Research on Heat Dissipation and Insulation Measures of a Prestressed Continuous Box Girder Bridge Section

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Abstract. Taking a prestressed concrete box girder as the research object, aiming at the problem that the concrete bridge durability is reduced due to the appearance of temperature cracks in the concrete box girder, this paper adopted different types of heat insulation materials, and theoretically analyzed the structural temperature field of concrete box girder under high temperature difference and low temperature environment from the aspects of whether the heat source was set inside the concrete box girder, which provides a reference for the technical application and promotion of thermal insulation materials in concrete bridges.

1. Introduction
Concrete box girder occupies a very important position in bridge construction because of its economic, reasonable and convenient construction characteristics. However, due to the low thermal conductivity of concrete materials, the external surface temperature of concrete structure in natural environment changes significantly under the action of natural external factors such as sunlight radiation and air temperature, while the internal temperature changes are still in the state before the effect, causing a non-linear temperature gradient inside the structure. The existing research shows that the temperature load caused by solar radiation and other factors may cause the internal stress of the concrete structure to exceed the allowable tensile stress of the concrete itself, which will cause large temperature deformation in the concrete bridge structure$^1$, and then cause large temperature stress, causing the structure to crack and appear cracks$^2$, thereby seriously degrading the durability and causing non-negligible damage to the concrete bridge structure. Therefore, the temperature effect of concrete box girder will directly affect the safety, durability and applicability of the bridge structure.

Research shows that the temperature effect of concrete bridge has received more and more attention, and the most effective method is concrete coating protection. Because of its good adaptability and characteristics of temperature reduction and heat insulation, heat reflective heat insulation coatings$^3$ are widely used in the fields of building exterior wall, oil and gas storage tank, steel structure building and heat supply network pipeline. In view of the problem that the concrete box girder temperature cracks lead to the durability reduction of the concrete bridge, this paper uses polyurethane insulation board insulation material, and analyzes the structural temperature field of the concrete box girder in the environment of high temperature difference and low temperature from the aspects of whether the heat source is set inside the concrete box girder, which provides a reference for the technical application and promotion of thermal insulation materials in concrete bridges.
2. Basic principles of heat transfer
There are three basic ways of heat transfer: heat conduction, heat convection and heat radiation. When the concrete box girder in the sunlight radiation environment, firstly, the heat of sunlight is transferred to the surface of concrete box girder through heat convection and heat radiation; then the surface temperature of the concrete box girder is transferred to the lower temperature part of the concrete box girder through heat conduction, forming the temperature field of the concrete box girder.

(1) Heat conduction
From a macro perspective, heat conduction is a physical phenomenon that the heat inside a solid transfers from the part with higher temperature to the part with lower temperature, and that the solid with higher temperature transfers the heat to another solid with lower temperature. The heat conduction conforms to Fourier's law, that is, the heat conducted through a unit cross-sectional area per unit time is proportional to the local temperature change rate in the direction perpendicular to the cross-sectional area, and its expression is:

\[ \Phi = -\lambda A \frac{\partial T}{\partial x} \]  

In the formula, \( \Phi \) is the heat flow rate, the unit is W; \( \lambda \) is the thermal conductivity, the unit is W/(m·℃); A is the area, the unit is m²; T is the temperature, the unit is ℃.

(2) Heat convection
Heat convection refers to the relative displacement between various parts of the fluid caused by the macroscopic motion of the object, and the heat transfer process caused by the mixing of cold and hot fluids. The basic calculation formula for convective heat transfer is the Newtonian cooling formula:

When the component is heated:  
\[ q = h(T_f - T_c) \]  
(2)

When the component is cooled:  
\[ q = h(T_c - T_f) \]  
(3)

In the formula, q is the heat flux density, the unit is W/m²; h is the convective heat transfer coefficient, the unit is W/(m²·℃); \( T_f \) and \( T_c \) are fluid temperature and component wall temperature respectively, in ℃.

