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Procedia Engineering 40 (2012) 125 – 130

Procedia Engineering

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Steel Structures and Bridges 2012

Optimisation of transversal disposition of steel and concrete composite road bridges

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Abstract

The paper deals with optimisation of transversal disposition of steel and concrete composite road bridges in terms of the number of steel beams. For this purpose, a parametric study was performed, in which a total of 32 superstructures of steel and concrete composite road bridges, with different number of steel beams, different road widths and theoretical spans, were modelled and assessed. The reliability verification of the superstructure has been done according to Eurocodes. A result of parametric study is a comparison of advantages of the double-beam and the four-beam variants in terms of material consumption when considering different transverse dimensions and spans of the bridge. The individual variants are compared on the basis of the consumption of structural steel, concrete and reinforcing steel bars.

Keywords: steel and concrete composite bridges, transversal disposition, optimisation

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1. Introduction

Steel and concrete composite bridges represent a very effective type of superstructure for spanning short and middle spans. The concrete slab, which creates a continuous bearing base for carriage way or railway, fulfils at the same time several other functions. By its flexural stiffness in transversal direction, it ensures the cross load distribution to the main steel girders, with which it also cooperates in transferring the load in the longitudinal direction. The slab significantly increases the stiffness of the steel structure in the vertical direction and by its horizontal wall stiffness it also allows to transfer the horizontal load effects (wind, centrifugal forces, braking and acceleration forces or sway forces).

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doi:10.1016/j.proeng.2012.07.067

An economical composite bridge design assumes minimizing the number of steel plate girders. The web contribution to the bending resistance of composite cross section is not generally proportional to the increase of the material consumption due to higher cross sectional area of the steel beam [1]. In the case of railway bridges, two or four steel beams are usually applied under each track. In the case of road bridges, there is a greater variability in this respect. Usually, from 3 to 5 (or more, if appropriate) steel beams are recommended to be applied at axial distances from 2.5 to 3.5 m, depending on the required total width of reinforced concrete slab, which is given by the type (categorical width) and number of transferred communications on the bridge (road, communication for pedestrians and cyclists). The effort to minimize the consumption of structural steel often leads to design of a bridge with only two dominant steel beams at axial distance from 6 to 8 m, or even more, if appropriate. However, the effectiveness of such a proposal may be questionable, because the consumption of structural steel is not the only criterion for the cost-effective design of the bridge object. It can be expected that lower consumption of structural steel will be at the expense of higher consumption of concrete and reinforcement in the reinforced concrete slab. In addition, a smaller number of steel beams will reflect in greater structural height, which is related to the communication vertical alignment, height of the bridge abutments and the embankments behind them.

This paper aims to contribute to the issue of optimising the transversal disposition of composite steel and concrete road bridges with respect to the number of steel beams being applied. The optimisation is based on comparative parametric study taking into account a traditional approach using higher number of girders as well as the currently preferred approach applying the double-beam variant. Different spans of girders, as well as different widths of road communication on the bridge, are considered in the study, in which the consumptions of structural steel, concrete and steel reinforcement are mainly observed. The reliability of superstructures is verified according to Eurocodes.

2. Parametric study

2.1. Disposal arrangement

The bridge structures transferring communications C6.5, C7.5, C9.0 and C11.5 with the theoretical spans 20, 30, 40 and 50 m, respectively, were considered in the parametric study. For illustration, characteristic transversal dispositions of a four-beam and a double-beam variant, respectively, for communication C9.5 are presented in Figure 1. The height of steel beams varies depending on the bridge span. The depth of concrete slab generally depends on the distance between steel girders, as well as on the span length. All the basic disposal parameters, which resulted from structural analyses, are summarised in Table 1. In case of communication C6.5, only three steel beams were used instead of four, since the ineffectiveness of four beams situated too close to each other is obvious.

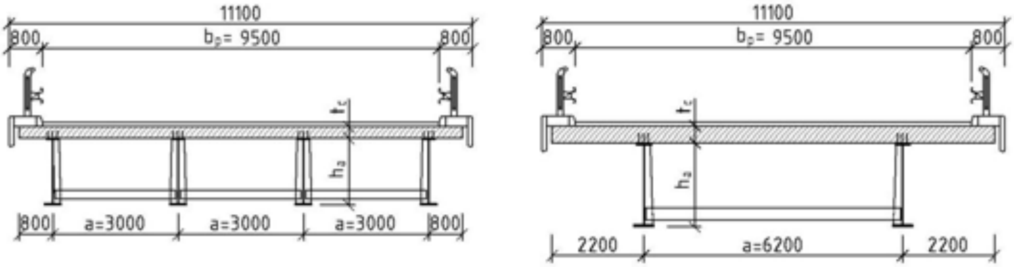

Fig. 1 Transversal disposition of composite bridge transferring communication C9.5 (a) four-beam variant; (b) double-beam variant

