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Constructive systems of fully reinforced lightweight concrete bridges

Jure Radić[(1)], **Ante Mihanović**[(2)] and **Ana Mandić**[(1)]
[(1)]Faculty of Civil Engineering, University of Zagreb, Kačićeva 26, HR-10000 Zagreb, CROATIA
e-mail: mandicka@grad.hr
[(2)]Faculty of Civil Engineering, University of Split, Matice hrvatske 15, HR-21000 Split, CROATIA
e-mail: ante.mihanovic@gradst.hr

SUMMARY

This paper deals with the possibility of using fully reinforced lightweight concrete systems in the bridge structures. Fully reinforced lightweight concrete systems are composed of a steel reinforcement skeleton with the main bearing capacity and lightweight concrete body as a secondary bearing material for a local and global stabilisation. Two examples are given in this paper; the example of a grill-shaped overpass over four spans and a box girder bridge over three spans. Lightweight concrete deck slab is reinforced with a grill-shaped reinforcement made of welded R trusses in two perpendicular directions. The reinforcement of the lightweight main girders, cross girders and walls of the lightweight box girder is designed as, at least, one truss with X-shaped diagonals.

***Key words**: fully reinforced lightweight concrete, steel reinforcement skeleton, trusses, grill-shaped overpass, box girder bridge.*

1. INTRODUCTION

Fully reinforced lightweight concrete structures are composed of a steel reinforcement skeleton with the main bearing capacity and a lightweight concrete body as a secondary bearing material for a local and global stabilization. The concrete body also has the corrosion, fire and moisture protection properties. The low specific weight of the lightweight concrete body gives lower stresses in the main structure and results in less reinforcement and concrete. The usage of these composite systems is possible in bridge structures. The reduction of the main structure weight has a suitable influence on abutments, piers and bearings.

The design assumptions of the fully reinforced lightweight concrete structures [1] are:

- material and geometrical nonlinearity is included,
- steel and lightweight concrete both transmit loading as nonlinear materials,
- small displacements and small strain theory can be applied,
- geometrical presentation of the structure is a 3D discretion of the lightweight concrete body and an askew discretion of the steel reinforcement skeleton in the 3D space of the lightweight concrete body. When it is obvious that the third direction has no influence on holding the girder, 2D discretion of the lightweight concrete body and 1D askew discretion of the steel reinforcement skeleton is possible.

The induced assumptions are strict ones, while standard assumptions allow the presentation of the lightweight concrete body as a group of line parts following the reinforcement skeleton. This way lightweight concrete body participates in the transmission of the forces as a composite with the steel in a line parts of the girder or structure.

The principles of fully reinforced lightweight concrete could be applied to bridge structures, slabs, ribbed structures, trusses, box girders as the main parts forming beam, arch, suspension and cable-stayed bridges [2].

Dimensions of these systems as well as the quality and amount of the reinforcement are to be in accordance with the safety and bearing capacity requests. The reinforcement, if necessary, can be protected with an anticorrosion coating.

The requested properties of the lightweight concrete body are as follows:

- the specific weight is less than *1500 kg/m³*,
- the compressive strength is higher than *2 MPa*,
- the flexural strength is higher than *0,2 MPa*,
- the shear strength is higher than *0,1 MPa* and
- the initial modulus of elasticity is between *300* and *1000 MPa*.

Adopted properties of the lightweight concrete body are as follows:

- the specific weight is *900 kg/m³*,
- the compressive strength is *4 MPa*,
- the flexural strength is *0,5 MPa*,
- the shear strength is *0,5 MPa* and
- the initial modulus of elasticity is *900 MPa*.

This paper represents a step into the spacious research of the possible usage of these composite systems in bridge structures. The design of the four span overpass and the design of the three span bridge is presented. The quality of reinforcement is *S 500*.

2. HIGHWAY OVERPASS IN LIGHTWEIGHT REINFORCED CONCRETE

The overpass, designed in a lightweight reinforced concrete, which is to cross the highway, is presented. Four spans *15,0+19,0+19,0+15,0 m* are chosen to provide the sufficient traffic profile of the highway and its possible expansion [3, 4]. The overpass is a grill-structure composed of three main continiuos girders at a distance of *3,5 m* connected with the *25 cm* thick slab and *100 cm* high cross girders at the end and in the middle of each field. A span to height ratio of the structure is *19,0/2,0=9,5* (Figures 1 and 2).

