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THE DESIGN OF GLUED LAMINATED TIMBER FOOTBRIDGE STRUCTURE ACCORDING TO EUROCODES

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Abstract.*The paper presents the conceptual design of the footbridge made of laminated wood. The supporting system of the main bearing elements is made of the laminated wood in the system of arch with three joints and the bridge deck is made of the composite timber-concrete structure system. The load patterns for which the dimensions of the supporting bridge structures were adopted (verified according to Eurocode) are presented.*

Key words: *footbridges, composite timber-concrete structures, Eurocode*

1. INTRODUCTION

The contemporary civil engineering requirements present progressively complex problems to the designers, both in the field of application of the new materials and in the usage of the traditional building materials but with the application of the new technologies and innovative methods in the production process and the construction, at the same time meeting the optimal requirements in terms of esthetics and cost-effectiveness.

Considerations of a more adequate and cost-effective application of material in the structures resulted in the appearance of composite beams. Although the composite beams of steel and concrete are the most frequent in application, other forms of composite materials may occur, among them the timber-concrete composite supports.

Timber, as well as steel has a relatively high tensile strength, so this engendered an idea to combine it with concrete. The composite timber-concrete supports, in respect to the classic timber structures, possess higher stiffness, fire resistance, stability and seismic resistance, and in comparison to steel and concrete, its own weight (dead weight) is lighter.

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2. FOOTBRIDGE DISPOSITION ELEMENTS

For the purpose of analysis of the actions on the bridge, a structural system whose primary girder of the structure is an arch with three joints. The structure consists of two girders at the mutual axial distance of 1.8 m. The width of the bridge is 3 m. The main support is of complex rectangular cross-section, 40 cm in width (composed of two elements 20 cm wide), and the height 100 cm, of the total span 64,6 m, designed of the laminated 1st class conifer timber. The total length of the bridge is 78.1 m.

Figure 1 presents the disposition of the adopted design of the footbridge.

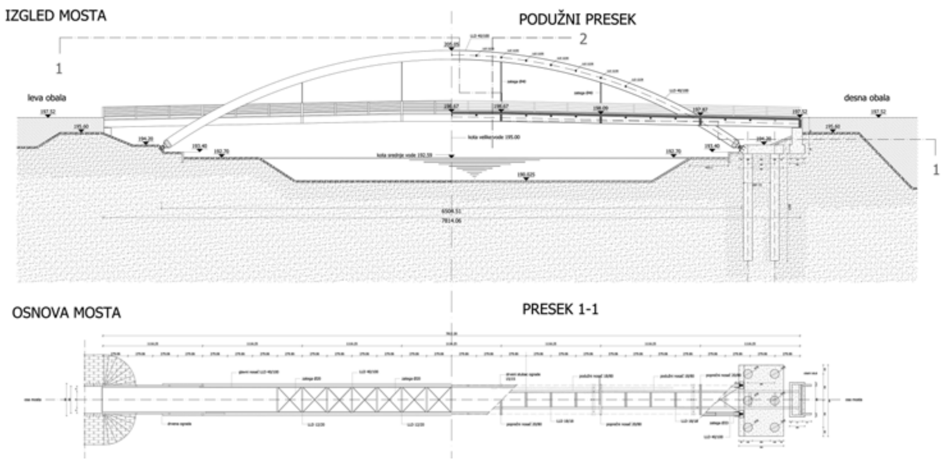

Fig. 1. Disposition of the footbridge

The primary girders have the joint supports of structural steel S235[1] (Č0361) and they transfer the load through them to the fundaments.

The primary girders are secured (buckling is prevented) by the structural element – bracing placed perpendicularly on the plane of the system. It is made of the transverse timber beams BS 16(h)[2] dimensions 12/20 cm and the steel diagonal tie Ø33 of steel S460 and connects the primary girders in the top zone of the bridge and a strut on the both ends of the bridge which connects the primary girders under the pavement substructure.

Third girder (roadway slab, pedestrian lane) pass through the arch. It consists of seven equal sections 11,16 m long, which are the simple beam – lengthwise, and cantilever column - crosswise. Each section is constructed as a timber-concrete composite structure, where concrete (C25/30[3]) makes the road deck, and timber (BS 16(h)) longitudinal girders. Each section is supported on the secondary timber crosswise beams, 20/80 cm. IN figure 2, the bearing elements of the bridge structure are presented in cross-section view.

