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Reliability levels for existing bridges evaluation according to Eurocodes

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Abstract

In the frame of research activities of the Department of structures and bridges, the modified reliability levels for existing bridge evaluation were derived. These levels were used for determining the partial safety factors for materials. Moreover, the partial safety factors of steel and concrete were determined depending on the age of the bridge and on the remaining lifetime of the bridge. New modified reliability levels for evaluation of existing bridges affect also the partial safety factors of loads. In the paper, the modification of reliability levels recommended according to Eurocode for bridge members subjected to bending are presented. These adjusted reliability levels should be used for existing bridge evaluation.

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1. Introduction

The evaluation of existing concrete bridge structures is the most important process in the global Bridge Management System (BMS) because of providing the basic information about existing bridges required from the viewpoint of decision making process related to the optimal bridge maintenance and rehabilitation strategy. Therefore, the existing bridge evaluation should be carried out, not only as the result of periodic inspection on the base of subjective evaluation of actual bridge condition, but from the viewpoint of the bridge reliability, i.e. from the viewpoint how the actual bridge condition affects the bridge reliability for remaining bridge lifetime. Thus, the bridge evaluation becomes relevant when the significant deviations from the project descriptions are found, when some relevant damage is observed or when the bridge lifetime has gone beyond the planned one, etc.

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The paper deals with determination of the modified reliability levels for evaluation of existing bridges. The theoretical approach, taking into account the conditional probability, was used. The modified levels depend on the age of the bridge and on the planned remaining lifetime and, moreover, influence the partial safety factors of materials and loads.

**Nomenclature**

- \(m_R, s_R\) basic parameters of the normally distributed random variable resistance \(R\) of the bridge structural element (mean value, standard deviation)
- \(m_S, s_S\) basic parameters of the normally distributed random variable load effects \(S\) of the same bridge element (mean value, standard deviation)
- \(\lambda\) intensity of load effects
- \(\lambda_o\) value of parameter \(\lambda\) at the time \(t = 0\)
- \(\lambda_{\text{insp}}\) value of parameter \(\lambda\) at the time of the periodic inspection \(t = t_{\text{insp}}\)
- \(\Phi^{-1}\) inverse distribution function of standardized normal distribution \(N(0,1)\)
- \(\varphi\) probability density function of standardized normal distribution \(N(0,1)\)

**2. Evaluation of existing bridges – reliability analysis**

The reliability level for the newly designed bridges for the total design lifetime \(T_d\) \((T_d = 100\) years\), which is represented by failure probability \(P_{f,d}\) \((P_{f,d} = 7.2 \cdot 10^{-5})\) or by reliability index \(\beta_d\) \((\beta_d = 3.8)\), is given in Eurocode [1]. However, the reliability level for evaluation of existing bridges for remaining lifetime \(t_r\) is not defined in the Eurocodes.

Generally, the process of the existing bridge evaluation has various differences in comparison to the reliability assessment of newly designed bridge. In the case of the existing bridge structure, new information concerning the actual bridge condition is available, which is unknown in the design phase. The certificates of material properties, measurements of actual bridge geometry, collection load data, results of proof load testing and especially results of the periodic inspections regularly performed within the lifetime of the observed bridge are the major resources of this information. The extra information unknown in the design phase could be used, not only for verification of the correct bridge performance or for detection of possible mistakes concerning the computational model assumptions or calculations, but also helps to reduce some uncertainty related to the bridge member resistance and load parameters entering the evaluation process.

In some countries, the problem of evaluation of existing bridges was solved in frame of the developing Bridge Management Systems based on computer-aided expert systems. The reliability-based evaluation of existing bridges is preferred in the works of American [2-3] and Canadian [4-5] authors. Theoretical outputs of these scientific studies create the background of the contemporary Canadian [6] and Ontario [7] standards for the evaluation of existing road bridges and determining their load carrying capacities in the form of Live Load Rating Factors (LLRF). Both standards are based on the probability model of the structural reliability verification with the differentiated reliability levels depending on the bridge component importance in the whole bridge structure.
In Europe, several authors and institutions have focused their research activities to this problem within the last few years [8-9]. A publication of the Joint Committee on Structural Safety (JCSS) [10] is being developed. This publication contains some practical and operational recommendations and rules for the assessment of existing structures.

From the bridge reliability point of view, the reduction of uncertainties of the load and resistance parameters decreases the failure probability of existing bridge structures, which means the possibility to adopt the lower reliability level for evaluation of existing bridge than ones, which should be used for newly designed bridge.

