Design Temperatures for Composite Concrete-Steel Girders: B- Case Study

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Abstract. Long-term metrological records for Adana city, which is located in the Mediterranean region in Turkey, were facilitated in this study together with a verified finite element thermal model. The aim of this study is to investigate the sectional temperature gradients in concrete-steel composite bridge girders. Solar radiation and air temperature history of more than 50 years was used, and a practical-size typical composite bridge girder was modeled for six selected months that represent the conditions of the four seasons in Adana. The analysis showed that the behaviors of positive vertical and lateral temperature gradients in summer were completely different from those in winter, while the negative temperature gradients exhibited similar sectional distributions in all seasons. The results also showed that the maximum vertical temperature gradient occurred in summer, while the maximum lateral temperature gradient occurred in winter. The maximum positive vertical gradients occurred at the top concrete surface in summer and within the steel web in winter. For the investigated conditions, the recorded maximum positive vertical gradients in summer and winter were approximately 15.0 and 12.2 °C, respectively, while the maximum positive lateral temperature gradients in summer and winter were approximately 6.1 and 10.9 °C, respectively.

Keywords: Composite girder; temperature gradients; thermal analysis; solar radiation.

1. Introduction
A simple and widely used technique to construct a bridge superstructure is by the use of series of parallel beams that are simply supported on interior piers or end abutments. These beams are topped with a concrete deck slab to form the runway surface of vehicles and pedestrians. The beams are mostly precast prestressed concrete beams or steel I-beams. The available bridge design standards [1-5] provide sufficient details for all types of loads. One of these load types is the ambient field thermal load including air temperature and solar radiation. The effect of the field thermal loads on bridge structures is twofold; the first is the overall temperature difference of the superstructure that causes axial movements or end moments, while the second is the temperature gradient along the depth of the superstructure that induce self-equilibrating stresses in the section [6-8]. The first is resolved in bridge design codes by subjecting the structure to design maximum and minimum temperature differences, to
which the end deformations or moments are calculated based on the construction mean temperature. On the other hand, virtual vertical gradient models are introduced for the different types of structures to calculate the induced stresses [9-11].

The thermal action provisions of the British, New Zealand and USA bridge codes were the earliest ones and were mostly conducted based on few leading researches [12-15]. Since that time, this issue was the focus of tens of research projects around the world. Although of the extensive literature available on thermal actions in concrete [16-19], steel [20-22] and composite [23-26] bridges, researches are still conducted in this field. The need of continuous research in this field arises from three major reasons. The first is the scientific challenges of the continuous development of new building materials and construction technologies. This reason pushes the transportation and research associations in different countries to support the costly research in this vital field, where extensive field structural control studies [27-31] and experimental measurements researches [32-37] were conducted recently. The second reason for the need of more studies to understand the effect of field thermal loads on bridge structures is the different configurations of the superstructure, where previous studies showed that the temperature gradient distributions in deep box-girders [38] or special non-standard precast girders [39] would behave differently from standard provisions. The third reason is the spatial dependent of such issue, where thermal loads are different for the different geographical locations. This means that the design temperature difference and the temperature gradient of some practice codes may not be applicable for other locations.

This research is a case study to evaluate the temperature gradients of concrete-steel girders in typical composite bridge superstructures in Adana/Turkey climate conditions. The article is a second part of a finite element research conducted for this purpose. In the first part, a finite element thermal model was introduced and verified with specially made experimental composite girder segment. In this article, the verified finite element thermal model is used together with extreme climate thermal records for more than 50 years for Adana Mediterranean region. The long term history records of solar radiation and air temperature were analyzed and different extreme conditions were selected to represent the four seasons of the year. Using the selected extreme records and the verified finite element model, the temperature gradients were investigated for a practical-size girder segment.