[1] According to EUROCODE 3
[2] According to EUROCODE 5
[3] According to EUROCODE 2

The primary and the third girder are connected through two stationary supports at the point of intersection of girder axes and the steel ties Ø40 of steel S235, which are arranged over the crosswise timber beams on the section ends on both ends of the bridge. The supports of the third girder are hinged, that is, no horizontal movement is allowed in the bearing, meaning they transfer the vertical load on the retaining concrete pier. C25/30.

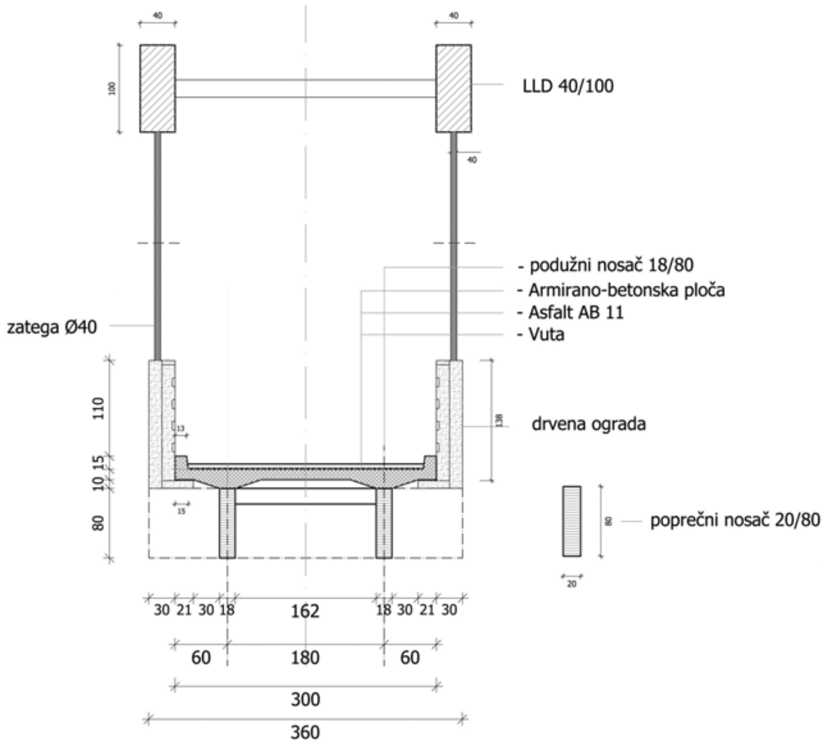

Fig. 2. Cross-section of the bridge

3. Bridge design concept

The loads and design of the structure was conducted according to the European standards, and on this basis the dimensions of the bearing elements of the structure were presented. The probabilistic concept of the limit states was used: bearing capacity limit state and serviceability limit state, using the partial coefficients wor the loads and materials.

The dead weight of the structure is calculated for:

– the load on the reinforced concrete slab of the dead weight of asphalt, railing, haunch and edge beam.
– the load of the laminated timber girders of its dead weight and of the weight of the reinforced concrete slab.

Within the variable load, the following influences were observed:

– wind force (for the area of Nis) affecting the structure was calculated according to the EC1 (ENV 1991-2-4) according to the following formula:

$$F_w = q_{ref} \cdot c_e(z_e) \cdot c_d \cdot c_f \cdot A_{ref} \qquad (3.1)$$

where: q_{ref} reference pressure of wind mean velocity,
$c_e(z_e)$ exposure coefficient,
c_d dynamic factor,
c_f force coefficient,
A_{ref} reference surface

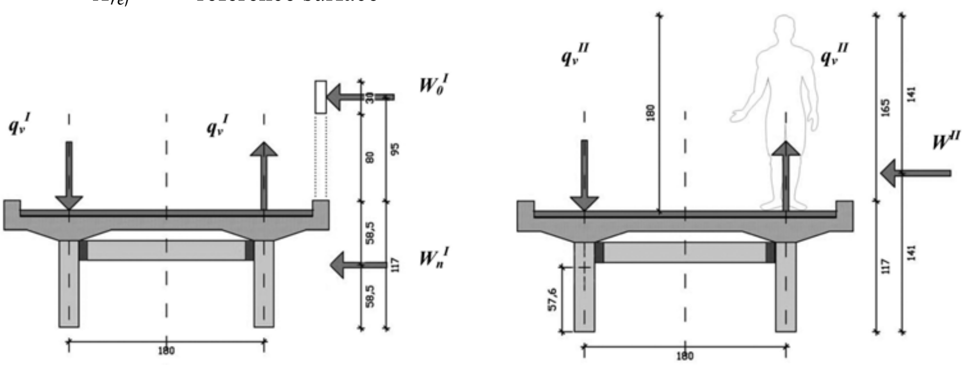

Fig. 3. Wind load patterns: for the unloaded bridge (left) and loaded bridge (right)

- snow force is s_k = 1,0kN/m^2 according to EC1

Figure 3 presents load patterns from the structure dead weight, and wind on the unloaded and loaded bridge.

