Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 13 (1988)

Artikel: Thermal response of concrete box girder bridges

Autor: Mirambell, Enrique / Aguado, Antonio

DOI: https://doi.org/10.5169/seals-13024

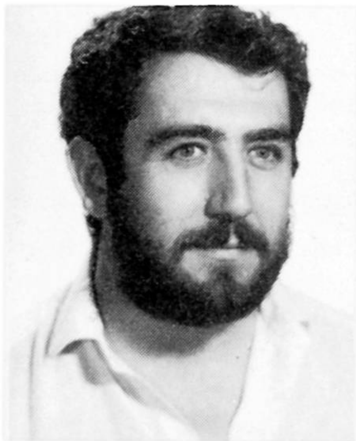
Thermal Response of Concrete Box Girder Bridges

Réponse thermique des ponts à poutre-caisson en béton

Das thermische Verhalten von Betonhohlkastenbrücken

Enrique MIRAMBELL
Assist. Professor
Univ. Politéc. de Cataluna
Barcelona, Spain

Antonio AGUADO
Prof. of Civil Eng.
Univ. Politéc. de Cataluna
Barcelona, Spain



SUMMARY
The present paper is based on the study of environmental thermal effects on concrete box girder bridges. First, we describe the analytical model used to obtain the time-dependent temperature distributions and the selfequilibrated longitudinal and transverse stress distributions. The influence of several factors -environment, physical properties, location of the bridge- on the thermal response of concrete box girder bridges is analyzed. Finally, some recommendations related to the determination of thermal actions to be considered in the design process are suggested.

RÉSUMÉ
L'exposé traite de l'influence des effets climatiques sur les ponts à poutre-caisson en béton armé ou précontraint. Il décrit le modèle analytique des distributions de températures au cours du temps, et les distributions des contraintes dans les directions longitudinale et transversale. Il étudie l'influence de quelques facteurs tels que l'environnement, les propriétés du béton, l'emplacement du pont sur ces distributions. Quelques recommandations pour la détermination de l'action thermique à considérer dans le projet sont faites.

ZUSAMMENFASSUNG
Die thermischen Wirkungen der Umgebung auf Betonbrücken mit Kastenquerschnitt werden untersucht. Es wird zuerst das analytische Modell beschrieben, das wir für das Erzielen der Temperaturverteilungen und der ausgeglichenen Längs-und Querspannungen benutzt haben. Dann wird der Einfluss verschiedener Faktoren — Umgebung, Eigenschaften des Betons, Lage der Brücke – auf die thermische Antwort von Brückenträgern untersucht. Als Folgerung werden einige Empfehlungen für die Festlegung der bei der Bemessung zu berücksichtigenden thermischen Wirkungen gegeben.

1. INTRODUCTION

The interest in reinforced and prestressed concrete bridge analysis and design in front of environmental thermal effects has increased considerably in recent years. Measurements in situ have shown that climatic and environmental conditions were more severe than the ones previously supposed in design. In some cases, this reason and an inaccurate design in front of thermal loads have induced the appearance of cracks in concrete bridges (Ref. [4], [7]).

The present paper is based on the study of environmental thermal effects on concrete box girder bridges, at sectional level. In the first place, we describe the analytical model used to obtain the time-dependent temperature distributions and the self-equilibrated longitudinal and transverse stress distributions within the cross-section of concrete box girder bridges. Likewise, the results derived from several parametric studies are presented.

These results show that strong correlations exist between the annual ambient temperature range at the location of the bridge and the annual effective temperature of the bridge and, also, between the incident solar radiation over the deck and the thermal imposed curvature. On the other hand, the analytical and experimental results show, in some cases, the importance of thermal horizontal gradients and thermal transverse loads.

2. ANALYTICAL MODEL

The analytical model used to obtain temperature distributions and stress distributions at sectional level is presented fully in Ref. [6]. However, the bases of the analysis are described here briefly.

