Construction and Building Materials 106 (2016) 523–532

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental analysis of temperature gradients in concrete box-girders

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HIGHLIGHTS

- A full-scale experimental box-girder segment was constructed and instrumented.
- Temperature gradients were analyzed in concrete bridges under environmental loads.
- The recorded maximum vertical and lateral gradients were 19.7 °C and 19.0 °C.
- Formulas were proposed to predict maximum temperature gradients in concrete girders.
- Simple formulas were proposed to predict the mean temperature of concrete bridges.

ARTICLE INFO

Article history:
Received 8 February 2015
Received in revised form 25 November 2015
Accepted 21 December 2015
Available online 28 December 2015

Keywords:
Temperature gradient
Concrete box-girder
Thermal loads
Solar radiation
Air temperature

ABSTRACT

This paper describes the construction and instrumentation of an experimental box-girder segment, aiming to analyze the temperature distributions in concrete bridges under the fluctuation of air temperature and solar radiation thermal loads. The instrumentation included air temperature, solar radiation, and wind speed sensors in addition to 62 thermocouples, while data acquisition continued for more than one year. The maximum vertical temperature gradient was recorded in June, while the maximum lateral gradient was recorded in December. Empirical formulas were proposed to predict the maximum vertical and lateral temperature gradients, in addition to the daily maximum and minimum mean temperatures of the bridge.

1. Introduction

The diurnal and seasonal variation of air temperature and solar radiation affects a bridge superstructure by two means. The first is the variation of the bridge mean temperature with time, which for simple span case, causes longitudinal expansion and contraction during the day or from a season to another. The second is the variation in the temperature distribution along the depth and the width of the superstructure, hence the difference between the temperature of the different fibers along the depth of the webs or the width of the slabs (or flanges), which is generally a nonlinear variation. The nonlinear temperature variations lead to nonlinear temperature gradients that cause stresses even in simply supported spans.

Imbsen et al. [1] reviewed many field studies that attributed visual damages in inspected bridges to the variation of air temperature and solar radiation. From inspections made on several bridges, Zichner [2] reported visual cracks along the webs and the bottom slabs of box-girders with crack width ranged from less than 0.2 mm to 0.4 mm. Elbadry and Ghali [3] showed that for a continuous box-girder bridge subjected to a nonlinear temperature difference of about 20 °C between the top and bottom surfaces, tensile thermal stress of approximately 2.8 MPa was predicted near the bottom surface, while the bottom fiber stress due to service loads was approximately 1.5 MPa. In addition, they reported that a transverse tensile thermal stress of more than 4 MPa was predicted due to temperature variations across the slabs and webs. Priestley [4] addressed that air temperature and solar radiation can cause transverse thermal tensile stresses of as high as 3.5 MPa. Other previous researchers [5–10] reported similar considerable stresses and deformations that can arise from the effects of air temperature and solar radiation.

To control the stresses and deformations that are motivated from the continuous rise and fall of air temperature and solar radiation, many researchers attempted to propose vertical temperature gradient models along the depth of the superstructure. One of the most widely distinguished gradient models is the fifth-order model suggested by Priestley [4] in 1976. This model considers a major nonlinear variation of temperature along the top 1.2 m of the

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http://dx.doi.org/10.1016/j.conbuildmat.2015.12.144
0950-0618/

superstructure and a minor linear variation along the bottom 0.2 m. Priestley's [4] model is still used by the New Zealand bridge design code [11]. The Australian bridge design code [12] also uses the Priestley's [4] fifth-order model, however, the maximum temperature gradient at the top surface is much lower.

In 1978, the British bridge design code BS 5400-2 [13] introduced a positive temperature gradient, which composes of two main parts. The first is a bilinear gradient along the top part ($\leqslant 0.4$ m) of concrete superstructures, while the second is a linear gradient along the bottom part of the superstructure. In 1985, Imbsen et al. [1] suggested a multi-linear temperature gradient, which was adopted by AASHTO [14] in 1989. Ten years later, the multi-linear temperature gradient model was simplified to a bilinear gradient, which is still used by the current provisions of AASHTO [15].

In the previously discussed multi linear temperature gradient models [13–15], temperature gradient values ($T1$, $T2$, $T3$, and if any $T4$) are specified at three or more points. These points are; the top surface, the connection points between the subsequent lines of the gradient model, and the bottom surface. These temperature gradients are determined for each region using statistical extremes analysis based on the climate records of this region. Potgieter and Gamble [16], Roberts-Wollman et al. [17], and Lee and Kalkan [18] introduced simplified expressions for the maximum positive temperature gradient at the top surface ($T1$) of bridge superstructures, using which the maximum difference between the top surface and the core temperatures is estimated.