2. The finite element thermal analysis
Based on the verified finite element thermal analysis from the first part of this research, a practical size model was constructed to include the possible size effect. The model was composed of a steel beam that has a flange width of 400 mm and a web depth of 1200 mm, which is topped by a concrete slab of 200 mm thickness. The slab width is 2000 mm, which is within the range of typical center-to-center spacing of adjacent girders in such type of composite bridge superstructures. On the other hand, the segment length was kept as 1000 mm to reduce the calculation time. The model was constructed, meshed and loaded using the same procedure described in part 1, where COMSOL multyphysics package [40] was used. Figure 1 shows the finite element geometry and mesh of the conducted composite beam.

3. The case study location and metrological history
Adana is a city that is located in the Mediterranean region in the south of Turkey with the geographical location of 36.98N latitude and 35.35E longitude as shown in the red circle in Figure 2. The verified COMSOL finite element thermal model, presented in the first part of this research, was adopted to analysis the temperature distributions in the composite beam using the long-term air temperature and solar radiation records of Adana. The long-term solar radiation and air temperature records of the city for approximately 50 years were facilitated in this research. The maximum vertical and horizontal temperature gradients of the composite concrete-steel bridge girders in Adana were investigated for six months, in which the maximum vertical and lateral temperature gradients are typically occur.
The data were provided by the Turkey State Meteorological Service include air temperature and solar radiation records for more than 50 years, since 1960 to 2013. These data were used to evaluate the extreme temperature and temperature gradients in composite concrete-steel girder bridges. The analysis was carried out for six different months that represent the four seasons of the year, which are April, June, July, October, November and December. The selected day of each month reflects the maximum daily air temperature difference. For each of these six months, the maximum daily average of total solar radiation was considered. The wind speed was taken as zero to maximize the temperatures and temperature gradients. The data listed in Table 1 represent the daily air temperature and solar radiation for Adana in the six months.

| Month     | Daily maximum hourly solar radiation W/m² | Daily air temperature °C |
|-----------|------------------------------------------|--------------------------|
|           | Maximum         | Minimum         | Difference |           |
| April     | 938.66          | 35.6            | 11.6       | 24         |
| June      | 960.87          | 40.8            | 18.5       | 22.3       |
| July      | 936.33          | 44              | 22.7       | 21.3       |
| October   | 798.63          | 38              | 15.8       | 22.2       |
| November  | 588.59          | 32.6            | 10.9       | 21.7       |
| December  | 551.38          | 30.8            | 8.6        | 22.2       |
4. Temperatures and temperature gradients
This section studies the maximum vertical and horizontal temperature gradients in the six selected
months. Figure 3 shows the noon (13:00) temperatures in 3D visualization for the composite beam
segment in selected days from the six tested months, while Figure 4 shows the 3D distributions during
the midnight hours. It is obvious that the highest daily temperatures were recorded in summer (June
and July), while the lowest were recorded in Winter (December). The temperatures were in the range
of approximately 45 to 63 °C in July, while ranged from approximately 21 to 32 °C in December.

Figure 3. Three-dimensional noon temperature distributions in the six months
Figure 4. Three-dimensional midnight temperature distributions in the six months
Similarly, Figure 4 shows that for the investigated days, the maximum beam temperature at midnight of the investigated day in June was approximately 42 °C, while the lowest was approximately 25 °C, which were close to but lower than those recorded in July that were approximately 44 and 29 °C, respectively. On the other hand, the maximum and minimum daily temperatures of the investigated case in December were approximately 25 and 15 °C, respectively. It is also shown in Figures 3 and 4 that the beam exhibited similar temperatures in spring (April) and autumn (October), which were in general lower than summer temperatures and higher than winter temperatures. It should be noticed that higher and lower temperatures can be recorded within the investigated months. The investigated days were selected so that the temperature gradients could be the highest, which require the highest daily temperature differences and solar radiations. Hence, the focus was not on the maximum and minimum daily temperatures.