Table 1. Basic disposal parameters in transversal direction

Double-beam variant													
Span length		**L = 20 m**			**L = 30 m**			**L = 40 m**			**L = 50 m**		
Communication category	**a (mm)**	**t_c (mm)**	**h_a (mm)**	**h_a/L**	**t_c (mm)**	**h_a (mm)**	**h_a/L**	**t_c (mm)**	**h_a (mm)**	**h_a/L**	**t_c (mm)**	**h_a (mm)**	**h_a/L**
C 6.5	4 600	300	1 500	1/13	290	1 700	1/18	290	2 100	1/19	290	2 600	1/19
C 7.5	4 600	290	1 500	1/13	290	1 800	1/17	280	2 200	1/18	280	2 700	1/19
C 9.5	6 200	400	1 600	1/13	380	2 000	1/15	380	2 500	1/16	370	3 000	1/17
C 11.5	7 700	440	1 700	1/12	440	2 300	1/13	430	2 700	1/15	420	3 000	1/17

Four(triple*)-beam variant													
Span length		**L = 20 m**			**L = 30 m**			**L = 40 m**			**L = 50 m**		
Communication category	**a (mm)**	**t_c (mm)**	**h_a (mm)**	**h_a/L**	**t_c (mm)**	**h_a (mm)**	**h_a/L**	**t_c (mm)**	**h_a (mm)**	**h_a/L**	**t_c (mm)**	**h_a (mm)**	**h_a/L**
C 6.5 *	2 800	250	1 100	1/18	250	1 500	1/20	250	1 900	1/21	250	2 400	1/21
C 7.5	2 500	250	1 100	1/18	250	1 500	1/20	250	1 900	1/21	250	2 400	1/21
C 9.5	3 000	250	1 100	1/18	250	1 600	1/19	250	2 000	1/20	250	2 500	1/20
C 11.5	3 400	250	1 100	1/18	250	1 700	1/18	250	2 000	1/20	250	2 600	1/19

2.2. Structural analysis

Two kinds of spatial computational models were processed for each of 32 bridge superstructures in program SCIA Engineer. The first model was used for local analysis of the reinforced concrete slab, as well as for the global analysis of the composite structure, while the second one was used for analysis of the steel girders in a construction phase. Geometrical schemes and visualizations of both kinds of models are shown in Fig. 2.

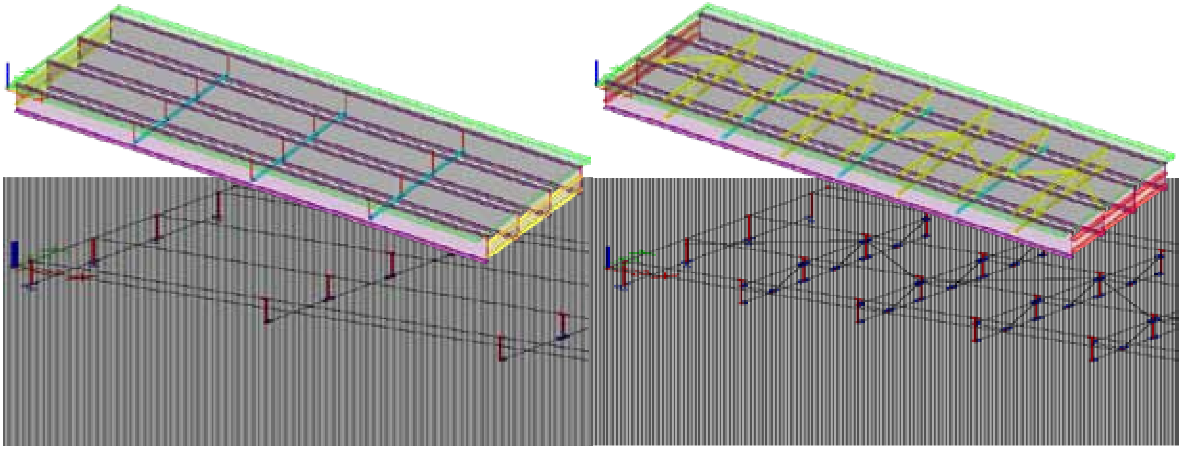

Fig. 2 Computational models: (a) for analyse of composite structure; (b) for analyse of steel girders in construction phase

The concrete slab was modelled in both kinds of models as a plate member of constant thickness, to which the steel girders were put in form of ribs. The transversal stiffeners, situated in the thirds (L=20m), the quarters (L=30m and L=40m) or the fifths (L=50m) of the span, were connected to the ribs by means of rigid arms. The second type of model differed from the first one by additional temporary transversal and longitudinal trussed stiffeners, ensuring the steel girders' stability during construction, and by material characteristics of the concrete slab (higher density and nearly zero modulus of elasticity).

