Temperature Records in Concrete Box-Girder Segment SubJECTED to Solar Radiation and Air Temperature Changes

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Abstract. This paper presents the experimental results of a full-scale concrete box-girder segment subjected to ambient thermal loads. The experimental segment was instrumented with 62 thermocouples to measure the concrete temperatures in different locations and a weather station to measure air temperature, wind speed, and solar radiation. The records from the different sensors were collected for more than one year at time intervals of 30 minutes. The full one-year records showed that the maximum vertical temperature gradient was occurred in June and was approximately 20 °C, while the maximum lateral temperature gradient was occurred in December and was 19 °C. Finally, a vertical temperature gradient model, which composes of three multi-linear parts, was proposed. The resulted temperature distributions, stresses, and deflection from the proposed model were closer to those of the experimental gradient compared to the AASHTO's and the NZ Bridge Manual's gradient models.

Keywords. temperature gradient; box-girder (BG); air temperature; solar radiation; thermal stress

1. Introduction

During the life cycle, concrete structures are subjected to many types of loads depending on their function and type of exposure. Structures in open environments, like bridges, are under direct and continuous exposure to ambient thermal loads [1]. The ambient thermal loads include the temperature and the speed of the surrounding air in addition to solar radiation. These loads are fluctuated and time dependent. The variation of thermal loads during the day and from a season to another adversely affects the structural members of concrete bridges [2-4].

As a bridge is continuously exposed to ambient thermal loads, it suffers cycles of heating and cooling phases, which lead to cycles of gain and loss of temperature. The continuous cycles of temperature exchange with the surrounding environment lead to time-dependent variations in the mean temperature of the bridge. On the other hand, the differential temperature gain and loss from surface to surface and the differential cooling between exterior and interior surfaces result in variations in the temperature of the different layers of each member, which cause nonlinear temperature gradients along the depth and the width of the superstructure [5, 6]. The nonlinear temperature gradients result in induced self-equilibrating stresses, which cause additional deformations and may lead to concrete cracking [7-12].
In a sunny day, especially in summer, the absorbed heat from solar radiation on the exterior surfaces increases the temperature of these surfaces during the day hours. This heat is conducted through the thickness of the different structural elements causing a temperature rise of the interior layers. However, and within the early hours after the noon, the absorbed heat at the surfaces is considerably larger than the conducted heat to interior layers, leading to a positive temperature gradient with surfaces hotter than cores [13]. Within the rest of the daytime hours and due to the concentration of the conducted heat from exposed surfaces, the interior layers reach their maximum temperature around sunset. During these hours, sunrays are striking the vertical surfaces from lower angles, while the cooling of the other exterior surfaces is already started. The cooling occurs by the convection of heat from the hot exterior surfaces to the colder surrounding air and the re-radiation of heat from these surfaces back to the surrounding atmosphere. During night hours, the temperatures of the exterior surfaces become low, while the temperatures of the interior layers are still high although of the slow inversed heat conduction, resulting in negative temperature gradients with colder surfaces and hotter cores.

The AASHTO Guide Specifications in 1989 [14] introduced a tri-linear temperature gradient model, which composed of three linear regions having maximum temperatures T1, T2, and T3. This model was simplified later to the bilinear gradient that is still dependent in the AASHTO specifications [15]. The bilinear model keeps the same values of T1 and T2 of the older tri-linear model. In both, the former and the current vertical gradient models, AASHTO subdivisions the United States area into four regions depending on the solar radiation intensities. Based on which, the temperatures T1, T2, and T3 are specified.

The Eurocode EN 1991 [16] gives two alternative approaches. The first is a simplified equivalent linear temperature gradient extends from the top surface to the bottom surface of the superstructure. This model suggests that the temperature at the top surface is 10 °C for the heating case and 5 °C for the cooling case. On the other hand, the second approach suggests the same bilinear temperature gradient model proposed by BS 5400 [17]. The New Zealand's Bridge Manual [18] and the Australian AS 5100.2 [19] use a fifth order temperature gradient model. This model extends from a maximum temperature T at the top surface of the superstructure and decreases along the top 1.2 m to a zero temperature. The maximum top surface's temperature gradients of the Australian AS 5100.2 [19] and the New Zealand's Bridge Manual [18] are 20°C and 32°C, respectively.

