EXPERIMENTAL DETERMINATION OF TORSIONAL STIFFNESS IN RIBBED BRIDGE DECK

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Abstract

A ribbed bridge decks will structurally behave as a grillage. A grillage has an efficient transverse load distribution, as well as transverse displacement distribution, due to transverse asymmetric load. In the case of bridge deck without diaphragms in the span, transverse load distribution depends on the torsional stiffness of longitudinal girders, diaphragms and deck slab. In standard bridge on-site testing, it is common to measure vertical displacements in the middle of the span and over the supports due to transverse symmetric and asymmetric static loading. A deflection in the middle of the span can be defined from the measured displacements in the middle of the span and over the supports. The results of the on-site testing on nine bridges were collected and used in this paper. The numerical results were calculated on three computational models which differ in torsional stiffness only for each single bridge. In this paper, experimental determination of torsional stiffness of bridge deck elements is carried out by using on site measured bridge deck deflection due to transversal asymmetric loading and adequate computational grillage models. Based on the conducted analyses, the coefficient of torsional stiffness reduction for verification of the serviceability limit state according to Annex C of EN 1990: 2000 is determined. The same coefficient is calculated using recommendation for torsional stiffness reduction in concrete elements defined by Model code CEB-FIB 1990 (MC 90). According to conducted analyses the design value of the coefficient of torsional stiffness reduction for verification of the serviceability limit state is proposed.

Keywords: ribbed bridge decks, torsional stiffness reduction

1 Introduction

Structurally, ribbed bridge decks made up of longitudinal girders fitted for prefabrication, transverse beams (diaphragms), and a deck slab will behave as a grillage. In the case of relatively stiff diaphragms placed over supports and in the span, the transverse load distribution mostly depends on the bending stiffness of the diaphragms. In some bridges the diaphragms may be omitted for reasons of simplicity of bridge deck construction. Anyhow, diaphragms should be always placed at two ends of the span. A bridge deck without diaphragms in the span has a less efficient, but still significant transversal load distribution achieved by diaphragms over supports and the deck slab composed with longitudinal girders. In this case, the contribution of the torsional stiffness of the longitudinal girders, diaphragms and deck slab on the transverse load distribution, as well as transverse displacement distribution, is significant. The torsional stiffness of a concrete element decreases drastically once cracking occurs. However, if the longitudinal girders are prestressed (in most cases) there are no cracks in the serviceability state. Usually, no significant crack occurs in the serviceability state even in transverse beams or the slab. The influence of the torsional stiffness on transverse displacement distribution is investigated in this paper.

2 On-site testings

On-site testing has been carried out on nine bridges, namely:

1 The bridge over the river Kupa near Jamnička Kiselica [1]
2 The bridge Strug near Bročice [2]
3 The bridge Slakovci – Otok over the river Bosut [3]
4 The bridge Vinično over the highway Zagreb – Varaždin – Goričan [4]
5 The bridge over the river Sava in Brod - south bridge [5]
6 The bridge over the river Sava in Brod - central bridge [5]
7 The bridge over the river Sava in Brod - north bridge [5]
8 The bridge Golubinjak on the highway Rijeka – Zagreb [6]
9 The bridge Vrata 1 on the highway Rijeka – Zagreb [7]

Vertical displacements were measured under static loading for different load schemes in several longitudinal measuring lines in the middle of the span and over the supports. Measuring lines positions in the cross-section and measuring points in the longitudinal view over the river Kupa near Jamnička Kiselica are shown in Figs. 1 and 2. Deflection in the middle of the span is calculated from vertical displacement in the middle of the span and vertical displacement at the nearest supports. [1-7]
In this paper, only the deflections measured in transverse asymmetric loading schemes are used to analyse the transversal displacement distribution.

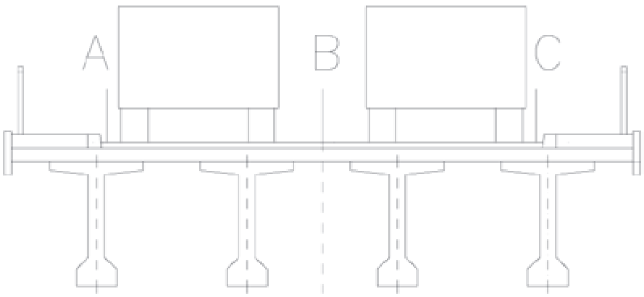

Figure 1 The measuring lines A, B and C in the bridge cross-section.

