COUPLED THERMAL STRESS ANALYSIS FOR SIMULATION OF CRACK PROCESSING IN CONCRETE BRIDGE BOX GIRDERS

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Abstract: *Temperature is known as one of the major reasons causing cracks in concrete structures. In the members like concrete bridge box girders thermal gradient may exist in many directions of the their sections. However in the current design code thermal gradient is modeled throughout the height of member section only. Moreover in the design practice the thermal gradient is mostly considered in the global analysis to get internal forces for the design purpose. Detail analysis accounting for local temperature distribution is rarely taken into account. Because of that many structure areas subjected to complicated stress condition aren't investigated properly in design and may crack in the service time.*

This paper presents a coupled thermal stress analysis considering the effect of solar radiation and the unequally distribution of temperature in the sections to simulate the cracking process in some local areas of concrete bridge box girders.

Keywords: *Concrete bridge box girders, coupled thermal stress analysis, thermal gradient.*

I. INTRODUCTION

Beside dead and live loads, shrinkage and creep of concrete, etc. thermal gradient in structure caused by solar radiation and other reasons may have a large effect in the stress distribution and crack development in concrete bridge girders. In current design codes thermal gradient is considered mostly in the vertical direction only. However, in the concrete bridge box girders thermal gradients may be found in horizontal and other directions because of the temperature difference between the inside and the outside of the box. These multi-directional thermal gradients cause a very complicated stress condition in concrete and the crack developing process is hardly to predict by usual analysis.

In some concrete bridge box girders in Vietnam many cracks have been found on the inner surface of the girder webs. They distributed diagonally to the girder longitudinal axis and symmetrically to pier position. Meanwhile there are no cracks found on the outer surface of the girder. In order to find out the reasons of these cracks many analysis have been performed including the global final stage analysis considering dead and live loads, the construction stage analysis taking into account of the effects of concrete creep, shrinkage and heat of hydration as well as the coupled stress and thermal detail analysis considering the unequally distribution of temperature in different parts of girder. The results of the global analysis shown that the effects of loads alone in the construction and final stages don't cause such cracks. Whereas the coupled thermal stress analysis presents that some areas in the box section subjected to pretty high stress. The combination of stress from thermal gradient and other actions can exceed the tension strength of concrete and causes cracks in the inside of the web.

This paper present the results of thermal transfer simulation and coupled thermal stress analysis to determine reasons of the cracks in the inside of concrete bridge box girders.

II. THE INVESTIGATED BRIDGE

Bridge NN has been built in 2000 in the Southern of Red Rive Delta (North Vietnam) with 7 spans box girder made of prestressed concrete. It lays in East-West direction. Five years after putting in the operation there are many diagonal cracks found in the inside of the girder webs. Some of them are 1.5 m long and some other are 8 cm deep and they distributed mostly symmetrically to pier positions (Figure 1). A long time observation shows that these cracks are now in still stand. A detailed investigation has been implemented but no cracks were found in the outside of the girders.

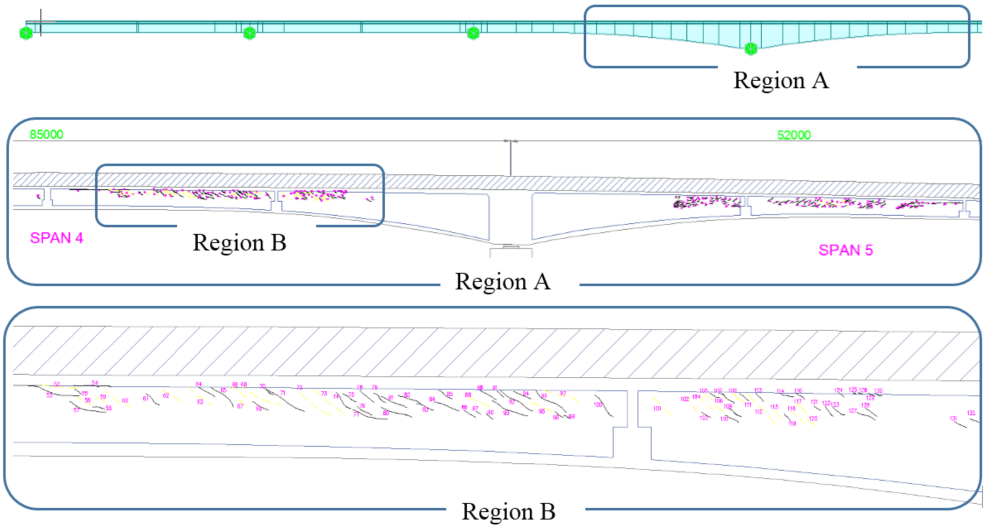

***Figure 1**. Crack pattern in the inside of the box girder of bridge*

III. THERMAL ABSORPTION AND TRANSFER IN THE GIRDER CONCRETE

3.1. Solar radiation

Beside the heat of hydration in the hardening process the thermal effect in concrete bridge in the service time comes mostly from the solar radiation. The sun's rays which are absorbed directly by the top surface cause it to be heated more rapidly than the interior region thus resulting in a temperature gradient over the bridge cross section.

