



COMPOSITE BRIDGE DECK SLAB CRACK DESIGN FOR ERECTION WITH PRECAST OMNIA PLATES

Andelko Vlašić, Nijaz Mujkanović, Mladen Srbić, Marija Kušter Marić

University of Zagreb, Faculty of Civil Engineering, Zagreb, Croatia

Abstract

Limiting the crack width in reinforced concrete structures is essential to ensure a durable structure as it prevents accelerated corrosion of the reinforcement. For composite bridges, Eurocode HRN EN 1994-2 defines a very strict condition of a maximum crack width of 0.15-0.2 mm, which must be met for frequent combinations of actions. Since cracks in the deck slab of continuous girder composite bridges are to be expected and are unavoidable in the areas of middle supports, a considerable amount of reinforcement must be installed in a very limited deck slab thickness of only 25 to 30 cm. Depending on the local load bearing plate direction, the deck plate can be subjected to both, a very large longitudinal bending moment derived from the local behaviour, and an axial tensile force derived from the composite action of the main girder. The summation of these internal actions in the areas where the most unfavourable superposition occurs leads to a complex calculation and design procedure, that results in a very large reinforcement area. Omnia panels are often used instead of conventional formwork to enable a faster and more efficient erection process. In this case, additional reinforcement must be placed in the limited in-situ part of the slab thickness to allow a continuous action between the precast elements of the omnia slabs. This paper presents a numerical model investigation of such an example, used to determine the crack reinforcement in a continuous composite girder bridge with a deck slab erected using omnia panels, whose longitudinal load bearing direction coincides with the direction of the main girder span. The derived reinforcement must satisfy the ULD design and SLS crack verification, taking into account both the local behaviour of the deck slab and the global behaviour of the main girder simultaneously.

Keywords: composite bridge, deck slab, omnia panels, crack width, reinforcement

1 Introduction

Bridge composite cross sections allowed for significant savings in steel consumption by employing a concrete deck slab in the load-bearing capacity of the main girder [1]. Thus, with thinner steel plates and a lower girder height, a higher section resistance is achieved than in the earlier historical practice where the concrete deck slab was only used to distribute the local actions on the steel girder.

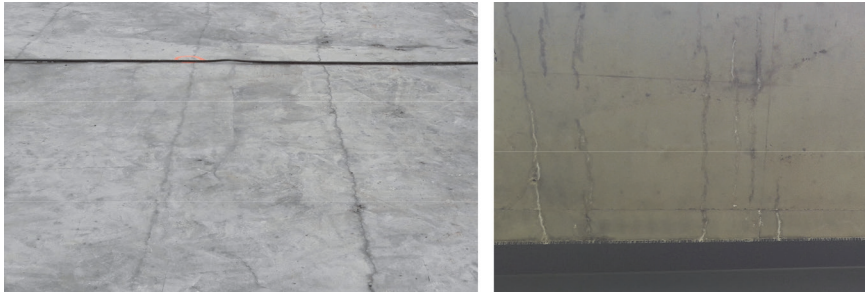


Figure 1 Example of cracks in deck slab of composite bridge to be avoided

Erection of composite bridges also offers advantages over all-steel bridges in terms of labour costs and construction time. All these advantages make composite bridges very competitive solutions in the span range from 20 m to 130 m. One of the main disadvantages of composite bridges is cracking in the deck plate when it is under tension. Depending on the structural system, the level of this tension can be several orders of magnitude higher than the tensile strength of the concrete, meaning that cracking cannot be avoided. This is particularly the case with the most common bridge structural system of a continuous girder, in which composite sections above the column supports are subjected to negative bending moments. The ultimate limit state (ULS) design of such bridges allows and requires that the concrete deck plate is assumed to be cracked, so that both the distribution of internal forces in the girder and the bearing capacity of the cracked sections are calculated disregarding the cracked concrete [2]. Due to this unavoidable cracking, the Eurocode for composite bridges [2, 3] specifies requirements for the serviceability limit state design (SLS) that prevent excessive cracking (Fig. 1). The required reinforcement area to limit the crack width can also be calculated using modern finite element software models, one of which is presented in this paper.

