Suggestion models of temperature differentials for the composite box girder bridge

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Abstract. The trend and behavior of Composite Box Girder Bridge (CBGB) are distinctly affected by the surrounding combination environment actions due to these constructions are erected in open environments. From this consideration, this research deals with the effect of the bridge's longitudinal axis, the geometrical configuration of CBGB and the thickness of the asphalt in addition to the season parameters on the temperature differentials under the combination of the surrounding environment actions; solar radiation, atmospheric temperature, and wind speed. To achieve this aim, the full-scale experimental composite concrete slab-steel box girder segment constructed on a campus of Gaziantep University and Finite Element (FE) program (COMSOL) activated. Two temperature differential models (vertical and horizontal) introduced during the typical summer actions, which considered as the reference thermal inputs when studied all parameters. This research demonstrated that the fashion of temperature differential weather along or across the CBGB was not sensitive under all ranges of the individual parameters generally. Additionally, based on the obtained results from this research, the vertical and horizontal of temperature differential models are proposed that can aid the engineers in design practices of such constructions without restoring to experimental tests that are always costly.

1. Introduction

The use of CBGB in urban highways has become extensive due to the advances in construction technology. A CBGB includes of the concrete deck and one or more U-shaped steel girders, ordinarily named “tub” girders.

The fluctuating environment actions: solar radiation, atmospheric temperature, and wind speed with time caused it no steady-state thermal condition exists within a CBGB. These actions are significant factors that could affect the design life of the bridge (Moorty and Roeder 1992; Fu and DeWolf 2004). Under some climate conditions, the thermal stresses can develop in the steel viaduct that is comparable to the stresses induced by dead and imposed load loads due to steel has high conductivity (Tong et al 2001). Depending on the numerical study accomplished by (Xu and Wu...
2007) on a cable-stayed bridge, they referred to the changes in dynamic features of the bridge due to damage in cables and girders may be smaller than those due to fluctuations in temperature. Choi et al (2011) confirmed that the stress and strain produce in early-age concrete decks in composite bridges under environmental loading. Additionally, the thermal stresses may earnestly affect the design life of the bridges by causing cracks in the concrete slab (Grisham 2005; William et al 2005; Writer 2007). The degradation of fiber-reinforced polymer composite bridge under hot/wet environment introduced by Jiang et al (2013).

Mosavi et al (2012) observed that the temperature variations could induce modal variability on a daily cycle based on the field testing conducted on a steel-concrete composite bridge in North Carolina. Numan et al (2016) referred to that the ideal thermal design of CBGB could achieve when the bridge orientation in E-W direction, shorter steel girder webs, longer lengths of the concrete slab cantilever, in addition to thicker concrete slabs. For a long-span suspension bridge, the temperature distribution along the girder in the longitudinal direction is non-uniform based on a study conducted by Xia et al (2017).

Based on the previous studies (Kennedy and Soliman 1987; Tong et al 2001; Au et al 2002; Chen 2008; Kim et al 2009; Zhou et al 2015) conducted to evaluate the temperature distributions and gradients of bridges under surrounding climatic actions. The structural temperature filed could simplify as the thermal gradient, which has practical value in the design for reasonable controlling the thermal displacement of composite girder bridges proposed by Tao (2009). By using statistical analyses, Numan (2017) determined the correlation between important environmental thermal parameters with maximum vertical and horizontal temperature and thermal stress gradients of CBGB.

In this research, the parametric studies are carried out to propose two models of temperature differential that can contribute to supplement the thermal action provisions for design objective of CBGB in Turkey. The current research also is focused on developing the understanding of FE thermal analysis of CBGB through emulating the heat fluxes inside the cavity, and the mutual irradiations between the exposed bridge surfaces and the ambient air concurrently, aside from the fundamental of heat transfer mechanisms.

