Thermal response analysis of reinforced concrete box girder during hot-mixed asphalt mixture paving

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Abstract. Hot-mixed asphalt (HMA) concrete has been extensively used in the concrete box-girder bridge deck pavement due to its excellent performance and driving comfort. Nevertheless, during HMA concrete construction, the high paving temperature may disturb the thermal field of the bridge, thereby causing the significant thermal response throughout the box girder. Therefore, this research aims to investigate the temperature behavior and thermal stress of a reinforced concrete box girder segment during HMA concrete paving. The transient thermal field theory and element deletion method were first adopted to establish a three-dimensional finite element model of a reinforced concrete box girder segment and simulate the dynamic paving process, respectively. Subsequently, the bridge monitoring data was used to validate the thermal field model and then the temperature distribution analysis was conducted. Finally, the thermal stress in the bridge was studied in cross-sectional area. Results demonstrate that the vertical temperature of the concrete box-girder during the paving process is declined with the increasing vertical distance to SFRC leveling layer, and its highest value occurs at 36min after starting to paving. Furthermore, in the vertical direction, the west web-plate is subjected to compressive stress at locations of two ends and tensile stress at locations of the middle. Meanwhile, the thermal stresses undergo a decline trend after short-term growth both in the box and flange slab in the transversal direction.

1. Introduction

In practice, the temperature-induced cracking has become one of common early distresses that occur in the bridge superstructures [1]. Exposed to the thermal actions (air temperature variations, solar radiation and so on), a concrete bridge is ineluctably subjected to the non-uniform thermal field, thereby causing the thermal deformations in the bridge components due to the thermal expansion and contracting of materials [2]. Once these deformations are retrained, the significant thermal stress will occur in the bridge, which might exceed the load-induced stress [3,4]. As a result, excessive thermal stress threatens the serviceability of bridge.

Currently, most researches have focused on the thermal field characteristics of the bridge in the natural environment. For instance, Zhao and Wang [5] studied the thermal field of a concrete bridge against different temperature boundary conditions. Gu et al [6] used the numerical simulation method to investigate the effect of wind speed, atmospheric cleanliness, bridge orientation and latitude, on the three-dimensional temperature changes throughout the box girder. Nevertheless, fewer attentions have been devoted to the thermal effects of the concrete box girder when hot-mixed asphalt (HMA) concrete is paving on the bridge deck. With the development of hot-mixed modified asphalt binder, the paving temperature of HMA pavement is higher than that of conventional asphalt pavement, which may cause
the significant thermal effects in the box girder. Moreover, steel fiber reinforced concrete (SFRC) has been applied as a leveling layer in many concrete bridges, and its high impact strength, toughness and thermal conductivity may contribute to the temperature changes of the concrete box girder.

In this research, the thermal response of the concrete box-girder segment containing SFRC leveling layer during HMA concrete paving was analyzed using a three-dimensional thermal field model. In detail, the temperature distribution characteristics were studied based on the established finite element (FE) model, followed by the mechanical response (thermal stress) analysis of the bridge during the paving process.

2. Description of the bridge and temperature monitoring

In this research, Dantu main line concrete box-girder bridge (Dantu Bridge) in China was selected for establishing the numerical model. Figure 1 shows the cross section of Dantu Bridge which is elongated in north-south direction. The box girder is 130 cm in height and 135 cm in width. In addition, there are 5 cm-thick SFRC leveling layer, 6 cm-thick sublayer asphalt pavement and 4 cm-thick asphalt concrete surface upon the box-girder section.

![Figure 1. Cross section of Dantu Bridge (Units are centimeter).](image)

In a mid-span cross section of Dantu Bridge, the temperature monitoring was conducted on October 20, 2004 to record the vertical temperature in real time during the asphalt concrete paving, using the resistance thermometers (RT-1) [7,8]. The arrangement of twelve vertical monitoring points in the west web-plate is shown in figure 2.

![Figure 2. Arrangement of the vertical monitoring points in the west-plate.](image)

3. Numerical simulation

3.1. Finite element model for thermal analysis

According to the geometrical configuration of the bridge in figure 1, a 21 m-long segment model of the concrete box-girder was developed using the commercial FE package ABAQUS 6.11, given that there is no obvious longitudinal temperature change on the non-paved bridge deck [9]. The FE model of concrete box-girder is shown in figure 3.

