Design Temperatures for Composite Concrete-Steel Girders: A- Verification of the Finite Element Model

Faten I. Mussa *, Sallal R. Abid*, Nildem Taysi c
a Department of Civil Engineering, University of Misan, Amarah, Iraq
b Department of Civil Engineering, University of Wasit, Kut, Iraq
c Department of Civil Engineering, Gaziantep University, Gaziantep, Turkey
* Corresponding author: sallal@uowasit.edu.iq

Abstract. Based on experimental records from a composite beam with a steel section and topping concrete flange, a finite element thermal analysis model was conducted and verified. The experimental beam was provided with 14 embedded and surface temperature sensors inside the concrete flange and on the steel section. The temperature records from the experimental beam were collected for two winter months. The finite element thermal model was conducted to simulate the thermal response of composite beams under the influence of open-field thermal conditions. The model solves for the conduction of heat in concrete and steel considering the different boundary conditions that include; solar radiation, reflected radiation, temperature of air and the speed of the ambient air. To verify the introduced thermal model, the predicted temperatures at the 14 thermocouples were compared with the experimental ones along the 24 hours of three days with different weather conditions. The comparisons showed that for the three days, the model could capture the temperature-time behavior accurately for all thermocouples with moderately low average absolute errors of 0.4 to 2.0 °C. Another notice was that the maximum errors in the steel section were higher than in concrete.

Keywords: Composite beam; solar radiation; temperature, finite element.

1. Introduction
Earlier researchers [1-8] reported carking, significant stresses and vibrations in bridge girders and superstructures, which were attributed to the induced temperature changes. The temperature changes in such structures arise from their nature as open-field structures, where the whole structure or most of which is directly exposed to ambient thermal actions. These actions include the hourly, daily and seasonally changing in the amount of solar radiations absorbed by the structure surfaces. In addition, the non-stopping time-dependent change of air temperature and speed is also a significantly affecting thermal action. The degree of influence depends on several parameters including, the location of the structure on which the weather history is strongly dependent, the type of the structure, its end conditions and of course the materials used to construct this structure.

Aiming to improve the knowledge in this field that directly influences the life span of vital constructions like bridges, continuous research works have been conducted during the last decades and recent years. Depending on which, design temperature models were recommended by many bridge
standards [9-14]. Models were introduced to consider the temperature gradient variation along the depth of the bridge superstructure for concrete, steel and composite structures. Some research works indicated that these models are unsuitable to accurately predict the temperature variation in some types of girders on in other locations. Therefore, the research on this vital point that influences the man’s daily life is continuous to build an advanced knowledge about this issue. Several researches [15-21] were conducted on constructed and used bridges as field studies, where continuous monitoring control sensors were embedded inside concrete or on surfaces of concrete and steel to evaluate the structural long-term response. Other studies [22-30] used experimental girders instrumented with temperature and strain sensors to exclude the effect of vehicle moving loads, which explicitly visualize the sole effect of thermal loads on the structural response of such girders. On the other hand, the simulation of thermal loads including solar radiations was found to be an attractive and cost-effective solution in this field of study [31-35].

This article presents a part of a multi-stage research work that was conducted to evaluate the thermal response of composite bridge girders to the changing loads of air temperature and solar radiation. In the first part, which is this part, a Finite Element (FE) thermal model is introduced to analyze the thermal exchange of the composite beam with the nearby field environment. The significance of the current research arises from the ability of the introduced FE model to consider all types of temperature and radiation thermal loads. These loads are fluctuated with time and represent the exact natural weather conditions of the field. The aim of this part is to verify the conducted thermal analysis with experimental records from an experimental field beam. The verified model can then be used in the second following stage to perform a case study research.