2 Outline of Eurocode crack design for composite bridges

2.1 Concrete cracking prevention

Although the Eurocode SLS design for crack control states that cracking is normal in reinforced concrete, it considers that cracking must be limited to an extent that does not affect the proper function or durability of the structure or make its appearance unacceptable [4]. Thus, the durability of the superstructure, which often has a demanding service life of 80-100 years, can be achieved, which is particularly important in an aggressive environment with sea and/or de-icing salts. Studies and practical examples have shown that a crack in concrete ≥ 0.2 mm can increase the chloride diffusion coefficient by a factor of 100 to 1000 [5, 6]. If the crack has a constant width, the depassivation time can be reduced by a factor of 50 to 100, so it is better if the cracks are shallower and “V”-shaped with the maximum width on the concrete surface. Eurocode offers two approaches for crack control design. In the first, more complex method, the crack widths are calculated according to 7.3.4 of HRN EN 1992-1-1 [4] from the strain in the reinforcement, considering the effects of tension stiffening and the strain of the concrete between the cracks. In the simplified approach control of cracking is controlled by limiting the maximum rebar diameter or spacing depending on the stress in the reinforcement.

2.2 Composite bridges crack design

For composite bridges general considerations from HRN EN 1992-1-1 [4] apply but modified according to HRN EN 1994-2 [2]. Again, either direct calculation of crack widths can be done (as previously defined in [4]), or a simplified conservative method can be used. Crack width w_k limitation may be determined by National Annex. Simplified method consists of ensuring the minimal reinforcement area according to section 7.4.2 (expression 7.1) and maximum bar diameter (Table 7.1) or maximum bar spacing according to section 7.4.3, Table 7.2 (numbering from HRN EN 1994-2 [2]). For minimum reinforcement calculation, maximum stress permitted in the reinforcement immediately after cracking is used, which is dependent on the bar diameter according to Table 7.1. The internal forces for such analysis are determined taking into account effects of cracking of concrete, by reducing section properties to only constructional steel and reinforcement when tensile stress in the concrete is larger than $2 \times f_{ctm}$ for rare combination of actions. The stresses in the reinforcement should be determined taking into account effects of tension stiffening of concrete between cracks according to 7.4.3 (3) [2].

2.3 Croatian National Annex additions

The Croatian National Annex for composite bridges HRN EN 1994-2/NA [3] provides additional requirements and verifications for crack design (Table 1). The limitation of the crack width w_k is set at 0.2 mm and must be satisfied for frequent combinations of actions. Special design requirements are specified for composite tension members ($w_k = 0.15$ mm), such as concrete members with shear connectors only at the ends of the member. The concrete deck plate in composite continuous girders can also be treated as such a tension member if only global actions are considered. In this case, the concrete deck plate acts as an upper flange of the composite girder, thus being in a pure tension stress state for sections with negative bending moment. In this case, the bending of the plate, because of the local plate behaviour in-between the main and cross girder supports, is disregarded. For such global actions only, the requirement is given that crack width of 0.15 mm must be satisfied according to Table 2.1 given in [3]. This table defines the maximum bar diameter depending on the stress in the reinforcement.

Table 1 Overview of HRN Eurocode crack design codes for composite bridges

Composite plate action	Plate internal forces	Crack width limitation [mm]	Design method according to
Global + Local	Axial tension + local bending	0.2	HRN EN 1994-2; 7.4.1, 7.4.2, 7.4.3; exp. 7.2; Table 7.1 and Table 7.2
Global	Axial tension	0.15	HRN EN 1994-2/NA; Table 2.1 (HR)

3 Bridge crack design example

3.1 Superstructure

An example of a crack design is shown for a continuous girder bridge over 4 spans 46 + 58 + 58 + 46 m (Fig. 2). The composite superstructure comprises two 3000 mm high steel girders with a spacing of 8 m and a total width of the bridge deck of 14.85 m. The 280 mm thick reinforced concrete deck is supported by 800 mm high steel cross girders with a longitudinal spacing of 4.0 m. Prior to the SLS crack design, an ULS design was made to determine the dimensions of the main and cross girders and the steel plate thicknesses. Traffic loads were selected according to HRN EN 1991-2 [7] (Load model 1) and HRN EN 1991-2/NA [8] ($\alpha_{Qi} = \alpha_{qi} = \alpha_{qr} = 1$; Load model 3 3000/200 kN vehicle). According to the ULS design, the web thickness of the main girder is between 20 and 28 mm, the top flange is between 1000×25 and 1000×40+900×50 mm and the bottom flange is between 1100×40 and 1100×50+1000×80 mm. The steel material is S355J2+N and the concrete of the deck plate is class C45/55. Due to the large distance between the main girders, the deck slab has predominately longitudinal bearing direction between the cross girders. In such a system, the concentrated double axle loads from the tandem system cause a local longitudinal bending moment in the deck plate, which coincides with the direction of the global bending moment of a main girder in which the deck plate acts in composite action as its upper flange. This is particularly disadvantageous for deck sections above supports, where large tension occurs in the deck plate due to the combined effect of global and local bending.

