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POUZDANOST I PROCJENA TRENUTNOG STANJA UPORABIVOSTI KONSTRUKCIJE

STRUCTURAL RELIABILITY AND EVALUATION OF CURRENT STATE OF CONSTRUCTION

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Stručni članak

Sažetak: *Većina oštećenja u armiranobetonskim konstrukcijama dogodilo se kao rezultat opterećenja, tj preopterećenja. Ako je to povezano s faktorom trajnosti konstrukcije, onda moramo gledati vrijeme nastajanja štete, tj. vrijeme kada je postalo jasno da je konstrukcija počela popuštati. Granično stanje uporabljivosti odgovara stanjima iza kojih zahtjevi za korištenje konstrukcije ili konstrukcijskih elementa više nisu ispunjeni. Ovaj članak se bavi pouzdanosti konstrukcije i indeksom pouzdanosti kao najčešće korištenom veličinom za prikaz pouzdanosti konstrukcije. Opći postupci procjene stanja konstrukcije i njihove granice detaljno su opisane u članku.*

Ključne riječi: *indeks pouzdanosti, oštećenje konstrukcije, pouzdanost konstrukcije, postupci procjene*

Professional paper

Abstract: *Most of the causes of damage in reinforced concrete constructions happened as a result of the load, i.e. overload. If this is connected to the durability factor of the construction, then we need to look at the time of damage formation – that is the time when it became clear that the structure began to yield. Serviceability limit state correspond to states beyond which requirements for use of construction or construction element are no longer fulfilled. This article deals with the structure reliability and index of reliability as the most commonly used measure of the structure reliability. General assessment procedures for construction and its boundaries are described in detail.*

Ključne riječi: *structure damage, structure reliability, index of reliability, evaluation procedures*

1. INTRODUCTION

Various authors, technical committees and regulations have dealt with damage classification through history. As for the rules, Eurocode 2 and Derzhavni budiveljni normi Ukrajini (DBN) prescribe restrictions in the design area of structure (due to the temperature effect, creep and shrinkage of concrete, long-term compressive stress, maximum crack). Regulations in other European countries are written in a similar way.

The RILEM (International Union of Laboratories and Experts in Construction Materials, System and Structures) technical committee DCC-104 in 1991, after a three-year work brought out a state-of-the-art report on the classification of damage in concrete structures. In summary, it can be said that most of the damage to concrete structures originates due to the generally poor design (design phase of construction), poor technology and poor quality of construction materials (construction phase), overloading of the structure (exploitation phase, but also the design!) and from a variety of atmospheric and chemical influences. The actual classification can be illustrated by the following picture (Fig 1):

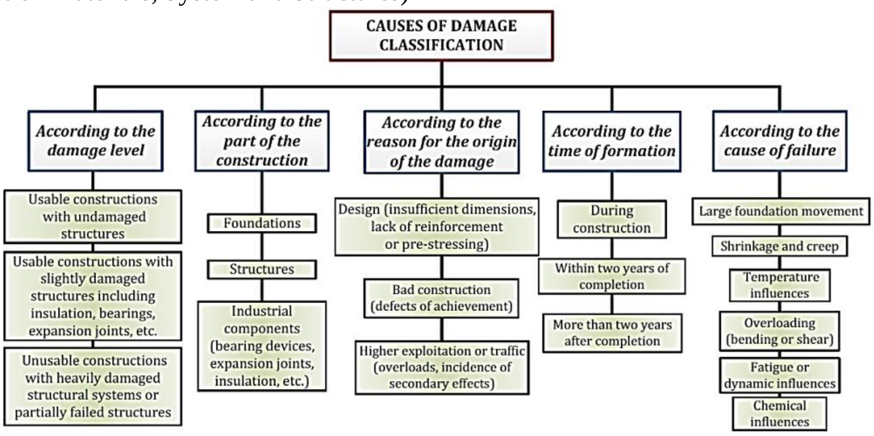

Fig 1 Classification of causes of damage on reinforced concrete structures

If we look at the cause of the damage, the most interesting thing is the appearance of cracks (a manifestation of damage) as a result of the load, i.e. overload. If this is connected to the durability factor of the construction, then we need to look at the time of damage formation – that is the time when it became clear that the structure began to yield (formation of cracks). Considering this, the formation of cracks can be divided due to: a) overloading without permanent deformation (short-term overloading in the elastic area of stress), b) overloading with permanent deformation (deformation over the elastic limit).

