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Numerical simulation of temperature induced structural static responses for long-span suspension bridge

Lan Chen[a] , Jingliang Deng[a], Linren Zhou[a,*], Yong Xia[b]

[a]*School of Civil Engineering and Transportation, South China University of Technology, Guangzhou510640, China*
[b]*Department of Civil and Environmental Engineering,The Hong Kong Polytechnic University, Hong Kong, China*

Abstract

Temperature effect is one of the most significant and negative effects on bridges, even worse for long-span bridges. In this study, numerical simulation method of temperature induced structural static responses for long-span suspension bridge is investigated. The finite element (FE) models for transient thermal and structural analysis of a long-span suspension are developed, respectively. The thermal boundary conditions are calculated and applied on the thermal FE models for thermal analysis to obtain the variations and distributions of structural temperatures. Then, structural temperatures are loaded on the structural FE models for structural analysis to obtain the structural static responses such as vertical displacements, inclinations and strains. The results are compared with the field measurements to verify the validity and efficiency of this method. The method can provide a feasible and efficient way for analysis and assessment of the temperature effects on long-span suspension bridges.

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Keywords: Long-span suspension bridges; temperature effects; structural static responses; finite element

* Corresponding author.
E-mail address: zhoulinren@scut.edu.cn

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1. Introduction

Bridges are key components in the national traffic systems. However, harsh service environment degenerates the performance of bridges even leads to catastrophic collapse. Temperature is one of the most negative effects on bridge. Bridges are exposed directly to the natural environment. The energy exchange between bridges and the surrounding environment by way of heat convection and heat radiation changes the temperatures of bridge and subsequently affects the structural responses. The structural responses of bridges, such as static and dynamical properties, are significantly affected by temperatures and their distributions[1-3].

The analysis of bridge temperature effects includes mainly two parts: structural temperature and induced structural responses. An accurate calculation of structural temperature is needed in the evaluation of temperature-induced structural responses on bridges. Zuk[4] was the first to study the temperature effects on bridges. Though the field data of several highway bridges, he identified the combined action of environmental conditions (e.g., solar radiation, air temperature, wind, humidity). Emanual and Hulsey[5] used the finite element (FE) models to calculate bridge temperatures as a function of time. Churchward and Yehuda[6] recorded the temperature of a poststressed twin-box concrete bridge at different instants of time and predicted the temperature profiles reasonably. Moorty and Roeder[7] succeeded in calculating the movements of a bridge affected by the temperature. Xu et al. [8] used the field monitoring data of Tsing Ma Bridge in 2005 to explore the temperature-displacement relationship of the bridge. Currently, investigations of temperature induced structural responses of bridges mostly base on the field measurements, which need to install a complete monitoring system on the bridge. It is laborious and expensive. What’s more, it is not effective for long-term and real-time analysis of thermal analysis and assessments for bridges.

In this study, the numerical simulation method of temperature induced structural static responses for long-span suspension bridge is investigated. Firstly, the finite element (FE) models for transient thermal analysis and structural analysis of a long-span suspension are developed respectively. Secondly, the thermal boundary conditions are calculated and applied on the thermal FE models for thermal analysis to obtain the structural temperatures. Then, the structural temperatures are loaded on the structural FE models for structural analysis and the structural responses of bridge calculated. Finally, the results are compared with the field measurements to verify the validity and efficiency of this method. The proposed approach can provide a feasible and high effective method for analysis and assessment of the temperature effects on long-span suspension bridges.

2. Relation of temperature and physical properties

A long-span bridge is a complex flexible structural system. The changes of temperature and temperature variation significantly affect the structural behavior of bridges. The temperature-varying parameters of building materials mainly includes Young's modulus and coefficient of thermal expansion. After exploring the effect of temperature variation on physical property of materials, Yu et al. [9] summarized the relation of temperature and some physical properties.

(a) Coefficient of thermal expansion of steel

$$\alpha_s = (0.004T + 12)\times 10^{-6}[\text{m/(m℃)}] \quad T \le 350℃ \tag{1}$$

(b) Coefficient of thermal expansion of concrete

$$\alpha_s = (0.008T + 6)\times 10^{-6}[\text{m/(m℃)}] \tag{2}$$

(c) Young's modulus of steel

$$E = E_0[1 - \frac{13(T-20)}{33000}] \qquad T \le 350℃ \tag{3}$$

where E_0 is the Young's modulus at 20 ℃.

