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COMPOSITE STEEL-CONCRETE GIRDERS WITH CIRCULAR HOLES

BY

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Abstract. In this paper some aspects concerning the design of steel-concrete composite structures are presented. The steel girders are built-up as rolled sections with circular holes in webs. This paper also presents, an adaptation of Euro norms EN 1994-1-1:2004. *Eurocode 4 - Design of composite and concrete structures – Part 1-1: General rules for buildings* and EN 1994-2:2004. *Eurocode 4 - Design of composite and concrete structures – Part 2: General rules and rules for bridges* to the design of composite steel-concrete girders with circular holes.

Key words: composite girders; rolled sections with circular holes; Euro codes.

1. Introduction

At present, it is widely accepted that composite steel-concrete structures provide efficient solutions for the majority of the constructions erected, and for this reason they are used in the field of civil constructions and bridges.

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Since a composite steel-concrete structure joins together the two materials mentioned, their calculus is based on both norms related to the calculus of the components of the two materials, namely Eurocode 2 – for the concrete components calculus, Eurocode 3 – for the steel components calculus as well as on Eurocode 4 – for the calculus of the composite steel-concrete structures.

In order to determine the characteristics of the cross sections of the composite parts in the elastic calculus, the method used is the transformed section method. The non-homogeneous steel-concrete cross section is made equivalent to a homogeneous section, resulting from the transformation of the concrete section in the slab into an equivalent steel section.

This transformation is made with the help of the equivalence coefficient, which represents the ratio between the modulus of elasticity of the concrete and steel, dependent upon the nature of the loadings acting upon the composite structure in discussion.

For short term loads, the equivalence coefficient is calculated with the relationship (SR EN 1994-1- 1/2006; SR EN 1994-2/2006):

$$n_0 = \frac{E_a}{E_{cm}}, \tag{1}$$

where: E_a is the modulus of elasticity of the steel in the steel girder; E_{cm} – the secant modulus of elasticity of the concrete in the slab.

The equivalence coefficient for long term loads is calculated according to EC2 (SR EN 1992-1-1/2004) with the relationship:

$$n_L = n_0\left[1+\psi_L \phi(t,t_0)\right], \tag{2}$$

where: ψ_L is equal to 1.1 for permanent loads; $\varphi(t,t_0)$ – the creep coefficient.

In the case of civil and industrial buildings, when assessing the equivalent section the equivalence coefficient n will be considered relative to the ultimate state type and the loading stage of check, so that:

$$n = \begin{cases} n_0 & \text{– for short term loads;} \\ 3\mathrm{n}_0 & \text{–for permanent and long term loads;} \\ (2\ldots3)\mathrm{n}_0 & \text{–for the effect of shrinkage and creep.} \end{cases} \tag{3}$$

In usual circumstances, in the design of civil and industrial buildings, it is admitted to simplify to $n = 2n_0$, for both long term and short term loads.

The elastic analysis of composite girders takes into account the following hypotheses:

a) the connection between the metal girder and the concrete slab is continuous and no slip occurs at the steel-concrete interface;

b) the plane sections will remain plane even after deformation;

c) steel and concrete are regarded as elastic materials.

On the basis of the hypotheses above, the composite steel-concrete section is considered as a section made of steel equivalent homogeneous material.

The equivalent steel area, A_1 is calculated with the relationship:

$$A_1 = A_a + A_s + \frac{b_{\text{eff}} h_c}{n}, \tag{4}$$

where: A_a is the area of the metal girder; A_s – the area of the flexible reinforcement (can be neglected); b_{eff} – the active width in the concrete slab with the role of flange for the composite girder; n – the equivalence coefficient (related to the load type).

The calculus can be performed by determining and checking the stresses in the depth of the section.

In composite sections, tension concrete is not taken into consideration when assessing the strength of the mixed section.

