Statistical evaluation of vertical and lateral temperature gradients in concrete box-girders

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Abstract: Atmospheric thermal loads are considered as one of the effective loads on bridge structures. The thermal actions in bridge superstructures are considered in most of the recent bridge design specifications. In this study, a concrete girder segment was cast in place in an open field to simulate the actual atmospheric exposure case of bridge girders. Inside and close the surfaces of the webs and flanges of the girder 62 thermocouples were distributed to measure the concrete temperatures in different sectional locations. In addition, the experimental field was provided with a compact weather station that records the three main influential atmospheric loads, which are the solar radiation and the temperature and speed of the field’s air. The experimental data from all sensors were recorded for a one-year that considers the variation of loads in the four seasons. The effective maximum temperature gradients, both vertically (along the depth of webs) and horizontally (along the width of flanges), were statistically correlated to the atmospheric loads and their derivatives. Nonlinear correlations were introduced to estimate the maximum gradients with determination coefficients of 0.92 to 0.96. The maximum errors between the experimental and predicted temperatures for the whole investigated period were in general less than 3.0 °C. The obtained correlations for the lateral gradients were more complicated than for the vertical gradient due to the effect of other parameters like the day index, which is related to the striking angle of solar radiations.

Keywords: Concrete bridge; box-girder; atmospheric loads; temperature gradient; solar radiation.

1. Introduction

Concrete as a composite material known for its low thermal conductivity has the potential of partial reserving of thermal energy for hours. Due to this feature, the temperature of concrete, when subjected to a low to moderate heat source, rises up slowly and drops down slowly. An example of such a type of heat source is the natural solar radiation. Solar radiation is fluctuated with the time of the day. It starts with rapid increase after sunrise reaching a maximum within the noon hours, then it drops rapidly to zero after sunset. The night hours and early morning hours before sunrise are the no-shine hours where solar radiation value is zero. For structures like bridges, solar radiation is considered in the design as one of the effective design loads. This is because of the permanent exposure to out-door conditions that include the variation of air temperature and wind speed in addition to solar radiation.
The position change of sun from sunrise to sunset, with respect to objects on the earth surface, is associated with the change of solar radiation intensity on the different parts of the superstructure, which is also associated with the time-dependent change of shadow length and distribution. Areas subjected to high intensities of solar radiation get warmer than shaded areas. Similarly, the solar-exposed surfaces of a member become warmer than their opposite shaded surfaces and interiors. The temperature differences between heated surfaces and colder cores result in temperature gradients [1-3]. The temperature gradients can be vertical along the depth of the superstructure or lateral along its width. Literature works on concrete I-girders showed that the lateral gradients were in general much lower than vertical gradients [4-7], while other researches on concrete box-girders reported effective lateral gradients [8-11]. The temperature gradients are unfavorable loads because they impose self-equilibrating stress that can be high enough to cause concrete cracking [12, 13].

The design of reinforced concrete bridges against thermal actions includes a defined model of vertical temperature gradient that affects along the depth of the superstructure or girder, which is represented by linear or nonlinear gradient distributions depending on the adopted design specification [14-17]. The maximum gradient value of each distribution is dependent on solar radiation amount, which varies from a location to another. Several recent researches attempted to evaluate the vertical temperature gradients of different shapes of concrete, composite or steel girders [18-24]. Some of these researches used experimental girders that were exposed to out-door environment, while others collected temperature measurements from fielded bridge structures. On the other hand, other studies attempted to evaluate the applicability of current temperature gradient provisions on typical or special girder configurations, while others suggested new gradient models or modifications to existing design models [25, 26]. Some other works [27-31], tried to estimate the maximum and mean temperatures of the bridge or the maximum temperature gradient values based on the measured thermal loads, where measurements-based correlations were made with solar radiation, air temperature and wind speed.

In the current research, experimental records from a concrete box-girder that was cast in an open field were utilized to evaluate the effect of out-door thermal loads on the imposed temperature gradients. Measurements of concrete temperature from several instrumented thermocouples in addition to associated measurements in the same location for solar radiation, temperature of air and its speed were collected and analyzed. Based on which, the maximum estimated vertical and lateral temperature gradients along the hot and cold seasons were predicted and nonlinear correlation formulas were presented.

