Assessment of the durability of corrosion-damaged prefabricated reinforced concrete structures

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Abstract. During exploitation, reinforced concrete structures are under the influence of an aggressive environment, as a result of which they are damaged and destroyed. The durability of structures depends on the nature of its interaction with aggressive environmental factors, which is described using general models of external influences, such as the action of loads, climatic, aggressive and other influences and their combinations. An example of calculating durability based on corrosion of concrete and reinforcement is given. The selected protective layer and the diameter of the reinforcement were checked in case of general corrosion. The average value of the service life in years was determined on the basis of carbonization of the protective layer of concrete and the formation of cracks in it. The methods for predicting the service life of reinforced concrete structures are analysed. The service life of the structure is determined taking into account the assessment of the technical condition of the structure according to external signs. In theoretical terms, the influence of various factors by the introduction of a multifactorial measure of damage is shown. The calculations for predicting the service life of structures and for determining the durability are analysed. The example of calculating the probabilistic service life is considered.

Keywords: prefabricated reinforced concrete structures, corrosion damage, durability, measure of damage.

1. Introduction

The concept of durability in the Eurocode is considered as the result of the implementation of measures taking into account the purpose of the reinforced concrete structure, the form of structural elements and parts, the quality of performance, the level of control, measures to protect the influence of an aggressive external environment, measures to maintain the reinforced concrete structure in good condition for the expected service life.

Durability can be considered at three levels: material, element and constructions, object as a whole.

Analysing the content of the concepts of longevity in Russian and foreign regulatory documents, we can distinguish two of the most important [1,2,3]:

1) sufficiency of initial quality characteristics to satisfy safety requirements and exploitative suitability not lower than the limits laid down in national standards;

2) economic rationale of the service life, including minimizing maintenance and repair costs.

The design parameters for assessing the durability of reinforced concrete structures include:

- material properties;
- geometric dimensions of structures;
- location of reinforcements.

According to [4], reliability is defined as the ability of a technical object to perform specified functions under certain conditions for a given period of time. Reliability indicators are quantitative characteristics of one or more properties that make up the reliability of an object, such as:

- reliability;
• durability;
• maintainability.

2. Methodology
Durability is one of the most important indicators of the quality of building structures. During exploitation, reinforced concrete structures are exposed to an aggressive environment, as a result of which they are damaged and destroyed. The use of special protective coatings and special materials in building structures ensure their durability [5].

According to the results of the surveys, it can be seen that the reinforced concrete structures designed without taking into account the requirements of durability are in disrepair after 5÷10 years, and there may be cases when the destruction occurred after only 3 years [6-9].

In [1], the basic requirements for materials of building structures that work in aggressive conditions are reflected.

Reinforced concrete structures have a finite service life, as they are subject to physical, chemical and mechanical changes, the result of which is their degradation and a decrease in their ability to perform the required functions [10]. The development of methods for predicting the durability of designed and evaluating the exploitation of reinforced concrete structures caused by [9,12]:

• the increasing use of reinforced concrete structures in difficult climatic conditions or in aggressive environments;
• the high cost of reinforcing, restoring and operating costs to maintain the required technical condition of structures and buildings;
• the use of new types of concrete and reinforcement for which the boundaries of durability have not yet received sufficiently reliable experimental confirmation.

The main issue in the field of durability is the prediction of the service life of new reinforced concrete structures, which is considered as a more guaranteed parameter than durability.

In practice, the durability and service life of reinforced concrete structures is controlled mainly by limiting the maximum allowable values of the water-cement ratio, concrete class, reinforcement and the thickness of the protective layer. New editions of domestic and foreign standards include the following factors: environment; protective layer; type and quality of materials, laying methods to ensure complete compaction; shape and dimensions of the structure. The limitation of the thickness of the protective layer is set depending on the class of aggressiveness of the environmental aggressiveness, diameter and location of reinforcement over the cross section of the element.

The following methods have been used to predict the service life of reinforced concrete structures:

• assessments based on a generalization of experience in design, construction and long-term exploitation of structures;
• deductive approaches, the conclusions of which are based on a comparison of the exploitational quality of similar reinforced concrete structures;
• mathematical modelling based on knowledge of the mechanisms of degradation processes;
• estimates obtained as a result of accelerated testing of materials and structures;
• destruction mechanics and finite element methods.

The general method is based on the use of expert assessments, which are based on general experience and knowledge obtained in laboratory and industrial tests of structures and materials, special studies.

The calculation of durability based on corrosion of concrete and reinforcement.
We accept the specified (assigned) service life of the column $t_d=50$ years Safety factor by service life for combined method $\gamma_1=2.5$ [13]. Then the estimated service life $t_d$:

$$c = c_{\text{env}} c_{\text{cur}} c_{\text{air}} a^{-0.7} (f_{\text{ck}} + 8)^{-1.4} t$$

We accept the following formula parameters:
\[ c_{\text{env}} = 80; c_{\text{cur}} = 1; c_{\text{air}} = 1; a = 4; f_{c_k} = R_{b,n} = 22 \text{ MPa} \text{ (B30)}. \]

Then \( c' = (\delta L / \delta t) t = 0.25 \text{ (mm)} \) \( d' = (\delta r / \delta t) t = 0.3 \text{ (mm)} \) – damaged concrete layer thickness; \( \delta L/\delta t \) and \( \delta r / \delta t \) – accordingly damage rates for concrete and reinforcement.

Define estimated parameters durability for combined method:

\[ t_d = 125 \text{ year}, \ c' = 0.259 \times 125 = 32.3 \text{ mm}. \]

\[ C_{\text{min}} = 20 + 32.3 = 52.3 \text{ mm}. \]

Accept \( C = 55 \text{ mm} \). Depth of damage to the surface layer of reinforcement \( (\text{thickness of the corrosion layer}) \)

\[ d = 0.03 \times 125 = 3.8 \text{ mm}. \]

Accept \( d = 10 \text{ mm} \).

