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Modeling of degradation processes in concrete: Probabilistic lifetime and load-bearing capacity assessment of existing reinforced concrete bridges

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A B S T R A C T

A large number of old bridges are to be found on highways and roads all around the world. Considering their age and deterioration level, many of them need to be reconstructed. However, in the majority of cases, the load-bearing capacity of such bridges is just reduced to take account of their current state in spite of the fact that these structures continue to deteriorate. Their detailed reliability and lifetime assessment should therefore be a primary goal. Advanced methods of reliability analysis in combination with nonlinear finite element method-based analysis represent effective tools for the assessment of existing bridges. Data regarding the current level of load-bearing capacity and its expected development in the coming years (and whether or not the required level of reliability will be met) may help in the systematic scheduling of bridge maintenance and/or facilitate decision making about the effective reconstruction of the structure. This paper introduces a method for the probabilistic determination of the load-bearing capacity of bridges with respect to the progression of ongoing degradation processes over time. The method is used to determine the current load-bearing capacity of a 60-year-old reinforced concrete bridge, and for its estimation in the coming years until the end of the theoretical service life of the structure.

1. Introduction

An important aspect of the design and assessment of concrete structures is ensuring a particular level of safety and reliability. The reliability of a structure comprises its safety against structural collapse, and its serviceability and durability. Each of these requirements can be noted as a particular limit state which is exceeded when the structure does not meet the relevant criteria. The reliability analysis of structures is focused on evaluation and the prediction of the probability of reaching certain investigated limit states, i.e. the failure probability, p_f.

Generally, ultimate limit states (ULS), which concern the safety of persons and/or the safety of the structure itself, and serviceability limit states (SLS), which concern the functionality and visual appearance of structures or the comfort of people using them, are investigated. The durability limit state (DLS) can also be investigated from the perspective of the influence of the surrounding environment. Structures should be designed so that instant degradation processes will not affect structural serviceability beyond an acceptable level during their design life.

Fundamentals and requirements as regards structural safety, serviceability and durability are described in current structural design standards, e.g. in Eurocode [1]. This description is mainly based on the limit state approach in combination with the partial safety factor method. The numerical values of these factors are calibrated and recommended in order to reach the acceptable level of structural reliability. During structural design or the assessment of existing structures, the deterministic design values of load E_d and structural resistance R_d are compared. To obtain a reliable design, the following must hold:

$$E_d = \gamma_{Ed} \cdot E \leqslant R_d = \frac{1}{\gamma_{Rd}} \cdot R, \quad (1)$$

where γ_{Ed} and γ_{Rd} are partial safety factors of load and resistance, respectively.

As an alternative to the comparison of deterministic values E_d and R_d, structural design and assessment can be based on the probabilistic approach, where each of the compared values E and R is conceived as a random variable defined using the appropriate probability density functions (PDFs) $f_E(\cdot)$ and $f_R(\cdot)$, respectively. The failure probability, p_f, can be then defined as:

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$$p_\mathrm{f} = P(R \leqslant E) = P(R - E \leqslant 0), \quad (2)$$

where $R - E$ can be noted as the safety margin $Z = G(R, E)$, where G is the limit state function.

Generally, each of the variables R and E is the function of several random variables X_i for $i = 1, 2, \ldots, N_\mathrm{V}$, with N_V being the number of random variables. Some degree of statistical correlation can exist among these variables. The failure probability can be defined using the joint probability density function of the vector of random variables $\mathbf{X} = (X_1, X_2, \ldots, X_{N_\mathrm{v}})$ as:

$$p_\mathrm{f} = \int_{D_\mathrm{f}} f(\mathbf{X})\mathrm{d}\mathbf{X}. \quad (3)$$

Here, the region of integration is limited to the failure domain, D_f, where $G(\mathbf{X}) \leqslant 0$. The reliability level can be alternatively described using the reliability index, β. The relationship between β and p_f is:

$$p_\mathrm{f} = \Phi_\mathrm{N}(-\beta), \quad (4)$$

where $\Phi_\mathrm{N}(\cdot)$ is the cumulative distribution function of the standard normal distribution.

The use of probabilistic methods and structural reliability theory in the analysis of existing bridges enables their verification with increased accuracy. This analysis is based on information about the current state of the investigated bridge obtained from diagnostic surveys, including the degree to which building materials have deteriorated. For example, in [2,3] it was demonstrated that the performance of a more thorough probabilistic analysis of bridge structures at their critical limit states leads to higher load-bearing capacities. As a result, in some cases structures may remain in service with no strengthening or rehabilitation without compromising the required level of structural safety. Consequently, the use of probabilistic methods has also been demonstrated to provide significant cost savings to bridge owners.

