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Analysis of effects of shrinkage of concrete added to widen RC girder bridge

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Abstract. Traffic flow capacity of some old road bridges is insufficient due to limited deck width. In such cases bridge deck widening is a common solution. For multi-girder reinforced concrete (RC) bridges it is possible to add steel-concrete composite girders as the new outermost girders. The deck widening may be combined with bridge strengthening thanks to thickening of the existing deck slab. Joint action of the existing and the added parts of such bridge span must be ensured. It refers especially to the horizontal plane at the interface of the existing slab and the added concrete layer as well as to the vertical planes at the external surfaces of the initially outermost girders where the added girders are connected to the existing bridge span. Since the distribution of the added concrete is non-uniform in the span cross-section the structure is particularly sensitive to the added concrete shrinkage. The shrinkage induces shear forces in the aforementioned planes. Widening of a 12 m long RC multi-girder bridge span is numerically analysed to assess the influence of the added concrete shrinkage. The analysis results show that: a) in the vertical plane of the connection of the added and the existing deck slab the longitudinal shear due to the shrinkage of the added concrete is comparable with the effect of live load, b) it is necessary to provide appropriate longitudinal reinforcement in the deck slab over the added girders due to tension induced by the shrinkage of the added concrete.

Keywords: bridge widening; concrete shrinkage; composite action; shear force; finite element method

1. Introduction

Since road traffic become more and more intense some bridges become obsolete due to insufficient traffic flow capacity and/or load carrying capacity. If bridge replacement can be avoided, deck widening is carried out (Modena *et al.* 2015). In the case of box-girder bridges cantilevers are extended and usually supported with added struts (Shushkewich 2003) or ribs (Niwa *et al*. 2016). In the case of multi-girder bridges addition of new outermost girders is a common solution (Hong and Park 2015, Mohammadi *et al*. 2014). It may also improve load carrying capacity especially if its deficiency was caused by deterioration of the existing outermost girders. The added girders may be connected to the existing span structure with cross-bracing (Hong and Park 2015, Mohammadi *et al*. 2014) or cross-beams (Nie *et al*. 2012) or with deck slab only (Wen 2011).

In the case of concrete structures (or structures with concrete deck slabs) it is desirable to construct the widening part of the bridge some time prior to connecting it to the existing deck. In this way, the dead load of the widened part of bridge is supported by itself and-what is even more important-internal forces induced by shrinkage of the added part of the structure are limited. However, this technique is unavailable if the added part cannot exist by itself-for example if only the new outermost girders are added (Mohammadi *et al*. 2014).

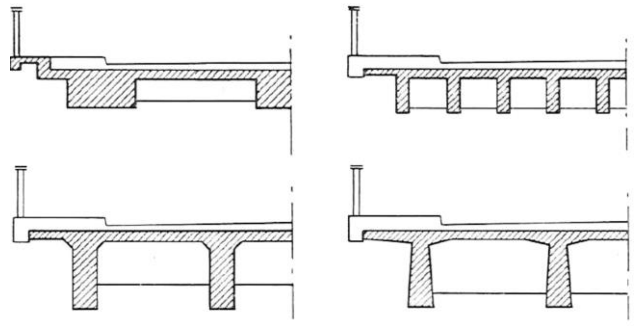

Fig. 1 Cross-sections of RC girder road bridges built in XX century

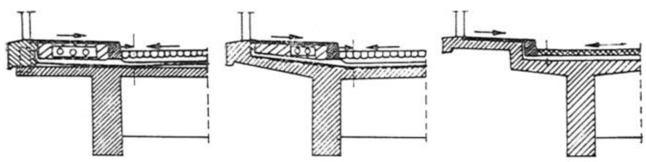

Fig. 2 Arrangements of cantilevers applied in old RC girder road bridges

Majority of road bridges that require deck widening were built in the XX century. Many of them are multi-girder RC bridges. Fig. 1 shows examples of their cross-section and Fig. 2 - various arrangements of cantilevers (Szczygieł 1972). Such bridges may be widened by addition of the new outermost in-situ or precast concrete girders or steel-concrete composite girders. The latter case is preferred due to smaller dead load and easier assembly.

