Winter temperature measurements in a composite girder segment

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Abstract. This article presents experimental results from a concrete-steel composite girder. The girder is composed of an I-shape steel beam that is topped by a reinforced concrete slab. The girder was constructed in an open environment so that it is freely subjected to the variation of the atmospheric thermal loads. These loads include the solar radiation, temperature of the surrounding air and speed of the wind. Therefore, a weather station that includes sensors to measure the three aforementioned thermal loads was installed beside the girder. The girder was instrumented with thermocouples that were either embedded in the concrete slab or attached to the steel beam. The thermocouples were distributed across the slab thickness, along its width and along the vertical centerline of the composite girder. The aim of this research is to provide experimental measurements that facilitate better understanding of temperature gradient distributions in composite bridge girders in winter. The test records were continued for approximately two months during the cold season. The test results showed that the negative vertical temperature gradient was higher than the corresponding positive one due to the low intensity of solar radiation. Similarly, the lateral positive temperature gradient along the width of the concrete slab was higher than the vertical positive temperature gradient due to the low altitude of solar radiations.

1. Introduction
The exterior parts of all structures are exposed directly to the environmental conditions that affect their durability. Other types of structures like bridges are totally and continuously exposed to the effects of environmental thermal loads. These loads arise mainly form the daily and seasonally variation of air temperatures and solar radiation intensities [1]. The superstructure of the bridge that composes of the top slab and the carrying girders is the part that is most affected by environmental thermal loads. This is due to the location of this part where the top slab is completely exposed to direct solar radiation during the day and cold winds during the night. Hence, it heats up faster than other elements during the hot day hours and cooled down faster during the cold night hours. Similarly, the exterior lateral surfaces of the girders are exposed to solar radiation. The heat is transferred then from the exteriors where open surfaces are in touch with air to the interior parts of the material. The heat transfer process from exposed surfaces to inner parts depends on some different influential factors, among which is the conductivity of construction materials used, hence, concrete and steel. Since concrete has a low thermal conductivity, temperature gradients arise in the superstructure. Such gradients induce thermal stresses that can be as effective as the dead loads of the structure itself [1].
Recently, several experimental works were conducted on concrete girders [2-6], steel girders [7-12] and composite girders [13, 14], while other works tried to simulate the thermal performance using the techniques of finite elements [15-20]. On the other hand, other researchers used field measurements to investigate thermal effects on composite bridges.

Numan et al. [13] constructed an experimental composite box-girder that is composed from a steel box girder and a top concrete slab. The segment was instrumented with thermocouples and strain gages to evaluate the effect of thermal loads from air temperatures and solar radiation. A finite element model was also conducted and verified using the obtained test results. Based on which, parametric studies were conducted to evaluate different geometrical parameters of the composite girder. The authors indicated that the top slab’s thickness is the most effective among the investigated geometrical parameters on the linear temperature gradient across the top slab. Abid et al. [14] recorded temperature and strain measurements from a composite girder which was constructed in an open environment. The measurements were recorded for six-month period that included the hot and cold seasons. Several thermocouples were installed inside the concrete and steel flanges and webs, while others were installed across the thickness of these elements. The effects of the girder’s size and depth and in addition to the thickness of the structural elements were the key parameters of their finite element models. The test results showed that solar radiation is the most dominant factor on temperature distributions. The authors also indicated that larger sections suffer higher temperature gradients than smaller ones, while the thickness of concrete elements has the most important role among the other geometrical parameters, which agrees with the finding of Numan et al. [13].

Although several researches on the effect of thermal loads on composite girders can be found in the literature, most of which are either field or numerical studies. However, experimental studies where only thermal loads are consider (no traffic loads) are very few. In this research, an experimental work was conducted on a concrete slab-steel beam bridge girder segment that was built in an open environment. The temperature variation of air, heat radiations from the sun, speed of the wind, concrete and steel temperatures were measured, analyzed and presented. The obtained temperature records can be helpful to understand the variation of temperature gradients in such types of composite bridges in winter, and can be utilized as useful database for future studies.

2. Experimental work

In this work, an experimental study was carried out to examine the effect of atmospheric loads of ambient air temperature, direct and indirect radiations from the sun and speed of wind on the thermal behavior of concrete-steel girder segments at the Gaziantep University campus/Turkey. The investigation was done using a system of sensors that include concrete and steel thermocouples, ambient temperature probe, air speed anemometer and radiation pyranometer, while the measurement units include the data logger and the connecting parts. The measurements from the sensors were recorded at time intervals of half an hour.

