Three-Dimensional Thermal Modeling of Temperature Variation in Concrete Box-Girders Using COMSOL Multiphysics®

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Abstract: The COMSOL's heat transfer module was used in this study to evaluate the temperature distribution in concrete box-girders subjected to exterior thermal conditions. The included thermal loads were air temperature, wind speed in addition to solar radiation. Moreover, the reflected radiation from the ground and other surroundings in addition to the mutual radiation between the different surfaces of the girder and the re-radiation of the exterior surfaces to atmosphere were modeled. The model's output temperatures were compared with experimental measurements from a full-scale concrete girder segment, which was constructed for this purpose. The results showed good agreement between the experimental records and the COMSOL's finite element model. The average absolute error between the measured temperatures of more than 60 experimental thermocouples and the COMSOL's predicted temperatures at the same locations was in general less than 1.5℃.

Keywords: Concrete, box-girder bridge, solar radiation, air temperature

1. Introduction

The continuous exposure to solar radiation and change in air temperature can alters the structural behavior of concrete structures. The heat gain and loss due to the environmental thermal loads was reported to cause equivalent stresses to those of service loads [1]. Furthermore, many researchers [2-5] have reported effective cracks that can be attributed to thermal loads. Because of the aforementioned structural effects, the problem of the environmental heating and cooling of the different types of bridges was seriously dealt during the last 30 to 40 years. Now days, most of the bridge design specifications around the world include special provisions to overcome the possible thermal deformations and stresses that arise from temperature gradients occur due solar radiation and air temperature fluctuation.

The modeling of the effect of the environmental loads on the superstructures of concrete bridges using the finite element method is not an easy problem. Many challenges arise from the variety of the time-dependent thermal loads on the boundaries of the bridge girders. Moreover, the configuration of the bridge, hence the shading effect and the surface-to-surface radiation between the mutual vision exposed surfaces make the problem more difficult.

In the current study, a reinforced concrete box-girder bridge segment with full-scale dimensions was constructed to be used as a benchmark for the finite element modeling of the influence of solar radiation, air temperature and wind speed changes, in addition to the other thermal loads on the thermal behavior of concrete bridge girders. The bridge segment composes of a 7.25m top slab and a 4.75m bottom slab, which were connected by two vertical walls of 2.0m net height each. The thickness of the slabs was 0.2m, while the thickness of the walls was 0.25m. The concrete section at the four slab-wall joints was increased using a 0.15×0.15m hunches. Many thermocouples were installed on the surfaces and along the mid-thickness of the slabs and the walls and were classified into four groups; the top slab group (T), the bottom slab group (B), the south web group (S) and the north web group (N). In addition, a weather station was installed in the site to monitor the air temperature, the solar radiation and the wind speed continuously. All measurements from all thermocouples and all sensors were collected automatically each 30 minutes using a data acquisition system, which was programmed to collect and save data for a complete one year extended from May 2013 to May 2014.

The aim of this paper is to focus on the using of the heat transfer module of COMSOL to

simulate the concrete box-girder segment with all of the boundary thermal loads and to predict the time-dependent temperature distribution of temperature in concrete bridge girders.

2. The time-dependent heat transfer problem

The partial differential equation that governs the heat conduction in the concrete bridge segment is,

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + Q = \rho c \frac{\partial T}{\partial t} \tag{1}$$

Where k is the thermal conductivity of concrete in $W/(m \cdot K)$, T is the temperature in absolute units K, Q is the rate of heat generated within the concrete in W/m^3, ρ is the density of concrete in kg/m^3, C_p is the concrete specific heat in $J/(kg.K)$.