2.3. Dimensioning of main structural elements

The main structural elements, i.e. the concrete slab and the steel girders, were loaded according to the corresponding parts of Eurocode 1 [2-3] and their reliability was estimated according to appropriate parts of Eurocode 2 [4], Eurocode 3 [5-6] or Eurocode 4 [7-8], respectively.

The main tension steel reinforcement in the concrete deck in transversal direction was specified in the middle of the span and at the supports. The concrete strength class C30/37 and steel bars of class B500B were considered in the proposal. The steel beams were proposed from the steel class S355. Firstly, they were estimated in the construction phase as the class 4 cross-sections, taking into account the local buckling of slender webs by means of effective cross-section characteristics. Their resistance to the lateral torsional buckling between the transversal truss stiffeners was determined using the software LTBeam [9]. Finally, the composite cross-section consisting of the concrete slab and the steel beam was estimated. All the proposed composite cross-sections satisfied the criteria for the class 1, and so the full plastic bending resistance could be taken into account in estimating the ultimate limit states. The effects of creep and shrinkage of concrete, as well as the effects of sequence of construction and temperature effects, were neglected. On the contrary, in estimating the composite cross-section at the serviceability limit states, the sequence of construction, as well as the effects of creep and shrinkage of concrete, had to be considered. All the 32 bridge superstructures were dimensioned so their utilization in the most unfavourable location was from 90% to 100%. In the most cases, either the bending resistance of the steel beam in the construction stage or the bending resistance of the composite cross-section in the serviceability limit states was decisive.

2.4. Evaluation of the results of parametric study

Comparison of the observed double-beam and four-beam variants (or triple-beam variant in the case of communication category C6.5) is made with regard to the consumption of structural steel, concrete and steel reinforcement. The consumption of structural steel is characterised mainly by the cross-sectional area of steel beams, whose total values for each considered variant are summarised in Table 2.

Table 2. Cross-sectional area of two beams (A_{a2}) or four (three*) beams (A_{a4}), respectively (m^2)

Span length	**L = 20 m**			**L = 30 m**			**L = 40 m**			**L = 50 m**		
Communication category	**2 beams**	**4(3*) beams**	$\frac{A_{a4}}{A_{a2}}$	**2 beams**	**4(3*) beams**	$\frac{A_{a4}}{A_{a2}}$	**2 beams**	**4(3*) beams**	$\frac{A_{a4}}{A_{a2}}$	**2 beams**	**4(3*) beams**	$\frac{A_{a4}}{A_{a2}}$
C 6.5 *	0,065	0,073	**1,14**	0,100	0,115	**1,16**	0,134	0,159	**1,19**	0,168	0,187	**1,11**
C 7.5	0,071	0,098	**1,38**	0,107	0,150	**1,41**	0,145	0,210	**1,45**	0,179	0,242	**1,35**
C 9.5	0,082	0,109	**1,34**	0,123	0,159	**1,29**	0,170	0,225	**1,33**	0,206	0,247	**1,20**
C 11.5	0,095	0,119	**1,25**	0,139	0,163	**1,17**	0,196	0,236	**1,20**	0,303	0,265	**0,87**

As might be expected, the total cross sectional area of steel beams for the four-beam variant is always higher than in the case of the double-beam variant, with the exception of communication C11.5 transferred over the 50m span. However, it is also obvious that the difference between both the variants, represented by the ratio A_{a4}/A_{a2}, gradually decreases with an increasing communication width. This statement seemingly does not apply for the communication C6.5, but this is caused by the use of three steel beams instead of four, and therefore it can be reasonably expected that this trend would be followed also for this case when using four steel beams. Moreover, in the aforementioned case (C11.5, L = 50m) even lower total cross-sectional area of steel beams was noticed using four beams than at the double-beam variant.

