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UPDATING MATERIAL FACTORS FOR ASSESSMENT OF HISTORIC REINFORCED CONCRETE BRIDGE

Abstract

This paper is focused on the reliability analysis of an existing reinforced concrete bridge from 1908. The load bearing capacity is assessed in accordance with valid standards using updated partial factors and the partial factors for structural design. Load bearing capacities obtained by these methods are critically compared. The application of the updated partial factors leads to 15 % higher load bearing capacity than the ordinary partial factor method used for structural design.

Keywords

Concrete bridge, load bearing capacity, partial factors and target reliability.

1 INTRODUCTION

More than 50 % of investments in construction are related to existing structures. This ratio is even greater in bridge engineering due to continuous degradation, ever increasing traffic intensities and general lack of financial resources for rehabilitations of bridges. That is why effective assessment of the load bearing capacity of existing bridges is becoming a crucial issue. In regard to this the present study is aimed at the assessment of historic reinforced concrete bridge and at the comparison results obtained by the partial factor method used for structural design and updated partial factor method.

Final report COST Action [1] estimates that more than million bridges exist in the 27 European countries and it represents approximately 400 billion Euros of replacement costs. Therefore, even small improvements in the methodology of assessment could lead to substantial savings. The qualified decisions about replacement or upgrade of bridges should be based on the available information and actual state of the bridge, unfavourable effects of environment and potential consequences due to malfunction of the bridge.

The case study is focused on the bridge built in 1908. The bridge is chosen on the basis of complexity of available information about geometry and material properties. A simple structural system - the reinforced concrete girder bridge with a single span –makes it possible to show clearly application and critical comparison of load bearing capacities obtained by applied methods.

The assessment is based on verification of bending moments as information concerning shear reinforcement is missing. However, the benefit of using updated partial factors is foreseen to be similar as in the case of bending moments.

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2 ASSESSMENT OF EXISTING BRIDGES

At present existing bridges are mostly assessed by the partial factor method for structural design that can hardly reflect bridge-specific conditions in reliability analysis. Assessments of existing bridges are then often conservative and lead to expensive costs for reconstruction. The assessment of existing road bridge in the Czech Republic is based on determining load bearing capacity V_i (the greatest actual weight of each vehicle given by conditions of crossing) in accordance with ČSN 73 6222 [2].

ČSN 73 6222 [2] assumes three different conditions of crossing for the assessment of load bearing capacities V_i:

- V_1 is determined for the crossing of a defined two-axle vehicle with a uniform loading representing normal traffic,
- V_2 is determined for the crossing of a single three-axle or six-axle vehicle with restricted access of other vehicles. Vehicle with more unfavourable effect is taken into account and
- V_3 is determined for the crossing of a nine-axle vehicle with controlled position on a bridge and described speed.

The most unfavourable transversal position of the vehicles for V_1 and V_2 and of the uniform load for V_1 is taken into account.

3 PARTIAL FACTOR METHOD

Partial factor method generally accounts for uncertainties in material and geometry properties and action effects; load bearing capacity V_i is estimated as follows:

$$V_i = k_i\, M_{Qi} \min[(M_{R\mathrm{d}} - \gamma_{G,\mathrm{sup}}\, M_{G\mathrm{k}}) / (\delta_x\, \psi_{0,Q}\, \gamma_Q); (M_{R\mathrm{d}} - \xi\, \gamma_{G,\mathrm{sup}}\, M_{G\mathrm{k}}) / (\delta_x\, \gamma_Q)] \quad (1)$$

where:

k_i – is a coefficient dependent on the type of load bearing capacity V_i derived from ČSN 73 6222 [2],

M_{Qi} – bending moment from vehicle and uniform loading defined for the different conditions of crossing (V_1 to V_3) according to ČSN 73 6222 [2],

$M_{R\mathrm{d}}$ – design value of flexural resistance in accordance to EN 1992-2 [3], using partial factor for γ_C for concrete and γ_S for reinforcing steel,

$\gamma_{G,\mathrm{sup}} = 1.35$ – partial factor for permanent actions,

$M_{G\mathrm{k}}$ – characteristic bending moment given by permanent actions,

δ_i – dynamic factor in accordance with ČSN 73 6222 [2],

$\psi_{0,Q} = 0.75$ – combination factor for traffic load,

$\gamma_Q = 1.35$ – partial factor for traffic load and

$\xi = 0.85$ – reduction factor.