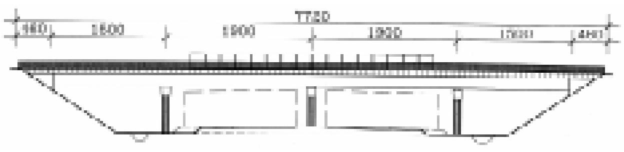


Fig. 1 Highway overpass - view

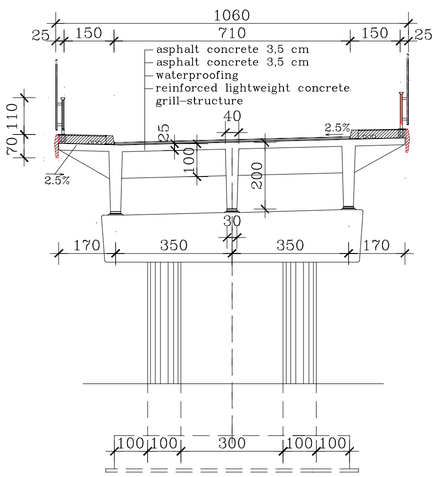


Fig. 2 Highway overpass - cross-section

Along with the dead weight and additional permanent load, the traffic loading with the vehicle SLW 60 is included in the loading analyses. The ultimate limit state (EC2) design is used [5, 6].

2.1 Roadway slab

Lightweight concrete roadway slab is reinforced with a grill-shaped reinforcement made of welded R trusses in two perpendicular directions. Lower R trusses of longitudinal direction are pulled into the higher R trusses of transversal direction and no particular connection is necessary [2].

The flexural design of a deck slab in transversal direction of the bridge is performed. The model of a continuous beam over two spans of *3,5 m* with two cantilevers of *1,7 m* is used. Primarily, the reinforcement is designed for the rectangle section of a slab one meter wide. Alternative design of the top and bottom reinforcement of the slab is effected on the truss model with top and bottom flanges having composite cross-sections.

Top reinforcement at the bearing and the bottom reinforcement in the middle–span remains the same along the slab and represents the longitudinal reinforcement of the *R* truss. In the bottom flange five bars are predicted: *4ϕ22+1ϕ25/m'*. In the top flange ten bars are predicted: *10ϕ16/m'*. Moreover, shear reinforcement due to local penetration of the roadway slab is designed and represents diagonals of the *R* truss (Figure 3).

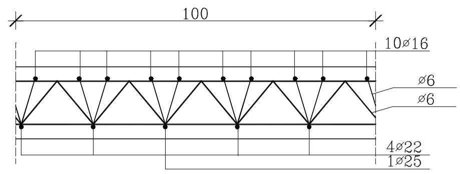
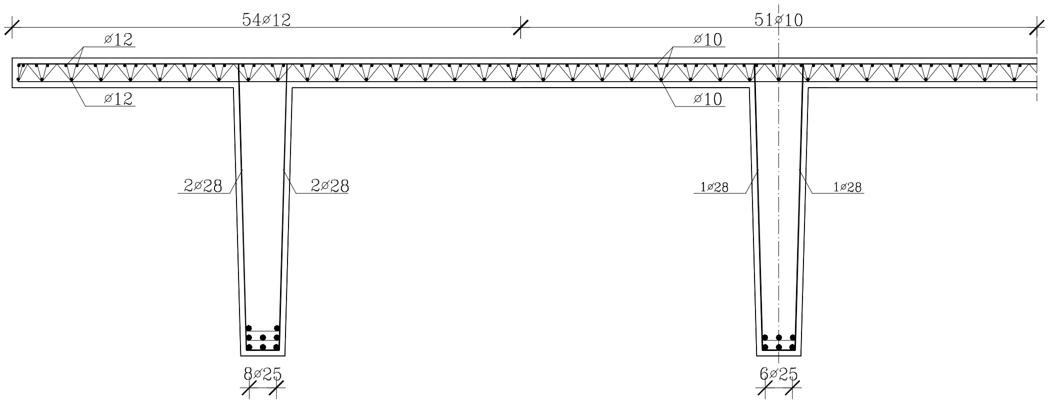


