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

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1. Introduction

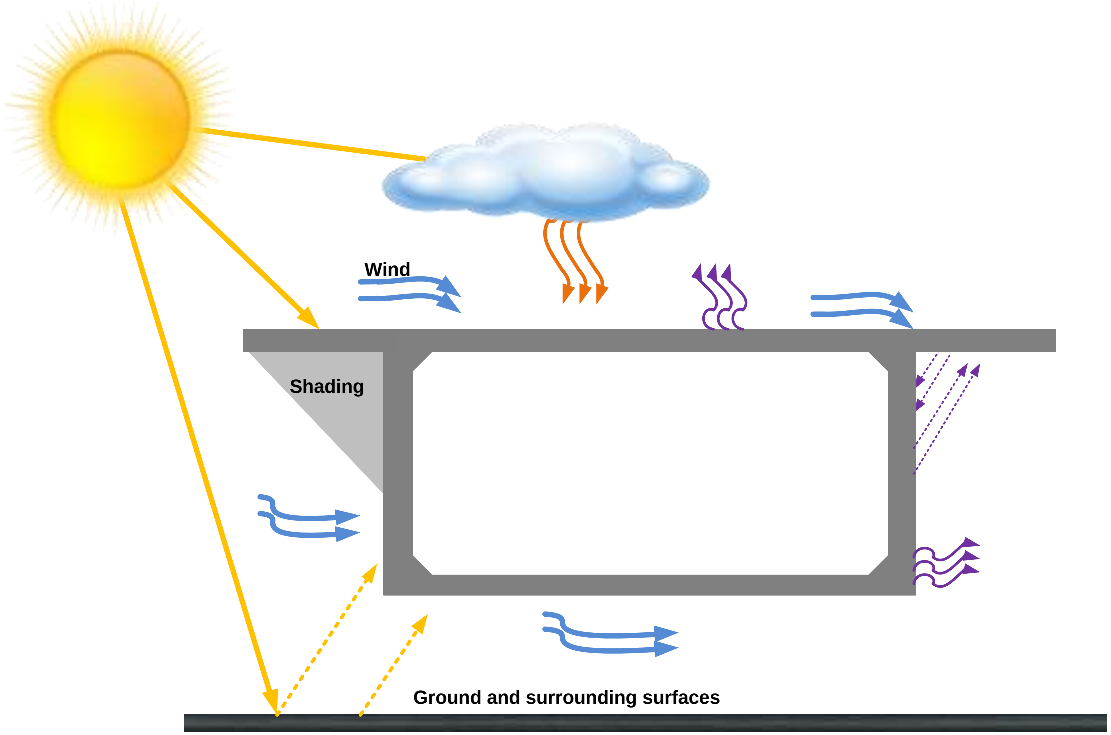

Figure 1: The environmental thermal loads

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 distribution of temperature in concrete bridge girders.

2. The time-dependent heat transfer problem

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

$$k\frac{\partial T}{\partial n}l+q=0 \qquad (2)$$

$$q=q_{con}+q_{sol}+q_{gr}+q_{ss}+q_{re} \qquad (3)$$

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

$$q_{sol}=\alpha I_{sol} \qquad (5)$$

$$q_{gr}=\alpha I_{gr} \qquad (6)$$

$$I_{gr}=\beta I_{sol}\frac{1-cos\theta}{2} \qquad (7)$$

$$q_{re}=\epsilon\sigma(T_s^4-T_a^4) \qquad (8)$$

k	Thermal conductivity	$W/(m\cdot K)$
ρ	Density	kg/m^3
c	Specific heat	$J/(kg.K)$
Q	Internally generated heat	W/m^3
T_s	Surface temperature	K
T_a	Air temperature	K
h_{con}	Convection Coefficient	$W/(m^2\cdot K)$
α	Solar absorption coefficient	
β	Reflection coefficient of the ground	
ϵ	Surface emissivity	
σ	Stefan-Boltzman constant	

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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.

Application of Boundary Conditions:

1- q_{con}

- adding a **Convection Cooling** node from the module interface
- Using empirical time-dependent formulas for the convection coefficients h_c

2- q_{sol}

- adding an **External Source** node from the module interface
- defining the solar parameters of the COMSOL's solar model.