2. The experimental composite beam
A composite beam segment made of a steel beam section and a topping concrete flange was constructed in an open field in Gaziantep University campus/Turkey. The length of the beam segment was 500 mm, where the span is not important for thermal load calculations as thermal loads are constant along the span sections for straight beams. The concrete topping flange was 800 mm wide and 100 mm thick, while the depth of the steel beam equals 500 mm and the width of its top and bottom flanges equal 200 mm with web and flanges thickness of 8 mm. The beam was instrumented with seven Concrete Thermocouples (TC1 to TC7) and seven Steel Thermocouples (TS1 to TS7). The TC thermocouples were installed in the formwork of the concrete flange, while the TS thermocouples were attached to the surface of the steel beam. The coordinates of the 14 thermocouples are detailed in Table 1 considering the datum to be at the center of the lower surface of the bottom steel flange. The geometry of the beam and the location of thermocouples are illustrated in Figure 1, while Figure 2 shows the tested beam. The environmental data including air temperature, wind speed and solar radiation were collected from weather sensors that were installed in the same field. The data collection was continued for more than two winter months from December to February. More details about the experimental work and experimental results are presented in a previous research by the authors [36].

| TC   | x (mm) | y (mm) | TS   | x (mm) | y (mm) |
|------|--------|--------|------|--------|--------|
| TC1  | -400   | 550    | TS1  | 0      | 500    |
| TC2  | -200   | 550    | TS2  | 80     | 492    |
| TC3  | 0      | 600    | TS3  | 4      | 470    |
| TC4  | 0      | 550    | TS4  | 4      | 250    |
| TC5  | 0      | 500    | TS5  | 4      | 30     |
| TC6  | 200    | 550    | TS6  | 80     | 8      |
| TC7  | 400    | 550    | TS7  | 0      | 0      |
3. Background of thermal analysis

The basic equations of heat transfer, namely the differential equation of heat flow in solids [37] is:

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) = \rho c \frac{\partial T}{\partial t}
\]  

(1)

where: \(k_x\), \(k_y\), \(k_z\) are thermal conductivities of the material in x, y and z-directions in W/m\(\cdot\)\(^\circ\)C. \(T\) is the temperature at any point (x, y, z) at any time, \(t\), \(\rho\) is the density in kg/m\(^3\), \(c\) is the specific heat capacity in J/kg\(\cdot\)\(^\circ\)C. It should be noticed that for early age concretes, the quantity of hydration heat should be considered in Equation 1. In this research however, the early age phase was not considered and that's why the value of this term was taken as zero.

The boundary equations associated with heat flow equation can be expressed as [37]:

\[
k_x \frac{\partial T}{\partial x} l_x + k_y \frac{\partial T}{\partial y} l_y + k_z \frac{\partial T}{\partial z} l_z + q = 0
\]

(2)

Where: \(l_x\), \(l_y\), \(l_z\) are the directions unit’s cosines perpendicular to the surface where the boundary loads are applied. The term \(q\) summarizes the thermal boundary loads per unit area in W/m\(^2\). For isotropic and homogeneous materials, the value of the material’s thermal conductivity is constant in all directions.

The value of \(q\) is the sum of three basic components of heat transfer mechanisms, namely; heat convection \(q_c\) between the beam surfaces and the field ambient air, heat irradiation \(q_i\) from the hot surfaces to the field environment, solar radiation \(q_s\) from the sun and reflected radiation from the ground and surrounding objects \(q_r\). This sum is given as:

\[
q = q_c + q_s + q_i + q_r
\]

(3)

The convection between the air and the surfaces of the composite beams is mostly considered as a cooling thermal load as soon as the surface temperatures become hotter than surrounding air, which is give as:

\[
q_c = h_c(T_s - T_a)
\]

(4)

where \(T_s\) is the temperature of the concrete or steel surface, \(T_a\) is the temperature of the field air, and \(h_c\) is the coefficient of convection transfer of heat in W/m\(^2\)K, which is simplified as linear or power functions of wind speed \(v\). One of the widely used empirical formulas that is suitable for regular sections like I and T beams is:

\[
h_c = 5.6 + 4.0v \quad \text{for } v \leq 5 \text{ m/s}
\]

(5)

\[
h_c = 7.2v^{0.78} \quad \text{for } v > 5 \text{ m/s}
\]