2.1. Temperature distributions

The differential equation that governs the heat transfer problem is

$$\mathrm{div}(-\underset{\sim}{K}\cdot \mathrm{grad}\ T)-\dot{q}+\rho c\,\frac{\partial T}{\partial t} = 0 \qquad (1)$$

Assuming that concrete verifies several hypotheses -continuum, isotropy and homogeneity- and that the hardening process has finished, the equation (1) is transformed into

$$\nabla^2 T = \frac{\rho c}{k}\frac{\partial T}{\partial t} \qquad (2)$$

ρ, density of concrete
c, specific heat
k, conductivity

The boundary condition at the external surfaces of the deck bridge is the Newmann condition, which can be expressed in two dimensions as

$$k\left(\frac{\partial T}{\partial x}n_x+\frac{\partial T}{\partial y}n_y\right)+aI+(h_c+h_r)(T-T_a) = 0 \qquad (3)$$

The analytical model developed to solve the differential equation (2), with the boundary condition (3), and determine the time-dependent temperature distributions within the cross-section of concrete box girder bridges is based on two-dimensional finite difference method. Characteristics of the numerical program developed can be found in Ref. [5]. The convergence and numerical stability condition is (Ref. [6]).

$$\Delta t \le \frac{\rho c}{k}\,\frac{1}{2\left(\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}\right)+\frac{1}{k}\left(\frac{h_1}{\Delta y}+\frac{h_2}{\Delta x}\right)} \qquad (4)$$

2.2. Self-equilibrated stress distributions

Temperature distributions within the cross-section of concrete box girder bridges are nonlinear. In order to obtain the stress distributions at sectional level, the Navier-Bernouilli hypothesis is assumed. Due to this fact, self-equilibrated longitudinal and transverse stresses are induced by temperature distributions in concrete box girder bridges. Such stress distributions are independent of the support conditions of the structure and can be obtained by means of the following equation:

$$\sigma(x,y) = E(\varepsilon_o+\psi_x y+\psi_y x-\alpha T(x,y)_{nl}) \qquad \begin{aligned} \varepsilon_o &= \frac{\alpha}{A}\iint T(x,y)_{nl}\,dx\,dy \\ \psi_x &= \frac{\alpha}{I_x}\iint T(x,y)_{nl}\,y\,dx\,dy \\ \psi_y &= \frac{\alpha}{I_y}\iint T(x,y)_{nl}\,x\,dx\,dy \end{aligned} \qquad (5)$$

3. INFLUENCE OF SOME PARAMETERS ON THE THERMAL RESPONSE OF CONCRETE BOX GIRDER BRIDGES. ASSOCIATED STRESS DISTRIBUTIONS.

The thermal response of concrete box girder bridges depends on many factors -environmental conditions, structural parameters, physical properties and parameters depending on location of the bridge-. In this chapter, results derived from parametric studies related to several variables are presented and analyzed. The basic study of reference can be seen in Fig. 1 and Table 1. Values of the different parameters are from Ref. [1].

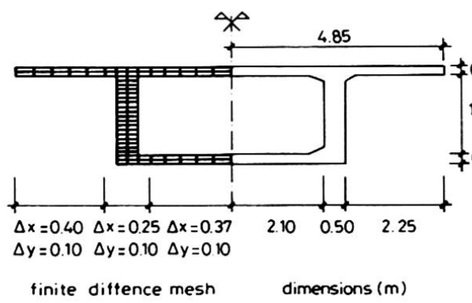


Fig 1. Cross-section and finite difference mesh.

Thermal and structural properties	Thermal diffusivity (m^2/h)	0.0023
	Absorbity	0.5
	Emissivity	0.88
	Thermal expansion coef. ($^oC^{-1}$)	8.0×10^{-6}
	Modulus of elasticity (MPa)	27386.
Environmental conditions	Ambient air temperature (^oC)	-5.÷20.
	Wind speed (m/s)	1.0
	Turbidity factor	1.8
	Day of the year	March, 21
Location and orientation of bridge	Latitude (^{o}N)	51.0
	Altitude (m)	1050.
	Azimuth (^{o})	0.

Table 1. Values of the different parameters in the reference study.

3.1. Influence of solar radiation

The influence of solar radiation intensity on the deck of the bridge may be considered by means of several explicit expressions (Ref. [2]). In this study, the effect of solar radiation is introduced in a general way, depending on several variables. The parameters which show a more significant influence are the day of the year and the latitude of the location of the bridge. The annual evolutions of the maximum vertical and horizontal thermal gradients, maximum daily range of effective temperature of the bridge and maximum temperature differences between the surrounding air and the air enclosed within the cell can be observed in Fig.2. Likewise, the annual evolution of the maximum longitudinal self-equilibrated tensile stress in concrete is presented in Fig.3.