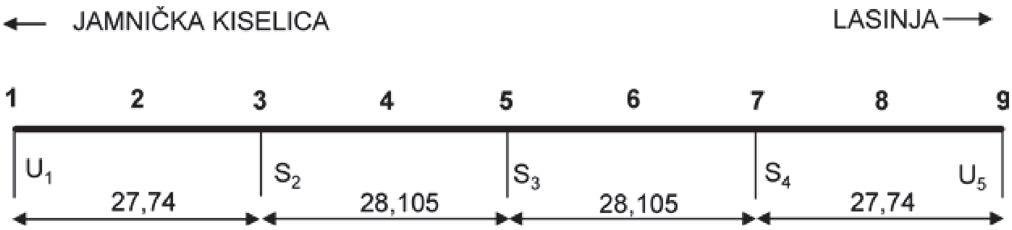

Figure 2 The measuring points 1-9 in the longitudinal bridge view.

3 Computational models

Theoretical displacements were calculated for each tested bridge by using three computational models. Computational models differ only in value of torsional moments of inertia according to Table 1.
It_o, torsional moments of inertia in plates, longitudinal girders and diaphragms are determined according to elements dimensions in design documentation. [1-7]
In this paper, torsional stiffness is represented by torsional moments of inertia. This can be done in the case where the whole element has the same material property as it is the case in analysed bridges.

Table 1 Torsional moments of inertia in bridge deck elements.

MODEL	TORSIONAL MOMENTS OF INERTIA IN ELEMENTS		
	PLATES	LONGITUDINAL GIRDERS	DIAPHRAGMS
1	It_0	It_0	It_0
2	$0{,}5It_0$	$0{,}5It_0$	$0{,}5It_0$
3	0	0	0

4 Transverse displacement distribution

Measured displacements are compared with theoretical ones. The transverse distribution coefficients are introduced to simplify the analysis [8].
The transverse distribution coefficient α_c represents deviation of theoretical middle span displacement at measuring point nearest to the loaded bridge edge to a mean value of theoretical middle span displacements at all measuring points in the cross-section for asymmetric bridge loading. The transverse distribution coefficient α_t represents deviation of measured middle span displacement at measuring point nearest to the loaded bridge edge to a mean value of measured middle span displacements at all measuring points in the cross section for asymmetric bridge loading. α_{tm} is a mean value of α_t for all bridge spans.
According to conducted analysis [8] the ratios of the transverse distribution coefficients α_{tm}/α_c in the relation to the ratios of torsional stiffness It/It_o are shown in Fig. 3 to Fig. 7. The ratios α_{tm}/α_c were calculated for $It/It_o=1$, $It/It_o=0{,}5$, $It/It_o=0$. Linear interpolation was employed to get values α_{tm}/α_c for other torsional stiffness ratios. The ratio $\alpha_{tm}/\alpha_c=1$ describes equality of transverse displacement distribution for tested bridge and a computational model. Using this fact it is easy to determine the value of torsional stiffness ratio which has to be used in computational model to satisfy the criterion of the equality of transverse displacement distribution for tested bridge and the computational model.

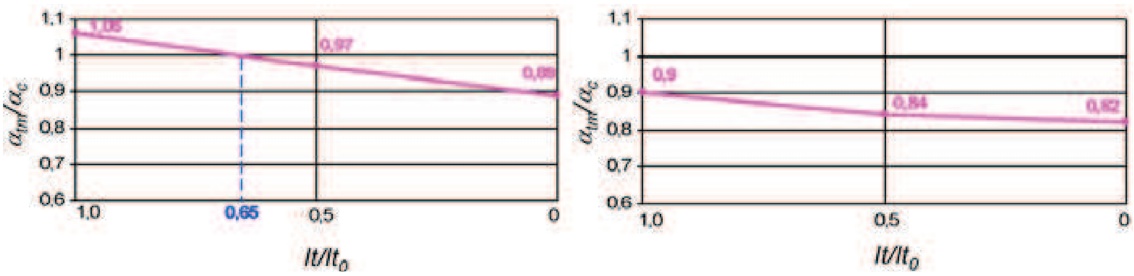

Figure 3 Left: The bridge over the river Kupa near Jamnička Kiselica; Right: The bridge Strug near Bročice.