Plate girders - if necessary - can be transported in

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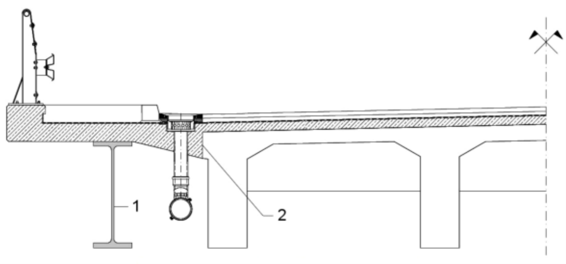


Fig. 3 Widening of RC beam-girder road bridge with additional steel-concrete composite girder: 1 - added beam, 2 - concrete-to-concrete connection (the added concrete is dashed)

segments, spliced on site and placed by crane where required. In-situ concrete girders need formwork while precast concrete girders are limited in span length due to technology and transport conditions. Moreover the plate girders can be used to support the new slab formwork (common solution for steel-concrete composite girders) while application of any concrete girders is likely to need scaffolding and shoring towers to support the formwork.

Widening of an RC multi-girder road bridge by addition of steel-concrete composite girders may be combined with bridge strengthening thanks to thickening of the existing deck slab. Such case is shown in Fig. 3. Joint action of the existing and the added parts of such bridge span must be ensured. Appropriate connection is necessary along the horizontal plane at the interface of the existing slab and the added concrete layer as well as the vertical planes at the external surfaces of the initially outermost girders where the added girders are connected to the existing bridge span.

2. Concrete shrinkage in refurbished bridge spans

Shrinkage of the portion of concrete added in the process of span widening and/or strengthening may have significant influence on internal force distribution yet it is sometimes neglected while designing bridge refurbishment. For cases similar to the one shown in Fig. 3 the shrinkage effects are even more complex due to non-uniform distribution of shrinking concrete in the bridge span cross-section. Finding the magnitude of the effects is critical to design effective and durable connection of the existing and the added parts of the widened and/or strengthened bridge structure.

In the case of the refurbished span shown in Fig. 3 the shrinkage of the added concrete is restrained due to coupling of:

a) the existing RC deck slab and the added concrete layer (Furtak 2012, Niwa 2016),
b) the steel beams and the added concrete slab (Al-Deen *et al*. 2011, Fan *et al*. 2010, Dias *et al*. 2015),
c) the existing RC structure and the added steel-concrete composite girders (Wen 2011).

As stated above all the conditions are reported and investigated in the literature but usually separately. The paper presents the analysis of the shrinkage of the concrete added in the process of span widening in the presence of all of these conditions combined. A multi-girder RC road bridge span is taken as an example.

3. Analysis of effects of shrinkage of added concrete

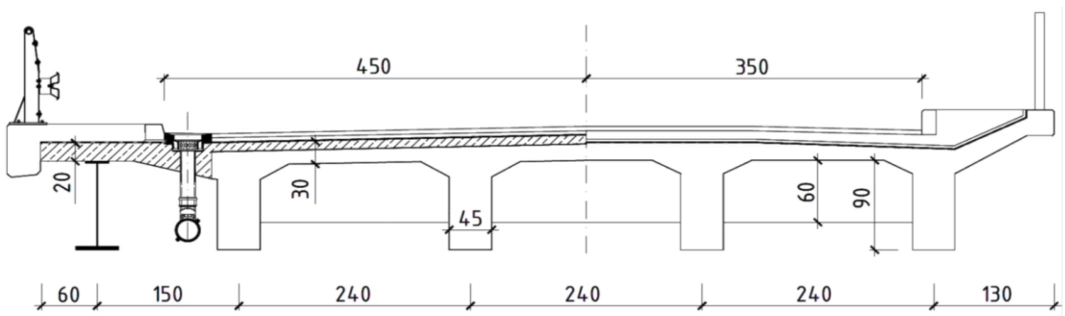
3.1 Analysed structure

Simply supported, 4-girder (prior to widening) RC span of theoretical length L_t=12,0 m is analysed. Its cross-section (based on a real structure) in given in Fig. 4(b). Cross-beams are situated at supports and in the middle of the span. They are rectangular in cross-section, 30×60 cm in dimension. Concrete slab is 20 cm thick with profiling concrete layer on top.

The span cross-section after refurbishment is shown in Fig. 4(a). It is assumed that the refurbishment includes the following:

- removal of existing cantilevers up to the external surface of the initially outermost girders,
- erection of the appropriate support extensions to allow for the added steel girders placement,
- placement of steel girders symmetrically on both sides of the span,
- installation of appropriate anchors in the existing slab and reinforcement of the added concrete,
- casting the new slab over the added steel girders together with the additional concrete layer over the existing deck.