During the last two decades several studies tried to better improve the knowledge about the influence of atmospheric thermal loads on bridge superstructures. Some studies were conducted based on the health monitoring systems that were facilitated in many important bridges in USA, Europe or China [1, 4, 10, 21-25]. Other studies, tried to assess the individual role of these thermal loads isolated from traffic loads by conducting experimental girders that are installed in open environments and instrumented with temperature and other sensors [2, 12, 26-29]. Others used the finite element method to investigate the effective parameters by conducting parametric studies [30-35].

In the current research, an experimental work was conducted on a specially made full-scale experimental concrete box-girder (BG) segment. The experimental segment was instrumented with thermocouples to measure the concrete temperatures and a weather station to monitor the ambient thermal loads. This paper focuses on the concrete temperature records of the whole test period extended for approximately continuous 13 months. Moreover, the paper presents the environmental recorded data in addition to the vertical and lateral temperature distributions and gradients for selected days from the four seasons of the year.

2. The experimental work

2.1. The box-girder segment
The experimental concrete BG segment has the full-scale dimensions shown in Fig. 1 and was constructed inside the campus of Gaziantep University in Gaziantep, Turkey (Latitude: 37° 2' 20" N and Longitude 37° 19' 2" E). The BG segment was constructed on (but thermally isolated from) a reinforced concrete frame that raises the segment 2.0 m above the natural ground level. The BG should be raised to allow free fluent of air and radiations to the bottom surface of the bottom slab. The concrete casting of the BG was started at about 11:30 AM and finished at about 1:00 PM in 25-May-2013. Normal concrete with specified cube strength of 35 MPa was ordered to cast the BG segment. To simulate the real BG, inside which the surfaces are isolated from direct contact with ambient air and solar radiation, special isolation boards were used to close the cavity of the BG as shown in Fig. 2.

2.2. Sensors and instrumentation

Two types of sensors were used in this study, sensors that measure the environmental thermal loads (weather station) and thermocouples to measure the concrete temperatures. The environmental sensors were attached to the BG segment and include an air temperature probe with solar shield, a three-cup anemometer, and a pyranometer. The three sensors were used to measure the ambient air temperature, the wind speed, and the global solar radiation on horizontal surfaces, respectively.
To monitor the temperature of concrete in the different parts of the BG, 62 type-T thermocouples were distributed in four groups according to their locations. The four groups of thermocouples are: the south-web group (SW) with 18 thermocouples (from SW1 to SW18), the north-web group (NW) with 18 thermocouples (from NW1 to NW18), the top-slab group (TS) with 17 thermocouples (from TS1 to TS17), and finally the bottom-slab (BS) group with 9 thermocouples (from BS1 to BS9). Fig. 1 shows the coordinates of each of the 62 thermocouples. Data acquisition system composed of data logger and multiplexers from Campbell Scientifics was used to record the measurements from the weather station and the 62 thermocouples at time intervals of 30 minutes. The measurements were continued for more than one year. However, the results are presented for a complete one-year cycle from 4-July-2013 to 3-July-2014.

3. Environmental thermal loads

Air temperature, wind speed, and solar radiation records are presented for four selected days. The selected days are 22-March-2014 to represent the spring, 14-June-2014 to represent the hot season, 11-October-2013 to represent the autumn, and finally 22-December-2013 to represent the cold season.

3.1. Air temperature

Air temperature data are essential to understand the thermal behavior of structures exposed to open environments. The air temperature controls both the convection cooling and the surface-to-ambient radiation on the exterior surfaces during the cold hours of the day. Fig. 3(a) shows the daily air temperature distributions for the four selected days. Excluding 14-June, the selected days represent the days in which the maximum daily difference between the daily maximum and the daily minimum air temperatures was occurred during each season. On the other hand, 14-June was the day of the maximum vertical temperature gradient along the depth of the BG, while 22-December was the day of the maximum lateral temperature gradient along the width of the BG. The corresponding daily maximum air temperatures of 22-March, 14-June, 11-October, and 22-December were 21.9, 31.3, 30.4, and 16.2 °C, respectively, while their daily minimum air temperatures were 3.3, 14.7, 6.8, and -2.2 °C, respectively.

3.2. Wind speed

The convection cooling on the exterior surfaces of the BG depends mainly on the temperature of the surrounding air in addition to its speed where the coefficient of convection cooling is a function of wind speed. Therefore, wind speed data are required to study the thermal behavior of bridge structures. Fig. 3(b) shows the hourly wind speed of the selected days. The daily maximum wind speeds of 22-March, 14-June, 11-October, and 22-December were 2.18, 2.41, 1.83, and 2.85 m/s, respectively, while the daily minimum wind speed for the four days was 0 m/s.

