the thermal peak at the junction of diaphragm, web, and bottom plate (corresponding to measuring point 18) also exceeded 60°C on the first day, as shown in Figure 3(a). The maximum temperature difference reached 16°C between the inside and outside of the bottom plate, which is quite large relative to its thickness (see Figure 3(b)). The top plate, web, and other parts have less heat generation and fast heat dissipation, thereby almost presenting no hydration heat problem. Especially, there was no obvious stage of heating and cooling for the top plate due to its thinnest thickness, the temperature field of which was greatly influenced by the atmospheric temperature (see Figure 3(c) and (d)).

After analyzing the measured data of zero block of Pier 2, it is found that the basic rule of the cast temperature field is similar with that of zero block of Pier 1. However, the thermal peak of each measuring point was slightly decreased, while the time of reaching the thermal peak was delayed, as shown in Figures 4 and 5. The reason is that compared with cement, the hydration heat of silica fume is smaller and the early exothermic rate is slower. Meanwhile, the descending curves of two sets of measuring points basically coincide, which reflects the similar heat dissipation conditions of the two zero blocks. If there is no special explanation for the quotation of measured data in subsequent chapters, it refers to the zero block of Pier 1.

| Component | Water-cement ratio | Water (kg/m³) | Cement (kg/m³) | Gravel (kg/m³) | Sand (kg/m³) | Silica fume % kg/m³ | FS-G high range water reducer % kg/m³ |
|-----------|-------------------|---------------|----------------|----------------|--------------|----------------------|--------------------------------------|
| Pier 1    | 0.36              | 172           | 465            | 1124           | 689          | 0 0                 | 1.2 5.58                             |
| Pier 2    | 0.36              | 172           | 435            | 1124           | 689          | 8 34.8              | 1.2 5.22                             |
Finite element simulation of cast temperature field in zero block of high strength concrete box girder

In this section, the cast temperature field of zero block of box girder will be simulated using ANSYS thermal analysis module.

Structural modeling. Considering the symmetry property of the zero block, only a quarter of solid model needs to be built, as shown in Figure 6 (the two symmetry planes are also indicated in this figure). Firstly, Solid70, a three-dimensional temperature element type defined

Figure 2. Arrangement of measuring points in sections of box girder (unit: cm).

Figure 3. Temperature evolution in different parts of zero block of Pier 1: (a) diaphragm, (b) bottom plate, (c) web, and (d) top plate.
by ANSYS, was selected – each element has eight nodes, and each node has only one degree of freedom, that is, temperature. Then, the parameters related to material properties were defined according to the recommended values in Zhu,\textsuperscript{21} including thermal conductivity, density and specific for transient heat transfer problem. Finally, the geometric model was meshed as shown in Figure 7. In order to simulate the process of concrete cast, all elements were killed at the beginning of the calculation (i.e. the “Ekill” command was executed), and the whole structure was divided into several groups in terms of the different pouring batches. Subsequently, the corresponding element groups were activated in sequence according to the pouring order (i.e. the “Ealive” command was executed). The grids would gradually expand to the whole structure with the concrete cast going on.

**Boundary conditions and loads.** Next, the heat release and convection of concrete were simulated according to the actual construction situation of zero block. The exponential formula is employed to describe the exothermic process of cement hydration\textsuperscript{21}:

\[
Q(t) = Q_0 (1 - e^{-mt})
\]

where \(Q(t)\) is the accumulated heat of hydration at age \(t\); \(Q_0\) is the value of \(Q(t)\) when \(t\) tends to be \(\infty\); \(m\) is a constant related to cement type, specific surface, and pouring temperature. The expression of heat generation rate can be obtained by deriving equation (1) as:

\[
\frac{dQ(t)}{dt} = mQ_0 e^{-mt}
\]

