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Procedia Engineering 210 (2017) 240–245

Procedia Engineering

www.elsevier.com/locate/procedia

6th International Workshop on Performance, Protection & Strengthening of Structures under Extreme Loading, PROTECT2017, 11-12 December 2017, Guangzhou (Canton), China

Numerical simulation method of thermal analysis for bridges without using field measurements

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Abstract

Structural temperatures have significantly negative effects on the performances of bridges. In this study, a numerical method of thermal analysis for bridges without using field measurements is proposed and investigated based on a long-span suspension bridge under weather conditions of a sunny day. Firstly, basic theory and methods of bridge thermal analysis are discussed. Secondly, the long-span suspension bridge and the structural health monitoring system are briefly introduced. Then, the finite element model of a typical section of the box girder of the long-span suspension bridge is constructed for transient thermal analysis to calculate the temperature variation and distributions. The thermal boundary conditions are calculated using the meteorological information from the nearby airport rather than the field measurements for thermal analysis. At last, the thermal boundary conditions are applied on the FF model to obtain the structural temperatures using transient thermal analysis. Besides, the conventional method using the bridge field meteorological measurements is also carried out for comparison. All the simulated results of structural temperatures are compared with the field measurements. All of them have good agreements. It is demonstrated that the proposed method is reliable and effective.

Peer-review under responsibility of the scientific committee of the 6th International Workshop on Performance, Protection & Strengthening of Structures under Extreme Loading.

Keywords: Bridges; temperature behavior; numerical simulation; transient thermal analysis

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10.1016/j.proeng.2017.11.072

1. Introduction

Bridges play a very important role in the transportation system. However, the long-term overload operation and harsh service environment result in damages even accidents on bridges. Temperature has been widely recognized as one of the most significant and negative environmental effects on bridges. The environmental thermal effects may have a more significant impact on structural behavior than the external operational loads[1-3].

Considerable efforts have been devoted to investigating temperature distribution and thermal effects on bridges based on field monitoring, laboratory test and numerical simulation. Zuk[4] discussed the effects of solar radiation, air temperature, wind, humidity, and material types on temperature distribution by investigating several highway bridges. Emanual[5] performed a finite element analysis used to calculate bridge temperatures as a function of time and investigated the temperature variations of a composite-girder highway bridge. Priestley[1-2] identified the vertical temperature gradients of prestressed and reinforced concrete bridges and compared the analytical results with those from laboratory and field experiment. Kennedy[3] explored the temperature distribution in composite bridges and proposed the linear temperature distribution through the depth of the slab and uniform distribution through the depth of the steel beam by synthesizing several theoretical and experimental studies on prototype bridges. Churchward[6] conducted a long-term field measurement on a post stressed twin-box concrete bridge. An analytical expression of the vertical temperature profile as a function of the maximum differential temperature and environmental parameter insolation was presented.

With the rapid developments in computer techniques, the structural temperature distribution and thermal effects have been widely investigated using finite element method [2]. The one-dimensional approaches were firstly studied. Emerson[7] established a finite difference model based on the assumption that the flow of heat through the bridge was linear. Kehlbeck[8] found a theoretical solution to temperature distribution of bridge. Hunt and Cooked[9] calculated temperature distribution of bridge by the way of the one dimensional unsteady heat conduction. Elbadry[10] presented a two-dimensional FE method to determine the time-dependent temperature variation of a concrete box-girder bridge. Xia et al[11] investigated the temperature distribution and associated responses of a long-span suspension bridge through field monitoring and numerical analysis. Zhou et al[12] conducted such a study on a long-span suspension bridge and explored the transversal temperature difference.

The finite element method can provides a higher efficiency and lower cost way for thermal analysis of bridges. The thermal boundaries are calculated based on lots of field meteorological measurements such as solar radiation, air temperature, humidity, wind speed and direction. Hence, a weather station should be established on the field of bridges. It is costly and lower efficiency. In this study, a numerical method of thermal analysis for bridges without using field measurements is proposed and discussed.

2. Basic theory for thermal analysis

The heat transfer processes of a bridge consist of heat conduction, heat convection, and thermal radiation[8,12]. Heat conduction exists in the interior of the box girder and is governed by the Fourier heat-transfer equation. Heat convection is a kind of energy exchange between solid surface and surrounding fluid. Thermal radiation is a kind of energy transfer caused by the emitting and absorbing radiation of the structural surface.