3.3. Solar Radiation

Solar radiation is the main heating source. The solar radiation reaches the exposed surfaces of the BG either directly (beam component) or be absorbed and diffused from the clouds and the other particles in the sky. In addition, the reflected radiation from the ground or the other surroundings of the bridge is a function of the hourly solar radiation. The mentioned thermal loads, composes the main heat source that is responsible on the heating of the bridge. Fig. 3(c) shows the hourly solar radiation distributions during the selected days. It is obvious that solar radiation on horizontal surfaces is maximum in summer and minimum in winter, while both spring and autumn show moderate values. The recorded maximum hourly solar radiations in spring, summer, autumn, and winter during the whole test period were recorded in 16-April-
2014, 18-July-2013, 6-October-2013, and 3-December-2013, which were 1129, 1168, 1038, and 796 W/m², respectively.

Fig. 3. Ambient thermal loads records for the selected days: (a) air temperature, (b) wind speed, and (c) global solar radiation on horizontal surface

4. Temperature-time curves of thermocouples
In this section, the variation of temperature with time along a complete one-year period is presented for selected thermocouples from the four groups. Figs. 4 to 6 show the daily maximum and minimum temperatures along thermocouples SW1, SW6, SW11, NW9, TS1, TS9, BS1, and BS5 for the period extended from July 2013 to July 2014. The selected thermocouples were chosen so that they can present the temperature variation along the vertical and lateral members at different locations. SW1 and SW6 can show the effect of concrete thickness above the top thermocouples along the webs, while SW11 and NW9 can show the differences between the temperature variations of the exterior and interior thermocouples across the central depth of webs. TS1 and TS9 are the edge and the central thermocouples in the top slab, while BS1 and BS5 are their corresponding ones in the bottom slab.

Comparison between Figs. 4(a) and 4(b) show that the variation in the daily maximum and daily minimum of the webs' thermocouples is strongly affected by the location from the top surface, thus, from the direct exposure to the environmental thermal loads. The surface thermocouple SW1 shows higher variation between the daily maximum and minimum than SW6. The maximum daily temperature differences (daily maximum - daily minimum) of SW1 and SW6 were 26.7 °C and 18 °C.

The comparison between NW9 (exterior surface) and SW11 (interior surface inside the BG cavity) clearly reveals that the temperature of the interior thermocouples inside the BG exhibited much lower daily temperature fluctuation than the opposite exterior thermocouples. As shown in Figs. 4(c) and 4(d), the differences between the daily maximum and minimum temperatures were higher in NW9 than in SW11. The maximum daily temperature differences of SW9, SW11, NW9, and NW11 were 20.5, 10.4, 16.9, and 8.4 °C, respectively.

As shown in Figs. 5(a) and 5(b), and due to its direct exposure to air temperature, solar radiation, and wind cooling, the exterior edge thermocouple TS1 showed higher daily temperature variation than the central thermocouple TS9. The maximum daily temperature differences of TS1 and TS9 were 28.9 °C and 15.9 °C. Figs. 6(a) and 6(b) show that the bottom slab's exterior edge thermocouple BS1 and the bottom slab's central thermocouple BS5 exhibited lower differences compared to those between TS1 and TS9. This is an expected result because the effect of thermal loads, especially solar radiation, is lower on the bottom slab than on the top slab due to the different locations and configurations. The maximum daily temperature differences of BS1 and BS5 were 19.4 °C and 9.2 °C.
Fig. 4. Daily maximum and daily minimum temperatures from July 2013 to July 2014 for thermocouples (a) SW1, (b) SW6, (c) NW9, and (d) SW11

Fig. 5. Daily maximum and daily minimum temperatures from July 2013 to July 2014 for thermocouples (a) TS1 and (b) TS9
5. Results of selected days

The temperature distributions along the webs and the slabs at time steps of maximum temperature gradients are discussed in this section for selected days. Table 1 shows the thermal loads and the recorded maximum vertical and lateral temperature gradients of the selected days. The presented days are those with the maximum hourly solar radiation and the maximum daily air temperature difference along the four seasons of the year. In addition, the days with the recorded maximum vertical and lateral temperature gradients are presented.