Calculation methods according to the limit states are based on the analysis of bearing capacity of materials. It is clear that the calculated bearing capacity is only theoretical state because it is insured with more safety factors. In fact, we can say that the theoretical strength of concrete is 55-65%.

2. CALCULATION OF THE EXISTING STRUCTURES

Serviceability limit state correspond to states beyond which requirements for use of construction or construction element are no longer fulfilled. They include structure retaining in the elastic range, the functionality of the structure or its parts, people comfort and external appearance of the structure. We differ reversible and irreversible serviceability limit states and three combinations of action for the usability calculation: characteristic, frequent and constant.

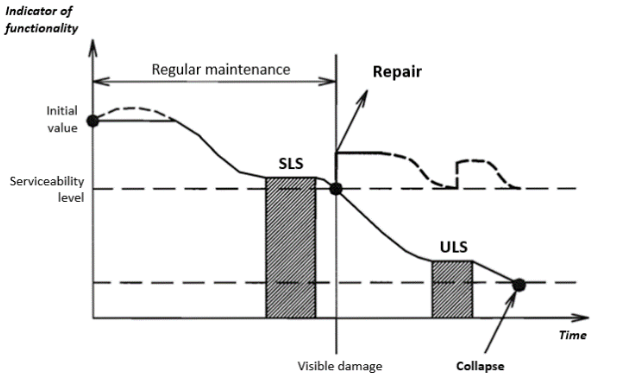

Fig 2 Possible behavior of the structure during the lifespan

The calculation model which is being implemented for calculation of existing structure must show appropriate behavior of the structure, resistance of its parts and load in accordance with the actual state of load on the existing structure.

2.1 Simple calculation methods

For lower-level assessment often is effectively calculating accordingly on basic conservative methods using simple calculation models taking into consideration safety of structure. Typical simple calculation methods are those conducted on the spatial framework and rod elements taking into consideration simplified distribution of load and linear elastic behavior of the material, resulting with equilibrium solution at the lower limit.

2.2 Complex calculation methods

When lower-level assessment has failed, more detailed calculation methods should be used. These include the finite element method and nonlinear methods (analysis of yield) which may result in higher bearing capacity. Specific modeling of time varying behavior material (shrinkage and creep of reinforced and prestressed concrete structures) and taking into account the interactions between the components of a material (adhesion, impact of embedded reinforcement) will reveal the hidden reserves of the structure and reduce the conservatism of simpler methods. When applying fully probabilistic assessment, stochastic finite elements can be used. The difference compared to conventional finite elements is that stochastic take into account of spatially interdependence of random variables. The method of stochastic finite element in contrast to the classical deterministic finite element method involves random changes in material and geometric properties of the model and random forces acting on it.

2.3 Adaptive calculation methods

In order to use within the evaluation of construction new information on its behavior (eg. due to long-term observation), calculation models need to be adjusted. By adapting the model it is possible to restore the structural variables (eg. properties of stiffness) by using measured data, such as changes in displacements, deformations, damage values (eg. the crack width).

2.4 Structure reliability

Approach to structural reliability assumes that the behavior and state of the structure is fully determined by a finite number of random variables and a finite number of connections between them. These variables are on the one hand the characteristics of the structure (geometry, resistance), on the other hand the characteristics of the observed actions on the structure. With relationships between these variables we can describe the failure of the individual parts or of entire construction.