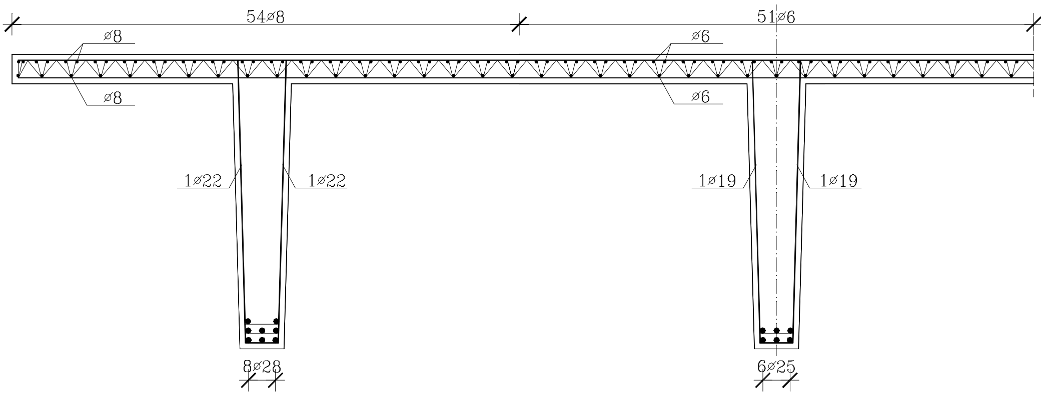
Fig. 3 Slab reinforcement of the overpass

2.2 Main girders and cross girders

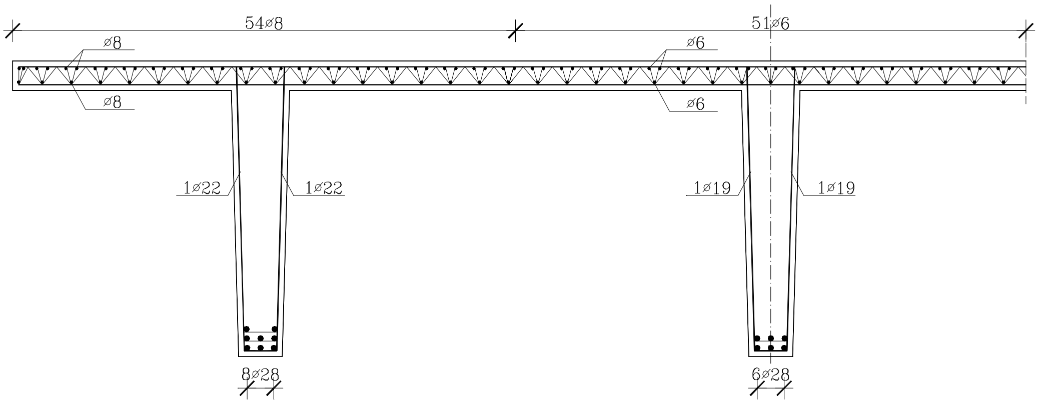
The edge and middle girders are designed with the effective slab width, using a beam model. Transversal distribution of the loading is performed using the influence lines based on Courbon's assumptions (cross girder is absolutely stiff, "eccentric compression method"). Reinforcement of the lightweight main girders is designed as, at least, one truss with *X*-shaped diagonals [2]. Preliminary flexural design of the reinforcement is performed for the reinforced concrete girder. The top reinforcement at the bearing and the bottom reinforcement in the middle–span represents the longitudinal flange reinforcement of the *R* truss. Shear design gives reinforcement of the *X* diagonals of the truss (Figure 4).



a) middle bearing



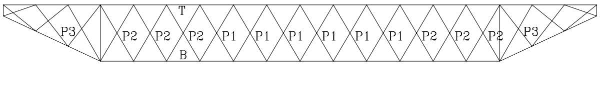
b) middle mid-span



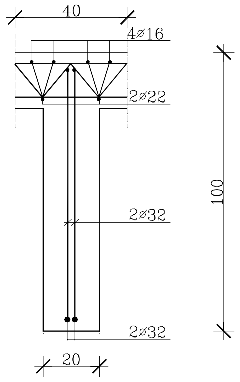
c) edge mid-span

Fig. 4. Reinforcement of the main girders in characteristic cross-sections

The same design method using the influence line is used for the cross girder (Figure 5).



a) Longitudinal section reinforcement



b) Cross-section reinforcement at the bearing

Fig. 5 Reinforcement of the cross girder

Girders are solid but can be modelled as a truss following the reinforcement skeleton with concrete lining (Figure 6). Secondly, the truss design of the reinforcement skeleton is developed, using this preliminary given reinforcement. Flanges and diagonals of the truss are modelled as composite sections made of reinforcement in a concrete body. The design is performed by a computer programme, using the model of a continuous truss. The bottom flanges are given with the concrete section *30×30 cm*, the top flanges with *309×25 cm*, and the diagonals with the concrete section *35×35 cm* with the proper reinforcement area inside the section.

