Ovidius University Annals Series: Civil Engineering, Year 25, 2023
DOI: 10.2478/ouacsce-2023-0003

Footbridges with a composite orthotropic deck

Cătălin Moga, Crina Feneșan and Mircea Suciu

***Abstract* – For average spans, the composite structures such as steel plate beams or box sections, with a monolithic or prefabricated concrete slab at the top flange used for the construction of footbridges are nowadays widely utilized. The use of composite orthotropic deck can be an advantageous solution, taking into account the following consideration: increases the structure's stiffness to bending and torsion; the steel deck has the function of bracing and ensures the lateral stability; the parameters regarding the dynamic behaviour of the structure are improved. In the case study, a working example and an analysis for the structure of a footbridge built over the Someș River in city of Cluj-Napoca are presented.**

Keywords – composite deck, concrete creep and shrinkage, dynamic analysis, footbridges, orthotropic plate, shear lag effect.

1. INTRODUCTION

Composite steel-concrete structures, offer efficiency solutions in most types of construction - civil, industrial and bridges.

For medium spans of 20 m to 40 m, the composite structures such as steel plate beams or with a box-section in structural cooperation with a monolithic or prefabricated concrete slab at the top flange are widely used for the construction of pedestrian walkways.

Considering the relatively low live loading of footbridges, compared to the design loads used for road bridges, the resistance structure usually results with a reduced rigidity.

This situation leads to the need to check the structure from the point of view of the dynamic behavior, so as to be avoided the phenomenon of resonance.

The use of composite orthotropic deck can be an advantageous solution for the following reasons: increases the bending and torsion stiffness of the beam; it is not necessary to arrange braces at the upper flanges in order to ensure the stability of the lateral buckling during installation; the parameters regarding the dynamic behavior of the structure, correlated with the traffic comfort of pedestrians, are improved.

In the case study from the paper, a working example and the analysis for the structure of a footbridge built over the Someș River in city of Cluj-Napoca are presented.

2. DESIGN BASIS OF COMPOSITE STRUCTURES

Modular ratio (Coefficient of equivalence)

To determine the cross-sectional characteristics of the composite sections, the transformed section method is used.

This section transformation is achieved by means of the modular ratio, which represents the ratio between the modulus of elasticity of the steel and concrete, depending on the nature of the loads acting on the considered composite structure [1], [2].

Short-term loading

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

where: E_a - is the modulus of elasticity of the steel; *Ecm* - is the modulus of the concrete.

Permanent loading and long-term actions

The modular ratio for long-term loads shall be assessed by taking into account the creep of concrete, with the formula:

$$n_L = n_0 \cdot (1 + \psi_L \cdot \varphi(t, t_0)) \tag{2}$$

where: ψ_L is the multiplier for concrete creep equal to 1.1 – for permanent loading, 0.55 – for shrinkage effect; $\varphi(t, t_0)$ – creep coefficient [1], [2].

3. COMPOSITE GIRDERS WITH ORTHOTROPIC DECK

In the case of decks used for the structure of the pedestrian walkways, as well as in the case of the bridges, the solution of open or semi-closed box girders with monolithic cast reinforced concrete slab can be adopted.

Figure 1 shows the deck of a pedestrian walkway on a central arche, which required the need to adopt a composite boxed section [3], [4].

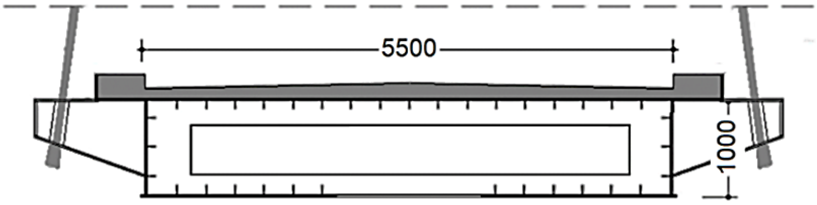

Fig. 1 Transversal cross-section of a deck for a footbridge on central arch

In the case of the orthotropic slabs, in a structural connection with a concrete slab, the effective (active) slab width correlates with the reduced effective width, resulting from the shear lag effect.