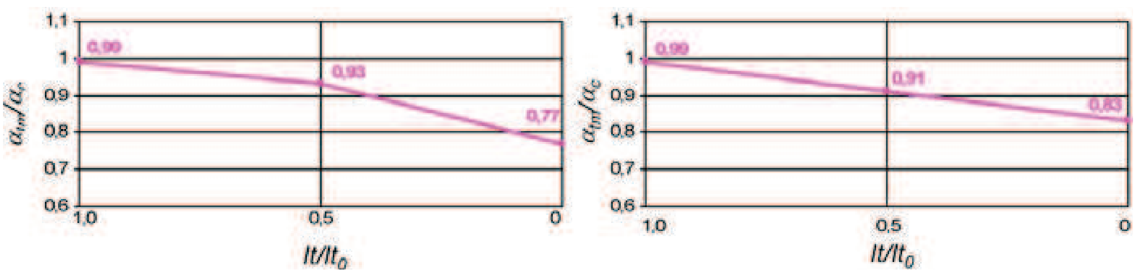

Figure 4 Left: The bridge Slakovci – Otok over the river Bosut; Right: The bridge Vinično over the highway Zagreb – Varaždin – Goričan.

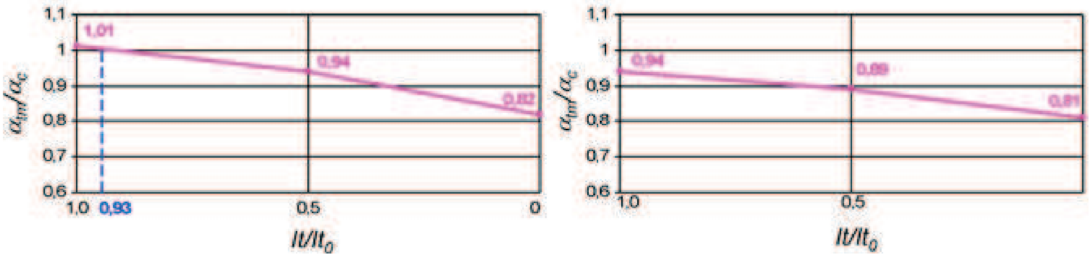

Figure 5 Left: The bridge over the river Sava in Brod - south bridge; Right: The bridge over the river Sava in Brod - central bridge.

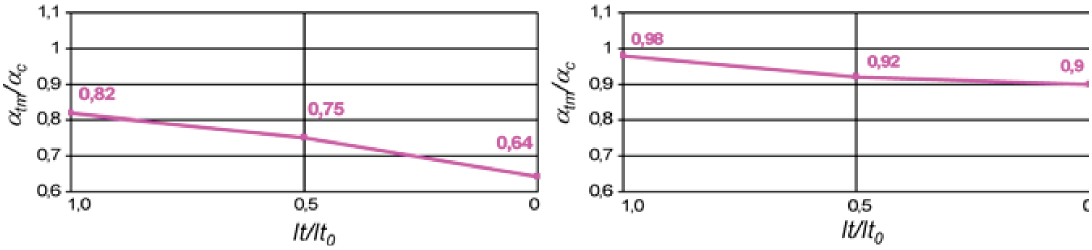

Figure 6 Left: The bridge over the river Sava in Brod - north bridge; Right: The bridge Golubinjak on the highway Rijeka – Zagreb.

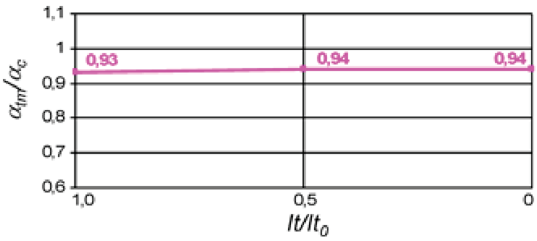

Figure 7 The bridge Vrata 1 on the highway Rijeka – Zagreb.

5 Evaluation

In cases where $\alpha_{tm}/\alpha_c > 1$ for $It/It_o = 1$ the values It/It_o for $\alpha_{tm}/\alpha_c = 1$ will be determined by using linear interpolation as it is shown in Fig. 2. and Fig. 4.