As the mobile load the following was observed:

– Equally distributed mobile load, that is, the load belonging to one main girder:

$$q_{fk} = 5{,}0 \text{ kN/m}'$$

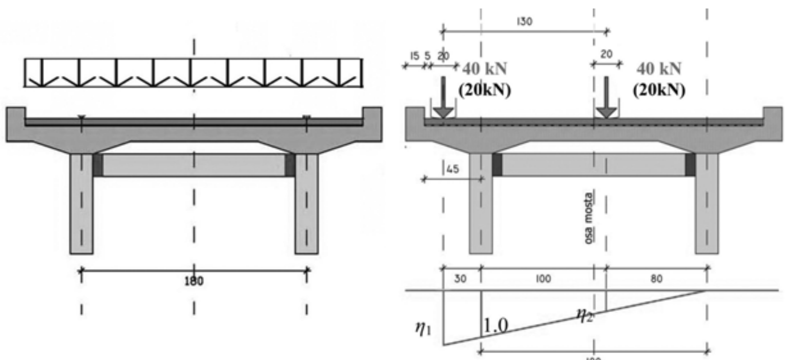

Fig. 4. Bridge load patterns

– service vehicle load (ambulance or fire-fighting vehicle)

Incident load (according to EC 1, Part 1: Traffic loads on the bridges, points 5.3.2.2 and 5.6.3 and Annex) presented in the figure 3. and the vehicle pattern is presented in the figure 4.

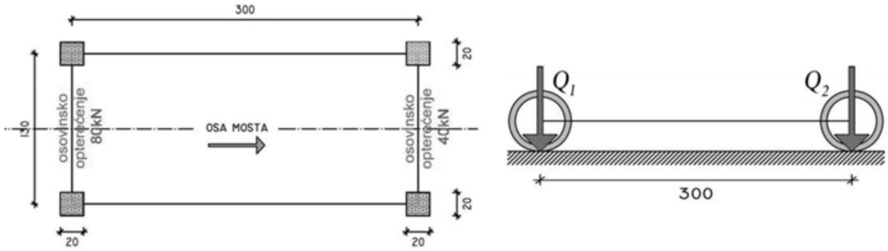

Fig. 5.Vehicle patterns

$$Q_{flk} = \max \begin{cases} 0.1 \cdot (5.0 + 9.0) \cdot Q_1 \text{ [kN]} \\ 0.6 \cdot 120 \text{ [kN]} \end{cases} \tag{3.2}$$

where is: Q_{flk} [kN] Horizontal load at the level of road deck in the direction of the vehicular movement

$$q_{fkl} = \frac{Q_{flk}}{Q_1} = 1.44 \text{ kN/m'}$$

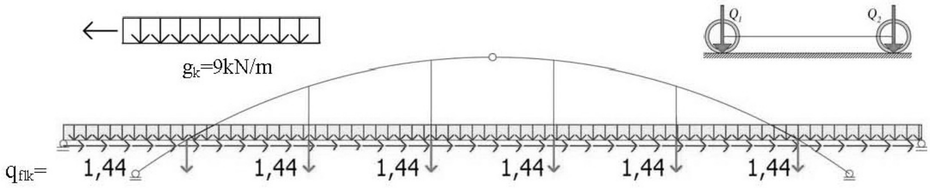

Fig. 6. Main girder load pattern

For the extreme values in the main girder, two groups of loads are considered, according to ENV 1991-3:

I: Constant and variable load action, with combinations:

$$\sum \gamma_{G,j} G_{k,j} + \gamma_{Q,1} Q_{k,1} + \sum_{i>1} \gamma_{Q,i} \psi_{0i} Q_{k,i} \tag{3.3}$$

vertical load for composite structures:

– dead weight + traffic load

$$V_{d,I} = \frac{(1{,}35 g_k + 1{,}35 q_k) \cdot l}{2} \text{ [kN]} \tag{3.4}$$

– dead weight + wind load (linear longitudinal wind load)

$$q_{wz} = q_{ref} \cdot c_e(z_e) \cdot c_d \cdot c_{fz} \cdot 1{,}5 \quad \text{[kN/m}^2\text{]} \tag{3.5}$$

$$V_{d,I} = (1{,}35 g_k + 1{,}35 q_k) l / 2 \ \ [\text{kN}] \tag{3.6}$$

– dead weight + snow load (linear longitudinal snow load)

$$s_k = 1 \cdot 1{,}5 \ \ [\text{kN/m}] \ \text{according to EC1} \tag{3.7}$$

$$V_{d,I} = (1{,}35 g_k + 1{,}35 q_k) l / 2 \ \ [\text{kN}] \tag{3.8}$$

– dead weight + wind load + snow load

$$q_{wz} + s_k = q_{ref} \cdot c_e(z_e) \cdot c_d \cdot c_{fz} \cdot 1{,}5 + 1 \cdot 1{,}5 \ \ [\text{kN/m}^2] \tag{3.9}$$

$$V_{d,I} = (1{,}35 g_k + 1{,}35 q_k) l / 2 \ \ [\text{kN}] \tag{3.10}$$

horizontal load:

– wind action on the unloaded bridge (EC 1:D2.1.1 P(2))

$$q_r^I = \frac{W_n^I (58.5 - 57.6) + W_0 (212 - 57.6)}{1.80} \ \ [\text{kN/m}^2] \tag{3.11}$$

– wind action on the loaded bridge (EC 1:D2.1.1 P(2))

$$q_r^{II} = \frac{W_n^{II} (141 - 57.6)}{1.80} \ \ [\text{kN/m}^2] \tag{3.12}$$

II: Constant, variable and incident load action, with combinations:

$$\sum \gamma_{GA,j} G_{k,j} + A_d + \psi_{1,1} Q_{k,1} + \sum \psi_{2,i} Q_{k,i} \tag{3.13}$$

– dead weight + concentrated incident load

$$V_{d,II} = (1{,}0 g_k) l / 2 + V \ \ [\text{kN}] \tag{3.14}$$

– dead weight + traffic load + concentrated incident load

$$V_{d,II} = (1{,}0 g_k + 0{,}7 p_k) l / 2 + V \ \ [kN] \tag{3.15}$$

On the basis of the obtained intersecting forces, the structural elements can be designed according to the EUROCODE standards for structures, satisfying both the bearing capacity and serviceability requirements..

For the prefabricated composite element timber=concrete, it is necessary to create an analysis according to the limit state of bearing capacity and limit state of serviceability according to the adopted ideal model of composite section of concrete slab with timber beams with mechanical fasteners. The analysis should demonstrate that the adopted section geometry and the applied materials fully match the criteria of the Eurocodes. In the figure 7. the cross section of the composite girder is presented with the distribution of normal stresses in the cross section.

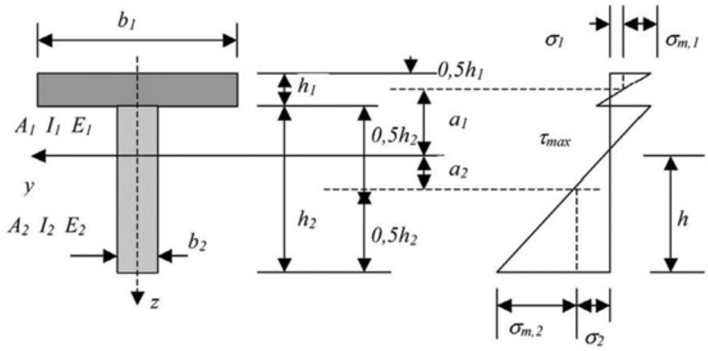

Fig. 7. Stress distribution in the composite girder cross section

Geometry characteristics of the concrete-timber composite girder cross section given on the figure above, where:

$A_1 = b_1 \cdot h_1$,	is the surface are of the reinforced concrete road deck slab
$I_1 = b_1 \cdot h_1^3 / 12$,	moment of inertia of the reinforced concrete road deck slab cross section
$\gamma_1 = [1 + \pi^2 E_1 A_1 s_{eff} / (K_u l^2)]^{-1}$	movement coefficient of the composition fasteners
a_1	distance of the composite slab centre of gravity from the section center of gravity
$A_2 = b_2 \cdot h_2$	surface area of the laminated timber girder cross section
$I_2 = b_2 \cdot h_2^3 / 12$,	moment of inertia of the laminated timber girder cross section
$\gamma_2 = 1.0$	movement coefficient of the composition

distance of the center of gravity of the cross section of the laminated timber girder from the center of gravity of the cross section defined by equation:

$$a_2 = \frac{\gamma_1 \cdot E_1 \cdot A_1 \cdot (h_1 + h_2)}{2\sum_{i=1}^{3} \gamma_i \cdot E_i \cdot A_i}$$

where: $E_1 = E_{cm}$ concrete elasticity module

$E_2 = E_{0,mean}$ laminated timber elasticity module

$E_1 = E_{cm} = 30000\text{N/mm}^2$ $\quad E_2 = E_{0,mean} = 13700\text{N/mm}^2$