As one can see from both figures, the most unfavourable situation is presented under summer conditions. During this season, nonlinearity of temperature distributions is very marked and, due to this effect, thermal actions and self-equilibrated longitudinal stresses are higher than the ones obtained during other seasons. The critical zones of the cross-section subjected to maximum longitudinal tensile stresses are the webs, while heating the deck, and the extreme fibers and the overhangings, while cooling the deck. Also, it may be interesting to analyze the annual evolution of the horizontal thermal gradient, which reaches the maximum value during the months of winter and it is zero during the months of spring and summer. That is due to the small inclination of the sun's rays with respect to horizontal plane during the winter season.

On the other hand, the influence of latitude must be considered in order to obtain the solar radiation intensity. The maximum thermal imposed curvatures occur under summer conditions, and the higher the latitude, the bigger the curvature produced and the smaller the self-equilibrated stresses induced are.

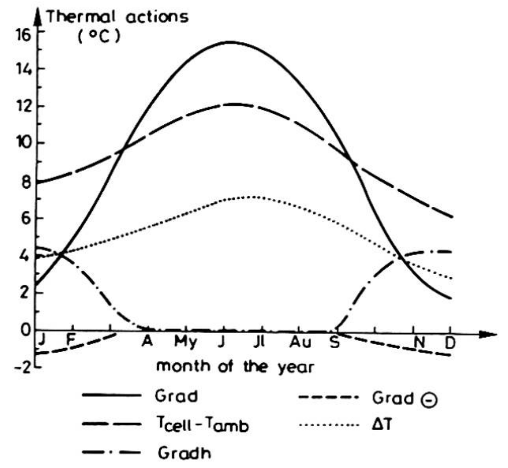


Fig.2. Annual evolutions of different thermal actions.

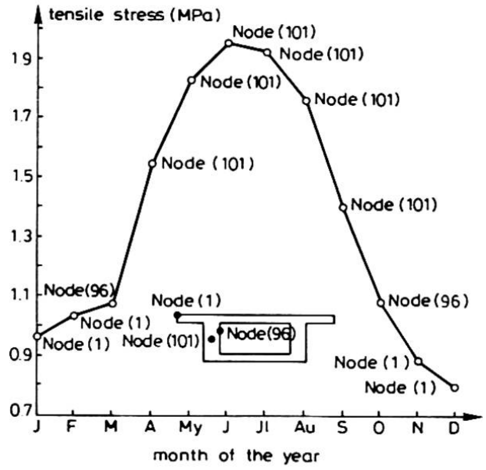


Fig.3. Annual evolution of the maximum longitudinal tensile stress.

3.2. Influence of asphalt thickness

The presence of asphalt cover on the concrete deck has an influence on the thermal response of concrete bridges due to its different thermal properties. In fact, as one can see from Figs.4 and 5, the presence of asphalt cover with a small thickness results in an increase of the thermal curvatures and the self-equilibrated thermal stresses while the presence of a thicker asphalt cover results in a decrease of the thermal curvatures and the thermal stresses.

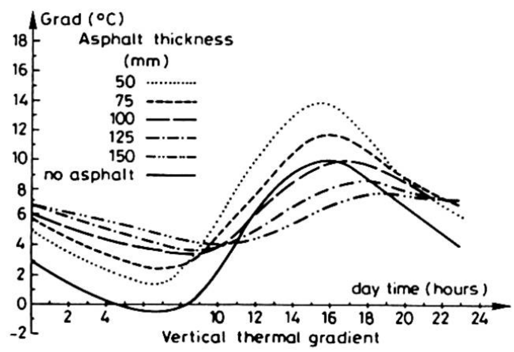


Fig.4. Daily evolution of vertical thermal gradients.

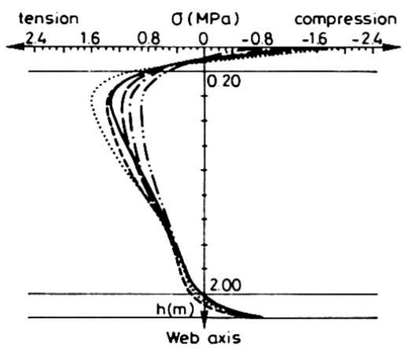


Fig.5. Self-equilibrated longitudinal thermal stresses corresponding to maximum curvatures (web axis).

