Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 74 (1996)

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DOI: https://doi.org/10.5169/seals-56099

Research on the Transversal Thermal Behaviour of a Prestressed Concrete Box Girder Bridge in Italy

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Summary

This paper contains a contribution to the knowledge of transversal thermal actions on bridges, still under discussion in the Project Team of EC1, Part 2.6, based on three consecutive years of in-situ monitoring of the Casilina bridge. A simplified data-processing approach for the evaluation of the transversal thermal actions and stresses is exposed.

1. Introduction

Movements and stresses induced in modern bridge configurations by thermal fields of climatic origin have been recognized for many years to be relevant to the serviceability and the integrity of these structures and of the category of integral bridges in particular [1].
A certain number of damages which has occurred in the past on both concrete [2],[3] and steel bridges [4], has attracted the attention of many research and design structural Engineers on this type of problems, all over the world.
It was generally agreed that a prerequisite for the evaluation of thermal effects in bridges was a accurate evaluation of the time and space temperature distributions resulting from the transient heat exchanges between the bridge surface and its environment.
A considerable number of theoretical and experimental researches performed during the last ten years by structural Engineers have demonstrated that realistic and a complete set of information on the thermal behaviour of a bridge can only be obtained by a combined and interactive use of both refined transient F.E.M. or F.D.M. analysis and continuous field measurements of the principal climatic variables and of the temperatures in a good, but necessarily limited, number of points within some cross-sections of the monitored bridge [5],[6],[7],[8].
It is known that non-linear, time dependent temperature fields arise under the influence of changes in solar and thermal radiation, wind speed and shade air temperature, and that both longitudinal (or global) and transversal (or local) stresses and deformations are induced in box girder bridges by these temperature changes (see for example ref.[5]).
It is also known that in the plane of a boxed cross section, which can be schematized as a closed frame of unit width, transverse bending moments and axial efforts are due to the restrained thermal movements of the component walls of the frame.

Nevertheless, for the sake of clarity, these basic notions will be shortly recalled in the following points.

1.1 Global thermal actions of a temperature field

Let us consider a rectilinear girder bridge with a cross section of constant height. It has been theoretically [7] and experimentally [8] found that for such a bridge the temperature distribution of climatic origin is at any instant non-linear and does not depend on the z abscissa taken along the bridge longitudinal axis.
Let $T(x,y,t^*)$ be the non-linear temperature field acting at a t^* instant over a homogeneous box section of a girder bridge (Fig.1). The field can be decomposed into the following quantities that may be called the global effective parameters of the temperature field.

1) Global mean temperature $T_m = \frac{1}{A}\iint_A T(x,y,t^*)dA$ [°C].

2) Global linear gradient along y axis $DT_y = \frac{1}{J_x}\iint_A T(x,y,t^*)ydA$ [°C/m].

3) Global linear gradient along x axis $DT_x = \frac{1}{J_y}\iint_A T(x,y,t^*)xdA$ [°C/m].

In the preceding expressions A is the area of the cross section and J_x, J_y are respectively its principal central moments of inertia.