The cross-section of the added steel-concrete composite girder is set in such a manner that its moment of inertia is



(a) (b)

Fig. 4 Cross-section: (a) ½ of refurbished span (the added concrete is dashed), (b) ½ of existing span

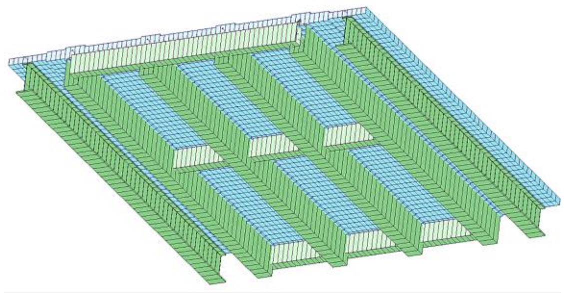


Fig. 5 Bottom view of the FE computational model; note: “beam element profile” and “shell element thickness” options are turned on

similar to the moment of inertia of RC girders after refurbishment.

The deck slab is thickened up to 30 cm (including 18 cm of the existing slab).

There are no cross-beams between the existing and the added parts of the structure - the added girders are connected to the existing structure by the deck slab only.

It was assumed that the existing structure was made out of the B30 class concrete (E_{B30}=31 GPa), and the added structure - of the C30/37 class concrete ($E_{C30/37}$=32 GPa) and S275 grade structural steel (E_{S275}=210 GPa).

3.2 Computational model and scope of analysis

3.2.1 Geometry

Finite element method, widely used for RC structures (Hara 2011, Tian and Li 2016), was applied to analyse the example span. A beam-and-shell element model was created in the Autodesk Robot environment (Fig. 5). RC and steel girder ribs were modelled with 2-node beam elements of 6 degrees of freedom per node while the deck slab was modelled with 4-node shell elements of 6 degrees of freedom per node. Elastic material behaviour and small strains were assumed. Beam and shell elements were situated in the centre plane of the deck slab. Then appropriate OFFSETS were declared for the elements modelling girder ribs to take into account the actual location of their centres of gravity.

3.2.2 Material properties

The value of the elastic modulus of the concrete within the existing part of the structure was set according to PN-EN 1992-1-1. The secant elastic modulus of the concrete after time t=∞ was computed as follows

$$E_{cm}(t) = \left(\frac{f_{cm}(t)}{f_{cm}}\right)^{0.3} \cdot E_{cm} \tag{1}$$

where

$$f_{cm}(t) = \beta_{cc}(t) \cdot f_{cm} \tag{2}$$

and

$$\beta_{cc}(t) = exp\left[s \cdot \left(1 - \sqrt{\frac{28}{t}}\right)\right] \tag{3}$$

where: E_{cm}, f_{cm} - the secant elastic modulus and mean cylinder compression strength of concrete after 28 days, $E_{cm}(t)$, $f_{cm}(t)$ - the values of E_{cm} and f_{cm} after t days, β_{cc} - the coefficient dependent on concrete age t, s - the coefficient dependent on cement type, where s=0.25 for normally hardening cements.

Taking into account Eq. (2), the Eq. (1) may be written as

$$E_{cm}(t) = \left[\beta_{cc}(t)\right]^{0.3} \cdot E_{cm} \tag{4}$$

Under the assumptions that concrete age $t \rightarrow \infty$ and s=0.25, it was obtained that $\beta_{cc}(\infty)$=exp(0.25)=1.284. Hence: $E_{cm}(\infty)=1.284^{0.3} \cdot E_{cm}=1.08 \cdot E_{cm}$.

The analysis of the effects of the shrinkage of the added concrete was carried out under the assumption that creep of the concrete is completed (t=∞). The shell elements modelling the added concrete were characterised with reduced value of elastic modulus. It was computed according to PN-EN 1994-2

$$E_{cm\varphi}(t) = \frac{E_{cm}}{1 + \psi \cdot \varphi(t, t_0)} \tag{5}$$

where: $E_{cm\varphi}(t)$- the secant elastic modulus of concrete after t days, E_{cm}- the secant elastic modulus of concrete after 28 days, ψ- the creep coefficient, $\varphi(t,t_0)$- the creep function.