It can be recognized that surface temperatures increase as the intensity of the solar radiation absorbed by the surface increases. The amount of solar radiation actually received by the surface depends on its orientation with respect to the sun's rays. So the intensity becomes maximum when the surface is perpendicular to the rays and is almost zero when the surface is parallel to the ray. Therefore, the solar radiation intensity received by a horizontal surface fluctuates from zero just before sunrise to maximum at about noon and decreases to zero right after sunset. It is found, however, that the maximum surface temperature generally takes place around 2 p.m. [1]. This lag of surface temperature is because of the daily air temperature variation which normally reaches its maximum value at 4 p.m. The coefficient of solar radiation absorption of a concrete surface depends on it's colour and has a normal value from 0.5 to 0.8. This value for asphalt surface is about 0.85 to 0.98.

Based on the results of measurement and calibration Thaksin Thepchatri and the co. authors [1] have proposed a model to predict the change of daily solar radiation intensity on horizontal surfaces under sinusoidal with the following equation

$$I(t) = \frac{1,7S}{T}\left(\frac{\sin^2\alpha + 2\sin\alpha}{3}\right) \quad (1)$$

Where, $I(t)$ is radiation intensity at time *t*; S total radiation in a day $\left(W/m^2\right)$; T total time of radiation (hour) and $\alpha = \pi t/T$.

According to Trinh Quang Dung in [2], the summer daily total radiation in the region of the investigated bridge is about 6 kW/m^2 and the total time of radiation is 10 hour, from 7 a.m. to 5 p.m.

3.2. Thermal emission

Bridge girder receives heat from solar radiation and emits heat into the surrounding environment, especially at night, making it cool. This heat emission depends on the property of the surface materials, surface temperature and the temperature of the surrounding environment. The degree of heat emission has a value of 0.85 to 0.95 regardless of the color of the surface [4].

3.3. Thermal convection

Convection is basically the heat transfer from concrete girders into the ambient air or vice versa, depending on the object that has a higher temperature. The heat is transferred by convection depends on the temperature difference between the bridge surface and the air, as well as wind speed. Thermal convection can be described with equation

$$Q_c = h_c\left(T_s - T_a\right) \quad (2)$$

Where, Q_c is the heat loss of girder by convection, T_s is the surface temperature, T_a is the temperature of ambient air environment and h_c is convection coefficient. Value of h_c depends on wind speed. Based on [5], convection coefficient h_c for bridge top surface can be determined by the equation

$$h_c = 13.5 + 3.88v \qquad \left(W/m^2 \circ C\right) \tag{3}$$

Where v is wind speed (m/s). For the bottom exposed surface a value of 0.45 of the top surface heat transfer was used. For inside surfaces of flanges and partially protected lower surfaces, a value of 0.2 of top surface heat transfer was used.

3.4. Heat transfer

The heat is transmitted in the concrete by the thermal conductivity and the process is described by the function for thermal conductivity of the material as follows

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{4}$$

Where, T is temperature of the material at time t and at the position of coordinates x, y, z; k is the coefficient of thermal conductivity; ρ is the density and c the specific heat of concrete.

IV. FINITE ELEMENT MODEL FOR COUPLED THERMAL STRESS ANALYSIS

The coupled thermal stress analysis for the bridge girder is performed by midas FEA - one of the few current software has this feature [3]. The girder is modeled by the solid elements (figure 2) with the material properties of structural concrete and asphalt determined according to the design documents and results of field measurements as listed in table 1.

Table 1. *Material properties for coupled thermal stress analysis*

	Concrete	Asphalt
Self-weight (kN/m^3)	24.5	21
Specific heat (J/(kg °C))	900 [6]	920 [6]
Coefficient of solar radiation absorption	0.5	0.9
Compressive strength (MPa)	45	
Tension strength (MPa)	2.2	

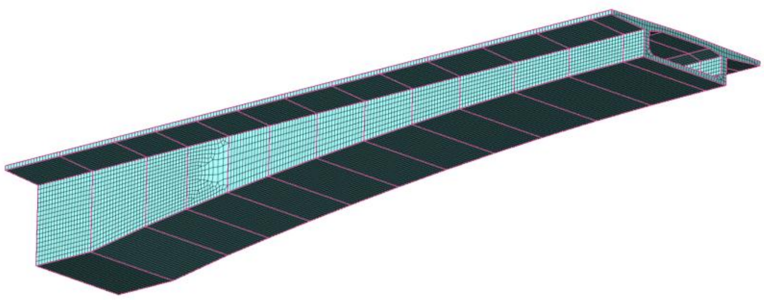

Figure 2*. Finite element model for the bridge girder*

Solar radiation on the surface of the bridge is described by equation (1) as shown in Figure 3. The daily temperature of the ambient air in June, based on recorded data from a weather station in the region, is shown in figure 4. In the finite element model on midas FEA, solar radiation is described in the form of load "flux" on the upper surface of the asphalt layer. The heat exchange between the girder concrete and ambient air is modeled as heat convection and emission functions as well as ambient temperature as outlined above.