Elastic shear lag at serviceability limit state (SLS)

In [5], the concept of taking shear lag into account is based on effectives width of the flange b_{eff}:

$$b_{eff} = \beta \cdot b_0 \tag{3}$$

Where: β is an efficiency factor given in [5] - Table 3.1 – EN1993-1-5.

Shear lag effect for ultimate limit states (ULS)

In the case of a flange in compression at ULS (ultimate limit state) verification, the plate buckling effects which results in an effective^p area of the flange may occur in addition to the shear lag effects. In the norm [5] two models of steps for interaction between shear lag and plate buckling are proposed:

Model 1 (Method b):

Calculate the effective^p area to plate buckling;

Define an effective^p stiffening ratio α_0^* to be used instead of the stiffened ratio α_0 and calculating the reduction factor β_{ult} instead of , where:

$$\alpha_0^* = \sqrt{\frac{A_{c.eff}}{b_0 t}} \tag{4}$$

Calculate the effective area A_{eff} for taking shear lag and plate buckling effects into account as follows:

$$A_{eff} = \beta_{ult} \cdot A_{c.eff} \tag{5}$$

Model 2 (Method c – recommended in [5]:

An elastoplastic reduction factor $\beta^k \geq \beta$ is directly applied to the effective^p area of the compression flange, where k is based on α_0:

$$A_{eff} = \beta^k \cdot A_{c.eff} \geq A_{c.eff} \cdot \beta \tag{6}$$

Examples of numerical calculation related to the shear lag effect are presented in the papers [6], [7].

4. SPECIFIC PROBLEMS REGARDING FOOTBRIDGES CHECKING

Dynamic analysis of the footbridge

Vertical and horizontal frequencies can be included in four ranges of resonance risk, Figure 2: Range 1: Maximum risk of resonance; Range 2: Medium risk of resonance; Range 3: Low risk of resonance and Range 4: Negligible risk of resonance [8], [9].

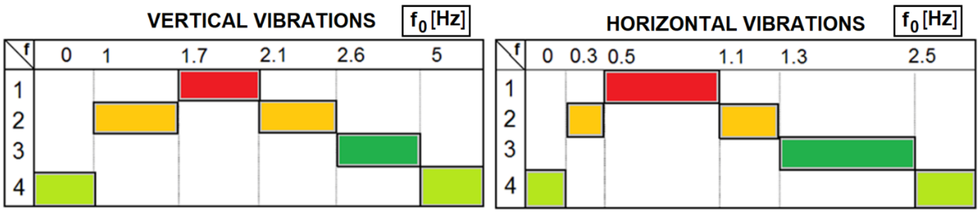

Fig. 2 Frequency ranges of the vertical and of the transverse vibrations

According to [10], the verification of the comfort criterion must be carried out if the fundamental frequency of the deck is lower than the values: 5 Hz – for vertical vibrations and 2.5 Hz – for horizontal (lateral) vibrations and torsion vibrations.

Also, four conventional ranges of vertical and horizontal accelerations are defined, Figure 3. In ascending order this corresponding to the maximum, medium and minimum comfort levels and range 4 corresponds to uncomfortable acceleration values [8].

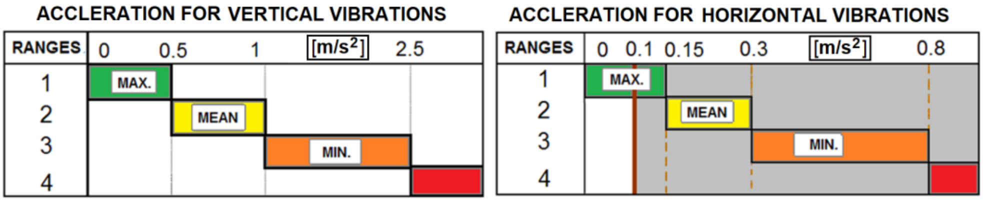

Fig. 3 Acceleration for vertical and horizontal vibrations

In the papers [11], [12] and [13] are presented aspects regarding the dynamic response and the footbridges design constructed in diverse solutions of steel and composite girders.

Creep and concrete shrinkage stresses

Figure 4 presents the scheme of calculation for the efforts resulting from the creep and the shrinkage of the concrete slab [14].