It is widely recognized that Young's modulus of concrete subject to temperature is a complex issue. However, Young's modulus of concrete has little change in the range of natural environment temperature. It is assumed to be constant in this study.

3. The long-span suspension bridge and SHM system

The suspension bridge, studied in this paper, is located at the mid-eastern of England. The main bridge is total length 2220 m with an asymmetry layout 280 m (north) + 1410 m +530 m (south), as shown in Fig. 1. The bridge deck (steel box-girder) was designed to be a streamlined hollow box with inclined upper webs. The height is 4.8 m and width is 18 m. The North tower of the bridge is located at the shore and the South tower is located in the river 500 m from the shore line. Tower height above piers is 155.5 m. Each tower has two columns connected by four cross beams along the vertical height[10].

Fig. 1. The long-span suspension bridge

A Structural Health Monitoring (SHM) system has been installed on the bridge. The sensor system can be generally divided into three parts according to the sensing characteristics: 1) Sensors for meteorological parameters, such as anemometer and air temperature sensors; 2) Sensors for structural temperatures; 3) Sensors for structural responses, such as accelerometer, GPS, extensometer and inclinometer. The monitoring of temperature and induced structural responses is one of the most important functions of the SHM system on this bridge. Besides the air temperature sensors of weather station, six temperature sensors are specially installed on the box-girder section at mid-span to analyze the temperature distribution and difference of the box-girder bridges.

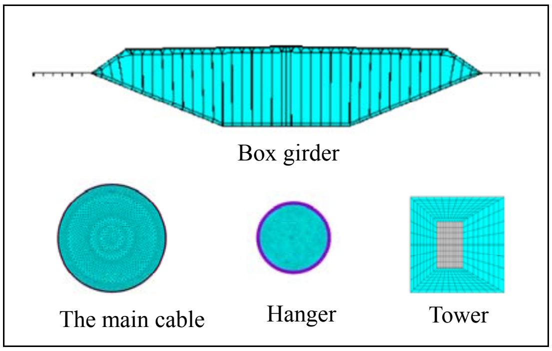

Fig. 2. FE Models for thermal analysis

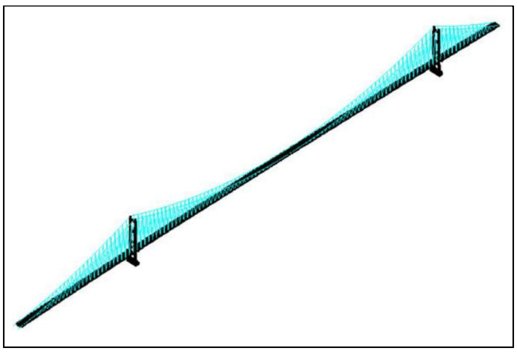

Fig. 3. FE Models for structural analysis

4. The FE model of the long-span suspension bridge

The FE models of the long-span suspension bridge are established using ANSYS software package. The FE models for thermal analysis are shown in Fig. 2. The 2-D models of the components of suspension bridge are established with PLANE55 elements. The FE model for structural analysis is developed using 3-D model technology, as shown in Fig. 3. The box girders, towers, cables and hangers are modeled with SHELL181, SOLID65 and LINK181 elements respectively. This long-span suspension bridge was completed on December, 1980. The local average temperature was about 4°C at that time. Therefore, the initial temperature of the FE models is set to be 4°C for thermal and structural analysis.

5. The measurements of temperature induced structural responses

The field measurements of bridge structural responses are the total responses of the bridge subject to all the external loads such temperatures, wind, traffic loads and vibrational excitation. Comparing with other actions, the temperature effects has obvious daily-cycle property. Therefore, the moving average method is utilized to extract the temperature induced structural responses from the field measurements.

In this study, the structural static measurements of GPS, inclination and extensometer of the bridge are concerned. The measurements of two sunny days, February 12 and July 24 2012, are selected for investigation. The original and extracted vertical displacements at mid-span of bridge are shown in Fig. 4. They are almost the same. It indicates the temperature induced displacements are the dominating components. The wind and vehicle loads slightly affect the vertical displacements. However, the lateral inclinations of bridge deck are more susceptive to the wind actions and traffic loads. The processed data using moving average method is more stable change than the original data, as shown in Fig. 5. The averaged inclinations can well present the results induced by temperatures.

