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Prediction of Bridge Temperatures

Prévisions des températures dans les ponts

Vorhersage von Brückentemperaturen

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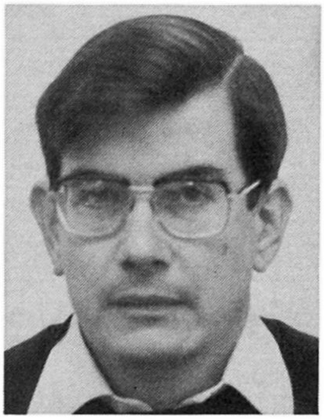

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SUMMARY
The paper describes a theoretical model for the prediction of bridge temperatures from meteorological data that brings together finite element heat transfer theory and solar irradiance theory. Comparison of the theoretical results with bridge temperature measurements in Canada and Australia shows the validity of the model for a range of bridge types and climate regimes.

RÉSUMÉ
L'article décrit un modèle théorique pour la prédiction des températures dans les ponts à partir de données météorologiques, ceci en combinant la théorie des éléments finis de transfert de chaleur avec la théorie de l'irradiation solaire. Une comparaison des résultats théoriques avec des mesures de températures sur des ponts au Canada et en Australie montre la validité du modèle pour différents types de ponts et de régimes climatiques.

ZUSAMMENFASSUNG
Es wird ein theoretisches Modell beschrieben, das Brückentemperaturen aus meteorologischen Daten mit Hilfe der Finite-Elemente-Wärmeübertragungstheorie und mit berechneten Sonneneinstrahlungswerten voraussagt. Vergleiche von theoretischen Ergebnissen mit Messungen an Brücken in Kanada und Australien zeigen, dass das Modell für verschiedene Brückentypen und Klimazonen gültig ist.

1. INTRODUCTION

Thermal loading of bridges is an important design case and as a result has been investigated both experimentally and theoretically by many researchers [1]. Maximum bridge temperatures are largely a function of the heat transfer conditions on the surfaces of the bridge particularly the solar radiation. Recently, solar heating has been widely studied in conjunction with solar collectors for water heaters and power generation.

This paper describes a theoretical model for the prediction of bridge temperatures from meteorological data that brings together finite element heat transfer theory and the work of the solar engineers. The aim is the reliable prediction of bridge temperature for a range of bridges and meteorological conditions. An accurate knowledge of bridge temperature extremes is essential for the structural engineer to assess the effects of thermal loading on his design.

The validity of the model is tested against field data obtained by the authors from their long term bridge instrumentation programmes in both Alberta, Canada and South Australia.

2. THEORETICAL MODEL

The basic heat transfer model used here is a development of the FETAB model from the University of Calgary [2]. The model represents the bridge cross-section as a finite element idealization and carries out a time step integration to compute the variation of the nodal temperatures given an initial condition. The developments described in this paper concern the representation of solar irradiance and the prediction of the starting temperature.

2.1 Overview of the Model

Since the model considers only the cross-section there is an implicit assumption that there is no variation of temperature along the bridge. This assumption is valid except for the ends of the bridge where a full three dimensional analysis is needed to model real behavior. The cross-section can be of any arbitrary shape or arrangement of materials. The model represents the cross-section as an assembly of constant heat flow triangular and/or bilinear quadrilateral heat conduction elements. One dimensional fictitious linear boundary elements are used to represent both the surface and radiant heat transfer between the bridge and the environment.

The surface heat transfer coefficient is a function of the nature of the surface and the wind speed. For concrete bridges values range from 4.0 W/(m^2 °C) in still air to 25 W/(m^2 °C) in light wind. The solar radiation absorptivity coefficient is taken as 0.7 for concrete and 0.9 for an asphaltic wearing course on the deck of the bridge.

The resulting finite element formulation of the heat conduction equations is solved using time step integration firstly to evaluate the nodal temperatures and then the stresses are calculated from the nodal temperatures using simple elastic theory.

The program is coded in FORTRAN 77 and will run on a variety of computers. All the results for this paper were obtained on either an IBM AT or an Apple Macintosh II personal computer.