The thermal loads on the bridge surfaces are described in the following boundary conditions equation.

$$k\frac{\partial T}{\partial n}l + q = 0 \tag{2}$$

The term q is the sum of all heat fluxes normal to the bridge surfaces in W/m^2, while l is the direction cosine of an outward vector perpendicular to the boundary [6].

$$q = q_{con} + q_{sol} + q_{gr} + q_{ss} + q_{re} \tag{3}$$

q_{con} is the term describes the convection heat transfer between the external surfaces of the bridge and the surrounding air, where,

$$q_{con} = h_{con}(T_s - T_a) \tag{4}$$

Where h_{con} is the coefficient of convection in $W/(m^2 \cdot K)$, T_s is the temperature of the surface, and T_a is the temperature of the surrounding air. Empirical formulas to estimate the heat transfer coefficients for concrete box girders were recommended by Kehlbeck [7]. For external surfaces, Equation 5 is used, in which C is a constant equals to 4.67 for top surface, 3.17 for vertical surfaces and 2.67 for bottom surfaces. On all the bridge surfaces, the convection is mixed of free and forced convections, except on the interior surfaces of the inside cavity of the box girder. Because the zero speed of air inside the box girder sets the forced convection term to zero,

only free convection is considered there as shown in Equation 6,.

$$h_{con} = 3.83\vartheta + C \tag{5}$$

$$h_{con} = 3.5 \tag{6}$$

q_{sol} is the solar radiation heat flux received by the exterior surfaces of the bridge, which is given by,

$$q_{sol} = \alpha I_{sol} \tag{7}$$

Where α is the absorption coefficient of the concrete surfaces, and I_{sol} is the total solar radiation on a horizontal surface. COMSOL [8] introduces a built in solar radiation model to calculate the time-dependent solar radiation. This model depends on a method used by the National Oceanic & Atmospheric Administration (NOAA) [8]. By defining the latitude, the longitude, time zone and date and time, COMSOL automatically computes the sun angles and determine the direction of sun rays at each time step. COMSOL correlates the Cartesian coordinates x, y and z with the zenith angle θ_z and the azimuth angles θ_a of the sun using the directional vectors i_x, i_y and i_z shown in Eq. (8) to Eq. (10). In the solar model of COMSOL, x, y and z represent the North, the West and the up directions respectively.

$$i_x = -cos\theta_a sin\theta_z \tag{8}$$

$$i_y = sin\theta_a sin\theta_z \tag{9}$$

$$i_z = -cos\theta_z \tag{10}$$

q_{gr} is the solar radiation reflected from the ground and other surroundings, which is given by,

$$q_{gr} = \alpha I_{gr} \tag{11}$$

$$I_{gr} = \beta I_{sol} \frac{1 - cos\theta}{2} \tag{12}$$

Where I_{gr} is the radiation fluxes reflected from the ground and other surroundings, β is the reflection coefficient of the ground, and θ represents the tilt angle of the exposed surfaces with the horizontal plane.

q_{ss} is the surface-to-surface irradiation heat flux, which received from other surfaces due to the mutual radiation between the exterior surfaces of the bridge. Surface-to-surface radiation is the most complicated part of

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problem, which makes it too long for the solution to converge. This difficulty of the surface-to-surface radiation arises from the amount of calculation required to estimate the view factors of all points on all external surfaces with respect to all other surface points on any visible boundary. To reduce the solution time, radiation groups feature was activated. Using this feature, the mutual radiations between the external face of each web and its opposite lower surface of the cantilever portion of the top flange were considered. Including the surface-to-surface radiation to the heat transfer analysis, the simulation becomes more accurate and more representative.

$$q_{re} = \epsilon\sigma(T_s^4 - T_a^4) \qquad (13)$$

q_{re} is the term describes the net of the surface radiosity and the ambient irradiation, ϵ is the surface emissivity, and σ is the Stefan-Boltzman constant, which equals $5.67\times 10^{-8}\,W/(m^2 \cdot K^4)$. This term calculates the amount of the heat emitted from the bridge surfaces to the surrounding atmosphere by log-wave radiation. The basic heat transfer equation (Eq. (1)) is linear, however, the nonlinearity of the boundary load q_{re} makes the whole problem nonlinear [9].