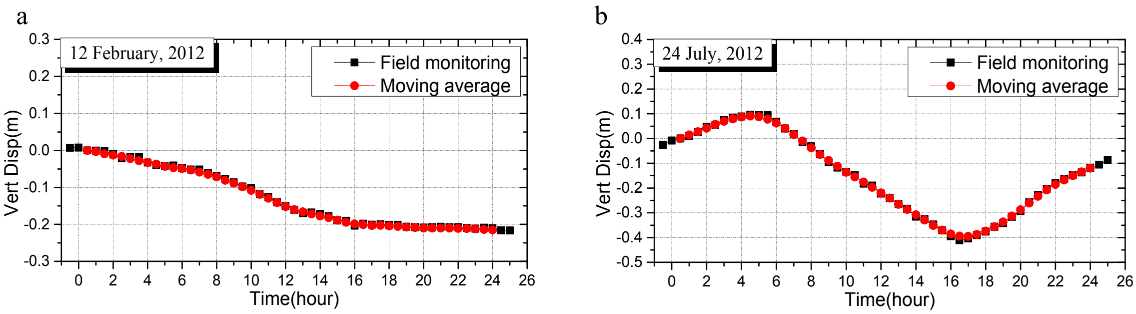

Fig. 4. Vertical displacements of the box girder at the mid span: (a) 12 February, 2012; (b) 24 July, 2012

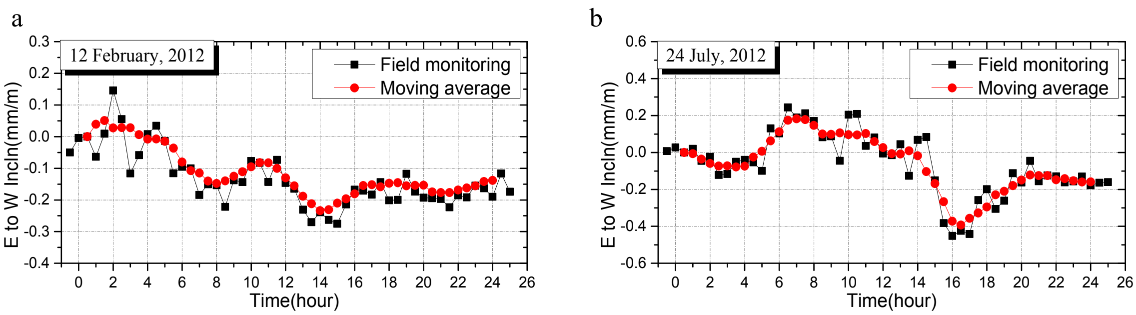

Fig. 5. lateral inclinations of the box girder at the mid span: (a) 12 February, 2012; (b) 24 July, 2012

6. Numerical simulation of temperature induced structural static responses

The 2-D FE models for thermal analysis and the 3-D FE model for structural analysis are established respectively. The thermal boundary conditions are applied to the 2-D models to obtain the variations and distributions of structural temperatures. Then, the structural temperatures are loaded on the 3-D model for structural analysis to obtain the structural static responses such as vertical displacements, inclinations and strains.

6.1. Temperature of the bridge

Based on the measured meteorological data from internet website, the thermal boundary conditions are calculated and applied on the 2-D FE models for the transient heat transfer analysis. The initial temperature for the first step calculation is set to be the air temperature. For the following calculation, the initial temperature is obtained from the final results of the pre-step. The calculated temperatures on the ground of the box girder are displayed as instance, as shown in Fig 6. The simulated temperatures demonstrate very good agreement with the measured results, which verify the validity and efficiency of this method.

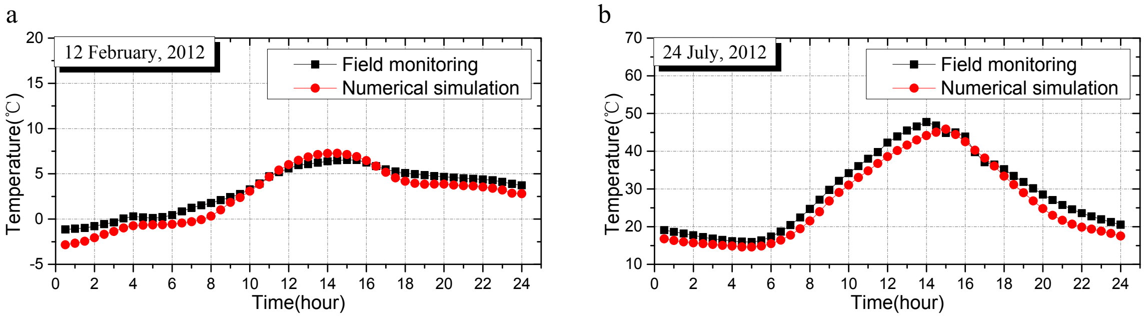

Fig. 6. Comparison of calculated and measured temperature on the ground of the box girder: (a) 12 February, 2012; (b) 24 July, 2012