2. The concrete box-girder
An experimental concrete box-girder with the full dimensions shown in Figure 1 was constructed in an open field to simulate the actual atmospheric exposure conditions of bridges. The box-girder had a length of 2.1 m and was constructed on concrete columns with a height of 2.0 m. The purpose of the supporting columns is to assure free air movement on the bottom surface of the bottom flange as in real case bridges. The girder was instrumented with 62 thermocouples that were aligned along different horizontal and vertical lines inside and across the top and bottom flanges and north and south webs. The thermocouples were attached firstly on isolated steel bears at specific spacing as shown in Figure 2(a) and these bars were then fixed along the centerlines of the girder members before concrete casting as shown in Figure 2(b). All thermocouples were then connected to a data acquisition system that is composed of a data logger and several multiplexers as shown in Figure 2(c).

In addition to the thermocouples, three other atmospheric sensors were installed on the girder to collect the solar radiation, wind speed and air temperature measurements as shown in Figure 2(d). The measurements of all sensors were arranged in groups of data that were recorded each 30 minutes along more than a complete one year. It should be mentioned that the girder was isolated at the cross-sectional surface using special isolation plates as shown in Figure 2(d). This isolation was important to simulate the
continuity along the longitudinal axis. Hence, the thermal loads are only received via those actual exposed surfaces. Similarly, this isolation assured correct simulation of the closed cavity of the box-girder. More details about the experimental girder and its instrumentation can be found in previous works [32, 33].

Figure 1. The cross-sectional geometry and dimensions of the experimental box-girder

3. Gradient evaluation and data processing
The concrete temperatures were collected at time steps of 30 minutes as mentioned in the previous section. For each time step, the temperatures along the vertical centerlines of each web of the girder were grouped starting from the top surface’s thermocouple and ending at the bottom surface’s one. Six thermocouples
were installed along the center of each web across the 200 mm depth of the top flange at 40 mm vertical spacing. Similarly, five web thermocouples were installed across the 200 mm thick bottom flange at 50 mm vertical spacing, while five more thermocouples were installed along the interior 2 m depth of the web. Hence, 16 thermocouples were fixed along the vertical centerline of each web to determine the vertical temperature distributions, from which the vertical temperature gradients were calculated along the south and north webs. Similarly, 11 thermocouples were installed along the horizontal centerline of the top flange and 7 thermocouples were installed along the horizontal centerline of the bottom flange. The aim from these thermocouples was to evaluate the horizontal temperature gradients. The temperature gradient at each time along the south web was calculated using three steps; (1) determining the minimum temperature from the 16 thermocouples, (2) subtracting the minimum temperature from the temperatures of the 16 thermocouples to obtain the gradient distribution, and (3) the maximum gradient at this time is determined among the 15 gradients. Then after, the maximum gradient from the 48 time steps was determined as the daily maximum vertical temperature gradient of the south web. The same procedure was followed to evaluate the daily maximum gradients along the north web and the top and bottom flanges. The maximum of the two webs was considered as the maximum vertical temperature gradient, while the daily maximum lateral gradient was evaluated along the top and bottom flanges separately.

For the statistical calculations, the maximum daily temperature gradients were collected for a complete one-year cycle together with the associated daily solar radiation, air temperature and wind speed records. However, some issues occurred in the data acquisition system in some discrete time periods so that some thermocouples were out of work. Consequently, the gradients could not be calculated accurately for these intervals. Similarly, the fluctuation of the cloud cover in some days led to a significant noise in the obtained temperature records due to the high fluctuation of solar radiation. Therefore, the one-year data were refined by excluding the records of these intervals from the records used in the statistical analysis, which prevented the unfavorable impact of these noisy and faulty data on the predicted correlations.

