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INDUCED STRESSES DUE TO THERMAL EFFECTS IN COMPOSITE STEEL–CONCRETE GIRDERS

BY

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Abstract. The temperature variations of the air in shadow, of the solar radiations and thermal radiations produce variations in the temperature distribution in the individual members of a structure. This paper presents the influence of the difference of temperature between the opposite faces of a steel–concrete composite cross section upon the internal stresses state. In the steel–concrete composite structures, the concrete from the composite structure slab cannot have a free deformation arising from the temperature variation along the height of the cross section because the slab is joined to the metal structure through joining members (connectors). Consequently, as the tendency to shorten or lengthen the concrete slab is prevented, internal stresses are induced to the composite structure, and these stresses overlap those produced by shortening or lengthening in the slab area. The mechanism through which stress develop from temperature variation are exemplified for the case of a simply supported steel–concrete composite girder.

Key words: composite girders; thermal effects; state of stresses; working example.

1. Introduction

The daily and seasonal shadow air temperature variations, the variations of solar radiations and thermal radiation produce variations of the temperature

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distribution in the individual members of a structure. The amplitude of thermal effects depends upon local climate conditions as well as upon the orientation, total weight and structure finishing.

The temperature distribution inside an individual structural member is made up of the following main components (Fig. 1):

a) the component of uniform temperature, ΔT_U;

b) the component of difference of temperature between the faces of the same member, ΔT_M;

c) the nonlinear component of the difference of temperature, ΔT_E.

This component establishes a field of stresses in equilibrium that does not involve an actual effect of loading in the member.

The National Annex recommends in the bridge design in Romania not to take into considerations the vertical nonlinear component in heat actions.

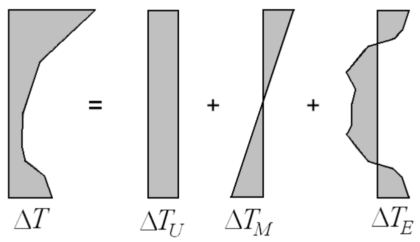

Fig. 1

The deformations of the structural members and the resulting stresses depend upon the geometry and boundary conditions of construction members (supports, joints, etc.) and the physical properties of the materials used.

When composite materials are used, special attention should be given to the fact that these materials are made up of components with differing coefficients of linear dilatation. In order to determine thermal effects, it is recommended to use the thermal linear dilatation coefficient in materials, as presented in Annex C from SR EN 1991-1-5.

The paper presents the influence of the difference of temperature between the opposite faces of a steel–concrete composite cross section (the component of the difference of temperature) upon the internal stresses state.

2. The Difference of Temperature

For a specified time interval, the heating and cooling of the upper face of the bridge deck produces a variation of temperature that can lead to a maximum heating (when the upper face is warmer) and a maximum cooling (when the lower face is warmer).

The vertical difference of temperature can produce effects in a structure, due to:

a) the prevention of structure free deformation due to its shape (for example, bearing frames, continuous beams, etc.);

b) friction among hinged supports;

c) non-linear geometrical effects (2^{nd} order effects).

The effect of the difference of temperature along the vertical line can be treated by a linear or non-linear distribution.

2.1. The Vertical Component of the Difference of Temperature

The effect of the difference of temperature along the vertical is taken into account by using several linear components for the difference of temperature equivalent to $\Delta T_{M.\text{heating}}$ and $\Delta T_{M.\text{cooling}}$. The values of these components are applied to the area between the upper face and the lower face of the bridge deck.

In the case of bridge decks with a composite structure, for protection layers of 50 mm, the following values are taken:

$$\Delta T_{M.\text{heating}} = 15^\circ\text{C}; \quad \Delta T_{M.\text{cooling}} = 18^\circ\text{C}.$$

For protection layers different from 50 mm the values for $\Delta T_{M.\text{heating}}$ and $\Delta T_{M.\text{cooling}}$ are multiplied by the factor k_{surface} given in SR EN 1991-1-5.

2.2. The Horizontal Component of the Difference of Temperature

In general, the component of difference of temperature requires consideration only in vertical direction. In several particular cases. (for instance, the configuration or orientation of the bridge may require the stronger sun exposure of a part than another of the bridge) a horizontal component of the difference of temperature is taken into account.

When no data are available and no higher values are indicated, it is recommended to use the value of 5ºC for the difference of temperature, as the linear difference of temperature between the external margins of the bridge, irrespective of the bridge width.