6.2. Structural static responses of the bridge

The temperatures calculated using thermal analysis of FE models are applied to the structural analysis FE model of the bridge. The FE model is solved with time step of half an hour according to the temperature results. The structural responses of vertical displacements and lateral inclinations at the mid-span, and the stain of Hessle Tower are discussed.

(1) Vertical displacements

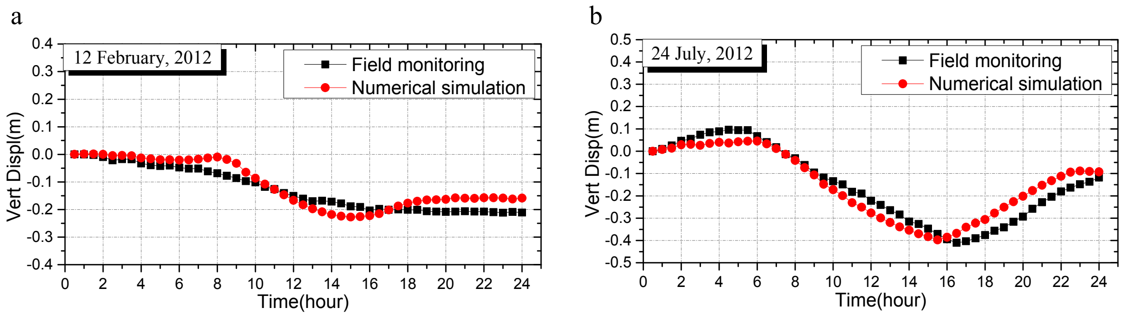

Fig. 7. Vertical displacements of field monitoring and numerical simulation at the mid span: (a) 12 February, 2012; (b) 24 July, 2012

The variations of vertical displacements at the mid span are shown in Fig. 7. It is found that the simulated results have good agreements with those of field measurements. In Fig. 7(a), the vertical displacement decreases approximately all the day because the temperature has continued to drop. In Fig. 7(b), both of them reach to maximum around 05:00, and drop to minimum at about 16:00. The vertical displacements show reverse tendency with the structural temperatures. As the temperature rises, the components of the bridge will expand, especially for the cables and the hangers, which contribute much to the change of vertical displacement.

(2) Lateral inclination

The variation of lateral (east to west) inclinations at the mid span is shown in Fig. 8. Compared with vertical displacements, the agreements between them are not good. The lateral inclinations of bridge box girder are more sensitive to the wind and traffic loads than to structural temperatures. The numerical simulation in this study does not take them into account. Although there is difference between the simulation results and the measurements, the variation tendencies of simulation results are consistent with the field measurements.

Observing Fig. 8(b), it is found that the inclinations vary with the changing of solar radiation on the bridge deck. The inclination appears positive value after the sunrise in the morning. It indicates that the altitude at the east side is higher than that of the west side. Similarly, in the afternoon to sunset, the inclination is negative value meaning the altitude at the west side is higher than that of the east side. However, Figure 8(a) does reveal the above phenomenon that because the day of February 12 was cloudy all the day.

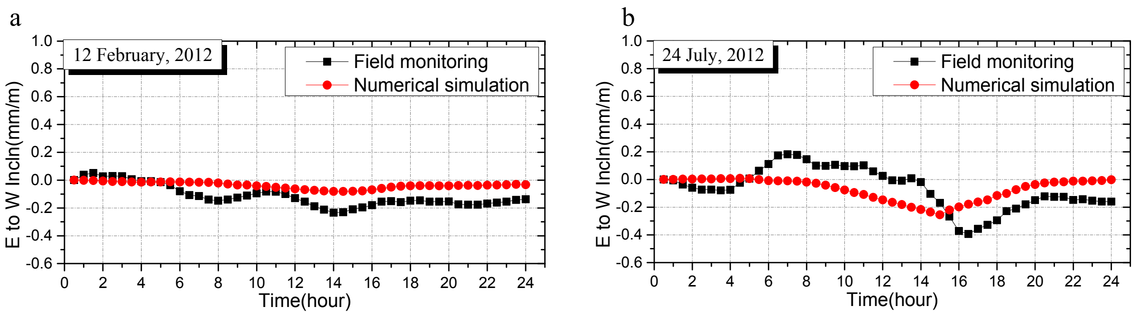

Fig. 8. Calculated and measured lateral inclinations at the mid span: (a) 12 February, 2012; (b) 24 July, 2012