2. Composite Circular Hollow Girders

In the following part, the paper presents an adaptation of the calculus method for composite steel-concrete girders as presented in the Eurocodes S*R EN 1994-1-1: 2006: Eurocode 4: Proiectarea structurilor compozite de oțel şi beton. Partea 1-1: Reguli generale şi reguli pentru clădiri*/ Design of composite steel-concrete structures. Part 1.1. General rules and rules for buildings (SR EN 1994-1-1/2006) and *SR EN 1994-2: 2006: Eurocode 4: Proiectarea structurilor*

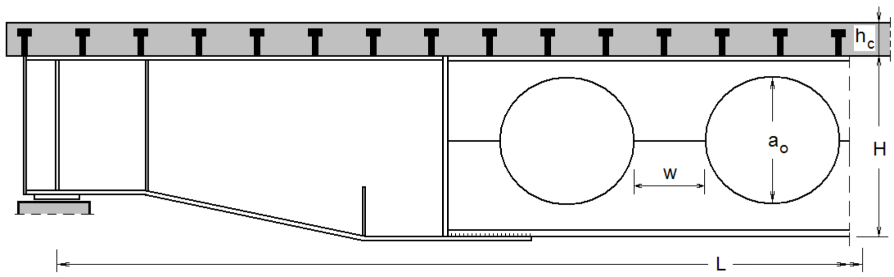


Fig. 1 – Composite hollow girder (Moga, 2014).

compozite de oțel şi beton. Partea 2: Reguli generale şi reguli pentru poduri,/Design of composite steel-concrete structures. Part 2. General rules *and rules for bridges* (SR EN 1994-2/2006) in the case of composite hollow girders, made with symmetrical steel flanges (with identical profiles) or unsymmetrical flanges (made with different steel profiles).

Fig. 1 shows a composite steel-concrete girder made from a steel girder with circular voids in structural work with a reinforced concrete slab, the girder support being made with a welded sector.

2.1. Building Phases

The calculus considers phases and steps in construction.

The construction phases, steps and the calculus relate to a composite steel-girder crossing structure of pedestrian bridge, utility pipe support, culvert type or others.

Phase 1: Metal girder not connected to the concrete slab

This building and structural behaviour phase occurs during the mounting of the main girders, until the reinforced concrete slab begins to act, that is after 28 days from the casting of the concrete.

Phase 1 contains the following loading stages (Moga *et al*., 2014):

a) *Step **1***: after mounting the main girders.

Girders take over own weight, the top flange is not normally fixed with other members that could prevent lateral buckling.

b) *Step **2***: after mounting the cross bars or the secondary girders and final bracings and possibly temporary bracings.

Girders take over related weights, but the buckling length of the compressed flange is reduced to the distance between the cross bars or the secondary girders.

c) *Step **3***: after casting the reinforced concrete slab (before setting).

The weight of the concrete casted in the slab is added to the previous loads, as well as the formwork weight and any other loads resulting from the casting process.

In general, measures are taken to prevent compressed flange buckling until cross bars are fitted in, and, in such a case steps **1**, **2** and **3** are discussed together, in the same manner.

Phase 2: The metal girder connected to the concrete slab

During this phase, girders take over two types of loads (Moga *et al*., 2014):

a) long term loads: the ”dead” weight added after the concrete sets;

b) short term loads: serviceable actions; wind actions; seismic action; the pavements net load, if necessary; other loads, if necessary.

2.2. The Stress State in the Structural Girder

The state of stresses in the structural girder is defined considering the construction phases mentioned before; for the composite steel-concrete girder different equivalence coefficients for concrete and steel are used in long-term and short-term loads.

The calculus hypothesis says that the hollow girders behave in the hollow area similar to truss girders, where the axial stress in the flanges can be found from the M/h_0 ratio (Moga, 2014; Moga *et al.*, 2014).

Phase 1: Metal girder not connected to the concrete slab

The unit stresses in the flanges of the metal girders are found from the axial forces resulting from the calculus bending moment.

The axial stresses in the flanges:

$$N_{Ed}^{F1} = \pm \frac{M_{Ed}^{F1}}{h_0}, \tag{5}$$

where: M_{Ed}^{F1} is the bending moment for a beam, in the middle of the span.