We may note the existence of a limit asphalt thickness above which the thermal actions and the self-equilibrated thermal stresses are less than their counterpart without asphalt cover. This limit depends on environmental conditions and on superstructure depth. In our case, the limit asphalt thickness is close to 10 cm.

3.3.- Influence of superstructure depth and location of the bridge

Consider a hypothetical prestressed concrete box girder bridge with variable superstructure depth just as the one presented in Fig.6. This hypothetical bridge is located in Barcelona, Spain, in one case, and Helsinki, in the other. The main results derived from both thermal analysis are presented in Table 2. Thermal properties and azimuth are the same of Table 1.

These results show that vertical thermal gradient and daily and annual ranges of effective temperature of the bridge decrease with an increase of superstructure depth. On the contrary, the minimum horizontal thermal gradient occurs always at midspan cross-section. A comparative analysis of the results obtained in both studies permits to conclude that bridges located at higher latitudes may be subjected to less vertical thermal gradients. However, they are subjected to larger horizontal thermal gradients due to the small inclination of the sun's rays.

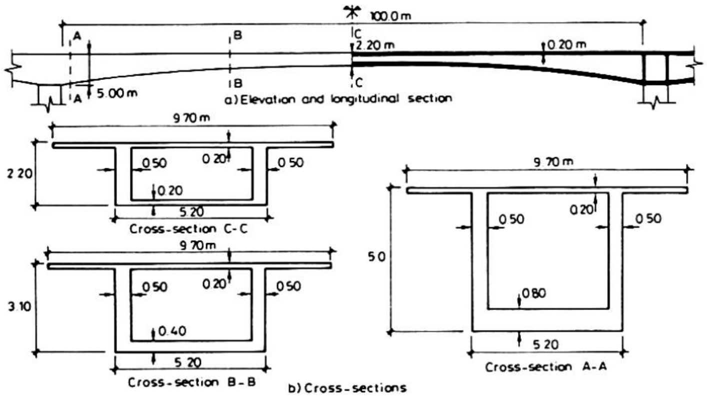


Fig.6. Elevation and longitudinal section of the bridge. Cross-sections.

In any case, it is interesting to point out that the horizontal thermal gradient and the temperature difference between the surrounding air and the air enclosed within the cell are significative. The effects produced by these thermal actions could be a source of cracks in concrete box girder bridges and, in general, have not been considered in design. Such results have already been indicated in several experimental analysis (Ref.[3]).

		Cross-section A-A		Cross-section B-B		Cross-section C-C	
Location of the bridge	Thermal actions (°C)	March, 21	June, 10	March, 21	June, 10	March, 21	June, 10
Barcelona	Grad	5.2	5.9	5.8	6.8	6.4	7.4
Latitude 41.4°N	Gradh	2.1	0.	0.5	0.	0.	0.
Altitude 100 m	ΔT	2.5	2.5	3.2	3.5	4.1	4.6
Wind speed 5 m/s	$T_{cell}-T_{amb}$	5.1	5.3	5.1	5.7	5.2	5.8
Helsinki	Grad	3.8	5.5	3.9	6.1	4.0	6.5
Latitude 60.1°N	Gradh	4.0	1.1	2.5	0.	1.4	0.
Altitude 100 m	ΔT	2.6	2.9	3.3	3.7	4.0	4.8
Wind speed 5 m/s	$T_{cell}-T_{amb}$	5.6	6.3	5.5	6.6	5.5	6.7

Helsinki, March 21, turb = 2.0, T_{amb} = -9÷-1°C
Helsinki, June 10, turb = 3.5, T_{amb} = 10÷19°C

Barcelona, March 21, turb = 2.0, T_{amb} = 9÷15.7°C
Barcelona, June 10, turb = 3.5, T_{amb} = 18÷25.1°C

Grad = maximum vertical thermal gradient.
Gradh = maximum horizontal thermal gradient.
ΔT = daily range of effective temperature of the bridge.

$T_{cell}-T_{amb}$ = temperature difference between surrounding air and air enclosed within the cell.