If the P_f indicates the probability of construction failure, then the reliability can be seen as the probability that there will be no failure (chance of survival) and can be defined as the complement of P_f. The probability of failure can be generally expressed with the function of of behavior g for which applies that the observed structure will "survive" if g>0, or it will come to a construction failure if g≤0:

$$\begin{aligned} P_f(g \leq 0) &= \int_{g \leq 0} \varphi(X) dX \\ &= \int_{g \leq 0} \varphi(x_1, x_2, \ldots., x_n) dx_1 dx_2 \ldots dx_n \end{aligned} \tag{1}$$

Here is φ(X) common function of probability density of the vector of all basic variables X. The calculation of this equation is often a very complex task. There are two basic methods of calculation probability of failure:

The exact methods (level III) based on simulation techniques that are time-consuming calculations. A simple rule can be given in the form of:

$$N > C/P_f \tag{2}$$

where N is the required number of samples, and C is a constant related to the level of confidence (Eng. confidence level) and the type of function that is determined by. The default value of C can be 100 and higher.

Approximate methods (level II) use approximate methods for determining probability of failure that are fast and reliable. The best known are FORM - First Order Reliability Method) and SORM - Second Order Reliability Method.

Approximation of failure surface in calculation point can be linear (FORM approximation) or another approximate function of the second order (SORM approximation). In FORM method the probability of failure is approximately expressed by:

$P_f = \varphi(-\beta)$ φ→ distribution function of a standard normal variable

In SORM approach the failure surface is approximated with hyperbolic paraboloid passing through calculation point. In this case, the probability of failure is given by expression that takes into account the different individual curves in calculation point:

$$P_f = \varphi(-\beta)\prod_{i=1}^{n}(1-k_i\beta)^{-1/2} \tag{3}$$

2.5 Index of reliability

The most commonly used measure of the structure reliability is the index of reliability.

$$\beta = -\varphi^{-1}(\mathrm{P_f}) \tag{4}$$

where $\varphi^{-1}(\mathrm{P_f})$ represents an inverse function of the standardized normal distribution probability of failure P_f. The general view can be presented by taking into consideration two variables, R and E resistance and effect of action impact. In the base case the reliability of the structure function of behavior (reliability limit) g can be described with:

$$g = R - E \tag{5}$$

Assuming that the R and E mutually independent random variables with normal distribution with medium values μ_R and μ_E and with standard variations σ_R and σ_E, then g also has a normal distribution with a median value and standard variation:

$$\mu_g = \mu_R - \mu_E \tag{6}$$

$$\sigma_g = \sqrt{(\sigma_R^2 + \sigma_E^2} \tag{7}$$

Distribution of reliability limit is shown on Fig 3 where the probability of failure can also be seen ($P_f = probability(g \leq 0)$, and also the probability of survival $P_s = probability(g > 0)$.

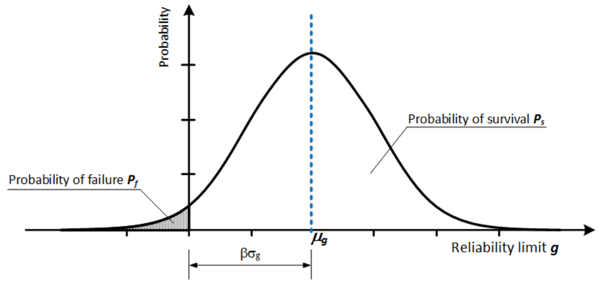

Fig 3 Distribution of reliability limit

Thus, the collapse of the structure corresponds to the event described with the inequality g <0. As g has a normal distribution, the probability of failure Pf can be determined by transforming g into standardized normal variable given by:

$$u = \frac{(g-\mu_g)}{\sigma_g} \tag{8}$$

For the critical value of function behavioral g = 0, standardized variable has a value of:

$$u = \frac{-\mu_g}{\sigma_g} \tag{9}$$

The probability Pf is then given with standardized normal function of distribution in critical point $u = -\mu_g/\sigma_g$,equal to the limit of reliability g = 0:

$$P_f = \varphi(-\mu_g/\sigma_g) \tag{10}$$

where φ represents standardized normal distribution function. Because there is connection between the probability of failure and index of reliability $P_f = \varphi(-\beta)$, in the observed base case of structure reliability, assuming a normal resistance distribution R and the effect action E, index of reliability is:

$$\beta = \frac{\mu_g}{\sigma_g} = \frac{\mu_R-\mu_E}{\sqrt{(\sigma_R^2+\sigma_E^2}} \tag{11}$$