which can be regarded as a basic property of concrete material. ANSYS can applies the heat generation rate as body load on the modes. In order to determine the values of \(Q_0\) and \(m\) accurately, the adiabatic temperature rise test on the cement specimen of zero block was conducted, thereby taking \(Q_0 = 346\,\text{kJ/kg}\) and \(m = 1.09\) with reference to the experimental data.
There is thermal convection between concrete and atmosphere on the boundary of box girder, which belongs to the third kind of boundary conditions. By defining the surface heat exchange coefficient, the convective boundary condition is applied to the surface of the solid in the form of surface load in ANSYS. The surface heat exchange coefficient is closely related to wind speed and concrete surface condition, which has great discreteness. Hence, its recommended value is hard to be given at present. However, many scholars think that it has a linear relationship with wind speed around the structure. In this study, the surface heat exchange coefficient is roughly estimated by substituting the measured wind speed into the following empirical formula proposed by Zhu:

\[ b = 21.8 + 13.53v \]

\( b \) and \( v \) represent the surface heat exchange coefficient and the wind speed respectively. Then the value of \( b \) was adjusted gradually until the calculated temperature field and the measured temperature field are in good agreement. At this time, the value of \( b \) is considered as an approximation of the actual situation.

The values of \( b \) and \( v \) at the boundaries of different components are shown in Table 2. After linear fitting, the relationship between \( b \) and \( v \) is obtained as follows:

\[ b = 18.5 + 3.5v \]

Equation (3) is compared with several commonly used expressions of heat exchange coefficient, as shown in Figure 8. It can be seen from this figure that the initial value of \( b \) proposed in this paper is close to that of Zhu, while its growth rate with wind force (i.e. the curve slope) is close to those recommended by Wei, Saetta, and Branco.

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Finite element analysis of early-age thermal stress

In recent years, many serious cracks are often found in fully prestressed concrete bridges which are designed to be free of tensile stress. Some of them are even forced to shut down for repair, resulting in considerable economic losses. Further investigation shows that it is closely related to the variation of natural environment and the thermal stress caused by the heat of hydration. The existing experimental researches indicate that the thermal stress in some parts of the bridge is greater than the load stress, which has become one of the main reasons for the cracks of prestressed concrete box girder. It motivates us to study the thermal stress field on the basis of the cast temperature field obtained before. Similarly, the analytical solutions for thermal stress can only be obtained in a few simple cases. As to box girders with relatively complex structural geometries and boundary conditions, the finite element method is usually employed.

Fortunately, the finite element model established in temperature analysis can be directly adopted in stress analysis, where only the temperature element Solid70 need to be converted into the corresponding structural element Solid45. The elastic modulus of early-age concrete is developing gradually, which was calculated according to the following exponential formula in the first 10 days:

\[ E(t) = E_0(1 - e^{-mt}) \]

where \( E_0 \) is the standard value of elastic modulus for C60 concrete, taken as \( 3.55 \times 10^8 \) Pa; \( m \) is supposed to be 0.42 in terms of the measured values of elastic modulus at the age of 3, 5, 7, and 10 days. After 10 days, the elastic modulus is considered to be stable, and is taken as the final value – \( E_0 \).

In this study, the incremental method was employed to calculate the early-age thermal stress field as follows. Firstly, the temperature difference between two adjacent days \( \Delta T_i = T_i - T_{i-1} \) was extracted based on the results of thermal analysis. The temperature difference

| Components | Positions | \( v \) (m/s) | \( \beta \) (kJ/(m² h°C)) |
|------------|-----------|--------------|---------------------|
| Top plate  | Upper surface | 5 | 37.58 |
|            | Lower surface | 3 | 27.16 |
| Web        | External surface | 5 | 37.58 |
|            | Internal surface | 3 | 27.16 |
| Bottom plate | Upper surface | 4 | 31.94 |
|            | Lower surface | 0 | 18.54 |
| Diaphragm  | External surface | 3 | 27.16 |
|            | Internal surface | 0 | 18.54 |
| Pedestrian crosswalk |  | 1 | 22.36 |