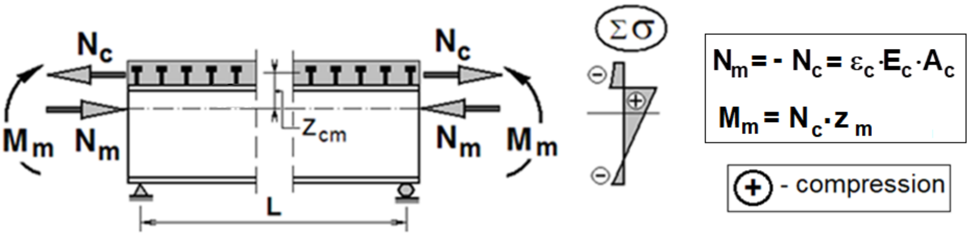

Fig. 4 Development of stresses due to concrete creep and shrinkage

The stresses due to the creep and the concrete shrinkage, at the center of the slab and the extreme fibers of the steel box girder have the following values:

$$\sigma_c = -\frac{N_c}{A_c} + \frac{1}{n}\left(\frac{N_m}{A_m} + \frac{M_m}{I_m} z_{cm}\right) \tag{7}$$

$$\sigma_{a.sup} = \left(\frac{N_m}{A_m} + \frac{M_m}{I_m} z_{as}\right) \qquad \sigma_{a.inf} = \left(\frac{N_m}{A_m} - \frac{M_m}{I_m} z_{ai}\right) \tag{8.a, b}$$

Stresses induced by the vertical component of the temperature

The strain from the temperature variation is:

$$\varepsilon_{c.\Delta T} = \alpha_T \cdot \Delta T_M \tag{9}$$

where: $\alpha_T = 1 \cdot 10^{-5} / {}^0C$ is the thermal dilatation coefficient, [15]-Table C.1.

Figure 5 [16] shows the stresses on the composite section.

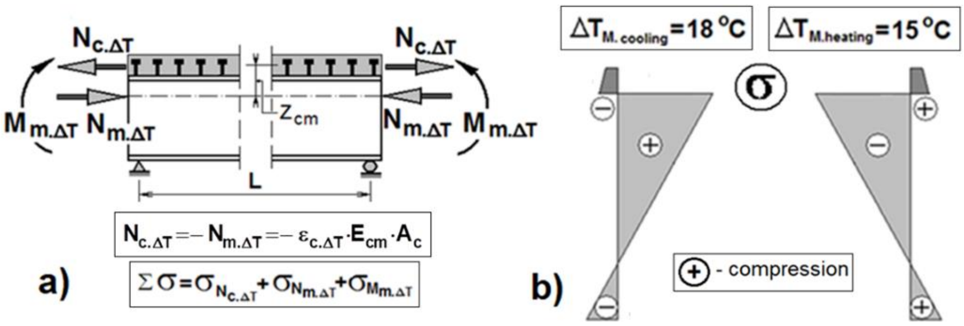

Fig. 5 Development of stresses due to thermal effect on composite girder depth

5. CASE STUDIES

Example 1: Active (effective) plate of an orthotropic deck

The reduced (active) plate widths from the shear lag effect for an orthotropic plate forming part of the structure of a one carriage lane road bridge or for a pedestrian walkway combined with a roadway is assessed, Figure 6 [17].

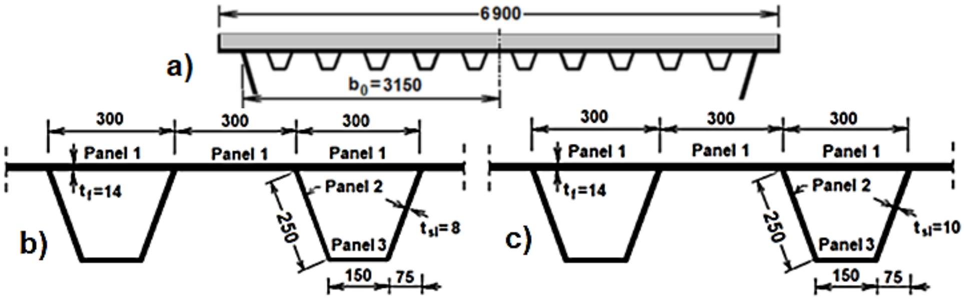

Fig. 6 Girder with an orthotropic deck: a) cross-section of the deck; b) details orthotropic deck for $t_{sl} = 8mm$; c) details orthotropic deck for $t_{sl} = 10mm$

The graphical results are presented in Figure 7.