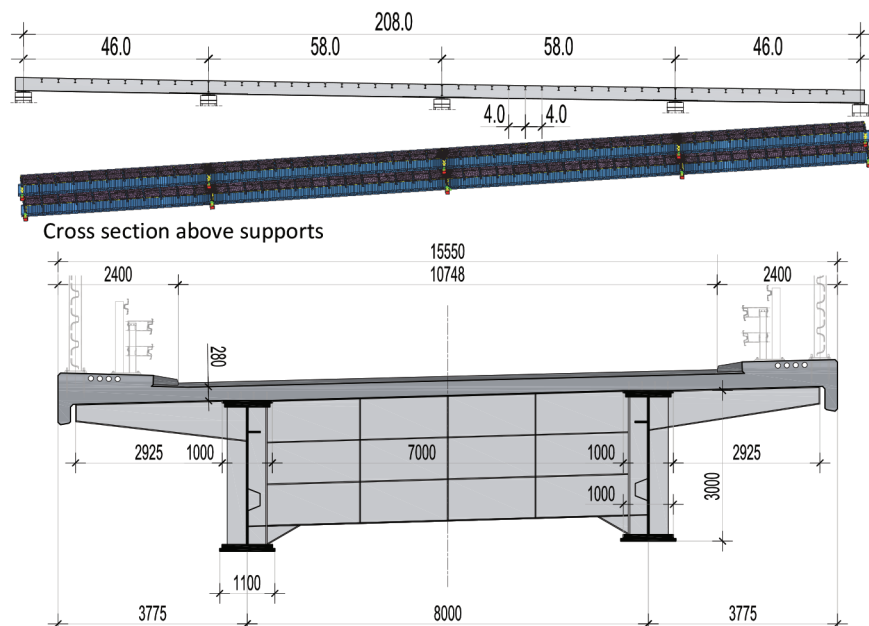


Figure 2 Composite bridge longitudinal and cross sections

3.2 Deck plate erection

Deck plate is erected without formwork using prefabricated 85 mm thick omnia panels and additional 195 mm in-situ concrete with a total thickness of 280 mm, and a length of 384 cm. Omnia panels are produced as an “R” girder, which is intended to bear the load of the in-situ concrete in the longitudinal direction between the cross girders. “R” girder has a height of 135 mm between the upper $\Phi 20$ and the lower $\Phi 25$ reinforcement rebars. The lower rebar is embedded in omnia panel concrete, while the upper is to be reinforcement of the in-situ concrete. A total of 7 omnia panels are used for the width of the bridge, 3 in the middle and 2 on each side. Concrete covers dimensions are calculated in Table 2.

Table 2 Calculation of concrete cover for upper and lower reinforcement zone

Zone	Initial Structural class	Exposure class	100 years life	Concrete class C45/55	Members with slab geometry	Special quality control (omnia)	Design Structural class	c_{min} [mm]	$c_{nom} = c_{min} + \Delta c_{dev}$ [mm]
Upper	S4	XD1	+2	-1	-1	/	S4	35	45
Lower	S4	XD1	+2	-1	-1	-1	S3	30	40

4 Numerical model

Two models were considered for the calculation of the crack control reinforcement. As already discussed, the crack width of 0.2 mm must be satisfied for simultaneous global and local actions, so a more detailed model is required that considers the complex behaviour where the deck plate is subjected to bending when supported by steel girders, but also acts as an upper flange of a composite girder in pure tension (model for global and local actions). Furthermore, for a crack width of 0.15 mm, which is only due to a global behaviour without local bending (if the deck plate is just a pure tension element), the reinforcement stresses must be evaluated, and the maximum rebar diameter of the reinforcement has to be chosen accordingly. For this purpose, another model was considered (model for global actions).

The global model is constructed with plate elements that serve only as a distribution grid for traffic loads, so that the local bending of the plate between the transverse girders is not considered. In this case, the main girders are defined with a composite cross section where the concrete plate acts as the top flange of such a section. Therefore, this plate is a pure tension element above supports (or a compression element at mid-span) for which a crack width limit of 0.15 mm applies. This model is therefore only used to calculate the stresses in the reinforcement, which are then used to limit the rebar diameter. In this particular bridge example, the calculated reinforcement stresses (taking into account the effects of tension stiffening of concrete between cracks) are 130 MPa, for which a maximum bar diameter of $\Phi 25$ is allowed (according to Table 2.1 from HRN EN 1994-2/NA [3]). In this model, cracking in the concrete above supports was considered for sections where the tensile stress is $> 2 \times f_{ctm}$ (up to 8 m on each side of the support) by reducing the cross section properties to steel and reinforcement only.

