Methodology for Calculation of Bridge Safety Factor in Lithuania

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METHODOLOGY FOR CALCULATION OF BRIDGE SAFETY FACTOR IN LITHUANIA

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Abstract. The paper reviews the United States and Slovenian safety factor calculation methodologies and proposes a method for more accurate estimation of residual strength of bridges designed and built in Lithuania. For more detailed analysis, the main parameters and defects directly affecting the strength of the bridges were analysed in detail, and the flows of heavy vehicles, which have significantly increased for previously designed bridges, were assessed.
This article proposes to calculate the dynamic factor of bridges, not according to the empirical formulas used in the United States and Slovenian safety factor calculation methodologies, but after performing the bridge dynamic test, because the results of Lithuanian bridge dynamic tests show that the parameter strongly depends on smoothness and damage of carriageway wearing surface. In order to evaluate the suitability of the Lithuanian bridge safety factor calculation methodology proposed in this article, a real bridge was selected, and its safety factors calculated according to the above mentioned and proposed methodology and the results obtained were compared.

Keywords: bridges, safety factor, resistance, defects, dynamic factor.

Introduction

Bridges are sophisticated and expensive transport structures that are of the great importance for economical, political, and cultural relations. For a long time, reinforced concrete bridges have been considered as durable structures that require only regular maintenance, but in the recent decades in all countries it was observed intensive physical and moral aging of these structures. Heavy duty vehicle flows, higher speeds and axle loads are the factors that significantly affect the faster deterioration of the bridge deck.

The deterioration of the bearing structures of bridges is directly influenced by defects occurring during the operation stage of the bridge: carbonization of concrete, corrosion of reinforcement, shear and normal cracks in the structures (Augonis M., Zadlauskas S., Rudžionis Ž., Pakalnis A., 2012). In order to follow the deterioration process of bridges, it is necessary to constantly monitor changes in their condition, trends in the development of defects, evaluate and predict their durability and, if necessary, take appropriate measures such as limiting the gross weight of heavy vehicles. One of the ways to bridge condition assessment is the bridge "safety factor" application (AASHTO 2010, 2011; Žnidarič A., 2015; Peris, A. and Harik, I., 2016). When calculating the bridge safety factor, the condition of the bearing structures of the bridge, the effects of permanent and variable loads acting on it, and the effects of dynamic loads and overloads are assessed in detail.

Until now, no bridge safety assessment methodology has been applied in Lithuania, therefore, there is a need to do research, to analyze the calculation methods used in the United States and Europe, and to propose a methodology suitable for Lithuanian bridge safety assessment. Since about 95 % of bridges in Lithuania are reinforced concrete, therefore, the methods of calculating the safety factor of bridges analyzed in this work have been developed for safety assessment of reinforced concrete bridges.

1. Bridge safety factor calculation methodology

For the evaluation of safety of bridges used in Europe and the United States ("ultimate limit state"), a bridge safety factor is calculated considering the factors mentioned above. The bridge safety factor indicates whether the bridge is safe to operate under certain damages, defects, and traffic flows, or whether it is unsafe, and it is necessary to limit the total weight of heavy vehicles. Process to compose assumptions for calculating the safety factor of bridges have been started since 1970. American (Nowak, A. S. and Gruni, H. N., 1994; Frangopol, D. E. and Estes, A. C., 1997) and Canadian (Allen, D. E., 1992; Bartlett, F. M., Buckland, P. G., Kennedy, D. J., 1992) scientists have paid much attention to the preparation of assumptions in their research works.