Table 2. The values of \( \beta \) and \( v \) at the boundaries of different components.
and gravity were then applied to the finite element model as body load. Secondly, the stress increment of the \(i\)th day \(\Delta \sigma_i\) was obtained according to the calculated elastic modulus value on that day, which was then superimposed with the temperature stress on the \((i - 1)\)th day. The above calculations were carried out by 11 times in total, where it took 1 day as the time interval for the first 10. The initial time of the last calculation was set as the end of the 10th day, while the end time was the one when the structure temperature field tended to be stable. At this moment, the zero block was considered in a uniform temperature field, which was consistent with the external temperature.

**Results**

**Result analysis on cast temperature field**

The calculation results on the cast temperature field of the zero block of Pier 1 was investigated for 10 days, where the step size was set as 0.25 days so that there were 40 time steps totally. Figures 9 to 11 show the time-varying curves of three most representative temperature indicators respectively: they are the temperature at the center of diaphragm (measuring point 19), the temperature at the junction of diaphragm and bottom plate (measuring point 18), and the temperature difference between the inner and surface of the bottom plate.

A more comprehensive comparison between the calculated and measured values is given in Table 3. It can be seen from this table that the maximum error between them is only 1.71\%, which indicates that the finite element model established in this paper simulates the cast temperature field well and provides a reliable reference for temperature control.

In order to investigate the distribution rule of the cast temperature field further, the temperature contours on day 1, day 2.5, day 5, and day 10 after pouring are given in Figure 12. It can be seen from these figures that the temperatures at the centers of the bottom plate and web reached the peak value on the first day, while the maximum temperature in the diaphragm appeared on day 2.5 and was equal to 71°C approximately. On the fifth day, the temperature fields on the most part of the zero block were stable and the cooling process was basically over. However, the temperature inside the diaphragm was still as high as 40°C even on the 10th day. Throughout the whole process of heating and cooling, the temperature field of each component varied independently to a large extent. For instance, in the heating stage, the temperatures of the diaphragm and the joints of the parts with large pouring volume rose fastest; in the cooling stage, the heat of hydration on these locations were also hard to dissipate. Therefore, the box girder structure with complex geometry is recommended to be divided into several parts according to their cast volumes and the heat dissipation conditions, and each
Table 3. Comparison between calculated and measured values of temperature field (°C).

| Components       | Items                        | Measured data | Calculated data | Errors  |
|------------------|------------------------------|---------------|-----------------|---------|
| Bottom plate     | Measuring point 4            | Max. temperature | 44.687         | 44.775  | 0.20%  |
|                  |                              | Time          | 0.98d           | 1d      |         |
|                  | Measuring point 5            | Max. temperature | 60.125         | 60.105  | -0.03% |
|                  |                              | Time          | 0.98d           | 1d      |         |
|                  | Measuring point 6            | Max. temperature | 52.437         | 53.333  | 1.71%  |
|                  |                              | Time          | 1.27            | 1       |         |
|                  | Temperature difference       | Max. value    | 15.438          | 15.33   | -0.70% |
|                  | between inside and outside   | Time          | 0.98d           | 1d      |         |
| Web              | Measuring point 11           | Max. temperature | 41.312         | 41.446  | 0.32%  |
|                  |                              | Time          | 1.3d            | 1.25d   |         |
|                  | Measuring point 12           | Max. temperature | 48.25          | 48.495  | 0.51%  |
|                  |                              | Time          | 1.3d            | 1.25d   |         |
|                  | Measuring point 13           | Max. temperature | 40.187         | 40.466  | 0.69%  |
|                  |                              | Time          | 1.3d            | 1.25d   |         |
|                  | Temperature difference       | Max. value    | 8.063           | 8.029   | -0.42% |
|                  | between inside and outside   | Time          | 1.3d            | 1.25d   |         |
| Diaphragm        | Measuring point 19           | Max. temperature | 70.812         | 70.75   | -0.09% |
|                  |                              | Time          | 2.4             | 2.5     |         |
| Junction of the above three | Measuring point 18           | Max. temperature | 63.251         | 63.145  | -0.17% |
|                  |                              | Time          | 1.27            | 1.25    |         |

Figure 12. Contours of cast temperature: (a) day 1, (b) day 2.5, (c) day 5, and (d) day 10 (unit: °C).
part can be analyzed independently. Meanwhile, the components with large cast volumes such as diaphragm are the key points of temperature control.