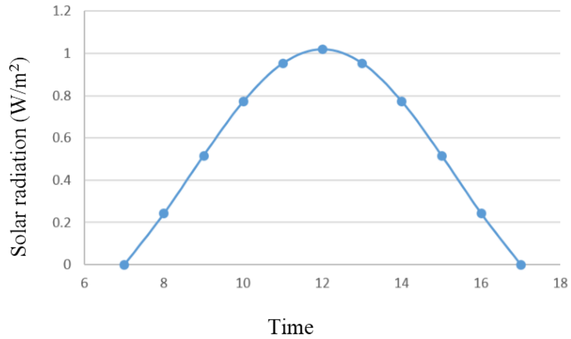

Figure 3. *Daily change of solar radiation on the bridge surface*

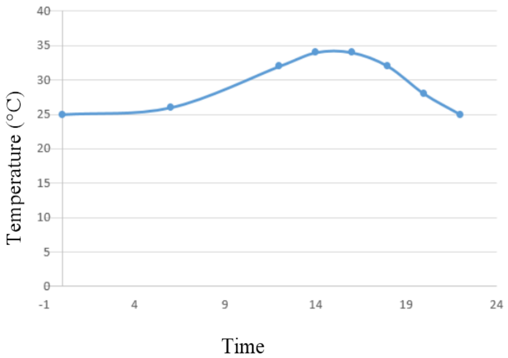

Figure 4. *Daily change of ambient air temperature*

V. ANALYSIS RESULTS

5.1. Distribution of temperature

The analytical results provide the distribution of temperature and thermal stress at regions in the structure. Figure 5 displays the change of temperature over day time of the bridge top surface. At around 2 p.m. the bridge surface reaches the highest temperature, nearly 53 °C. Also at that time, the temperature gradient is the largest under both vertical and horizontal directions (figure 6). The difference of temperature on top surface and the bottom surface of the top flange is about 28 °C (figure 7) and between the outer surface and inner o of the web is about 7 °C (figure 8). Thus, on the vertical direction, the thermal gradient calculated fairly agrees with one introduced in Vietnamese bridge design code 22 TCN 272-05.

5.2. Distribution of stress

The coupled thermal stress analytical results show that principal stress 1 has a considerable large value of ca. 1.5 MPa in the inside area near the top edge of the web and that the stress difference between the inner surface and the outer surface is relatively big (figure 9 and figure 10). In the investigated area, the direction of the principal stress 1 skewed ca. 52 degrees compared to the longitudinal axis of the beam. Meanwhile, from global the analysis taking into account of the dead and prestressing loads, principal stress 1 at this area has a value of ca. 1.0 MPa (figure 11) and skewed ca. 58 degrees above longitudinal axis of the beam. Because the directions of principal stresses 1 of the aforementioned causes are quite close together so their values can be added together. Thus the principal stress 1 caused by dead and prestressing load plus thermal gradient at the inner top edge of the web can reach a value of 2.5 MPa, greater than the tensile strength of the concrete. When combined with stresses from other actions such as shrinkage, live load, etc. the total stress can be big enough to cause inclined cracks developed in the inner surface of the girder web.