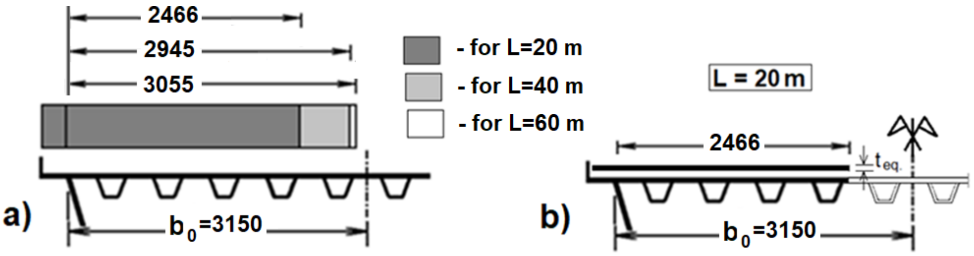

Fig. 7 Effective (active) plate width: a) Relation effective widths - deck span; b) Equivalent in steel of the deck slab

Example 2: Footbridge over Someș River

This example presents some aspects related to the structural design and dynamic behaviour of a composite superstructure footbridge of 31.50 m span, constructed in the area of a park near the Someș River in the city of Cluj-Napoca [18].

For the analysis a modular ratio between concrete and steel $n = 2 \cdot n_0$ will be considered, given by [2] - SR EN 1994-1-1:2006 §5.4.2.2(11) in a simplified method.

Shear lag effect

According to [5]-SR EN 1993-1-5 §3.1(1), the shear lag phenomenon can be neglected if the condition $b_0 \leq L_e/50$ is fulfilled, where L_e is the length between the null bending moment points. In this case the condition $b_0 \leq L_e/50 = 31500/50 = 630mm$ is fulfilled for the panel between the webs and it is not fulfilled for the cantilever areas.

In Figure 8 the cross-section of the superstructure is presented.

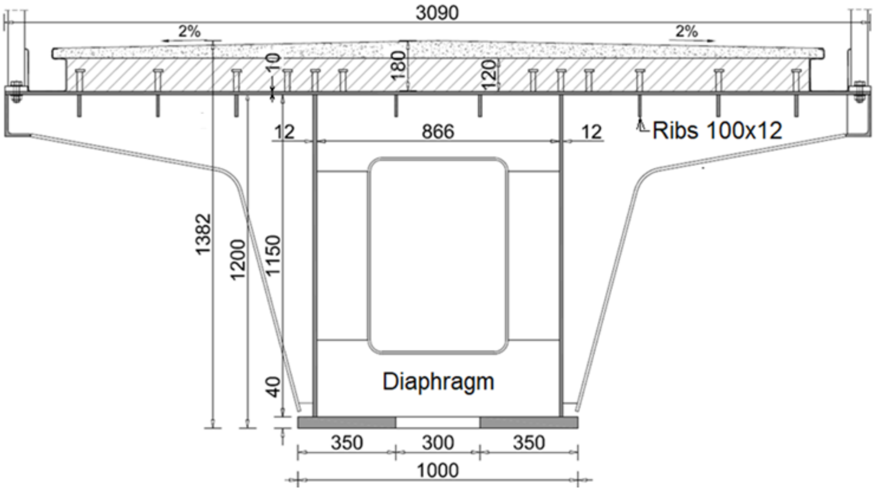

Fig. 8 Cross-section of the deck for the central section

In Figure 9.a the geometrical characteristics of the steel cross-section girder and of the composite girder are presented. In Figure 9.b the maximum stresses at the middle of the beam obtained from the permanent loading, live loading and the wind action, taking into account the action coefficients are presented.

