Experimental study of steel-concrete bridge girder subjected to environmental condition

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Abstract. This paper presents the experimental result for four-season for steel-concrete composite bridge girder in Iraq. The model was put in an open environmental condition to be subjected to variation in thermal loads, these loads are solar radiation, ambient air temperature, and wind speed. The model was equipped with seven thermocouples in concrete and seven thermocouples in steel and one between steel and concrete to measure temperature. This article aims to provide an experimental measurement to understand the behavior of temperature distribution in Iraq. The practical study is the first in Iraq to be conducted on this type of bridge. The result showed the solar intensity, ambient air temperature and wind speed are higher effects for a sunny day, and the temperature distribution inside the girder, for the same thermocouple the temperature shows different behavior concerning the season.

Keywords: composite bridges girder, solar radiation, thermal loads, temperature distribution, and temperature gradient.

1. Introduction

The steel girder bridges are extensively used in bridge construction. These bridges are subjected to environmental conditions like solar radiation, ambient air temperature, the heat of hydration, and humidity. Therefore, knowing how the temperature distribution inside the body of the bridge is crucial in many engineering issues because if a hot structure is not allowed to extend freely in all directions then stresses will be advanced within the structure. The values of these thermal stresses can affect the body. There is no regular thermal state inside the bridge due to the change of ambient temperature and solar radiation during the day [1–5].

Most previous studies have been studied the effect of thermal load on concrete bridges [6], Priestley studied the temperature distribution of prestressed and reinforced concrete bridges subjected to vertical temperature gradients as convection. The effect of temperature on the cracks in the reinforced and prestressed concrete bridges was discussed. The model of temperature distributed suggested by Priestley is adopted by the New Zealand code [7] as a thermal gradient in a design of the concrete bridge, This model is shown in Figure 1.

Elbadry and Ghali [1] showed the significance of environmental temperature effects on the behavior of concrete bridges and showed temperature changes induced by atmospheric conditions on the cross-section of the bridge structure which might be normally nonlinear and which cause stresses substantial significance in both longitudinal and transverse directions. Giussani [8] studied the long-term behavior of composite steel-concrete bridge girders subjected to static loads, thermal gradients, and shrinkage. Daily and seasonal temperature changes are considered, through experimental work, the researcher adopted in his evaluation, the law of linear elasticity of the steel girder bridge and behavior of linear viscous elasticity of the concrete slab. While the thermal gradients gave non-linear distributions along the vertical axis of the bridge, these nonlinear temperature gradients have significant effects and should be carefully considered when designing the bridge. Zhou and Yi [9] convection was studied by...
illustrating the three types of bridges are steel bridge, concrete bridge, and a steel-concrete composite bridge girder. The researchers used the differential equation of heat transfer and solved it by the finite element technique of numerical analysis. The researchers noted that most of the coefficients used in the solution to predict the results were based on field estimation. Also, they found that the temperature gridline at the interface layer between concrete and steel, the temperature is nonlinear due to different heat transfer coefficients. Abid et al., Tayşi N and Özakça M [10] studied thermal behavior in bridges with precast concrete girders that are exposed to environmental changes of the Gaziantep, Turkey. The work was included two stages of construction, first is a construction of a single girder, the second stage is the construction of a deck slab superstructure. they concluded that the temperature distribution has a major effect on the movement of concrete bridge girders.

\[ t(z) = \left( \frac{z}{1200} \right) T \]
\[ t'(z) = 5 - 0.05h \, ^\circ C \]
\[ T = 32 - 0.2h \, ^\circ C \]
\[ h = \text{Blacktop thickness (mm)} \]

\textbf{Figure 1.} Temperature gradient for the concrete bridge adopted by New Zealand specification [6,7].