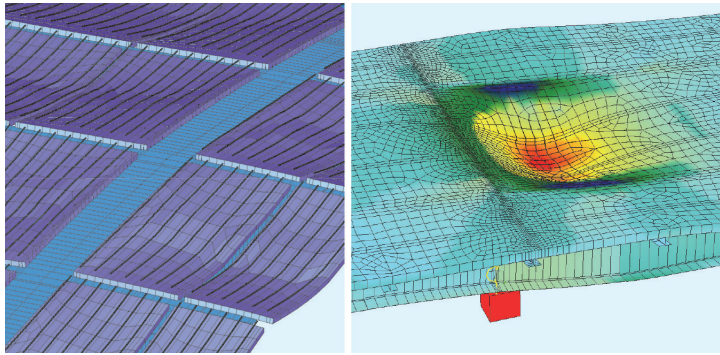


Figure 3 Local actions model: construction stage of placing omnia panels (left); Tandem load main vehicle in the central lane besides the support (right)

A more detailed model was used to consider both the global and local effects on the plate. This model considers area elements for the deck plate defined separately above girders, which are then defined with non-composite cross sections (steel only). A rigid connection is defined between the main/cross girders (beam elements) and the deck plate (area elements) to simulate composite action. The construction stages are also considered, whereby the construction stage in which omnia panels („R“ girders) are simply supported on main/cross girders steel grillage, and then loaded with in-situ concrete is examined separately (Fig. 3 left). Several traffic loading schemes were considered for the finished plate cross section (omnia + cast-in-situ concrete), with the main notional lane in the centre of the bridge (Fig. 3 right), left and right on the carriageway, and in a position with wheels at the edge of omnia panels. The tandem loads were considered in the most unfavourable longitudinal direction. For this local model, the flexural and axial stiffness of the cracked plate above supports (8 m left and right) was reduced to 50% by reducing the modulus of elasticity of the concrete.

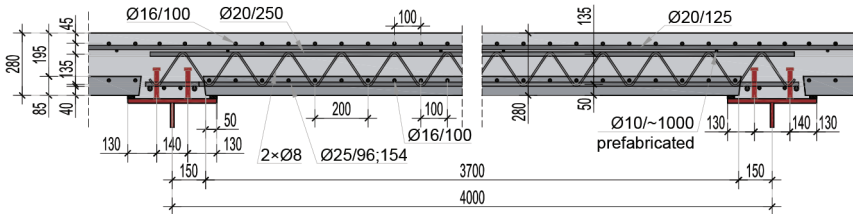
5 Design results summary

The SLS crack design was carried out using Sofistik 2024 area elements design module for frequent combination envelopes, in which the crack width is calculated directly from the material strain, for previously defined reinforcement layers in the longitudinal and transverse directions. The software then automatically increases the reinforcement area in each layer until the desired crack width criterion is met. The diameter and spacing of the reinforcing rebars are then selected for the calculated required reinforcement area, considering the restrictions specified in Tables 7.1 and 7.2 of [2], and Table 2.1 of [3]. The summary of the selected reinforcement is given in Table 3 and Fig. 4 for deck plate above supports (8 m to the left and right of each middle support) and in the middle of the spans. The lower reinforcement zone is embedded in the prefabricated omnia panels, while the reinforcement of the upper zone should be placed on site before in-situ concreting.

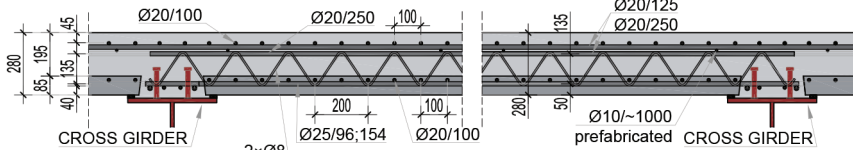
Table 3 Design summary for reinforcement for deck above supports (8 m left and right of supports)

Section	Zone	Direction	Needed reinforcement area [cm ² /m]	Chosen reinforcement
Above support	Upper	Cross	31	Φ20/10 (31.4 cm ² /m)
		Longitudinal	44	2 × Φ20/12.5 (50.3 cm ² /m)
	Lower	Cross	28	Φ20/10 (31.4 cm ² /m)
		Longitudinal	39	Φ25/9.6;15.4 (39.3 cm ² /m)
Total:			428 kg/m ³	
Middle of span	Upper	Cross	20	Φ16/10 (20.1 cm ² /m)
		Longitudinal	29	Φ20/12.5 + Φ20/25 (37.7 cm ² /m)
	Lower	Cross	18	Φ16/10 (20.1 cm ² /m)
		Longitudinal	25	Φ25/9.6;15.4 (39.3 cm ² /m)
Total:			329 kg/m ³	