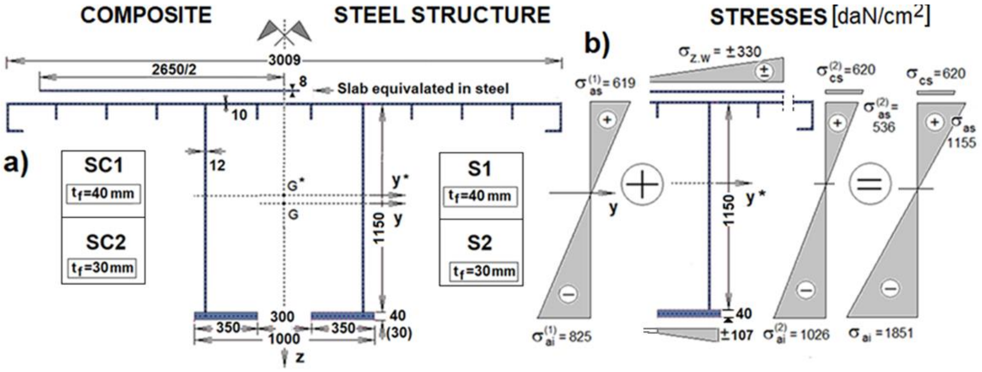

Fig. 9 a) Geometrically characteristics of the steel and of the composite girder;
b) Stresses at central span

The steel deck was mounted as assembled on the abutments, without the use of intermediate scaffolding, Figure 10.

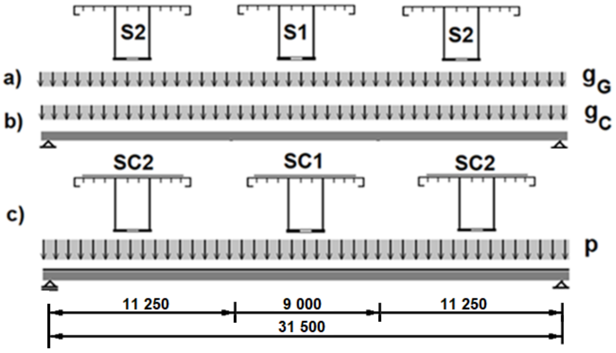

Fig. 10 Loading schemes of the footbridge

In the Figure 11 some photos of the footbridge during the installation are presented.

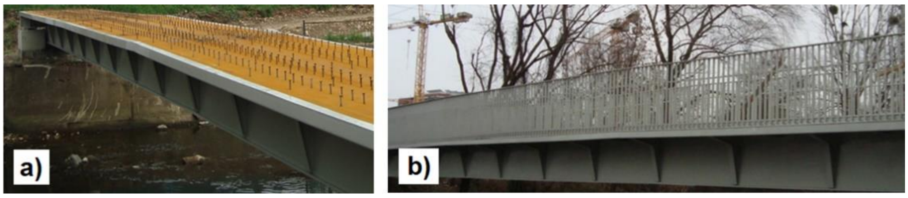

Fig. 11 Footbridge during the execution

6. CONCLUSION

Pedestrian walkways belong to the category of bridges, but as a result of low loads, the resistance structures result with high slenderness in the case of small and medium spans on metal girders or steel-concrete composites. The use of composite orthotropic plates for the deck can be an advantageous solution.

In the case of composite structures, the stresses resulting from the creep and shrinkage of concrete, as well as the stresses from the variation of the temperature field on the depth of the girder section, cumulatively can reach about 30-40% of the stresses produced by the live load, and as consequence have also to be taken into account.

7. REFERENCES

[1] *** SR EN 1994-2: 2006. Eurocode 4: *Design of composite steel-concrete structures – Part 2: General rules and rules for bridges*

[2] *** SR EN 1994-1-1: 2006. Eurocode 4: *Design of composite steel-concrete structures – Part 1-1: General rules and rules for buildings*

[3] Guțiu Șt., Moga P., Danciu A., Moga C. (2013), *Lateral Torsional Buckling Resistance of Steel Plate Girders according to Euronorms.* The 8th International Conference "Bridges in Danube Basin" Springer Vieweg. ISBN 978-3-658-03713-0. Timişoara

[4] Guțiu Șt., Moga C., Danciu Alexandra D. (2019), *Dynamic analysis of a footbridge structure on a central arch*. DOI: 10.2478/rjti-2019-0011. ROMANIAN JOURNAL OF TRANSPORT INFRASTRUCTURE. Article No 5, Romanian Journal of Transport Infrastructure, Vol.8, 2019, No.2 58

[5] *** SR EN 1993-1-5: 2008. Eurocode 3: Design of steel structures – Part 1-5: Plated structural elements