BS 5400 Part II [11] specifies a model proposing temperature distribution throughout a composite bridge section and also for the changes in the overall length of the bridge deck a single temperature known as the effective bridge temperature is used. The bridge code gives tables for the minimum and maximum effective temperatures, which are related to temperature data from the thermal maps for the location of the bridge. AASHTO specifications [12] suggested a model for the temperature distribution throughout the bridge section as shown in Figure 2. this figure illustrates the solar radiation zone of the United States, for other zones, it clearly indicated the need to adopt the heat map of the zone. To determine the movement changes in the bridge during the year, this specification has relied on two methods. The first is general, depending on the type of bridge and the classification of the zone thermally, the zone is either cold or moderate, and it is moderate if the freezing days are less than 14 days. As for the second method, it relied on a set of maps drawn up for the United States that determine the maximum and minimum design temperature for each zone inside the United States. Iraqi Standard [13] refers to the British Standard No. 153 Part (3A) or other approved equivalent design code to the inclusion of thermal effects.

From the foregoing, we find that it is important to determine the temperature effects on bridges. But when reviewing most of the international specifications, it can be seen that they are set for a specific region. The current study aims to focus on the effect of solar radiation and air temperature variation in addition to the other thermal loads on temperature gradient distributions in composite bridges in Iraq.
2. Experimental work of composite segments

Experimental works included casting a segment of composite concrete-steel. Figure 2 shows the dimension of the composite segment. The steel beam depth is 500 mm, the width of the flange is 250 mm and the thickness of the web and flange is 8 mm. In the first step of the experimental work, the I-steel girder was welding as specified dimensions. The bolts were used as shear connectors, two rows of bolts were welded at the top flange with a distance of 125 mm. In the second stage, the framework of the concrete slab was made of plywood.

The thermocouples used to measure the temperature at certain points, the thermocouples were placed in the specific location as shown in Figure 3, Table 1 shows the coordinates of thermocouples. The total number of thermocouples were fifteen, seven thermocouples are installed for both concrete (TC) and steel (TS) and one (TCS) between steel section and concrete. At the last step, the concrete was cast as shown in Figure 4, the sides of the concrete slab and steel were completely isolated by using foam to make the sample turn out to be an internal bridge and to prevent heat transfer from these faces as shown in Figure 5.
Table 1. Thermocouples coordinates.

| ID   | X    | Y    | ID   | X    | Y    |
|------|------|------|------|------|------|
| TC1  | 380  | 550  | TS9  | -4   | 472  |
| TC2  | 190  | 550  | TS10 | -4   | 250  |
| TC3  | 0    | 550  | TS11 | -4   | 28   |
| TC4  | -190 | 550  | TC12 | 0    | 600  |
| TC5  | -380 | 550  | TCS13| 0    | 500  |
| TC6  | 0    | 525  | TS14 | -105 | 8    |
| TC7  | 0    | 575  | TS15 | 0    | 0    |
| TS8  | -105 | 492  |      |      |      |

# The origin in the center of the bottom surface steel flange.

Other types of sensors were used to measure wind speed, air temperature, and solar radiation during the day. Campbell Scientific's products are used to compose the data acquisition system of the study, the data logger type is CR1000 with multiplexers AM16/32 channel. The sensors and data logger used are shown in Figure 6.
3. Results

3.1. Environmental Data

Solar radiation, wind speed, and air temperature measured are displayed for four chosen days. The chosen days are 20-March-2020 to represent the spring season, 24-July-2020 to represent the summer season, 15-September-2020 to represent the autumn, and 15-January-2020 to represent the winter season. Air temperature is important in studying the thermal behavior of bridges because it affects the radiation of the outer surface to the ambient and the convection cooling during the hours of the day. Figure 7 shows the ambient air temperature that records for a different season, the maximum air temperature of 15-January, 20-March, 24-July, and 15-September were 16.43, 31.79, 50.03 and 44.4 °C respectively, while their daily minimum temperatures were 4.09, 16.58, 33.97 and 26.86 °C respectively. So, the maximum temperature is 50.03 °C on a sunny day and the minimum temperature was 4.09 °C on a cold day so the difference between the two records is 45.94 °C. Solar radiation represents the external heat source. The measured total solar radiation was recorded on a horizontal surface, total solar radiation comes from direct radiation and diffuse radiation on the horizontal surface from the particles in the surrounding media. Figure 8 shows the solar radiation during the chosen days. The maximum value of solar radiation occurs at the mid-day (12:00) while during the night it's recorded zero values. The maximum solar radiation occurs in the summer (980 W/m²), while the maximum solar radiation occurs in the winter (498.7 W/m²). One of the most important factors affecting convection cooling of the surface is wind speed and surrounding temperature, so wind speed must be recorded to study the temperature distribution during the day. Figure 9 shows the wind speed of the chosen days. The maximum wind speeds of 15-January, 20-March, 24-July, and 15-September were 4.27, 7.52, 4.18, and 9.15 m/s, respectively.