The reliability margin $G(t)$ is the basic parameter of structural reliability and it is described by the formulae

$$G(t) = R(t) - S(t)$$  \hspace{1cm} (1)

In the theoretical analysis, it is assumed that the bridge structural element was designed for total design lifetime $T$ with corresponding reliability index $\beta$ given by the formula

$$\beta = \left( m_R - m_S \right) / \sqrt{s_R^2 + s_S^2}$$  \hspace{1cm} (2)

The bridge inspection was performed at the time $t_{\text{insp}} < T$ during which the observed structural element was found to be without relevant failure due to overcrossing its limit states. This positive information expresses that resistance $R$ of the observed structural element satisfies the following relation

$$R > \max \left( S_i \right) \text{ for } i = 1 \ldots N(t)$$  \hspace{1cm} (3)

The load effects $S_1, S_2 \ldots S_n$ are mutually independent normally distributed and occur in succession but randomly in time and $N(t)$ means the random number of them within time interval $(0, t)$. $N(t)$ is considered as the random variable having Poisson distribution with parameter $\lambda(t)$ (intensity of load effects) which is constant or linearly dependent on time $t$ according to relation

$$\lambda(t) = \lambda_0 + \left( \lambda_{\text{insp}} - \lambda_0 \right) \cdot t / t_{\text{insp}}$$  \hspace{1cm} (4)

If the following formula is considered

$$L(t) = \int_0^t \lambda(\tau)d\tau$$  \hspace{1cm} (5)

then time occurrence of individual sets of load effects $S_i$ satisfies the following dependence

$$P(N(t) = n) = L(t)^n \cdot e^{-L(t)} / n! \text{, for } n = 0, 1 \ldots k$$  \hspace{1cm} (6)

If the parameter $\lambda(t)$ is constant in time, the following relation may be obtained using the relation (4)

$$L(t) = \lambda \cdot t$$  \hspace{1cm} (7)
and if the parameter is linearly dependent on time, using substitution (4) to (5), the following relation can be obtained

\[ L(t) = \lambda_0 \cdot t + \left( \left( \frac{\lambda_{\text{insp}}}{\lambda_0} - 1 \right) \cdot t^2 \right) \left/ \left( 2 \cdot t_{\text{insp}} \right) \right. \]  
\[ \]  
(8)

As has been shown in [11], the updated failure probability \( P_{fu} \) of the observed structural element, at the time period \( (t_{\text{insp}}, T) \), should be obtained by means of the conditional probability according to the formula

\[ P_{fu} = \left( P_f(T) - P_f(t_{\text{insp}}) \right) / \left( 1 - P_f(t_{\text{insp}}) \right) \]  
\[ \]  
(9)

The corresponding updated reliability index \( \beta_u \) of the observed structural element for the remaining time period \( (t_{\text{insp}}, T) \) can be determined in accordance with

\[ \beta_u = -\Phi^{-1} \left( P_{fu} \right) \]  
\[ \]  
(10)

The failure probability \( P_f(T) \), \( P_f(t_{\text{insp}}) \) can be obtained for normally distributed bridge element resistance \( R \) and normally distributed load effects \( S_i \) using the following formula for complete probability [11]

\[ P_f(T) = P \left[ \max(S_i)(i = 1 \ldots N(T) > R) \right] = \int_{-\infty}^{\infty} \left[ 1 - e^{-L(T)\phi \left( \frac{x - m_S}{s_S} \right)} \right] \cdot \frac{1}{s_R} dx \]  
\[ \]  
(11)

Using the information (3), the updated reliability index \( \beta_u \) should be greater than the designed index \( \beta_d \). Next, we are able to solve back the adjusted target failure probability \( P_{ft} \) (or target reliability index \( \beta_t \)) for which the element should be evaluated for remaining lifetime \( (T-t_{\text{insp}}) \) so that we can achieve the required value of the target failure probability \( P_{ft} \) with minimal single inspection. The updated reliability index \( \beta_u \) is increasing in time (significantly in the end of lifetime). From this reason, the target reliability index \( \beta_t \) is decreasing with time.

3. Reliability levels

The reliability level, given by failure probability \( P_{fu} \) or by reliability index \( \beta_u \), depends just on the full remaining lifetime \( (T - t_{\text{insp}}) \) – from time of inspection \( t_{\text{insp}} \) to the end of the lifetime \( T \). But practically, it is usual to evaluate the structure for the shorter lifetime – selected time interval. For example, it could be the time between the two inspections or if the structure does not satisfy limit state criteria for full remaining lifetime \( (T - t_{\text{insp}}) \). In at case, the structure could be evaluated on the shorter remaining lifetime – planned remaining lifetime \( t_r \).

The theoretical approach is the same as mentioned above. But, the lifetime \( T \) of the member should be shorter to determine the required reliability of observed member for planned interval \( t_r \). It means that the total lifetime is not \( T = 100 \) years, but it is equal to sum \( t_{\text{insp}} + t_r \).
This approach is important for bridge owner, because it gives to owner ability to save the funds. The results are shown in Fig. 1.

![Fig. 1. Target reliability index $\beta_t$ in dependence on time of inspection and planned remaining lifetime](image)

The obtained reliability levels depend on the age of the bridge and on the planned remaining lifetime. The results of the reliability levels for the bridge element without degradation due to regularly performed maintenance are shown in Tab. 1 and Tab. 2.