The experimental work included the casting of a slab segment on an I-steel beam. Figure 1 shows the detailed dimensions of the composite T-beam composed from the steel I-beam and the concrete topping slab. The I-steel beam depth is 500 mm and the width of its flange is 200 mm, while the thickness of web and flanges of the steel beam equals 8 mm. Figure 2 shows a top view of the concrete deck slab, which is 800×500 mm in plan dimensions (width × length) and 100 mm thickness. The reinforcing steel bars are 10 mm diameter and are spaced equally at 100 mm. Before concrete casting of the concrete slab, the thermocouples were installed inside the segment, which were distributed so that the temperature can be measured along the slab width and across its thickness, while other thermocouples were installed along the steel beam. Fourteen temperature sensors (thermocouples) were installed along several concrete sections and on the steel beam of the composite I-beam. Seven thermocouples were installed for both concrete (TC) and steel (TS). Figure 3 shows the locations of the thermocouples installed in the girder segment.
3. The environmental results during the test period
Figures 4 to 6 demonstrate the data collected from the environmental sensors from 21-December-2015 to 22-February-2016. Figure 4 shows the hourly air temperature change and the daily air maximum,
minimum and difference (max-min) temperatures along the full recorded time. The maximum recorded air temperature during the recorded test period was 23.0 °C, while the minimum recorded air temperature was -9.9 °C. The maximum daily temperature difference (max-min) was 18.6 and the minimum daily temperature difference was 1.4 °C. Figure 5 illustrates the hourly and daily maximum solar radiation intensities. The maximum recorded solar radiation intensity during the examined period was 870 W/m². On the other hand, Figure 6 shows the hourly wind speed variation along the test period. The maximum recorded speed of atmospheric air along the full recorded time was 5.05 m/s, while the minimum recorded wind speed was 0 m/s, while the daily average speed was about 0.1 m/s.

![Figure 5](image5.png)

**Figure 5.** Hourly variation and daily maximum solar radiation during the test period.

![Figure 6](image6.png)

**Figure 6.** Hourly change of wind speed during the test period.
4. Hourly temperatures of thermocouples

Figures 7 to 9 show the hourly average and mean temperatures of the fourteen thermocouples fixed in concrete and on the steel section during the studied period. Figure 7 presents the hourly average temperatures of the seven concrete thermocouples fixed in the concrete part along the studied period. The recorded maximum of concrete average temperature was 31.0 °C, and the minimum recorded value was -8.4 °C, while the mean average temperature of the concrete thermocouples during the same period was 6.6 °C. Figure 8 shows the hourly average temperature of the seven thermocouples fixed on the steel section of the composite T-beam. The hourly average temperatures of the thermocouple were limited between 30.0 °C and -9.0 °C. The average value for the hourly average temperatures of the steel thermocouples during the examined period was 6.4 °C. Figure 9 illustrates the hourly mean temperatures of all thermocouples during the studied period. The highest mean temperature was 30.9 °C while the minimum recorded value was -8.6°C. In the design of thermal movements, the highest and lowest mean temperatures are used.

![Figure 7. Hourly average temperatures of the seven concrete thermocouples along the test time.](image)

![Figure 8. Hourly average temperatures of the seven steel thermocouples along the test time.](image)
Figure 9. Hourly mean temperatures of all thermocouples along the test time.

5. The vertical temperature gradient
As mentioned in the previous section, the thermocouples were installed at different places distributed as vertical and horizontal grids in the composite T-beam to evaluate the temperature variations along the vertical and lateral sections. Figures 10 and 11 illustrate the hourly changes in temperature differences in the segment during the studied period. The visualization of these temperature differences gives a better understanding of how thermal gradients are distributed in the composite T-beam. TC3, which is instrumented at the top of the concrete topping slab, recorded the maximum temperature along the vertical centerline during the hot hours of the day, which composes the positive temperature gradients. On the other hand, after several night cooling hours, TC3 records the lowest temperature (in the concrete slab) along the vertical centerline, which leads to the distributions of the negative vertical temperature gradients. To evaluate the temperature difference along the full height of girder, the temperature of TC3 should be compared with temperature of those thermocouples along the vertical centerline of the girder. The thermocouples along the vertical centerline of the girder starting from the upper fibre of the top concrete slab and ending at the base of the steel beam are TC3, TC4, TC5, TS1, TS3, TS4, TS5, and TS7. Therefore, TC3 is compared at each time step with the minimum (Figure 10) and maximum (Figure 11) temperatures of these thermocouples.

