Temperature and Stress Fields of Anchorage Mass Concrete of a Suspension Bridge

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Abstract. Because of its huge volume, the method of block and layer pouring is usually used in the construction process of suspension bridge anchorage. In order to avoid the temperature cracks of mass concrete caused by hydration heat in the construction process, a three-dimensional finite element model is established based on the anchorage of a suspension bridge. The influences of the temperature of mixture placing to mold, the thickness of layers, the ambient temperature and the maintenance measures on the temperature at the centre, the temperature difference between the top surface and middle point and the tensile stresses at the surface are analyzed. The results show that the temperature at the centre, the temperature difference between the top surface and middle point increase with the increase of the temperature of mixture placing to mold and the thickness of layers are positively correlated. When the temperature of mixture placing to mold changes from 15°C to 35°C, the temperature at the centre increases by 19.06°C, the temperature difference between the top surface and middle point increases by 10.85°C, and the tensile stresses at the surface increases by 0.72 MPa; when the thickness of layers increases from 1 m to 3 m, the temperature at the centre increases by 15.46°C, the temperature difference between the top surface and middle point increases by 16.87°C, and the tensile stresses at the surface increases by 1.51 MPa. The temperature difference between the top surface and middle point decrease with the increase of the ambient temperature, while the temperature at the centre increases with the increase of the ambient temperature. Moreover, the temperature difference between the top surface and middle point decrease with the improvement of curing conditions. Therefore, in the actual project, reducing the temperature of mixture placing to mold, the reasonable layer thickness, the suitable ambient temperature and good maintenance measures, which can effectively reduce the cracking risk of mass concrete.

1. Introduction

With the rapid development of the transportation industry, people's demand for long-span bridges that span wide rivers and ocean is becoming stronger and stronger. Suspension bridges are increasingly valued by the engineering community for their excellent spanning capabilities. As the main load-bearing structure and common anchorage form of suspension bridge, anchorage, due to its huge volume, generates a lot of heat during the construction process due to the hydration of cementitious materials in the concrete, which leads to a sharp rise in the internal temperature of the concrete, while the outer edge of the concrete dissipates heat rapidly, thus forming a larger temperature gradient in the concrete. The tensile stress on the concrete surface caused by the excessive temperature gradient will cause cracks in the concrete and further develop into deep cracks, which affect the safety and durability of the structure. There have been some researches on crack control of mass concrete at home and abroad. Some scholars used numerical simulation to study the influence of structural size,
solar radiation and type of formwork on the temperature rise and the associated potential of cracking in the mass concrete, like this [1]; some experts conducted a simulation analysis on the early hydration heat of mass concrete, and some temperature control measures are summarized, but there is a lack of data to support the effectiveness of crack control, like this [2]. In short, the research on mass concrete in various countries mainly focuses on the influence of placement temperature of concrete, type of cement, etc. on the temperature and stress fields, like these [3-5]. However, the systematic research on the mechanical properties of mass concrete in the construction process of suspension bridge anchorage is less. Therefore, this paper establishes a three-dimensional finite element model, and systematically analyzes the effects of the temperature of mixture placing to mold, the thickness of layers, ambient temperature and maintenance measures on the temperature at the centre, the temperature difference between the top surface and middle point and the tensile stresses at the surface. It provides references for crack control in the construction of anchorage mass concrete in the future.

2. Finite element method of temperature and stress fields

2.1. Basic physical properties of concrete
The thermodynamic parameters of concrete mainly depend on the thermal properties of aggregates, cementitious materials and water used in concrete. For important projects, the specific heat capacity and heat conduction coefficient of concrete should be determined by experiments, while for ordinary projects or in the preliminary design stage, it can be calculated according to formulas:

\[ c = \frac{\sum W_i c_i}{\sum W_i} \]  
\[ \lambda = \frac{\sum W_i \lambda_i}{\sum W_i} \]

Where: \( W_i \) is the quality of each component of concrete; \( \lambda_i \) is the heat conduction coefficient of each component of concrete; \( c_i \) is the specific heat capacity of each component of concrete.

The adiabatic temperature rise of concrete adopts the hyperbolic formula recommended in the literature, like this [6]:

\[ \theta(\tau) = \frac{\theta_0 \tau}{n + \tau} \]

Where: \( \theta_0 \) is the final adiabatic temperature rise value of the heat of hydration when \( \tau \to \infty \), \( \theta(\tau) \) is the adiabatic temperature rise value when the age is \( t \), and the unit is °C.