It was assumed that ψ=0.55. The value of creep function referring to creep completion, on the basis of PN-EN 1992-1-1, is $\cdot\varphi(\infty,t_0)$=1.0. Hence: $E_{cm\varphi}(\infty)=E_{cm}/1.55$.

Finally, for the computational model, the elastic modules of concrete within the existing part (E_{cm1}) and the added part ($E_{cm2\varphi}$) of the structure were assumed as follows: $E_{cm1}=31 \cdot 1.08$=33.5 GPa and $E_{cm2\varphi}$=32/1.55=20.6 GPa.

3.2.3 Loading

The model loading was assumed as total strain of unrestrained shrinkage of the added concrete. It was computed as the sum of the final value of autogeneous shrinkage strain and the final value of drying shrinkage strain.

The final value of the autogeneous shrinkage strain was computed according to PN-EN-1992-1-1

$$\varepsilon_{ca}(\infty) = 2.5 \cdot \left(f_{ck} - 10\right) \cdot 10^{-6} \tag{6}$$

where: f_{ck} - the characteristic cylinder compression strength of concrete after 28 days [MPa]. In the case of the C30/37 concrete: f_{ck}=30 MPa. So, the final value of the autogeneous shrinkage strain equals: $\varepsilon_{ca}(\infty)=5 \cdot 10^{-5}$.

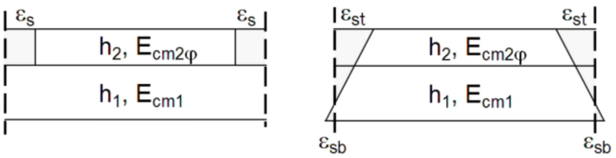
The final value of the drying shrinkage strain was computed according to PN-EN-1992-1-1

$$\varepsilon_{cd,\infty} = k_h \cdot \varepsilon_{cd,0} \tag{7}$$

where: $\varepsilon_{cd,0}$ - the nominal value of unrestrained drying shrinkage strain, k_h - the coefficient dependent on the notional size h_0

$$h_0 = \frac{2 \cdot A_c}{u} \tag{8}$$

where: A_c- the concrete cross-sectional area, u- the



(a) (b)

Fig. 6 Analysis of shrinkage strain in the thickened deck slab: (a) unrestrained shrinkage of the added concrete (ε_s=ε_{cs}), (b) equivalent shrinkage in the thickened slab (existing slab coupled with the layer of added concrete); ε_{st}, ε_{sb}-shrinkage strain at the top and bottom fibres respectively

perimeter of that part of the cross section which is exposed to drying. In the analysed case the nominal value of the unrestrained drying shrinkage strain was assumed as $\varepsilon_{cd,0}$=0.027%. Taking into account an average thickness of the added concrete as d=15 cm, it was computed that h_0=2$\cdot d\cdot B$/(B+2$\cdot d$)≈2$\cdot d\cdot B$/B=300 mm, where: B - the deck slab width. On such basis it was computed that k_h=0,75. So, the final value of the drying shrinkage strain equals: $\varepsilon_{cd,\infty}$=0.75·0.00027≈0.0002.

Finally, the unrestrained shrinkage strain of the added concrete, computed as ε_{cs}=ε_{ca}+ε_{cd}=5$\cdot 10^{-5}$+0.0002≈0.0002, was assumed as the model loading.

In the case of the deck slab connected to the added girders, the concrete shrinkage strain ε_{cs}=0.0002 was taken as uniformly distributed over slab thickness.

In the case of the added concrete layer coupled with the existing slab, to compute shrinkage strain at its top and bottom fibres (ε_{st} and ε_{sb}-see Fig. 6), it was assumed that both are made of such concrete as the existing slab. It was necessary since the two layers of the thickened deck slab had to be modelled with a single layer of shell elements.

To compute shrinkage strain at the top and bottom fibres of the thickened deck slab, an auxiliary coefficient was introduced-the relationship of elastic modules of the existing and the added concrete

$$m = \frac{E_{cm1}}{E_{cm2\varphi}} \cdot \frac{31 \cdot 1.08}{\frac{32}{1.55}} \approx 1.622 \tag{9}$$

where: E_{cm1}-the secant elastic modulus of the existing concrete, $E_{cm2\varphi}$-the secant elastic modulus of the added concrete (creep taken into account).