Figure 10 shows that the maximum difference temperature was from 0.4 to 7.1 °C, while the minimum temperature difference was less than 0.5 °C. This means that the highest +ve vertical temperature gradient along the tested period is 7.1 °C. Figure 11 shows that the maximum recorded values of (TC3-Max) were from -0.3 to 0.0 °C and the minimum values ranged from -12.8 to -0.8 °C. This means that during the early morning hours or late night hours, the maximum negative temperature gradient was 12.8 °C along the full tested period. It is understood that in winter, the intensities of solar radiation are low and so as the air temperatures, therefore, lower positive vertical temperature gradients are expected than in hot seasons. On the other hand, the drop of temperature during the cooling hours of this season leads to significant negative vertical temperature gradients.
Figure 10. Hourly changes of the temperature differences of (TC3-Min).

Figure 11. Hourly changes of the temperature differences (TC3-Max).

Figure 12. Hourly changes of the temperature differences (TC7-TC4).
6. The lateral temperature gradient

The differences between the temperatures of the thermocouples along the horizontal direction are shown in Figures 12 to 14. The lateral temperature gradients are obtained from the recorded temperatures in the transverse direction of the section. Therefore thermocouples were installed along the horizontal centerline of the concrete slab to evaluate this gradient. The lateral temperature differences were evaluated using the thermocouples TC1, TC2, TC4, TC6, and TC7 from north to south. Figure 12 shows the hourly temperature differences of the southern edge thermocouple TC7 and the slab’s central thermocouple TC4. This temperature difference shows the lateral temperature gradient at the southern edge of the top concrete slab. The maximum value of the difference of (TC7-TC4) ranged from 1.3 to 9.3 °C, while the minimum value ranged from 0.06 to -2.5 °C. Figure 13 shows the hourly temperature differences between TC7 and TC1, which is the northern edge thermocouple. Thus the temperature difference (TC7-TC1) shows the lateral temperature gradient between the southern edge and the northern edge of the concrete slab. The maximum value of the difference of (TC1-TC7) ranged from 1.4 to 9.2 °C, while the minimum value of the difference was between -0.01 and 0.4 °C. Figure 14 shows the hourly temperature differences between the northern edge thermocouple TC1 and the central thermocouple TC4. The maximum difference (TC1-TC4) ranged between 2.6 and -0.3 °C, while minimum difference ranged from -0.34 to -4.8 °C. The comparison between the results of the difference of (TC1-TC4) with the results of the difference of (TC7-TC4) shows that the values of the maximum
and minimum differences of (TC7-TC4) were higher. This is an expected result, as it is expected that the temperature of the southern edges of the girder are higher than that of the northern edges because of the motion of the sun in winter and hence the quantity of the received solar radiation by both edges. Where the sun completely moves to the south of equator in winter, which concentrates the radiations on the southern edges are exposed to solar radiation, while northern edges are mostly shaded. Thus, the temperature at the southern edge thermocouple is generally higher that all other points along the slab.

7. Conclusions
The followings can be addressed as the most important results and conclusions.
1- In winter, the intensity of solar radiation is lower than other seasons. Therefore, the highest temperature difference between the thermocouple installed at the top surface and those along the vertical centerline of girder was only 7.1 °C. This value can be considered as the maximum recorded positive vertical temperature gradient along the test period.
2- Significant maximum negative temperature difference of 12.8 °C was recorded between the top surface thermocouple and those along the vertical centerline of the girder. This result is also attributed to temperature variation in winter’s days and nights.
3- Owing to the low altitude of sunrays in winter, the maximum recorded temperature difference between the laterally distributed thermocouples was higher than the vertical one. Where the highest lateral temperature difference recorded between the outermost southern thermocouple and the central one of the top concrete slab was 9.3 °C, while the highest difference between the central thermocouple and that at the northern edge was only 4.8 °C. This is due to the much higher amounts of radiations received by southern surfaces owing to solar motion in winter.

8. Reference
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