(3) Heat radiation
Radiation is the way that objects transmit energy through electromagnetic waves, and the phenomenon of emitting radiant energy due to heat is called heat radiation. The Stefan-Boltzmann equation can be used to calculate the radiant heat flux of real objects.

\[ \Phi = \varepsilon \sigma A (T_1^4 - T_2^4) \]  

In the formula, \( \varepsilon \) is the emissivity of the object, its value is always less than 1; \( \sigma \) is the Stefan-Boltzmann constant, its value is 5.67×10⁻⁸W/(m²·K⁴); A is the radiation surface area in m²; \( T_1 \) and \( T_2 \) are the thermodynamic temperatures of radiating surface 1 and radiating surface 2, respectively, in K.

3. Heat dissipation analysis of concrete box girder

3.1. Calculation model and parameters
(1) Calculation model
In order to understand the heat dissipation of concrete box girder under the change of ambient temperature, numerical analysis is carried out on the root beam section with larger heat dissipation area, and the comparison is carried out under three working conditions: no insulation layer, 5cm polyurethane insulation board insulation layer, 5cm polyurethane insulation board insulation layer + heating arrangement inside the box, as shown in Figure 1.
(2) Thermal parameters of materials
According to the “Thermal design code for civil building” (GB 50176-2016), the thermal parameters of materials used in the calculation are as follows:
- Reinforced concrete: density 2500kg/m$^3$, thermal conductivity 1.74W/m$\cdot$K, specific heat capacity 920 J/kg$\cdot$K;
- Asphalt concrete: density 2100kg/m$^3$, thermal conductivity 1.05W/m$\cdot$K, specific heat capacity 1680 J/kg$\cdot$K;
- Polyurethane insulation board: density 35kg/m$^3$, thermal conductivity 0.024W/m$\cdot$K, specific heat capacity 1380 J/kg$\cdot$K

(3) Boundary conditions and loads
Take the top surface, bottom surface, two sides of the concrete beam section and the inner surface of the box as heat dissipation surfaces, and the cross-sections at both ends are non-heat dissipation surfaces, as shown in Figure 2:

(a) Heat dissipation surface outside the box (b) Heat dissipation surface inside the box (c) Non-heat dissipation surfaces at both ends

Figure 2 Boundary conditions.

(3) Temperature monitoring point
According to the position shown in Figure 3, the influence of the insulation layer on the temperature field of the top, side and bottom of the box girder was compared.

Figure 3 Location of the temperature change.
(4) Temperature field curve

Because the concrete box girder has a long cantilever, the webs on both sides receive less direct solar radiation, and the bottom of the girder is not exposed to sunlight all day long, so there is a vertical temperature gradient in the concrete box girder; In addition, due to the poor heat transfer performance of concrete and the lack of air circulation inside the box, there will be a large temperature difference between the inside and outside of the box in the case of cold current cooling.

This calculation is mainly aimed at the analysis of the effect of insulation layer on the heat dissipation of concrete box girder, so the temperature gradient of concrete box girder and the temperature difference between the inside and outside of the box are not considered in the calculation. It is assumed that the temperature of box girder body is evenly distributed, and the temperature inside and outside the box girder is consistent.

According to relevant data, the average temperature in August 2020 in the area where the bridge is located is 33°C, so the initial temperature of the box girder body is set to 33°C, and the ambient temperature outside the box girder is taken as the temperature curve of the half year period from August 1, 2020 to January 31, 2021 as shown in the figure, in which the lowest temperature of 3 °C appeared on the night of December 31.

3.2. Analysis of calculation results
3.2.1 Without insulation layer. Without the insulation layer, the comparison curve between the concrete beam temperature and the ambient temperature is shown in the figure. It can be seen from Figure 6 that the temperature of the concrete beam changes with the change of the ambient temperature, and the change trend is basically the same. However, due to the poor heat transfer performance of concrete materials, and the intraday fluctuation range of the beam temperature is smaller than the ambient temperature.

Figure 4 Half-year temperature change curve at the bridge location. Figure 5 Internal heating of box girder.