**Result analysis on early-age thermal stress**

Thermal stress results from the internal and external constraints on the structural deformation caused by variation of the temperature. On the other hand, the magnitude and direction of principal tensile stress determine whether the concrete cracks or not as well as the cracking direction. In this section, the finite element results of the longitudinal thermal stress in top plate, bottom plate, and web of zero block are analyzed. Compared with the measured data, the distribution of the principal tensile stress in early age is obtained, so as to provide a basis for preventing the potential cracking risk.

Firstly, the FEM results for longitudinal thermal stress in section 1.1 of zero block are given for some representative moments, as shown in Figure 13 (stress symbols take tension as positive and compression as negative).

In the temperature rising stage, the increment of internal temperature is higher than that of surface temperature, so the longitudinal expansion of the internal concrete is constrained by the surface concrete. As can be seen from Figure 13(a) and (b), it produces longitudinal compressive stress for internal concrete and tensile stress for surface concrete. However, since the elastic modulus of early-age concrete is small, the values of stress at this time are small. In the temperature cooling stage, the internal temperature decreases much more than the surface temperature, so that the longitudinal shrinkage of the internal concrete is constrained by the surface concrete. Thus, it leads to longitudinal tensile stress for internal concrete and compressive stress for surface concrete. Because the elastic modulus of concrete has already developed in this stage, the stress increment caused by unit temperature difference is large. Thus, the superposition of the stress field not only makes the longitudinal stress generated in temperature rising stage be offset, but also remains a large reverse stress, that is, the internal concrete is in tension, while the internal concrete is in compression, as shown in Figure 13(c) to (h).

At the same time, the strain along the bridge were also measured for some measuring points. According to the measured frequency of the embedded vibrational chord strain gauges, the concrete strains can be obtained through the following conversion formula:

$$\varepsilon = K(f_i^2 - f_0^2)$$

where $\varepsilon$ represents the strain of concrete ($\mu e$); $K$ is the sensitivity coefficient of the strain gauge ($\mu e$/ Hz$^2$); $f_i$ and $f_0$ denote the measured frequency and the initial frequency respectively. Table 4 shows the measured data of points 5 and 18 in the bottom plate and point 16 on the flange surface.

Since the stress relaxation caused by shrinkage and creep was not considered, the calculation results are larger than the values of measured stress, but the trends of two are basically consistent as shown in Table 4. It should be noted that whether the concrete cracks and the directions of the cracks mainly depend on the magnitude and direction of the principal tensile stress. Due to the varying direction of principal stress at different times in the same location, the increment of the principal stress cannot be superimposed directly. Instead, the stress components should be superimposed firstly, and then the principal stress at that location can be synthesized. Accordingly, the calculation results of the first principal stress at the center and surface of diaphragm, top plate, web, and bottom plate are shown in Figures 14 to 17.