2. Experimental work
The full-scale experimental CBGB segment constructed on the campus of Gaziantep University, Turkey at Latitude 37˚ 02′ 22′′ N, and Longitude 37˚ 19′ 07′′ E. The longitudinal axis of experimental CBGB oriented to the east-west direction. Figure 1 shows the details of the cross-section of the CBGB segment. The length of the CBGB segment was 6.56 feet. The superstructure of the CBGB segment contains; the reinforced concrete slab as the upper portion, while the trapezoidal steel box girder as the lower portion.

The cross-section areas of the superstructure of the bridge were covered by private insulation boards to affirm the thermal isolation along the cavity of the bridge. Additionally, the CBGB was lifted from the ground surface by reinforced concrete columns to emulate two meanings; the convection cooling and ground reflected radiation simultaneously. On the other hand, to simulate the heat transfer in the superstructure of the bridge apart from the effects of the columns, the insulating materials (mainly three layers of plywood) were placed at the contact surface between the steel girder and the columns.

The embedment and surface thermocouples type-T, embedment and surface Vibrating Wire Strain gauges (VWSG model 4200L), 108-temperature probe, CS300 pyranometer, and NRG#40 anemometer are used as sensors to measure the temperature of concrete and steel component, thermal stress in two portions of CBGB, ambient air temperature, global solar radiation, and wind speed, respectively. Additionally, the data acquisition system used, including mainly CR1000 data logger, three AM16/32 multiplexers, AVW200 spectrum analyzer. Eight sets include thirty-two thermocouples distributed in the mid-span section of the experimental CBGB segment in addition to one thermocouple that hanged inside the box girder to measure the confined air temperature inside the enclosure system. The eighteen VWSGs also distributed in the mid-span of the CBGB segment, and
they divided into six sets. Figure 2 shows the distribution pattern for thermocouples and VWSGs used in this work. The hourly experiment measurements gathered for a complete one-year cycle (from June 01, 2015 to May 31, 2016). Figure 3 shows the experimental CBGB segment after completion of construction works and set up the sensors. Figure 4 shows the daily maximum temperature for selected thermocouples (C3, H3, and F3) and also the daily maximum thermal stress for selected VWSGs (b1, f2, and d2) during the whole experimental period.

Figure 1. The details of the cross-section of the experimental CBGB segment (all dimensions are in inch).

Figure 2. The distribution pattern within the experimental CBGB segment: (a) thermocouples, (b) VWSG (all dimensions are in inch and $S_c$ denotes spacing center to center).

Figure 3. The experimental CBGB segment with sensors.
3. Finite element analysis

The transient heat conduction process was emulated based on three-dimensional Fourier partial differential formulation introduced by (Thepchatri et al 1977), it can express as follows,

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

where $k$ is the isotropic thermal conductivity coefficient of the material in Btu/hr/ft/°F, $T$ is the temperature at an arbitrary point ($x$, $y$, and $z$) in °F, $\rho$ is the material density in lb/ft$^3$, $c$ is the specific heat of the material in Btu/Ib/°F, and $t$ is the time in hr.

The boundary conditions including; surface convection, solar radiation, and reflected radiation, which associated with the equation (1) modeled in the COMSOL 4.3a program. Furthermore, the mutual irradiations between the exposed bridge surfaces and the ambient air temperature simultaneously, besides the heat fluxes inside the enclosure system was simulated in COMSOL. Therefore, the heat transfer with surface-to-surface radiation interface under the hemicube method and the radiation in participating media interface were activated. The hemicube method achieves the high accuracy in the obtained numerical results of CBGB due to emulate the shadowing effect on each element face at each time step of the solution depends on the sun trajectory during the daytime. On the other hand, radiation participating media interface under the discrete ordinate method discussed absorption, emission, and scattering process at each surface inside the cavity of CBGB and solved simultaneously. Table 1 shows the thermal properties of each component for CBGB.
**Table 1.** Thermal properties of concrete and steel component.