The American Bridge Design Standard (AASHTO, 2010) provides the following formula for calculating the bridge safety factor:

$$RF = \frac{\phi_c \phi_s \phi R_n - (\gamma_{DC} DC + \gamma_{DW} DW)}{\gamma_{LL}(LL + IM)} \tag{1}$$

where: ϕ_c – condition factor (usually is assumed as 1.0); ϕ_s – system factor (usually is assumed from 0.85 till 1.0); ϕ – resistance factor (if no analysis carried out, assumed as 1.0); R_n – nominal resistance of bridge deck; γ_{DC} – load factor for structural components and attachments (usually is assumed as 1.25); DC – dead load of structural components and non-structural attachments; γ_{DW} – load factor for wearing surfaces and utilities (usually is assumed as 1.50); DW – dead load of wearing surfaces and utilities; γ_{LL} – load factor for live loads (1 table); LL – vehicular live load; IM – vehicular dynamic load allowance (2 table).

Table 1. Load factors for live loads (γ_{LL})

Heavy duty vehicles	Load factor for live loads	Number of heavy vehicles per day ≤1000	Number of heavy vehicles per day ≥1000	Unknown number of heavy vehicles
Routine vehicles	γ_{LL}	1.65	1.80	1.80
Special permits vehicles	γ_{LL}	1.40	1.50	1.50

Table 2. Dynamic load allowance (IM)

Bridge span	IM
Bridge span 40 m or less	33%
Bridge span more than 40 m – smooth carriageway wearing surface without defects in deck joints – small irregularities in carriageway wearing surface – rough carriageway wearing surface, high impulses when moving heavy vehicles	 10% 20% 30%

Scientists at the National Building and Civil Engineering Institute ZAG, Slovenia (Žnidarič, A., 2010, Žnidarič, A., Lavrič, I., Kalin, J. 2010) have developed a methodology for calculating the safety factor of bridges. For bridges built in this country, their safety factor is calculated using the following expression:

$$RF = \frac{\Phi \cdot R_d - \gamma_G \cdot G_n}{\gamma_Q \cdot G_Q \cdot DAF} \qquad (2)$$

where: Φ – bridge deck capacity reduction factor; R_d – design resistance of bridge deck; G_n – characteristic value of permanent action; G_Q – characteristic value of variable action; γ_Q – load factor for variable loads (assumed according to the flow of heavy vehicles over the bridge under investigation, but not less than 1.40); γ_G – load factor for permanent loads (assumed equal to 1.20); DAF – dynamic amplification factor.

In the developed methodology, the bridge deck dynamic factor is calculated according to the formula given in German bridge design standard (DIN 1072):

$$DAF = 1.4 - 0.008 \cdot L \qquad (3)$$

where: L – bridge span length.

The capacity reduction factor of the bridge deck is calculated using the following expression:

$$\Phi = B_R \cdot e^{-\alpha_R \cdot \beta_C \cdot V} \qquad (4)$$

where: B_R – the bias of carrying capacity, i.e., the ratio between the true and the design mean resistances of the critical section. In most cases assumed as 1.0, if no more detailed material analysis has been performed; α_R – the deterioration factor, accounting for the condition of the bridge (see Table 3); V – the coefficient of variation of the member resistance and is taken 10% when calculated from experiments, 15% when based on design information and 20% if less reliable information is used; β_C – the target value of the safety index, taken 3.5 for the normal service life (up to 20 years) and 2.5 for limited service life (up to 6 years or until the next main inspection).

Table 3. Values of deterioration factor (α_R)

Class	Inspected condition	Necessary intervention	Condition rating R_c	Deteriotiation factor, α_R
1	Very good	No maintenance/repair work required	<5	0.3
2	Good	Regular maintenance work needed	3 – 10	0.4
3	Satisfactory	Intensified maintenance/repair work within 6 years	7 – 15	0.5
4	Tolerable	Substantial repair work needed within 3 years	12 – 25	0.6
5	Inadequate	Immediate posting and repair required	22 – 35	0.7
6	Critical	Immediate closing and repair/strengthening required	>30	0.8

An overview of the methodologies used to calculate the safety factor for bridges in different countries of the world has shown that they have the same basic parameters, but differently measured. Each of the methodologies describes four main components: the bearing capacity of bridge deck considering various factors, the effects of permanent and variable loads, and the dynamic loads caused by heavy vehicles. Although these components are similar, in America and Slovenia different partial factors are used for permanent and variable loads, the impact of dynamic loads on the bridge is assessed differently, different system of assessment of the condition of the bridges, different operating conditions of the bridges. As the factors mentioned in Lithuania are also different, this paper presents a methodology for calculating the safety factor of bridges operating in Lithuania.