Table 1 Thermal loads and maximum vertical and lateral temperature gradients of the selected days.

| Day     | Daily air temperature difference °C | Max. hourly solar radiation W/m² | Daily ave. wind speed m/s | Max. vertical temperature gradient °C | Max. lateral temperature gradient °C |
|---------|-------------------------------------|----------------------------------|---------------------------|--------------------------------------|-------------------------------------|
| 18-Jul-2013 | 10.3                                 | 1162                             | 2.55                      | 16.02                                | 8.81                                |
| 6-Oct-2013  | 9.3                                  | 1038                             | 1.4                       | 11.74                                | 12.55                               |
| 11-Oct-2013 | 23.6                                 | 783                              | 0.58                      | 14.18                                | 18.37                               |
| 3-Dec-2013  | 14.1                                 | 796                              | 0.93                      | 7.63                                 | 11.01                               |
| 22-Dec-2013 | 18.4                                 | 526                              | 0.59                      | 11.01                                | 19.0                                |
| 22-Mar-2014 | 18.6                                 | 821                              | 0.6                       | 16.6                                 | 15.2                                |
| 16-Apr-2014 | 9.2                                  | 1129                             | 1.07                      | 12.66                                | 5.93                                |
| 10-Jun-2014 | 19.2                                 | 973                              | 1.23                      | 18.56                                | 9.01                                |
| 14-Jun-2014 | 16.6                                 | 1015                             | 0.96                      | 19.71                                | 8.39                                |

5.1. Maximum vertical and lateral temperature distributions for the selected days

Fig. 7(a) shows the maximum vertical temperature distributions in the selected days, which were all recorded along the south web. The presented distributions are termed as "maximum distributions" because from which the maximum vertical temperature gradients are derived. It is clear in the figure, that the average web temperature was higher in the hot days, thus in 18-July, 10-June, and 14-June than in other days, while the lowest average temperatures were recorded in December. The spring and autumn distributions seem to have close average web temperatures as shown in the distributions of 6-October, 11-October, 22-March, and 16-April.
The temperature distributions of the hot days show steeper temperature variation along the depth of the top slab. The temperature decreased from the highest temperature at the top slab sharply to the lower end of the web-slab's junction (0.4 m below the top surface), then followed by a mode of temperature stabilization along the clear depth of the web (from the top slab's junction to the bottom slab's junction). Along the depth of the bottom slab, a minor temperature increase occurred as shown in Fig. 7(a).

The distributions of October and March show lower temperature variations across the top slab. Another notice is that the region of stable or semi-constant temperature along the web seems to be shorter from the top slab's junction to about the mid height of the web. Below the mid height of the web, the temperature increased gradually down to the bottom surface of the bottom slab. The temperature at the bottom surface was significant compared to the top surface's temperature. The temperature distributions of winter (December) show much lower temperature variation across the top slab compared to hot days. In addition, the temperature difference between the top surface and the bottom surface was low as shown in Fig. 7(a).

Fig. 7(b) shows the temperature distributions along the top slab in the selected days and at the time steps of maximum lateral gradients. As discussed in Fig. 7(a), Fig. 7(b) shows that the average temperatures of the slab were much higher in summer compared to winter or even spring and autumn. Two important notes can be drawn from Fig. 7(b). The first is that for all days, the temperature was almost stable along the interior width of the slab (between webs), while significant temperature variations occurred along the southern and northern cantilevers. The second note is that the maximum temperature variations occurred always at the southern edge of the slab and that it was much higher in winter (December) and autumn (October) than in summer (June and July) as shown in Fig. 7(b) and listed in Table 1.

5.2. Vertical and lateral temperature distributions in the selected days

From the presented nine days in Table 1, two days were selected for more-detailed presentation. The selected days were 22-December-2013 and 14-June-2014, in which the maximum lateral and vertical temperature gradients were recorded. The vertical distributions along SW and NW in addition to the lateral distributions along TS and BS are visualized for selected time steps. The presented time steps are 6:00 AM, 12:00 PM, 3:00 PM, and 6:00 PM.
5.2.1. Vertical and lateral temperature distributions in 22-December

Fig. 8(a) shows the vertical temperature distributions along the SW in 22-December. It is shown that solar radiation has almost equivalent effect on both the top horizontal surface and the southern vertical surfaces. In winter, sun rises in the southeast, moves along the south of the zenith and sets in the southwest. Thus, solar radiation affects the southern surfaces of the girder, while the northern surfaces are shaded. This explains why the temperatures of the southern web (especially nears the mid-height) were as high as the temperatures of the top surface during the day hours. The recorded temperatures at the top surface at 12:00 PM and 3:00 PM were 12.4 °C and 15.2 °C, while the temperatures at 1.6 m below the top surface were 14 °C and 17.1 °C. At the same time steps, the temperatures at the bottom surface were close to those at the top surface, which were 11.3 °C and 16.3 °C. The temperatures of the web kept high after sunset compared to the temperatures of the top and bottom surfaces as shown in the temperature distribution at 6:00 PM.