| Material property          | Concrete slab | Steel girder |
|----------------------------|---------------|--------------|
| Thermal Conductivity (Btu/hr/ft/˚F) | 0.81          | 26.6         |
| Specific heat (Btu/lb/˚F)    | 0.23          | 0.11         |
| Absorptivity                | 0.50          | 0.65         |
| Emissivity                  | 0.90          | 0.95         |
| Density (lb/ft\(^3\))       | 150           | 490          |

Tetrahedral elements were used to mesh the volume of CBGB, whereas triangular elements were used to mesh the boundary surfaces. The order of these elements was quadratic for the temperature calculation and linear for the surface radiosity. Figure 5 shows the mesh quality in the CBGB segment. From this figure, it found that the average quality of mesh was more than 0.80; therefore, the current mesh used can appreciate the thermal actions of such superstructures throughout the daily thermal cycle with high accuracy. The main assumptions in the current FE simulation were: the difference in thermal expansion between concrete and steel overlooked and the mean value used, which was 6.25×10\(^{-6}\) in/in/˚F. The full thermal interaction between the concrete slab and the steel girder achieved. All surrounding surfaces have the same reflectivity and albedo of 0.25. Besides, the initial bridge temperature and strain reference temperature are considered equal to the mean of readings for thirty-two thermocouples at 04:00 a.m. To reduce from the influence of the last assumption, the combined environment actions of solar radiation, atmospheric temperature, and wind speed inserted to FE analysis before three days from the target day.

![Figure 5. The mesh quality of CBGB segment in COMSOL software.](image)

### 4. Comparison of experimental and numerical results

The obtained results of the numerical analysis compared with those gathered from experimental measurements of the CBGB segment to verify the current thermal FE model. Three locations of thermocouples represented by C3, H3, and F3, and also three locations of VWSGs represented by b1, f2, and d2 of CBGB segment were selected during the full-range of two selected days to clarify the comparison of experimental and numerical results, as shown in figure 6 and figure 7, respectively. The days (August 03, 2015, and January 13, 2016) were selected to simulate extreme thermal conditions (summer and winter conditions). The hourly global insolation, atmospheric temperature, and wind speed measurements of these days used as the thermal input data in the current FE simulation. In figure 6 and figure 7, EXP refers to the experimental measurements, while NUM refers to the numerical results obtained from the FE simulation.
Figure 6. Comparison of experimental and numerical temperatures for selection thermocouples on:
(a) August 03, 2015, (b) January 13, 2016.

Figure 7. Comparison of experimental and numerical thermal stress for selection VWSGs on:
(a) August 03, 2015, (b) January 13, 2016.

As depicted in figure 6 and figure 7, the hourly numerical temperatures and thermal stresses matched well with the experimental ones. Therefore, it disclosed that the current FE analysis capable of simulating the actual thermal performance of CBGB efficiently.
5. Parametric studies
The series of parametric studies were conducted to submit the influences of the orientation of the bridge’s longitudinal axis, the geometrical configuration of CBGB, and the thickness of the asphalt topping layer in addition to the season on the temperature differentials. Two temperature differentials were calculated during the daily thermal cycle, involving vertical and horizontal temperature differentials. The vertical temperature differential was calculated through computing the average temperature at each elevation in the composite system, then taking the absolute of subtracted the lowest value from all calculated vertical average temperatures. For the same computational procedures followed in computing the horizontal temperature differential, but by taking the average temperature at each distance interval along the width of the composite system.

The vertical and horizontal temperature differentials on the experimental CBGB segment during the ideal summer’s day (sunny and clear that is August 03, 2015) of Gaziantep city illustrated in figure 8. The functions of temperature differentials in figure 8 used references when studying the other suggestion parameters. From this figure, it noticed that the peak value of the vertical and horizontal temperature differentials recorded at the top surface, and southern side of CBGB, respectively due to these locations be more sunlight than the other external surfaces depending on the sun path during the summer days.

