THERMAL ACTIONS ON COMPOSITE CONCRETE-STEEL BRIDGES. COMPARISON BETWEEN EUROCODE AND THE RESULTS OBTAINED ON MONITORED BRIDGES

Miguel Ortega Cornejo*, Francisco Millanes Mato, Juan Luis Mansilla Domínguez*****

*Eng., Project Manager IDEAM S.A. Madrid. Spain

** Prof., PhD., Eng., Universidad Politécnica de Madrid,
President IDEAM S.A., Madrid, Spain.

***Eng. IDEAM S.A. Madrid. Spain

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Abstract: *This paper compares the analysis of the thermal actions on composite concrete-steel bridges following Eurocode EN-1991-1-5 with the results of the temperature data registered in two composite monitored bridges. The instrumentation's analysis shows a very good correlation between the maximum/minimum shade air temperature and the maximum/minimum uniform bridge temperature component. On the other hand, the instrumentation has proved the existence of a horizontal component of the thermal action higher than that proposed by Eurocode caused by the different exposure of the steel webs to the sun in a classical composite deck at dawn and at dusk.*

The different thermal inertia of concrete respect to steel generally causes the partial steel section to be always hotter than the partial concrete section during the day, whereas at night the partial steel section is always colder than the partial concrete section. The vertical temperature difference proposed by the Eurocode has been tallied with the results measured.

1. THERMAL ACTION ON COMPOSITE BRIDGES ACCORDING TO EN 1991-1-5.

Eurocode EN-1991-1-5 [1] defines the thermal action on composite steel-concrete bridges (type 2) the same way for both steel bridges (type 1) and concrete bridges (type 3), with two components: the uniform temperature component and the vertical and horizontal difference component.

1.1. Uniform Temperature Component

The uniform temperature component depends on the maximum and minimum temperature which the bridge will reach. The minimum and maximum uniform temperature components $T_{e,.min}$ and $T_{e,.max}$ of the bridge depend on the minimum and maximum air shade temperature T_{min} and T_{max} for the site where the bridge is. For a composite bridge EN-1991-1-5 [1] defines this correlation as:

$$T_{e,min} = T_{min} + 4,50\ ºC \quad (1)$$

$$T_{e,max} = T_{max} + 4,50\ ºC \quad (2)$$

1.2. Range of uniform bridge temperature component

Eurocode EN-1991-1-5 [1] proposes a value of 10 ºC for the initial temperature T_0 at the time of the structure being restrained. This value seems to be adequate for central Europe, but in Spain a value of 15 ºC could be more accurate due the local weather conditions. The Spanish codes of actions on bridges [2,3] also proposed the use of 15 ºC as the initial temperature.

The characteristic value of the maximum contraction range of the uniform bridge temperature component $\Delta T_{N,con}$ should be taken as:

$$\Delta T_{N,con} = T_0 - T_{e,min} \quad (3)$$

and the characteristic value of the maximum expansion range of the uniform bridge temperature component $\Delta T_{N,exp}$ should be taken as:

$$\Delta T_{N,exp} = T_{e,max} - T_0 \quad (4)$$

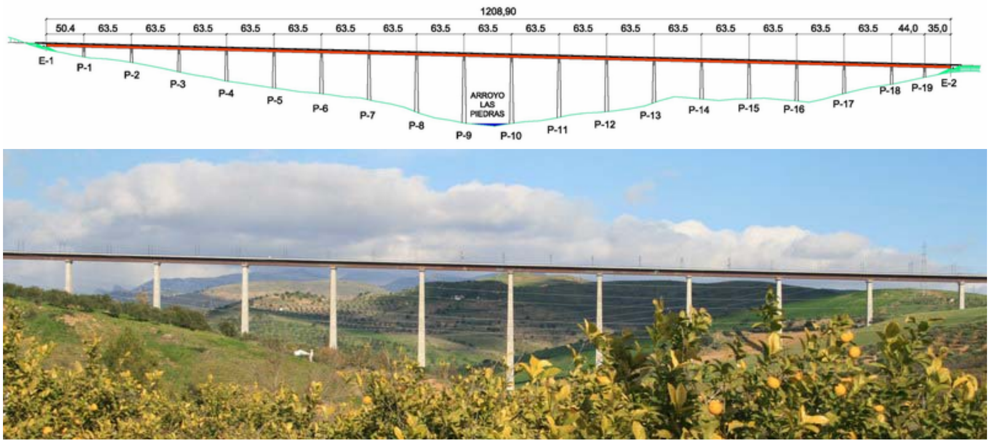
The overall range of the uniform bridge temperature component is:

$$\Delta T_N = T_{e,max} - T_{e,min} \quad (5)$$

2. RESULTS OF THE TEMPERATURE INSTRUMENTATION OF VIADUCT ARROYO LAS PIEDRAS.

Viaduct “Arroyo las Piedras”, designed by IDEAM is the first composite high speed railway bridge in the Spanish high speed railway lines [4,5,6] (Figs. 1a & 1b).

The temperature instrumentation of the bridge has permitted a continuous monitoring of the thermal effects during nearly two years, between autumn 2007 and summer 2009, with measures recorded every 10 minutes, which supply very reliable information of the seasonal and daily variation of the thermal actions on the composite deck.



Figures 1a & 1b: Elevation view of Viaduct "Arroyo las Piedras".

The thermal instrumentation of the viaduct consists of 4 thermometers located on mid span 6, one in the middle of the upper concrete slab, one located on the middle of the bottom concrete precast slab, and two more thermometers located one on each steel web (Fig.2).

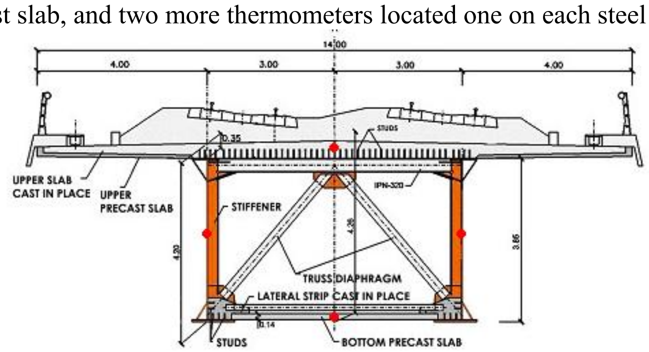


Figure 2: Situation of the thermometers located on the deck.

In addition to these 4 thermometers, the air shade temperature has been monitored, so as to compare its results with those obtained from the bridge temperature, with an exterior thermometer located near pier P-15.

All the information obtained with these 5 thermometers permits the advance of important results related to the response of composite bridges to temperature phenomena.

During the period of data registration, more than one year, the air shade temperature has varied between a minimum of +4º C and a maximum of +37º C, what is a reasonable range located within the range of the minimum and maximum air shade temperature that the national Spanish codes defines for the site of the bridge, located near Málaga, with T_{min}=-8º C, and T_{max}=46ºC.

We have verified that the upper concrete slab temperature is very stable, with diary oscillations inferior to 1º C or 2º C (Figs. 3 to 6), due to the important isolation of the thick waterproofing membrane of the slab and the thickness of the ballast with more than 40 cm above the upper slab.

The thermal effects on upper concrete slabs of ballasted railway composite bridges are sensibly more reduced than on road bridges. The thermal inertia of the upper concrete slab shows a smooth and slow seasonal behaviour, with temperatures always within the diary range of the air shade temperature.

The values measured in winter oscillate between 11ºC and 14ºC, while in spring these values vary from 13ºC to 24ºC, and from 24ºC to 33ºC in summer.

The temperature registered in the bottom concrete precast slabs, with 14 cm thickness, follows the well known behaviour of normal concrete elements, where the great thermal inertia of the material and its location always on shade lead to smooth daily variations, displaced in time respect to the air shade temperature (Figs. 3 to 6):

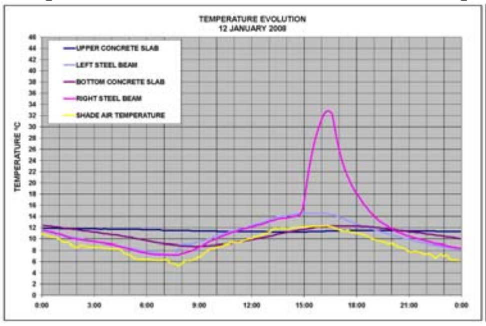
- concrete temperature curves sensibly follow that of the air shade temperature, displaced around 2 to 4 hours in time;
- minimum temperature values happen around 9:00 am in the morning, with 3 or 4 ºC above the minimum air shade temperature. This happens in winter as well as in summer;
- maximum temperature value of the deck reach values 1 or 2ºC over the air shade temperature in summer, meanwhile in winter they are quite similar.