In this study, an experimental full-scale reinforced concrete box-girder segment was constructed and instrumented with different sensors and a considerable number of thermocouples. Air temperature, solar radiation, and wind speed in addition to concrete temperature at different locations in the slabs and webs of the girder were measured and recorded for more than one year. The objective of this paper is to analyze the vertical and lateral temperature gradients in addition to the variations in the bridge mean temperature that arise from the continuous fluctuation of air temperature and solar radiation. The experimental results are presented and discussed for the whole test period and for specific days selected from the different seasons.

2. The experimental work

A full-scale reinforced concrete box-girder was constructed to evaluate the effect of exposure to the environmental thermal loads on temperature and temperature gradient distributions in concrete bridges. Before the construction, a suitable site was chosen in the campus of Gaziantep University. Because real bridges are mostly constructed in open areas where no shadings are exist from surrounding structures, and to better simulate the real thermal loads on bridges, the site was selected so that the distances to the nearest buildings would be less than their shade lengths, hence no shadings from the surrounding buildings would affect on the constructed box-girder. To monitor the temperature distribution in the box-girder, thermocouples were installed in different locations inside and on the surface of the webs and slabs as shown in Fig. 1.

2.1. The experimental concrete box-girder segment

The experimental box-girder segment has a top slab width of 7.25 m, an overall depth of 2.4 m, and a length of 2.1 m. The detailed dimensions of the box-girder are shown in Fig. 1. The bridge segment was supported by a reinforced concrete frame, which has a height of 2 m. This frame was used to raise the box-girder from the ground to simulate the actual loading of the ground reflected radiation. Moreover, this supporting frame allows free fluent of air to the lower surface of the bottom slab, hence, simulating the actual convection loading on this surface. Similar to the actual case, the supporting frame was thermally isolated from the box-girder. Two layers of plywood were used on the top of the frame before the reinforcing of the box-girder segment.

The material components of the concrete mix were Ordinary Portland Cement, water, crushed sand, and crushed gravel, while the mix proportion in kg/m^3 was 380, 171, 902, and 988, respectively. In addition, 1% by cement weigh of super plasticizer was used in the concrete mix. The cube compressive strength of the concrete used in both the box-girder and the supporting frame was 35 MPa. The reinforced concrete box-girder segment was designed to withstand self weight only. 12 mm diameter bars at 150 mm c/c were used in both directions for both the top and bottom layers of the slabs. For walls (webs), two layers of 16 mm diameter bars at 150 mm were used as vertical reinforcement, while the lateral reinforcement composed of 12 mm diameter bars spaced at 150 mm. Additional 12 mm diameter bars were distributed along the slab-wall haunches.

To satisfy thermal isolation along the span direction and to prevent air and light from entering the box cavity, insulation boards with external waterproof plastering were used to seal the cross-section of the box-girder. Fig. 2a shows the box-girder segment during the construction of the formwork, while Fig. 2b shows the box-girder sealing with the isolation sheets.

2.2. Instrumentation of the experimental box-girder segment

A weather station of three sensors provided by Campbell Scientific was attached to the experimental box-girder segment to monitor the environmental thermal loads. The 108 temperature probe was used to monitor the shade temperature of the air, the three-cup NRG#40 anemometer was used to monitor the speed of the wind, and the CS3 apogee silicon pyranometer was used to monitor the global solar radiation intensity.

Type-T thermocouples were installed inside the webs and the slabs and on the exterior and interior surfaces to measure concrete temperatures. The thermocouples were distributed in four groups according to their locations. The groups were the south web (SW), the north web (NW), the top slab (TS), and the bottom slab (BS), which were consisted of 18, 18, 17, and 9 thermocouples, respectively. The locations of all thermocouples are clearly shown in Fig. 1. PVC ducts were used to arrange the exit of the thermocouple wires from the concrete of the box-girder. Four ducts were installed for the four groups of thermocouples as shown in Fig. 1. The experimental data were recorded at time intervals of 30 min starting from the casting day of the box-girder in 25-May-2013 to 3-July-2014.

3. Air temperature, wind speed and solar radiation

The environmental records from the air temperature probe, the anemometer, and the pyranometer are presented in this section. The boundary thermal loads that control the heat transfer in the box-girder are dominated by these measurements, thus, the presentation of the environmental results is required to understand the thermal behavior of the box-girder. For the whole period extended from 25-May-2013 to 3-July-2014, Fig. 3 shows the daily maximum and the daily minimum air temperatures in addition to the difference between the daily maximum and minimum temperatures. The maximum air temperature along this period was 38.4 °C, which was recorded in 3-July-2014, while the minimum air temperature was recorded in 12-December-2013 and was −8.7 °C. On the other hand, the maximum daily temperature difference was recorded in 11-October-2013 and was 23.4 °C.