2.2 The Initial Condition

Time step integration procedures require an initial set of nodal values for the analysis. Following the work of Emerson [3], this is usually the average bridge temperature just before dawn when temperature differentials across the section are at a minimum. Emerson's observation, originally made in England, has been confirmed by the author's field tests in both Alberta and South Australia. Accepting the uniform temperature field and starting the analysis at dawn still leaves the question of the value of the starting temperature. From observations of a concrete box girder in England Emerson suggested the starting temperature was the average air temperature for the previous 24 hours. Observations on concrete roof slabs [4] showed the thinner slabs cooled down to the air temperature at dawn. Deduction from heat transfer physics suggests the starting temperature should be a function of the thermal mass of the bridge. Larger masses take longer to cool down overnight and at dawn would be at higher temperatures than thin slabs.

Inspection of the authors field data shows that bridge temperatures at dawn correlate well with the average temperature in the bridge a "time constant" before dawn. The time constant maybe estimated from heat transfer theory using the following procedure:

(a) Determine the thickness t_e of all the concrete "slab(s)" which make up the bridge cross-section. For a composite girder bridge the top flange is the "slab" but in a box girder both webs and the flanges are "slabs".

(b) Determine the thermal mass per square metre of surface area, M_t , for the slab

$$M_t = t_e \; c \; p$$

where: t_e = Slab thickness (m)
c = Specific heat of slab (J/Kg'C)
p = Density of slab (Kg/m^2).

(c) Determine the average rate of surface heat transfer per hour, S, over the time constant period

$$S = 3600 \; h_t \; n.$$

where: h_t = Surface heat transfer coefficient (W/m^2 ·C)
n = Number of external surfaces (2 for simple slab but 1 a box girder as the interior face is not counted).

(d) Determine the time constant TC for the "slab" in hours

$$TC = M_t \; / S.$$

For a large concrete box girder the time constant can be 24 hours in contrast to 2 hours for a thin slab. The time constant for steel sections is effectively zero. Where the section is made of parts of differing thickness the time constant and starting temperature for each part must be calculated separately. The first time step will smooth any temperature differentials between different parts of the cross-section. If this differential is 10% or less then a uniform value can be taken without much effect on the final result. While the procedure provides a way of calculating the starting temperature for most days comparison with the field data shows it does not work when the bridge is cooled down with the passage of a cold weather front and/or rain overnight. For example cold fronts occur approximately once a week in South Australia with varying degrees of intensity and not necessarily at night. Conversely, the Chinook conditions of Alberta will heat the bridge.

2.3 Radiant Heat Transfer

Solar radiation is the dominant heat transfer mechanism heating the bridge during daylight. In solar engineering terminology, the total irradiance, I, must be calculated for the inclined surfaces that form the flange and webs of the bridge. In addition, if the bridge cross-section has cantilever wings as part of the top flange then parts of the web will be in shade during the day. Unfortunately, only radiation on a horizontal surface is measured by the weather bureau and only then at selected stations. This leaves the problem of first estimating solar irradiance on a horizontal surface from scarce data and then converting the result to the required inclined surface of the webs and flanges.

Major weather stations report hourly radiation totals on a horizontal plane. For a bridge with a large thermal mass, irradiance or radiation intensity at a given time can be directly calculated from the hourly data. Small variations due to cloud do not influence bridge temperatures. However, many stations only report the daily total radiation. For the model irradiance is calculated from the daily total using the method proposed by Collares and Rabl [5]. If the bridge site is not located near a weather station measuring solar radiation it maybe possible to interpolate values from adjacent stations. As an alternative the program calculates irradiance from an estimate of atmospheric turbidity [6].

Solar irradiance on any inclined surface, I_r, is calculated following the method proposed by Hay [7].

$$I_r = I_d \frac{\text{Cos}(\varnothing)}{\text{Sin}(E)} + D_h\{K_t \frac{\text{Cos}(\varnothing)}{\text{Sin}(E)} + 0.5(1 - K_t)(1+\text{Cos}(\beta))\} + R\,\text{Sin}^2(\beta)$$

where:
- I_d = Direct radiation component on a horizontal surface (W/m^2)
- D_h = Diffuse radiation component on a horizontal surface (W/m^2)
- R = Reflected radiation component on a horizontal surface (W/m^2)
- K_t = Clearness index ie Global radiation at ground level divided by the solar constant at the limits of the atmosphere
- E = Solar elevation angle
- β = Tilt angle of the surface
- $\varnothing$ = Angle of incidence of the solar beam to the surface.