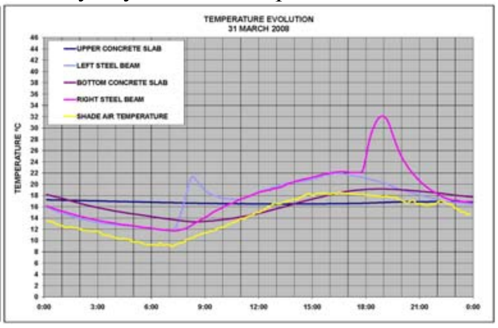
The temperature evolution of the steel beams is more influenced, due to the small thermal inertia of the steel, by the seasonal conditions, and meanly because of the direct radiation of the sun:

- during the night the steel temperature is very similar to the air shade temperature (Figs. 3 to 6). The small differences of the minimum values of the steel temperature oscillate between 0ºC/ 2ºC (winter); 1ºC/ 3ºC (spring); 2ºC/ 4ºC (summer) over the minimum air shade temperature:
- the beam located in the shade side, not directly exposed to the sunbeam, follow very accurately the air shade temperature (Figs. 3 to 6), with maximum values around 2ºC/ 4ºC over the maximum air shade temperature;
- the sun radiation due to the direct sunbeam induces very important peaks of the steel temperature of the beam directly exposed to the sun:
  - at dusk, west steel beam reaches a maximum relative peak in comparison with east steel beam with around 16 to 18º C hotter in winter (Fig. 3) (coinciding with the maximum steel temperature, around 15:00 pm), 8 to 10ºC in spring (Figs. 4) (lower than in winter because the peak coincides with a reducing tendency of the steel temperature) and even lower in summer, between 4 to 6ºC (Fig. 5), because the radiation of the sun happens very late, around 21:00 pm, with the steel temperature very reduced far from the maximum shade steel temperature.
  - at dawn happens a similar phenomenon, the east steel beam reaches a maximum relative peak in comparison with west steel beam with around 10 to 12º C hotter in summer (Fig. 5) (around 8:00 am), 8 to 10ºC in spring (Fig. 4), and around 1 to 2ºC in winter (Fig. 3), due to the reduced period of the winter radiation of the sun in the morning.

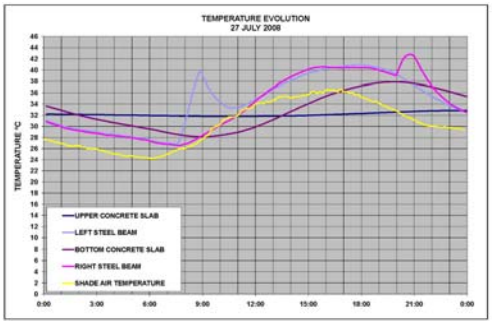
As a consequence of the sunshine, the steel beams directly exposed to the sun radiation have registered maximum temperature values of 38ºC in winter , 36ºC in spring and 44ºC in summer (always in the west steel beam at dusk) (Figs. 3 to 5).

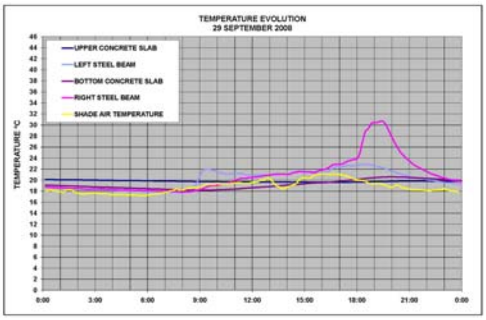
The maximum transverse difference of the temperature happens, surprisingly, in winter at around 15:00 pm in the afternoon (Fig. 3). Anyway, the great relative stiffness of the upper concrete slab, with respect to the flexibility of the steel beams, annuls the transverse effect due to the transverse difference of temperature, with practically no curvature or deformation of the deck. The steel beam directly exposed to the sun, suffers a reduced compression around 20/25 N/mm^2 without practically any resistance repercussion.