2.1. Solar radiation effects

Several types of radiations are given off or absorbed by a surface of bridge, such as direct solar radiation, atmospheric radiation, diffuse radiation, reflected radiation, environmental radiation and structural irradiation [13]. The solar radiation is affected by several factors such as dates, the latitude and the altitude of the bridge, atmospheric turbidity and the cloudiness of the sky [8]. The calculation method of each type of radiation can refer to relevant literatures [8, 10, 14].

2.2. Heat-transfer analysis

The temperature at certain point of bridge structure can be stated as: $T = T(x, y, z, t)$ .The bridge temperature field of a cross section at time t can be expressed by three-dimensional transient heat conduction differential equation in the Cartesian coordinates:

$$\rho c\frac{\partial T}{\partial t} = \lambda(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) + \theta \quad (1)$$

where ρ is the density; c is the specific heat capacity; λ is the thermal conductivity (W/m·k); θ is the time rate of heat generated per unit volume; t is the time.

The solution of heat transfer differential equation must satisfy the initial and boundary conditions in order to obtain the temperature of a point at any time. A pre-analysis of one or several consecutive days are can reduce the negative effect of the unknown initial condition. In the pre-analysis, the initial temperatures of the bridge can take the air temperature. In this study, the thermal analysis of two consecutive days is performed, and the results of the last day are used for investigation.

Thermal boundary conditions for thermal analysis control the heat exchange between bridge and the surrounding air. The heat flux on the boundary is expressed as

$$\lambda\frac{\partial T}{\partial n} = h(T_a - T_v) + q \quad (2)$$

where n is normal to the surface, h is convection coefficient, T_a is the air temperature, T_v is the structural surface temperature, and q is the boundary heat flux .

For a bridge surface, the heat flux q consists of emitting radiation (structural irradiation G_V) and solar irradiation I.

$$q = I - G_v \quad (3)$$

The emitting radiation is estimated by

$$G_v = C_s \times \varepsilon_v \times T_v^4 \quad (4)$$

where C_s is the Stefan–Boltzmann constant and ε_v is the emissivity coefficient of structure surface.

Finally, the absorbed radiation is calculated as

$$I = \alpha I_0 \quad (5)$$

where α ($0 < \alpha < 1$) is absorptivity coefficient of the surface material and I_0 is amount of the solar radiation absorbed by a surface.

3. The long-span suspension bridge and SHM system

The long-span suspension bridge for this study is a total length of 2,220 m with a main span of 1410m, as shown in Fig. 1. The lengths of the north side span and south side span are 280m and 530m, respectively. The bridge girder was assembled from 124 box segments, each typically 18.1 m long, 22 m wide, and 4.5 m high, with four stiffened bulkheads. Furthermore, cantilevered footpaths and cycle tracks increased the total width to 28m. The upper roadway surface of the box is an 18.2m wide orthotropic steel deck that was originally covered with 41-mm-thick asphalt [15].

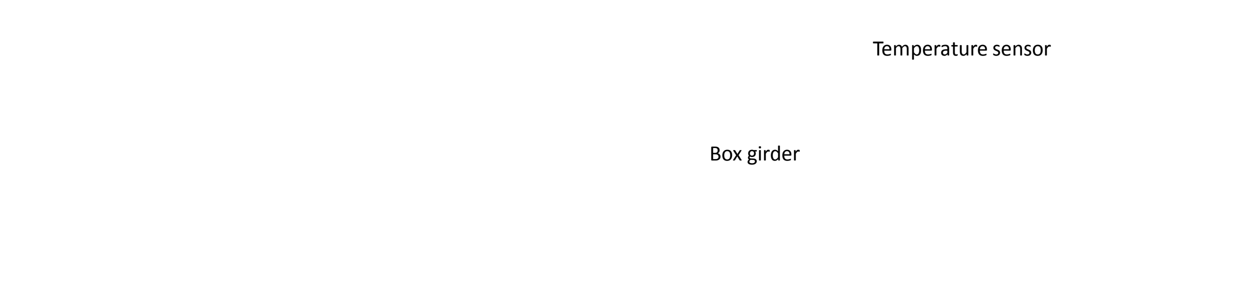

Fig. 1. The long-span suspension bridge

A Structural Health Monitoring (SHM) system has been installed on the bridge. Several meteorological sensors have been placed around the bridge to record the meteorological parameters such as wind and air temperature. An on-site weather station has been implemented at the mid-span of bridge. Meteorological sensors include anemometer and air temperature sensors. Meanwhile, meteorological measurements from a weather station of a nearby airport are available and integrated into the data base of SHM system. The temperature monitoring is one of the most important functions of the SHM system on this bridge. Besides the air temperature sensors of the weather station, six temperature sensors, as shown in Fig. 1, are specially installed on the bog-girder section at the mid-span to analyze the temperature distribution and difference of the box girder.