The angle of incidence of the solar beam to the suface may be calculated from the solar and surface geometry.

$$\cos(\phi) = \cos(E)\cos(\gamma)\sin(\beta)\cos(a_S) + \cos(E)\sin(\gamma)\sin(\beta)\sin(a_S) + \sin(E)\cos(\beta)$$

The solar and surface geometry is shown in Figure 1. A standard algorithm [8] is incorporated in the program to calculated the solar position angles, E and γ, for any site and time. The direct component of radiation is simply the total irradiance, I, less the diffuse part. Here the diffuse component of radiation is modified to include a circum-solar part as well as that diffusing from the sky hemisphere. Finally, the reflected component is the total irradiance multiplied by the ground reflectance.

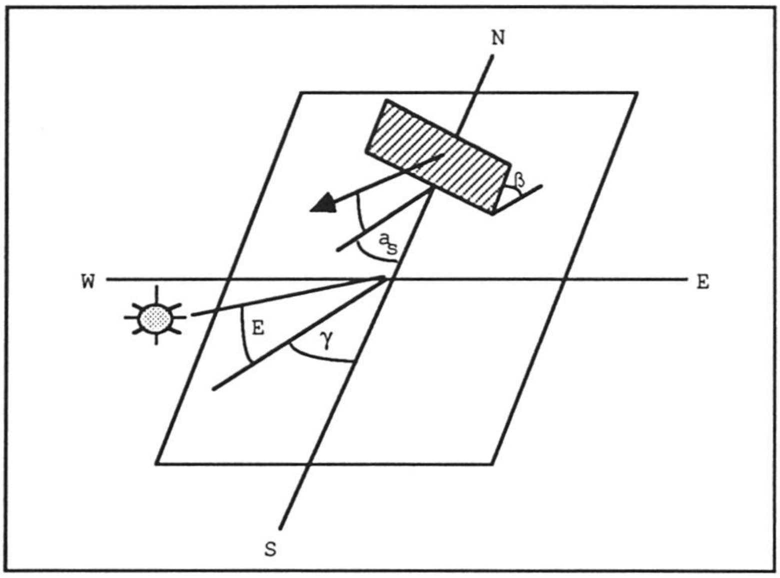

Fig. 1 Solar and Surface geometry.

The final step is to compute the diffuse component of the total radiation as measured at a weather station. Diffuse radiation depends on the meteorological conditions at the site for the day in question. Here the Orgill/Hollands approach [9] is used for Canada and the modification suggested by Spencer for Australia [10]. The approach is a set of empirical relationships between the diffuse component and the clearness index and has been calibrated from weather data in the respective countries. The modular format of the computer program allows further subroutines to be added for other countries. The universal model suggested by Hollands and Crha [11] is also incorporated in the program as a default option.

3. COMPARISON WITH FIELD DATA

The theoretical model is compared with the field data measured at three bridges of differing cross-sections in Canada and Australia.

The first bridge is located in Calgary, Canada and carries the light rail transit (LRT) system over the Bow River. Details of the bridge cross-section and location of the temperatures measuring stations are given in Figure 2. Full details of the bridge construction and instrumentation are given in an earlier paper [12]. The bridge is unusual in that the webs of the box girder are fully exposed to solar heating since the cantilever wings extend from the bottom flange and provide no shade to the webs. Temperature measurements began in 1986.