In this case the index of reliability represent the distance of reliability limit average value g from the start (zero), taking a standard variation σ_g from g as a unit measure. However this expression for the probability of failure and index of reliability is valid only by assuming normal distribution of both primary variables R and E. In the general case, when R and E have a non-normal distribution, the above expressions can be considered as first assessment, and the more accurate probability of failure can be determined by the expression:

$$P_f = \int_{-\infty}^{+\infty}\varphi_E(x)\varphi_R(x)dx \tag{12}$$

$\varphi_E(x) \rightarrow$ function of probability density of the action effect E

$\varphi_R(x) \rightarrow$ distribution function of resistance R

When failure probability is known, the index of reliability is determined from the expression:

$$\beta = -\varphi^{-1}\,(P_f) \tag{13}$$

The probability of structure failure, and therefore its reliability is time-variable. If the resistance of a structure reduces with time, with increasing the load, index of reliability over time will be reduced. Three possibilities of reliability change are shown in Fig 4.

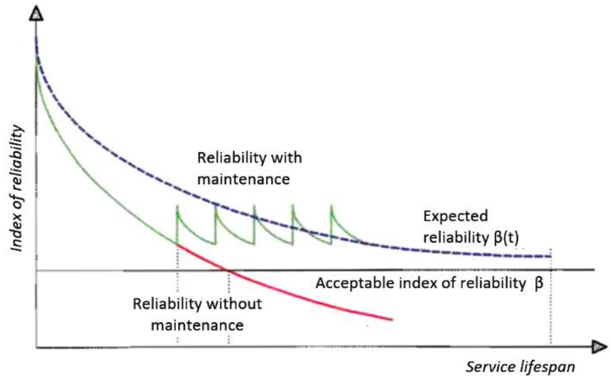

Fig 4 Possibilities of reliability change in construction lifespan due to structure maintance: The blue curve shows the expected behavior of the structure in its lifespan; red line shows the unacceptable behavior of the structure as the lower limit of acceptable behavior has been reached during construction usage; green line shows the behavior of the structure by taking adequate activities at specific time intervals which maintained the level of reliability.

3. EVALUATION PROCEDURES OF CURRENT STATE OF CONSTRUCTION

Evaluation of existing structures can be implemented through procedures of various sophistication and with different investment efforts. General assessment procedures can be divided into three categories:

1) Assessment based on measurements - methods in which the effects of actions are determined by direct measurements, not by construction calculations. As the measures of serviceability can be determined only by direct measurements, these are assessment methods exclusively of serviceability limit states.
2) Assessment based on models - methods in which the effects of actions are determined by calculation models. With this methods can be modeled and hence evaluate the ultimate limit state of construction as well as serviceability limit state. The methods consists of three steps: 1. collecting data on actions and resistance of structure; 2. calculation of effects on construction model; 3. evaluation of bearing capacity and usabillity (serviceability).
3) Informal assessment – methods based on experience and judgement of engineers that deals with evaluating. Structure condition is evaluated based on visual inspection. Therefore, these methods are more or less subjective and are applied only exceptionally.

The proposed assessment levels are not strict, and the boundaries between them are flexible (all shown through Table 1):

- Level 0: informal qualitative assessment - assessment based on the experience of engineers to visually assess the effects of the aging (cracks, flaking, chipping, corrosion), mainly used for preliminary evaluation of the structure.
- Level 1: determination of the action effect by measurements - evaluates the usage by comparing the measured and limit values given by regulations or determined individually.
- Level 2: assessment approach by partial factors based on a documentation review - evaluates the capacity and serviceability of existing structure on the simple calculation models by using data from main and detailed design and inspection documentation.
- Level 3: assessment approach by partial factors based on additional tests - evaluates the capacity and usability of existing structure in an improved and detailed calculation models by using data on the structure obtained from detailed non-destructive tests.
- Level 4: assessment of targeted reliability with modified partial coefficients - Values of partial coefficients are adjusted for a group of structures with similar structural behavior or actions. Targeted reliability is adopted, and assessment of capacity and usability is carried out taking into consideration values that are adjasted to a specificconstruction.
- Level 5: fully probabilistic assessment - structure reliability calculation is carried out directly (without partial factors) for what is necessary to know the statistical properties of all the basic variables. Uncertainties are modeled probabilisticly.