2. Condition of bridges assessment in Lithuania

In Lithuania, the condition of bridges administered by the Lithuanian Road Administration under the Ministry of Transport and Communications is assessed through the annual and substantive inspections, static and dynamic tests. During the annual inspection, bridges are evaluated using a five-point grading system. Each bridge element is visually inspected, and its condition assessed. The most important factor in the overall estimate of the bridge is the condition of the bearing structures. Because the static and the dynamic tests of the bridges are expensive, therefore they are carried out only for the problematic ones, and for the most of them only one or another type of inspection is carried out. Visual assessment of the condition of the bridge is not objective and sufficient to comprehensively evaluate the condition of the bridges and to plan investments for their repair, because: visual evaluation of the bridge does not always allow to avoid "human factor" errors and it is not clear what impact the defect has on the bearing capacity of the bridge, and how safe it is to operate such a structure in the future. Therefore, from 2015 to 2016, specialists from the Bridge Research Department of the Public Road and Transport Research Institute have developed a new bridge management system, in which appeared the parameter characterizing the bridge safety - the bridge safety factor.

2.1. Calculation of bridge safety factor in Lithuania

In the new bridge management system developed in Lithuania, it is proposed to calculate the bridge safety factor taking into account the safety factor expressions proposed by American and Slovenian scientists, however, by introducing the notations of permanent and variable loads, partial factor and dynamic factor used in Lithuania. It is proposed to calculate the safety factor of Lithuanian bridges by the following expression:

$$RF = \frac{\varphi \cdot R_d - (\gamma_{G1} \cdot G_{k1} + \gamma_{G2} \cdot G_{k2} + \gamma_{G3} \cdot G_{k3})}{\gamma_Q \cdot Q_k \cdot \mu_{din.}} \quad (5)$$

where: φ – bridge deck capacity reduction factor; R_d – design resistance of bridge deck; G_k – characteristic value of permanent action; Q_k – characteristic value of variable action; γ_Q – load factor for variable loads; γ_G – load factor for permanent loads; μ_{din} – bridge deck dynamic factor.

The deterioration of the bridge condition is evaluated by calculating the cross-section strength reduction index of the bridge load-bearing structures according to the following expression:

$$\varphi = \frac{1}{e^{\alpha_R}} \quad (6)$$

The deterioration factor of the bridge elements (α_R) directly depends on the condition rating of the bridge load-bearing structures. Since this parameter cannot be expressed in points, Table 4 presents the values of the deterioration factor of the bridge load-bearing structures as a percentage of their condition rating.

Table 4. The deterioration factor values of the bridge load-bearing structures

Bridge rating, in points	Deterioration factor of bridge load-bearing structures, α_R
5	0.05
4	0.10
3	0.20
2	0.25
1	0.35

In Lithuania, the Public Road and Transport Research Institute has carried out more than 150 dynamic tests of various types and conditions bridges, which accurately measured the static and dynamic deflections of the bridges decks and calculated the dynamic factors of the decks from the moving loads of heavy vehicles. According to the results of performed research, it is proposed to relate the dynamic factor of bridge decks to the rating of the condition of the bridge deck wearing surface. The approximate equivalent of the bridge deck dynamic factor is given in Table 5.