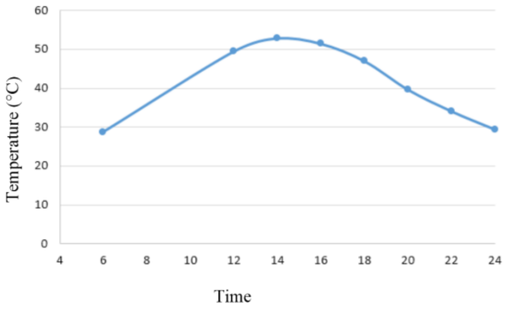

Figure 5. *Daily distribution of temperature on the top surface*

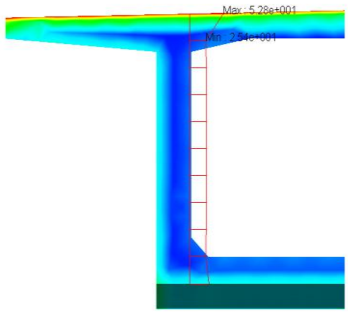

Figure 6. *Thermal gradient at 2 p.m*

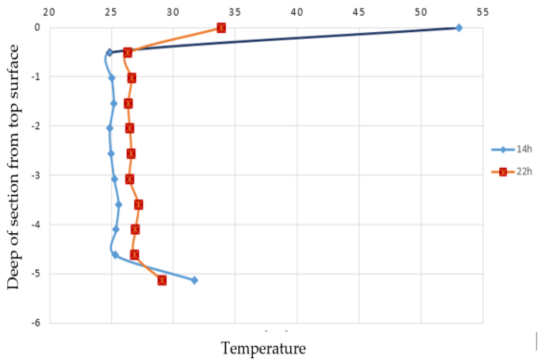

Figure 7. *Thermal gradient on the height of web (vertical direction)*

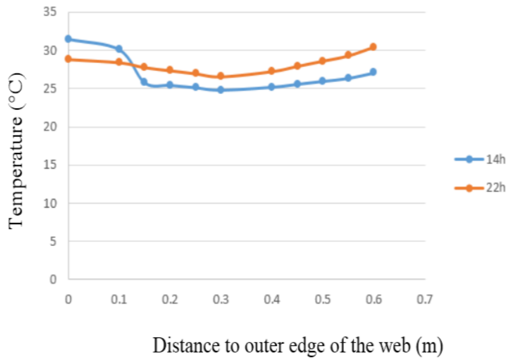

Figure 8. *Thermal gradient on the width of web (horizontal direction)*

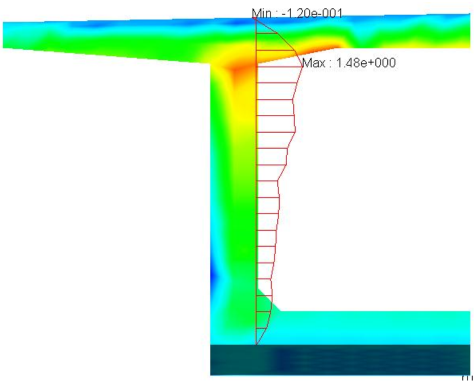

Figure 9. *Distribution of thermal principal stress 1 in in the height of web (vertical direction)*

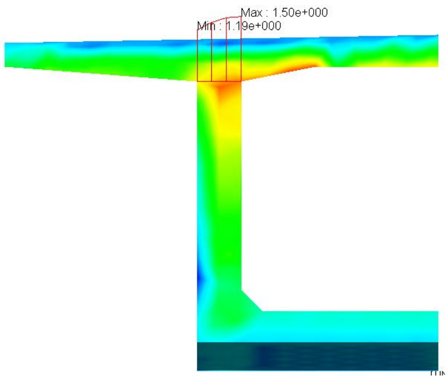

Figure 10. *Distribution of thermal principal stress 1 in in the width of web (horizontal direction)*

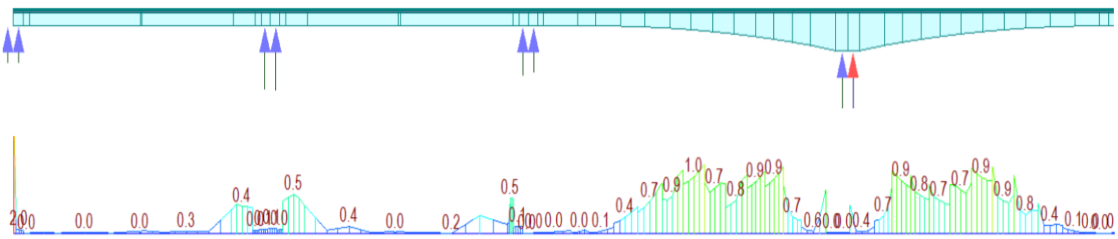

Figure 11. *Distribution of principal stress 1 caused by dead load and prestress on the beam length*

VI. CONCLUSION

Due to solar radiation and the temperature difference between the inside and the outside, a multi-directional large thermal gradient can develop in concrete bridge box girders. These can cause a large local tensile stress in some areas of structure. However, in design practice, the thermal gradient is typically considered in the global analysis to get internal forces. Detailed analysis accounting for local temperature distribution is rarely taken into account. In many bridge box girders there are many cracks found, which cannot be predicted by global analysis.

A coupled thermal stress analysis can provide the detail distribution of temperature and stress in different areas of structure. The results of such analysis on a specific bridge shows that the local thermal stress can be one of the main co-causes of cracks in concrete.

For the concrete bridge box girders in regions of intensive solar radiation and large daily temperature change, it is necessary to perform a coupled thermal stress analysis for predicting the stress distribution to develop appropriate structural solutions and reinforcement layout.

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