(6)
The calculations of the received solar radiations by a horizontal surface in the ground can be simplified by the following equation, in which the total received radiation from the sun $I_s$ is reduced by the absorption coefficient of the surface $\alpha$, where:

$$q_s = \alpha I_s$$

(7)

The reflected radiation $q_r$ is the sum of all radiations reflected from the ground and absorbed by the surfaces of the beam. The reflected radiation depends on the solar radiation $I_s$ and the inclination of the surface, where it is also multiplied by the absorption coefficient $\alpha$. On the other hand, $q_{ir}$ is the cooling budget of hot surfaces to the field atmosphere by long wave radiation, which is also a function of the surface and air temperatures difference and is typically expressed as [37]:

$$q_r = \varepsilon C_s (T_a^4 - T_s^4)$$

(8)

where $C_s$ is a constant equals $5.67 \times 10^{-8}$ W/m$^2$K$^4$ and $\varepsilon$ is the emissivity coefficient of the surface.

4. The finite element temperature analysis

In this study, the COMSOL [38] finite element program was adopted to accomplish the analysis of the thermal transfer of the composite concrete-steel beam. COMSOL includes two options of radiation interface. The surface-to-surface radiation module was used here to deal with the heat transfer equation and the boundary conditions. This module considers the mutual radiations between the beam surfaces with mutual visions, which results in a more accurate solution. Previous thermal analyses of temperature distributions and thermal response of concrete box girder [39], concrete precast girders [40, 41], composite girders [42] and steel beams [28] were conducted successfully using COMSOL heat transfer module.

Majorly, tetrahedral elements were utilized to mesh the volumes of the concrete flange and the steel section of the composite beam. Triangular surface elements were also generated to apply the surface boundary convection, radiation and irradiation boundary loads, while edge and vertex elements were also auto generated for edge and point boundaries. To guarantee high calculation quality, fine auto mesh was adopted. After several trials, it was found that auto meshing of the program yields the most accurate results. The program automatically reduces the size of the elements wherever downsizing is required as shown in Figure 3. The volume of the beam was meshed using more than 31500 elements. The materials properties used in the thermal analysis of the concrete flange and steel section are listed in Table 1.

![Figure 3 The mesh of the composite beam](image-url)
Table 2. Materials thermal properties

| Material       | ρ (kg/m³) | k (W/m K) | c (J/kg K) |
|----------------|-----------|-----------|------------|
| Concrete flange| 2400      | 1.5       | 900        |
| Steel section  | 7850      | 44.5      | 475        |

5. Verification of temperature predictions

To check the adequacy of the conducted finite element thermal analysis, the temperatures obtained from the experimental beam in the 14 thermocouples were compared with the predicted temperatures. The comparisons were considered for the 24 hours of three selected days. These days were 2-January, 4-February, and 18-February, which were selected to check the adequacy of the model for different weather conditions of very cold, cold, and warm winter days. Noting that air temperatures of the three selected days were in the ranges of -9.3 to 0 °C, -3.2 to 13.3 °C and 4.5 to 23 °C for the very cold, cold, and warm days, respectively. For optimized visualization of results, only four concrete thermocouples and four steel thermocouples are presented here. The concrete thermocouples include the two surface ones TC1 and TC3 and the interior thermocouples TC2 and TC4. The four thermocouples were selected because they can be considered representative for the seven concrete thermocouples as shown in Figure 1. On the other hand, four thermocouples attached to the top flange (TS2), web center (TS4), bottom flange (TS6) and bottom surface (TS7) of the steel section were selected to represent the seven steel thermocouples.

Figures 4 to 10 show the daily variation between the predicted and experimental temperatures at different thermocouples during the three selected days. To evaluate the accuracy of the model, the Average Absolute Error (AAE) and the Maximum Absolute Error (MAE) were adopted as error measurements between the predicted and experimental temperatures. AAE (Equation 9) calculates for the 24 hours average of the absolute differences between experimental and predicted temperatures of each particular thermocouple, while MAE is the maximum absolute difference between experimental and predicted temperatures of each particular thermocouple during the 24 hours.

\[
AAE = \frac{1}{n} \sum_{i=1}^{n} |X_{FE,i} - X_{Exp,i}|
\]

where \( X_{FE,i} \) is the predicted temperature, \( X_{Exp,i} \) is the experimental temperature of each particular thermocouple at the same time step and \( n \) is the number of records which is 48 readings for the day (each 30 minutes).

