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Assessment of Load Bearing Capacity of Concrete Bridge after Exceeding the Design Life

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Abstract. Advanced methods of reliability analysis based on simulation techniques of Monte Carlo type in combination with nonlinear finite element method analysis represent effective tools for reliability assessment of the existing bridges. Knowledge of current level of load bearing capacity of the bridge and its development in the coming years while meeting the required level of reliability may help to schedule the bridge maintenance systematically and efficiently and/or it can facilitate decision-making on the manner and extent of its reconstruction. The paper briefly introduces the methodology of probabilistic determination of the load bearing capacity of bridges with respect to the ongoing deterioration processes in time. The methodology is applied to determine the current level of load bearing capacity of a reinforced concrete parapet beam bridge and for its estimation in the coming years until the end of the theoretical service life of the structure.

Introduction

Questions of reliability assessment, assessment of load bearing capacity and residual service life of road bridges considering the current state of the structure are the object of the codes [1–4]. If the time dependence of structural response, $R(t)$, and influence of loading, $E(t)$, are available, the residual service life, t_{res}, can be assessed based on the assumption that the failure probability at the time, $P_{\mathrm{f}}(t)$, is less than or maximally equal to the target value of failure probability, $P_{\mathrm{f,t}}$, which corresponds to the value of the target reliability index, β_{t}. Hence, the failure probability is the function, increasing in time and can be defined as:

$$P_{\mathrm{f}}(t_{\mathrm{res}}) = P\left\{R(t_{\mathrm{res}}) - E(t_{\mathrm{res}}) \leq 0\right\} = P_{\mathrm{f,t}}. \tag{1}$$

When applying the probabilistic methods, the assessment of load bearing capacity in successive time nodes is performed in the same way as in the case of load bearing capacity assessment at the actual time. At first, based on the results of diagnostic survey, the statistical analysis of measured data, including an estimation of probabilistic models of input random variables is performed. Further, mathematical modeling of degradation processes of concrete, such as concrete carbonation or chloride ingress, is performed at stochastic level. Consequently, corrosion of reinforcement may initiate in cases when carbonation depth permeates through the whole thickness of concrete cover and/or concentration of chloride ions reaches the critical value. The value of load bearing capacity is assessed for the ultimate as well as the serviceability limit state with respect to the deterioration of the materials. The complex methodology was described in details by authors in [5] and [6].

A single deterministic calculation of structural response is performed repeatedly in selected time nodes from 1 to i with the vector of random input variables, $\mathbf{X}_v$, which is generated for all of the realizations $v = 1, 2, \ldots, n$ at the time of putting the bridge into service and/or in the actual time. Total number of $n \times i$ deterministic calculations is performed. The influence of material deterioration is established into the calculation in the following time node using the value of the effective area of reinforcement. Decreasing of the area of reinforcement is calculated based on the mathematical modeling of corrosion, being in progress from the initiation time, t_i, for all of n realizations separately. Reliability analysis is performed in all of time nodes from 1 to i as a statistical evaluation of the set of structural responses for appropriate model of traffic load corresponding to the investigated load bearing capacity type, V. On the basis of the theoretical model of response, $R(t)$, an estimation of load bearing capacity, $V(t)$, at the time, t, is performed for the target level of reliability and investigated limit state.

The assessment of load bearing capacity of the bridge No. 00431-3 after exceeding its design life

The road bridge No. 00431-3 across the Volyňka river (see Fig. 1) crosses the road of the 3rd class in the village Přední Zborovice in the Czech Republic. Supporting structure is made of two-span reinforced concrete parapet beams with span lengths of about 2 × 14 m. The total length of the beams is 29.5 m. The beam has longitudinal haunches near the pier. The reinforced concrete crossbeams (9 pieces per one span) are fixed to the outer beams and support the bridge deck. The height of the beam is 1.87 m and width is 0.4 m (see Fig. 2).