It can be seen from the above figures that the inner part of each component in zero block is first in compression and then in tension, while the situation is contrary on the surface. Besides, the conversion time from compression to tension, the time that tensile stress achieves the peak value and the magnitude of the peak value are closely related to the pouring volume and heat emission conditions of each component. As shown in Figure 14, the maximum tensile stress appears on the side surface of diaphragm at the beginning of the concrete placement, and it reaches the peak value of 2.94 MPa 3 days later. The reason is that the diaphragm is the thickest component, and thereby the temperature difference between inside and outside is the biggest. Figure 13(b) and (c) and Figure 15 also show that the tensile stress on the surface of the flange cannot be ignored in the heating stage, which can reach 1.5 MPa 2 days after pouring. Additionally, the internal compressive stress is decreasing gradually and turns into tensile stress in thinner components like bottom plate and web firstly. In comparison, the pouring volume of the joint between top plate and web is large, so that the tensile stress appears later (on the fifth day). By the seventh day, this position replaces the diaphragm surface and subjects to the largest tensile stress in the whole structure, where the residual tensile stress can exceed 2 MPa. The diaphragm has the largest volume, and therefore the conversion time from compression to tension of internal concrete is the latest. Figure 14 shows that it is still in compression on the 10th day, whereas its residual tensile stress is only 1.68 MPa finally.

According to the analysis of cast temperature field in the previous section, it can be seen that the distribution of temperature stress basically depends on the change of temperature field. Actually, the time when
Figure 13. Contours of longitudinal thermal stress: (a) day 1, (b) day 2, (c) day 3, (d) day 4, (e) day 5, (f) day 7, (g) day 8, and (h) the stable one (unit: MPa).
the tensile stress on the surface of the box girder reaches the peak just corresponds the end of the heating stage of internal concrete. The time when the increment of internal tensile stress of box girder reaches the maximum coincides with the time when the temperature difference reaches the maximum, because the difference between the internal cooling rate and the external cooling rate is the largest at this moment. As for the magnitude of the increment of tensile stress, it mainly depends on the value of the temperature difference.

It should be noted that the compressive stress accumulated during the heating stage is usually not considered, which is taken as the safety reserve against tensile stress (the reason is that the elastic modulus of the concrete in the early age is usually too small so that the strain is hard to result in stress). However, for high-strength concrete, especially for the one containing early strength composition, the early elastic modulus increases rapidly so that the accumulated compressive stress during the heating stage cannot be ignored. Otherwise, the calculation results will become too conservative. Taking the central node of diaphragm as an example (see Figure 14), the final residual tensile stress is 1.68 MPa when the early compressive stress is accumulated, which will not lead to cracks in general. However, if the early compressive stress is not considered, the final residual tensile stress will achieve 3.33 MPa, which is enough to cause cracks. Therefore, it may produce the opposite conclusions with and without considering the compressive stress accumulated in the early age of high-strength concrete.

**Discussions**

The experimental data shows that the compressive strength of high-strength concrete developed very
rapidly in early age. Under the sealed curing, the com-
pressive strength of concrete with silica fume can reach
more than 30% of 28d strength on the first day and
67% on the third day. Even for the high-strength con-
crete without silica fume, the compressive strength can
also approach 22% of 28d strength on the first day and
51% on the third day. The development of the com-
pressive strength with age can be described by the fol-
lowing formula21:

\[
f_{cu}(t) = f_{cu}^{28d}[1 + m \ln(t/28)]
\]

where \(f_{cu}(t)\) represents the compressive strength at dif-
ferent ages; \(f_{cu}^{28d}\) denotes the 28d compressive strength;
\(m\) is the coefficient related to the type of cement. For
the high-strength concrete without silica fume, when \(m\)
is taken as 0.234 the calculation results obtained from
equation (6) is in good agreement with the experimental
results. Based on the compressive strength of concrete,
the corresponding splitting tensile strength \(f_{tcu}(t)\) can be
calculated by the formula \(f_{tcu}(t) = \alpha f_{cu}^{28d}(t)\), where \(\alpha\) and \(\gamma\)
are the regression parameters.6 We substituted \(\alpha = 0.232\)
and \(\gamma = 66\) into the above equation to determine the ten-
sile strength of the concrete within 15 days after pouring,
which are compared with the maximum tensile stress cal-
culated by ANSYS, as shown in Figure 18.