$(EI)_{ef} = E_1 I_1 + \gamma_1 E_1 A_1 a_1^2 + E_2 I_2 + \gamma_2 E_2 A_2 a_2^2$, bending stiffness of the composite girder

4. STRESS CHECK IN THE MAIN GIRDER AND BRACES

In the case of the spatial action of load, the following influences are controlled.:
- bending :

$$k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 , \quad (4.1)$$

$$\frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 \quad (4.2)$$

where:

$\sigma_{m,y,d}$, $\sigma_{m,z,d}$ - are the calculated bending stress in relation to the main axes

$f_{m,y,d}$, $f_{m,z,d}$ - corresponding bending stiffness.

For the value of k_m factor, the following should be adopted:

– for the rectangular cross section k_m = 0,7,

– for other cross sections k_m =1,0.

– shear : $\tau_d \leq f_{v,d}$. (4.3)

– combined bending and axial tension

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 , \quad (4.4)$$

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} + k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 , \quad (4.5)$$

where:

$\sigma_{t,0,d}$ – is the design tensile stress parallel to the grain,

$f_{t,0,d}$ – design tensile strength, parallel to the grain.

– combined bending and axial compression:

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 , \quad (4.6)$$

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1 , \quad (4.7)$$

where:

$\sigma_{c,0,d}$ – is the design compressive stress parallel to the grain,

$f_{c,0,d}$ – the design compressive strength parallel to the grain.

After this check, the stability should be checked (chapter 5.2.1 in EC 5).

5. STABILITY CHECK OF COMPRESSED BARS AND BENDED GIRDERS

5.1. Compressed bars

The additional influence of the bending stress caused by the initial curve of the unloaded bar, eccentricity of the normal force and the displacement according of the second order theory, should be included in the calculation as if caused by the equally distributed transversal load.

The relative slenderness ratios are defined as:

$$\lambda_{rel,y} = \sqrt{\frac{f_{c,0,k}}{\sigma_{c,crit,y}}} \geq 0,5\,, \tag{5.1.1}$$

where:

λ_y and $\lambda_{rel,y}$ - correspond to the bending around **y** axis (buckling in **z** direction)

λ_z and $\lambda_{rel,z}$ - correspond to the bending around **z** axis (buckling in **y** direction)

In the case when $\lambda_{rel,z} \leq 0,5$ and $\lambda_{rel,y} \leq 0,5$ the stresses should meet the conditions given in the expressions 5.1.10 a and b in EC 5.

In this case the stresses should meet the following conditions:

$$\frac{\sigma_{c,0,d}}{k_{c,z} f_{c,0,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} + k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} \leq 1\,, \tag{5.1.2}$$

$$\frac{\sigma_{c,0,d}}{k_{c,y} f_{c,0,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} + \frac{\sigma_{m,y,d}}{f_{m,y,d}} \leq 1\,, \tag{5.1.3}$$

where:

$$k_{c,y} = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}} \quad k_{c,z} = \frac{1}{k_y + \sqrt{k_z^2 - \lambda_{rel,z}^2}} \text{, is analogous for } k_{c,z}, \tag{5.1.4}$$

$$k_y = 0,5[1 + \beta_c(\lambda_{rel,y} - 0,5) + \lambda_{rel,y}^2]\,, \tag{5.1.5}$$

in the preceeding expressions:

σ_m – is the bending stress due to the transversal load,

β_c – is the factor for the bar with the initial imperfection in comparison to the straight bar defined in chapter 7 of EC 5:
– for solid timber: $\beta_c = 0,2$
– for glued laminated timber: $\beta_c = 0,1$

5.2. Bended girders – lateral torsional stability

The additional influence of the bending stress caused by the initial curve of the unloaded bar, eccentricity of the normal force and the displacement according of the second order theory, should be included in the calculation as if caused by the equally distributed transversal load.