[6] Moga P., Guțiu Șt.I., Anghel F., Moga C., Danciu A. (2016): *Footbridge over the Somes River in Cluj-Napoca*, Romania, The 9th International Conference “Bridges in Danube Basin” published in “Procedia Engineering 156” ELSEVIER, ISSN 1877-7058, DOI: 10.1016/j.proeng.2016.08.259, p. 249-256, http://authors.elsevier.com/sd/article/S1877705816324651, WOS:000383246700034

[7] Moga C., Feneșan C., Suciu M. (2021): *Shear lag and local buckling interaction in orthotropic deck of steel bridges*, Buletinul Univ. Tehn. „Gh. Asachi”. Vol. 67. Nr. 1/2021. SCIENDO. DOI: 10.2478/bipca-3021-0006

[8] *** SETRA (2016), Technical guide. *Footbridges. Assessment of vibrational behavior of footbridges under pedestrian loading,* Service d’Études Techniques des Routes et Autoroutes. Paris

[9] *** FIB Bulletin 32 (2005): Guide*lines for the design of footbridges. Guide to good practice*. Fédération Internationale du béton, ISBN 978-2-88394-072-7

[10] *** EN 1990. *Basis of structural design*, (1990)

[11] Guțiu Șt. I., Moga C., Danciu A., Suciu M. (2016): *Constructive solutions for medium span footbridges*, 16th International Multidisciplinary Scientific Geoconference, Bulgaria, ISBN 978-619-7105-69-8, ISSN 1314-2704, pp 517-524, WOS: 000391650000063

[12] Guțiu Șt. I., Moga C., Danciu A. (2016): *Elastic and plastic design of composite steel-concrete girders with circular holes*, 16th International Multidisciplinary Scientific Geoconference, Bulgaria, ISBN 978-619-7105-69-8, ISSN 1314-2704, pp 549-556, WOS:000391650000072

[13] Moga C., Drăgan D., Nerișanu R. (2021): *Relation of natural frequencies to traffic pedestrians’ comfort of some steel footbridges*, Ovidius University Annals. Series: Civil engineering, pag. 7-15, SCIENDO, DOI: 10.2478/ouacsce-2021-001. ISSN 2392-6139/ISSN-L 1584-599

[14] Vayas, I., Iliopolos, A. (2013): *Design of Steel-Concrete Composite Bridges to Eurocodes*. CRC Press. Taylor & Francis Group

[15] *** SR EN 1991-1-5: *Actions on structures*. Part 1-5: *General actions Thermal actions*

[16] Moga C., Guțiu Șt. I., Danciu A., Suciu M. (2016): *Concrete shrinkage stresses and thermal effects in the composite girders according to Eurocodes*, 16th International Multidisciplinary Scientific Geoconference, Bulgaria, ISBN 978-619-7105-69-8, ISSN 1314-2704, pp 501-508, Accession Number: WOS: 000391650000066

[17] Moga C., Alb C., Suciu M. (2021): *Effect of design parameters on shear lag in orthotropic deck of steel road bridges,* Buletinul Univ. Tehn. „Gh. Asachi”. Vol. 67. Nr. 2/2021. SCIENDO. DOI: 10.2478/bipca-3021-0018, pag. 95-104

[18] Moga C., Guțiu Șt.I., Danciu A., Cristea B. (2020): *Technical aspects and structural verification of a footbridge with composite steel-concrete box girder*. Buletinul Univ. Tehn. „Gh. Asachi”. Vol. 66. Nr. 2/2020

Note:

Feneșan Crina – Technical University of Cluj-Napoca, 28 Memorandumului Street, 400114-Cluj-Napoca, Romania (corresponding author to provide phone: +40-730-919394; e-mail: Crina.Fenesan@cfdp.utcluj.ro)
Moga Cătălin – Technical University of Cluj-Napoca, 28 Memorandumului Street, 400114-Cluj-Napoca, Romania (e-mail: Catalin.Moga@dst.utcluj.ro)
Suciu Mircea – Technical University of Cluj-Napoca, 28 Memorandumului Street, 400114-Cluj-Napoca, Romania (e-mail: Mircea.Suciu@cfdp.utcluj.ro)