3- q_{gr}

- adding a **Heat Flux** node from the module interface
- defining the time-dependent heat fluxes from solar radiation based on equations 6 and 7

4- q_{ss} and q_{re}

- adding a **Surface-to-Surface Radiation** node from the module interface
- defining **Radiation Groups** to reduce the solution time

3. The COMSOL finite element model

The COMSOL's Solar Model:

COMSOL introduces a built in solar model to calculate the time-dependent solar radiation. This model depends on a method used by the National Oceanic & Atmospheric Administration (NOAA) .

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

3. The COMSOL finite element model

The Surface-to-Surface Radiation setting:

Surface-to-surface radiation is the most complicated part of problem. This difficulty of 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.

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 method 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.

The direct Integration method is a more simplified but with low accuracy 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. Because shadowing effects are important, the hemi-cube method was used in the current study.

4. Verification of the COMSOL's finite element model

In this study, a reinforced concrete box-girder segment with full-scale dimensions was constructed in Gaziantep University, which was instrumented by 64 thermocouples distributed at different locations in the segment. In addition, weather station was installed with the girder segment to continuously monitor the solar radiation, the air temperature and the wind speed.

Figure 2: Construction of the experimental full-scale box-girder segment

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4. Verification of the COMSOL's finite element model

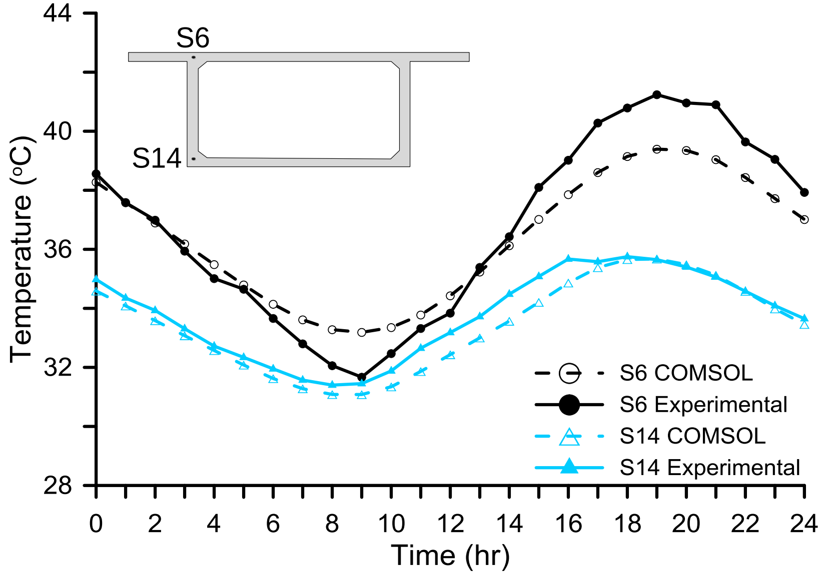

Figure 3: Experimental and the predicted temperatures at thermocouples S6 and S14 during the 24 hours of July 10.

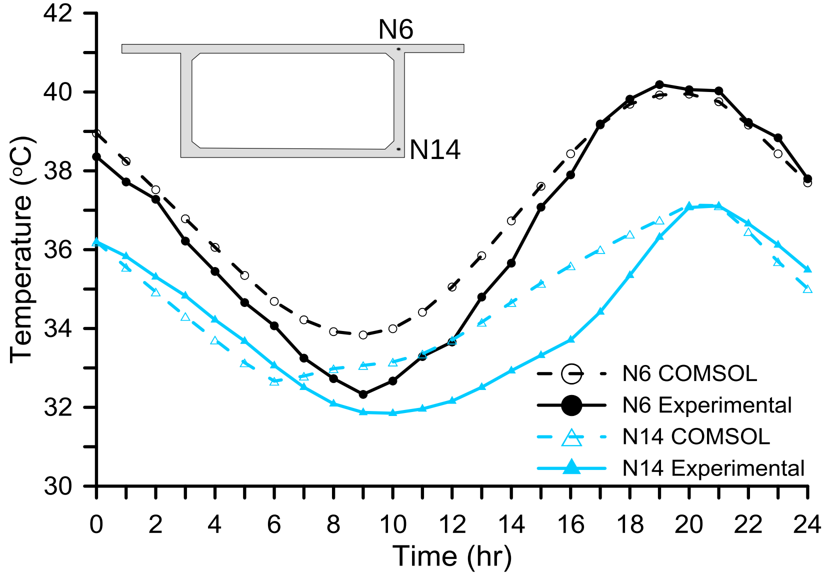

Figure 4: Experimental and the predicted temperatures at thermocouples N6 and N14 during the 24 hours of July 10.