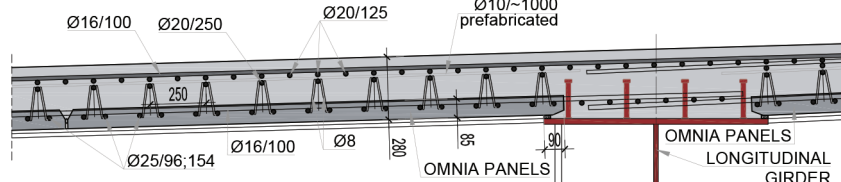
Longitudinal section in the middle of span



Longitudinal section above supports



Cross section in the middle of span



Cross section above supports

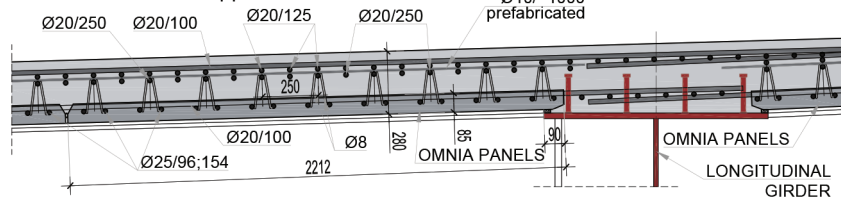


Figure 4 Deck reinforcement details (longitudinal and cross sections)

6 Conclusion

Cracks in the reinforced concrete deck plate of composite bridges are unavoidable, so it is extremely important to comply with SLS crack design to ensure their durability. If the deck plate is subjected to large axial tensile and shear forces due to concentrated vehicle loads (80-90% of deck internal forces derive from live traffic load), the crack width also has a significant effect on its shear resistance. According to the Eurocode and the Croatian National Annex, crack widths of 0.2 mm and 0.15 mm must be satisfied. A special case for such a design is when the deck plate is supported by cross girders, when large bending moments and axial forces occur in the deck slab from both the local and global load bearing system. At the same time, erection method using omnia panels as prefabricated elements is chosen. Due to the limited thickness of the deck plate, these omnia panels must comprise complete reinforcement in the lower zone of the plate. The full ULS and SLS design for such a bridge has shown that a considerable amount of reinforcement must be used for such a deck plate, which can only be attained by using $\Phi 25$ reinforcing rebars for sections above supports. This is also the maximum permissible diameter due to restrictions for 0.15 mm crack width. The diameter and spacing of the deck plate rebars lead to a challenging execution to properly reinforce and concrete the deck plate. Increasing the steel girder top flange area, so that it is comparable to the lower flange area can have a positive effect on reducing the required reinforcement.

References

- [1] Vlašić, A., Srbić, M., Hrelja Kovačević, G.: Comparative analysis and applicability of optimal composite sections for small to middle span girder bridges, 20th IABSE Congress The Evolving Metropolis, Zürich: International Association for Bridge and Structural Engineering (IABSE), 2019. pp. 1270-1274
- [2] HRN EN 1994-2:2012: Eurocode 4 - Design of composite and concrete structures - Part 2: General rules and rules bridges, EN 1994-2:2005+AC2008, Croatian Standards Institute HZN, 2012.
- [3] HRN EN 1994-2:2012/NA: Eurocode 4 - Design of composite and concrete structures - Part 2: General rules and rules bridges – National Annex, Croatian Standards Institute HZN, 2012.
- [4] HRN EN 1992-1-1:2023: Eurocode 2 - Design of concrete structures - Part 1-1: General rules and rules for buildings, Croatian Standards Institute HZN, 2023.
- [5] Kušter Marić, M., Mandić Ivanković, A., Vlašić, A., Bleiziffer, J., Srbić, M., Skokandić, D.: Assessment of reinforcement corrosion and concrete damage on bridges using non-destructive testing, Građevinar, 71 (2019) 10, pp. 843-862, DOI: 10.14256/JCE.2724.2019
- [6] Milić, P., Kušter Marić, M.: Climate change effect on durability of bridges and other infrastructure, Građevinar, 75 (2023) 9, pp. 893-906, DOI: 10.14256/JCE.3756.2023
- [7] HRN EN 1992-2:2023: Eurocode 1 – Actions on structures - Part 2: Traffic loads on bridges and other civil engineering works, Croatian Standards Institute HZN, 2023.
- [8] HRN EN 1992-2:2012: Eurocode 1 – Actions on structures - Part 2: Traffic loads on bridges – National Annex, Croatian Standards Institute HZN, 2012.