Fig. 1 Side view of analyzed bridge

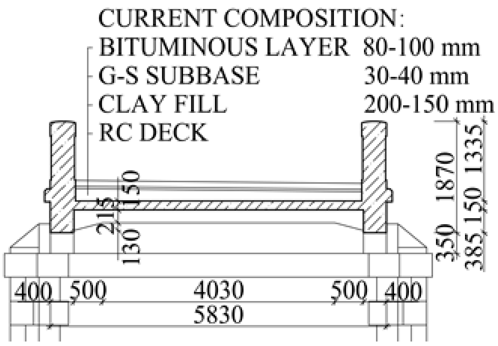

Fig. 2 Transversal section of the bridge

Based on the findings of diagnostic survey (DS) from March 2012 [7] poor current condition of the bridge was assessed which corresponds to the age of the structure about 100 years. The violation of durability limit state (depassivation of reinforcement, spalling of concrete cover and corrosion of reinforcement) is observed mainly on the bottom side of parapet beams, crossbeams as well as on the bridge deck. The loss of the reinforcement bar area in the beams is sporadically as much as 25 %.

The paper takes up the work of authors [6] in which the analyzed bridge was evaluated at the time of reaching its design life, i.e. $t = 100$ years. In the following text the focus is on the development of the theoretical value of the normal load bearing capacity of the bridge, $V_n(t)$, after exceeding the design life, be specific at times $t = 125$ years and $t = 150$ years after putting the bridge into service. The assessment of normal load bearing capacity is performed using the fully probabilistic approach in combination with the nonlinear finite element method (FEM) analysis for the ultimate (ULS) as well as the serviceability (SLS) limit states.

Mathematical modelling of degradation processes. Considering the age of the bridge it was necessary to respect instant degradation processes, such as carbonation of concrete or chloride ingress. Consequently, corrosion of reinforcement and subsequent decreasing of the effective area of reinforcing bars may initiate in cases when carbonation depth permeates through the whole thickness of concrete cover and/or concentration of chloride ions reaches the critical value.

Within the frame of probabilistic modelling of concrete degradation, the mathematical models of carbonation *Carb6* and ingress of chloride ions *Chlor1a* implemented in FReET-D software [8, 9] were used. The model *Corr1* was used in case of modelling of corrosion process. Stochastic models of individual model parameters were adopted from recommendations of [9] and modified according to DS results.

Modelling of degradation processes was performed in the time frame of $t = 0$–150 years by reason of a possible prediction of loss of reinforcement area and value of normal load bearing capacity, respectively in time nodes also after exceeding the design life of the bridge. Reinforcement bar diameter weakened by corrosion due to the effect of CO_2 (d_c) and chloride ions (d_{Cl}) over time is depicted in Fig. 3. Corrosion due to chloride ingress has not started yet because of sufficient thickness of concrete cover in places of their action. Final values along with the values of percentage loss of reinforcement area for uniform corrosion are summarized in Table 1. According to mathematical modelling, the percentage loss of the reinforcement area due to concrete carbonation in current time (t = 100 years) reaches the value of 17.82 %, which is fully in agreement with the diagnosed value 18.3 % on the average. Based on this agreement, we can say that models used for modelling of degradation processes work well and the prediction of the deterioration level can be performed for the future years after exceeding the structural design life.

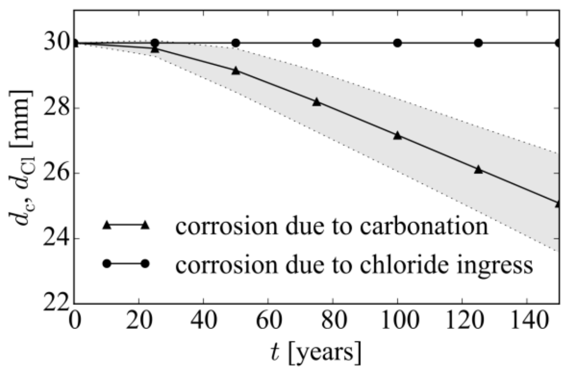

Fig. 3 Reinforcement bar diameter weakened by corrosion due to CO_2 and Cl^- action in time

Table 1 Reinforcement bar diameter weakened by corrosion due to CO_2 and Cl^- action in time

	Mean	Coefficient of variation	$1-\frac{d(t)^2}{d_i^2}$
	[mm]	[-]	[%]
d_i	30.00	-	-
d_c(100 years)	27.17	0.04	17.82
d_c(125 years)	26.13	0.05	23.95
d_c(150 years)	25.09	0.06	29.83
d_{Cl}(100 years)	30.00	0.00	0.00
d_{Cl}(125 years)	30.00	0.00	0.00
d_{Cl}(150 years)	30.00	0.00	0.00