Table 1 The classes and levels of structure evaluation and adequate procedures

<table>
<tr><th colspan="2">LEVELS OF EVALUATION</th><th colspan="3" rowspan="2">EVALUATION PROCEDURE</th></tr>
<tr><td>OBJECTIVE OF EVALUATION</td><td>EVALUATION LEVEL</td></tr>
<tr><td colspan="2">INFORMAL ASSESSMENT</td><td colspan="3" rowspan="2">Assessment based on the experience of engineers to visually assess the effects of the aging (cracks, flaking, chipping, corrosion), mainly used for preliminary evaluation of the structure.</td></tr>
<tr><td>Qualitative state assessment</td><td>Level 0</td></tr>
<tr><td colspan="2">EVALUATION BASED ON MEASUREMENTS</td><td colspan="2">Determination of the effects of actions</td><td>The process of proving</td></tr>
<tr><td>Quantitative evaluation of usability</td><td>Level 1</td><td colspan="2">Measuring the values of certain parameters under the applied load (actual or experimental)</td><td>Comparison of measured
and limit values</td></tr>
<tr><td colspan="2">EVALUATION BASED ON MODELS</td><td>Collection of data</td><td>Calculation model</td><td>The process of proving</td></tr>
<tr><td rowspan="4">Quantitative evaluation of the bearing capacity and usability</td><td>Level 2</td><td>From designs and regulations
Construction examinations</td><td>Basic models
Detailed models</td><td>Deterministic (exceptionally)
Semi Probabilistic (parc. coefficient.)</td></tr>
<tr><td>Level 3</td><td rowspan="2">Construction examinations (measurements) and material testing.
Monitoring for system recognition
Load monitoring
The evidential load</td><td>Detailed models (FEM, nonlinear calculations)
Adjusted models</td><td>Semi Probabilistic (parc. coefficient.)</td></tr>
<tr><td>Level 4</td><td>Detailed models (MKE, nelinearni proračuni)
Adjusted models</td><td>Semi Probabilistic (parc. coefficient.)
Approximate probabilistic methods (FORM, SORM)</td></tr>
<tr><td>Level 5</td><td>As for levels 3 and 4
+
The statistical data properties</td><td>Simple adjusted models
Stochastic models of finite elements</td><td>Approximate probabilistic methods (FORM, SORM)
Simulation probabilistic methods (MCS)</td></tr>
</table>

4. CONCLUSION

There are different methods to assess the reliability, and to improve the prediction of lifetime and the management of civil engineering structures in an uncertain context. Main questions while designing construction are: How can the most likely failures and the most critical failure scenarios, which could optionally be the basis of risk analysis, be highlighted; How can uncertain data, describing the geotechnical characteristics of materials, be represented and used; what are the consequences of heterogeneity and variability for structural safety; How can the reliability or durability of a system be quantified; how can information gained over time be used to update reliability calculations; How can a policy of inspection and maintenance be optimized? In an engineering context, methods we use must allow us to analyze a system, its failure modes, and to model the failure scenarios in order to evaluate their criticality.

Maintenance optimization must be planned using reliability methods, including a presentation of the concepts of maintenance and lifecycle costs of a system. Cost models for the maintenance of components and systems must be defined in order to allow the selection of an optimal maintenance policy. Designers (engineers) should remain cautious: the result of any study are highly dependent on assumptions made and models used (whether physical, mechanical or probabilistic). Main question will always be: is the problem well-posed and the system being studied well defined, and analyzed by structural and functional approaches? An analysis of a system makes sense only for the problem being solved, especially in the context of a multicriteria analysis. There is not one single unique definition of components and their relationships.

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