Calculation and forecasting of operational durability of reinforced concrete structures

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Abstract. Based on analytical and experimental data, the durability properties of reinforced concrete and reinforcement necessary for modeling degradation and calculating the durability of reinforced concrete elements under various types of corrosion damage are substantiated.

A probabilistic model has been developed for predicting and assessing the durability and reliability of reinforced concrete elements, taking into account the statistical variability of design parameters and the kinetics of degradation processes during long periods of operation. An analysis of the method for calculating and predicting the durability of reinforced concrete elements based on deterministic probabilistic models of degradation of structural elements operating under aggressive environmental influences has been carried out.

The necessary assessment of the stress-strain state of reinforced concrete structures under conditions of long-term operation in aggressive environments as a result of corrosion damage is given, and their residual life is studied, taking into account the reduction in the cross-sectional area of concrete and reinforcement

Keywords: durability, reliability of reinforced concrete structures, residual life, corrosion damage.

Introduction

In the context of climate change on the planet and in particular on the territory of the Russian Federation and the emergence of global risks in the construction industry, it requires a correct and timely assessment of the challenges posed by global warming. Climate variability and extremeness are observed more and more in different regions of the country. Based on this, the issue of durability, reliability and safety of buildings and structures becomes very relevant.

Under conditions of long-term operation of reinforced concrete structures in aggressive environments, it is necessary to assess their stress-strain state as a result of corrosion damage, to determine their residual life, taking into account the decrease in the cross-sectional area of concrete and reinforcement[12].

Corrosion damage to reinforced concrete elements can affect the strength of the material, change design calculations, redistribute forces in building sections and disrupt the joint

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operation of concrete with reinforcement, as well as lead to other consequences that reduce the
deformation characteristics of reinforced concrete [3, 4]. The most unfavorable result of the
development of the corrosion process in reinforced concrete structures is a decrease in their
bearing capacity and serviceability, which leads to non-compliance with safety requirements
and the limit state at design loads [5].

Corrosion of reinforcing steel is one of the most common damages to reinforced concrete. Initially, reinforcement corrosion is caused by a violation of operating conditions, aggressive
environmental influences, a decrease in the protective characteristics of reinforced concrete,
design errors and manufacturing defects, as well as the service life of the structure can be
significantly reduced [6].

Bridges, parking lots and swimming pools, as well as other structures that are used in
aggressive conditions, are exposed to corrosion of various types of structures. In general,
consideration of the problem of reliability of reinforced concrete structures and structures,
taking into account corrosion damage, is implemented by creating methods for predicting and
evaluating durability [5, 7]. When analyzing the durability properties of reinforced concrete
structures, it is necessary to determine the following features of this problem: the first is the
probabilistic nature of non-force and force effects, their relationship and complexity; the
second is the instability of the technical qualities of structures and materials; and, finally, the
third - the influence of the time factor on the properties of materials and the characterological
features of the impact [8, 9].

Methods

Damage to a concrete element not loaded by external forces caused by a unilateral action of a
chemical aggressor with constant characteristics (composition, intensity, temperature,
atmospheric pressure) under conditions of stable compressed humidity of the environment and
concrete, considered as elements obeying the non-linearly generalized Goldberg-Waage law
entropion aging assessment of concrete destruction [1,10]:

\[ \Delta \partial(t,t_0) = \frac{(\partial(t_0) - \partial(t,t_0))}{\partial(t_0)} = 1 - \left[ \frac{\Delta \partial(t,t_0)}{\partial(t_0)} \right] \]

where: \( \Delta \partial(t,t_0) \) - damage depth, by time t,
\( \partial(t_0) \) - current damage depth; \( \partial(t_0) \) - critical, in particular, maximum depth in case of damage
type decrease, depending on \( \sigma R \); \( \Delta \partial(t,t_0) \) is the current relative deficit of damage, \( t,t_0 \) is the
start time and current monitoring time, \( \alpha, m \) are the parameters of damage kinetics determined
experimentally for each variant of the combination of concrete and aggressor, depending on the
level of stress state [2,11,12].

\[ \frac{d\Delta \partial(t,t_0)}{dt} = - \alpha[\Delta \partial(t,t_0)]^m \]  

(1)

Solution (1) is possible in the form:

\[ \partial(t,t_0) = f(m, \alpha, m, t) \partial(t_0) \]

(2)

where: \( m = 1 \) - \{[(\Delta \partial(t, t_0))^{(m+1)}] + \alpha[(-m) + 1](t - t_0)^{1/(m+1)} \}

(3)

In addition, for each combination of concretes of different nominations and different
concentrations, such as aggressive substances (as well as temperatures, etc.), their numerical
values of the specified parameters are calculated.

Thus, for each level of the stress state, there are numerical values of its parameters \( \delta cr, m, \alpha \),
which can be taken from experimental data and correspond to the nth combination of
concrete and aggressor, which provides a sufficient set of information to assess the damage
kinetics [8,13].

The mechanical characteristics of corrosion-damaged concrete are taken as the
multiplication of their initial values by the damage function in the form of a power series and
are determined from fixed values of \( Kc \) depending on the distance \( Z \) measured from the contact
surface of the corrosive environment and concrete.
where: $p$ and $\partial$ respectively, the height of the intact and damaged layers of the concrete section.