Equivalent characteristics (A, J) of the thickened deck slab (Fig. 6) were computed as follows:

- the equivalent cross-sectional area of the thickened deck slab of unit width

$$A = h_1 + \frac{h_2}{m} \tag{10}$$

- the distance from the slab centre of gravity to its top fibre

$$z_0 = \frac{h_1 \cdot \left(h_2 + \frac{h_1}{2}\right) + \frac{h_2}{m} \cdot \frac{h_2}{2}}{A} \tag{11}$$

- the equivalent moment of inertia in flexure of the thickened deck slab of unit width

$$J = \frac{h_1^3}{12} + h_1 \cdot \left[z_0 - \left(h_2 + \frac{h_1}{2}\right)\right]^2 + \frac{h_2^3}{12 \cdot m} + \frac{h_2}{m} \cdot \left(z_0 - \frac{h_2}{2}\right)^2 \tag{12}$$

The unrestrained shrinkage of the added concrete implies compression and bending in the thickened deck slab. The equivalent shrinkage strains at its top and bottom fibres (Fig. 6) were computed as follows:

- the shrinkage strain of the thickened deck slab at its top fibre

$$\varepsilon_{2t} = \frac{\varepsilon_s \cdot \frac{h_2}{k}}{A} + \frac{\varepsilon_s \cdot \frac{h_2}{k} \cdot \left(z_0 - \frac{h_2}{2}\right)}{J} \cdot z_0 \tag{13}$$

- the shrinkage strain of the thickened deck slab at its bottom fibre

$$\varepsilon_{1b} = \frac{\varepsilon_s \cdot \frac{h_2}{k}}{A} - \frac{\varepsilon_s \cdot \frac{h_2}{k} \cdot \left(z_0 - \frac{h_2}{k}\right)}{J} \cdot \left(h_1 + h_2 - z_0\right) \tag{14}$$

where: h_1, h_2 - according to Fig. 6, k=1+$\psi\cdot\varphi(t,t_0)$=1.55.

For the analysed case the following strains were obtained: ε_{2t}=-0.000217, ε_{1b}=+0.000064.

Concrete shrinkage was modelled as the equivalent temperature change (Kianousha *et al*. 2008, Ma and Gao 2006). Namely cooling (or heating) was applied to FE elements modelling concrete deck slab, according to the expression

$$\Delta T = \frac{\varepsilon_s}{\alpha_{cT}} \tag{15}$$

where: ΔT-the temperature difference, ε_s-the concrete shrinkage strain, α_{cT} - the coefficient of thermal expansion of concrete, α_{cT}=1$\cdot 10^{-5}$ 1/°C.

The Autodesk Robot allows to specify uniform or non-uniform temperature difference distribution over shell element thickness. In the former case only the temperature difference (heating or cooling) is required. In the latter case the temperature difference refers to the slab centre-plane. Besides, the temperature difference gradient over the slab thickness, taken as temperature difference at its top and bottom fibres, is required. Thus the temperatures at the slab edge fibres are given.

In the analysed case, based on the computed shrinkage strains, the following were obtained:

- for the added deck slab: the temperature difference ΔT=-20℃,
- for the thickened deck slab: the temperature difference ΔT=-7.63℃, the temperature difference gradient ΓT= -28.14℃.

The described modelling of the added concrete shrinkage was applied to analyse its influence on internal force distribution in the deck slab.

3.3 Analysis results

Fig. 7 shows the distribution of longitudinal forces in the deck slab in the vertical cross-section in the middle of

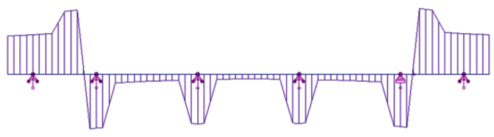


Fig. 7 The distribution of longitudinal forces in the deck slab in the cross-section in the middle of the span (L_t/2); the positive part of diagram (above the horizontal axis) denotes tension; the symbols mark bearings under girders; extreme values of the diagram: -620/+988 kN/m

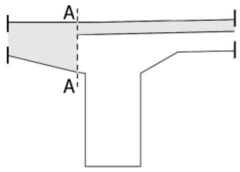


Fig. 8 The initially outermost RC girder; location of the vertical plane (A-A) where the added and existing parts of the structure meet each other (the added concrete is shaded)

the span (L_t/2). Due to the shrinkage of the added concrete the deck slab over the added girders is in tension while the rest of it, within existing part, is in compression. Thanks to large in-plane stiffness of the existing deck slab the compression distribution is similar for all RC girders.