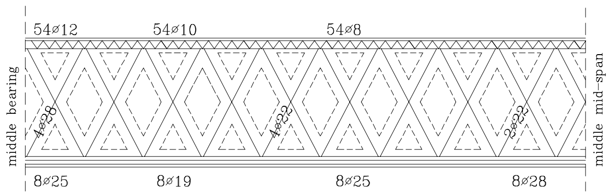


Fig. 6 Longitudinal disposition of the border main girders reinforcement in the middle field

The result are the forces in the flanges and diagonals which are to be less than ultimate forces of the corresponding adequate section composed of lightweight concrete and given reinforcement.

The ultimate longitudinal compressive force of resistance is given by:

$$N_{Rd} = A_c \times 0,85 \times f_{cd} + A_s \times f_{yd} \qquad (1)$$

and the ultimate longitudinal tensile force of resistance by:

$$N_{Rd} = A_s \times f_{yd} \qquad (2)$$

while the ultimate state request is:

$$N_{Sd} \leq N_{Rd} \qquad (3)$$

3. BOX-GIRDER BRIDGE IN LIGHTWEIGHT REINFORCED CONCRETE

The bridge over three spans *40,0+50,0+40,0 m* is formed as a fully reinforced lightweight concrete box girder with thin solid walls and a solid slab. The thickness of the deck slab of the box is *35,0 cm* and the thickness of the walls is *20,0 cm*. A span to height ratio of the bridge structure is *50,0/5,0=10,0* (Figures 7 and 8).

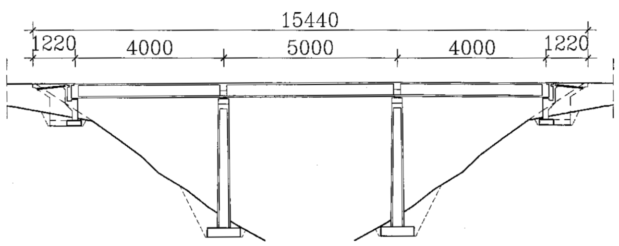


Fig. 7 Box girder bridge: longitudinal section

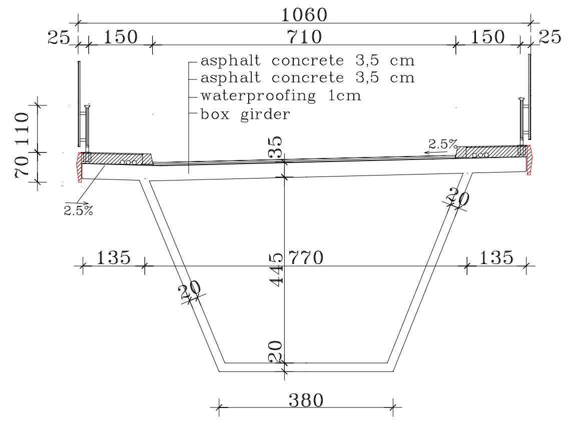


Fig. 8 Box girder bridge: cross-section of the superstructure

3.1 Deck slab

The deck slab of the box girder is reinforced using the same principles as for the deck slab of the overpass.

The flexural design of a roadway slab in transversal direction of the bridge is developed. The model of a beam over one span of *6,0 m* with two cantilevers of *2,2 m* is used. Primarily, the reinforcement is designed for the rectangle section of a beam one meter wide. Alternative design of the top and bottom reinforcement of the slab is performed on the truss model with top and bottom flanges having composite cross-sections.

Top reinforcement at the bearing and the bottom reinforcement in the middle–span remains the same along the slab and represents the longitudinal reinforcement of the *R* truss. In the bottom flange five bars are predicted: *2ϕ28+3ϕ32 /m'*. In the top flange ten bars are predicted: *10ϕ22 /m'*. Moreover, shear reinforcement due to local penetration of the deck slab is designed and represents diagonals of the *R* truss (Figure 9).

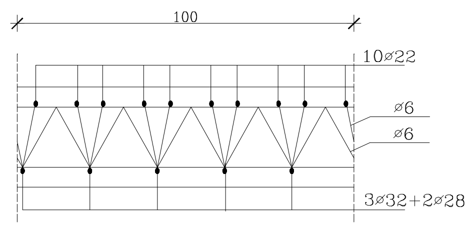


Fig. 9 Slab reinforcement of the box-girder bridge

3.2 Main girders and cross girders

Preliminary flexural and shear designs of the reinforcement are developed for the beam model of the bridge. Three loading positions giving maximal forces are applied.

Position 1 – main line of the traffic scheme is in the middle of the bridge section, continuous traffic load is symmetric – gives maximal flexural moment and adequate transversal force, M_{max} and V_{ad}.