Figure 4. Hourly experimentally recorded and FE predicted temperatures at thermocouple TC1
Figure 4 visualizes well agreement between the predicted and the recorded temperatures results at thermocouple TC1, which is the southern edge one. Gaps between the predicted and experimental results occurred during the daily maximum temperature times (noon times) and at late night hours. The AAE recorded for TC1 were 1.18, 1.25 and 1.5 °C in the very cold, cold and worm days, respectively, while the MAE in the same days were 3.42, 3.62 and 4.18 °C, respectively. It is obvious that the very cold day (2-January) recorded the lowest error values, while the worm day (18-February) recorded the highest errors. The general behavior of the temperature variation with time was almost the same for experimental and FE results as it is clear in the figure. The results at thermocouple TC2 (interior, mid-depth of concrete flange) also reveal the good accuracy of predicted temperatures as shown in Figure 5. The AAE was 0.7, 1.2 and 1.24 °C in the three selected days, respectively, while the MAE was 1.87, 2.37 and 3.28 °C, respectively. As for TC1, the lowest errors were recorded in the very cold day, while the highest ones were recorded in the worm day. The results of the two types of errors at thermocouple TC2 were lower than thermocouple TC1. This is because TC1 is a semi-surface (edge) thermocouple that is directly exposed to the variation of thermal loads.

Figure 6 demonstrates the results at thermocouple TC3 which gave a good agreement between the predicted and recorded temperatures. The AAE records were 0.76, 1.2 and 1.32 °C in the very cold, colder and worm days, respectively. The MAE values in the corresponding days were 2.26, 2.0 and 3.62 °C, respectively. It is obvious that the errors in TC3 are higher than those of TC2, but lower than of TC1. TC3 is also a semi-surface thermocouple, which increases the possibility of higher temperature fluctuation than TC2. On the other hand, edge surfaces are subjected to more solar radiation fluctuation in winter than top surface due to the low inclinations of sun rays, which makes TC1 suffers higher temperature fluctuations. Similarly, a good agreement of results was obtained at thermocouple TC4 as shown in Figure 7. This thermocouple is an interior one that is embedded at the central depth of the top concrete flange below TC1. The AAE was in the range of 0.67 to 1.26 °C for the three days, while the MAE ranged from 1.77 to 3.39 °C, respectively.

Figure 8 shows the results of the selected days at the thermocouple TS2. The figure shows a good agreement between the predicted and recorded temperatures. The recorded AAE values in the very cold, cold and worm days were 0.51, 1.09 and 1.33 °C, respectively. On the other hand, their corresponding MAE values were 1.57, 2.21 and 3.79 °C. It is obvious that the worm days exhibited the highest errors between experimental and predicted temperatures. This is an expected result because this is the day that recorded the highest daily air temperature difference and solar radiation among the three days.
Figures 9 and 10 show that the errors in TS4 and TS6 were the highest among all thermocouples. However, these variations still within the accepted range of errors between the predicted and recorded temperature results. The recorded AAE for TS4 were 1.07, 1.31 and 1.83 °C in the very cold, cold and warm days, respectively, while the corresponding MAE values were 3.75, 5.59 and 5.29 °C, respectively. For TS6, the AAE values were 0.75, 1.35 and 2.04 °C and the MAE values were 2.6, 4.6 and 5.61 °C in the three days, respectively. It is expected that TS4 and TS6 would exhibit such errors because of their locations in the center of the steel web and the southern edge of the flange, where maximum solar radiation intensities are received in winter. Adding to that the low specific heat of steel, which is approximately half that of concrete as addressed in Table 1, which means that steel heats up quickly and cools down quickly compared to concrete. Such conditions can result in more inaccurate experimental readings, inaccurate predictions or time lags that increase the gap between the predicted and experimental temperatures. However, the almost identical behaviors with time support the reliability of the current FE model in predicting the beam temperatures. The minor differences along the rest of the day also support this conclusion, whereas shown in Figures 9 and 10, this gap was only occurred within short time intervals. As sown in Figure 11, similar trend of results was also obtained for the lower surface thermocouple with comparable errors but slightly lower than those at TS4 and TS6. The partial mid-day drop in the temperatures of the web’s thermocouples shown in Figures 9 to 11 are attributed to two reasons. The first is the low inclination angles of solar radiations in winter due to the sun movement in this season, which keep the southern vertical surfaces under the heating phase along almost all shining hours, while the second is the shadowing effect of the overhanging flange wings that partially obstruct this heating.
Figure 8. Hourly experimentally recorded and FE predicted temperatures at thermocouple TS2