Using (4), one can calculate the value of the remaining force resistance and take into account the value lost due to corrosion damage of the force resistance in relation to the assessment of strength and deformability [6,14,15].

The reduction in the cross-sectional area of the reinforcement as a total design factor is calculated using the following formula:

$$ A_s = \frac{n(D-2\partial)}{4} $$

(5)

where:

$$ k = \frac{k}{\sqrt{b}}, n $$

(6)

$k$ and $n$ are empirical coefficients, $b$ is the size of the protective layer, mm.

Thus, the calculated values of the cross-sectional area of the working reinforcement, as well as the mechanical characteristics of concrete under conditions of corrosion damage, are not constant along the height of the cross-section. In the area located near the zone of maximum corrosion impact, their values are minimal and gradually increase, reaching maximum values in the zone of stabilization of the degradation process [5, 7,16].

### Results

The probability that the resistance of reinforced concrete structures will be less than the loads, and the probability of the end of the service life should be less than the allowable failure probability:

$$ P_v(t) = P_{rs}\left[\{R(t_e) - Q(t_e)\}_{te} = S < 0\} < P_{v,max}(t) = \int_0^x F_r(x)f_Q(x)dx $$

(7)

where: $P_v(t)$ - is the probability of structural failure during $t_e$ of a given (assigned) service life; $P_{rs}$ - event probability; $P_{v,max}$ is the maximum allowable failure probability, the latter can be defined as the level of safety (reliability) of actually operated structures; $F_r$ - is the probability distribution function of the force $R$; $f_Q$ - is the area of the probability distribution of the magnitude of the force $Q$ (Figure 1).

![Figure 1. Model of change in resistance R and element force Q during operation](image-url)
This approach opens up the possibility of designing reinforced concrete structures with a given service life. This method is especially useful for structural calculations of reinforced concrete structures in cases where the use of standard stochastic methods would be too complicated [5, 9, 18, 18]. Based on the solution of equation (7), the reliability of reinforced concrete structures can be taken as follows:

$$H = \exp\left\{ \frac{T\sigma}{2\pi\sqrt{\sigma^2 + \sigma^2_r}} \exp\left\{ -\frac{(m_r - m_s)^2}{2(\sigma^2 + \sigma^2_r)} \right\} \right\}$$

(8)

where: $\sigma^2$ - stress dispersion - in the case of solving nonlinear problems, can be determined from the results of the iterative process;

$\sigma^2_r$ - bearing capacity spread; $m_r$ - mathematical expectation of throughput; $m_s$ - is the expected stress; $T$ - service life.

If the parameters of the cross section, the type of load and the static design of the structure, as well as the characteristics of the corrosion process are known, then:

$$H = \exp\left\{ \frac{T\sigma^2 + \beta^2}{2\pi\sqrt{K\sigma^2_\alpha + K^2\sigma^2_r}} \exp\left\{ -\frac{(K^2 - K\sigma_\alpha)^2}{2(K\sigma^2_\alpha + K^2\sigma^2_r)} \right\} \right\}$$

(9)

where: $\sigma^2_\alpha$ - is the variance of the loading effect; $mr$ - mathematical expectation of the bearing capacity; $K$ is a coefficient depending on the size of the cross section of the element of the considered structure; $KC$ is the coefficient taking into account the corrosion damage of the structure, $\alpha$ and $\beta$ are the constants of the correlation function, chosen so that the experimental deformation curve coincides with the theoretical one [3, 7, 19].

From where it is easy to find the service life of a structure when the parameters of the cross section are known, provided that $\sigma_R=0$, taking into account the level at which emissions are prohibited (deterministic level):

$$T = \frac{2\pi\ln H}{K\sigma_\alpha \exp \left\{ \frac{(K^2 - K\sigma_\alpha)^2}{2K\sigma^2_\alpha} \right\}}$$

(10)

Or, if the period of operation is known, the cross-sectional dimensions:

$$K = \frac{K^2 m_r}{m_r + \sigma^2_\alpha/2A}$$

(11)

где:

$$A = -\ln \frac{2\pi(H)}{T\sqrt{\alpha^2 + \beta^2}}$$

(12)

Discussion

The reliability condition that takes into account the statistical variation of loads (forces) and the resistance of materials at the time $T = 0$, when the load distribution density and resistance are far from each other, and the probability of failure is initially small [5, 20]. Over time, the distributions approach each other, forming an intersecting area of increasing size, which illustrates the probability of destruction (Figure 1).

Conclusions
1. Corrosion of steel is by far the biggest durability problem for reinforced concrete structures, although other failure mechanisms can lead to failure of the concrete itself, freeze-thaw scale formation, exposure to moisture, acid or sulfate, thermal cracking, drying shrinkage, impact, erosion and wear.

2. When designing and calculating structures, it is necessary to take into account the degree of wear of structural elements, the actual bearing capacity and residual durability of existing reinforced concrete structures.

3. The use of mathematical and physical models of reliability and durability prediction gives a quantitative and qualitative assessment of the operational state of structures.

4. It is necessary to develop methods for calculating and predicting the durability of buildings and structures in an aggressive environment using composite reinforcement of various types.

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