![Figure 3. Finite element model of the concrete box-girder.](image)
3.2. Temperature boundary conditions and material parameters

In the paving process of HMA concrete, the paver could be seen as a movable heat producer. Therefore, the temperature variation in the concrete box-girder during HMA concrete construction is treated as the transient temperature field [10]. In addition, the continuous temperature change of the bridge deck and pavement system is subjected to solar radiation, radiation heat transfer and natural convective heat transfer. Furthermore, there is no solar radiation in the sides, bottom and inner of box girder, and negligible natural convection occurs in the boxes [11]. As a result, according to the transient thermal field theory, the temperature boundary conditions of FE model are presented by equation (1).

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\begin{align*}
-k \frac{\partial T_{x}}{\partial y} &= h_{i} f(T_{i}(t) - T_{a}) + q(t) + \varepsilon \sigma \left[(T_{i}(t) - T_{s})^{4} - (T_{s} - T_{r})^{4}\right] \\
-k \frac{\partial T_{y}}{\partial y} &= h_{i} f(T_{i}(t) - T_{a}) + \varepsilon \sigma \left[(T_{i}(t) - T_{s})^{4} - (T_{s} - T_{r})^{4}\right] \\
-k \frac{\partial T_{z}}{\partial y} &= \varepsilon \sigma \left[(T_{i}(t) - T_{s})^{4} - (T_{s} - T_{r})^{4}\right]
\end{align*}
\]

where \(k\) and \(\varepsilon\) are thermal conductivity coefficient and emissivity coefficient of the materials, respectively; \(T_{i}, T_{s}\) and \(T_{r}\) are pavement surface temperature, ambient air temperature and absolute zero, respectively; \(T_{s}\) and \(T_{r}\) are the temperature of the sides and bottom of the box and the inner-surface temperature of the box, respectively; \(q(t)\) is solar radiation intensity; \(h_{i}\) and \(\sigma\) are natural convective heat transfer coefficient and Stefan-Boltzmann constant, respectively.

According to some investigations [11-15], the required parameters for numerical simulation are listed in Table 1, including some parameters in equation (1) and material thermal parameters.

| Temperature boundary parameters | Materials | Reinforced concrete | SFRC | Asphalt concrete |
|-------------------------------|-----------|----------------------|------|-----------------|
| \(q(t)\) W/m² | \(q(t)=0, t \in [0, 12-c/2]\) | \(k\) (W/m·K) | 1.7 | 2.2 | 1.0 |
| | \(q(t)=q_{0}\cos\pi(t-12)/12, t \in (12-c/2, 12+c/2)\) | \(\varepsilon\) | 0.9 | 0.9 | 0.81 |
| | | Density (kg/m³) | 2500 | 2600 | 2100 |
| | | Specific heat (J/kg·K) | 850 | 900 | 810 |
| | | Modulus (MPa) | 4.04E4 | 3.45E4 | 1200 |
| \(h_{s}\) W/(m²·K⁻¹) | \(h_{s}=4.0\times10^{5.8}\) | Poisson ratio | 0.225 | 0.2 | 0.35 |
| \(\sigma\) W/(m²·K⁻¹) | 5.6697E-8 | Expansion coefficient (10⁻³°C) | 1 | 1 | 5 |

Note: \(q_{0}\) is maximum sunshine intensity at noon, where \(q_{0}=1.572Q/c\), in which \(Q\) and \(c\) are daily total solar
radiation and effective duration of sunshine, respectively; \( v \) is the wind speed, m/s.

3.3. Thermal field model

Before the thermal analysis, the local meteorological data during HMA concrete paving was used to determine the initial thermal field of the model. In addition, the paving temperature and thickness of HMA concrete were chosen as 142°C and 6cm according to the field measuring results in the Master thesis of Zhu [7]. Furthermore, the element deletion method was adopted to simulate the dynamic paving process of HMA concrete and its procedures are summarized below [11].

- Along the longitudinal direction, dividing the 21m-long FE model into 21 parts and deactivating all solid elements of HMA concrete;
- Defining 22 heat transfer steps. In detail, the paving process was simulated by reactivating the solid elements of HMA concrete in the first 21 steps part by part at 30-second interval. Moreover, the temperature variations of the model after paving were simulated by the 22nd step.

