Investigation of temperature gradients in composite girders in the southern region of the black sea

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Abstract. Based on an experimental composite concrete slab-steel beam girder and using a verified finite element thermal model, a case study analysis was performed to evaluate the temperature gradients in composite girders in the Black Sea’s Turkish city Samsun. The case study was conducted based on extreme data records of approximately 50 years. The extreme daily solar radiation and air temperature difference were utilized in finite element thermal analysis for six months that represent the different seasons of the year. The investigated months were the hot months (April, June, and July) and cold months (October, November, and December). The study focused on the vertical temperature gradients (along the vertical centerline of the girder) and the lateral temperature gradients (along the horizontal centerline of the topping concrete slab). The finite element results showed that the maximum vertical temperature gradient occurred in June and was 13.55 °C, while the maximum lateral temperature gradient occurred in December and was 10.11 °C. The results also showed that different behaviors of the positive vertical gradient were recorded for the cold months than those for the hot months. Similarly, the distributions of the positive lateral gradients were different for the two groups of months. These differences were attributed to the different sun movements and solar radiation striking angles in summer and winter.

1. Introduction
In most of the recent bridge design specifications, the thermal actions due to the influence of exterior exposure conditions are considered in the design of all types of bridge structures. The exterior exposure means that the bridge structure is always subjected to the continuously changing climate thermal loads. The most influential of which is the solar radiation and air temperature, while wind speed is also an effective cooling load. The actions of the atmospheric thermal loads that are required to be considered by bridge specifications are two types. The first is the daily and season-to-season mean temperature change of the bridge structure. This temperature change is calculated as a difference from the construction temperature. If the overall mean temperature of the superstructure increased it would expand along its runway span, while it would shrink if its mean temperature decreased. Hence, longitudinal thermal movements are the expected actions if the spans are simply supported. If, however, the span ends are restricted, then the restricted end movements would cause end moments [1-6]. The second action of temperature change is the daily rising and dropping sectional temperature gradients. The available design provisions recommend considering the effect of self-equilibrating due to the temperature gradients along the vertical axis of the superstructure. Different linear or nonlinear gradient models are proposed by the design provision to calculate for the different superstructure types [7-11].
Owing to the continuous development in the construction industry and material science, several researches were conducted during the last two decades to evaluate and improve the adequacy of the design provisions. A better understanding of the thermal movements in the bridge girders was the target of several field studies [12-18], experimental studies [19-27], and numerical studies [28-35]. The finite element method was used extensively to conduct parametric studies that were difficult to be conducted experimentally due to the extremely costly construction and instrumentation programs. On the other hand, other studies [4, 36-38] used the experimental records or historical records of climate conditions for a long period to evaluate the expected thermal actions based on the long-term extreme conditions. Based on these studies, statistical formulas were introduced to evaluate the daily temperature changes and most severe positive and negative temperature gradients. Simplified formulas were introduced by some studies to calculate the vertical and lateral temperature gradients in concrete and composite girders.

In this work, a gradient analysis case study is introduced based on a finite element model which was first verified using an experimental steel-concrete composite girder [25]. The analysis includes the studying of the temperature gradients in concrete slab-on-steel beam girders. The vertical gradient along the depth of the girder and the lateral gradient along the top concrete slab was investigated for six months that represent the four seasons of the year. The analysis was conducted based on extreme weather records for approximately 50 years for a humid subtropical-climate Turkish region. The input extreme thermal loads include the air temperature, solar radiation, and wind speed of Samsun city, which is located on the southern coast of the black sea.

Figure 1. The location of Samsun (Black sea region/Turkey).

2. The case study and climate history
Samsun is one of the famous Turkish cities that is located on the Black Sea coast with a latitude and longitude of 41.28 N and 36.33 E as shown in Figure 1. The weather of Samsun is classified as a subtropical climate with moderately hot summers and cold winters. The solar radiation of this region in summer is generally not as high as along the Mediterranean coast, where daily maximum solar radiation intensities of more than 800 W/m² are generally recorded during the sunny summer days. On the other hand, the general case of the
maximum temperature in the hottest summer days is between 35 and 38 °C, but slightly lower or higher maximum temperatures were also recorded.

