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Assessment of the reliability of bent reinforced concrete elements under corrosive effects

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Abstract. The main problem of reducing the reliability and durability of reinforced concrete structures is the corrosion of concrete and reinforcement of operated buildings and structures. Calculation of structures made of reinforced concrete, taking into account environmental influences, is complicated by the stochastic nature of the parameters of corrosion processes. The conducted studies are aimed at solving the problem of improving the methodology of the probabilistic approach to the calculation of corrosion-damaged reinforced concrete elements. The article considers a probabilistic assessment of reliability for the most common bent reinforced concrete elements, taking into account corrosive wear and the time factor. The modeling of the effect of corrosion processes on the stress-strain state of a reinforced concrete element was carried out using the concrete deformation diagram, which takes into account the decrease in strength characteristics with an increase in the concentration of an aggressive medium in concrete. The scheme of propagation of an aggressive environment in concrete is adopted according to the diffuse front method. Corrosion processes in reinforcement were taken into account by reducing the effective cross-sectional area of reinforcing bars. The change in the properties of steel (its embrittlement) with an increase in the concentration of an aggressive medium was not taken into account. Reinforcement corrosion was simulated after the incubation period, after the concentration of the aggressive medium on the surface of the reinforcing bars reached a critical value. The determination of the moment of the onset of the limit state in the element was carried out on the basis of a nonlinear deformation model at each point of the section of the element to achieve the maximum possible tensile or compression strains in concrete and reinforcement. To solve the problem of reliability assessment, the method of statistical modeling implemented in a specialized software package was used. To apply this method, according to previous studies, the probabilistic parameters of all random variables were taken: mathematical expectation and standard deviation. Based on the results of the reliability assessment, graphs of the decrease in the reliability of a bent reinforced concrete element from the time of exposure to an aggressive environment were obtained.

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1 Introduction

The assessment of the reliability and durability of reinforced concrete structures largely depends on the choice of the calculation model of corrosion processes. The development of corrosion damage is significantly influenced by the degree and nature of the aggressive environment, as well as the characteristics of the concrete and reinforcement of the structure. The main parameters of the calculation model are the depth of the corroded layer of concrete or the corrosion rate, the mathematical model of corrosion and the stress-strain state of the element. When modeling corrosion processes, as a rule, two methods are used: physical-chemical and mathematical. In the mathematical model, one of the possible functional dependencies of the corrosion rate, the time of action of an aggressive medium and the depth of the damaged layer are specified with the coefficients of operating conditions that determine the development of corrosion processes. Setting the initial values of the physicochemical model is associated with the evaluation of experimental data obtained for specific, strictly individual conditions for the occurrence of corrosion processes. At different times, V.M. Bondarenko, E.A. Guzeev, A.S., Zalesov, V.I. Kolchunov, V.M. Moskvin, I.G. Ovchinnikov, A.I. Popesko, V.I. Rimshin, V.P. Selyaev, V.I. Solomatov, V.I. Travush and others [1-12].

Most of all the parameters taken into account in the calculations of reinforced concrete structures are not constant, but are of a random nature. Taking into account the variability of the design parameters in the design allows you to calculate the numerical value of reliability as the probability of failure-free operation of structures. The main approaches to reliability assessment were developed in the works of V.V., Bolotin, A.S. Lychev, V.D. Reiser, B.S. Rastorguev, A.R. Rzhanitsyn, N.N. Skladnev, B.I. Snarksis, Yu.D. Sukhov, A.P. Kudzis, A.G. Tamrazyan, V.S. Utkin, V.P. Chirkov and others [13-18].

During the impact of an aggressive environment on a reinforced concrete element, a number of independent processes occur, which can be taken into account separately:

1. The impact of an aggressive environment on the outer surface of the element at the initial stage. A certain stress-strain state arises in the element from the acting load, the aggressive environment does not change its properties.
2. Diffusion of an aggressive substance into the porous structure of concrete. There is a change in the properties of the material and a change in the initial stress-strain state.
3. Accumulation of the concentration of an aggressive medium near the surface of the reinforcing bars to a critical level, which contributes to the onset of corrosion processes in the reinforcement.
4. Development of corrosion processes in reinforcement, leading to a decrease in its effective cross-sectional area. Accumulation of corrosion damage in concrete. Change in the stress-strain state of the element due to degradation processes in concrete and reinforcement corrosion.
5. The onset of the limit state due to the development of excessive deformations in concrete or reinforcement.

All these processes are random in nature and depend on the duration of exposure to an aggressive environment.