According to the analysis in Section 3.2, the location
of the maximum principal tensile stress in zero block
varied with the growth of concrete age and the corre-
sponding redistribution of temperature stress. The max-
imum principal tensile stress appeared on the side
surface of the diaphragm in the first 7 days after pour-
ing; after that, it was found at the joint of top plate and
web, which leads to the fluctuation of the correspond-
ing curve as shown in Figure 18. Figure 18 also shows
that the problem of surface cracking is more prominent
from the first day to the fifth day after pouring. After
formwork removal, several cracks were found on the side of diaphragm plate, with the length of 5–15 cm and the width of less than 0.1 mm, the directions of which were basically consistent with the directions of the principal tensile stress obtained before. As the surface begins to be compressed in the later period, these cracks closed gradually, which may do little harm to the structural strength, but would affect the durability of the structure to a certain extent. Therefore, it is necessary to pay attention to the water conservation and avoid to remove the formwork too early, for the purpose of reducing the probability of cracks. It can also be seen from Figure 18 that, the tensile stress is always less than the tensile strength of the concrete 5 days later after pouring, so it can be judged that there will be no deep cracks endangering the structural strength.

Conclusions

(1) Compared with the general static and dynamic structural analysis, the process of concrete pouring contains too many uncertain factors, so that the determination of thermodynamic parameters plays a very important role in the simulation of the cast temperature field as well as the corresponding stress field. In this study, the thermodynamic parameters are selected carefully in terms of the statistical data, the empirical formulas as well as the measured data in an actual project, which leads to a reliable simulation results by means of the finite element software. The comparison between the calculated and measured values of temperature field shows that the maximum error among all measuring points is only 1.71%. As for the temperature stress field, because the stress relaxation caused by shrinkage and creep is not considered, the calculation results are larger than the values of measured stress, but the trends of two are basically consistent with each other. Meanwhile, the directions of the principal tensile stress calculated in this study also coincide with the directions of the observed cracks well.

(2) Compared with the most common mass concrete structures (e.g. the dams, the anchorages, and the pile caps of bridges), the zero block of box girder usually has more complex geometry and variable heat dissipation conditions. Although its cast volume is relatively small, the temperature rise caused by the heat of hydration is still considerable due to the heavy use of high strength concrete. The simulation results show that, the heat of hydration in different components of the zero block have different characteristics, since the cast volumes and the heat dissipation conditions of them are different from each other. Accordingly, each component can be considered independently to find out its distribution of temperature field and the corresponding stress field in the pouring process. In this study, the evolution of the cast temperature and stress is investigated carefully for each component of zero block based on the simulation results and measured data. Particularly, the key indexes are analyzed quantitatively including the peak value of the temperature, the maximum temperature difference between the inside and outside, the maximum tensile stress, the time and location of them as well as their relationship with thermal cracks, which can provide an important reference for the temperature control of similar projects.

(3) Although the early strength of the high-strength-concrete is relatively high, it still has the potential risk of thermal cracks due to its rapid exothermic rate during hardening. Particularly, in 1–5 days after pouring, the thermal cracks tend to appear on the surfaces of those components with large cast volume such as diaphragm. Hence, it is necessary to pay attention to the water conservation and avoid to remove the formwork too early. On the other hand, the internal concrete of large components usually accumulates large compressive stress in the process of heating, which can offset part of the tensile stress in the process of cooling, so there are generally no inside deep cracks endangering the structural strength.

Author contributions

Conceptualization, P.Z. and H.X.; methodology, P.Z.; software, P.Z.; validation, P.Z. and R.W.; formal analysis, P.Z and H.X.; investigation, P.Z. and R.W.; resources, H.X.; data curation, P.Z.; writing – original draft preparation, P.Z and R.W.; writing – review and editing, P.Z. and R.W.; visualization, P.Z and H.X.; supervision, H.X.; project administration, H.X.; funding acquisition, P.Z. All authors have read and agree to the published version of the manuscript.

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