3. The COMSOL finite element model

The COMSOL's heat transfer module with surface-to-surface radiation interface was used in this study to solve Equation (1) and to simulate the surface thermal loads described in Equation (2), simultaneously.
CMOSOL offers two methods to calculate the view factors and solve the irradiation of the bridge surfaces; the Hemi-cube method and the Direct Integration method. The Hemi-cube is the more sophisticated one, which considers the effect of shadowing, and hence it is an accurate method but more time consumer. This method evaluates the view factor of each element face in the mesh by rendering digital images of the geometry in five different directions [8]. The solution time can be reduced by reducing the image resolution, i.e. the pixels. Where, the solution time of the surface irradiation changes quadratically with the resolution of the virtual snapshots [8]. On the other hand, Direct Integration is the simple method, in which the obstruction of elements faces by other elements is not considered, which means that the shadowing effect is not

taken into account. As a result, the accuracy of the Direct Integration method is lower than the Hemi-cube method. Because shadowing effects are crucial, the hemi-cube method was used in the current FE model with a radiation resolution of 256 pixels. To increase the accuracy of both the temperature field and the radiosity simulation, the element size was reduced and the element order was raised. COMSOL [8] recommends using linear elements for radiosity with fine mesh to optimize the solution time, while trials showed that quadratic elements give slightly better agreement with the experimental results, but with a significant increase in the solution time. Therefore, quadratic elements were used for both temperature and radiosity. A total number of 76767 tetrahedral elements were used to mesh the FE model of the experimental box-girder bridge segment.

The used concrete thermal conductivity was $1.6\,W/(m \cdot K)$, while specific heat and concrete density were $950\,J/(kg.K)$ and $2400\,kg/m^3$, respectively. The surface emissivity was 0.85, while and surface absorption coefficient was 0.5. The application of these values was found to be efficient, which was verified using the recorded environmental and temperature data from the experimental box-girder bridge segment.

In this work, the initial bridge temperature was considered to be equal to the average temperature of all thermocouples at mid night, which is the initial time of the heat transfer analysis.

4. Verification of the COMSOL finite element model

Temperature and weather records of a hot summer day were used to check the accuracy of the conducted finite element model. The solar radiation records from the pyranometer, the air temperature records from the air temperature probe and the wind speed records from the anemometer were used as the base data to apply the different thermal loads on the boundaries of the box-girder segment. Many days were checked from the period extended from May 2013 to May 2014, in which very good agreement was recorded between the experimental and the predicted results. In this paper, a summer hot day was used to visualize the comparison between the experimental box-

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girder temperatures and the COMSOL predicted temperatures, which is the July 10.
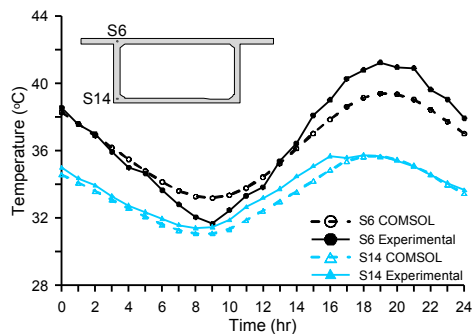

Figure 1. Comparison of the experimental and the predicted temperatures at thermocouples S6 and S14 during the 24 hours of July 10.
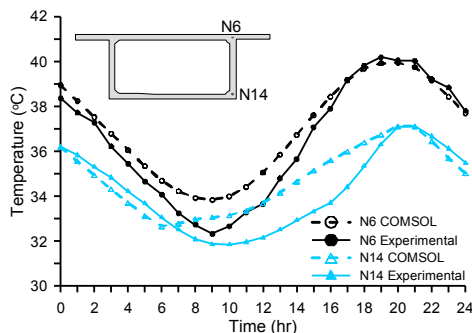

Figure 2. Comparison of the experimental and the predicted temperatures at thermocouples N6 and N14 during the 24 hours of July 10.

Figure 1 shows the recorded temperature-time curves of two thermocouples along the south-web (S6 and S14) associated with the COMSOL's predicted temperature-time curves at the same locations. As shown in Figure 1, the predicted curves simulates both the time dependent fashion of change and the temperature values at each time step. The temperature at both locations is shown to decrease during the early morning hours to reach the minimum between 8:00 and 9:00 am. This reveals the effect of the convection cooling and the long-wave re-radiation to atmosphere during the dark hours, which lead to fast temperature drop on the exterior surfaces, which in turn results in slower drop in the cores temperature due to the heat conduction. After which, it is shown that solar radiation causes a quick heat gain at the exposed surfaces leading to a temperature rise of those surfaces. The solar heating continues during the morning hot hours (beyond 9:00 am) and keeps increasing to reach a maximum after about two to three hours from the midday. After which, the temperature tends to decrease

again due to the surface convection cooling and re-radiation. The mean absolute error between the measured temperatures of 18 thermocouples installed along the south web and the predicted temperatures at the same locations during the 24 hours ranged from 0.4 to 1.5℃, which reflects the good agreement between the experimental and the predicted temperatures.