Figure 9. Hourly experimentally recorded and FE predicted temperatures at thermocouple TS4

Figure 10. Hourly experimentally recorded and FE predicted temperatures at thermocouple TS6
To summarize, Table 3 shows the average values of the AAE and MAE errors between the experimental and predicted temperatures for three groups of thermocouples, which are: the seven concrete thermocouples, seven steel thermocouples and the 14 thermocouples. The table obviously shows that in general, the average of AAE values is relatively low, where these values range from approximately 0.7 to 1.5 °C for all groups of thermocouples. Adding this to the very good agreement in the time-dependent between experimental and predicted temperatures, it can be concluded that the introduced thermal model could simulate the thermal response of the composite beam successfully.

The table also shows that the worm day exhibited noticeably higher AAE and MAE errors compared to the other two days, which was attributed to the distinguishably higher daily air temperature difference (maximum-minimum air temperatures) and the higher solar radiation of this day, where the average of the daily maximum errors was less than 3.3 °C for the cold days, while it was approximately 4.3 °C for the worm day. The errors in the steel section were also higher than in the concrete section which was attributed to several influencing parameters as discussed earlier. For example, in the cold day, the average of AAE of concrete thermocouples was 1.17, while that of steel thermocouples was 1.24. Similarly, their MAE averages were 2.46 and 4.07 °C, respectively.

Table 3 Average AAE and MAE errors for the groups of thermocouples

| Thermocouple | Very Cold Day | Cold day | Worm Day |
|--------------|--------------|----------|----------|
| Group        | AAE  | MAE  | AAE  | MAE  | AAE  | MAE  |
| Concrete     | 0.70 | 2.03 | 1.17 | 2.46 | 1.35 | 3.68 |
| Steel        | 0.77 | 2.67 | 1.24 | 4.07 | 1.72 | 4.87 |
| All          | 0.74 | 2.35 | 1.21 | 3.27 | 1.54 | 4.28 |

6. Conclusions
This article is the first part of a research study that investigates the thermal response of composite bridge girders exposed to open-field thermal conditions. The aim of this article is to introduce and verify a finite element thermal model that can simulate the thermal behavior of such type of girders. The model was verified using experimental records from an experimental composite girder. The verifications were carried out along the full day hours of three winter days with different weather conditions. The followings can be concluded from the conducted comparisons:
1. The introduced model could capture the time-dependent behavior of concrete and steel temperatures at the different locations with acceptable accuracy, where the obtained average errors of the 14 thermocouples were moderately low. The average of the 24-hours absolute average errors (AAE) of all thermocouples was in the range of approximately 0.7 to 1.5 °C for the three days.
2. The maximum absolute errors occurred along the noon hours and the midnight hours. The MAE was approximately twice the AAE, where the average of MAE values of all thermocouples along the three days was from 2.35 to 4.28 °C.
3. The errors in the steel section were higher than those in the concrete topping flange. This can be attributed to the faster cooling and heating of steel due to its much smaller thickness, which might induced time lags between experimental and predicted temperatures that resulted in higher errors.
4. The highest errors among three days were recorded in the worm day, which is attributed to the higher daily air temperature variation and higher solar radiation. The difference between the daily maximum and minimum air temperatures was 18.5 °C for the worm day, while it was 9.2 and 16.5 °C for the very cold and cold days.