From figure 8, it also founded that the zero temperature in the vertical temperature differential recorded at 8.63 inches from the top surface of the concrete slab (at the region between the upper flange and web of steel girder) due to this region of the bridge almost shaded during the heating time steps. On the other hand, the zero temperature in the horizontal temperature differential achieved at the northern side of the bridge because the north boundaries of CBGB subjected to direct beam solar radiation at the sunrise and sunset times only. It is worth to mention that the specific heat, the thermal conductivity, and the density of asphalt considered as 0.22 Btu/Ib/˚F, 0.58 Btu/hr/ft/˚F, and 131 Ib/ ft$^3$, respectively.

Table 2 shows the details of current parametric studies. $\beta_1 = 0^\circ$ represents the basis of the longitudinal axis of the CBGB segment (E-W direction). The orientation of the longitudinal axis of CBGB rotated towards the north direction when studied the effect of bridge orientation parameter on temperature differentials.
Table 2. The details of current parametric studies.

| Study | Parameter                                  | Variation range | Variation step |
|-------|--------------------------------------------|-----------------|----------------|
| 1     | Bridge orientation ($\beta_1$) (deg.)      | 0-90            | 30             |
| 2     | Cantilever length of concrete slab ($L_c$) (in.) | 28-82           | 18             |
| 3     | Steel girder depth ($H_s$) (in.)           | 58-124          | 22             |
| 4     | Slab thickness ($T_s$) (in.)               | 8-14            | 2              |
| 5     | Asphalt topping layer ($T_a$) (in.)        | 0-6             | 2              |
| 6     | Steel web angle ($\theta_w$) (deg.)       | 75.87-90        | 4.71           |
| 7     | Season                                     | Summer-spring   | One day for each season |

The obtained results of the influences of each parametric study on the temperature differentials briefly outlined in the following paragraphs:

5.1 Bridge orientation
The findings from figure 9 proved that the effect of the bridge orientation on the vertical and horizontal temperature differentials was very pronounced. The values of temperature in both of vertical and horizontal temperature differential achieved the highest levels when the longitudinal axis of the bridge settled at $\beta_1=90^\circ$. This result expected due to both northern and southern sides of the superstructure at $\beta_1=90^\circ$ became more open to direct sun rays than those for other orientations.

5.2 Geometrical configuration
Figure 10 to figure 14 shows the findings of influences geometrical configuration of CBGB on temperature differentials, including cantilever length of concrete slab, steel girder depth, slab thickness, asphalt topping layer, and steel web angle, respectively.

As a result of increasing the cantilever length of the concrete slab (from 28 to 82 in.) caused to increase the shaded area on the steel webs of the box girder. Accordingly, the temperature values in
vertical differential (especially along the steel girder) decreased, at the same time, the temperature values in the horizontal differential decreased, as shown in figure 10.

The recording temperatures in both vertical and horizontal differential functions increased as an increase of the steel girder depth (from 58 to 124 in.) because the larger ratio of the steel web area became more sunlit for the model with deepest steel webs than the others, as shown in figure 11.

The results graphed in figure 12(a), it found that the increase concrete slab thickness work in increasing the temperature readings within the concrete slab, and at the same time is decreasing the temperature readings in all steel strata in the vertical temperature differential. This owing to the concrete has a low thermal conductivity property; therefore, the thickest concrete slab caused to keep in the heat energy for a longer time than the other thicknesses. This reason also explains why temperatures decreased in the horizontal temperature differential when increased the concrete slab thickness, as shown in figure 12(b).

Since the asphalt material is a low conductor to heat energy, therefore the increase of asphalt thickness topping layer worked to reduce the total amount of heat energy receiving by the top horizontal surface of the bridge. Hence, the magnitude temperatures are decreased in both of vertical and horizontal differential functions, as shown in figure 13.

The change of angle in the webs of steel box girders from 75.87˚ to 90˚ led to an increase of the incidence angle of solar radiation on the steel surface (the angle between the sun’s rays and the surface normal). Therefore, the temperature values increase in both the vertical and horizontal thermal differentials, as shown in figure 14.

![Figure 10](image_url)  
**Figure 10.** Effect of cantilever length on: (a) vertical temperature differential, (b) horizontal temperature differential.
Figure 11. Effect of girder depth on: (a) vertical temperature differential, (b) horizontal temperature differential.