4. Results and discussion

A nonlinear regression was used for developing the relation between the concrete temperature gradient and the surrounding thermal loads and their derivatives. The analyzed concrete temperature gradients were the vertical, top flange lateral and bottom flange lateral. The developed nonlinear relations were formed using the least square algorithm which determines the suitable model weights that give the minimum error.

4.1 Maximum vertical temperature gradient

The nonlinear regression between the thermal loads and the vertical temperature gradient is as follows:

\[ T_{ver} = b_1 + b_2 \times DT^{b_3} + b_4 \times I^{b_5} + b_6 \times W^{b_7} + b_8 \times SW^{b_9} + b_{10} \times SI^{b_{11}} \]

Where

- \(T_{ver}\) is the vertical temperature gradient (°C)
- \(DT\) is the daily maximum air temperature difference (Daily maximum-Daily minimum) (°C)
- \(I\) is the daily accumulated solar radiation (MJ/m²)
- \(W\) is daily average wind speed (m/s)
- \(SW\) is the square of \(W\)
- \(SI\) is the square of \(I\)

Table 1. Coefficient of vertical temperature gradient nonlinear regression

| \(b_1\) | \(b_2\) | \(b_3\) | \(b_4\) | \(b_5\) | \(b_6\) | \(b_7\) | \(b_8\) | \(b_9\) | \(b_{10}\) | \(b_{11}\) |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| -5.03 | 0.32  | 0.86  | 0.19  | 2.25  | -0.16 | 2.47  | -0.07 | 1.00  | 0.32  |
Figure 3 shows the coefficients of determination between the predicted and experimental data. It is shown that the developed model is of well prediction of the relation between the input and output variables with $R=0.97826$ (i.e. $R^2=0.96$). The figure also shows that the data are scattered closely to the best line fit. Figure 4 shows representation of the predicted and the experimental (i.e. actual) data along the 262 days. It can be shown from the figure that the two graphs have quite the same trend and values. The residuals are also shown in black line with maximum errors less than of ±3 °C. In a previous research [32], a different nonlinear formula was obtained from the same source data, which was also adequate enough to accurately predict the maximum vertical temperature gradient.

![Figure 3](image1.png)

**Figure 3.** The determination of regression of the maximum vertical temperature model

![Figure 4](image2.png)

**Figure 4.** The time waveform of the predicted and experimental maximum vertical temperature gradients as well as the residuals
4.2 Maximum lateral temperature

The nonlinear multivariate regression was developed for the maximum lateral temperature gradient for both top and bottom flanges. Equations 3 and 4 represent the relation between the input and output variables. In comparison with Equation 1, it can be seen clearly that these formulas are more complex and more include more parameters. This complexity reflects the more complicated influence of the different thermal loads on lateral temperature gradients compared to the vertical temperature gradient. For instance, the day index parameter calculates for the sequence of the day in the year, which means that it determines the season of the day. Solar radiations in cold seasons are of lower inclination angles than in hot seasons, which means that solar radiations are highly concentrated on vertical surfaces and hence leading to higher lateral gradients. The inclusion of this parameter increased the accuracy of the obtained formulas significantly, which reflects its essential influence on lateral temperature gradients. On the other hand, it was almost ineffective on the vertical temperature gradient for the same reason.

\[ T_{\text{maxT}} = b_1 + b_{12} \cdot DT^{b_3} + b_4 \cdot I^{b_5} + b_6 \cdot SI^{b_7} + b_8 \cdot QI^{b_9} + b_{10} \cdot 3I^{b_{11}} + b_{12} \cdot W^{b_{13}} + b_{14} \]

\[ \cdot SW^{b_{15}} + b_{16} \cdot QW^{b_{17}} + b_{18} \cdot N^{b_{19}} + b_{20} \cdot (IN)^{b_{21}} + b_{22} \cdot SN^{b_{23}} + b_{24} \]

\[ T_{\text{maxB}} = b_1 \cdot DT^{b_3} + b_4 \cdot I^{b_5} + b_6 \cdot SI^{b_7} + b_8 \cdot QI^{b_9} + b_{10} \cdot 3I^{b_{11}} + b_{12} \cdot W^{b_{13}} + b_{13} \cdot SW^{b_{14}} + b_{15} \]

\[ \cdot QW^{b_{16}} + b_{17} \cdot N^{b_{18}} + b_{19} \cdot (IN)^{b_{20}} + b_{21} \cdot SN^{b_{22}} + b_{22} \cdot QN^{b_{24}} \]  (2)

Where:

\( T_{\text{maxT}} \) & \( T_{\text{maxB}} \) are the maximum lateral temperature gradients for the top and bottom flanges of the box girder, respectively.