The results of the maximum vertical positive and negative temperature gradients for Adana in the six tested months are shown in Figures 5 and 6. The maximum positive gradients of Adana city were 15.05, 15.48, 14.49, 13.33, 13.11 and 12.25 °C in April, June, July, October, November and December, respectively as shown in Figure 5. The figure shows explicitly that different vertical temperature gradient distributions can be easily recognized between summer and winter. It is obvious in the figure that in the hot season, the maximum values of the maximum vertical positive temperature gradients occur at the top of the segment (concrete part), while the maximum value takes place in the bottom part (steel part) in the cold season. The different behaviors are attributed to the different sun movements during the two seasons. Where solar radiations in summer strike mostly the horizontal surfaces (top concrete flange) due to their higher inclination angles with the horizon. This results in higher heating on the concrete flange than on the steel web and lower flange. On the other hand, the low striking angles in winter accumulate the heating budget on vertical surfaces (web of the steel section), which increase the temperature of this part compared to the top surface. For the same reason, it is also shown in the figure that at the time of maximum vertical gradients, the temperature of the lower steel flange is higher than web temperature in summer (June and July), while the opposite stands in winter (December). Another notice is that in summer, the maximum temperature difference occurs across the concrete flange, where it is in general more than 14 °C for the investigated cases. On contrary, the temperature gradient across the top concrete flange is approximately 2 °C in December. The temperature gradient in April follows the same trend of variation with section depth to that of summer as shown in Figure 5, yet with higher temperature gradient along the web and at the steel’s bottom flange. This minor deviation is attributed to the slightly lower inclination angles of sunrays in April. On the other hand, the gradients in autumn (October and November) flowed the same trend of variation of December, but with higher gradients at the top surface and the bottom steel flange. This difference in gradients is attributed to the higher solar radiations and lower solar angles compared to December. The maximum temperature gradient at the top surface of the girder (concrete flange) equals 15.05, 15.48, 14.49, 6.08, 3.32 and 2.13 °C in April, June, July, October, November and December, respectively, while the sequence for the maximum temperature along the steel beam is 11.11, 6.27, 7.01, 13.33, 13.11 and 12.25 °C, respectively.

Figure 6 shows the maximum vertical negative temperature gradients in Adana for the same six months. On contrary to the different variation trends of the positive vertical temperature gradient with the depth of the girder in the six months, the negative temperature gradient exhibited the same trend for all months. In general, three nonlinear gradient distribution regions can be distinguished for all months. As shown in Figure 6, low gradients were recorded at the top concrete surfaces that range from approximately 2.0 to 3.0 °C for all months with the zero gradient occurs within the topping concrete. Then the gradients vary nonlinearly along the steel web with significant negative gradients range from more than 8.0 to approximately 12.0 °C. Finally, it is noticed in the figure that there is a trend of stabilized gradient along the lower half of the steel beam. For Adana city, the maximum negative temperature gradients at the top surface of the concrete flange were -2.61, -2.93, -3.05, -2.48,-2.21 and -1.96 °C in April, June, July, October, November and December, respectively, while
the maximum values along the steel beam were -11.35, -11.84, -11.99, -9.98, -9.07 and -8.35 °C, respectively. It can be summarized that both positive and negative vertical temperature gradients reach their higher values in summer and lowest values in winter.

Figure 5. Maximum vertical positive temperature gradients in Adana.

Figure 6. Maximum vertical negative temperature gradients in Adana.