Similar results can be shown in Figure 2 for the thermocouples N6 and N14, which installed in the north web. The average absolute error for the 18 north web thermocouples ranged from 0.5 to 1.2℃. Similarly, 17 thermocouples were installed in the top slab and 9 thermocouples were installed in the bottom slab, in which the mean absolute errors were in the ranges of 0.8 to 1.2℃ and 0.5 to 1.0℃, respectively. The good matching of the COMSOL's temperature-time curves to the experimental ones reflects the adequacy of the COMSOL model to simulate the heat transfer problem and to apply all effective thermal loads accurately.
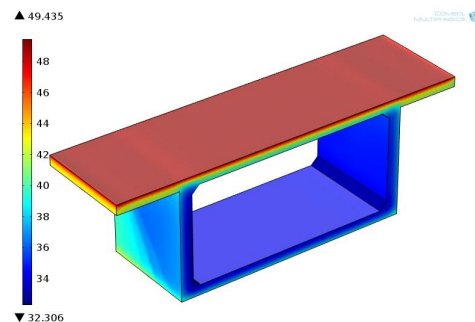

Figure 3. COMSOLS's 3D temperature distribution in the modeled box-girder at the time of the maximum temperature.
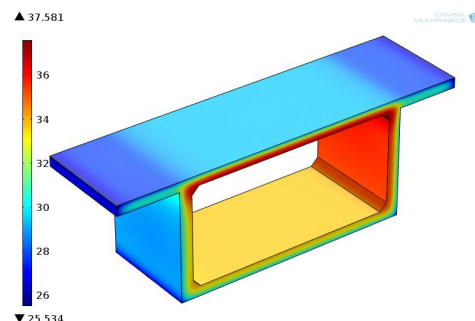

Figure 4. COMSOLS's 3D temperature distribution in the modeled box-girder at the time of the minimum temperature.

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Figures 3 and 4 show the three-dimensional temperature distribution in the modeled concrete box-girder segment at the time steps of maximum and minimum temperatures, while Figure 5 shows the time-dependent fluctuation of the girder's maximum, minimum and average temperatures.
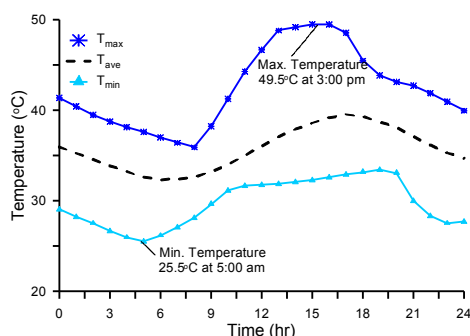

Figure 5. The predicted time-dependent variation of the girder's maximum, minimum and average temperatures.

5. Conclusions

A full-scale experimental concrete box-girder segment was used to verify a three-dimensional thermal finite element analysis carried out using COMSOL Multiphysics. This analysis investigates the heat transfer process occurs in concrete girders subjected to the daily and the seasonally variation of solar radiation, air temperature and wind speed. COMSOL heat transfer module with surface-to-surface radiation was used to perform the thermal analysis and to simulate all thermal loads simultaneously.

The comparison between the measured temperatures in 62 thermocouples distributed in the different members of the concrete girder and the predicted temperatures of the COMSOL model showed good agreement between them. The mean absolute error during the 24 hours of the studied day between the recorded and the predicted temperatures for the 62 thermocouples was in the range of 0.4 to 1.5℃, which reveals that the proposed COMSOL model could simulate the heat transfer problem adequately and apply the different boundary thermal loads simultaneously and accurately. The modeled thermal loads included the solar radiation, the surface convection, the ground reflected

radiation, the re-radiation and the surface-to-surface radiation.

6. References

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Acknowledgements

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