The analysis of girder temperatures in this study was conducted based on the weather record history of more than 50 years, which was provided by the Turkish State Meteorological Service. The extreme days were considered for each month based on the daily maximum solar radiation and daily maximum air temperature difference, which was calculated based on the maximum daily maximum air temperature and average daily minimum air temperatures. The extreme records of the selected spring and summer months are given in Table 1, while Table 2 shows the extreme records of the selected autumn and winter months.

Table 1. Extreme solar radiation records for solar radiation and air temperature of Samsun in hot months.

| Month | April | June | July |
|-------|-------|------|------|
| Daily maximum hourly solar radiation (W/m²) | 858 | 861 | 830 |
| Daily maximum air temperature (°C) | 37 | 37.4 | 36.1 |
| Daily minimum air temperature (°C) | 7.7 | 16.7 | 18.4 |
| Daily average air temperature (°C) | 29.3 | 20.7 | 17.7 |

Table 2. Extreme solar radiation records for solar radiation and air temperature of Samsun in cold months.

| Month | October | November | December |
|-------|---------|----------|----------|
| Daily maximum hourly solar radiation (W/m²) | 649 | 516 | 412 |
| Daily maximum air temperature (°C) | 38.4 | 28.8 | 26.9 |
| Daily minimum air temperature (°C) | 14 | 8 | 5.7 |
| Daily average air temperature (°C) | 24.4 | 20.8 | 21.2 |

3. The experimental composite beam
To study the distributions of web and flange gradients, a composite girder was cast and left in an open area in Gaziantep University/Turkey, to be freely subjected to atmospheric air and solar radiation. The girder had the sectional dimensions shown in Figure 2. The girder segment was 500 mm in length and was provided with 14 thermocouples (7 in the concrete slab and 7 on the steel beam) as illustrated in Figure 2. Sufficient details about the experimental composite girder (Figure 3) and the experimental temperature results can be found in a previous study [25]. The temperatures of concrete and steel from the thermocouples and the air temperature, speed of the wind, and total solar radiation were measured every 30 minutes, where the data logger was set to record all the 17 measurements automatically for a long time.

4. The finite element thermal modeling
The thermal analysis of the composite girder was conducted using the multi-physics finite element software COMSOL [39]. The analysis was carried out in two stages. In the first, the finite element model was constructed for the experimental composite girder considering all dimensions and boundary conditions, where the actual time-dependent air temperature, wind speed, and solar radiation from the experimental field were used. These records were fed to the model and the temperature outputs of the steel beam and the concrete top slab were attained along the 24 hours of specific days. The finite element temperatures were compared with the experimental temperatures to verify the constructed finite element model. Once the model was verified, it was used in the second stage to conduct the extreme case study analysis of Samsun city. For which, a practical size girder was modeled and used to analyze the vertical and horizontal gradients in addition to mean temperatures.
To assure high analysis accuracy, the auto meshing option was activated with fine triangular surface elements and tetrahedral volume elements. This option optimizes the best mesh distribution and tenderizes the mesh size around the thermocouple positions to increase the accuracy and reduce the run time. Figure 4 shows the mesh distribution of the modeled experimental girder, where more than 31500 tetrahedral elements and approximately 14000 triangular surface elements were utilized. The density, thermal conductivity, and specific heat of the concrete slab were considered as 2400 kg/m$^3$, 1.5 W/mK, and 900 J/kgK, respectively, while 7800 kg/m$^3$, 44.5 W/mK, and 475 J/kgK were used for the steel beam.

