Design method for reinforced concrete structure durability with the use of safety coefficient by service life period

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Abstract. The given method uses the safety coefficient by service life period and similar principles as for stochastic method. Moreover, the problem of forecasting the safety is examined in a deterministic form. The given option for the solution is compact in terms of design on an applied level in the format of the boundary conditions method, keeping the efficient control of safety within the service life period. This method has the advantage to design reinforced concrete structures for specified service life period. The proposed method is also applicable for the design of reinforced concrete elements of hydraulic structures in cases when the application of the other stochastic methods would be very complicated. The advantage of the given method is allowing including the stochastic nature of loading parameters and material strength.

1. Introduction

The safety coefficient is determined by the use of direct stochastic methods. Based on the operational period of hydraulic structures, the proposed method takes into consideration the life cycle of structure elements. The new elements of the given method by relation to regulations [2] are accepting time factors in estimating the probability of damage \( P(t) \), safety factor \( \theta(t) \), and especially reliability coefficient by service life period \( \gamma_t \). In comparison, in other foreign works they have used different values, for instance, strength safety factor \( G \) [3, 4], safety factor \( Z \) [4], reliability factor \( Z \) [5], and composite function of structure element functionality \( Z \) [6]. Based on this in our work we are intended to use the safety factor, which is presented in documents [7, 9].

2. Methods

In the given method the use of stochastic methods is spread to the solution of functionality problems [7, 10]. The use of the reliability coefficient by service life period allows to estimate the durability of structural elements in the deterministic formulation. The uniqueness of the method is in estimating the probability of damage, related to durability in conditions of probable decrease of reliability coefficient \( \theta(t) \) for \( t \rightarrow t_d \). The formulas used from [1, 8] in the deterministic option are given below:

\[
R(t) - S(t_d) > 0
\]

(1)

\[
t_L - t_d > 0
\]

(2)

\[ R(t) - S(t_d) > 0 \]

\[ t_L - t_d > 0 \]
In designing structure element durability set by time design value of service life \( t_d \) is examined, which is equal to the product of mean service life value to reliability coefficient by service life period, and it means that we can use the following equation:

\[ t_d = \gamma_t t_g \]  

where
\( \gamma_t \) is reliability coefficient by service life period;
\( t_g \) is specified service life.

Coefficient measure \( \gamma_t \) depends on the maximally allowable probability of damage. Based on this, the coefficient \( \gamma_t \) is determined together with design results. In comparison to deterministic approaches, the examined approach presents guarantees to safety control against damage during the service life period of the structural element. Based on this we can determine safety reserve as follows using the following relationship:

\[ \theta(t) = R(t) - S(t) \]  

where
\( R(t) \) is structure element resistance;
\( S(t) \) is stress.

When the safety coefficient is used, the requirement for a specified service life period is transformed into a requirement of mathematical expectation for service life period. The reason for it is that applied durability models that are optimal for realities of structure element design, often demonstrate the mean quality or mean degradation, since mean values of the function are often used in the design. As an outcome the safety coefficient for service life period is the ratio of the mean service life period to a specified service life period, i.e.:

\[ \gamma_t = \mu(t_L)/t_g \]  

where
\( \gamma_t \) is safety coefficient by service life period, corresponding to accepted design service life period;
\( \mu(t_L) \) is the value of service life period;
\( t_g \) is a specified service life period.

Reinforced elements of structures are provided with material characteristics to meet reliability conditions in deterministic option in the form of boundary conditions method, expressed in terms of principles of operational quality guarantee of keeping specified reliability during structure service life period:

\[ R_d(t_d) - S_d(t_d) \geq 0 \]  

where
\( R_d(t_d) \) is design value for the resistance of reinforced concrete elements of the structure at the end of service life;
\( S_d(t_d) \) is design value for the impact of environmental on reinforced concrete structure element at the end of the design service life period.

Under mechanical and chemical impact on structure element reliability conditions correspond with the following relationship:

\[ S_{ds} \leq S_{de} \]  

Based on this, design parameters for mechanical and corrosion impacts are given with [8]:

\[ S_{de} = S(\sum_j \gamma_{cG_j} \cdot G_{kj} \cdot \gamma_c - a_k; \sum_m \gamma_{Qj} \cdot \gamma_{Qc} \cdot \psi_{Qc} - Q_{kj}) \]  

where
\( G_{kj}; Q_{kj} \) is characteristic values for constant and varying mechanical impacts;
\( \gamma_{cG_j} \cdot \gamma_{cQj} \) is reliability coefficients for constant and temporary loads, correspondingly, and only for corrosion impacts;
\( \psi_{Qc} \) is the coefficient for the combination of temporary loads and corrosion impacts.
Design value for structure element resistance is given in the following form:

\[ R_{D,C} = R(X_{C,D}; \gamma_c a_k; ...) \]  
(9)

where

- \( X_{C,D} \) is design characteristics for concrete and rebar under corrosion impacts;
- \( \gamma_c a_k \) is design value for the depth of corrosion in steel rebar.