2.2. Temperature field
According to the heat conduction theory, considering the three-dimensional unstable temperature field, the problem solved is that the concrete temperature \( T \) in the region \( R \) should satisfy the Laplace equation (refer to this article [7]):

\[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{1}{\alpha} \left( \frac{\partial \theta}{\partial \tau} - \frac{\partial T}{\partial \tau} \right) = 0 \]

Initial conditions:

\[ T(x, y, z) = T_0(x, y, z) \]

The first type of boundary conditions: the concrete surface temperature \( T \) is a function of time \( t \), which is:

\[ T(\tau) = f(\tau) \]
The second type of boundary conditions: the heat flux on the concrete surface is a known function of time, namely:

\[-\lambda \frac{\partial T}{\partial n} = f(\tau)\]  

(7)

The third type of boundary conditions: when concrete is in contact with air, the heat flow \( q \) across the surface of the concrete is:

\[q = -\lambda \frac{\partial T}{\partial n}\]  

(8)

The heat flux passing through the concrete surface is proportional to the difference between the concrete surface temperature \( T \) and the air temperature \( T_a \), namely:

\[-\lambda \frac{\partial T}{\partial n} = \beta(T - T_a)\]  

(9)

According to the variational principle and the finite difference algorithm, the variational functional and governing equation of the three-dimensional transient temperature field problem are:

\[I(T) = \int_\Gamma \left[ \frac{1}{2} \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 + \left( \frac{\partial T}{\partial z} \right)^2 + \frac{1}{\alpha} \left( \frac{\partial \theta}{\partial \tau} - \frac{\partial T}{\partial \tau} \right) \right] dxdydz + \int_\Gamma \beta \left( T - T_a \right) Tds\]  

(10)

\[\begin{bmatrix} [H] + \frac{1}{\Delta t_n} [R] \end{bmatrix} \{T_{n+1}\} - \frac{1}{\Delta t_n} [R] \{T_n\} + \{F_{n+1}\} = 0\]  

(11)

Where: \([H]\) is the heat conduction matrix; \([R]\) is the conduction supplementary matrix; \(\{T_n\}\) and \(\{T_{n+1}\}\) is the nodal temperature vector; \(\{F_{n+1}\}\) is the nodal temperature load vector; \(t\) is time; \(\Delta t\) is the time step; \(n\) is the number of time series, \(\Gamma\) is the boundary of \(R\).

2.3. Temperature stress field

Under complex stress conditions, the strain increment of concrete includes: elastic strain increment, temperature strain increment, creep strain increment, autogenous volume strain increment, and shrinkage strain increment, namely

\[\Delta e_n = \Delta e^e_n + \Delta e^c_n + \Delta e^l_n + \Delta e^a_n + \Delta e^d_n\]  

(12)

From the mechanical equations, geometric equations and physical equations, the temperature stress finite element governing equation of the time period on the element \(R\) is:

\[\begin{bmatrix} [K] \end{bmatrix} [\Delta \delta] = \{\Delta P^c\}^e + \{\Delta P^c\}^f + \{\Delta P^c\}^l + \{\Delta P^c\}^a + \{\Delta P^c\}^d\]  

(13)

Where: \([K]\) is the element stiffness matrix; \([\Delta \delta]\) is the nodal displacement increment; \(\{\Delta P^c\}^e\), \(\{\Delta P^c\}^f\), \(\{\Delta P^c\}^l\), \(\{\Delta P^c\}^a\) and \(\{\Delta P^c\}^d\) are respectively the nodal load increment vector caused by creep, temperature change, dry shrinkage, autogenous volume deformation and external load.

3. Influence factors of temperature and stress fields

3.1. Establishment of three-dimensional finite element model

The size of the anchorage of a suspension bridge is: 65 m × 44.5 m × 44.5 m. In order to avoid temperature cracks, the structure is divided into four blocks for construction, and each block is constructed layer by layer. The material is shown in table 1:
Table 1. Thermal properties of materials used in finite element simulation.

| Basic parameters | Heat conduction coefficient (kJ/(m·h·°C)) | Specific heat capacity (kJ/(kg·°C)) | Poisson's ratio | Thermal expansion coefficient | Density (kg · m⁻³) |
|------------------|------------------------------------------|-----------------------------------|----------------|-------------------------------|-----------------|
| Rock             | 9.34                                     | 0.98                              | 0.17           | 10⁻⁵                         | 2400            |
| Concrete         | 10.05                                    | 0.88                              | 0.2            | 10⁻⁵                         | 2443            |

Figure 1. Three-dimensional finite element model of anchorage.