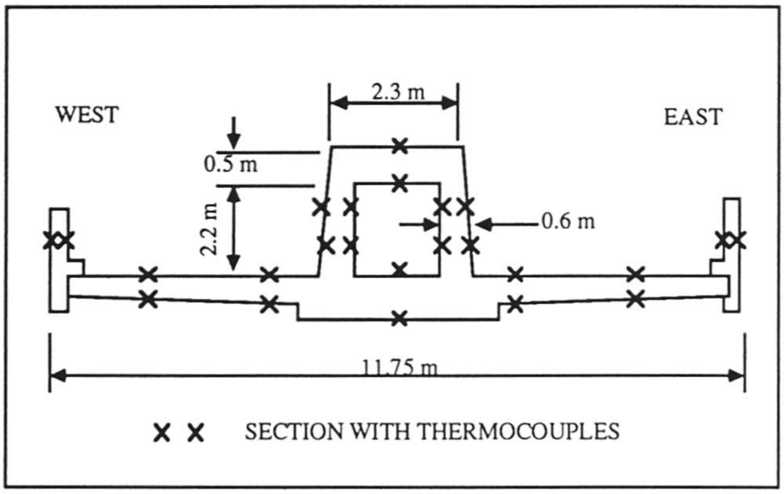

Fig. 2 Cross-section of Calgary LRT Bridge

Calgary enjoys clear skies in summer with high solar radiation given its altitude and low atmospheric relative humidity. The results presented here are for 3 August 1986 a typical summer day. Figure 3 shows the variation of solar radiation measured at a weather station approximately 10 kilometres from the bridge and that predicted by the computer model.

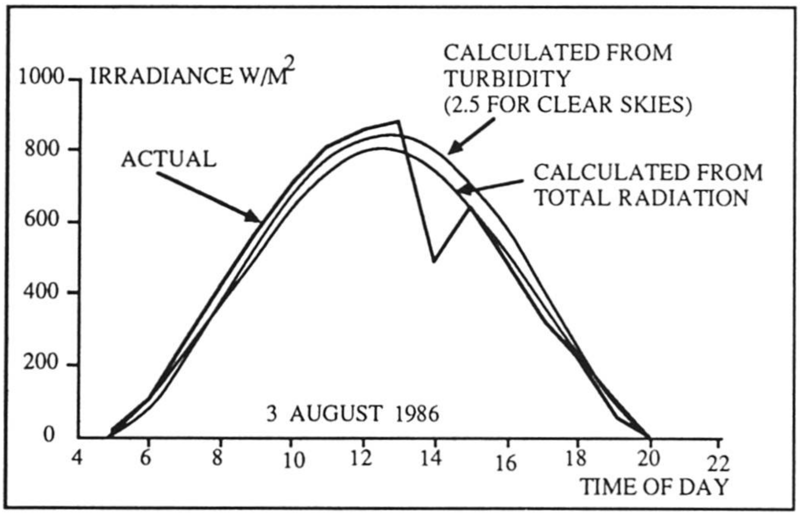

Fig. 3 Variation of irradiance, Calgary LRT Bridge

The rapid heating of the faces of the webs is shown in Figure 4 which plots both the measured variation of surface temperature and the computer prediction. The heating is local to the surface as shown in Figure 5 which plots the temperature profile through the webs at the time of maximum surface temperature. Each web only receives high incident solar radiation for a few hours when the sun is low in the sky. A simple elastic analysis of these temperature profiles yields tensile eigenstresses of 3.2 and 3.4 MPa for the outer fibres of the east and west webs respectively. The stress calculation assumed a 45 MPa concrete with a linear coefficient of thermal expansion of $0.00001/K^{-1}$ and all other concrete properties calculated from f'_c according to the ACI Code [13]. No distress was observed in the webs and the predicted tensile stresses are reduced by the prestress.