Figure 12. Effect of slab thickness on: (a) vertical temperature differential, (b) horizontal temperature differential.
Figure 13. Effect of asphalt thickness on: (a) vertical temperature differential, (b) horizontal temperature differential.

Figure 14. Effect of web angle on: (a) vertical temperature differential, (b) horizontal temperature differential.

5.3 Seasons
The extra three ideal days (October 08, 2015, January 13, 2016, and March 24, 2016) were selected to emulate the effect of fall, winter, and spring season on the temperature differentials. The combined meteorological data, involving global solar radiation, atmospheric temperature, and wind speed for each selected day used as thermal load inputs in the current FE analyses. It is well known, both the global solar radiation and ambient air temperature in the summer be at a higher level than the other three seasons. For these reasons explained why the temperature values in both along and across the
CBGB increased in summer as compared to the three seasons, as shown in figure 15. A closer look at the findings in figure 15 (b), it is found the temperature values in the horizontal temperature of both the fall and spring season matched to a great extent due to the number of daylight hours in these days, besides the sunrise and sunset time are almost equal.

![Figure 15. Effect of season on: (a) vertical temperature differential, (b) horizontal temperature differential.](image)

6. Proposed models for temperature differential

The simplified shape of the function of vertical temperature differential is proposed by jointing three important vertical points (temperatures) together linearly (bilinear model within the total height of the superstructure) in this research. These points represent the maximum temperatures recorded within the strata of reinforced concrete slab and steel box girder (T1 and T3, respectively), and zero-point (zero temperature) (T2). Based on the obtained results from figure 9 to figure 15 show that the maximum temperature within the concrete slab registered at the top surface, which was 26.70°F when the thickness of the concrete slab of 14 inches. On the other hand, the maximum temperature value in the box steel girder recorded at the lower face steel plate, which was 12.50°F when the longitudinal axis of the bridge settled at β=90°. Generally, the zero temperature achieved at a distance 8.63 inches from the upper surface of the CBGB bridge under all suggestion ranges of individual parameters.

The simplified form of the function of horizontal temperature differential is also proposed by jointing four important vertical points (temperatures) together linearly (tri-linear model within the total width of the superstructure). The first two points represent zero and the maximum temperature readings (T1, and Tii) at the northern side of CBGB, while the other points represent to the maximum temperature readings (Tiii, and Tiv) at the southern side of the CBGB. Based on the obtained results from figure 9 to figure 15, at the northern side of CBGB, the zero temperature occurred in the far north of the bridge, while the maximum temperature reading achieved near to the vertical axis of CBGB when the orientation of the bridge settled at β1=90°, which was 20.50°F. On the other hand, the maximum temperature readings registered at the southern side of the bridge was 23.30°F (near to the vertical axis of CBGB) and followed by 14.20°F at the far south of CBGB when the bridge orientation settled at β=90°.

Figure 16 shows the shape of vertical and horizontal temperature differential functions under environmental thermal loads of Gaziantep and the realistic ranges of each parameter study.
7. Conclusions
The main conclusions derived from this research can be summarized as follows:

- The differences between the numerical and the experimental results were small and within an acceptable range. Therefore, the current FE model able to emulate the real thermal performance for complicated superstructures of CBGB.
- The findings of parametric studies revealed that the location of minimum and maximum temperature values did not change, besides the shape function of both vertical and horizontal thermal differentials not to be sensitive during the daily thermal impacts in general.
- When the thickness of the concrete slab changed from 8 to 14 inches, the highest temperature value recorded, which was 26.70°F. Therefore, the effect of the concrete slab thickness on the vertical temperature differential was very pronounced than the other parameters.
- The highest temperature recorded in the horizontal differential was 23.30°F when the bridge settled at $\beta_1 = 90\degree$. Hence, it disclosed that the orientation of the longitudinal axis of CBGB has a higher impact on the horizontal temperature differential than the other six parameters.

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