This article takes the working condition (the thickness of layer is 2.5m, the ambient temperature is 20°C, the temperature of mixture placing to mold is 20°C, and the 6mm thick steel is used for maintaining) as the background, while keeping the other three conditions unchanged, adjusting one of the factors to find the law of the temperature and stress fields of the anchorage mass concrete. See below.

3.2 Influence of the temperature of mixture placing to mold
When the temperature of mixture placing to mold increases from 15°C to 35°C, as shown in figure 2 to 7: the temperature at the centre, the temperature difference between the top surface and middle point and the tensile stresses at the surface all increase with the increase of the temperature at the centre. The temperature difference between the top surface and middle point and the tensile stresses at the surface, and have obvious linear correlation. When the temperature of mixture placing to mold changes from 15°C to 35°C, the maximum temperature at the centre increases from 58.64°C to 77.70°C, the maximum temperature difference between the top surface and middle point increases from 20.10°C to 30.95°C, and the maximum tensile stresses at the surface increases from 1.7 MPa to 2.42 MPa. With the increase of the temperature of mixture placing to mold, the time of each peak appears earlier.

Figure 2. Time history curve of T.  
Figure 3. Time history curve of ΔT.  
Figure 4. Time history curve of σ.
Description: for the convenience of expression, the meaning of the following symbols: T: the temperature at the centre; ΔT: the temperature difference between the top surface and middle point; T₀: the temperature of mixture placing to mold; σ: the tensile stresses at the surface; A: the ambient temperature; M: the maintenance measures; L: the thickness of layers.

3.3. Influence of the thickness of layers
When the thickness of layers varies between 1m and 3m, it can be drawn from figure 8 to 13: the temperature at the centre, the temperature difference between the top surface and middle point and the tensile stresses at the surface increase with the increase of the thickness of layer. When the layer thickness increases from 1 m to 3 m, the temperature at the centre increases from 50.80 °C to 66.26 °C, and the temperature difference between the top surface and middle point increases from 9.74 °C to 26.61 °C, and the tensile stresses at the surface increased from 0.62 MPa to 2.13 MPa.
3.4. Influence of the ambient temperature
When the ambient temperature increases from 15°C to 35°C, it can be drawn from figure 14 to 19: the temperature at the centre increases slightly, from 63.3°C to 63.7°C, the temperature difference between the top surface and middle point and the tensile stresses at the surface decrease with the increase of the ambient temperature, and there is an obvious linear relationship. The maximum temperature difference between the top surface and middle point is reduced from 22.8°C to 13.8°C, and the tensile stresses at the surface is reduced from 1.94 MPa to 1.61 MPa. And as the time increases, the rate of change of the core temperature increases.

3.5. Influence of the maintenance measures
The following 4 maintenance measures are adopted: open air; 6mm steel plate; 6mm steel plate + 5cm polystyrene. Derived from figure 20 to 25: it is concluded that the temperature rise curve of the concrete in the early stage does not change significantly, but in the cooling stage, the cooling rate is different. The performance is that the concrete is in the working condition with better maintenance measures. The cooling rate in the cooling stage is relatively small. Therefore, the temperature difference between the top surface and middle point and the tensile stresses at the surface are smaller when the maintenance measures are good.
4. Conclusions

Based on the work documented in this paper, the following conclusions are drawn:

The higher temperature of mixture placing to mold will speed up the rate of cement hydration, which will increase the temperature at the centre, the temperature difference between the top surface and middle point and the tensile stresses at the surface. The thickness of layers has a huge impact on the concrete construction process. The excessive thickness of layers will significantly increase the temperature at the centre, the temperature difference between the top surface and middle point and the tensile stresses at the surface. The higher the ambient temperature, it is beneficial to prevent the mass concrete from cracking, but when the ambient temperature increases, it also increases the risk of concrete cracking due to shrinkage, good maintenance measures are beneficial to reduce the risk of concrete cracking. At the same time, it should be explained that the steel formwork basically has no insulation effect. Taking measures to reduce the temperature of mixture placing to mold, determining the appropriate thickness of layers, and taking good maintenance measures can effectively reduce the risk of concrete cracking, and the suspension bridge anchorage construction is carried out in a suitable ambient temperature, which has important engineering significance to the safety and durability of bridge structures.

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