Open Field Temperature and Strain Records of a Concrete-Steel Composite Beam

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Abstract. Open field structures, like bridges, are loaded with the typical static, moving and dynamic loads in addition to the open-field thermal loads. These loads include the time-dependent changing of solar radiation and air temperature in addition to the speed of this air. Due to the importance of bridge structures and their high construction costs and long planned life spans, special focus are given to the thermal response of these structures in bridge design codes. With the advances of construction technologies and the use of new composite materials and configurations, updates in code specifications become required, which make the researches in this field of a vital and continuous need. An experimental concrete-steel composite beam with special configuration was cast and installed in an open field. Several temperature and strain sensors in addition to metrological sensors were used to observe its long-term thermal response. The presented experimental records can be helpful for a better understanding of the thermal behavior of such configuration of composite beams under open-field thermal loads. Along two-month cold-season measurements, a maximum temperature difference, within the beam body, of 13.3 °C was recorded, with maximum net tensile and compression thermal strains of 40 and 110 micro-strains.

Keywords: composite beam; solar radiation; temperature profile; thermal induced strain.

1. Introduction

For any constructional structure, the design should consider the exposure type of the elements of this construction. Structures and elements that are constructed in open fields are subjected to additional unfavorable types of loads that influence the long-term integrity of the structure and the durability of the material. Such issues arise mainly due to the time-dependent fluctuations of amounts and angles of received radiations from the sun, which also impose air temperature alterations [1-4]. Structures like bridges are among the important types of constructions that are under the influence of such types of additional and permanently changing thermal loads. Therefore, special care in the design and construction should be given to reduce the effects of open-field thermal loads, and hence reduce the maintenance costs and extend the life span of such vital costly structures [5].

During the daytime, especially in summer, a net gain of energy occurs, resulting in a temperature rise through the structure such that the top surface becomes warmer than the soffit. Owing to the concrete’s low heat conductivity, this rise in temperature results in temperature gradients within the bridge superstructure. These gradients are denoted as positive gradients. Conversely, the net loss of heat which occurs typically during night time, results in a reduction of temperature in the structure, and thereby creating negative gradients of temperature with warmer soffit than the top. The resulted deformations from temperature gradients, when restrained, produce stresses in the structure. To calculate the resulted stresses, these gradients must be calculated [6-9]. The temperature gradients are governed by the heat flow through the body and are functions of the density of the material, and material’s thermal properties like its specific heat and conductivity [10]. Significant research work was conducted up to day to enrich the knowledge in this field. Field measurements [11-13], experimental tests [14-21] and numerical solutions [22-30] were made to improve the understanding of the thermal
behavior of the different types of bridge superstructures and girders under the open-field thermal loads. Along the last two decades several researches were conducted on composite concrete-steel girders, where long-term structural monitoring programs are being applied on most of long-span bridges, especially in China and USA. These programs are still being applied for larger number of bridges due to their activity. Due to the advancements in construction materials and composite structures, more recent experimental researches were published in this filed. Im and Chang [31] observed a steel-concrete composite box girder bridge by thermocouples for more than 6 years. Their observations revealed that the hourly maximum and hourly minimum temperatures showed a tendency to follow the Gumbel distribution. Francesca [32] studied the long-term behavior of composite beams subjected to static and temperature loads. The researcher pointed that; the thermal stresses were not significant owing to the restricted design that considered the possible temperature gradient effects. Most recently, Liu et al. [33] analyzed one-year temperature records in a long-span cable-styled composite bridge. They investigated the vertical and lateral temperature gradients in the girders and conducted an extreme value analysis for long-term return, based on which gradient models were proposed and compared with a standard design model. Abid et al. [34] conducted experimental tests and numerical analysis to assess temperature profiles in composite beams. They showed that increasing the size of girder would result in an increase in temperature gradients. Other recent studies [28] focused on the thermal behavior of the composite concrete-filled-steel-tubes used in composite truss-bridges. Lu et al. [30] analyzed the field of temperature in a steel box-girder with a concrete deck using the aids of the finite element method and facilitated historical meteorological records for this purpose.