Figures 7 shows the maximum positive lateral temperature gradient calculated along the width of the top concrete flange. As for the positive vertical gradients, different distinguished variation trends are obvious for summer and winter. It is shown that for summer months (June and July) and April, three different regions can be distinguished for the mid-day lateral gradients. The zero gradient is located at the northern edge which increases almost linearly to reach the second region, which is a semi-stabilized region along most of the interior width of the top surface. Then after followed by the third region which is a continuous increase that ends with the maximum lateral temperature gradient at the southern edge. This trend is attributed to the movement of sun in summer, where the sun rises and sets at the north-east and north-west, which increases the temperature of the northern edge at these times compared to the southern edges. During the late morning hours and the few afternoon hours after mid-day, the sun moves completely to the south of the equatorial plane, which means that northern surfaces do not receive any solar radiation at this time. This would of course increase the temperature of southern edges and decrease the temperature of northern edges leading to the distributions shown in Figure 7 for June, July and April. On the other hand, the lateral temperature gradients in winter showed more elegant distribution with a temperature rise at both edges and semi-stable interior region. However, the maximum vertical gradient is also recorded at the southern edge, which is noticeably
higher than the northern edge. This is because sun moves along the southern are of the equator along the full day hours. Hence sun rises at south-east and sets at south-west, which assures continuous heating of the southern surface along the whole day. On the other hand, the low solar inclination angles in winter lead to much lower heating of the top surface compared to the edges. As a result, the temperature of the top surface is lower than both edges. To summary, the maximum lateral temperature gradients occur in winter and are located at the southern edge of the top concrete flange, while summer conditions lead to much lower lateral temperature gradients. The maximum positive lateral temperature gradients in April, June, July, October, November, and December were calculated to be 6.12, 4.29, 5.56, 10.05, 10.44 and 10.88 °C respectively.

As recorded for the negative vertical gradients, the negative lateral temperature gradients also exhibited a similar trend of variation for the six months as shown in Figure 8, which shows the maximum negative lateral temperature gradients for Adana in the six months. The distributions show almost equal lateral gradients at both edges and a semi-stabilized interior region. The maximum negative lateral gradients of Adana were -4.54, -5.1, -4.73, -5.98, -5.01 and -5.12 °C in April, June, July, October, November and December, respectively.

![Figure 7](image1.png) **Figure 7.** Maximum lateral positive temperature gradients in Adana.

![Figure 8](image2.png) **Figure 8.** Maximum lateral negative temperature gradients in Adana.
Figure 9 shows the average temperature of the whole composite girder along the 24 hours of the selected days from the six months. These temperatures were calculated by the model by integrating the products of element areas by their temperatures. On the other hand, the maximum and minimum temperatures of the girders in the same days are shown in Figures 10 and 11, respectively. The first notice on the figures is that all of the girder temperatures change in a sinusoidal fashion, which reflects the strong influence of air temperature on the maximum, minimum, and average temperatures of the beam. The second general notice is that the maximum values of maximum, average and minimum temperatures were recorded in July (hottest selected day), while the minimum values were recorded in December (coldest selected day).
5. Conclusions
Long-term metrological history for the Mediterranean Adana region was facilitated in a finite element thermal study to investigate the extreme temperature gradients in composite bridge girders in this region. Within the limits of the investigated parameters, the followings are the most important conclusions:

1- The sectional distribution behaviors of the positive vertical and lateral temperature gradients in summer were different from their corresponding behaviors in winter, while similar vertical and lateral gradient distributions were recorded for the negative temperature gradients in summer and winter. The maximum vertical gradients were recorded in summer while the maximum lateral gradients were recorded in winter.

2- The predicted maximum positive vertical temperature gradients in Adana city were approximately 15.0, 15.5, 14.49, 13.3, 13.1 and 12.3 °C in April, June, July, October, November and December, respectively, which were recorded in the top concrete surface in the hot months and within the steel web in the cold months. On the other hand, the maximum negative vertical gradients were recorded within the steel web in all seasons, which were approximately 11.4, 11.8, 12.0, 10.0, 9.1 and 8.4 °C for April, June, July, October, November and December, respectively.

3- The maximum values of the positive lateral temperature gradients along the centerline of the topping concrete flange were occurred at the southern edges in all months. The highest lateral gradients were recorded in winter and the lowest were recorded in summer, which is attributed to the low inclination angles of solar radiations in winter. The maximum recorded gradients were approximately 6.1, 4.3, 5.6, 10.0, 10.4 and 10.9 °C in April, June, July, October, November, and December, respectively.

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