In case of absence of steel depassivation the equation (7) gets the form (6) and it is presented the following way:

\[ \gamma_c P_k(t_{serv}) < d/\gamma_c\mu \]  
(10)

where

- \( \gamma_c P_k(t_{serv}) \) is design value for the depth of aggressive environment penetration into concrete during the planned service life period of structure element;
- \( d/\gamma_c\mu \) is the nominal value for concrete protective layer thickness, decreased to the corresponding value for reliability coefficient \( \gamma_c\mu \).

Stochastic methods are applied to determine the relationship between the safety coefficient and the probability of damage. Based on the above-mentioned material properties relationship (6) transforms into the following:

\[ R(t_d) - S(t_d) > \theta_{min} \]  
(11)

where

- \( \theta_{min} \) is an allowable level of safety reserve, which guarantees the main safety of the structure element from mechanical impacts and considers the process of concrete damage during the structure operation period under the impact of the environment.

In designing the loads safety of reinforced concrete elements can be estimated with safety characteristics \( \beta = \beta_0 \) considering the method of boundary conditions. For normal distribution safety characteristics \( \beta^* \) is taken in the following form following [8]:

\[ \beta^* = \frac{D_{max} - D_G}{v_D D_G} = \frac{1}{v_D} \left( \frac{D_{max}}{D_G} - 1 \right) \]  
(12)

where

- \( D_G \) is mean degradation, corresponding to the specified service life period;
- \( D_{max} \) is maximal possible degradation;
- \( v_D \) is coefficient of variation.

The existing research has justified that safety characteristics parameters can be determined using the design formula in the following form:

\[ \beta^* = \frac{(R - \bar{R})}{(\sigma^2 - 2k_{RF} \sigma_F^2)^{1/2}} \]  
(13)

where

- \( S = (\bar{R} - \bar{F}) \) is the mathematical expectation of resistance;
- \( \sigma \) is standard deviation;
- \( k_{RF} \) is the coefficient of correlation under study between stress and carrying capacity.

With the use of safety characteristics, we can determine load and non-load factors for the probability of damage under simultaneous action. Based on this the formula is presented in the following form:

\[ \beta_t = \frac{R_d - S_d - tv_{R,max}}{(S + S^2 + t^2 v_R)^{1/2}} \]  
(14)

where

- \( t \) is duration of the impact of the aggressive environment;
- \( v_R \) is decrease velocity of resistance.

Based on the mechanical impacts on the structure element, the safety reserve can be presented in the following form:

\[ \theta_{min} = \beta_m \sigma_o \]  
(15)
\( \sigma \) is mean quadratic deviation of safety reserve; 
\( \beta_m \) is the required value of safety characteristics for random value \( m \) under load action.

For normal law of distribution of random value \( \theta = R - S \) to estimate the functionality of reinforced concrete elements the probability \( P(\theta > 0) = \Phi(\beta) \) is used in the case of asymmetry coefficients are close to zero. Parameters \( P(\theta > 0) \) and \( \beta_0 \) tabulated in work [11], \( \beta_0 = 0; 1.64; 3.1; 3.3 \) match with \( P% = 50\%; 45\%; 99.9\%; 99.99\% \). Based on [7] safety characteristics \( \beta_m = 3.8 \) for structural elements of first group boundary conditions match with \( 7.2 \times 10^{-5} \) and \( \beta_m = 2.5 \) for structures of the second group boundary conditions match with \( 6.2 \times 10^{-5} \). The given parameters are presented based on definitions of normative values for loads and material strengths.

Safety in terms of durability is expressed in terms of mechanical safety based on regulations, that the decrease of the degree of the latest as the result of degradation processes will be at the end of service life period within borders of allowable values. The given safety in real design is controlled with safety coefficient by service life period. Relationships between safety requirements concerning durability and safety coefficient by service life period are given in [7].

Based on this, \( \theta(t) \) can be presented in the following form:

\[
\theta(t) = \theta_c(1 - kt^n)
\]  

where
- \( \theta_c \) is safety reserve at \( t = 0 \); 
- \( n \) is exponent; 
- \( k \) is constant-coefficient, \( n \), which is a characteristic of degradation phase.