The rapid variation of the longitudinal forces in the deck slab near the plane where the added and existing parts meet each other (section A-A in Fig. 8) generates substantial longitudinal shear forces. They have to be transferred by transverse reinforcement in the added concrete as well as, for example, adhesive anchors installed in the existing slab. Fig. 7 also shows that appropriate longitudinal reinforcement in the deck slab over the added girders (regions in tension in Fig. 7) is required.

Fig. 9 shows the distribution of the longitudinal shear forces in the plane A-A (Fig. 8) along the span. The existing part of the structure restrains the shrinkage of the added concrete. The distribution of the longitudinal shear forces along the span is non-uniform. The extreme shear force occurred near supports reaching almost 640 kN/m. It can be seen that the distribution of the aforementioned reinforcement and adhesive anchors is likely to be non-uniform along the span.

For comparison, the extreme shear force in the A-A plane (Fig. 8) caused by the live load LM1 (α_Q=α_q=1.0), given in PN-EN 1991-1-2, was computed. The presented model was used to set influence line of transverse load distribution for the initially outermost girder. Then the part of the live load carried by the initially outermost girder was computed and 2D analysis of the girder was carried out to find the extreme shear force V (near the support) in the A-A plane. It was found that V≈930 kN/m.

It means that near support the value of the longitudinal shear force due to the shrinkage of the added concrete in the vertical plane where the added and existing parts meet each other (A-A in Fig. 8) is comparable with the value of the force caused by the live load LM1 (α_Q=α_q=1.0). For the analysed span the value of the force due to shrinkage reached almost 70% of the value of the force caused by the

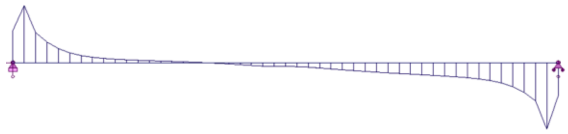


Fig. 9 The distribution of the longitudinal shear forces in the plane A-A (Fig. 8) along the span; the symbols mark bearings at the ends of the span; extreme values of the diagram: -637/+556 kN/m

live load LM1.

It should be noted that for the above analysis the shrinkage strains were computed under the assumption that they are not restrained by reinforcement. The reduction of shrinkage strains due to such restraint may reach 30% (Flaga 2011).

It is important to remember that the computed shrinkage strains are based on the final (the largest) value of the creep function. In time creep reduces advancing shrinkage effects gradually so it is possible that the computed total shrinkage strains may not be the extreme ones.

4. Conclusions

Nowadays some older RC girder road bridges require widening due to insufficient traffic flow capacity. Addition of steel-concrete composite girders offers better time and cost efficiency comparing to application of RC girders. Deck widening can be combined with bridge strengthening due to thickening of the deck slab. The critical issue of such refurbishment is effective and durable connection of the existing and the added parts of the bridge span. The connection must provide reliable transfer of internal forces implied by live load as well as rheology effects, including the added concrete shrinkage.

Based on the presented analysis the following conclusions are drawn:

- due to non-uniform distribution of the added concrete in the span cross-section the refurbished bridge structure is particularly sensitive to the concrete shrinkage,
- in the vertical plane of the connection of the added and the existing deck slab the longitudinal shear due to the shrinkage of the added concrete is comparable with the effect of live load,
- the anchors crossing the aforementioned vertical plane are likely to be non-uniformly distributed along the span due to longitudinal shear concentration near supports,
- it is necessary to provide appropriate longitudinal reinforcement in the deck slab over the added girders due to tension induced by the shrinkage of the added concrete.

The conclusions presented above are valid also for the deck widening completed with the use of precast concrete girders.

References

Al-Deen, S., Ranzi, G. and Vrcelj, Z. (2011), "Shrinkage effects on flexural stiffness of composite beams with solid concrete slabs: An experimental study", *Eng. Struct.*, **33**(4), 1302-1315. https://doi.org/10.1016/j.engstruct.2011.01.007.

Autodesk Robot, https://www.autodesk.com/products/robot-structural-analysis/overview, accessed 28.08.2017.

Dias, M., Tamayo, J., Morsch, I. and Awruch, A. (2015), "Time dependent finite element analysis of steel-concrete composite beams considering partial interaction", *Comput. Concrete*, **15**(4), 687-707. http://dx.doi.org/10.12989/cac.2015.15.4.687.