3.1 Partial factors for structural design

Application of partial factors for structural design is great disadvantage of this method. Conservative values of these factors have been intentionally proposed to cover most situations in design when information about real material properties or structural geometry is unavailable. Therefore, they may be inappropriate, often overly conservative for assessing a specific existing bridge. Partial factors of material properties for structural design are $\gamma_\mathrm{C} = 1.5$ for concrete compressive strength and $\gamma_\mathrm{S} = 1.15$ for yield strength of reinforcement.

3.2 Updating of partial factors

Partial factors can be updated in accordance with EN 1990 [4], ISO 2394 [5], ČSN 73 0038 [6] and with scientific publications [7, 8]. Fully probabilistic approach to reliability analysis of existing bridges is then described in [9, 10]. These prescriptive documents allow for updating partial factors for material properties γ_M and for action effects γ_G and γ_Q due to wind, snow, thermal or traffic actions. However this study is focused only on updating of partial factors for material properties:

$$\gamma_M = f_k / f_d = \exp(-k_n V_X + \alpha_R \beta V_R) \quad (2)$$

where:

f_k – is the characteristic value,

f_d – design value,

k_n – coefficient of 5% lower fractile provided in EN 1990 [4] for n experimental results and known or unknown coefficient of variation V_X (Tab. 1),

V_X – coefficient of variation for the material strength,

α_R – sensitivity factor according to EN 1990 [4] a ISO 13 822 [11],

β – reliability index [4] and

V_R – coefficient of variation for resistance.

Tab.1: Values of k_n for 5% lower fractile of material property in accordance with EN 1990 [4].

n	1	2	3	4	5	6	8	10	20	30	∞
V_X known	2.31	2.01	1.89	1.83	1.80	1.77	1.74	1.72	1.68	1.67	1.64
V_X unknown	-	-	3.37	2.63	2.33	2.18	2.00	1.92	1.76	1.73	1.64

Sensitivity factor α_R indicating effect of the variable on reliability can be estimated by FORM (First Order Reliability Method). Approximate values of α_R are provided in Tab. 2.

Tab.2: Reliability factors α in accordance ISO 13 822 [11].

Basic variable	Sensitivity factor α
Dominant resistance parameter	0.8
Non-dominant resistance parameter	$0.4 \times 0.8 = 0.32$
Leading actions	– 0.7
Accompanying actions	$-0.4 \times 0.7 = -0.28$

Index β is an indicator of structural reliability derived from failure probability P_f (Tab. 3). EN 1990 [4] differentiates target reliability with respect to consequence classes CC1, CC2, CC3 for small, middle and great failure consequences (Tab. 4). ISO 13 822 [11] provides a similar, somewhat more detailed reliability differentiation (Tab. 4).

Tab.3: Corresponding reliability indices and failure probabilities.

P_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1.28	2.32	3.09	3.72	4.27	4.75	5.20

Tab.4: Target reliability indices for different failure consequences and reference period of 50 years.

	Failure consequences			
Standard	Very small	Small	Middle	Great
EN 1990	-	3.3	3.8	4.3
ISO 13 822	2.3	3.1	3.8	4.3

Coefficient of variation for resistance V_R is estimated on the basis of coefficients of variation of material strength, geometrical properties and model uncertainty (V_X, V_{geo} and V_θ, respectively):

$$V_R = \sqrt{[V_X^2 + V_{geo}^2 + V_\theta^2]} \quad (3)$$

Tab. 5 indicates informative coefficients of variation according to ČSN 73 0038 [6].

Tab.5: Informative values of coefficients of variation according to ČSN 73 0038 [6].