2 Methods

The condition for ensuring reliability in a general form can be expressed through the inequality:

$$P_f\left(t\right) = P\left(\tilde{R}(t) - \tilde{Q}(t)\right) \geq \left[P_f\right] \tag{1}$$

where $P_f\left(t\right)$ – probability of failure-free operation, $\tilde{R}(t)$ – material strength characteristic, $\tilde{Q}(t)$ – load characteristic, $\left[P_f\right]$ – regulatory reliability level, t – building operating time.

The influence of the aggressive environment on the properties of concrete can be represented as a diagram of concrete deformation, which takes into account the concentration of the aggressive environment at each point of the material. In previous studies, the deformation diagram was presented as a combination of two dependencies, separately taking into account compression and tension:

$$\sigma = \begin{cases} A_p(C) \cdot \varepsilon - B_p(C) \cdot \varepsilon^3 \\ A_c(C) \cdot \varepsilon - B_c(C) \cdot \varepsilon^3 \end{cases} \tag{2}$$

where A, B – experimental coefficients that take into account the nonlinearity of deformation, depending on the concentration of an aggressive medium C at a point.

Curves of the deformation diagram can be obtained by experimental methods by testing concrete samples at different concentrations of an aggressive medium in the material. In reality, all the coefficients included in the formula are random, which is represented as a separate curve of the deformation diagram for each point of the element and the concentration of the aggressive medium:

$$\tilde{\sigma} = \begin{cases} \tilde{A}_p(\tilde{C}) \cdot \varepsilon - \tilde{B}_p(\tilde{C}) \cdot \varepsilon^3 \\ \tilde{A}_c(\tilde{C}) \cdot \varepsilon - \tilde{B}_c(\tilde{C}) \cdot \varepsilon^3 \end{cases} \tag{3}$$

Under the influence of an aggressive environment on the reinforcement, corrosion processes develop, reducing its effective cross section and changing the properties of steel, and its embrittlement occurs. Changes in the properties of steel during corrosion processes have little effect on the overall reliability of the structure and can be neglected when calculating the reliability. The steel deformation diagram, taking into account the stochastic nature of the physical and mechanical characteristics, can be written as:

$$\tilde{\sigma}_s = \begin{cases} \tilde{E}_s \cdot \tilde{\varepsilon} & | \quad \sigma < \tilde{\sigma}_T \\ \tilde{\sigma}_T & | \quad \sigma \geq \tilde{\sigma}_T \end{cases} \tag{4}$$

During the diffusion of an aggressive substance into the porous structure of concrete, its concentration inside the material increases, chemical interaction with the components of the cement stone, a change in its physical and mechanical characteristics, deformation and destruction occur. Under the influence of an aggressive environment in concrete, a pattern of distribution of the concentration of the medium over the material is formed, which also determines the law of distribution of the physical and mechanical characteristics of concrete. Currently, several models are used to describe the process of diffusion of an aggressive medium in concrete: distribution of an aggressive medium by a clear front, penetration by a diffuse front, and penetration by the diffusion mechanism (fig. 1). To assess the reliability, the mathematically most convenient model is the model of penetration of an aggressive medium by a diffuse front.

According to the conducted experimental studies, it has been established that after the start of the interaction of the structure with an aggressive environment, the corrosion of reinforcement in concrete does not begin immediately, but after the concentration of the aggressive environment near its surface reaches a certain critical value C_{cr}. The spread of an aggressive medium through an element can be described by Fick's second law in terms of the diffusion coefficient D, exposure time, and surface concentration C_s.

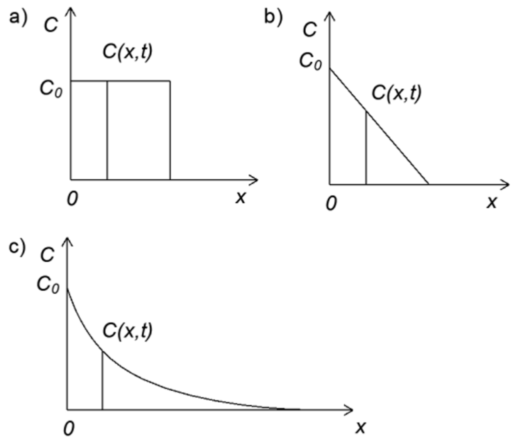

Fig. 1. Scheme of penetration of an aggressive environment into concrete

a) a clear front; b) blurred front; c) diffusion penetration.