Position 2 – main line of the traffic scheme is by the edge of a roadway curb, continuous traffic load is symmetric – gives maximal transversal force and adequate torsion moment, V_{max} and M_{Tad}.

Position 3 – main line of the traffic scheme is by the edge of a gangway, continuous traffic load is asymmetrical – gives maximal torsion moment and adequate transversal force, M_{Tmax} and V_{ad}.

The main reinforcement of the lightweight walls (bottom flange and webs) is designed as, at least, one truss with *X*-shaped diagonals (Figure 10) [2].

The flexural design gives top reinforcement at the bearing and the bottom reinforcement in the middle–span which represents the longitudinal flange reinforcement of the *X* trusses in the webs of the box. The shear design gives reinforcement of *X* diagonals of the trusses in the webs. The torsion design gives additional longitudinal and transversal (diagonal) reinforcement in the webs and bottom flange of the box (Figure 11).

At the walls connection, reinforcement could be connected with steel plates (Figure 12).

Secondly, the box-girder is designed, using this preliminary given reinforcement. The webs and the bottom flange of the box girder are trusses with composite sections made of reinforcement in a concrete body (Figure 10). The design is performed by a computer programme using the model of a continuous box girder. Diagonals and chords of the trusses in the webs and the bottom flange of the box are given with the concrete section *20×20 cm*. The edge chords of the top flange of the box are given with the concrete section *270×35 cm*, and the middle chords of the top flange are given with the concrete section *500×35 cm* with the adequate reinforcement area. The reinforcement is either a single reinforcement or a linearly widespread one (Figure 13).

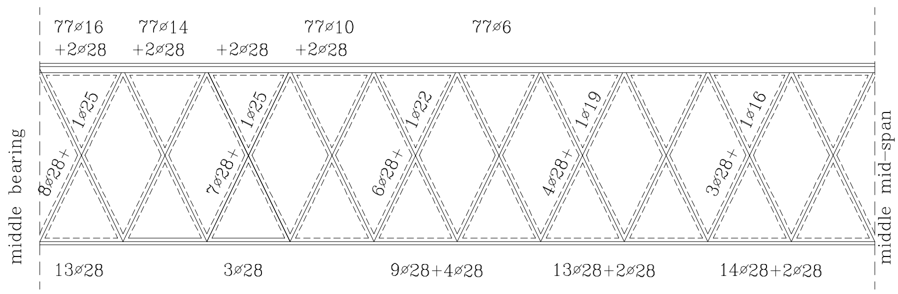
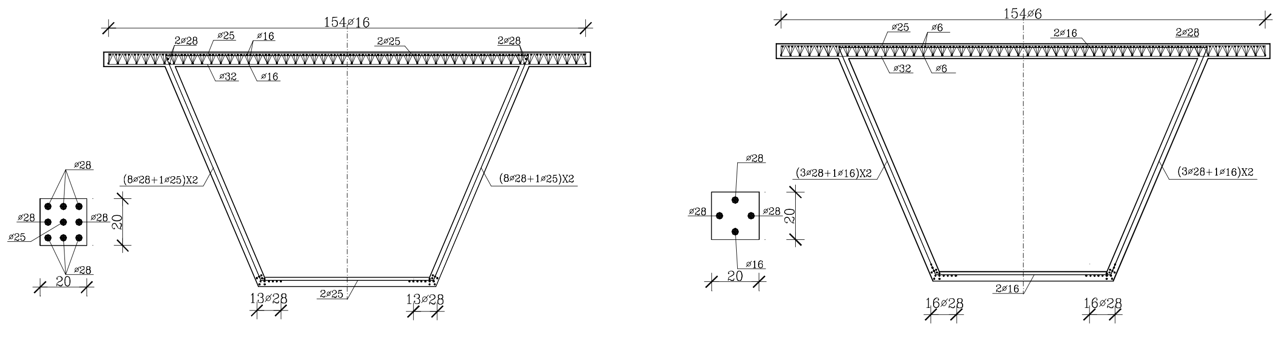