Material	V_X	V_{geo}	V_θ
Concrete	0.15	0.05	0.05
Reinforcement	0.05	0.05	0.05

4 INFORMATION ABOUT THE BRIDGE

4.1 Load bearing structure

The single span bridge consists of four main longitudinal reinforced concrete girders stiffened by several transversal beams, reinforced concrete slab and stone masonry abutment. Scheme of the structural system is shown in Fig. 1.

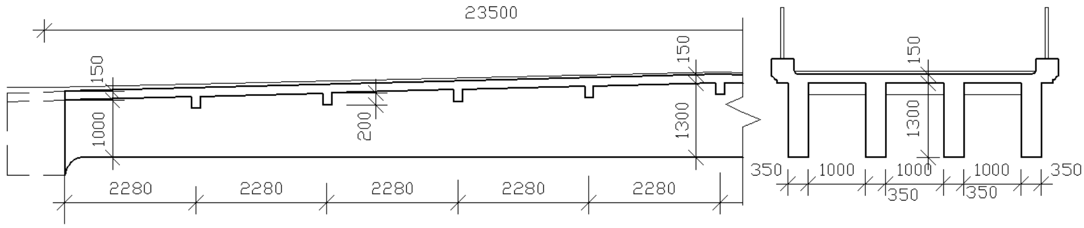

Fig.1: Schematic longitudinal section and cross section in the mid-span of the bridge (dimensions in mm)

4.2 Inspection outcomes

Inspection of the bridge revealed:

- Concrete degradation at the bottom part of both outer longitudinal girders caused by deicing salts and chloride ingress,
- Insignificant corrosion of longitudinal and shear reinforcement and
- Damage of road pavement at about 20 % of the total area, mainly in the area of bridge expansion joints.

No visible degradation and damage was observed at remaining parts of the bridge.

4.3 Load effects and structural model

In addition to the traffic loads described above, the bridge is exposed to permanent actions including layers of the road pavement and self-weight of the structural model. According to ČSN 73 6222 [2] thermal and wind effects are neglected.

Load effects (internal forces) are estimated using a slab-wall model developed in Scia Engineer 2012, considering the following simplifications:

- The slab is not inclined,
- The transversal beams are replaced by increasing slab depth by 1 cm,
- Reinforcement of concrete and the effect of a vehicle restraint system are neglected and
- Influence of cracks on stiffness is not considered.

4.4 Results of tests and measurements

18 measurements of yield strength of reinforcement f_y include three destructive tests and fifteen non-destructive tests by hardness tester. Eight measurements of concrete compressive strength f_c include two destructive tests and six non-destructive tests by Schmidt hammer. Concrete cover c was measured at 59 locations. Statistical characteristics of f_y, f_c, and c obtained from the measurements are provided in Tab. 6.

Tab.6: Characteristics obtained from measurements.

Variable	Units	Mean	Coefficient of variation	Characteristic value
Yield strength of reinforcement	MPa	269	0.025	257
Concrete compressive strength	MPa	26.9	0.1	21.6
Concrete cover	mm	47	0.45	47

5 ASSESSMENT OF LOAD BEARING CAPACITIES V_i

5.1 Basic variables and partial factors

Values of basic variables and partial factors applied in the assessment are given in Tab. 7 and Tab. 8. In addition dynamic factor δ dependent on the type of load bearing capacity V_i and first natural frequency is considered according to ČSN 73 6222 [2]. In this study the following values of dynamic factor are accepted: $\delta(V_1) = 1.35$, $\delta(V_2) = 1.35$ and $\delta(V_3) = 1.05$.

Tab.7: Basic variables.

Variable	Symbol	Value
Longitudinal reinforcement	A_s	12214 mm^2
Yield strength	f_y	257 MPa
Height of the beam	h	dependent on distance x from support: 1 m for $x = 0$; 1.3 m for $x = 11.75$ m
Concrete cover	c	47 mm
Width of the beam	b	350 mm
Depth of the slab	d	150 mm
Axial distance of beams	a	1.35 m
Length of the beam	L	23.5 m
Concrete compressive strength	f_c	21.6 MPa

Tab.8: Applied partial factors.