The relative slenderness ratio for the bending is defined as:

$$\lambda_{rel,m} = \sqrt{f_{m,k} / \sigma_{m,crit}}\ , \tag{5.2.1}$$

where:

$\sigma_{m,crit}$ – is the critical value of the bending stress, calculated according to the classic stability theory, with the characteristic stiffness value determined as the population 5-percentile values.

$$f_{m,k} = 32\frac{\text{N}}{\text{mm}^2}$$

$$f_{m,d} = f_{m,y,d} = k_{\text{mod}} \cdot f_{m,k} / \gamma \tag{5.2.2}$$

the stresses should meet the following condition:

$$\sigma_{m,d} \leq k_{crit} f_{m,d} \quad (5.1.1)$$

where:

k_{crit} – is the factor of lateral buckling which reduces the buckling bearing capacity..

For the girders with the initial imperfection (in comparison the straight bar) within the range defined in the chapter 7 in EC 5, k_{crit} can be determined according to the (EC5:5.2.2c-e):

$$k_{crit} = \begin{cases} 1 & za \quad \lambda_{rel,m} \leq 0{,}75 \\ 1{,}56 - 0{,}75\lambda_{rel,m} & za \quad 0{,}75 < \lambda_{rel,m} \leq 1{,}4 \\ 1/\lambda_{rel,m}^2 & za \quad 1{,}4 < \lambda_{rel,m} \end{cases} \tag{5.2.3}$$

Factor k_{crit} = 1 for the girders where the lateral displacement along the compressed side and support torsional rotation is prevented.

Relative slenderness ratio for bending can be thus expressed:

$$\lambda_{rel,m} = \sqrt{\frac{l_{ef} \cdot h_s}{\pi \cdot b^2} \cdot \frac{f_{m,k}}{E_{0,05\cdot}} \cdot \sqrt{\frac{E_{0,50}}{G_{50}}}} = \sqrt{\frac{279 \cdot 100}{3{,}14 \cdot 40^2} \cdot \frac{32}{10800} \cdot \sqrt{\frac{13500}{840}}} = 0{,}25$$

$$k_{crit} = 1$$

$$\sigma_{m,d} = 11{,}19\frac{\text{N}}{\text{mm}^2} \leq k_{crit} f_{m,d} = 1{,}0 \cdot 17{,}23\frac{\text{N}}{\text{mm}^2}$$

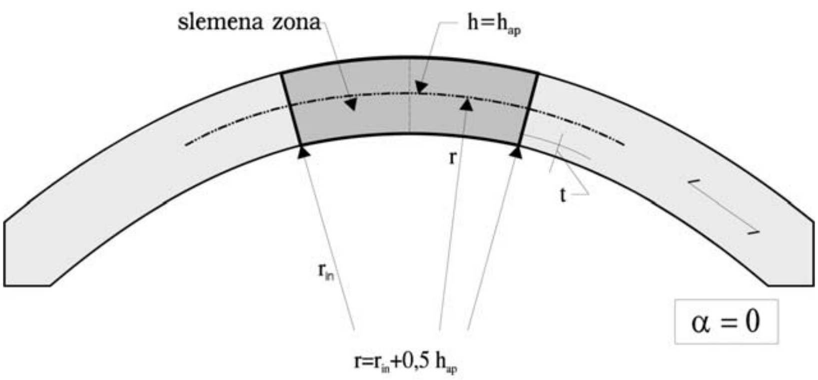

Fig. 8. Curved girder of constant height

6.CONCLUSION

The solution of the bridge represent a contemporary concept of the bearing structure made of a peculiar combination of different materials such as timber, steel and concrete. Such structure can be relied on, in terms of reliability and durability, provided that the elements exposed to the atmospheric influence has been adequately protected. The paper presents the analysis of actions on the footbridge, done according to Eurocode.

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PRORAČUN PEŠAČKOG MOSTA OD LEPLJENOLAMELIRANOG DRVETA PREMA EVROKODOVIMA

Dragoslav Stojić, Radovan Cvetković, Nikola Stojić

U radu je predstavljeno idejno rešenje pešačkog mosta od lepljeno lameliranog drveta. Noseći sistem konstrukcije glavnih nosača je lepljeno lamelirano drvo sistema luka sa tri zgloba, a kolovozna ploča je spregnutog sistema drvo-beton. Date su i šeme opterećenja za koje su primenom Evrokodova proverene usvojene dimenzije noseće konstrukcije mosta.