Figure 4 shows the thermal field distributions at different heat transfer steps during the simulation process.

![Figure 4](image)

**Figure 4.** Simulating the paving process at different heat transfer steps. (a) Step 8, (b) Step 12 and (c) Step 16.

3.4. Model validation

To validate the accuracy of thermal field model, the comparisons between the simulated and measured temperature at the pavement surface, Point ①, Point ③ and Point ④ were conducted, as shown in figure 5. It can be found from figure 5 that the difference between the simulated and measured temperature is less than 5°C. When taking the field measurement errors and simulation simplification into account, the simulated results are considered to agree well with the measured results, indicating the feasibility of the established FE model and simulation method. In addition, as shown in figures 5(b)-5(d), the closer the locations are to the top of web-plate, the greater the influence of HMA concrete paving on the vertical temperature is. In detail, the highest temperature of the box girder occurs at 36 min at Point ①, while there is no obvious influence of HMA concrete construction on the vertical temperature at Point ④. Therefore, the critical time for thermal analysis was chosen as 36 min after the paving begins, due to the highest temperature difference in the vertical direction at this time.
Figure 5. Comparison between the simulated and measured results. (a) Pavement surface, (b) Point ①, (c) Point ③ and (d) Point ④.

4. Thermal stress analysis

4.1. Mechanical model and data acquisition

The geometry of the mechanical model in this research was same with that of the thermal field model. Additionally, the simply supported constraints were set as the boundary conditions of the mechanical model, which can ensure the longitudinal expansion of the concrete box-girder. Moreover, the mechanical parameters of materials were determined according to the results in table 1. Furthermore, the thermal stress analysis was conducted in the mid-span cross section where the mechanical state is considered to be the most unfavorable.

Subsequently, the data acquisition scheme of the mechanical model was formulated to analyze the thermal effects of the box girder after the paving begins. In detail, the vertical arrangement of the data acquisition scheme was determined according to figure 2. Besides, in the transversal direction, the measuring locations were arranged as shown in figure 6, including Point #1 at the middle of the box and Point #2 at the flange slab.

Figure 6. Transversal arrangement of the data acquisition scheme.

4.2. Thermal stress distribution in the vertical direction

The thermal stress distribution in the vertical direction at the critical time is illustrated in figure 7 (X-axis is represented by the vertical distance to the top of SFRC leveling layer). It can be found from figure 7 that both transversal and longitudinal thermal stresses present the compression status (negative number) at two ends and the tension status (positive number) at the middle in the west web-plate. In addition, the most unfavorable tension status occurs between Point ③ and Point ⑤. Due to most of damage in cement concrete occurring in the tension status, Point ④ was chosen to analyze the characteristics of thermal stress distribution during the whole paving process, as figure 8 shows. It indicates that in the tension status, the thermal stress has a trend from rising to decline, and the highest values of transversal and longitudinal stress both are close to 4 MPa, which is considerable and non-negligible in the stress field analysis of the concrete box-girder.
4.3. **Thermal stress distribution in the transversal direction**

Figure 9 illustrates the thermal stress distribution of two transversal points during the whole paving process. As shown in figure 9, two measuring locations, including Point #1 in the box and Point #2 in the flange slab, are in the tension status. Besides, the thermal stress presents a short-term increase, followed by a decline trend on the measuring locations in the box and flange slab. Moreover, transversal stress is larger than longitudinal stress at Point #1 in the box, which is opposed to Point #2 in the flange slab.

5. **Conclusions**

This paper investigated the thermal effects of the concrete box girder segment containing SFRC leveling layer after the paving begins, and the following conclusions can be drawn.

- The influence of HMA concrete construction on the temperature distribution in the vertical direction is attenuated as the vertical distance to the top of SFRC leveling layer increases. Moreover, the highest vertical temperature difference occurs at 36 min after starting to paving.
- In the vertical direction, the west web-plate is subjected to compressive stress at locations of two ends and tensile stress at locations of the middle. In addition, at Point ④ the unfavorable tensile stresses present a trend from rising to decline during the whole HMA concrete paving, the highest values of which are close to 4 MPa.
- In the transversal direction, the thermal stresses undergo a decline trend after short-term growth.
both in the box and flange slab.

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