Partial factors	Symbol	For new structures	Updated partial factors			
			$\beta = 2.3$	$\beta = 3.1$	$\beta = 3.8$	$\beta = 4.3$
For permanent actions	$\gamma_{G,\text{sup}}$	1.35	-	-	-	-
For traffic load	γ_Q	1.35	-	-	-	-
For concrete strength	γ_C	1.5	1.01	1.09	1.17	1.23
For yield strength of reinforcement	γ_S	1.15	1.06	1.10	1.13	1.16

The updated partial factors in Tab. 8 are assessed by approach in section 3.2. The coefficients of variation V_X are obtained from Tab. 6. In the assessment the informative values of V_{geo} and V_θ are considered (Tab. 5).

5.2 Assessment and comparison of the load bearing capacities

Load bearing capacities V_i are estimated for all cross sections of each longitudinal girder. Due to the symmetry of the bridge load bearing capacities V_i are same for the pairs of the inner and outer girders. The inner girders have smaller load bearing capacities V_i and consequently load bearing capacities of the inner girders are discussed hereafter only.

Self-weight of the load bearing structure is estimated on the basis cross-section characteristics and concrete volume density of 24 kNm^{-3}. Other permanent actions are described by a uniform loading with the characteristic value of 0.65 kNm^{-2}.Vehicles are defined by crossing of axle loads with respect to the considered crossing conditions described in above.

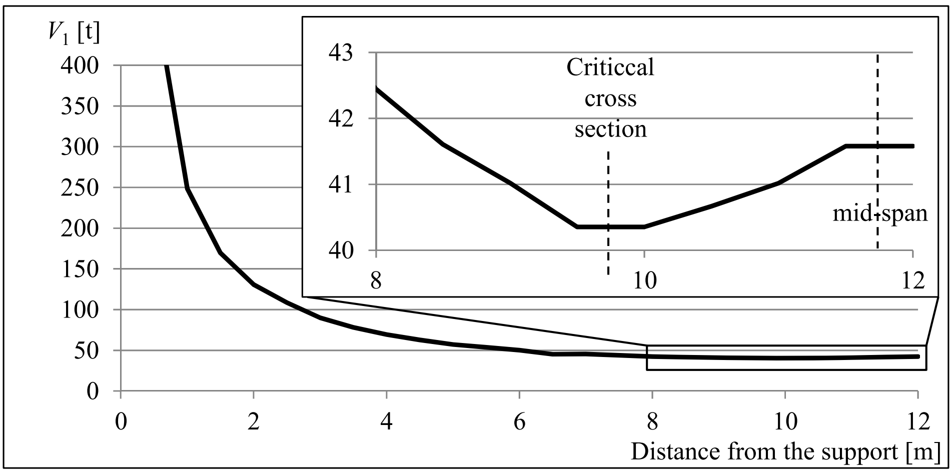

Fig.2: Variability of load bearing capacity V_1 with the distance from supports for partial factors for structural design

Fig. 2 (partial factors for structural design) and Fig. 3 (updated partial factors) show the variability of load bearing capacity V_1 given in tons with the distance from support. In addition the figures illustrate identification of the critical cross section where V_1 is minimised. Similar trends are observed for the load bearing capacities V_2 and V_3. Moreover Fig. 3 provides results of V_1 for different target reliability levels.

Load bearing capacities V_i are different in each cross section, since load bearing capacity of the bridge is the smallest value in critical cross section. Critical cross section is not in the mid-span due to crossing of axle loads and geometry of the girders. Load bearing capacity V_1 is the smallest while V_3 attains the highest values.