2.3. Stresses Produced from the Vertical Component of the Difference of Temperature

The concrete in the slab of the composite structure cannot have a free deformation arising from the temperature variation along the height of the cross section as the slab is joined to the metal structure by connectors.

Consequently, the concrete slab tendency of shortening or lengthening is prevented and, within the composite structure, internal stresses are induced; these stresses overlap the stresses produced during shortening or lengthening, in the slab area.

The mechanism through which stress develop from temperature variation are exemplified for the case of a simply supported steel–concrete composite girder.

When the slab is colder than the lower part of the cross section, the slab has a shortening tendency and the stresses developed are similar to those produced by concrete shrinkage, respectively stresses with an opposite sign when the slab has a higher temperature.

Loading arising from temperature is regarded as a short term load, the calculus section being defined with the help of the coefficient of equivalence for short term loadings (that is the equivalence coefficient, n_0).

The specific deformation from the temperature variation is

$$\varepsilon_{c.\Delta T} = \alpha_T \Delta T_M \,, \tag{1}$$

where: $\alpha_T = 1 \times 10^{-5}/{}^0\text{C}$ is the thermal dilation coefficient of the concrete and steel in the steel-concrete composite structures (SR EN 1991-1-5, Annex C, Table C.1).

The axial stress produced in the concrete slab will be

$$N_{c.\Delta T} = -N_{m.\Delta T} = -\varepsilon_{c.\Delta T} E_{cm} A_c \,. \tag{2}$$

Fig. 2 presents the stresses occurring in the composite cross section when the slab has a lower temperature than the part opposite to the cross section (the temperature difference being $\Delta T_{M.\text{cooling}}$ = 18ºC).

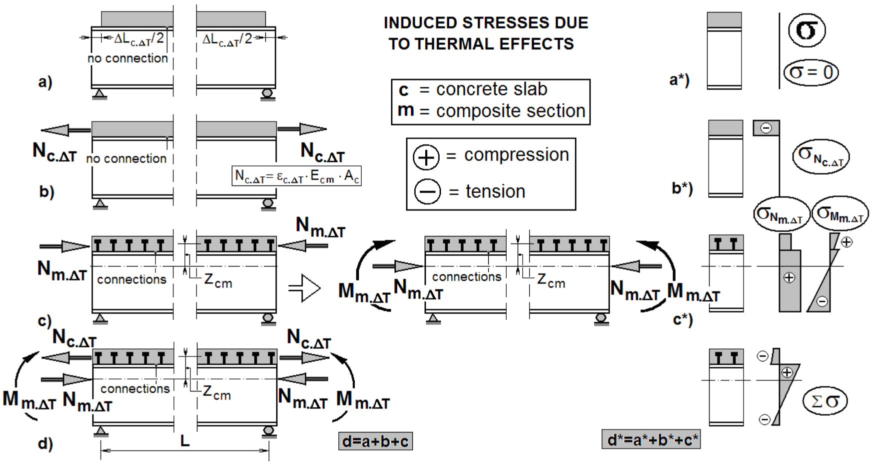

Fig. 2 – Development of stresses due to concrete slab contraction.

When the concrete slab temperature is higher than that of the opposite end (with a temperature difference of $\Delta T_{M.\text{heating}}$ = 15ºC), the stresses produced have an opposite sign, than previously.

The stresses in the concrete slab and metal girder are as follows:
a) *in concrete*:

$$\sigma_c = -\frac{N_{c.\Delta T}}{A_c} + \frac{1}{n_0}\left(\frac{N_{m.\Delta T}}{A_m} + \frac{M_{m.\Delta T}}{I_m} z\right); \tag{3}$$

b) *in steel:*

$$\sigma_a = \frac{N_{m.\Delta T}}{A_m} + \frac{M_{m.\Delta T}}{I_m} z\,. \tag{4}$$

A_m and I_m represent the area and the inertia moment of the composite concrete-steel section where the equivalence coefficient taken is n_0.

3. Numerical Application

The state of stresses is assessed in the cross section of a steel–concrete composite girder following the variation of temperature along the height of the girder).

The following data are known:
a) composite girder cross section (Fig. 3);
b) concrete grade: C40/50;
c) S420 steel.

The web of the metal girder is provided with longitudinal stiffening elements so that the grade for the section is 3 (stresses are considered).