Figures 3 & 4: Air shade temperature and temperature of the 4 thermometers located on the deck in a typical winter day (13th of January) and a typical spring day (31th of March)





Figures 5 & 6: Air shade temperature and temperature of the 4 thermometers located on the deck in a typical summer day (27th of July) and a typical autumn day (29th of September)

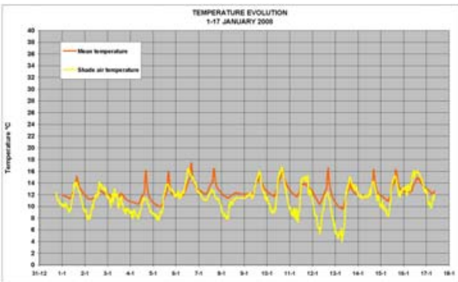
The viaduct composite deck tends to behave as a unique material deck in which the thermal deformations of the different elements have been made compatible. In our case, the results of the mean equivalent temperature of the composite cross section are approximately:

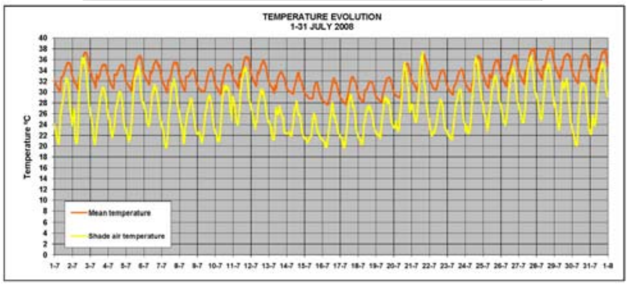
$T_{mean.eq.} \approx 0,56 \cdot T_{upper\ slab} + 0,14 \cdot T_{inf.slab} + 0,30 \cdot T_{mean,steel}$

What indicates that a composite viaduct tends to response with thermal oscillations equivalent to 70% of those of a concrete viaduct plus the 30% of the ones of a steel viaduct, confirming the very favourable characteristic of the composite viaducts with respect to the thermal imposed deformations.

The maximum and minimum values of the mean equivalent temperature of the cross section of the composite deck obtained along the measuring period have been:

- maximum 38,5ºC (with≈36,5ºC of the air shade temperature concomitant, 13-08-08)
- minimum 7ºC (with ≈ 4ºC of the air shade temperature concomitant, 16-12-08)





Figures 7 & 8: Correlation between the air shade temperature and the mean equivalent temperature of the composite cross section in winter (January-08) and in summer (july-08).

3. CONTRAST OF THE INSTRUMENTATION RESULTS WITH EN-1991-1-5.

3.1. Uniform temperature component of the deck.

The values obtained from the instrumentation for the mean equivalent temperature of the composite cross section of the deck, seem to be concordant with the criterion established by Eurocode (EN-1991-1-5) [1], which indicates a mean equivalent maximum and minimum temperature for composite bridges 4,50ºC over the maximum and minimum air shade temperature (eq.1 & 2), what in our case will bring to:

$T_{e,max}$= 50ºC; $T_{e,min}$= -3ºC and ΔT_N= 53ºC.