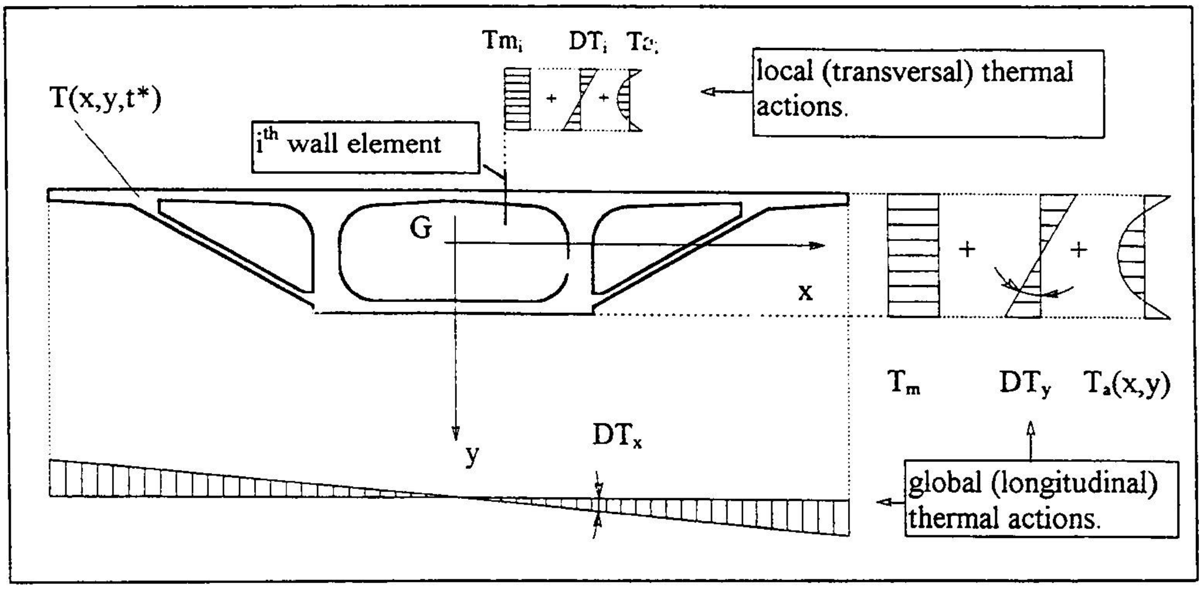


Fig.1. Decomposition of a temperature field into global (longitudinal) thermal actions and local (transverse) thermal actions.

T_m is responsible for the axial uniform movements of the bridge while DT_y, DT_x are respectively responsible for the cross sections rotation around its x (horizontal) and y (vertical) central principal axis of inertia.
The differences between the global effective parameters at a t^* instant and those at the instant t_0 of restraint of the structure (initial instant) may be called global (or longitudinal) thermal actions because they concern the whole cross section of the bridge.

If the movements induced by the global thermal actions are not freely allowed, axial forces and bending moments arise which are usually calculated by schematizing the girder bridge as a continuous beam. The associated stresses have been called secondary thermal stresses (**M.J.N. Priestley** [9]) because they may be present only in statically indeterminate structures.
The remaining self-compensated non-linear part of the temperature field

4) $$T_a = T(x,y,t) - \left[T_m + xDT_x + yDT_y\right],$$

produces axial displacements and rotation of the end cross sections which are meanly equal to zero and thus are not able to cause any axial force or bending moment even if the structure is statically not determinate.
On the other hand, when cross-sections can be supposed to remain plane (Saint-Venant's bodies), at a sufficient distance from the ends axial stresses arise which are proportional to expression (4) and are sometimes called residual stresses or, better, primary thermal stresses [9] because they do not depend on the restraint of the structure but only on the non linearity of the temperature field.

1.2 Local thermal actions of a temperature field

Modern girder bridges often have boxed cross sections. In addition to global thermal actions, and hence global thermal effects, local temperature distributions over the thickness of each wall element of the section must also be considered due to the closed frame transversal behaviour of the box sections.
If $T_i(s, t^*)$ is the local temperature distribution across the thickness S_i of the i^{th} wall element at the instant t^*, it can be decomposed in the same way used for the global quantities into the following effective local parameters of the temperature distribution.

5) Local mean temperature $$T_{m_i} = \frac{1}{S_i}\int_S T(s,t^*)ds.$$

6) Local linear gradient $$DT_i = \frac{12}{S_i^3}\int_S T(s,t^*)s\,ds, \qquad \text{with: } (-S_i/2 \le s \le + S_i/2)$$

In each i^{th} wall element, the differences between the local effective parameters at a t^* instant and those acting at the initial restraint instant of the element are called local (transversal) thermal actions because they act on the cross section regarded as a closed plane frame of unit width.
The remaining self-compensated non-linear part of the temperature distribution across the thickness of the i^{th} wall element

7) $$T_{a_i} = T_i(s,t^*) - \left[T_{m_i} + sDT_i\right],$$

induces tension and compression stresses in the thickness of the element that are self-equilibrating and independent of the end restraint of the wall element.
Concrete box girder bridges may experience heavy cracking due to longitudinal thermal actions, like in the case of the Market Viaduct [3], but also crack damages due to transversal thermal actions, like in the case of the Jagtbrücke [2].
In spite of this, transversal thermal actions have been quite disregarded by researchers and the level of available knowledge and experience about this topic is nowaday much lower to that reached on longitudinal thermal actions.
For this reason, an attempt has been made to offer the first insight into this problem by illustrating a simplified procedure used to evaluate the magnitude and time variations of transversal thermal actions from the great number of experimental data recorded from the

Casilina bridge. Further research will be devoted in the future for the assessment of the statistical properties of such transversal action distribution.