Assessment of normal load bearing capacity. An estimation of normal load bearing capacity $V_n(t)$ of the bridge (as the maximum immediate total weight of one vehicle; vehicles of such weight can cross a bridge in an arbitrary number and with no transport limitation) in time nodes t = 100, 125 and 150 years was performed at the global level of the structure. Values of normal load bearing capacity were assessed for the target reliability level, defined by the target value of reliability index β_t, corresponding to the ultimate as well as the serviceability limit state. According to [4] the target values of reliability indices were considered for the analyzed bridge as follows: for ULS $\beta_t = 3.8$ and $\beta_t = 3.1$, respectively, for common bridges and bridges on the roads of 3rd class, respectively. In case of SLS $\beta_t = 1.5$ and $\beta_t = 1.3$, respectively, for irreversible process with medium and small consequences of damage, respectively.

Nonlinear probabilistic analysis in individual time nodes with respect to the current condition of the bridge was performed using ATENA FEM software [10], in which the computational model of the structure was created, and reliability software FReET [8]. The deterministic analysis was performed in each of time nodes repeatedly with a total number of 32 realizations of the vector of input random variables. Here, particular vectors of realizations of input random variables were generated using Latin hypercube sampling simulation technique, which is capable to cover the space of random variables very well with a relatively small number of samples [11]. The set of 32 structural responses was obtained through the use of successive loading by the increment of unit traffic load according to the valid loading scheme defined in [12], including dynamic effects. The loading scheme related to normal loading class consists of a three-axle vehicle in every traffic line and a continuous load over the bridge width. The load was placed to make out the most unfavorable influence of loading in bending and the model was loaded up to the reaching of the investigated limit state. The influence of ongoing degradation processes was taken into account using results of mathematical modelling (see Table 1). The reinforcement area in the computational model, A_r, for the assessment of normal load bearing capacity was assumed as:

$$A_r = \frac{\pi \cdot d(t)^2}{4}. \tag{2}$$

Based on repeated deterministic FEM calculation of structural damage in ATENA software the set of 32 values of normal load bearing capacity V_n was obtained for ULS and SLS. Consequently, the set of structural responses was statistically assessed in FReET software and normal load bearing capacity of the bridge was estimated. Resulting histograms of values of normal load bearing capacity along with the theoretical probability density functions are displayed in Fig. 4 for individual limit states and time nodes. Resulting values of normal load bearing capacity assessed using fully probabilistic (FP) analysis in individual time nodes, including model uncertainties are summarized in Table 2. The estimation of load bearing capacity was carried out assuming that the structural response has Weibull maximum 3-parametric distribution in case of ULS and log-normal 3-parametric distribution in case of SLS (see solid lines in Fig. 4). These were chosen based on the tests of goodness of fit and correspond to the simulated histograms. Most commonly used normal distribution is also displayed for comparison (see dashed lines in Fig. 4). Values of load-bearing capacity for the actual time were also compared with the value assessed according to current Czech technical standard ČSN 73 6222 [12] using deterministic approach. In case of deterministic analysis using partial safety factors, the reliability level is supposed to be approximately 3.8.

Finally, Fig. 5 shows the decreasing trend of mean values of normal load bearing capacity over time, which is caused by the loss of the reinforcement area due to degradation processes in concrete.