7. Reference
[1] Prakash Rao D S (1986) Temperature distributions and stresses in concrete bridges. ACI J., 83, 588-596
[2] Elbadry M, Ghali, A (1986) Thermal stresses and cracking of concrete bridges. ACI J., 83, 1001-1009.
[3] Fu H C, Ng S F, Cheung M S (1990) Thermal Behavior of composite Bridges. J. Struct. Eng., 116, 3302-3323.
[4] Moorty S, Roeder C W (1992). Temperature-dependent bridge movements. J. Struct. Eng., 118, 1090-1105.
[5] Lucas J-M, Berred A, Louis A (2003) Thermal actions on a steel box girder bridge. Struct. Build., ICE Proc., 156(SB2), 175-182.
[6] Xia Y, Xua Y, Weia Z, Zhoub H, Zhouc X (2011) Variation of structural vibration characteristics versus non-uniform temperature distribution. Eng. Struct., 33, 53-146.
[7] Zhou G D, Yi T H (2013) Thermal loads in large-scale bridges: A state-of-the-art review. Int. J. Distrib. Sens. Netw., 2013, 1-17.
[8] Abid S R, Tayşi N, Özakça M (2016) Experimental analysis of temperature gradients in concrete box girders. Constr. Build. Mater., 105, 523-532.
[9] BS 5400: Part 2 (1978) Steel concrete and composite bridges, specifications for loads. British Standards Institution, London, UK.
[10] AASHTO (1989) AASHTO guide specifications: thermal effects in concrete bridge superstructures. American Association of State Highway and Transportation Officials, Washington DC, USA.
[11] AS 5100.2 (2004) Bridge design-part 2: design loads. Standards Australia, Sydney, Australia.
[12] EN 1991-1-5:2003. (2009) Eurocode 1: Actions on structures-part 1-5: general actions-thermal actions. European Committee for Standardization.
[13] AASHTO (2012) AASHTO LRFD bridge design specifications. American Association of State Highway and Transportation Officials, Washington DC, USA.
[14] Bridge Manual SP/M/022 (2013) Section 3: design loading. NZ Transport Agency, Wellington, New Zealand.
[15] Roberts-Wollman C, Breen J E, Cawrse J (2002) Measurements of thermal gradients and their effects on segmental concrete bridge. J. Bridge Eng., 7, 166-174.
[16] Giussani F (2009) The effects of temperature variations on the long-term behaviour of composite steel-concrete beams. Eng. Struct., 31(10), 2392-2406.
[17] Koo K, Brownjohn J, List D, Cole R (2013) Structural health monitoring of the Tamer suspension bridge. Struct. Control Health Monit., 20, 609-625.
[18] Xia Y, Chen B, Zhou X-Q, Xu Y-L (2013) Field monitoring and numerical analysis of Tsing Ma Suspension Bridge temperature behaviour. Struct. Control Health Monit., 20, 560-575.
[19] Xue J, Briseghella B, Lin J, Huang F, Chen B (2018) Design and field tests of a deck-extension bridge with small box-girder. J. Traffic Transp. Eng., 5(6), 467-479.
[20] Liu J, Liu Y, Jiang L, Zhang N (2019) Long-term field test of temperature gradients on the composite girder of a long-span cable-style bridge. Adv. Struct. Eng., 22(13), 2785-2798.
[21] Lin J, Xue J, Briseghella B, Xue J, Tabatabai H, Huang F, Chen B (2020) Temperature monitoring and response of deck-extension side-by-side box-girder bridges, *J. Perform. Constr. Facil.*, 34(2), 04019122.

[22] Wang Y, Shi Y, Lin C (2010) Experimental study on the temperature of steel members in sunshine, *J. Build. Struct.*, 31, 140-147.

[23] Song Z, Xiao J, Shen L (2012) On temperature gradients in high-performance concrete box girder under solar radiation. *Adv. Struct. Eng.*, 15(3), 399-415.