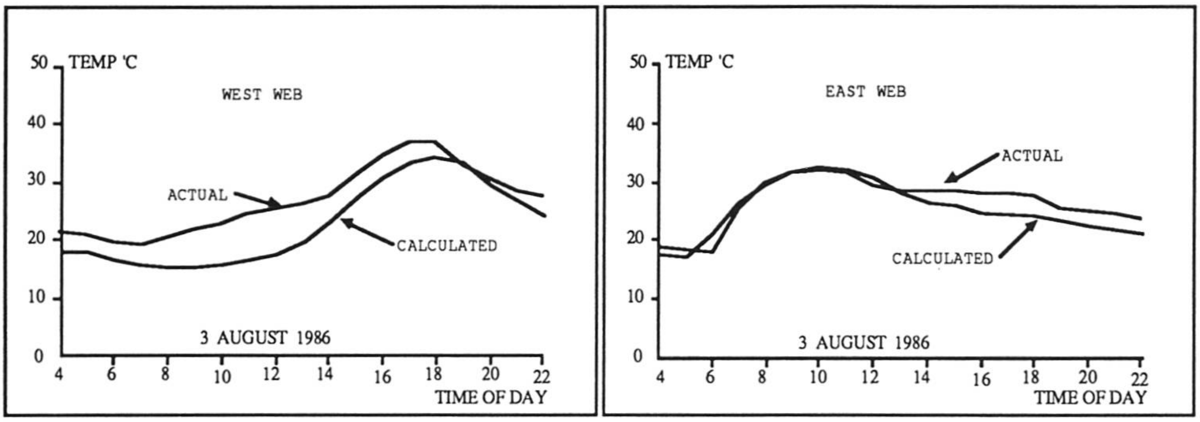

Fig.4 Variation of web surface temperature, Calgary LRT Bridge

The measured and predicted variation of average bridge temperature and the temperature differential through the top flange are shown in Figure 6. The discrepancy in top flange temperature suggests that the temperature sensor is not at the surface of the concrete. The field data suggests lower surface temperatures for the top flange than either web yet the top flange is heated far longer and has identical surface characteristics. The pattern in these results with maximum values in the late afternoon is typical of large concrete box girders. It is the high surface temperatures in the unshaded webs that are unusual in the Calgary LRT bridge.

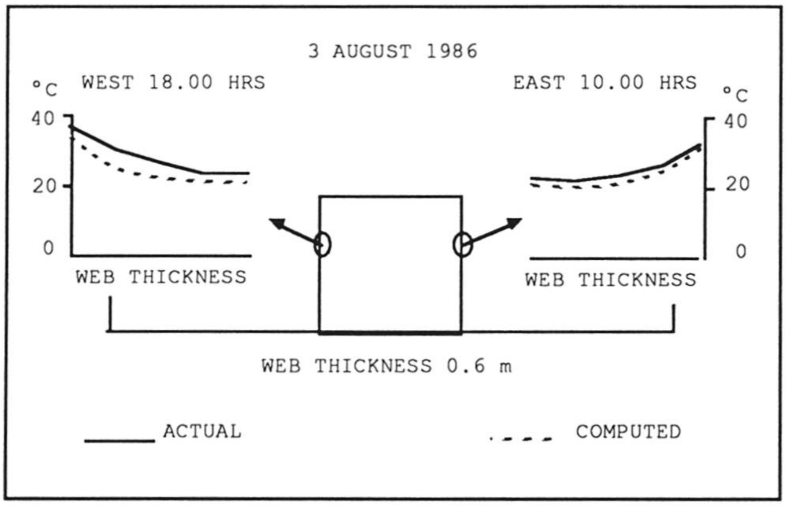

Fig. 5 Web temperature profiles, Calgary LRT Bridge

The remaining two bridges are located in South Australia. Here the climate varies from mediterranean in the south to semi-desert conditions in the north of the State. The hot dry summers with low atmospheric humidity produce high solar irradiance.