The stresses in the flanges in the middle of the hollow Fig. 2:

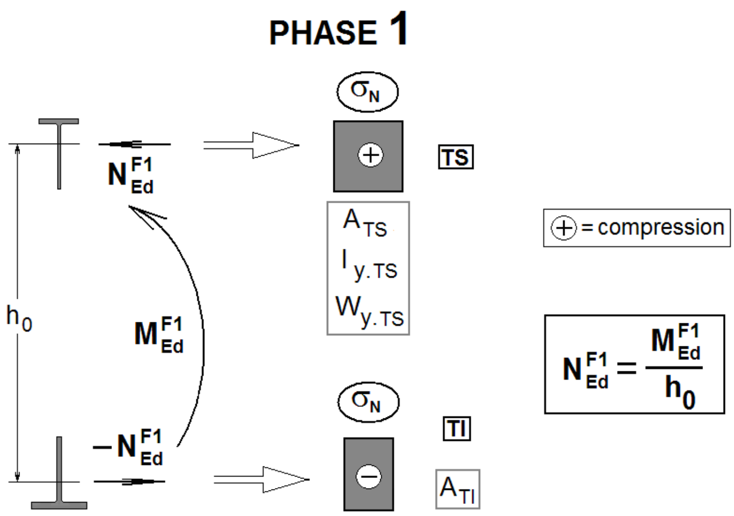


Fig. 2 – State of stresses in the flanges – Phase 1 (Moga *et al.*, 2014).

a) top flange:

$$\sigma_a^{F1} = \frac{N_{Ed}^{F1}}{\chi A_{TS}}, \tag{6}$$

where: χ is the reduction coefficient for the buckling of the top flange.

b) bottom flange:

$$\sigma_{TI}^{F1} = \frac{N_{Ed}^{F1}}{A_{TI}}, \tag{7}$$

Phase 2: Metal girder connected to the concrete slab
Long term loads (lt), Fig. 3.

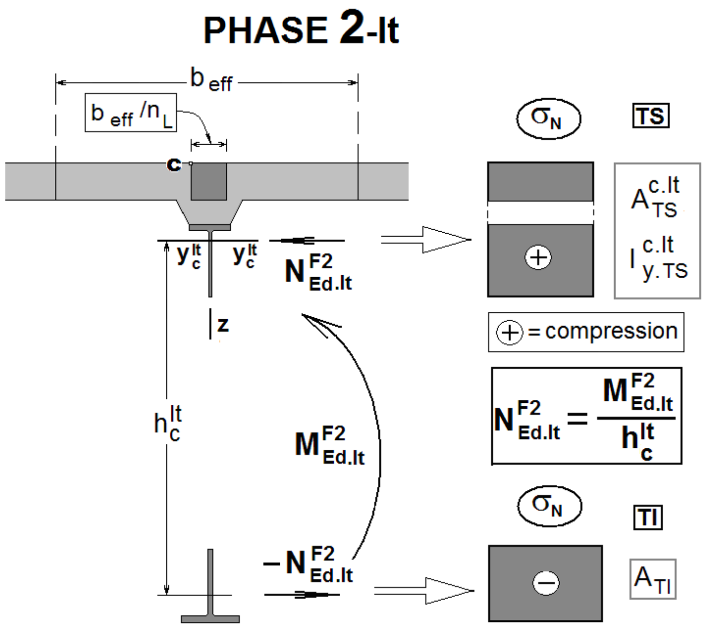


Fig. 3 – State of stresses in the flanges – Phase 2: Long term loads (*lt*) (Moga *et al.*, 2014).

Axial stresses in flanges:

$$N_{Ed.lt}^{F2} = \pm \frac{M_{Ed.lt}^{F2}}{h_c^{lt}} \tag{8}$$

Stresses in flanges

a) top flange:

$$\sigma_{a.lt}^{F2} = \frac{N_{Ed.lt}^{F2}}{A_{TS}^{c.lt}} \text{ – in steel;} \tag{9.a}$$

$$\sigma_{c.lt}^{F2} = \frac{N_{Ed.lt}^{F2}}{A_{TS}^{c.lt}} \text{ – in concrete (steel equivalent);} \tag{9.b}$$

b) bottom flange:

$$\sigma_{TI.lt}^{F2} = \frac{N_{Ed.lt}^{F2}}{A_{TI}}, \tag{10}$$

Short term loads (st), Fig. 4.