4. Simulation study

4.1. The FE model for thermal analysis

The temperature along the longitudinal direction of bridge is usually assumed as constant. Therefore, a box girder section is used to analyze the temperature distribution and thermal actions of the bridge. The FE model of box girder section, which consists of 38,620 elements, is established using ANSYS as shown in Fig.2. The air filling inside the box is modeled using PLANE55 element in the FE model to reduce the uncertainties effects caused by the thermal boundary conditions. The interaction of thermal radiation of the inside surfaces is calculated by AUX12 Radiation Matrix method and the results are read and applied on the inside surface using super element MATRIX50.

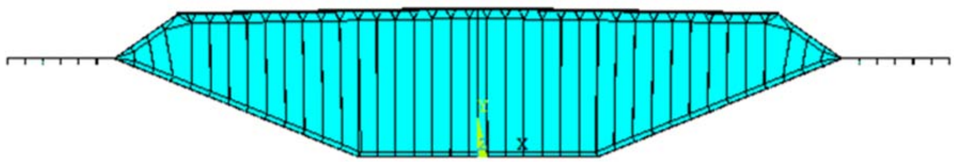

Fig. 2. FE model of the box-girder section for thermal analysis

4.2. The thermal boundary conditions

Traditionally, the thermal boundaries for bridge thermal analysis are calculated based on the field environmental measurements such as solar radiation, air temperature, humidity, wind speed and direction. All these meteorological parameters are monitored and collected through the structural health monitoring system (or a weather station) established on the field of bridges. It is costly and lower efficiency. In this study, a numerical method of thermal analysis for bridges without using field measurements is discussed. The environments for calculation of thermal boundary conditions are obtained from a nearby official weather station rather than field monitoring. This approach is feasible since a completed meteorological monitoring system has been established with density weather stations around the world especially in and around the cities. All the stations share the information on the Internet, including the unofficial weather stations such as those of airports.

For this study of the suspension bridge, a weather station at the nearby airport is available; it is about 15 kilometers away from the bridge. The meteorological data of air temperature, wind speed and direction from the airport weather station is utilized for the calculation of thermal boundary condition.