Fig. 10 Longitudinal disposition of the web reinforcement



a) middle bearing *b) middle mid-span*

Fig. 11 Box girder reinforcement in characteristic cross-sections of the bridge

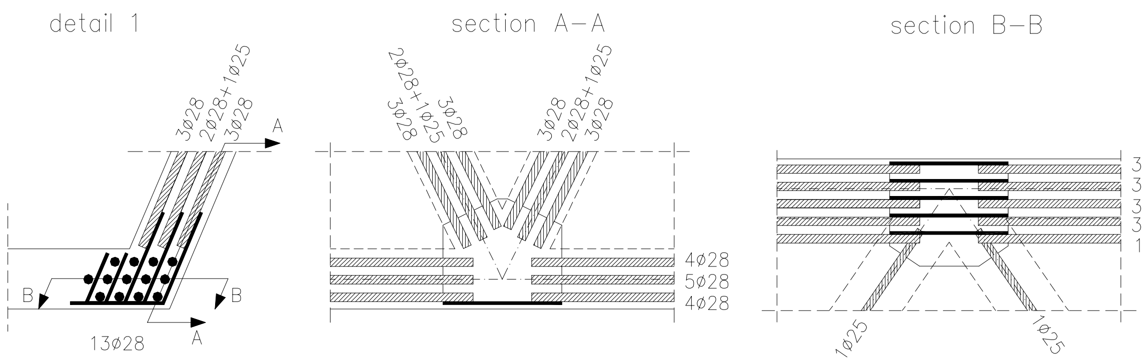


Fig. 12 Steel plates for reinforcement connection

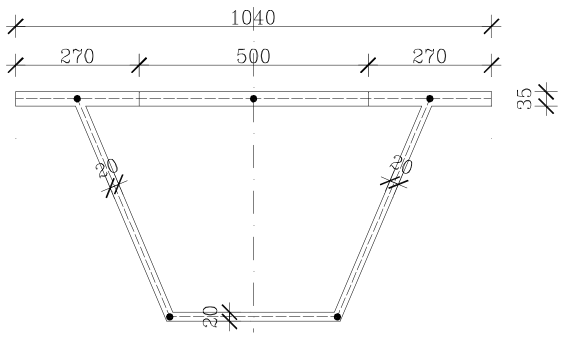


Fig. 13 Skech of the cross-section of the box modell

The result are the forces in the flanges and diagonals which are weaker than the ultimate forces of the corresponding adequate section composed of lightweight concrete and the given reinforcement.

The ultimate longitudinal compressive force is given by Eq. (1), the ultimate longitudinal tensile force of resistance by Eq. (2) and the ultimate state request by Eq. (3).

The cross sections of the chords mainly satisfy the ultimate state request. The sections are appropriately reinforced.

4. DEFLECTION EVALUATION

The deformability of fully reinforced lightweight concrete structures depends mainly on the reinforcement skeleton. When a typical fully reinforced girder is dominantly under flexion, deformation could be monitored on the truss model. Participation of the lightweight concrete body alongside the bars can be considered. The absence of lightweight concrete body will give slightly larger deformations and deflections.

Deflections are computed for one girder of the overpass on the previously described continuous truss model with bottom and top flanges and diagonals modelled as lightweight concrete section with the proper reinforcement area inside the section. For the box shape bridge previously described a continuous box girder model with a bottom flange and webs of the box as trusses is used.

The serviceability limit design gives maximum deflections. The elasticity modulus for lightweight concrete [7] is used:

$$E_{cm} = 9500\left(f_{ck}+8\right)^{1/3} \cdot \left(\frac{\rho}{2200}\right)^2 = \\ = 9500\left(4+8\right)^{1/3} \cdot \left(\frac{900}{2200}\right)^2 = 3640\ N/mm^2 \quad (4)$$

The maximum short-time deflection of the overpass in the centre of the middle-span is:

$$f_{st} = f_g + f_p = 5{,}37 + 18{,}31 = 23{,}68\ mm \quad (5)$$

The maximum short-time deflection of the bridge in the centre of the middle-span is:

$$f_{st} = f_g + f_p = 52{,}31 + 65{,}08 = 117{,}39\ mm \quad (6)$$

Lightweight concrete creeps more than normal concrete, but elastic deformations of lightweight concrete are greater, so the ratio of creep and elastic deformations is less for lightweight concrete than for normal concrete.

According to Ref. [1], creep of concrete with the specific weight of $900\ kg/m^3$ can be evaluated as $\varphi(t,t_0)=0{,}6$ so long-term deflections are approximately:

– for the overpass:

$$f_{lt} = 0{,}6 \cdot f_g = 0{,}6 \cdot 23{,}68 = 14{,}21\ mm \quad (7)$$

– for the bridge:

$$f_{lt} = 0{,}6 \cdot f_0 = 0{,}6 \cdot 52{,}31 = 31{,}39\ mm \quad (8)$$

Total deflection is the sum of the short-time and long-time deflections and is smaller than the limited deflection $L_{eff}/250$:

$$f_{tot} = f_{st} + f_{lt} = 23{,}68 + 14{,}21 = 37{,}89\ mm < \\ < L_{eff}/250 = 0{,}7 \cdot 19000/250 = 53{,}2\ mm \quad (9)$$

$$f_{tot} = f_{st} + f_{lt} = 117{,}39 + 31{,}39 = 148{,}78\ mm \approx \\ \approx L_{eff}/250 = 0{,}7 \cdot 50000/250 = 140\ mm \quad (10)$$

The deflection control for the overpass is appropriate, and for the box-girder bridge the difference can be compensated with the higher surpass.