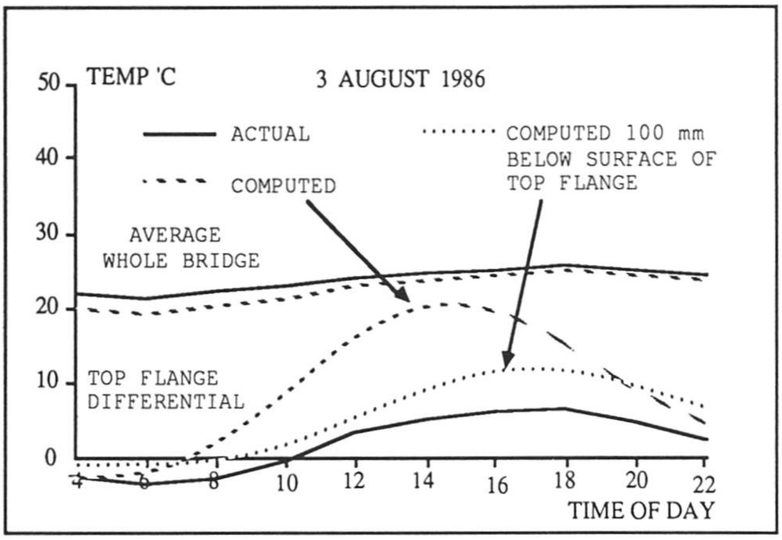

Fig. 6 Variation of temperatures, Calgary LRT bridge

Bridge temperature measurements were made at Swanport Bridge over the River Murray from July 1985 to May 1987 [14]. The bridge is a 3.0 m deep concrete box girder of ten 72 m spans. Figure 7 shows the cross-section of the bridge and the location of the instrumentation. The conventional arrangement of cantilever wings means that the webs are in shade for much of the day and so high web temperatures do not occur.

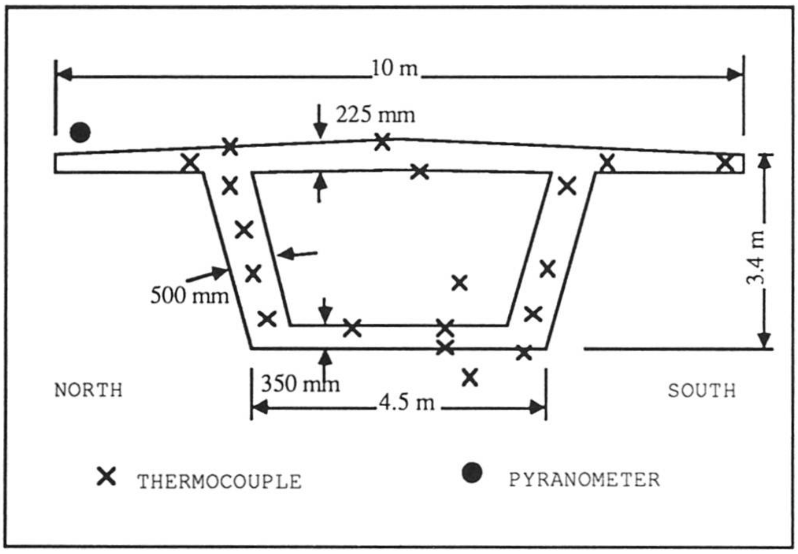

Fig. 7 Cross-section of Swanport Bridge.

Figure 8 shows the daily variation of irradiance measured at the bridge site and calculated by the computer model for the summer day of 29 January 1986. Both figures 3 and 8 show that the Collares Rabl procedure for calculating irradiance from the daily total tends to underestimate the peak irradiance.The figures also show that the assumption of an atmospheric turbidity of 2.5 for clear skies in Calgary and 4,5 for light cloud cover at Swanport is realistic. Although actual hourly values of solar radiation could have been input to the model such data are not widely available. The use of daily values is a more realistic test of the model.

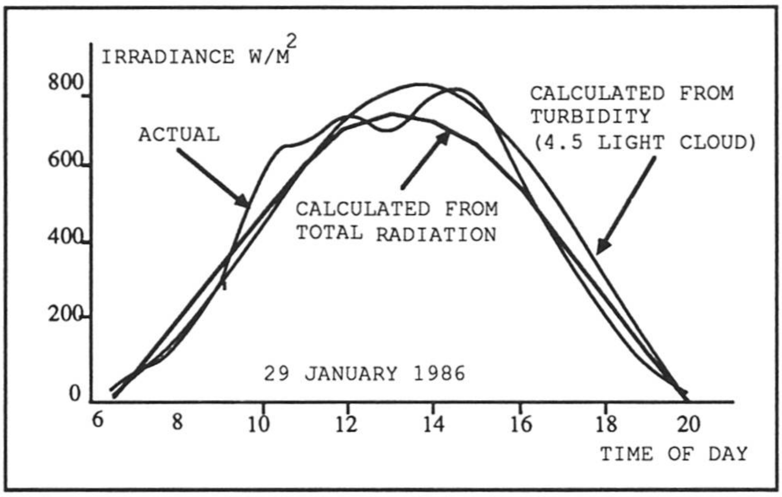

Fig. 8 Variation of irradiance, Swanport

The measured and predicted daily variation of average bridge temperature and top flange differential temperature for Swanport Bridge are show in Figure 9. For Swanport Bridge the measured and predicted surface temperatures at the top of the top flange agree. Results from both bridges show that the time constant procedure is realistic to evaluate the initial starting temperature for the analysis.