2. Field monitoring of Casilina bridge

The Casilina bridge is a prestressed segmental box girder bridge of the motorway Fiano Romano-San Cesareo, near Rome. The static scheme is that of a continuous beam (whose longitudinal axis almost coincides with the North-South direction) with three intermediate spans of 50 m and two end spans of 30 and 40 m. The cross-section has a three cellular trapezoidal form with a constant height of 240 cm and a 130 mm thick asphalt pavement The construction was carried out post-tensioning precast segments erected in balanced cantilever from the piers.
The shrinkage, creep and thermal behaviour of the bridge was extensively monitored within the framework of the research programme named E.V.E.R. (Effetti Viscosità E Ritiro).

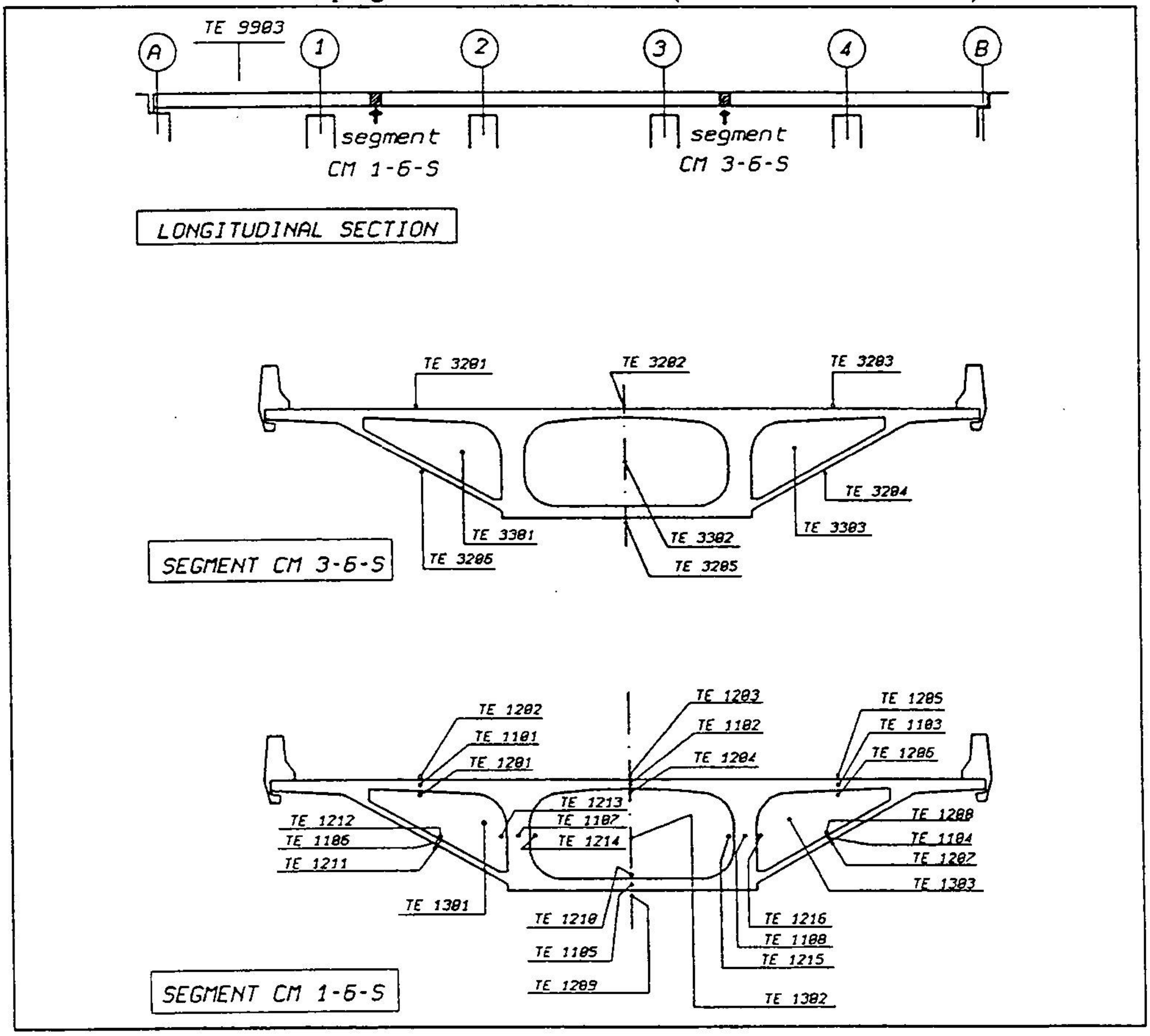


Fig.2. Longitudinal and cross sections of the bridge with the location of the thermistors.