The time after which the concentration of the aggressive medium reaches the value C_{cr} is called the incubation period. In the case of using the model of propagation of an aggressive environment by a blurred front, the incubation period at a known value of the critical value C_{cr} can be found by the formula:

$$\tilde{t}_{inc} = \frac{\tilde{a}_s}{\left(8 \cdot \tilde{D} \cdot \left(1 - \frac{\tilde{C}_{cr}}{\tilde{C}_s} \right)^2 \right)} \tag{5}$$

where a_s – is the thickness of the concrete protective layer.

The development of reinforcement corrosion processes in concrete can be described by several mathematical models, taking into account the time of exposure to an aggressive environment, the thickness of the protective layer, the depth of corrosion, and the empirical parameter of damage. We accept the corrosion model, taking into account the stochastic nature of all quantities, in the form:

$$\begin{cases} \tilde{\delta} = 0 & \mid \quad t < \tilde{t}_{inc} \\ \tilde{\delta} = \tilde{k} \cdot \left(t - \tilde{t}_{inc} \right)^{\tilde{n}} & \mid \quad t \geq \tilde{t}_{inc} \end{cases} \tag{6}$$

where $\tilde{k}$ and $\tilde{n}$ – random coefficients obtained empirically, $\tilde{\delta}$ – the depth of corrosion damage.

The development of corrosion processes in steel reinforcement can proceed in the form of continuous uniform corrosion around the entire perimeter of the rod, in the form of pitting corrosion and in the form of uneven corrosion with a flat or sickle-shaped front. With this in mind, the development of corrosion processes can be described as a random function:

$$\tilde{F}_s(t) = f\left(\tilde{d}_0; \tilde{k}; \tilde{n}; \tilde{t}_{inc}; t\right) \tag{7}$$

where d_0 – the initial reinforcement diameter.

With uniform corrosion wear and the stochastic nature of the initial parameters, the corrosion development function can be described as:

$$\tilde{F}_s(t) = \begin{cases} \dfrac{\pi \cdot \tilde{d}_0^2}{4} & \mid \; t \le \tilde{t}_{inc} \\ \dfrac{\pi \cdot \left(\tilde{d}_0 - 2\tilde{\delta}(t)\right)^2}{4} & \mid \; t > \tilde{t}_{inc} \end{cases} \tag{8}$$

In each period of time, for each point of the section of the element, the onset of the limit state can be set on the basis of a nonlinear deformation model:

$$\begin{aligned} &\left|\varepsilon_{b,\max}\right| \le \varepsilon_{b,ult} \\ &\varepsilon_{s,\max} \le \varepsilon_{s,ult} \end{aligned} \tag{9}$$

The calculation of normal sections, taking into account individual deformation curves, is carried out taking into account the equations of equilibrium of internal and external forces, the hypothesis of flat sections, as well as the equations for the distribution of deformations over the section according to the formulas:

$$\begin{aligned} &\tilde{M}_x = \sum \tilde{\sigma}_{bi} \cdot \tilde{A}_{bi} \cdot \tilde{Z}_{bxi} + \sum \tilde{\sigma}_{sj} \cdot \tilde{A}_{sj} \cdot \tilde{Z}_{sxj} \\ &\tilde{M}_y = \sum \tilde{\sigma}_{bi} \cdot \tilde{A}_{bi} \cdot \tilde{Z}_{byi} + \sum \tilde{\sigma}_{sj} \cdot \tilde{A}_{sj} \cdot \tilde{Z}_{syj} \\ &\tilde{N} = \sum \tilde{\sigma}_{bi} \cdot \tilde{A}_{bi} + \sum \tilde{\sigma}_{sj} \cdot \tilde{A}_{sj} \\ &\tilde{\varepsilon}_{bi} = \tilde{\varepsilon}_0 + \frac{1}{\tilde{r}_x} \cdot \tilde{Z}_{bxi} + \frac{1}{\tilde{r}_y} \cdot \tilde{Z}_{byi} \\ &\tilde{\varepsilon}_{sj} = \tilde{\varepsilon}_0 + \frac{1}{\tilde{r}_x} \cdot \tilde{Z}_{bxj} + \frac{1}{\tilde{r}_y} \cdot \tilde{Z}_{byj} \end{aligned} \tag{10}$$

The reliability of the design, as a function of a number of random parameters and the time of exposure to an aggressive environment, can be calculated using various methods (two moments method, hot spots method, enumeration method, statistical modeling method, etc.). For numerical calculation methods on a computer, the most applicable method is statistical modeling, which consists in artificially modeling the normal or other distribution of all random parameters in order to calculate the safety margin according to the established deterministic dependencies. The probability of obtaining a negative result of the safety margin determines the probability of failure of the structure (element reliability).