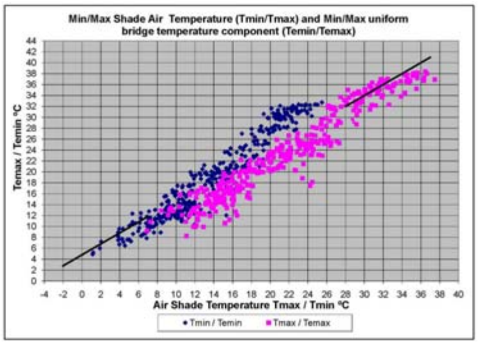


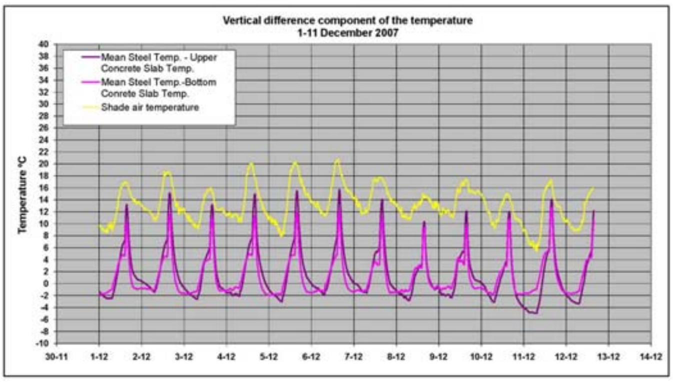
Figure 9: Correlation between T_{max}/ T_{min} air shade temperature and $T_{e,max}$/ $T_{e,min}$ obtained from the instrumentation. Comparison with EN-1991-1-5 [1].

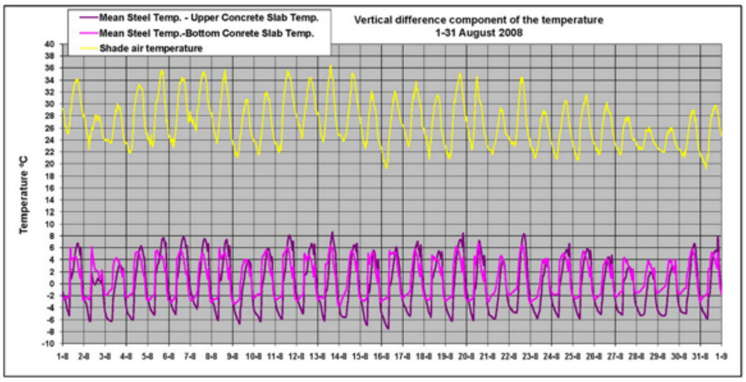
The overall range of the uniform temperature of a composite deck can be confirmed that is similar to the air shade temperature range, as Eurocode [1] establishes, and only 5 to 7ºC over the range of the uniform temperature of a composite deck, and very inferior to that one of a steel deck.

3.2. Vertical difference component of the temperature.

It has been observed, directly from the thermometers located on the deck, how the different thermal inertia of the concrete respect to the steel generally causes the partial steel section is always hotter than the partial concrete section during the day, whereas at night the partial steel section is always colder than the partial concrete section. This effect is independent of the season of the year, winter or summer, which leads to an important conclusion.

Every day a vertical difference of the temperature happens with the steel partial section hotter than the concrete partial section, and every night the steel partial section is always colder that the concrete partial section (Figs. 10 & 11).





Figures 10 & 11: Steel mean temperature minus upper concrete slab temperature or inferior slab temperature (winter and summer).

So a composite cross section always develops every day the double curvature, positive curvature during the day with the steel partial section hotter than concrete, and negative curvature during the night with the partial steel section colder than concrete.
The maximum values observed of the vertical difference of the temperature between steel and concrete are: +16 ºC (during the day, in winter Fig. 10) and -8 ºC (during the night, in summer Fig. 11).
These values measured are generally higher than those proposed by the Eurocode (EN-1991-1-5)[1] in its approach 2 simplified for composite cross sections, which proposes +10ºC. In the new Spanish code of actions for road bridges [3] (future update), we have proposed the value of +18ºC, a similar value to the historical values recommended in the Spanish codes of thermal actions [2,3] since 1972.

3.3. Horizontal difference component of the temperature.

As described on section 2 the horizontal difference component of the temperature, obtained as the difference between the mean temperature of both steel beams, yields higher results than those proposed by Eurocode (EN-1991-1-5) [1], which recommends, only in exceptional cases, the use of a difference of 5ºC between edges of the transverse cross section.
The maximum measured values of the horizontal difference component of the temperature, reach values from 16 to 18ºC at dusk in winter (Fig. 3) due to the sunbeam on the west beam, while the east beam is on shade.
This maximum value decreases to 8/10ºC in spring (Fig. 4), and becomes lower in summer 4/6ºC (Fig. 5), because the sunbeam happens very late (around 21:00 pm) when the air shade temperature tends to low values.
At dawn, the horizontal difference component of the temperature is by contrast lower with maximum values in summer, with sunbeam in the east steel beam, reaching values from 10 to 12ºC (Fig. 5) (around 8:00 am), 8 to 10ºC in spring (Fig. 4), and only 1 to 2ºC in winter due to the reduced and weak radiation of the sun early in the morning.

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