\( QI \) is \( I^3 \)

\( QW \) is \( W^3 \)

\( 3I \) is the average of the accumulated solar radiation of the two past days and the target day.

\( N \) is the index of the target day (\( n/365 \))

\( SN \) is the square of \( N \)

\( QN \) is the triple of \( N \).

The multivariate regression weights for the maximum lateral temperature gradients for the top and bottom flanges are shown in Tables 2 and 3, respectively. The coefficients of regression between the predicted and actual data are shown in Figures 5 and 6. The coefficients indicate a very good similarity and a very good agreement with \( R^2 \) values of approximately 0.92 and 0.94 for the top and bottom maximum lateral temperature gradients, respectively. Figures 7 and 8 illustrate both the predicted and actual maximum lateral temperature gradients for the top flange of the concrete box girder. The residuals of all the investigated days show that the maximum errors are in between \( \pm 2.5 \) °C.
Table 2. Coefficients of max lateral temperature gradient nonlinear regression (Top flange)

|   | b_1 | b_2 | b_3 | b_4 | b_5 | b_6 | b_7 | b_8 | b_9 | b_{10} | b_{11} | b_{12} | b_{13} |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|--------|--------|--------|
|   | 0.62 | 1.63 | 0.41 | -0.34 | 1.39 | 2.33 | 0.44 | -31.53 | -0.34 | 1 | 8.02 | 0.52 |
| b_{14} | b_{15} | b_{16} | b_{17} | b_{18} | b_{19} | b_{20} | b_{21} | b_{22} | b_{23} | b_{24} | b_{25} |
|   | -9.18 | 0.02 | 10.02 | -0.14 | 10.51 | -0.15 | 0.09 | 1.47 | -0.24 | -0.45 | 0.09 | -0.33 |

Table 3. Coefficients of max lateral temperature gradient nonlinear regression (Bottom flange)

|   | b_1 | b_2 | b_3 | b_4 | b_5 | b_6 | b_7 | b_8 | b_9 | b_{10} | b_{11} | b_{12} | b_{13} |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|--------|--------|--------|
|   | 0.81 | 0.85 | -57.39 | -0.85 | 5.69 | 0.09 | -0.04 | 0.56 | -0.26 | 1.11 | 4.01 | 1.05 | 9.32 |
| b_{14} | b_{15} | b_{16} | b_{17} | b_{18} | b_{19} | b_{20} | b_{21} | b_{22} | b_{23} | b_{24} |
|   | -0.07 | -4.91 | 0.19 | -1.94 | 0.46 | 0.08 | 1.51 | -0.56 | 0.23 | -1.61 | 0.15 |

Figure 5. The regression of the maximum lateral temperature gradient (Top flange)

Figure 6. The regression of the maximum lateral temperature gradient (Bottom flange)
5. Conclusion
1. The temperatures of the concrete box girder were obtained for one year and the outliers are removed. Multivariate nonlinear regression models were developed to correlate the thermal loads and their derivatives (inputs) to the maximum temperature gradients (output).
2. Three models were developed to describe the behavior of (a) maximum vertical temperature gradient (b) maximum lateral temperature gradient in the top flange of the girder (c) maximum lateral temperature gradient in the bottom flange of the girder.
3. Generally the three nonlinear models can estimate the temperature gradients efficiently with squared correlation coefficient $R^2 = 0.96$ for the maximum vertical temperature gradient, $R^2 = 0.92$ for maximum lateral temperature gradient (top flange) and $R^2 = 0.94$ for maximum lateral temperature gradient (bottom flange).
4. The regression models 2 and 3 for the lateral temperature gradients were more complex compared with model 1 (vertical temperature gradient), where more parameters were required to be included to obtain better correlations, which reflect the dependency of lateral temperature gradients on additional parameters like the day index. This parameter was important because it has a direct relation with the inclination angle of solar radiation.