Table 1: The mean absolute error (MAE) between the measured and the predicted temperatures during the 24 hours of 10-July-2013

MAE (°C)	South Web (18 TC)	North Web (18 TC)	Top Slab (17 TC)	Bottom Slab (9 TC)
Min	0.4	0.5	0.8	0.5
Max	1.5	1.2	1.2	1.0

4. Results of the COMSOL's finite element model

Figures 5 shows the three-dimensional temperature distribution in the modeled concrete box-girder segment at the time step of the maximum bridge's temperatures, while Figure 6 shows the time-dependent fluctuation of the girder's maximum, minimum and average temperatures.

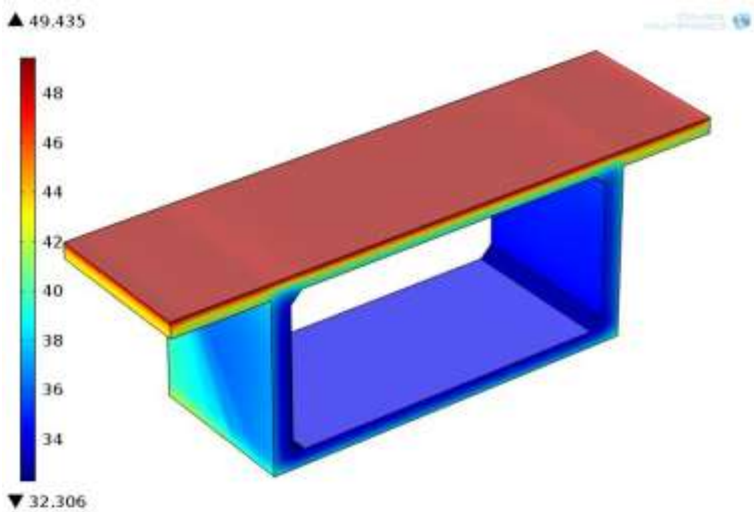

Figure 5: COMSOLS's 3D temperature distribution in the modeled box-girder at the time of the maximum temperature.

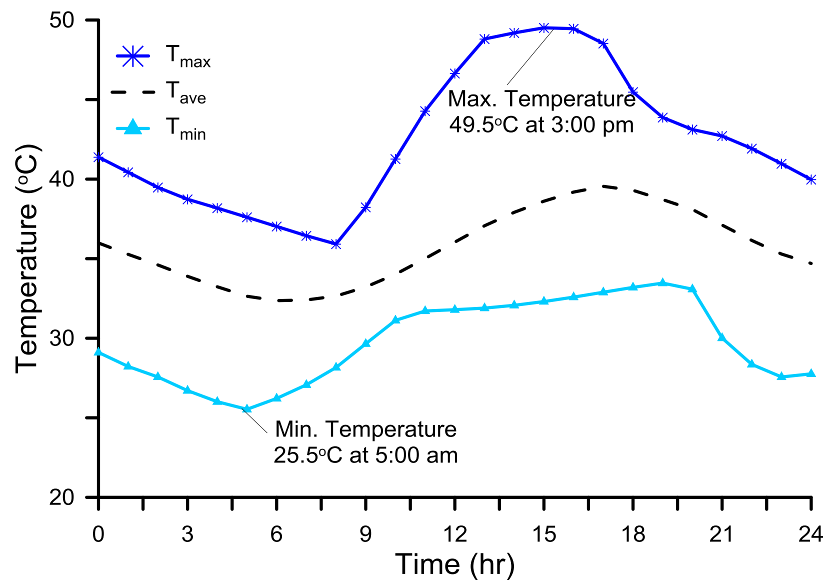

Figure 6: The predicted time-dependent variation of the girder's maximum, minimum and average temperatures.

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