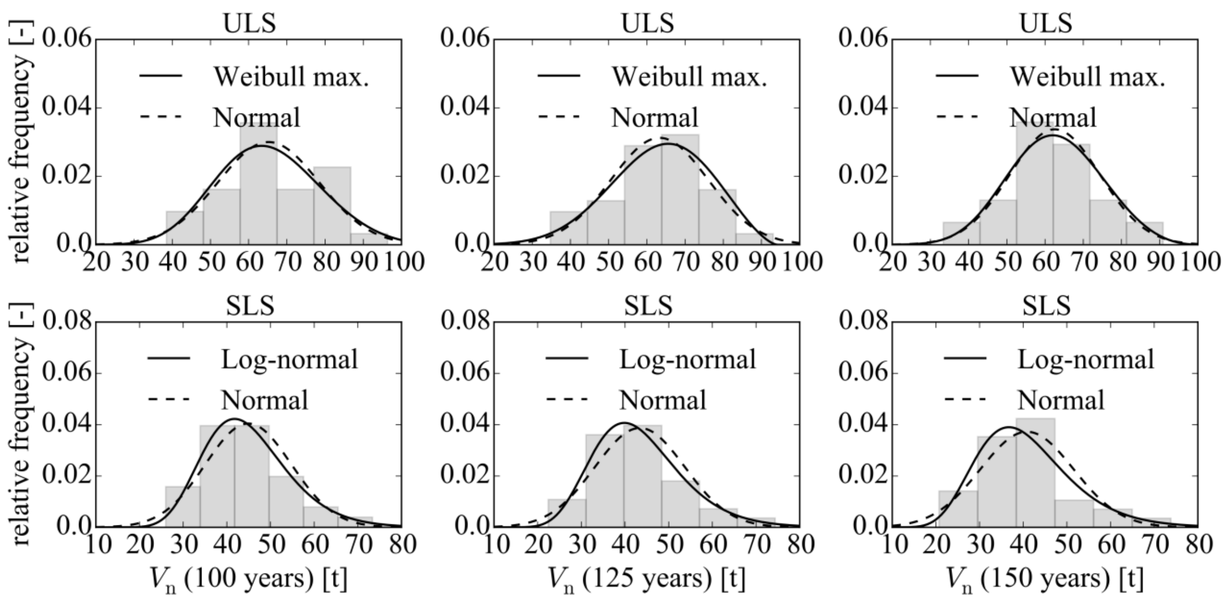

Fig. 4 Resulting histograms of normal load bearing capacity along with the theoretical probability density functions for the ultimate and the serviceability limit states in the investigated time nodes

Table 2 Comparison of values of normal load bearing capacity assessed using fully probabilistic approach for the ultimate and the serviceability limit states in the investigated time nodes with the value assessed according to ČSN 73 6222

	Normal load bearing capacity at time [tons]		
	V_n (100 years)	V_n (125 years)	V_n (150 years)
FP: ULS – β_t = 3,8	21	20	19
FP: ULS – β_t = 3,1	28	28	27
FP: SLS – β_t = 1,5	31	29	26
FP: SLS – β_t = 1,3	32	30	27
ČSN 73 6222	19	-	-

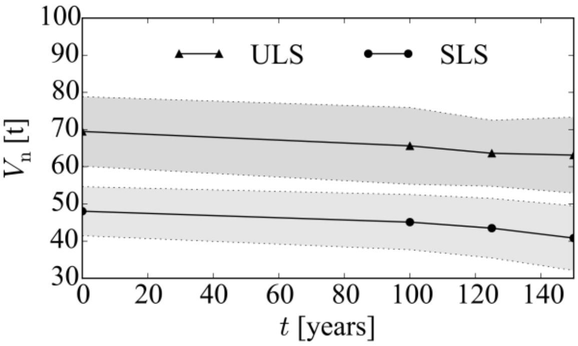

Fig. 5 Development of normal load bearing capacity over time for the ultimate and the serviceability limit states

Summary

The aim of the paper was to introduce the methodology of load bearing capacity assessment of existing structures after exceeding their design life with respect to instant degradation processes in concrete and reinforcement using advanced tools of nonlinear mechanics and probabilistic methods.

Proposed methodology was applied to the analysis of the 100 years old reinforced concrete parapet beam bridge. Values of normal load bearing capacity were assessed for the ultimate as well as the serviceability limit state considering the actual state of the structure. The estimation of values of load bearing capacity was also performed in the time frame of 50 years after exceeding the bridge design life.

It has been proven that probabilistic methods represent an effective tool in cases of evaluation of load bearing capacity and reliability of existing concrete bridges at the actual time with the successive prediction of load bearing capacity for the future. In this manner more realistic conception of gradual decreasing of level of load bearing capacity in time, with respect to the deteriorating condition of the structure due to degradation processes, is obtained. Further, the direct application of probabilistic methods can also serve to gaining valuable information for decision making about maintenance and repairs of bridges.

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