![CS300 pyranometer](image1)

![data logger CR1000](image2)

**Figure 6.** The data logger and sensors
3.2. Temperature-time curves of thermocouples

In this part, the temperature changes in some thermocouples are presented during the day and for the selected days that represent the four seasons. Figures 10 to 15 illustrate the temperature change during the twenty-four hours for the selected days. Three thermocouples were selected in concrete (TC12, TC3, and TCS13) and three in the steel section (TS9, TS10, and TS11). The selected thermocouples are all located in the centerline of the section and are used mainly to represent the temperature with the depth. TC12 represents the temperatures on the upper surface of the concrete slab, which is affected by heating by sunlight during the day and cools rapidly as a result of the convection, TC3 represents the temperatures in the middle of the concrete slab, while the third thermocouple TCS13 is located in the interface between the concrete slab and the steel section. The second group of thermocouples located in the steel section, TS9 and TS11 are located at the upper and lower of the section while the TS10 is located in the mid of the steel section.
In general, Figures 10 to 15 show that the temperature variation during the cold day (15th January) is very low, so that the temperature curve is close to the flat curve, while the variation is clear during the hot day (24 July) and on the 15th September. It can also be observed that there are jumps in the temperature of the thermocouples in the steel section, this rise in temperature is within the period of sunrise and sunset, and the reason for this rise is due to the exposure of parts of the steel section to direct sunlight, as some parts are outside the shade in these periods, which causes jumps in temperatures of steel section within this period.

The effect of solar heating clear in the top surface of the concrete slab where the maximum temperature of the top concrete surface was 66.86, 53.39, 34.07, and 16.15 °C occurred on 24-July, 15-September, 20-March, and 15-January respectively, when comparing the 15-September and 20-March, 15-September is considered a hot day while 20-March is a cold day.

Figure 10. The temperature of thermocouple (TC12) during a day in the chosen days.

Figure 11. The temperature of thermocouple (TC3) during a day.

Figure 12. The temperature of thermocouple (TCS13) during a day in the chosen days.

Figure 13. The temperature of thermocouple (TS9) during a day in the chosen days.
3.3. Lateral temperature distributions

Figures 16-19 show the temperature distribution in the mid-layer of the concrete slab at 3:00, 9:00, 15:00, and 21:00 for the chosen days (20-March, 24-July, 15-September, and 15-January). In general, it can be concluded that the temperature distribution through this layer (mid of concrete slab) is almost uniform in all times. The effect of the side surfaces was not clear at the temperatures near these surfaces, and the reason was due to the isolation of these surfaces, this explains the regularity of temperatures. When comparing the temperatures at 3:00 and 9:00, it can notice the temperatures increased in 24-July and 15-September, as for the other days, the increase was not perceptible, the temperature increase is due to the influence of the model by sunlight. At 15:00, the temperature increasing continues for 24-July, 15-September, and 20-March while 15-January is not affected at this time, the reason is due to the weak of solar radiation in the winter. Figure 19 shows the decreasing temperatures that increased during the day due to the sunset.
3.4. Vertical temperature distributions