The consumption of concrete is represented by the necessary depth of reinforced concrete slab, which resulted from its proposal in the transversal direction. In the case of multi-beam variants, the depth of slab is constant t_c = 250 mm, regardless of the communication width and the span length. In the case of the double-beam variant, the depth of reinforced concrete slab is always naturally higher and it significantly increases proportionally to the increasing communication width. All the proposed depths of reinforced concrete slab for the double-beam variant are summarised in Table 3. The slight decrease in the necessary depth of slab with an increasing span may be caused by the lower vertical stiffness of the higher steel beams supporting the slab at the abutments, which results in lower negative bending moments in this location. The percentage of the four-beam variant slab depth to the double beam variant is presented in Table 3.

Table 3. The percentage of the four-beam variant slab depth to the double-beam variant

Span length	**L = 20 m**		**L = 30 m**		**L = 40 m**		**L = 50 m**	
Communication category	t_c **(mm)**	$\frac{t_{c4}}{t_{c2}}$	t_c **(mm)**	$\frac{t_{c4}}{t_{c2}}$	t_c **(mm)**	$\frac{t_{c4}}{t_{c2}}$	t_c **(mm)**	$\frac{t_{c4}}{t_{c2}}$
C 6.5	300	**0,83**	290	**0,86**	290	**0,86**	290	**0,86**
C 7.5	290	**0,86**	290	**0,86**	280	**0,89**	280	**0,89**
C 9.5	400	**0,63**	380	**0,66**	380	**0,66**	370	**0,68**
C 11.5	440	**0,57**	440	**0,57**	430	**0,58**	420	**0,60**

Consumption of steel reinforcement is represented by the necessary cross-sectional area of the main tensile reinforcement, which is presented in Table 4. According to these results, it can be stated that the cross-sectional area of steel reinforcement of the four-beam variant represents 60–67% of the cross-sectional area of steel reinforcement of the double-beam variant.

Table 4. Comparison of cross-sectional areas of steel reinforcement

	Cross-sectional area of steel reinforcement ($\cdot 10^{-4}$ **m**^{2}**/m**$^{-1}$**)**											
Span (m)	**L = 20 m**			**L = 30 m**			**L = 40 m**			**L = 50 m**		
Commun. category	**2 beams**	**4(3*) beams**	$\frac{A_{s4}}{A_{s2}}$	**2 beams**	**4(3*) beams**	$\frac{A_{s4}}{A_{s2}}$	**2 beams**	**4(3*) beams**	$\frac{A_{s4}}{A_{s2}}$	**2 beams**	**4(3*) beams**	$\frac{A_{s4}}{A_{s2}}$
C 6.5 *	129,79	82,81	**0,64**	129,79	78,45	**0,60**	124,89	78,45	**0,63**	127,43	78,45	**0,62**
C 7.5	132,34	86,27	**0,65**	128,60	84,26	**0,66**	126,24	78,45	**0,62**	129,98	78,45	**0,60**
C 9.5	155,98	104,26	**0,67**	160,72	99,35	**0,62**	156,70	99,35	**0,63**	156,72	99,35	**0,63**
C 11.5	187,18	117,21	**0,63**	184,63	110,29	**0,60**	181,02	108,28	**0,60**	174,92	110,29	**0,63**

3. Conclusions

This paper deals with optimisation of the transversal disposition of composite steel and concrete road bridges with respect to the number of steel beams being applied. Based on the comparative parametric study, focused on consumption of material, the following conclusions may be deduced:

- From the viewpoint of consumption of structural steel, the double-beam variant is, with one exception, always more favourable than the four-beam variant. However, the difference in consumption of steel for the production of steel beams for individual variants gradually decreases with increasing width of the structure.
- Despite the lower consumption of steel, the double-beam variant does not always have to be more favourable, because of the consumption of concrete and concrete reinforcement, which is always higher in comparison with the multi-beam variant.
- Besides the material consumption also the height of steel beams should be mentioned, which in the case of the double-beam variant ranges from 1/19L to 1/12L, while for the multi-beam variant it ranges from 1/21L to 1/18L. Thus, together with the greater depth of the reinforced concrete slab, the double-beam variant requires the grater structural height than the multi-beam variant.

In conclusion, the results of parametric study can serve as a guide on choosing the optimal transversal disposition of steel and concrete composite bridges. Consumption of material directly affects the cost of building the bridge structure, which is a major factor when choosing the final proposal. However, also other factors, e.g. limited structural height, may need to be taken into account when determining the number of steel beams.

Acknowledgements

This paper presents results of works supported by the Slovak Research and Development Agency under the contract No. SUSPP-0005-07 and by the Scientific Grant Agency of the Slovak Republic under the project No. 1/0364/12.

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