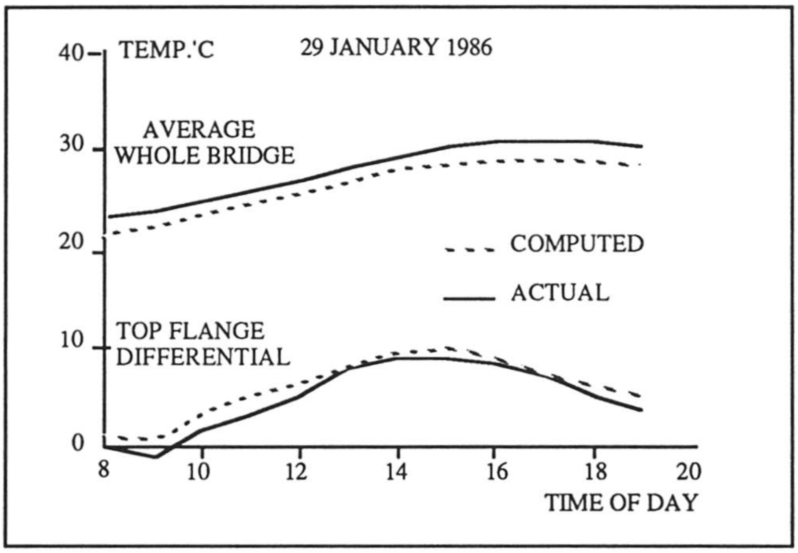

Fig. 9 Variation of bridge temperatures, Swanport

Earlier work on a composite box girder bridge by Dilger and Ghali [15] in northern Alberta had shown the potential for solar heating of steel webs. Temperature differentials of 42° C were measured between the web heated by the low sun on an early spring morning and the web at sub-zero temperatures in the shade.

In 1983 temperature measurements were made on Cottonbush Creek Bridge [16] located near Coober Pedy in the desert area of South Australia. The bridge is a conventional composite girder bridge with 760 mm deep steel beams at 2.2 m centres overlaid by a 180 mm thick concrete slab. Figure 10 shows the cross-section and the details of the temperature measuring stations. The daily variation in the bottom flanges of the outer steel girders on each side is shown in Figure 11. The figure also shows the temperature variation of the first inboard girder permanently in the shade. Extreme temperature differentials do occur between the girders but are only a third of the magnitude of those occuring in the Alberta bridge.