The vertical temperature distribution is very important for design purposes, especially in the summer season, for this reason, all international specifications of bridge designs suggest models commensurate with a special thermal zone, these models are used to calculate the stresses that are generated as a result of temperatures, the thermal stresses change during the day and throughout the year. Solar radiation has a great effect on the temperature distribution because it is the external heat source, especially on horizontal surfaces during the day, and this effect appears in the hottest months (summer). Figures 20-27 show the temperature distributions with the depth of the composite section of the chosen days (20-March, 24-July, 15-September, and 15-January) every three hours. The temperature distributed in the coldy day (15-January) approximate uniform with the depth because the external source (solar radiation) has little effect. Figures 20-27 show the temperature distributions with the depth of the composite section of the chosen days (20-March, 24-July, 15-September, and 15-January) every three hours.

Figure 18. The temperature in the mid-layer of the concrete slab at 15:00 on the chosen days.

Figure 19. The temperature in the mid-layer of the concrete slab at 21:00 on the chosen days.

Figure 20. Temperature distribution through the depth at 0:00.

Figure 21. Temperature distribution through the depth at 3:00.
Figure 22. Temperature distribution through the depth at 6:00

Figure 23. Temperature distribution through the depth at 9:00

Figure 24. Temperature distribution through the depth at 12:00

Figure 25. Temperature distribution through the depth at 15:00

Figure 26. Temperature distribution through the depth at 18:00

Figure 27. Temperature distribution through the depth at 21:00
The temperature distribution in the cold day (15-January) is approximate uniform with the depth because the external source (solar radiation) has little effect. The maximum gradient of temperature is obtained when the top surface temperature reach the highest value. The maximum temperature of top surface occurred at 15:00, these temperatures equal 34.07, 66.18, 54.45, and 16.09 °C for 20-March, 24-July, 15-September, and 15-January respectively. The minimum temperature of top surface occurred between 3:00 and 6:00, these temperatures equal 22.93, 32.78, 27.67, and 12.52 °C for 20-March, 24-July, 15-September, and 15-January respectively. The maximum difference of the top surface temperature between hot day (24-July) and cold day (15-January) is 53.66 °C.

3.5. Section temperature
Expansion joints of bridges are selected depending on seasonal temperature changes. Average temperatures on a hot and cold day must be known in order to estimate the highest and lowest average temperature. Table 2 shows the maximum and minimum average of temperature for the section in the chosen days. The maximum difference of average of temperature between hot day (24-July) and cold day (15-January) is 50.63 °C. This difference is used to choose the type of expansion joints, but it should be noted that the chosen days represent the extreme days in terms of temperatures for the year 2020, but there are years when the temperatures are more extreme, therefore, this difference needs more study to determine the appropriate value in the design of the expansion joints.

Table 2. Maximum and minimum average of temperature in the chosen day.

| Day          | Average of temperature (°C) |
|--------------|----------------------------|
|              | Maximum | Minimum |
| 15-January   | 16.18   | 12.44   |
| 20-March     | 32.30   | 23.23   |
| 24-July      | 63.12   | 33.38   |
| 15-September | 50.53   | 27.45   |

4. Conclusion
The followings can be drawn as the most important concluding remarks from the experimental work conducted in this study,

- The maximum air temperature of 24-July was 50.03 °C while daily minimum temperatures was 4.09 at 15-January, So, the difference between the two measured values is 45.94 °C.
- The maximum solar radiation occurs in the summer (980 W/m²), while the maximum solar radiation occurs in the winter (498.7 W/m²).
- The temperature variation of thermocouples during the cold day (15th January) is very low, so that the temperature curve is close to the flat curve, while the variation is clear during the hot day (24 July) and on the 15th September.
- The thermocouples in steel section have a jumps in the temperature measured, this rise in temperature is within the period of sunrise and sunset due to the exposure the steel section to direct sunlight.
- The temperature distribution through middle layer of concrete slab is almost uniformly during the day.
- The temperature distribution in the cold day (15-January) is approximate uniform with the depth while the maximum temperature distribution with the depth is occurring in the hot day at 15:00
- The maximum difference of average of temperature between hot day (24-July) and cold day (15-January) is 50.63 °C.
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