It is evident that the thermal effects of open-field exposure can influence the structural response of bridge structures, which makes this field of construction industry a continuously vital research area that attract the attention of more research projects. In this research, experimental thermal measurements on a concrete-encased-steel composite beam are introduced to assess the influence of open-field’s thermal loads on such special type of composite beams.

2. The experimental composite beam

The experimental work was carried out in the campus of Gaziantep University/Turkey. The beam location assures that solar radiations reach all parts of the beam without any shading obstruction from nearby buildings and constructions, which also ensures free air flow on all parts that guarantees accurate simulation of ambient thermal loading of bridge structures.

Two instrumentation sets were utilized in this work, where a set of three sensors that, in group, compose an optimized weather station were used. These included a solar-protected sensor to record air temperatures and another sensor to record the speed of the field wind in addition to a solar pyranometer. The three sensors were attached to a steel frame only few meters away from the test beam and connected directly to the data logger, where simultaneous measurements were captures each 30 minutes. The second sensors set included thermocouples and strain gages that were imbedded in the beam to capture the temperature and thermal strain records. Type T thermocouples were used as shown in Figure 1 to reduce the measurement errors and vibrating wire strain gages (Figure 2) were used to accurately record the strains. The thermocouples and strain sensors were also connected to the same data logger to take simultaneous measurements at the same times of those from the weather stations.

Twelve thermocouples were embedded or installed on the upper concrete flange and web in addition to the lower flange of the concrete section. These were the concrete thermocouples and were termed as IC1 to IC12 with the locations shown in Figure 3. Similarly, three thermocouples were installed on the surfaces of the embedded steel section as shown in the figure, which are termed as IS1 to IS3. The instrumented thermocouples were put together in the sectional plane located at the center of the beam’s length. The wires of all sensors were bundled and collected as shown in Figure 4 to facilitate their connection to the recording acquisition system. On the other hand, two strain gages of the same
type were installed in the concrete materials. Figures 5(a) and (b) show the locations of the strain gages in orthogonal position.

![Figure 1. The thermocouple type T](image1.png)

![Figure 2. Vibrating wire strain gage](image2.png)

![Figure 3. The dimensions of the beam and the locations of thermocouples](image3.png)

In this work, a composite beam was prepared by embedding an I-steel section in an I-shape formwork that was cast with concrete. The web height of the steel section was 400 mm, while the steel section flanges were 200 mm wide. The steel plates from which the steel section was fabricated have a thickness of 8 mm as shown in Figure 5(a). The sections of the exterior concrete beam were made with 100 mm thickness, while its total depth from the bottom surface to the top surface was 500 mm. On the other hand, 800 mm was the width of the top flange, while that of the bottom flange was 300 as shown in Figure 3. The beam segment was made with a limited length of 500 mm to reduce. Reinforcing bars of 10 mm diameter were distributed in both directions in the top flange at 100 mm spacing as shown in Figures 4 and 5(b).
Figure 4. The instrumented composite beam before concrete casting

(a) cross section (b) top view

Figure 5. The locations of strain gages

3. The temperature records

Temperature records from the instrumented thermocouples are demonstrated graphically in Figures 6 to 8, which show the hourly maximum, minimum and difference (max-min) temperatures of thermocouples for two winter months from 21-December to 22-February. The highest maximum hourly temperature value was 36.5 °C at thermocouple IC4 in 18-February at 2:00 PM and the lowest value was -7.3 °C in 3-January at 6:00 AM at thermocouple IS2. The highest value of the hourly minimum temperature of the 15 thermocouples was 24.3 °C in 21-December at 1:00 PM at IC4 and the lowest value was -8.4 °C in 28-January at 4:30 AM at IC7. For the hourly difference (max-min) temperature of thermocouples, the highest value was 13.3 °C in 1-January at 1:30 PM and the lowest value was 0.0 °C on many days as shown in Figure 8.
Figure 6. Hourly maximum temperatures of thermocouples

Figure 7. Hourly minimum temperature of thermocouples

Figure 8. Hourly difference (max-min) temperature of thermocouples
4. The vertical temperature gradient