For the second stage analysis, the concrete slab width was taken as 2000 mm with a thickness of 200 mm, while a 1200 mm depth steel beam was used with 400 mm wide flanges. The length of the segment was also increased to 1000 mm, while the same procedure of meshing of the experimental model was used in this stage using the COMSOL finite element software.
To verify the conducted finite element, the temperatures of concrete and steel were compared with the temperatures of the 14 thermocouples installed in and on the experimental composite girder. Figures 5 and 6 show the comparisons for selected thermocouples that represent surface and core concrete temperatures in addition to web and flange steel temperatures. The change of temperature with time could be accurately simulated by the finite element model. The differences between the predicted and recorded temperatures were also reasonable. The differences between the finite element and experimental concrete temperatures from the seven thermocouples were in the range of 0.01 to 4.2 °C. The average 24-hour error of the seven concrete thermocouples ranged from approximately 1.2 to 1.5 °C. Similarly, the average 24-hour error of the seven steel thermocouples ranged from approximately 1.3 to 2.0 °C. Therefore, the introduced finite element thermal analysis model can be considered adequate to be used for the second stage analysis. A similar thermal analysis procedure using COMSOL was verified in previous studies for different types of girders [3, 21, 28].

5. Results and discussion
This section studies the maximum vertical and horizontal temperature gradients in six selected months that represent the hot, cold, and moderate seasons. The six months investigated were April, June, July, September, November, and December. The details of the extreme loads of the selected months are presented in Tables 1 and 2 as introduced in section 2.

5.1. Vertical temperature gradients
The vertical temperature gradients along the vertical centerline of the composite beam are shown in Figures 7 and 8 in the six months. Figure 7 shows the positive (mid-day) vertical temperature gradient distributions, while Figure 8 shows the negative (night) vertical temperature gradient distributions.

It is clear that for the hot season, the maximum values of the maximum vertical positive temperature gradients occurred at the top of the concrete slab, where the maximum temperature of the concrete slab in April, June, July, October, November, and December were 11.42, 13.55, 12.79, 3.71, 0.72 and 1.02 °C, respectively. Oppositely, the maximum gradient values in the cold months were recorded along with the steel web, where the maximum recorded steel gradients were 7.87, 1.82, 5.09, 10.23, 9.14, and 8.83 °C for April, June, July, October, November, and December, respectively. As a result, the maximum temperature

![Figure 5. Comparison between experimental and finite element temperatures of the concrete slab.](image1)

![Figure 6. Comparison between experimental and finite element temperatures of the steel beam.](image2)
gradients in Samsun in April, June, July, October, November, and December were 11.41, 13.55, 12.79, 10.23, 9.14, and 8.83 °C, respectively. The different behaviors of the positive temperature gradient distributions in the hot and cold seasons can be attributed to the different inclination angles of solar radiations in the two seasons. Where, in the hot season, the sun rays strike from high solar altitude angles, leading to a higher heating load on the concrete slab. On the contrary, in the cold season, the sun rays strike from low solar altitude angles during the whole day, which leads to quicker heating for the steel beam compared to the topping concrete slab.

The negative temperature gradient distributions shown in Figure 8 show that the distributions follow almost the same trend of variation in the six months, but with different maximum values. The maximum negative gradients always occur along with the steel web. This behavior can be attributed to the significantly higher thermal conductivity of steel compared to concrete, where the thermal conductivity of steel is approximately 30 times that of steel. Thus, the steel web, which is subjected to the highest cooling budget due to its higher surface area, cools much faster than the concrete slab. Consequently, its temperature drops quickly leading to high negative gradients compared with the concrete slab as shown in Figure 8. The maximum concrete negative temperature gradient values in Samsun in April, June, July, October, November, and December were -2.25, -2.71, -2.85, -2.32, -1.85, and -1.75 °C, respectively, while they were -10.53, -11.05, -11.33, -9.59, -7.89 and -7.49 °C in the steel beam.

![Figure 7](image-url)

**Figure 7.** Positive vertical positive temperature gradients in Samsun in the six months.
Figure 8. Negative vertical positive temperature gradients in Samsun in the six months.

5.2. Lateral temperature gradients
Figures 9 and 10 show the maximum positive and negative lateral temperature gradients calculated along the centerline of the top concrete slab. The gradients were obtained for the investigated six months.