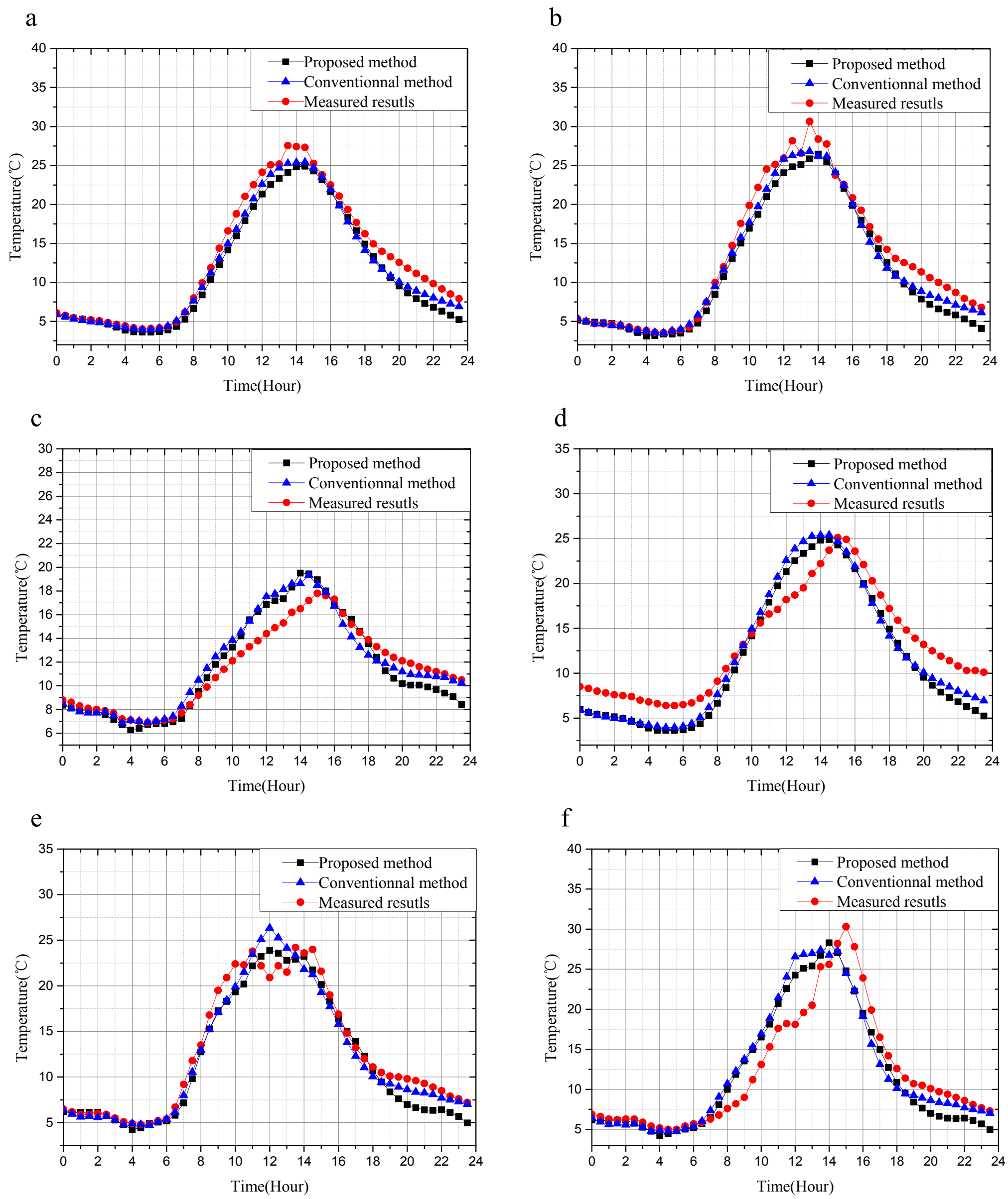

Fig. 3. Measured and simulated temperatures of the bridge deck for September 22, 2012: (a) interface between the cover and plate; (b) top of the asphalt cover; (c) bottom of the box girder; (d) top of the box girder; (e) east of the box girder; (f) west of the box girder

4.3. Temperature distributions of the box-girder section

Based on the measured meteorological data from internet website, the thermal boundary conditions are calculated and applied on the FE model for the transient heat transfer analysis. The initial temperature of the box girder is obtained from the final results of a pre-analysis of the previous day. Besides, the conventional method using the bridge field measurements for thermal analysis also carries out for comparison.

The temperatures of the box girder on a sunny day (September 22, 2012) are calculated using the proposed method and conventional method respectively. The results are compared with the field measurements, as shown in Fig. 3. The structural temperature slightly decreased and reached the minimum in the early morning. The temperature then increased to the maximum in the early afternoon and decreased in the evening and at midnight. The simulated temperatures using conventional method in Fig.3 (a, b, c. e and f) demonstrate a good fit with the monitored results. However, Fig 3 (d) shows the rise and fall of the monitored and simulated data are not a perfect match. The simulated temperatures are about 3.0 ^{O}C lower than the measurements during the early morning and night. However, the simulated temperatures are much higher than the measurements at noon. These errors are possibly attributed to the thermal properties of materials, the transient local cloud cover and wind speed.

The simulated temperatures using proposed method at the observed points have very good agreements with those obtained by conventional method with occasional anomalies. There are minor errors between the two method results during the time from 22:00 to 23:30 caused by the difference of air temperature and wind speed between the airport and the bridge field. It can be concluded the proposed method of bridge thermal analysis without using field measurements is feasible and effective.

5. Conclusion

In this study, the temperature distribution of a long-span suspension bridge is investigated. A new numerical method of thermal analysis for bridges without using field measurements is proposed. The FE models are constructed suing ANSYS software packages to calculate the temperature variation and distributions. The numerical results of proposed method are compared with those of conventional method and field measurements. They have good agreements in variation and extreme value. It is demonstrated the reliability and feasibility of the method for thermal analysis of bridge without using field environmental measurements.

The proposed method can provide a feasible way for offline analysis and assessment of the temperature effects on the bridges, especially the bridges without SHM system or weather station for field meteorological monitoring. The accuracy of this method mainly relies on the difference of meteorological data between the available weather station and the bridge field.

Acknowledgments

This research is supported by the Technology Planning Project of Guangdong Province (Project No. 2014A020218003), and the Fundamental Research Funds for the Central Universities (Grant No. 2017ZD020).

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