Table 5. Approximate evaluation of bridge deck dynamic factor based on carriageway wearing surface rating in points

Rating of bridge carriageway wearing surface	Bridge deck dynamic factor, μ_{din}
5	1.02
4	1.10
3	1.15
2	1.20
1	1.30

The rating of the bridge carriageway wearing surface is described in points:

- 5 points – smooth carriageway wearing surface, no defects;
- 4 points – smooth carriageway wearing surface, only with localised defects; no defects in deck joints;
- 3 points – rough carriageway wearing surface, ruts formed; small depressions formed in deck joints;
- 2 points – rough carriageway wearing surface, localised defects at the ends of the bridge or along the sidewalk, damaged deck joints;
- 1 point – very rough carriageway wearing surface, deep ruts formed; deep depressions formed in the wearing surface at the midspan of bridge deck; very damaged deck joints.

2.2. Evaluation of partial factor of permanent loads acting on the bridge

Bridges in Lithuania are designed according to various bridge design standards. Bridges designed in Lithuania can be divided into five different bridge design periods. Period I – bridges designed from 1945 to 1948. During this period, permanent loads of designed bridges were calculated without partial factors. Period II – from 1953 to 1962. The permanent loads of the bridges designed during this period were also calculated without partial factors. Period III – bridges designed from 1962 to 1984. During this period, the partial factor of designed bridge deck bearing structures, sidewalks, barriers, and handrails of the bridge was 1.10. The partial factor of bridge deck waterproofing, levelling layer, sidewalk protective coating and asphalt pavement was 1.50. Period IV – bridges designed from 1984 to 1997. During this period, the partial factor of designed bridge deck bearing structures, sidewalks, barriers, and handrails of the bridge was 1.10. The partial factor of bridge deck waterproofing and levelling layer was 1.30, and for sidewalk protective coating and asphalt pavement it was 1.50. Period V – bridges designed since 1997 until these days. The partial factor of bridge deck bearing structures and overlays designed during this period and currently being designed in Lithuania is assumed to be 1.35.

Because of the different bridge design periods, the methodology proposes to group the bridge deck permanent loads into three groups for each bridge design year, and apply different partial factors:

- partial factor of bridge deck bearing structures, sidewalks, barriers and handrails of the bridge (γ_{G1});
- partial factor of bridge deck waterproofing and levelling layer (γ_{G2});
- partial factor of bridge asphalt pavement and sidewalk protective coating (γ_{G3}).

2.3. Evaluation of partial factor of variable loads acting on the bridge

The European bridge design standards (Eurocode 1, 2000, 2004) assume partial factor for variable loads equal to 1.35, however American bridge design standards (AASHTO, 2010) and research of foreign scientists (Koteš, P., Vichan, J., 2012) indicate that the values of the partial factor of variable loads are directly dependent on the number of heavy vehicles per day. In this methodology it is proposed to calculate the partial factor of variable loads by considering the influence of heavy vehicle flows (see Table 6).

The analysis of traffic flow intensity in Lithuania is carried out by specialists of the Road Research Department of the Institute of Road and Transport Research and is an annually updated database of the number of heavy vehicles passing through one or another monitored bridge per day.

Table 6. Calculation of partial factor for variable loads

Total daily flow of heavy vehicles	Partial factor of variable load
<250	1.40
>250<1000	1.45
>1000<5000	1.55
>5000	1.60

3. Calculation of bridge safety factor according to Lithuanian proposed methodology by different bridge parameters

Non-continuous one spans reinforced concrete girder bridge (14.10 m) built in Lithuania was chosen to calculate the bridge safety factor. Ribbed bridge deck is made from 6 pcs prefabricated T-girders. The bridge was built in 1950, bridge length 16.10 m and width 8.68 m. The bridge is designed according to Russian bridge design standards, design loads – H-13 and HG-60. 58 heavy vehicles pass through the bridge per day. The overall condition of the bridge is bad (rating of load bearing structures – 2 points). Rating of carriageway coating – 3 points. Bearing capacity of bridge deck (resistance for one T-girder normal cross-section) R_d = 9546 kNm. Characteristic load of bridge deck bearing structures, sidewalks, barriers, and handrails of the bridge – G_{k1} = 1383 kNm. Characteristic load of bridge deck waterproofing and levelling layer – G_{k2} = 239 kNm. Characteristic load of bridge asphalt pavement and sidewalk protective coating – G_{k3} = 545 kNm. Effect of variable loads – Q = 167 kNm. Bridge deck dynamic factor – μ_{din} = 1.39.