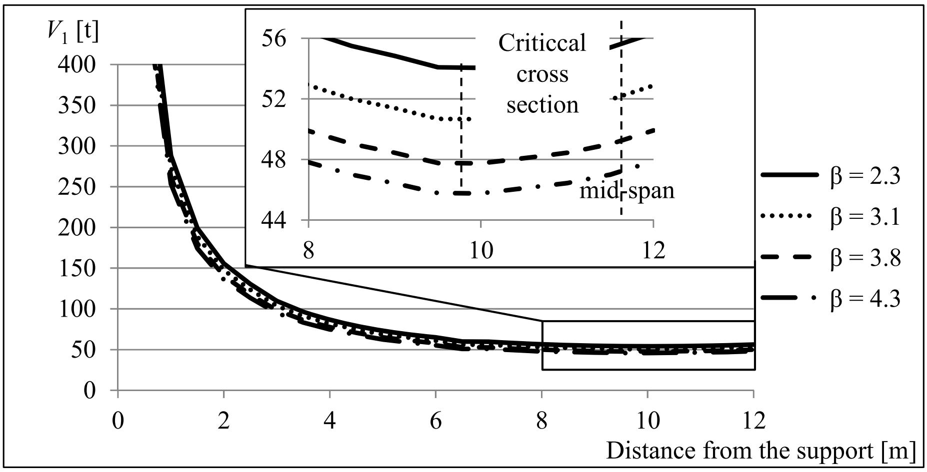

Fig.3: Variability of load bearing capacity V_1 with the distance from supports for updated partial factors and different target reliability levels

Tab. 9 gives load bearing capacities V_i assessed by the considered methods and the distance of a critical cross section from the support. The location of the critical cross section depends on a type of crossing. Load bearing capacities V_i assessed by updated partial factors are about 15 % higher for the most common target reliability index $\beta = 3.8$.

Tab.9: Load bearing capacities *Vi* obtained by the considered methods and the distance of a critical cross section from the support.

	Critical cross section [m]	Load bearing capacity [t]				
		Partial factors for structural design	Updated partial factors			
			$\beta = 2.3$	$\beta = 3.1$	$\beta = 3.8$	$\beta = 4.3$
V_1	10	40	51	48	45	43
V_2	10	56	72	68	64	61
V_3	9.5	106	136	128	121	115

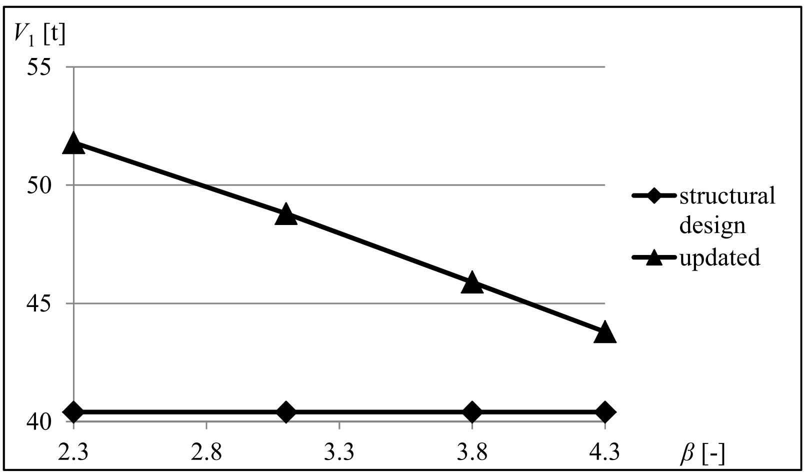

Fig.4: Comparison of load bearing capacities V_1 assessed by different partial factors

Tab. 9 and Fig. 4 indicate that the target reliability index is not reflected in the assessment by partial factors for structural design. For updated partial factors, the reliability index β significantly influences the load bearing capacities V_i that decrease with increasing β.

Note that the presented study is focused on the Ultimate limit state related to bending moment failure mode. With respect to other common failure modes, it is foreseen that the benefit of using updated partial factors would be similar as in the case of bending moments.

6 CONCLUSIONS

Numerical study indicates that:

- Partial factors for structural design are unnecessarily conservative,
- Updated partial factors can readily incorporate a required target reliability level and can better reflect real structural conditions AND
- Load bearing capacities V_i assessed by updated partial factors are about 15 % higher for the most common target reliability index $\beta = 3.8$.

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