Figure 9 shows that there are two distinguishable differences and one common agreement between the gradient distributions of the hot and cold seasons. The agreement is that for all months, the maximum positive lateral temperature gradients occurred at the southern surfaces of the girder. On the other hand, the first difference is that the maximum lateral gradients are much higher in cold months (October, November, and December) than in hot months (April, June, and July). The maximum positive lateral temperature gradient values (at the southern edge of the concrete slab) in April, June, July, October, November, and December were 5.78, 4.36, 4.95, 8.85, 9.36, and 10.11 °C, respectively. The second difference is that the zero temperature gradient occurs along the middle length of the concrete slab in the cold months, while this part is hotter in the hot months, where the zero temperature gradient occurs at the northern edge of the slab.

The different movement scenarios of sun movement between the hot and cold seasons explain the distinguished differences and the agreement between the two seasons. In winter, the daily radiation from sun rays comes from the southern half of the equator, where sunrises from the south-east and sets at the south-west. Consequently, the northern edges receive the minimum amount of solar radiation along the day, while these radiations are concentrated on the southern edges of the girder. As a result, high maximum lateral temperature gradients are expected at the southern edges of the concrete slab. The low altitude angles of solar radiations in winter explain the low temperatures of the top surface of the slab compared to its edges, which explains the zero gradient lines along the intermediate slab width between edges as shown in Figure 9 for October, November, and December. On the other hand, the solar radiations in the hot months strike from higher altitude angles, which results in a higher heating load on the top surface of the girder. Consequently, the zero temperature gradient is shifted from the interior mid-width of the slab to the northern edge. For the same reason, the lateral gradients in the hot season are much lower than the vertical gradients and much lower than the lateral gradients in winter.
Figure 9. Positive lateral temperature gradient distributions.

Figure 10 shows that as for the negative vertical temperature gradients, the negative lateral temperature gradients exhibited almost the same behavior and close maximum gradient values in the cold and hot months. This similarity is attributed to the absence of solar radiations that makes the large differences in positive temperature gradients. The edges are subjected to a quicker cooling load due to the larger exposed surface area compared to the interior cores, which results in steep negative gradients at both edges compared to the mid-width of the concrete slab as shown in Figure 10. The recorded maximum lateral temperature gradients in Samsun in April, June, July, October, November, and December were -5.4, -5.1, -4.58, -5.7, -4.13, and -4.33 °C, respectively.

Figure 10. Negative lateral temperature gradient distributions.
6. Conclusions
Based on the results obtained from the finite element case study presented in this article, the following are the most important concluding remarks.

1- In general, the maximum positive vertical temperature gradients were recorded in summer, while the maximum positive lateral temperature gradients were recorded in winter. The maximum positive vertical temperature gradient was 13.55 °C which was recorded in June, while the maximum positive lateral temperature gradient was 10.11 °C and was recorded in December.

2- The distributions of the positive vertical temperature gradient in the hot months (April, June, and July) were different from those in the cold months (October, November, and December). The two main differences were the location of the maximum gradient and the value of the maximum gradient. In the hot months, the maximum gradient was recorded at the top surface of the concrete slab with a much lower gradient and less variation along with the steel web. On the contrary, the maximum gradient variation and maximum positive gradient values were recorded along with the steel web in the cold months (October, November, and December). The different behaviors were attributed to the different striking angles of solar radiation in the different seasons. The maximum vertical temperature gradients in Samsun in April, June, July, October, November, and December were 11.41, 13.55, 12.79, 10.23, 9.14, and 8.83 °C, respectively.

3- Similarly, the distributions of the positive lateral temperature gradients were different in the hot months from those in the cold months due to the different sun movements and sun rays' striking angles. The maximum gradients were recorded at the southern edge for all months but with significantly higher values for the cold months. The zero gradients were located along the slab mid-width between the two edges in the cold months, while it was recorded at the northern edge in the hot months. The maximum positive lateral temperature gradients in Samsun were 5.78, 4.36, 4.95, 8.85, 9.36, and 10.11 °C in April, June, July, October, November, and December, respectively.

4- The negative vertical temperature gradients were of similar distributions and comparable maximum values for all months. Similarly, the differences between the distributions and maximum values of the negative lateral temperature gradients of the six months were minimal.

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