The calculations of the bridge safety factor according to AASHTO 2010 methodology is given in Table 7, according to the methodology presented by the Slovenian researchers in Table 8, according to the methodology proposed in Lithuania in Table 9.

Table 7. Calculation of bridge safety factor according to AASHTO 2010 methodology

Titles of assumed/calculated parameters	Values of assumed/calculated parameters
1) Bridge condition factor, ϕ_c	1.0
2) Bridge system factor, ϕ_s	1.0
3) Resistance factor of bridge elements, ϕ	1.0
4) Nominal resistance of bridge deck, R_n	9546
5) Load factor for structural components and attachments, γ_{DC}	1.25
6) Dead load of structural components and non-structural attachments, *DC*	1928
7) Load factor for wearing surfaces and utilities, γ_{DW}	1.50
8) Dead load of wearing surfaces and utilities, *DW*	239
9) Load factor for live loads, γ_{LL}	1.65
10) Vehicular live load, *LL*	1715
11) Vehicular dynamic load allowance, *IM*	(0.33*1715) = 566
The safety factor of the bridge over the Gėluotas and Vašuokas lake	**1.80**

Table 8. Calculation of the bridge safety factor according to the methodology presented by Slovenian scientists

Titles of assumed/calculated parameters	Values of assumed/calculated parameters
1) Bridge deck capacity reduction factor, Φ	0.78
2) Design resistance of bridge deck, R_d	9546
3) Load factor for permanent loads, γ_G	1.20
4) Characteristic value of permanent action, G_n	2167
5) Load factor for variable loads, γ_Q	1.40
6) Characteristic value of variable action, G_Q	1715
7) Dynamic amplification factor, *DAF*	1.29
The safety factor of the bridge over the Gėluotas and Vašuokas lake	**1.56**

Table 9. Calculation of the bridge safety factor according to the methodology proposed in Lithuania

Titles of assumed/calculated parameters	Values of assumed/calculated parameters
1) Bridge deck load-bearing structures rating, in points	3
2) Bridge deck capacity reduction factor, φ	0.82
3) Design resistance of bridge deck, R_d	9546
4) Characteristic load of bridge deck bearing structures, sidewalks, barriers, and handrails, G_{k1}	1383
5) Characteristic load of bridge deck waterproofing and levelling layer, G_{k2}	239
6) Characteristic load of bridge asphalt pavement and sidewalk protective coating, G_{k3}	545
7) Load factor for variable loads, γ_Q	1.40
8) Partial factor of bridge deck bearing structures, sidewalks, barriers and handrails of the bridge, γ_{G1}	1.10
9) Partial factor of bridge deck waterproofing and levelling layer, γ_{G2}	1.50
10) Partial factor of bridge asphalt pavement and sidewalk protective coating, γ_{G3}	1.50
11) Characteristic value of variable action, G_Q	1715
12) Bridge deck dynamic factor, μ_{din}	1.39
The safety factor of the bridge over the Gėluotas and Vašuokas lake	**1.48**

Conclusions

1. After comparing three differ methodology for bridge safety factor calculations it was found that the main differences are with nodal loads coefficients, bridge capacity coefficients and dynamic coefficient.

2. The main differences comparing proposed methodology with Slovenian and AASHTO methodology's is that if there are problems with bridge deck capacity we do bridge dynamic testing and for safety factor coefficient calculation we use real bridge deck dynamic factor but not calculated by empirical formulas. Bridge dynamic coefficient calculated by empirical formulas depends by the length of the bridge, but in reality it depends by the asphalt surface and roughness.
3. After comparing bridge safety factors calculated in table 7, table 8 and table 9 it was found that the highest one is by AASHTO 2010 methodology and the lowest one is by methodology proposed in Lithuania.

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