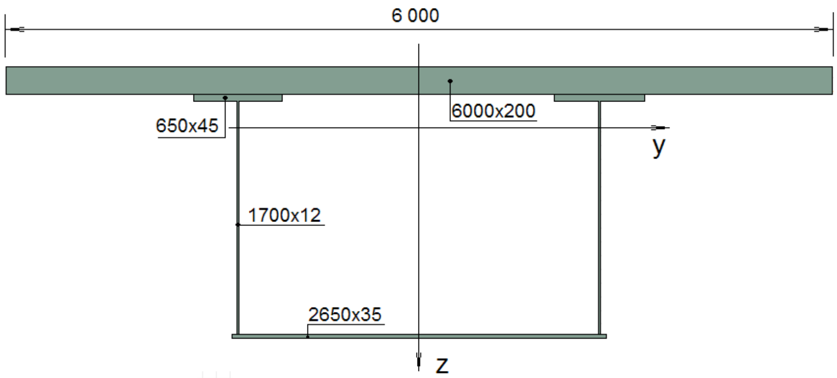

Fig. 3 – Cross section of composite girder.

3.1. Stress Calculus when the Slab is Colder ($\Delta T_{M.\text{cooling}}$ = 18ºC)

The specific deformation arising from the difference of temperature:

$$\varepsilon_{c.\Delta T} = \alpha_T \Delta T_M = 1\times10^{-5}\times18 = 1.8\times10^{-4}\,.$$

The equivalence coefficient for short term loadings is:

$$n_0 = \frac{E_a}{E_{cm}} = \frac{210,000}{22,000\left(\frac{f_{cm}}{10}\right)^{0.3}} = \frac{210,000}{22,000\left(\frac{48}{10}\right)^{0.3}} = \frac{210,000}{35,220} = 5.96;$$

$$E_{cm} = 22,000\left(\frac{48}{10}\right)^{0.3} = 35,220 \ \text{N/mm}^2.$$

The axial stress developed in the concrete slab will be:

$$N_{c.\Delta T} = -N_{m.\Delta T} = -\varepsilon_{c.\Delta T} E_{cm} A_c = 1.8\times10^{-4}\times0.3522\times10^6\times12,000 = $$
$$= 760\times10^3 \,\text{daN}.$$

The bending moment:

$$M_{m.\Delta T} = N_{m.\Delta T}\cdot z_{cm} = 760\times10^3\times55.6 = 422.56\times10^5 \ \text{daN}\cdot\text{cm}.$$

1. *The equivalent steel section*
The equivalent steel width of the concrete slab:

$$b^*_{\text{eff}} = \frac{b_{\text{eff}}}{n_0} = \frac{6,000}{5.96} = 1,007\,\text{mm}.$$

The composite section equivalent in steel is given in Fig. 4.

$A_m = 3,934 \ \text{cm}^2$
$I_m = 2.5\times10^7 \ \text{cm}^4$

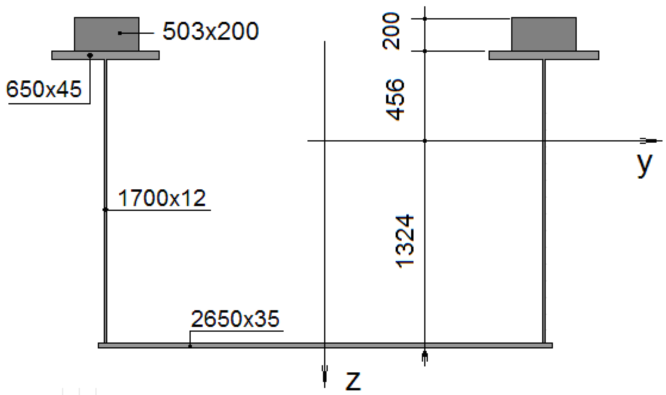

Fig. 4 – Characteristics of equivalent in steel cross section.

The unit stresses found from temperature are:
a) *in concrete:*
a$_1$) in the upper fibre:

$$\sigma_{c.\sup} = -\frac{N_{c.\Delta T}}{A_c} + \frac{1}{n_0}\left(\frac{N_{m.\Delta T}}{A_m} + \frac{M_{m.\Delta T}}{I_m} z_{cs}\right) =$$

$$= -\frac{760\times 10^3}{12{,}000} + \frac{1}{5.96}\left(\frac{760\times 10^3}{3{,}934} + \frac{422.56\times 10^5}{2.5\times 10^7} 65.6\right) = -12.3\ \text{daN/cm}^2;$$

a$_2$) in the lower fibre:

$$\sigma_{c.\inf} = -\frac{N_{c.\Delta T}}{A_c} + \frac{1}{n_0}\left(\frac{N_{m.\Delta T}}{A_m} + \frac{M_{m.\Delta T}}{I_m} z_{ci}\right) =$$

$$= -\frac{760\times 10^3}{12{,}000} + \frac{1}{5.96}\left(\frac{760\times 10^3}{3{,}934} + \frac{422.56\times 10^5}{2.5\times 10^7} 45.6\right) = -18\ \text{daN/cm}^2;$$

b) *in steel:*

b$_1$) in the upper fibre:

$$\sigma_{a.\sup} = \frac{N_{m.\Delta T}}{A_m} + \frac{M_{m.\Delta T}}{I_m} z_{as} = \frac{760\times 10^3}{3{,}934} + \frac{422.56\times 10^5}{2.5\times 10^7} 45.6 = 270.3\ \text{daN/cm}^2;$$

b$_2$) in the lower fibre:

$$\sigma_{a.\inf} = \frac{N_{m.\Delta T}}{A_m} - \frac{M_{m.\Delta T}}{I_m} z_{ai} = \frac{760\times 10^3}{3{,}934} - \frac{422.56\times 10^5}{2.5\times 10^7} 132.4 = -30.6\ \text{daN/cm}^2.$$

The stresses diagram arising from shrinkage is given in Fig. 5.

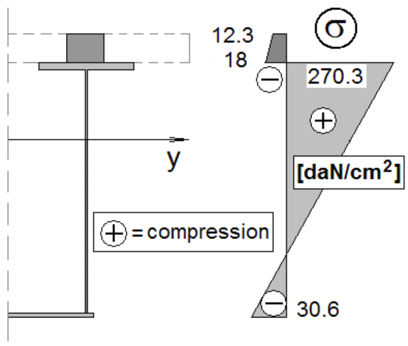

Fig. 5 – Stress distribution due to effect of cooling.

3.2. Stress Calculus when the Slab is Warmer ($\Delta T_{M.\text{heating}}$ = 15ºC)

The specific deformation arising from the difference of temperature:

$$\varepsilon_{c.\Delta T} = \alpha_T \Delta T_M = 1\times 10^{-5}\times 15 = 1.5\times 10^{-4}.$$

The equivalence coefficient for short term loadings is

$$n_0 = 5.96\,;\; E_{cm} = 35{,}220\ \text{N/mm}^2.$$

The axial stress developed in the concrete slab will be

$$N_{c.\Delta T} = -N_{m.\Delta T} = -\varepsilon_{c.\Delta T} E_{cm} A_c = 1.5\times10^{-4}\times0.3522\times10^{6}\times12{,}000 = 634\times10^{3}\ \text{daN}.$$

The bending moment:

$$M_{m.\Delta T} = N_{m.\Delta T} z_{cm} = 634\times10^{3}\times55.6 = 352.5\times10^{5}\,\text{daN}\cdot\text{cm}.$$

The unit stresses found from temperature are:
a) *in concrete*:
a_1) in the upper fibre:

$$\sigma_{c.\sup} = \frac{N_{c.\Delta T}}{A_c} - \frac{1}{n_0}\left(\frac{N_{m.\Delta T}}{A_m} + \frac{M_{m.\Delta T}}{I_m} z_{cs}\right) =$$

$$= \frac{634\times10^3}{12{,}000} - \frac{1}{5.96}\left(\frac{634\times10^3}{3{,}934} + \frac{352.5\times10^5}{2.5\times10^7}65.6\right) = 10.3\ \text{daN/cm}^2;$$

a_2) in the lower fibre:

$$\sigma_{c.\inf} = \frac{N_{c.\Delta T}}{A_c} - \frac{1}{n_0}\left(\frac{N_{m.\Delta T}}{A_m} + \frac{M_{m.\Delta T}}{I_m} z_{ci}\right) =$$

$$= \frac{634\times10^3}{12{,}000} - \frac{1}{5.96}\left(\frac{634\times10^3}{3{,}934} + \frac{352.5\times10^5}{2.5\times10^7}45.6\right) = 15\ \text{daN/cm}^2;$$

b) *in steel:*
b_1) in the upper fibre:

$$\sigma_{a.\sup} = -\left(\frac{N_{m.\Delta T}}{A_m} + \frac{M_{m.\Delta T}}{I_m} z_{as}\right) = -\left(\frac{634\times10^3}{3{,}934} + \frac{352.5\times10^5}{2.5\times10^7}45.6\right) = -225.4\ \text{daN/cm}^2;$$

b_2) in the lower fibre:

$$\sigma_{a.\inf} = -\frac{N_{m.\Delta T}}{A_m} + \frac{M_{m.\Delta T}}{I_m} z_{ai} = -\frac{634\times10^3}{3{,}934} + \frac{352.5\times10^5}{2.5\times10^7}132.4 = 25.5\ \text{daN/cm}^2.$$

The unit stress diagram arising from shrinkage is given in Fig. 6.