5. APPROXIMATE MATERIAL CONSUMPTION

The reinforcement list was a base for the calculation of the material consumption per square meter of the surface of the fully reinforced lightweight concrete overpass and bridge. Table 1 presents the analogy of material consumption for the fully reinforced lightweight concrete overpass and a typical Croatian reinforced concrete ribbed overpass [3]. Table 2 presents the analogy of the material consumption for the fully reinforced lightweight concrete box girder bridge and prestressed box girder bridge Dobra – Vrbovsko with similar spans [8]. The height of the prestressed box–girder is *4,0 m*.

Table 1. Concrete and reinforcement consumption per square meter of the surface of the overpass

	Fully reinforced lightweight concrete overpass	*Typical Croatian reinforced concrete ribbed overpass*
Concrete volume (m^3)	*302*	*391,3*
Reinforcement per square meter of the surface (kg/m^2)	*74*	*85 – 114*
Concrete quantity per square meter of the surface (m^3/m^2)	*0,44*	*0,57*

Table 2. Concrete and reinforcement consumption per square meter of the surface of the box-girder bridge

	Fully reinforced lightweight concrete box-girder bridge	*Dobra – Vrbovsko bridge*	
		reinfor-cement	*cables*
Reinforcement per square meter of the surface (kg/m²)	*123*	*75*	*23*
Concrete quantity per square meter of the surface (m³/m²)	*0,63*	*0,8*	

6. IDEAS FOR THE TRUSS CONSTRUCTION

The problem of these structural systems represents joining the steel reinforcement to the truss. This paragraph gives some cues for the truss construction possibilities. The bars in the chords, due to variation of profiles, are connected with the lap connection (butt welds are expensive for this kind of structures with numerous joints). Joining diagonals with chords follows the principles of welding the unbroken fill on the chord of *R*-truss. But, diagonal bars have various profiles in some fields of the truss; hence, in order to receive an unbroken fill, the bars are to be welded to each other beforehand. Consequently, diagonals are made as bent bars and set forward to each other (Figure 14).

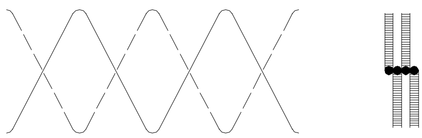


Fig. 14 Diagonals of the truss

Firstly, longitudinal trusses are set. The top flange reinforcement is widespread transversally in the slab so it is to be set afterwards. Currently, the top flange reinforcement consists of constructive bars. At the cross girder position, transversal trusses are pulled into the upper part of longitudinal *X* trusses. Transversal trusses are supported by a crossing point of *X* diagonals (Figure 15). The top flange reinforcement of transversal trusses is, at the same time, the reinforcement of the slab (main reinforcement of transversal flexural design of the slab) so it is to be set afterwards along with the setting of the slab reinforcement. In the current phase of the construction, only two constructive bar profiles represent the top chord of the transversal truss. Just at the end, small trusses of the slab are set; lower *R* trusses of longitudinal direction are pulled into the higher *R* trusses of transversal direction.

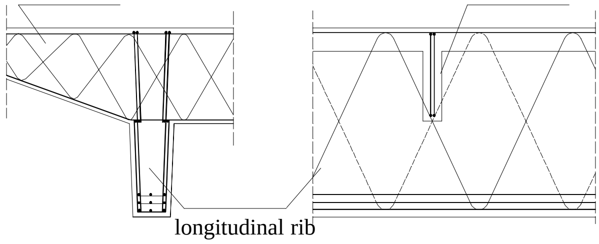


Fig. 15 Setting of longitudinal and transversal trusses

7. DYNAMIC CHARACTERISTICS

Dynamic characteristics of the ligthweight concrete bridge superstructure are examined in order to compare these structures behaviour with the structures made of normal reinforced concrete.

Using the previously described truss model of the lightweight concrete bridge superstructure, the total mass of the structure, frequency and the natural period of the first mode of vibration are computed.