[Graphs showing temperature changes over time]

Figure 6 Comparison of concrete beam temperature and ambient temperature.
3.2.2 With insulation layer. Since there is no insulation layer on the top surface, the temperature change curve at point A under this working condition is basically consistent with the change in ambient temperature. The location of point B is close to the insulation layer and is affected by the heat conduction of the insulation layer and the beam, so the temperature changes slightly. There is a change range of 0.5 ℃ under the lowest temperature on December 31, 2020, that is, there is a heat dissipation effect of 0.5 ℃ on the concrete beam.

Compared with the large change of the ambient temperature, the temperature change curve of point C on the side of the box girder is relatively flat, and has a certain thermal insulation effect during the period of low ambient temperature. There is an insulation range of about 2 ℃ at the lowest temperature on December 31, 2020, which can reduce the heat dissipation range of about 2 ℃ of the concrete beam.

Compared with the large change of the ambient temperature, the temperature change curve of point D and point E on the bottom of box girder tend to be flat obviously, and the insulation effect is significant during the period of low ambient temperature. At the lowest temperature on December 31, 2020, Point D and Point E have a thermal insulation range of about 7.7 ℃ and 5.3 ℃ respectively, which can reduce the heat dissipation range of about 7.7 ℃ and 5.3 ℃ for concrete beams. At this time, the temperature of the beam body can basically be maintained at 13.5 ℃~15 ℃.
temperature is about 6.9 °C, and the bottom surface temperature is about 10.8 °C; After setting the insulation layer, the temperature field of the beam body changes significantly, and the temperature of the top surface does not change much (7.1°C), but the bottom surface temperature can be maintained at about 15°C. The insulation effect of the insulation layer is obvious, which can greatly reduce the heat dissipation of the concrete and ensure the temperature of the beam body.

![Figure 12](image1.png)

(a)Working Condition 1: Without Insulation Layer
(b)Working Condition 2: 5 cm polyurethane insulation board insulation layer

Figure 12  Temperature field of concrete box girder at the lowest temperature.

3.3. TDD insulation layer + Heating arrangement inside box during low temperature period

The temperature change at point A on the top surface directly above the inside of the box is more obvious, it is basically kept above 15°C during the low temperature period. Point B is located at the edge and heating inside the box has no effect on it, so the temperature change at point B is more consistent with the ambient temperature; The temperature at point C in the inner side of the box changes significantly, and it basically remains above 15°C during the low temperature period; The temperature changes at points D and E are greatly affected by the heating in the box, and it basically remains above 20°C during the low temperature period.

![Figure 13](image2.png)

Temperature curve of Point A

![Figure 14](image3.png)

Temperature curve of Point B

![Figure 15](image4.png)

Temperature curve of Point C

![Figure 16](image5.png)

Temperature curve of Point D
The temperature field cloud diagram of the concrete beam during the low ambient temperature period at the end of December 2020 is shown in the figure. It can be seen from the figure that during the low ambient temperature period, except for the outer side of the flange, the temperature of the rest of the parts is basically kept above 15℃, and the heat preservation effect of 5cm polyurethane insulation board insulation layer + heating inside the box during the low temperature period is more obvious.

4. Conclusion
(1) Without insulation layer, the temperature of concrete beam changes with the change of ambient temperature, and the change trend is basically the same. However, due to the poor heat transfer performance of concrete materials, the intra-day fluctuation range of beam temperature is smaller than that of ambient temperature;

(2) When 5cm polyurethane insulation board is installed on both sides and bottom of the concrete beam, it has little effect on the top surface temperature of concrete beam, but it can reduce the heat dissipation range of about 2℃~5℃ on the side and 5℃~7℃ on the bottom;

(3) In the annual minimum temperature period with the ambient temperature of 3℃, the bottom concrete temperature can be maintained at about 15℃, and the insulation effect of the insulation layer is obvious, which can greatly reduce the heat dissipation of the concrete and ensure the temperature of the beam.

(4) The heat preservation effect of 5cm polyurethane insulation board insulation layer + heating inside the box during the low temperature period is more obvious, except for the outer side of the flange, the temperature of the rest of the beam is basically kept above 15℃ in the low ambient temperature period.

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