(3) Strain of Heslle Tower

The SHM system of Humber Bridge has been extended with strain measurement after the year of 2012. The strain of Heslle Tower is measured using extensometer. The results of a sunny day (15 January, 2013) is discussed. The calculated results and field measurements are shown in Fig. 9. The calculated and measured results are very close. The variation of the strain reveals obvious daily-cycle property; however, the amount of change is not larger. Comparing with other components of this suspension bridge, the concrete tower has bigger thermal inertia and small surface-to-volume ratio; therefore, the temperature effects care relative small.

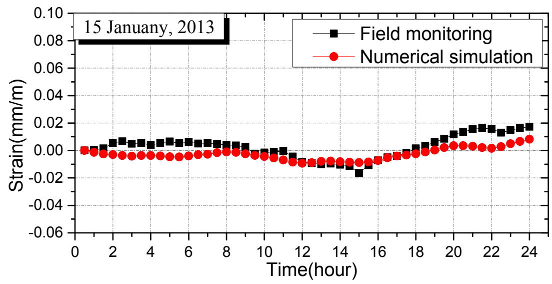

Fig. 9. Calculated and measured strain of Hessle Tower

7. Conclusion

In this paper, numerical simulation method of temperature induced structural responses for long-span suspension bridge is investigated. FE models for thermal and structural analysis are constructed respectively. The bridge temperatures and temperature induced structural static responses are simulated and discussed, such as such as vertical displacements, inclinations and strains. The numerical results are compared with the field measurements for method validation.

The numerical results of the bridge temperatures and structural responses show good agreements with the field measurements. The variation of vertical displacements at mid-span of the bridges reveals obvious daily-cycle property according the changing of structural temperature. The vertical displacements show reverse tendency with the structural temperatures. The lateral inclinations can reasonably clarify the effects of solar radiation on bridge. However, the daily-cycle property of lateral inclinations is not considerable as much as the vertical displacements since the box girder is more sensitive to the lateral wind actions and asymmetrical traffic loads than to structural temperatures. The structural temperature variation and distribution have remarkable effects on the structural static responses of long-span suspension bridge, especially the vertical displacement at the mid span. Therefore, the temperature effects should be particularly calculated and evaluated for the bridge design, construction and operation.

Acknowledgments

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References

[1] Priestley, M. J. N., Design temperature gradients for concrete bridges, New Zealand Engineering. 31 (1976) 213-219.
[2] Priestley, M. J. N., Design of concrete bridges for temperature gradients. ACI Journal Proceedings. 75 (1978) 209-217.
[3] Kennedy J., and Soliman, M., Temperature distributions in composite bridges. Journal of Structural Engineering. 113 (1987) 65-78.
[4] Zuk, W., Thermal behavior of composite bridges -insulated and uninsulated. Highway Research Record. 76 (1965) 231-253.
[5] Emanual, J. H., and Hulsey, J. L., Temperature distributions in composite bridges. Journal of Structural Engineering. 104 (1978) 65-78.
[6] Churchward, A., and Yehuda, J. S., Prediction of temperatures in concrete bridges. J. Struct. Div. 107(1981) 2163–2176.
[7] Moorty S, Roeder CW., Temperature-dependent bridge movements. Journal of Structural Engineering (ASCE). 118 (1992) 1090–1105.
[8] Y. L. Xu, B. Chen, C. L. Ng, K. Y. Wong, and W. Y. Chan., Monitoring temperature effect on a long suspension bridge. Struct. Control Health Monit. 17 (2010) 632–653
[9] M. Yu, X. X. Zha, J. Q. Ye, and Y. Li., Fireresponse and resistance ofconcrete-filled steel tubular frame structures. International Journal of Structural Stability and Dynamics. Vol. 10, No. 2 (2010) 253-271
[10] Brownjohn, J. M. W., Dumanoglu, A. A., Severn, R. T., and Taylor, C. A., Ambient vibration measurements of the Humber Suspension Bridge and comparison with calculated characteristics. Proc. Inst. Civ.Eng. 83 (1987) 561–600.