$It/It_o = k_t$ is a coefficient of torsional stiffness reduction determined from criterion that tested bridge and the computational model have equal transverse deflection distribution ($\alpha_{tm}/\alpha_c = 1$). For some bridges, there is determined that the real torsional stiffness of elements is greater than the calculated one (in the cases where $\alpha_{tm}/\alpha_c < 1$ for $It/It_o = 1$). The reasons for this behaviour may be different: (a) the dimensions of constructed elements are greater then the ones in the project documentation, (b) in the computational model, the stiffness of non-structural elements (pavement, concrete fences, asphalt,...) is not included, (c) the supports are not ideal as they are modelled. In this cases $k_t = 1$ will be taken for further analysis. It will be unreasonable to take greater torsional stiffness then the one predicted in the design documentation. The experimental determined coefficients of torsional stiffness reduction are shown in Table 2.

Table 2 The coefficients of torsional stiffness reduction k_t.

Bridge	1	2	3	4	5	6	7	8	9
$k_t = It/It_0$	0,65	1,0	1,0	1,0	1,0	0,93	1,0	1,0	1,0

The design value of the coefficients of torsional stiffness reduction for serviceability limit state (SLS) will be determined by using EN 1990:2000 (Annex C). The target value for reliability index β for SLS and for reference period of 50 years is *1,5*. The uncertain basis variable in our case represents modal uncertainties (uncertainties of torsional stiffness). The value of the sensitivity factor for the uncertain basis variable for resistance, a_R, determined according to EN 1990 is *0,8*.
The design value of the coefficients of torsional stiffness reduction with assumption of normal probability distribution for huge number (*n>30*) of independent measured data can be derived from next equation:

$$k_{td,s} = k_{tm} - \alpha_R \cdot \beta \cdot \sigma \tag{1}$$

where :
λ_n - the fractile factor
s_n – the standard deviation the coefficients of torsional stiffness reduction based on the sample.
The standard Bayesian prediction formula and Student's t-distribution were used to compute

$\lambda_n = 1{,}357$.

Then:

$$k_{td} = 0{,}953 - 1{,}357 \cdot 0{,}116 = 0{,}796 \tag{3}$$

According to Model code CEB–FIB 1990 (MC 90) the torsional stiffness K per unit length is defined as follows:

$$K_I = \frac{0{,}30 E_{cm} \cdot It_0}{1 + 1 \cdot \varphi} \tag{4}$$

$$K_{II} = \frac{0{,}10 E_{cm} \cdot It_0}{1 + 0{,}3 \cdot \varphi} \tag{5}$$

$$K_{III} = \frac{0{,}05 E_{cm} \cdot It_0}{1 + 0{,}3 \cdot \varphi} \tag{6}$$

where:
K_I - the torsional stiffness in stage I, uncracked
K_{II} - the torsional stiffness in stage II, cracked
K_{III} - the torsional stiffness in stage II, torsional and shear cracks
E_{cm} - the modulus of elasticity of concrete
It_o - the torsional moment of inertia in uncracked stage
φ - the creep coefficient to be used for long term loading.

On the basis of the results of testing, applied testing loads and according to the fact that longitudinal girders are prestressed we can conclude that no cracks occur in elements during the testing. The creep coefficient determined for short-term testing is $\varphi = 0$. According to previous facts the Eq. (4) is:

$$K_I = 0{,}30 E_{cm} \cdot It_0 \tag{7}$$

The torsional stiffness per unit length according to the theory of strength of material is:

$$K_t = G \cdot It \tag{8}$$

Using analogy in Eqs. (7) and (8) it can be seen that in MC 90

$$0{,}3 \cdot E_{cm} = G \tag{9}$$

As it is known from the theory of concrete structures, the shear modulus is approximately determined as $G = 0{,}4E_{cm}$. This value is greater then the one in Eq. (9).
Based on this consideration it is obvious that MC 90 has introduced the torsional stiffness reduction even for uncracked elements. In MC 90, there is a quotation: “In the expression for KI the factor 0,30 takes account of the non-linear behavior of concrete before cracking.” It leads to the conclusion that the design value of the coefficients of torsional stiffness reduction for uncracked elements according to MC 90 is

$$k_{td,s} = \frac{0{,}30}{0{,}40} = 0{,}75$$

This value is similar to the value in Eq. (3).
The proposed value $k_{td,s}$ is 0,75.

6 Conclusion

In this paper the design value of the coefficient of torsional stiffness reduction for verification of the serviceability limit state based on experimental research and MC90 recommendation is proposed. As it is known that the torsional stiffness of a concrete element decreases drastically once cracking occurs authors proposed two computational models for limit states verification, one for SLS and the other for ULS.

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