Table 2. Results of thermal analysis of the same bridge (Fig.6) located in Barcelona (Spain) and Helsinki (Finland).

4. THERMAL ACTIONS TO BE CONSIDERED IN DESIGN

Starting from the results of existing parametric studies (Ref.[5]), some of them shown in this paper, it may be possible to determine the thermal actions to be considered in design. This will be useful to bridge designers, in order to take into account the environmental thermal effects in the design process, in a simple and realistic way.

Related to annual range of effective temperature of the deck, the results show a strong correlation between this thermal action and the annual ambient temperature range at the location of the bridge. On the other hand, in the study of vertical thermal gradient, the main environmental factor is the solar radiation. However, in this case, the influence of superstructure depth and asphalt thickness are well known and significative. Fig.7 shows, as an example, the map of Spain with the isolines of vertical thermal gradient related to concrete box girder bridges (depth 2.20 m.) located on the Iberian Peninsula.

This map has been obtained from data processing of solar radiation, ambient air temperature and wind speed, collected in several reports of the Meteorology Institute of Spain. The values of the thermal actions to be considered in design predicted by this study are in good agreement with the values derived from temperature controls carried out in several concrete bridges located in Spain (Ref. [5]).

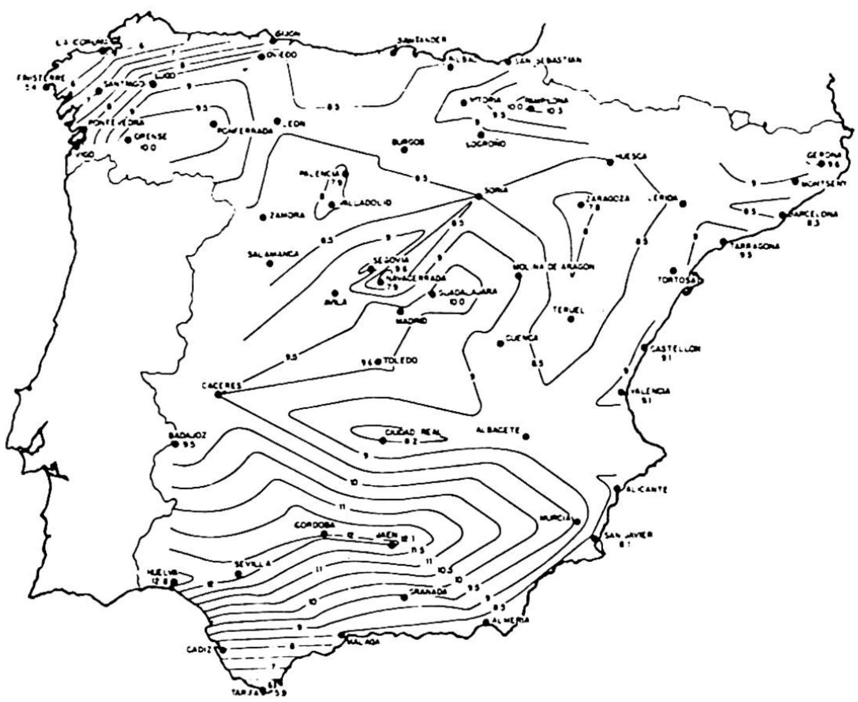


Fig.7. Isolines of vertical thermal gradient on concrete box girder bridges (depth=2.20 m) located in Spain.

5. CONCLUSIONS

In the first place, environmental thermal effects must be considered in the design process of concrete box girder bridges and, basically, in serviceability limit state.

The main climatological parameter required to determine the design effective temperature range is the annual range of ambient temperature at the location of the bridge. The main climatological parameter required to determine the design thermal gradient is the solar radiation intensity. In this case, other variables such as superstructure depth and asphalt thickness must also be taken into account in design.

The variables which show a greater influence on the horizontal thermal gradient are the latitude of the location and the azimuth of the bridge and the day of the year. Depending on these variables, the horizontal thermal gradient can be significant and it must be considered in design.

Finally, the transverse thermal stresses due to nonlinearity of temperature distributions and temperature difference between the surrounding air and the air enclosed within the cells must be considered in design. Basically, these thermal effects must be taken into account when sudden changes in the evolution of ambient temperature appear.

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