Table 1. Reliability levels for existing bridge evaluation for bridges with age < 60 years without degradation

| Remaining lifetime [years] | The age of the bridge [years] | 10. years | 20. years | 30. years | 40. years | 50. years |
|-----------------------------|------------------------------|-----------|-----------|-----------|-----------|-----------|
|                             | $\beta_t$ | $P_{ft}$ | $\beta_t$ | $P_{ft}$ | $\beta_t$ | $P_{ft}$ | $\beta_t$ | $P_{ft}$ | $\beta_t$ | $P_{ft}$ |
| 2                           | 3.328    | $4.38 \times 10^{-4}$ | 3.153    | $8.09 \times 10^{-4}$ | 3.039    | $1.19 \times 10^{-3}$ | 2.954    | $1.57 \times 10^{-3}$ | 2.886    | $1.96 \times 10^{-3}$ |
| 5                           | 3.517    | $2.19 \times 10^{-4}$ | 3.377    | $3.67 \times 10^{-4}$ | 3.282    | $5.16 \times 10^{-4}$ | 3.208    | $6.8 \times 10^{-4}$ | 3.149    | $8.21 \times 10^{-4}$ |
| 10                          | 3.623    | $1.46 \times 10^{-4}$ | 3.515    | $2.2 \times 10^{-4}$ | 3.437    | $2.94 \times 10^{-4}$ | 3.375    | $3.7 \times 10^{-4}$ | 3.323    | $4.46 \times 10^{-4}$ |
| 20                          | 3.697    | $1.09 \times 10^{-4}$ | 3.622    | $1.16 \times 10^{-4}$ | 3.563    | $1.83 \times 10^{-4}$ | 3.514    | $2.21 \times 10^{-4}$ | 3.471    | $2.59 \times 10^{-4}$ |
| 30                          | 3.727    | $9.7 \times 10^{-5}$  | 3.669    | $1.22 \times 10^{-4}$ | 3.621    | $1.47 \times 10^{-4}$ | 3.58    | $1.72 \times 10^{-4}$ | 3.545    | $1.97 \times 10^{-4}$ |
| 40                          | 3.743    | $9.08 \times 10^{-5}$ | 3.696    | $1.09 \times 10^{-4}$ | 3.656    | $1.28 \times 10^{-4}$ | 3.621    | $1.47 \times 10^{-4}$ | 3.589    | $1.66 \times 10^{-4}$ |
| 50                          | 3.753    | $8.72 \times 10^{-5}$ | 3.714    | $1.02 \times 10^{-4}$ | 3.679    | $1.17 \times 10^{-4}$ | 3.648    | $1.32 \times 10^{-4}$ | 3.62    | $1.47 \times 10^{-4}$ |
| 60                          | 3.76     | $8.48 \times 10^{-5}$ | 3.726    | $9.72 \times 10^{-5}$ | 3.696    | $1.10 \times 10^{-4}$ | 3.668    | $1.22 \times 10^{-4}$ |
| 70                          | 3.766    | $8.31 \times 10^{-5}$ | 3.734    | $9.38 \times 10^{-5}$ | 3.708    | $1.05 \times 10^{-4}$ |
| 80                          | 3.77     | $8.18 \times 10^{-5}$ | 3.742    | $9.12 \times 10^{-5}$ |
| 90                          | 3.773    | $8.07 \times 10^{-5}$ |
Table 2. Reliability levels for existing bridge evaluation for bridges with age ≥ 60 years without degradation

| Remaining lifetime [years] | The age of the bridge [years] | 60. years | 70. years | 80. years | 90. years |
|---------------------------|-------------------------------|-----------|-----------|-----------|-----------|
|                           | βt                            | Pt        | βt        | Pt        | βt        | Pt        |
| 2                         | 2.828                         | 2.35·10^{-3} | 2.777    | 2.75·10^{-3} | 2.732    | 3.15·10^{-3} | 2.692    | 3.56·10^{-3} |
| 5                         | 3.098                         | 9.75·10^{-4} | 3.053    | 1.13·10^{-3} | 3.014    | 1.29·10^{-3} | 2.978    | 1.45·10^{-3} |
| 10                        | 3.279                         | 5.22·10^{-4} | 3.239    | 6.00·10^{-4} | 3.204    | 6.78·10^{-4} | 3.172    | 7.57·10^{-4} |
| 20                        | 3.434                         | 2.97·10^{-4} | 3.401    | 3.35·10^{-4} | 3.371    | 3.74·10^{-4} |
| 30                        | 3.512                         | 2.22·10^{-4} | 3.483    | 2.48·10^{-4} |
| 40                        | 3.561                         | 1.85·10^{-4} |

4. Conclusions

The paper presents the results of the research concerning the reliability levels for evaluation of existing bridges. The modified reliability levels for evaluation were determined which depend on the bridge age and on the planned remaining lifetime. The values of the levels are valid for members subjected to bending. This approach introduces the theoretical reliability basis for modification of partial safety factor method allowing for the major differences between the existing bridge evaluation and design of the new ones.

Concurrently, it is possible to determine the partial safety factors of materials and loads from the new modified reliability levels.

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