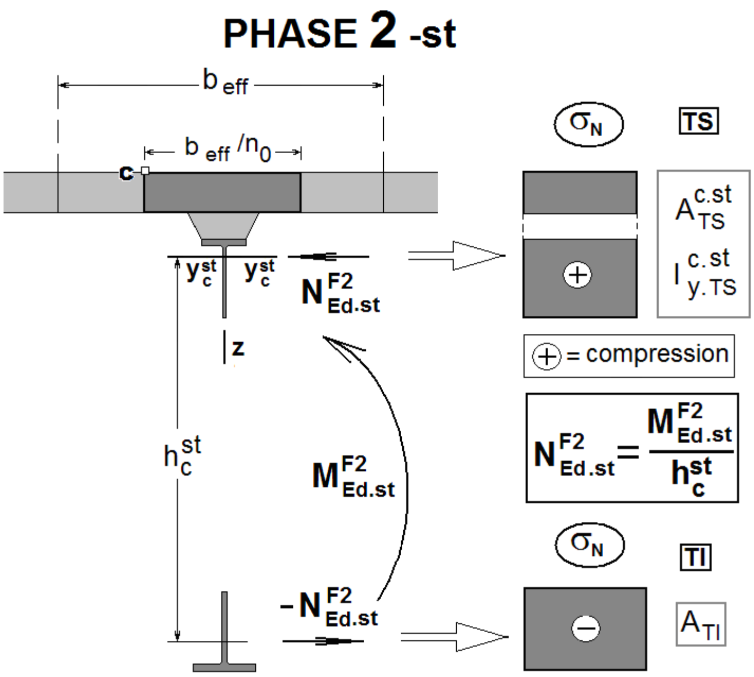


Fig. 4 – State of stresses in the flanges – Phase 2: Short term loads (*st*) (Moga *et al.*, 2014).

Axial stresses in flanges:

$$N_{Ed.st}^{F2} = \pm \frac{M_{Ed.st}^{F2}}{h_c^{st}} \tag{11}$$

Stresses in flanges:

a) top flange:

$$\sigma_{a.st}^{F2} = \frac{N_{Ed.st}^{F2}}{A_{TS}^{c.st}} \text{ – in steel;} \tag{12.a}$$

$$\sigma_{c.st}^{F2} = \frac{N_{Ed.st}^{F2}}{A_{TS}^{c.st}} \text{ – in concrete (steel equivalent);} \tag{12.b}$$

b) bottom flange:

$$\sigma_{TI.st}^{F2} = \frac{N_{Ed.st}^{F2}}{A_{TI}}. \tag{13}$$

Total stresses

a) top flange:

$$\sigma_a = \sigma_a^{F1} + \sigma_{a.lt}^{F2} + \sigma_{a.st}^{F2} \le \frac{f_y}{\gamma_{M0}} \text{ – in steel;} \tag{14.a}$$

$$\sigma_c = \frac{\sigma_{c.lt}^{F2}}{n_L} + \frac{\sigma_{c.st}^{F2}}{n_0} \le \frac{0.85 \cdot f_{ck}}{\gamma_c} \text{ – in the concrete;} \tag{14.b}$$

b) bottom flange:

$$\sigma_{TI} = \sigma_{TI}^{F1} + \sigma_{TI.lt}^{F2} + \sigma_{TI.st}^{F2} \le \frac{f_y}{\gamma_{M0}}. \tag{15}$$

2.3. Determination of the Reduction Coefficient χ of the Compression Flange

For members with a constant cross section (uniform members), subjected to constant axial compression, the value of the reduction coefficient χ can be calculated function of the relative slenderness $\overline{\lambda}$, with the relationship (SR EN 1993-1-1/2006):

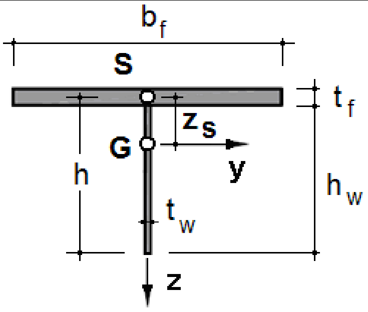
$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \overline{\lambda}^2}}; \quad \chi \le 1, \tag{16}$$

where: $\varphi = 0.5\left[1 + \alpha\left(\overline{\lambda} - 0.2\right) + \overline{\lambda}^2\right]$; α – imperfection factor; α = 0.49 – the ***c*** buckling curve (*T* sections).