Fan, J., Nie, X., Li, Q. and Li, Q. (2010), "Long-term behavior of composite beams under positive and negative bending. II: Analytical study", *J. Struct. Eng.*, ASCE, **136**(7), 858-865. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000176.

Flaga, K. (2011), "Naprężenia skurczowe i zbrojenie przypowierzchniowe w konstrukcjach betonowych [Shrinkage stress and subsurface reinforcement in concrete structures]", Seria Inżynieria Lądowa, Monography 391, Politechnika Krakowska. (in Polish)

Furtak, K. (2012), "Ocena wpływu skurczu betonu na wartości naprężeń w płaszczyźnie zespolenia dźwigarów z płyta dwuwarstwową [Assessment of influence of concrete shrinkage on stress at the interface of steel girders and bi-layer slab]", Technical Transactions, Civil Engineering, Issue 21, Year 109, 37-50. (in Polish)

Hara, T. (2011), "Application of computational technologies to R/C structural analysis", *Comput. Concrete*, **8**(1), 97-110. https://doi.org/10.12989/cac.2011.8.1.097.

Hong, S. and Park, S.K. (2015), "Effect of vehicle-induced vibrations on early-age concrete during bridge widening", *Constr. Build. Mater.*, **77**, 179-186. https://doi.org/10.1016/j.conbuildmat.2014.12.043.

Kianousha, M.R., Acarcanb, M. and Ziaria, A. (2008), "Behavior of base restrained reinforced concrete walls under volumetric change", *Eng. Struct.*, **30**, 1526-1534. https://doi.org/10.1016/j.engstruct.2007.10.009.

Ma, B.G. and Gao, Y.L. (2006), "Finite element analysis for shrinkage in the interface of functionally graded concrete segment used shield tunnelling", *J. Wuhan Univ. Technol. (Materials Science Edition)*, **S1**, 98-102.

Modena, C., Tecchio, G., Pellegrino, C., da Porto, F., Zanini, M. and Donà, M. (2015), "Retrofitting and refurbishment of existing road bridges, in Maintenance and Safety of Aging Infrastructure", *Mainten. Saf. Ag. Infrastr.*, 469-533.

Mohammadi, A., Yakel, A. and Azizinamini, A. (2014), "Phase and Widening Construction of Steel Bridges", FDOT Research Project Number BDK80-977-28, Department of Civil and Environmental Engineering, Florida International University, Miami, Florida.

Nie, J.G., Wang, Y.H., Zhang, X.G., Fan, J.S. and Cai, C.S. (2012), "Mechanical behavior of composite joints for connecting existing concrete bridges and steel-concrete composite beams", *J. Constr. Steel Res.*, **75**, 11-20. https://doi.org/10.1016/j.jcsr.2012.02.019.

Niwa, J., Matsumoto, K., Sato, Y., Yamada, M. and Yamauchi, T. (2016), "Experimental study on shear behavior of the interface between old and new deck slabs", *Eng. Struct.*, **126**, 278-291. https://doi.org/10.1016/j.engstruct.2016.07.063.

PN-EN 1991-2:2007 Eurocode 1: Actions on Structures, Part 2: Traffic Loads on Bridges. (in Polish)

PN-EN 1992-1-1:2008 Eurocode 2: Design of Concrete Structures, Part 1-1: General Rules, and Rules for Buildings. (in Polish)

PN-EN 1994-2:2010 Eurocode 4: Design of Composite Steel and Concrete Structures, Part 2: General Rules and Rules for Bridges. (in Polish)

Shushkewich, K. (2003), "The strutted box widening method for prestressed concrete segmental bridges", *PCI J.*, **48**(6), 64-81.

Szczygieł, J. (1972), "Mosty z betonu zbrojonego i sprężonego [Bridges of reinforced concrete and prestressed concrete]", Warszawa, WKŁ. (in Polish)

Tian, H. and Li, F. (2016), "Probabilistic-based prediction of lifetime performance of RC bridges subject to maintenance interventions", *Comput. Concrete*, **17**(4), 499-521. https://doi.org/10.12989/cac.2016.17.4.499.

Wen, Q.J. (2011), "Long-term effect analysis of prestressed concrete box-girder bridge widening", *Constr. Build. Mater.*, **25**, 1580-1586. https://doi.org/10.1016/j.conbuildmat.2010.09.041.

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