The difference in the temperature between the thermocouples installed along web centerline was calculated to study the vertical temperature gradients. Figures 9 to 11 show the hourly alteration of temperatures and differences between the daily maximum and daily minimum temperatures of thermocouple IC1 and the thermocouples IC2, IC3 and IC10 during the study period. The maximum temperature difference value of (IC1-IC2), (IC1-IC3) and (IC1-IC10) were 3.11, 5.7 and 6.66 °C, respectively, while the corresponding minimum values were -1.4, -2.2 and -1.25 °C, respectively. The thermocouple IC1 was considered as the top surface’s thermocouple, hence, to which the gradients along the vertical axis of the girder are calculated. IC2 is the thermocouple installed in the top concrete flange, 25 mm below the top surface (25 mm below IC1); while IC3 is the thermocouple installed at the center of the top concrete flange (50 mm blow the top surface). On the other hand, IC10 is the girder’s bottom surface’s thermocouple (installed on the bottom surface of the bottom concrete flange). Therefore, the differences of IC1 with IC2 and IC3 show the temperature gradient within the top concrete flange, while its difference with IC10 show the general linear gradient between the top and bottom surfaces of the girder. It is obvious that the daily maximum difference with the top surface (TC1) was higher for IC3 compared to IC2, which is attributed to the deeper location of IC3 in the top concrete flange compared to IC2, where thicker concrete means slower heat conduction.
5. Thermal strains

The recorded thermal strains from the two vibrating-wire gages are visualized in Figure 2. Each presented strain record shows the net value that is resulted from the subtraction of the initial record from each in time-record. This means that the figure shows the net thermal strains considering the time at which the recording was started as an initial time and its record as a datum one. The starting time was at 12:00 AM of 21-December. For better visualization, the strains were drawn in the figure for the first 10 days only, hence, from 21 to 30-December.

Due to the variances of temperature vertically from the top surface down to the bottom surface, which induce nonlinear gradient profiles, nonlinear thermal strains are induced attempting to give rise to nonlinear sectional deformations. These strains are termed as the free thermal strains. As a resistance from the section to such prohibited distortions, according to Euler-Bernoulli beams, self-equilibrating strains are induced to equalize the nonlinear profiles to linear ones. Hence, such strains would be compression in warmer fibers (to equalize the unrequired nonlinear expansion) and tension in colder fibers (to equalize the unrequired nonlinear contraction). The recorded thermal strains in both gages reflect the expected behavior with time as shown in Figure 12. The strains are shown to be tension within the night hours (no shine hours), where the gradient profiles are negative at the top surface (the location of the strain gages) along these hours. On the other hand, such variation is reversed within the
day shining hours, which are the daily heating times, so that compression strains are induced owing to the positive gradient profiles. The greater heating power during the noon, owing to the concentrated solar radiations, increases the compression strains to their maximum values, while the sinusoidal variation tends to its zero values staring from sunset. Similar sinusoidal hourly alteration of thermal strains was recorded for the rest days as shown in Figure 12. The maximum recorded compression strain was approximately 110 micro-strains along the test period, which 10 winter days, while the maximum recorded tensile strain was 40 micro-strains.

7. Conclusions
Based on the records collected from the strain gages, thermocouples and the weather sensors installed in or beside the composite beam during the period from 21-December to 22-February, the followings can be drawn:
1- The temperature difference (max-min) during the studied period (cold season) for the 15 thermocouples was higher in concrete than in steel. The maximum difference was 13.3 °C at 1:30 PM and the minimum difference was 0 °C at different times. In addition, the recorded maximum temperature in the beam was 36.5 °C, while the recorded minimum temperature was -7.3 °C, which were recorded at IC4 and IS2, respectively.
2- The sinusoidal alteration of thermal strains with time reflected the direct relation with the time-dependent alteration of temperature gradient, which is directly correlated to the hourly heating and cooling budgets. The strains at the top surface of the beam were compression along the day hot hours, where the gradient profiles were positive, and tension along the dark night hours, where the gradient profiles were negative. The open-field heating and cooling loads from 21-December to 30-December resulted in a maximum compression strain of 110 micro-strains and a maximum tensile one of 40 micro-strains.
3- Several special girder configurations are used nowadays in bridge construction such as deep girders, Y-shaped girders and multi-cell box girders. The investigation of thermal responses of such composite bridge girder configurations in both the hot and cold seasons is still required and recommended.

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