Measurements were executed every hour from 18.00 a.m. of 2nd April 1987 until 10.00 a.m. of 7th August 1987 and every two hours from that instant until 14.00 p.m of 31st July 1990 when

the programme was stopped. Referring only to the thermal aspect of the campaign, some around 600.000 data were collected in this period. The instrumentation used, as well as the data measurement, storage and transmission techniques have been already described in reference [8]. Therefore it shall be here only briefly recalled, with reference to figure 2, that segments C.M 1.6.S and C.M 3.6.S were equipped with respectively 24 and 6 embedded thermistors and that ambient air temperature was measured in 6 points inside the box cells. Shade air temperature has been recorded several meters above the bridge deck surface.
All the measures have been systematically submitted to a numerical procedure of validation in order to define their reliability and, when possible, to reconstruct some missing data [8].

2.1. Evaluation of global thermal actions

The global effective parameters of a temperature field can be exactly calculated with relations (1) to (3) only when the function $T(x,y,t^*)$ is completely known all over the cross section. It is evident that by direct measurement the temperature field can be known only in a limited number of points and that, in order to calculate the global effective parameters, simplifying assumptions on the form of the temperature field have to be introduced. An alternative and more precise method is to develop a F.E.M. heat transfer model of the bridge where the boundary conditions reproduce with sufficient accuracy the time-histories of the climatic variables of the surrounding environment. The soundness of the numerical model must be checked, and if necessary fitted back, by comparison with the experimental data. Once the calculated time distributions of the temperatures in the measurement points fit satisfactorily the measured distribution, than the numerical outputs can be used at any instant to accurately calculate the effective parameters.
This kind of interactive analysis was carried on the Casilina bridge; a detailed description of which may be found in reference [8].
The absolute value and the sign of global thermal actions are generally very difficult to evaluate because the thermal fields at the initial instants are not known and also because it is sometimes even very difficult to establish exactly which were the initial instants when the restraint operations lasted some days. Since the monitoring of the thermal rensponse of the Casilina bridge included also the construction phases, it was in this case possible to individuate, within a rather small range of uncertainty, the global effective parameters at the times when the different spans were joined together, and hence the global thermal actions acting on the bridge [11].

2.2. Evaluation of local thermal actions

The evaluation of the local thermal actions may be carried out in a simpler way than that needed for global thermal actions due to the relative small and almost uniform thickness of the wall elements. Indeed, it has been found [8] that, at sufficient distance from the ends, the local temperature field is almost uniform along the length of each element and varying only in the thickness of it. Therefore, in order to calculate the local effective parameters from expressions (5),(6), it would be necessary to know the temperature distributions $T_i(s,t^*)$ along the thickness S_i of each wall element. Since the thicknesses of the elements are relatively small, a sufficiently accurate evaluation of the local effective parameters can be performed asssuming that each $T_i(s,t^*)$ is parabolic along the correspondent S_i and imposing to $T_i(s,t^*)$ to assume just the experimental values at the three points of S_i where the thermistors were located.
Under these assumptions, if T_{1i} ,T_{3i} are the measured temperatures at the outer surfaces and T_{2i} is the measured temperature at middle thickness of every i^{th} wall element at a generic t^* instant, it is easy to obtain the instantaneous, approximate expressions of the local effective parameters:

8) Local mean temperature $T_{m_i} \approx \frac{T_{1i} + 4T_{2i} + T_{3i}}{6}$.

9) Local linear gradient $DT_i \approx \frac{T_{1i} - T_{3i}}{S_i}$,

The self-compensated non-linear part of the local temperature distribution becomes:

10) $$T_{a_i} \approx \left(\frac{T_{1i} - 2T_{2i} + T_{3i}}{6}\right)\left(\frac{12s^2}{S_i^2} - 1\right) = B_i\left(\frac{12s^2}{S_i^2} - 1\right), \quad \text{with: } (-S_i/2 \le s \le + S_i/2)$$

The time-histories of each T_{mi}, DT_i and B_i quantity has then calculated from the measured temperatures according to expressions (8),(9),(10) and plotted all over the three years of monitoring time.