Fig. 8(b) shows that the temperature distributions along NW were much stable along the clear height of the web than along SW. This is attributed to the stabilized shading effect, hence, the limited solar radiation effect on the north web during the day hours. The effect of solar radiation on the top and bottom surfaces was close to that of the south web. The temperatures of the top surface thermocouple NW1 at 12:00 PM and
3:00 PM were 9.8 °C and 11.7 °C, while the corresponding temperatures were 6.7 °C and 10.4 °C at the bottom surface. During the night hours, the temperature of the web decreased but still semi-uniform along the mid-height of the web, while the temperatures at the top and bottom surfaces decreased noticeably due to the convection cooling and the surface re-radiation.

Figs. 8(c) and 8(d) show that almost at all of the time steps, the temperature was semi-uniform along the interior width of the slabs, while the temperatures of the edges were higher during the day and lower during the night. Since the effect of solar radiation on the southern surfaces was much higher than on the northern surfaces, the maximum temperatures occurred at the southern edges of TS and BS with the maximum temperature jump (compared to interior thermocouples) occurred at 12:00 PM. Another notice is that the temperature distributions along the bottom slab were more stable than along the top slab, which is attributed to the lower effect of solar radiation on the bottom slab compared to the top slab.

5.2.2. Vertical and lateral temperature distributions in 14-June

For design purposes, the vertical temperature distributions in 14-June are more important than from the other days. The vertical temperature gradients are much higher in summer than in other seasons. Therefore, the design gradients are calculated for summer conditions in all of the current bridge design codes. In June, the sun rises in the northeast moving towards the south, crossing the east-west-zenith plane about two to three hours before the noon. This movement is then reversed, from the south to the north, reaching the sunset in the northwest. Thus, solar radiation on horizontal surfaces is much higher than on vertical surfaces, also solar radiation on the north web is very limited during the mid-day hours. Therefore, solar radiation increases the temperature of the top surface noticeably during the day's hot hours, which leads to much higher temperatures at the top surface compared to the rest parts.

Figs. 9(a) and 9(b) clearly illustrate that the temperatures at the top surface were much higher than the mid-height temperatures, which resulted in higher temperature gradients. At 12:00 PM and 3:00 PM, the temperatures at the top surface of SW were 43.5 °C and 47.5 °C, while the temperatures at the mid-height of SW were 26.4 °C and 28.3 °C. Similarly, the temperatures at the top surface of NW were 40.7 °C and 45.2 °C, while the temperatures at the mid-height of NW were 26.2 °C and 28.3 °C. Another difference between the vertical temperature distributions of 14-June from those in winter and spring is that due the high altitude of the sun, solar radiation has much lower effect on the bottom surface compared to the top surface. The temperatures at the bottom surface at 12:00 PM and 3:00 PM were 33 °C and 35.2 °C for SW, and 29.3 °C and 32.5 °C for NW. The vertical temperature distributions during the cold hours show that as in winter, the temperatures of the top and bottom surfaces decreased noticeably to be lower than along the interior depth of the webs as shown in the temperature distributions at 6:00 AM.

Figs. 9(c) and 9(d) show the temperature distributions along the width of the top and bottom slabs, in which it is clear that the temperature jumps at the southern edges were lower than those in December. Because of the sun movement in summer, the temperature jumps at the northern edges were equivalent to those at the southern edges. The temperatures of the northern thermocouples (TS17 and BS9) were higher than the southern ones (TS1 and BS1) at times close to sunrise and sunset (6:00 AM and 6:00 PM).
Based on the recorded temperature distributions along the depth of the experimental BG segment in 14-July, vertical temperature gradient model is proposed in this study for single-cell box-girders. The model composed of three parts as shown in Fig. 10. The first part is a tri-linear that extends along the webs from the top surface to 1.2 m below with a maximum surface temperature $T$. The second part is a bilinear that extends along the thickness of the top slab (above the BG's cavity) with a maximum top surface temperature of $0.6T$, while the third is another bilinear that extends along the thickness of the bottom slab with a maximum temperature gradient at the bottom surface of $0.2T$. The temperature $T$ should be determined based on an extreme value analysis for each region depending on the solar radiation and daily air temperature-difference record-history and with a suitable return period.