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} - \text{sections Class 1, 2 and 3.} \tag{17}$$

How stability is lost and the critical buckling force are given in Table 1 (Moga *et al.*, 2012). The critical buckling force will be $N_{cr} = \min . N_{cr.i}$.

Table 1
Critical Buckling Forces

Monosymmetric T section	
Loss of stability	Critical compression force
Bending buckling	$N_{cr} = \min\left[N_{cr.y} = \frac{\pi^2 EI_y}{L_{cr.y}{}^2};\quad N_{cr.z} = \frac{\pi^2 EI_z}{L_{cr.z}{}^2}\right]$
Shear buckling	$N_{cr.T} = N_\omega = \frac{A}{I_0}\left(GI_t + \frac{\pi^2 EI_\omega}{L^2_{cr.T}}\right)$
Flexural – torsional buckling	$N_{cr.TF} = \frac{I_0}{2(I_y + I_z)}\left[(N_{cr.z} + N_{cr.T}) - \sqrt{(N_{cr.z} + N_{cr.T})^2 - 4\frac{(I_y + I_z)}{I_0}N_{cr.z}N_{cr.T}}\right]$
Characteristics: $I_0 = I_y + I_z + Az_s^2$; $i_o^2 = \frac{I_y + I_z + Az_s^2}{A}$; $I_\omega = \frac{(b_f t_f)^3}{144} + \frac{(ht_w)^3}{36}$	

3. Conclusions, Remarks and Comments

The paper presents an adaptation of the calculus for composite steel-concrete girders from the European norms, to the calculus of the composite hollow girders, made with steel flanges that can be symmetrical (identical basic profiles) and unsymmetrical (differing basic profiles).

In Phase 1 of construction, attention shall be paid to the stability of the compressed flange by assessing the buckling reduction coefficient χ.

Usually, the girder flanges are selected to have different dimensions so that the bottom flange is more developed than the top flange. For this purpose, two types of laminated profiles will be used. The application of unequal steel flanges solution makes the position of the composite section centroid to get closer to the middle of the section.

The following remarks need to be added for the composite steel concrete girders:

a) in the initial variants of the Eurocode EC4 regarding the calculus of the composite steel-concrete girders there was used a partial safety coefficient for the steel γ_a = 1.10, while in the final variant, they use coefficient γ_{M0} = 1.0;

b) it is appreciated that coefficient γ_a = 1.10 could be justified for the composite steel-concrete structure from the following viewpoints:

b_1) lack of structural homogeneity of the composite material (made from steel, concrete and reinforcement);

b_2) the high global safety coefficient of the concrete, respectively γ_c/8.05 = 1.50/0.85 = 1.76, compared to that of the steel – γ_{M0} = 1.0;

c) the unique steel-concrete equivalence coefficient (n = 2n_0) is accepted for a simplified calculation, according to SR EN 1994-1-1:2004 § 5.4.2.2(11);

d) for an “accurate” assessment of the equivalence coefficient the recommendations from SR EN 1994-1-1:2004 § 5.4.2.2 and SR EN 1994-2:2006 shall be implemented;

e) in the case of girders with circular hollows, it is also recommended to check the stresses at a certain distance from the hollow middle as the effect of the shear force can be significant.

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GRINZI CU GOLURI CIRCULARE COMPOZITE

(Rezumat)

Se prezintă o adaptare a metodologiei de calcul a grinzilor compuse oțel-beton prezentată în euro-normele *SR EN 1994-1-1: 2006: Eurocod 4: Proiectarea structurilor compozite de oțel şi beton. Partea 1-1: Reguli generale şi reguli pentru clădiri* şi *SR EN 1994-2: 2006: Eurocod 4: Proiectarea structurilor compozite de oțel şi beton. Partea 2: Reguli generale şi reguli pentru poduri,* la calculul grinzilor cu goluri compozite, realizate cu tălpi metalice simetrice (realizate din profile de bază identice) sau nesimetrice (realizate din profile metalice de bază diferite).