3 Results

Let us evaluate the reliability of a single-span hinged reinforced concrete beam loaded with a uniformly distributed load, taking into account all the above hypotheses. The cross section of the beam is assumed to be 300x600 mm, the span is 6 m, the reinforcement of the tension zone is provided by A500C rods. The beam around the entire perimeter is under the influence of 1% chloride-containing environment during the entire period of operation. To calculate the reliability of bent reinforced concrete elements, the statistics of the distribution of all random parameters of structures is given. When determining the coefficients of the concrete deformation curve, the experimental data of Mezhnyakova A.V. [19], obtained during testing of concrete samples aged in chloride-containing media.

To calculate the reliability of a reinforced concrete bending element, the following algorithm is applied:

1. Performing a static analysis of the structure, determining the dangerous section and the curvature of the bent axis of the beam.
2. Dividing the beam section into sections, strains and stresses are calculated at each point of the section. The reinforcement in the section is modeled without division into sections.
3. Calculation of the initial reliability of the element P_{f0} without taking into account corrosion processes. The calculation is made by the method of statistical modeling.
4. Establishment of the time step for the calculation of corrosion processes. Determination of the concentration of an aggressive medium in each section of the section at each moment of time.
5. At the moment when the concentration of an aggressive medium reaches a critical value at the location of the reinforcing bars, the calculation of the corrosion depth and the residual area of the reinforcing bar.
6. Calculation of strains and stresses in each section of the section of the element according to the found values of the curvature of the neutral axis.
7. Verification of the condition for the onset of boundary deformations. Calculation of the reliability of the element at a given point in time by the method of statistical modeling.

Based on the results of calculating the reliability of a bent reinforced concrete element, taking into account the impact of an aggressive environment, a graph of dependence of reliability on the time of operation of the structure was plotted (fig. 2). It has been established that the reliability of the element, which initially has a significant margin, decreases to the minimum allowable level P_f=0.9973 within 6-20 years of operation, depending on the diameter of the reinforcing bars. The concentration of an aggressive environment reaches a critical level on the surface of reinforcing bars after six years of operation, which contributes to the onset of the development of corrosion processes in the reinforcement.

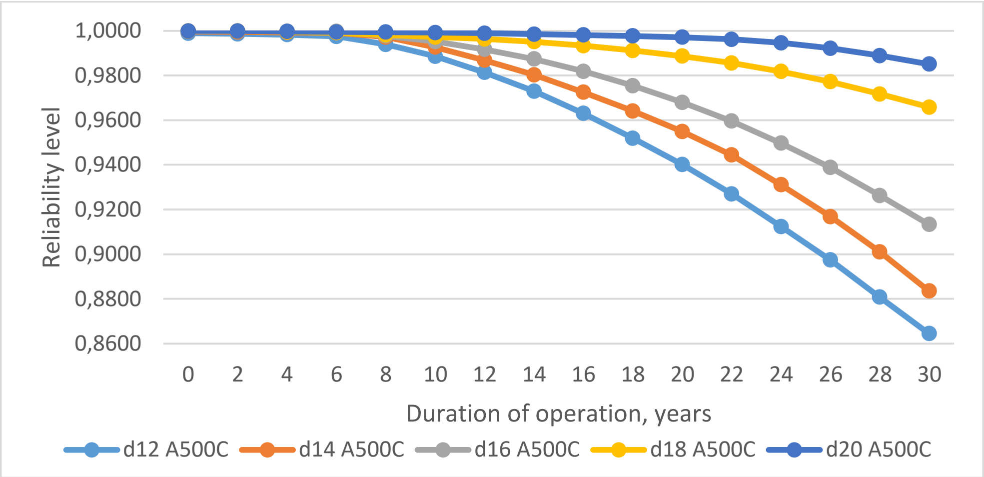

Fig 2. Reliability of a bent reinforced concrete element

4 Conclusions

The proposed method for assessing reliability makes it possible to calculate its numerical value for a bent reinforced concrete element at any time during the operation of the structure in an aggressive environment. For the studied reinforced concrete element, the impact of an aggressive environment leads to the initialization of the corrosion processes of reinforcing bars after 6 years of operation. Further corrosion of the reinforcement and a decrease in the effective diameter of the rods, as well as the accumulation of corrosion damage in compressed concrete, leads to a decrease in the level of structural reliability after 6-20 years of operation below the recommended value.

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