In Fig. 7 are presented comparatively the stresses resulting in the two possible situations, that is when:

a) the concrete slab has a lower temperature than the opposite part;
b) the concrete slab has a higher temperature than the opposite part.

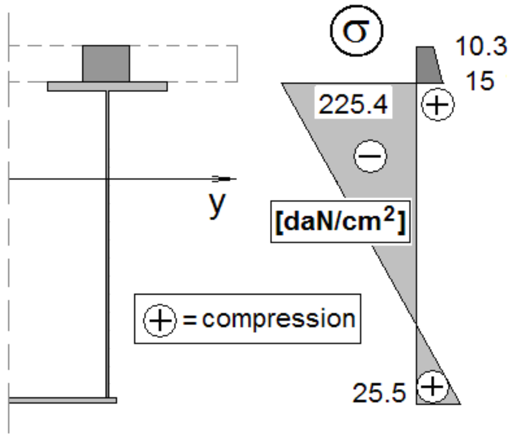

Fig. 6 – Stress distribution due to effect of heating.

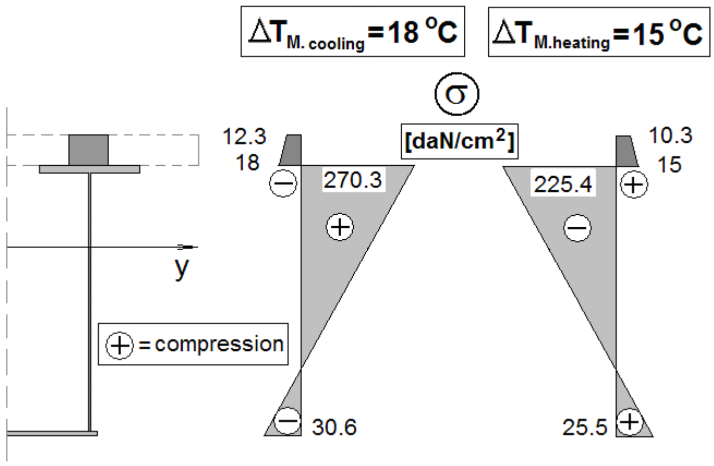

Fig. 7 – Stress distribution due to thermal effect of cooling and heating.

4. Final Remarks And Conclusions

The variation of the temperature field along the height of the composite girder cross section modifies the internal state of stresses both in the concrete slab and the metal part. The stresses overlap those produced from permanent and net loads having an important effect upon the overall state of stresses..

According to SR EN 1994-2, the thermal stress effects can be neglected in the analyses that check the ultimate stress states other than fatigue, in the case of composite members in all cross sections of Class 1 or Class 2, where no approximations are required for the lateral buckling in the limit states of usual service.

From the numerical example given above, it yields that the stresses produced from the difference of temperature between the two end faces of the section have high values, with maximum values of 8%...12% from the strength of the materials in use, steel and concrete.

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EFORTURI DIN VARIAȚIA CÂMPULUI DE TEMPERATURĂ PE SECȚIUNEA GRINZILOR COMPUSE OȚEL–BETON

(Rezumat)

Variațiile de temperatură ale aerului la umbră, radiației solare şi radiației termice, produc variații ale distribuției de temperatură în elementele individuale ale unei structuri.

Se studiază influența diferenței de temperatură între fețele opuse ale unei secțiuni transversale compuse oțel–beton asupra stării de eforturi unitare interioare.

În structurile compuse oțel–beton, betonul din dala structurii compuse nu poate avea deformația liberă din variația de temperatură pe înălțimea secțiunii deoarece dala este legată de structura metalică prin elementele de legătură (conectori).

Prin urmare, tendința de scurtare sau de alungire a dalei de beton fiind împiedicată, în structura compusă sunt induse eforturi interioare, eforturi care în zona dalei se suprapun peste cele produse din scurtare sau din alungire.

Mecanismul de dezvoltare a eforturilor din variația de temperatură se exemplifică pe structura unei grinzi compuse oțel–beton simplu rezemate, de tip cheson.