References

[1] Zhou G D, Yi T H 2013 Thermal loads in large-scale bridges: A state-of-the-art review Int. J. Distrib. Sens. Netw. Article ID 217983 1-17.
[2] Abid S R, Mussa F, Tayşi N, Özakça M 2018 Experimental and finite element investigation of temperature distributions in concrete-encased steel girders Struct. Control Health Monit. 25(1) e2042.
[3] Moorty S, Roeder C W 1992 Temperature-dependent bridge movements J. Struct. Eng. 118 1090-1105.
[4] Lee J-H 2012 Investigation of extreme environmental conditions and design thermal gradients during construction for prestressed concrete bridge girders J. Bridge Eng. 17(3) 547-556.
[5] Abid S R 2018 Three-dimensional finite element temperature gradient analysis in concrete bridge girders subjected to environmental thermal loads Cogent Eng. 5(1) 1447223.
[6] 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.
[7] 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.
[8] 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.
[9] Abid S R, Tayşi 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.
[10] 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.
[11] Gu B, Chen Z, Chen X 2014 Temperature gradients in concrete box girder bridge under effect of cold wave J. Central South Univ. 21 1227-1241.
[12] Prakash Rao D S 1986 Temperature distributions and stresses in concrete bridges ACI J. 83 588-596.
[13] Elbadry M, Ghali, A 1986 Thermal stresses and cracking of concrete bridges ACI J. 83 1001-1009.
[14] AASHTO 2012 AASHTO LRFD bridge design specifications. American Association of State Highway and Transportation Officials, Washington DC, USA.
[15] Bridge Manual SP/M/022 2013 Section 3: design loading. NZ Transport Agency, Wellington, New Zealand.
[16] AS 5100.2 2004 Bridge design-part 2: design loads. Standards Australia, Sydney, Australia.
[17] EN 1991-1-5:2003 2009 Eurocode 1: Actions on structures-part 1-5: general actions-thermal actions. European Committee for Standardization.
[18] Lucas J-M, Berred A, Louis A 2003 Thermal actions on a steel box girder bridge Struct. Build., ICE Proc. 156(SB2) 175-182.
[19] Abid S R 2020 Temperature variation in steel beams subjected to thermal loads. Steel Compos. Struct. 34(6) 819-835.
[20] 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.
[21] 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.
[22] Mussa F, Abid S R, Tayşi N 2020 Winter temperature measurements in a composite girder segment IOP Conf. Ser.: Mater. Sci. Eng. 888 012074.
[23] 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.
[24] Chen D, Wang H, Qian H, Li X, Fan F, Shen S 2017 Experimental and numerical investigation of temperature effects on steel members due to solar radiation Appl. Therm. Eng. 127 696-704.
[25] Li D, Maes M A, Dilger W H 2004 Thermal design criteria for deep prestressed concrete girders based on data from confederation bridge Canadian J. Civ. Eng. 31 813-825.
[26] 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.
[27] 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.

[28] 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.

[29] Roberts-Wollman C L, Breen J E, Cawrse J 2002 Measurements of thermal gradients and their effects on segmental concrete bridge J. Bridge Eng. 7(3) 166-174.

[30] Lee J.-H, Kalkan I 2012 Analysis of thermal environmental effects on precast, prestressed concrete bridge girders: temperature differentials and thermal deformations Adv. Struct. Eng. 15(3) 447-459.

[31] Liu J, Liu Y, Zhang G Jiang L, Yan X 2020 Prediction formula for temperature gradient of concrete-filled steel tubular member with an arbitrary inclination. J. Bridge Eng. 25(10) 0402007.

[32] Abid S R, Tayşi N, Özakça M 2016 Experimental analysis of temperature gradients in concrete box girders Constr. Build. Mater. 106 523-532.

[33] Tayşi 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.