Calculation is also performed for the same model with the replacement of lightweight concrete-LC (with a specific weight *9 kN/m³* and modulus of elasticity *3640 MPa*) by the normal concrete-RC (with a specific weight *25 kN/m³* and modulus of elasticity *30472 MPa*).

The calculated values are given in the Table 3.

Fully reinforced lightweight concrete structures have a considerably smaller stiffness than reinforced concrete structures. Also, with lightweight concrete, the mass is reduced, but not so much as stiffness. The specific ratio of stiffness and mass for lightweight concrete structures decreases in comparison to normal concrete structures. This gives lower frequencies and higher periods of vibration, namely fully reinforced concrete structures are dynamicaly more flexible. Hence, dynamic coefficients are considerably smaller.

Comparison of approximately calculated seismic force according to:

$$S = M \cdot R(T) \tag{11}$$

where *M* is the mass of the structure and *R(T)* is the spectral acceleration of the design spectrum corresponding to the fundamental period (for seismic zone IX and B class of soil) gives:

$$S_{RC} = 1732 \cdot 4{,}8 = 8314\ kN \tag{12}$$

$$S_{LC} = 960 \cdot 3{,}7 = 3552\ kN \tag{13}$$

Seismic loading of the fully reinforced lightweight concrete superstructure, due to smaller dynamic coefficient and reduced mass, is *2,34* times smaller in this example.

Consequently, this also gives larger displacements of the lightweight concrete structure, so for example transversal displacement in the level of the roadway slab for fully reinforced concrete structure is *48 mm*, and for the reinforced concrete structure it is *28 mm*, namely *1,78* times larger.

Table 3. Dynamic characteristics of the bridge superstructure, seismic load and displacements

Superstructure type	Mass (t)	Frequency ω (1/sec)	Period T (sec)	Seismic force S (kN)	Displacement u_y (mm)
RC	1732	3,372	1,863	8314	28
LC	960	2,349	2,675	3552	48

8. CONCLUSION

The utilization of fully reinforced lightweight concrete systems in the bridge design have some advantages and disadvantages. The lightweight concrete body, besides being a secondary bearing material for a local and global stabilisation, has also protection properties in preserving the durability of the main bearing system - the steel reinforcement skeleton.

The low specific weight of the lightweight concrete body yields lower stresses in the main structure and results in less reinforcement and concrete. This fact is obvious in the analogy of material consumption for the fully reinforced lightweight concrete overpass and a typical reinforced concrete ribbed overpass. Concrete saving per square meter of the surface of the bridge is *23%*, and the reinforcement saving is *25%*.

The material consumption for the fully reinforced lightweight concrete bridge over three spans *40+50+ 40 m* is compared with the material consumption of the Dobra-Vrbovsko bridge with similar spans. Concrete saving per square meter of the surface of the bridge is *22%*, and reinforcement saving is a bit more complex, namely cables and reinforcement were used for the Dobra-Vrbovsko bridge.

These structures, in comparison with classical bridge structures in reinforced concrete, are more economical. However, they need higher height to span ratio of the structure and therefore it is important to provide a sufficient traffic profile under the fully reinforced lightweight concrete overpass.

Deflection evaluation is appropriate,but these structures during construction will need higher surpasses.

The problem of these structural systems is represented by the construction of joints. Some cues for the truss construction possibilities are given under paragraph 6. However, this problem is much more complex and it is to be taken into consideration in detail. The rationality and economy of these structures should include the cost of the workmanship.

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KONSTRUKTIVNI SUSTAVI POTPUNO ARMIRANIH LAKOBETONSKIH MOSTOVA

SAŽETAK

U ovom radu razmatra se mogućnost primjene potpuno armiranih lakobetonskih sustava u konstrukcijama mostova. Potpuno armirani lakobetonski sustavi sastoje se od čeličnog armaturnog kostura, kao primarnog nosivog dijela i lakobetonskog tijela kao ispune prostora i sekundarnog nosivog dijela. Ovdje se daju primjeri jednog rebrastog nadvožnjaka preko četiri raspona i jednog sandučastog mosta preko tri raspona. Kolnička ploča armirana je tako da joj armatura formira gusti roštilj nastao od zavarenih nosača postavljenih u dva smjera. Pri tome su zavareni nosači svaki za sebe izrađeni kao zavareni R nosači. Armatura glavnih nosača, poprečnih nosača i stijenki sanduka formira se kao bar jedna rešetka s križnim dijagonalama.

Ključne riječi: *potpuno armirani laki beton, čelični armaturni kostur, armaturne rešetke, rebrasti nadvožnjak, sandučasti most.*