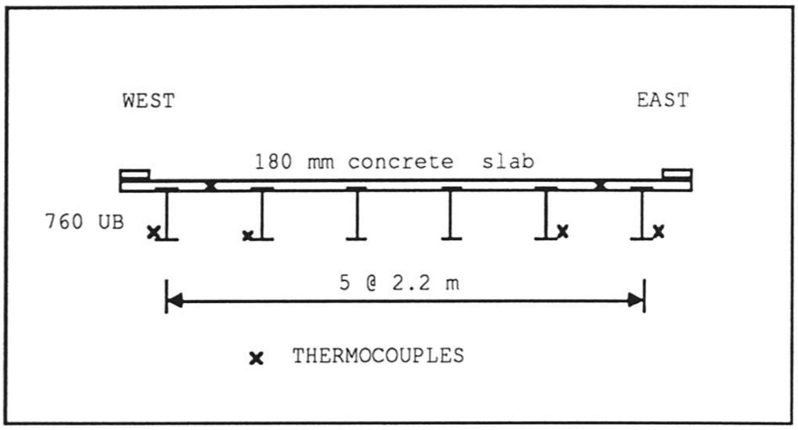

Fig. 10 Cross-section of Cottonbush Creek bridge

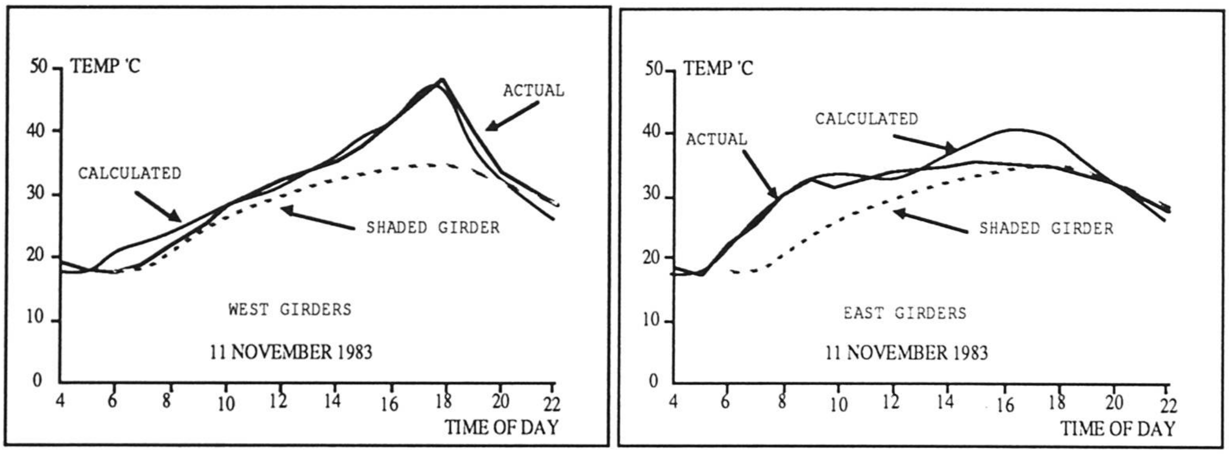

Fig 11 Variation of girder temperatures, Cottonbush Creek

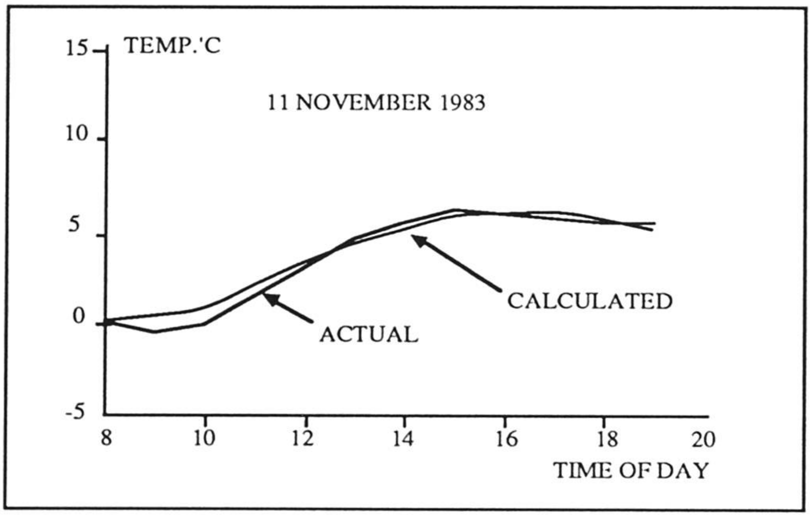

Fig. 12 Slab to girder differential, Cottonbush Creek.

The temperature differential between the slab and supporting beams is shown in Figure 12. The differential is computed from the average slab temperature and average temperature of the shaded steel girders at any time. Both computed and field results are similar for this composite girder bridge. On the 11 November 1983 ambient temperature climbed from 18.7°C at dawn to 36.2°C in the afternoon with a peak irradiance of 1080 W/m^2 .

4. CONCLUSIONS

The modified computer model does predict the temperatures in a range of bridges types both in Canada and Australia.

The results suggest that the solar heating models first suggested for solar collectors are applicable to the calculation of bridge temperatures. Initial starting temperatures for the time step analysis can be predicted using the "time constant" approach for a range of cross-sections.

Both the Calgary LRT bridge and the composite girder bridge show that temperature differentials can exist in the webs of concrete box girders and between steel beams providing they are exposed to radiation and not permanently in the shade from an overhanging deck slab.

The structural implications of these temperatures are beyond the scope of this paper but the computer model can be realistically used as a first step in that wider analysis.

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