[24] Abid S R, Al-Gasham T S (2020) Finite element simulation of vertical temperature gradients in a standard W40×235 steel beam. *IOP Conf. Ser.: Mater. Sci. Eng.*, 988, 012035.

[25] Hagedorn R, Marti-Vargas J R, Dang C N, Hale W M, Floyd R W (2019) Temperature gradients in bridge concrete I-girders under heat wave. *J. Bridge Eng.*, 24(8), 1-14.

[26] Abid S R, Taşı N, Özakça M (2020) Temperature records in concrete box-girder segment subjected to solar radiation and air temperature changes. *IOP Conf. Ser.: Mater. Sci. Eng.*, 870, 012074.

[27] Zhao L, Zhou L-Y, Zhang G-C, Wei T-Y, Mahunon A D, Jiang L-Q, Zhang Y-Y (2020) Experimental study of the temperature distribution in CRTS-II ballastless tracks on a high-speed railway bridge. *Appl. Sci.*, 10(6), 1980.

[28] Abid S R (2020) Temperature variation in steel beams subjected to thermal loads. *Steel Compos. Struct.*, 34(6), 819-835.

[29] Abid S R, Al-Bugharbee H (2020) Prediction of the maximum temperature of steel I-beam under the effect of environment parameters. *IOP Conf. Ser.: Mater. Sci. Eng.*, 988, 012033.

[30] Abid S R, Al-Bugharbee H (2020) Experimental records based-simplified modeling of mean temperatures of steel beams in open environment. *IOP Conf. Ser.: Mater. Sci. Eng.*, 988, 012034.

[31] Chen D, Qian H, Wang H, Chen Y, Fan F, Shen, S (2018) Experimental and numerical investigation on the non-uniform temperature distribution of thin-walled steel members under solar radiation. *Thin Wall. Struct.*, 122, 242-251.

[32] Wang H, Zhang Y-M, Mao J-X, Wan H-P, Tao T-Y, Zhu Q-X (2019) Modeling and forecasting of temperature-induced strain of long-span bridge using an improved Bayesian dynamic linear model. *Eng. Struct.*, 192, 220-232.

[33] Abid S R, Taşı N, Özakça M (2014) Three-dimensional thermal modeling of temperature variation in concrete box-girder using COMSOL. In *proceedings of the 2014 COMSOL conference in Cambridge*, Cambridge, UK, 1-5.

[34] Lin J, Xue J, Huang F, Chen B (2020) Research on the thermal boundary conditions of concrete closed girder cross-sections under historically extreme temperature conditions. *Appl. Sci.*, 10, 1274.

[35] Lu H, Hao J, Zhong J, Wang Y, Yang H (2020) Analysis of sunshine temperature field of steel box-girder based on monitoring data. *Adv. Civ. Eng.*, 2020, 1-10.

[36] Mussa F, Abid S R, Taşı N (2020). Winter temperature measurements in a composite girder segment, *IOP Conf. Ser.: Mater. Sci. Eng.*, 888, 012074.

[37] Ghali A, Favre R, Elbadry M (2002) Concrete structures stresses and deformations. Spon Press, London, UK.

[38] COMSOL v 4.3a. (2012). COMSOL Multiphysics user's guide. Stockholm, Sweden.

[39] Taşı N, Abid S R (2015) Temperature distributions and variations in concrete box-girder bridges: experimental and finite element parametric studies. *Adv. Struct. Eng.*, 18(4), 469-486.

[40] Abid S R (2018) Three-dimensional finite element temperature gradient analysis in concrete bridge girders subjected to environmental thermal loads. *Cogent Eng.*, 5(1), 1-15.

[41] Abid S R, Abbass A A, Alhatmey I A (2019) Seasonal temperature gradient distributions in concrete bridge girders: A finite element study, *In Proceedings of 2019 Developments in eSystems Engineering (DeSE)*, Kazan, Russia, 374-379.

[42] Abid S R, Mussa F, Taşı N, Özakça M (2018) Experimental and finite element investigation of temperature distributions in concrete-encased steel girders. *Struct. Control Health Monit.*, 25(1), 1-23.