In figure 3 are reported the time variations of the effective mean temperatures and of the linear gradients, within the wall elements of the cross section, calculated during a typical summer period where a great amount of direct solar radiation occurs and where the most severe transversal efforts, according to **M.N.Elbadry, A.Ghali** [5] and **M.Ramezankhani, P.Waldron** [6], should occur.

It can first of all be observed that the thermal rensponses of the two lateral sloping webs are almost coincident as well as that of the vertical internal webs. This is due to the broad lateral overhanging cantilevers and to the great inclination of the lateral webs which produce almost a total sheltering of these wall elements from the direct solar radiations. Now, since also the thermal rensponses of the lateral upper slabs are almost the same, it follows that the global horizontal gradient must be aspected to be practically zero as it is indeed (see ref. [8]) thus confirming the good thermal behaviour of trapezoidal sections theoretically already predicted in [6].

The number of variables that occur in the evaluation of transversal thermal effects still remains quite large, in spite of the already introduced simplified calculation of the local effective parameters, making it difficult to formulate simple design rules but, in the present case and in similar other cases, it may be reduced without significantly affecting the level of accuracy requested for structural design calculations. We can indeed notice that the mean temperatures of the three upper slabs differ from each other not more than about 3°C during only a few hours per day. For this reason they can be unified with good approximation in their mean value:

11) $$T_s = \frac{T_{m1} + T_{m2} + T_{m3}}{3}.$$

For the same reason this operation can be performed also on the mean temperatures of the sloping webs and of the bottom slab, thus obtaining:

12) $$T_i = \frac{T_{m4} + T_{m5} + T_{m6}}{3}.$$

The mean temperatures of the central webs are not only almost coincident but also almost constant troughout this time interval; let us indicate with T_0 their average value:

13) $$T_0 = \frac{T_{m7} + T_{m8}}{2}.$$

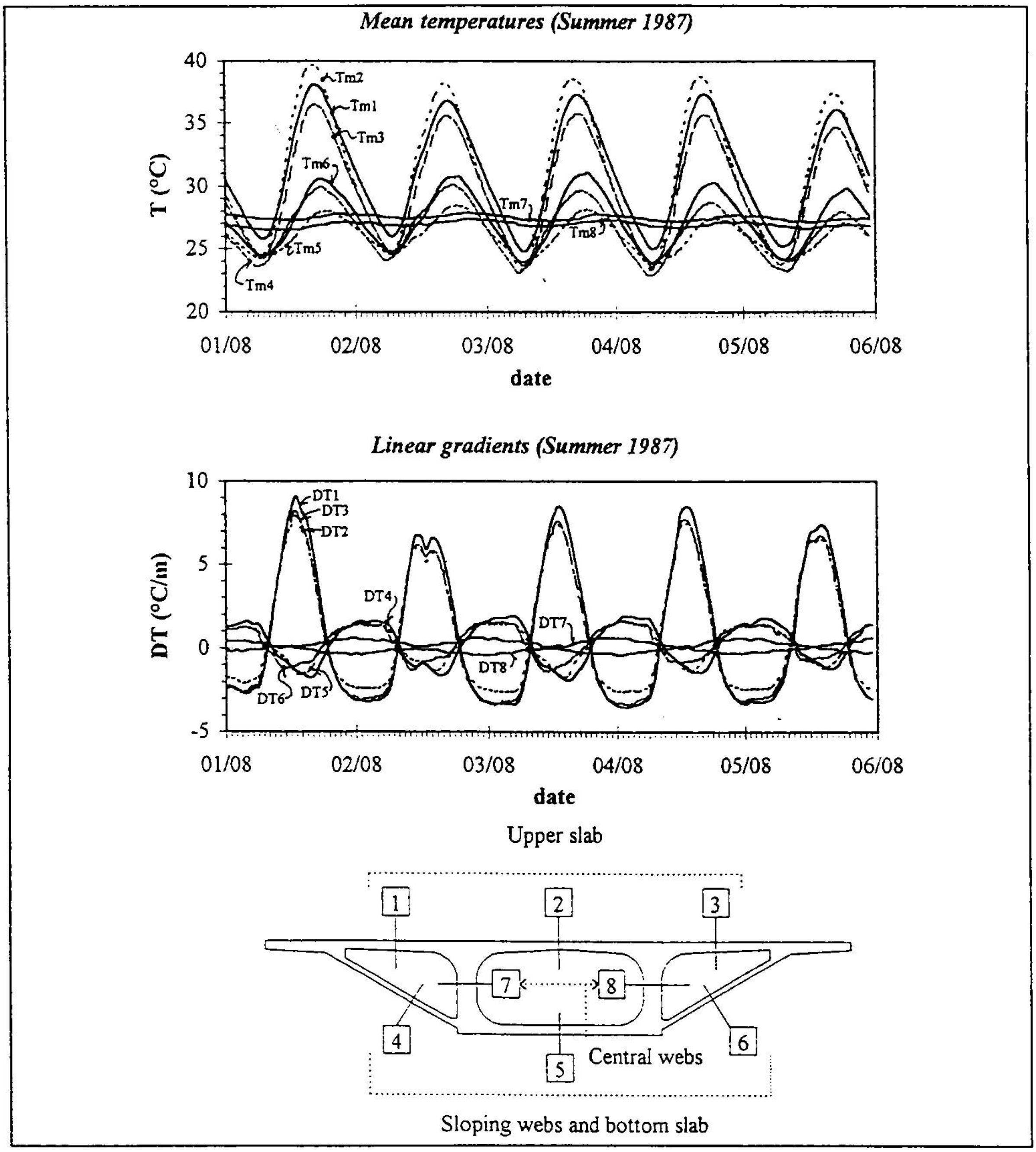


Fig. 3. Tipical summer daily distributions of the effective parameters mean and linear gradients within the wall elements of the cross section.

Similar considerations may be applied to the linear gradients thus obtaining the mean quantities DT_S,DT_I, DT_O.

It has been already said that the recording of the temperatures during the erection of the bridge allowed a reasonable evaluation of the absolute value and of the sign of the global thermal actions that the Casilina bridge experienced during the monitoring period and which are reported in reference [11].

This recording cannot be performed with respect to transversal thermal actions because no temperature measurement has been carried on during the concreting.

Nevertheless it is known that, even if the temperature field would change with time but remaining uniform at any instant all over the cross section, there would be a uniform expansion or contraction without any transversal effort. Transversal stresses occur at the generic instant t^* only when mean temperatures T_{mi} of the wall elements are different from each other and when the linear gradients DT_i and the quantities B_i are different from zero.