The recorded maximum vertical temperature gradient in 14-July was 19.7 °C. This temperature was set as the temperature $T$ in the proposed temperature gradient model for comparison purposes. Figs. 11(a) and 11(b) show that the proposed gradient model follows the same variation of the recorded vertical temperature.
gradient. The temperature errors between the experimental and the proposed vertical gradients are minimal as shown in the figures.

All dimensions in mm, \( t_{TS} \): thickness of top slab, \( t_{BS} \): thickness of bottom slab, \( D \): depth of the superstructure

Fig. 10. The proposed vertical temperature gradient distribution

Fig. 11 The experimental and the proposed vertical temperature gradient distributions: (a) along the webs and (b) across the thickness of the top and bottom slabs

6.2. Comparison with AASHTO's and Bridge Manual's temperature gradients

The AASHTO's [15] and the NZ Bridge Manual's [18] gradient models were used to compare with the proposed model. From weather record history of about 40 years of Gaziantep/Turkey, the average daily global solar radiation in June and July was around 24 MJ/m². Therefore, zone 2 of the AASHTO model was selected for the comparison purpose. The self-equilibrating stresses were calculated based on the uncracked section as detailed by Ghali et al. [20] for the experimental BG segment and the deflection was calculated based on an assumed 40 m simply supported span.
The stress at the top surface was 3.86 MPa for the experimental temperature gradient, while for the proposed, the AASHTO, and the NZ models, the stresses at the top surface were 3.82, 2.4, and 3.67 MPa, respectively. On the other hand, the maximum deflections (considering vertical gradients only) at the mid span due to the experimental gradient and the proposed model were 3.6 and 3.62 mm, while for the AASHTO and the NZ models, the maximum deflections were 10.1 and 4.7 mm, respectively.

In addition to the shape and depth of the gradient model, another difference between the NZ and the AASHTO models is that NZ suggests different distribution of temperature along the thickness of the top slab above the BG’s cavity. The area of the top slab is larger than that of webs and has a longer moment arm to the center of gravity, hence the resultant axial force and bending moment of the top slab are higher and controls the net self-equilibrating stresses. Therefore, AASHTO model leads to different stress distribution, also it over estimates the thermal bending moment and hence the deflection, while the NZ model shows closer stress distribution and deflection to that of the experimental gradient.

In the current proposed model, the importance of the existence of a different temperature distribution along the thickness of the top slab (above the box cavity) was recognized as shown in Fig. 10, which in result led to very close stress distribution and almost identical deflection.

7. Conclusions

Based on more than one-year temperature and solar radiation records from a full-scale experimental concrete box-girder segment, and within the limits of the current study, the below points can be concluded:

1- The daily temperature records of 62 thermocouples along a complete one-year cycle showed that the differences between the recorded daily maximum and minimum temperatures were higher for surface thermocouples than for interior thermocouples. The recorded maximum daily temperature differences for SW1 and SW6 were 26.7 °C and 18 °C, while were 20.5 °C and 10.4 °C for SW9 and SW11. Similarly, the maximum daily temperature differences for TS1 and TS9 were 28.9 °C and 15.9 °C, while for BS1 and BS5 were 19.4 °C and 9.2 °C.

2- Along the complete test period, the maximum vertical temperature gradient was recorded in June and was approximately 20 °C, while the maximum lateral temperature gradient was recorded in December along the top slab and was 19 °C. In summer, the temperatures of the top surface were much higher than the interior and the bottom surface temperatures, which resulted in higher vertical temperature gradients compared to the other seasons. In addition, the variation of temperature within the top 0.4 m of the web height, and especially across the thickness of the top slab, was higher than in other seasons.

3- A multi-linear temperature gradient model was proposed based on the experimental gradients of this study. The proposed gradient model recognized the importance of the existence of different temperature gradient distribution across the top slab thickness above the cavity of the BG from that along the webs. The proposed gradient model composes of three parts. (1) A tri-linear temperature gradient along the webs from the top surface to 1.2 m depth with a maximum surface temperature T. (2) A bilinear gradient along the thickness of the top slab (above the BG's cavity) with a maximum top surface temperature of 0.6T. (3) Another bilinear along the thickness of the bottom slab with a maximum temperature gradient at the bottom surface of 0.2T. The proposed gradient model showed minor temperature deviations from the experimental maximum gradient distribution and resulted in much closer self-equilibrating stresses and deflection to those of the experimental distribution compared to the AASHTO’s and the NZ Bridge Manual’s gradient models.

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