It is assumed that the increase of reserve loss by \( \Delta \theta(t) = \theta_c - \theta(t) \) is a normally distributed quantity and standard \( \theta \), specified from degradation, and it is directly proportional to \( \Delta \theta(t) \). Based on this, the coefficient of variation \( v_D \) is presented as constant:

\[
\mu(\Delta \theta) = \theta_c kt^m
\]

\[
\sigma(\Delta \theta) = v_D \theta d kt^m
\]

During the periods of structure operation \( \mu(\Delta \theta) \) decreases and parameter \( \sigma(\Delta \theta) \) increases. Safety reserve transformation is given in the following form:

\[
\beta_t \sigma_t = \theta_t - \theta_{\min}
\]

\[
\beta_t = (\theta_t - \theta_{\min}) / v_D (\theta_c - \theta_t)
\]

where
- \( \sigma_t \) is standard deviation \( \Delta \theta_t \); 
- \( \theta_t \) is a safety reserve; 
- \( \beta_t \) is required safety parameter for \( t = t_\theta \).

Parameter \( \gamma_t \) now depends only on \( \beta_t \), coefficient of degradation variation and exponent \( n \) and it does not depend on service life period, also a parameter \( \gamma_t \) depends on the maximally allowable probability of damage to the structure element.

Necessary parameters for the degree of probability of damage for engineering structures are provided, according to data [12], the condition must be \( \beta_m > 3.72 \). According to Eurocode requirements the value \( \beta_m = 3.8 \) is reached in case of damages that are accompanied with human casualties of serious catastrophes. But in other cases \( \beta_m = 3.1 \) it means that it corresponds to the probability of damage \( 9.7 \times 10^{-4} \) with the condition if at the beginning of service life period, \( \beta_m = 3.8 \). Damages from deformation, cracks by the second-degree boundary conditions, \( \beta_m = 2.5 \) with probability \( 6.2 \times 10^{-3} \) result in significant repair expenses. Usually in design safety reserve for mechanical impact in operation practice is provided with safety coefficients on loads and materials [13].
3. Results and discussion

Based on the above mentioned assumptions and work performed by us [14, 15, 16, 17, 18, 19], we can formulate the design order of mean service life period for structure elements with the use of safety coefficient by service life period. The probability for a fail-proof operation will be in the following form:

\[ P\{Z_d > 0\} = P\{R_d - S\} = \Phi(\beta_t) \]  \hspace{1cm} (21)

where

\( \beta_t \) is safety characteristics;

\( Z = R - S \) is the relative deviation of the quantity from the mean value for normal law of distribution;

\( \Phi \) is a function of the normal distribution;

\( \beta_t \) is safety characteristics, it is determined from the following equation:

\[ \beta_t = \frac{(R_d - S_d - t \times V_{Rmt})}{\sqrt{S_d^2 + S^2 + 2 \times S \times S + r^2 \times S^2}} \]  \hspace{1cm} (22)

where

\( S^2 VR \) is velocity variance for \( cov(R_d, V_d) = 0 \);

\( R \) is structure resistance;

\( S \) is structure stress, where \( S \) and \( R \) obey the law of normal distribution;

\( cov(R_d, V_d) \) is a correlation moment of distribution of resistance and stresses.

Structure element operation duration under load in aggressive environment conditions is determined as follows:

\[ t = t_{serv} - t_1 + \beta_t S^2 T_1 \]  \hspace{1cm} (23)

Coefficient of characteristics of safety is determined from the following equation:

\[ \beta_t = \frac{(R_d - S_d - t \times V_{Rmd})}{\sqrt{S^2 \times R + S^2 \times S + r^2 \times S^2 \times \beta_t}} \]  \hspace{1cm} (24)

where

\( V_{Rmd} \) is mean value for the velocity of resistance change;

Mean quadratic deviation for an operation time of structure to boundary state (standard):

\[ S - T = (R_d - S_d - t \times V_{Rmt}) / \beta_t V_{md} \]  \hspace{1cm} (25)

Where

\( t \) is \( SV_{Rmd} \);

\( V_{Rmd} \) is mean value for resistance;

\( S^2 R_d \) is resistance variance;

\( S_d_{md} \) is mean value of stress;

\( S^2 S_d \) is stress variance;

Compared to the study [20] the method we are proposing determined the mean service life period for building elements and hydraulic structures in years.

The mean service life period of structure elements is determined as follows:

\[ T_{servmd} = t_{serv} + \beta_t (S \times T_1 + S \times T) \]  \hspace{1cm} (26)

4. Conclusions

Based on the above-mentioned information structure safety eventually covers the safety in mechanical impacts and safety in terms of durability. In reality the safety by service life period is revealed with the quantity of coefficient of safe service life period. It is also planned that structure resistance \( R \) and loads \( S \) can be given with their characteristic values.

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