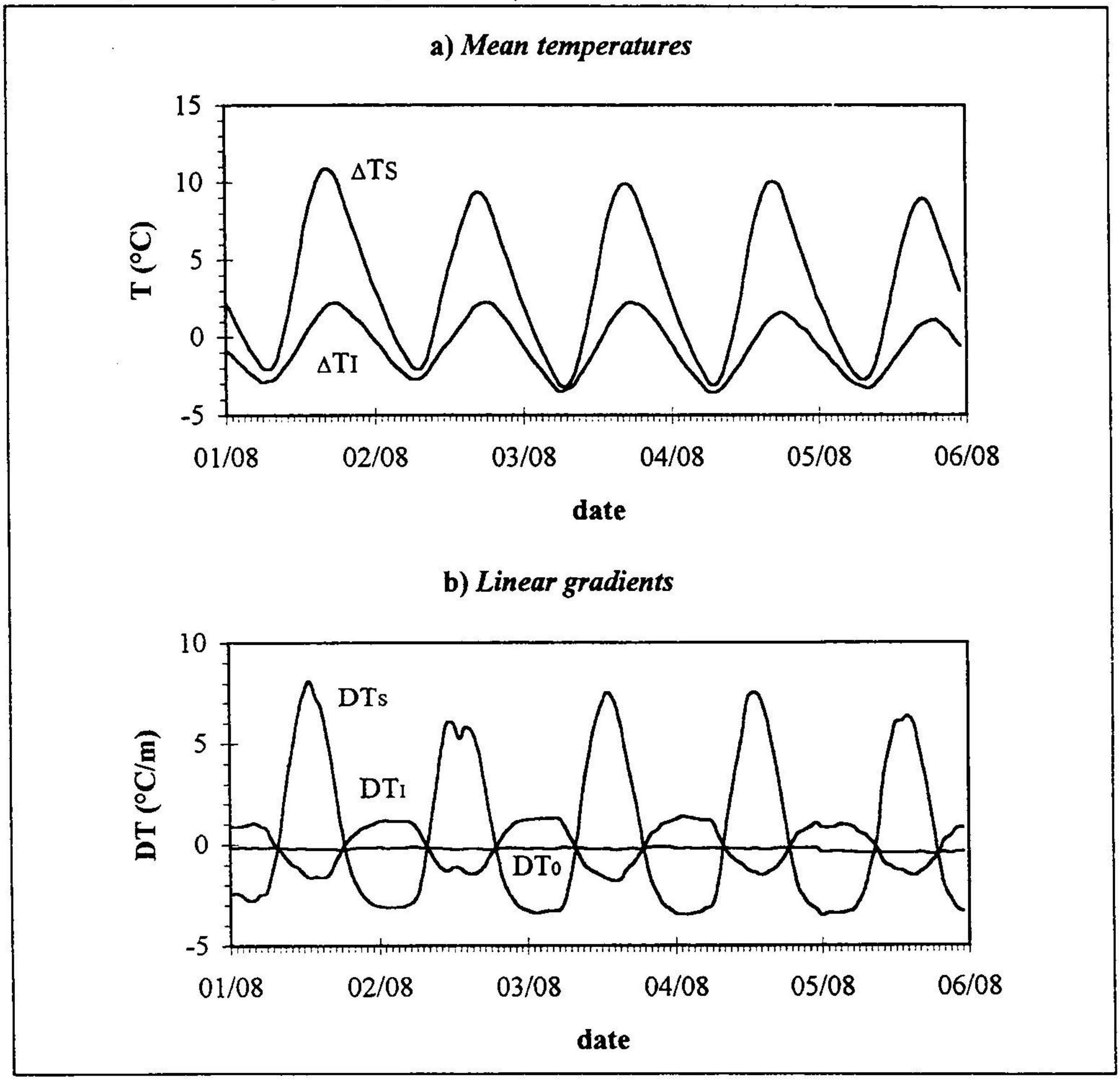


Fig.4. Hourly distributions of the daily variations of transverse thermal actions.

Therefore, it is evident that in the present case, within the performed simplifications, the daily variations of the transversal efforts induced by mean temperature differences depend only on the following two quantities:

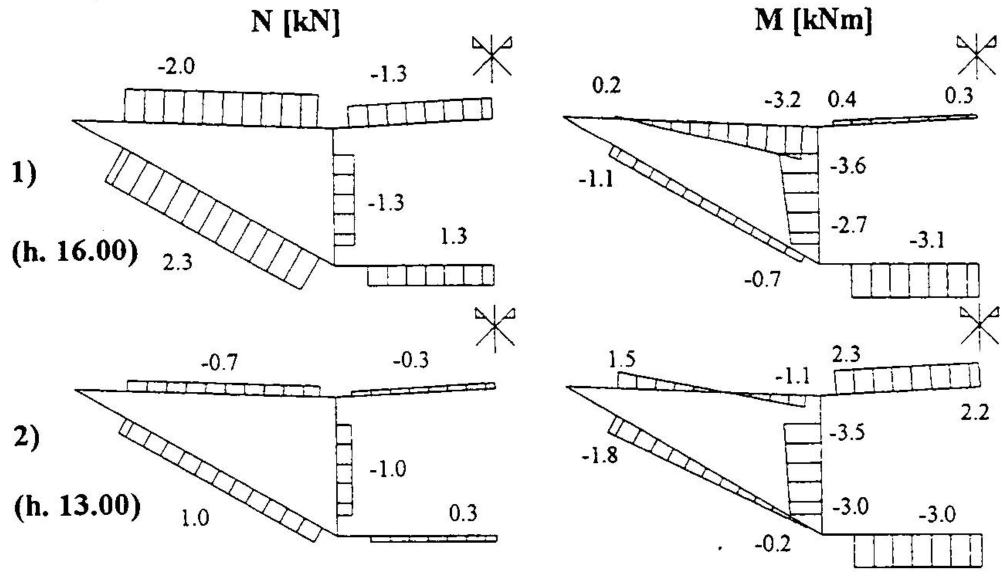
14) $$\Delta T_S = T_S - T_0 \qquad \Delta T_I = T_I - T_0 .$$

that may be than regarded as the daily variations of the local thermal actions "mean temperatures".