With regard to the current level of deterioration of existing bridges, the importance of load-bearing capacity and reliability evaluation is growing. It is important to define the so-called limiting lifetime of structures in connection with the exceeding of technical, functional or financial requirements concerning structural durability. Nevertheless, the classical (ultimate or serviceability) limit states may not be reached.

In the case of reinforced concrete bridges, the reinforcement depassivation limit state (which can be classified as a durability limit state) can also be involved. Here, the protective layer on the reinforcing bars can be depassivated due to the action of atmospheric CO_2 or chloride ingress from de-icing salts or other aggressive substances, possibly leading to the initiation of reinforcement corrosion. The resulting corrosion products have a severalfold higher volume than the original material and can lead to the erosion of the concrete layer. The reinforcing bars are thus under direct attack. In connection with the decrease in the reinforcement area, the load-bearing capacity of the bridge is consequently reduced. It hence appears that predictive models are needed to estimate how resistance, loads and safety level will change over time in order to assess existing bridges more realistically.

The verification of limit states associated with the durability of structures may be performed according to Model Code 2010 [4] using the fully probabilistic format, partial safety factor format, deemed-to-satisfy approach or avoidance-of-deterioration approach. Note that only the fully probabilistic approach provides quantitative information about safety level, and that there are also other reasons why the dominance of this format is evident.

In the case of durability, the service life format consists of determining the remaining design life, t_d, of a structure or structural component, and its comparison with the predicted service life, t_s. In order to ensure the safety of the structure and its components, the predicted service lives, t_s, should meet or exceed their design lives, t_d, i.e.:

$$t_\mathrm{s} \geqslant t_\mathrm{d}. \quad (5)$$

The predicted service life t_s can be determined as the sum of two service life periods – so-called initiation time, t_i, which is the time when the initiation of reinforcement corrosion takes place, and the propagation period, t_p, which is the part of the design life after corrosion initiation:

$$t_\mathrm{s} = t_\mathrm{i} + t_\mathrm{p}. \quad (6)$$

Frequently, the initiation period only serves as a decisive limit state considered to be a limit for service life, i.e.:

$$t_\mathrm{s} = t_\mathrm{i}. \quad (7)$$

In the probabilistic approach, the failure probability, p_f, at time t_d is compared with the specific target failure probability value, $p_\mathrm{f,t}$. The predicted service life t_s is a function of random variables X_i and of time t:

$$p_\mathrm{f}(t_\mathrm{d}) = P\{t_\mathrm{s}(X_i, t) < t_\mathrm{d}\} \leqslant p_\mathrm{f,t}. \quad (8)$$

As an alternative means of expressing the reliability level, reliability index β can be utilized instead of the failure probability in practice. This indicator of structural reliability is well-known today and is prescribed in design codes. In the case of the service life format, the value β is then compared with the target reliability level defined by the design value of the reliability index, β_t.

In the paper, a deteriorated reinforced concrete bridge is analyzed as a case study. The advanced Monte Carlo type simulation method is used in combination with a nonlinear finite element method-based (FEM) computational model to assess the load-bearing capacity and reliability of the bridge over time. The influence of degradation processes, such as concrete carbonation, chloride ingress or corrosion of reinforcement, is also taken into account based on phenomenological models. The prediction of load-bearing capacity over the design life is also performed.

2. Methodology

When using probabilistic methods, the procedure for the load-bearing capacity assessment of existing bridges is as follows. First, deterministic analysis is performed to identify the critical limit state. Next, the target reliability level is defined according to the appropriate standards, such as ČSN ISO 13822 [5] and TP 224 [6], where the minimum safety requirements in terms of the target reliability index, β_t, are specified. Values for the target reliability indices, β_t, and corresponding probabilities of failure, p_f, according to TP 224 [6] and *fib* Bulletin No. 34 [7] (for the durability limit state) are presented in Table 1 and can be specified in more detail depending on residual lifetime estimates, the consequences of damage, or considering the economic, social and environmental consequences. Very small (category CC1a), small (CC1b), medium (CC2) and high (CC3) consequences of damage (COD) are distinguished with respect to possible loss of human life and the consequent reliability levels are then specified; see Table 1.

The next step in the process of assessing load-bearing capacity is the stochastic modeling of basic variables, such as material properties and loads. Here, the information from bridge inspections should be included to reduce model uncertainties. After the description of input variables via statistical parameters and theoretical models of PDFs with regard to all information and other recommendations, repeated deterministic analyses are performed with generated vectors of random variables. Finally, the failure probability or reliability index is calculated using probabilistic methods. The computed reliability index, β, is then compared with