The daily variations of the thermal actions "linear gradients" can be calculated from DT_S, DT_I, DT_0 taking as reference those values at a certain time of the day when the gradients are all almost zero. This temporal reference is usually taken early in the morning when the temperature field is normally almost uniform [5], [6] as confirmed in figure 3 too.
Figure 4 collects two typical summer hourly distributions of the daily variations of transversal actions mean temperature and linear gradients.
In an attempt to evaluate also the absolute value and sign of transversal thermal actions, let us notice that precast segments have been placed in a sheltered, shadowed shed to assure a good curing. In the period subsequent to the early phase of the hardening process, where the temperature fields are greatly affected by the production of hydratation heat and are therefore strongly non-linear, it may be reasonably supposed that the temperature field was almost uniform over the cross section.
If this hypothesis is accepted, the daily distributions of the mean temperatures of figure 4 and of the linear gradients of figure 3 are to be regarded as very close to the absolute transversal thermal actions.

3. Transversal thermal efforts and stresses

The problem of the calculation of the stresses induced by assigned time dependent thermal actions in a concrete structure is very delicate because of the interactive relaxation effects of cracking and creep [12],[13].
Nevertheless, many authors have calculated the level of thermal stresses under the simple assumption of linear elastic behaviour of the reinforced concrete (see, for example ref.[5],[6],[14]).



($\alpha = 1.2 \times 10^{-5}$ °C^{-1} ; $E = 3 \times 10^4$ MPa)

Fig.5. Elastic axial forces and bending moments due to thermal loading.

For this reason, in order that direct comparisons with other studies be made possible, some elastic calculations of transversal stresses have been executed schematizing the cross section as

a closed frame composed by wall elements of constant height and unit width rectangular cross section.
Two combinations of transversal thermal actions have been applied:
1) maximum daily variation of the mean temperatures with associated linear gradients and self-compensated, non-linear temperature distribution,
2) maximum daily variation of linear gradients with associated mean temperatures and self-compensated, non-linear temperature distribution.
Figure 5 illustrates the obtained results.
Table I indicates the primary and secondary elastic thermal stresses calculated at the outer surfaces of each wall element for both load conditions. Negative signs indicate compression.

	Load condition (1) 1/8/87, h16.00 ΔT_S= +7.5°C ; ΔT_I= 0°C ; DT_S= 8°C/m ; DT_I= -1.7°C/m [MPa]			**Load condition (2)** 1/8/87, h13.00 ΔT_S= 11°C ; ΔT_I= 2°C ; DT_S= 5°C/m ; DT_I= -1.5°C/m [MPa]		
(i)	σ'_c	σ''_c	$\sigma'_c+\sigma''_c$	σ'_c	σ''_c	$\sigma'_c+\sigma''_c$
1;3	-0.65	+0.30 -0.32	-0.35 -0.97	-1.30	-0.15 +0.14	**-1.45** **-1.16**
2	-0.07	+0.03 -0.04	-0.04 -0.11	-0.50	-0.22 0.22	-0.72 -0.28
4;6	-0.14	-0.32 +0.35	-0.46 +0.21	-0.14	+0.56 -0.54	+0.42 -0.68
5	-0.36	-0.30 +0.31	-0.66 -0.05	-0.29	+0.29 -0.29	0.00 -0.58
7;8	-0.07	+0.08 -0.10	+0.01 -0.17	+0.07	-0.09 +0.08	-0.02 +0.15

Table I: Elastic primary (σ'_c) and secondary (σ''_c) transversal thermal stresses in the wall elements.

4. Conclusions

The daily changes of the transversal temperature actions have been obtained by a simple processing procedure of the in-situ collected temperature measurements performed on a concrete box girder bridge near Rome during three years of continuous monitoring.
A typical set of summer days with clear sky and a great amount of solar radiation has been considered as a significant climatic condition where the maximum daily variations of the transversal thermal actions and of the related elastic primary and secondary transversal thermal stresses are likely to be expected.
The resulting low magnitude of the thermal actions and of the calculated elastic thermal stresses, confirms the favourable transversal thermal behaviour of closed trapezoidal cross-sections where broad lateral cantilevers and a relevant slope of the lateral webs minimize the harmful effects of direct lateral solar radiation.
It has also confirmed the relative greater importance of primary transversal stresses in comparison with secondary transversal stresses.
Further research work is in course to assess the statistical meaning of these results. In deep box girder bridges with vertical webs, it has been found on the contrary that transversal thermal actions can reach a high intensity. Therefore, more research work was judged necessary within the Project Team on Part 2.6 of Eurocode 1 to assess reliable rules on this topic.

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