3. Results and discussion

We check the selected protective layer and the diameter of the reinforcement in case of general corrosion. On the outside, the column reinforcements are susceptible to damage due to concrete carbonation.

Defining reinforcements in relation to general corrosion in this case are clamps.

Define the average value of the service life \( \mu (t_L) \) in years on the basis of carbonization of the protective layer of concrete and the formation of cracks in it:

\[
\mu (t_L) = \frac{C_h^2}{\left[ c_{\text{env}} c_{\text{air}} a (f_{c_k} + 8) \right]^2} \frac{80C_h}{D_h r} + 80C_h
\]

where \( C_h = C - D_h = 55 \text{ mm} - 10 \text{ mm} = 45 \text{ mm} \) \( \text{– concrete thickness for transverse reinforcement} \); \( D_h \) \( \text{– clamp Diameter} \); \( c_{\text{env}} = 1 \) \( \text{– the factor, considering the influence of the environment} \); \( c_{\text{air}} = 0.7 \) \( \text{– the factor, considering the air composition} \); \( r \) \( \text{– corrosion rate of steel reinforcement before cracking (12 mm)} \); coefficients depending on the type of binder: \( a = 1800, b = -1.7 \) \( \text{for Portland cement} \). The first term characterizes the penetration time of the environment in concrete protective layer; the second – cracking time in the protective layer due to corrosion of the reinforcement under the assumption of the maximum allowable loss of the radius of the cross section of the reinforcing bar.

\[
\mu (t_L) = \frac{45^2}{\left[ 1 \times 0.7 \times 1800 \left( 22 + 8 \right)^{-1.7} \right]^2} + \frac{80 \times 45}{10 \times 12} = 164.3 \text{ year}
\]

\( \mu (t_L) = 165 \text{ year} \), which is longer than the estimated service life of 125 years. Therefore, the selected thickness of the protective layer is acceptable for this type of degradation.

Duration and safety indicators of the column during exploitation \( t_{\text{serv}} = 15 \text{ year} \) with prolonged action of the load in an aggressive environment are found with the following initial data: column resistance \( R \) and effort \( S \) obey the law of normal distribution: average resistance \( R_{d,mi} = 1.25 \text{ MN} \); resistance variance \( S^2 R_{d} = 0.03 \text{ MN} \); average value of effort \( S_{d,mi} = 0.8 \text{ MN} \); force dispersion \( S^2 S_{d} = 0.01 \text{ MN} \).

Uptime probability:
P\{Z_d > 0\} = P\{R_d - S = \Phi \{\beta_t\}\}, \tag{3}

where \(\beta_t\) – safety feature; relative deviation of values \(Z = R - S\) from the average value under the normal distribution law; \(\Phi\) – normal distribution function:

\[
\beta_t = \frac{R_{mt} - S_{mt}}{\sqrt{S^2 \times R + S^2 \times S \times 2 \times \text{cov}(R, S)}} \tag{4}
\]

Then \(\Phi(2.25) = 0.99809 = 98.809\%\), that is, in the initial period, the reliability of the column is quite high. Through time \(t_1\) with parameters \(T_{1, \text{mt}} = 3\text{year}\) and \(S^2 T_1 = 0.3\text{year}^2\) column resistance decreases according to a quasilinear law with parameters:

- average value of the rate of change of resistance \(V_{R, \text{mt}} = 0.04 \text{MN/year}\);

- speed dispersion \(S^2 VR = 10^{-4} \text{MN/year}^2\) with covariance \(\text{cov}(R_d, V_R) = 0\).

Duration of work under load in aggressive environments:

\[t = t_{\text{serv}} - t_{\text{ve}} + \beta_t S^2 T_1\]

\[t = t_{\text{serv}} - t_{\text{ve}} + 1.25 - 0.8 - 0.04 t_{\text{ve}} R_{\text{mt}} = 5\text{year} \tag{5}\]

Average of the quadratic deviation of column operating time to limit state (standard):

\[S \times T = \frac{R_d - S_{\text{ve}}}{\beta_t \times V_{R, \text{mt}}} = 1.25 - 0.8 - 0.04 t_{\text{ve}} = 5\text{year}\]

Assuming that actual service life obeys the law of normal distribution and the depreciation rate during the service life is constant, then the law of conservation over time of reinforced concrete structures (value, reverse depreciation) can be expressed as: \(v = e^{-\alpha t}\), where \(\alpha\) – experimental coefficient, receiving indicative values 0.003 – 0.005; \(t\) – years.

Assuming an exponential law and with a chain diagram of the accumulation of damage to reinforced concrete structures approximate value of the relative reliability of structures during exploitation \(y = y / \gamma_0\) and value of these damage \(\varepsilon = 1 - y\) through \(t_f\) years of exploitation can be found by the formula:
\[ e = 1 - e^{-\lambda t} \quad (7) \]

where:
\[ \lambda = -\frac{\ln y}{t_F} \quad (8) \]

Constant depreciation, determined by survey data based on changes in bearing capacity at the time of surveys; \( \gamma \) – actual safety factor of structures, taking into account the damage; \( y = \gamma / \gamma_0 \) – relative reliability, determined by categories of the technical condition of the structure depending on its damage; \( t_F \) – term exploitation of the constructions by the time of survey. Transforming (8), we obtain an expression for determining the exploitation of the structure in years from the beginning of exploitation:
\[ t = \frac{\ln y}{\lambda} = \frac{\ln \left( \frac{\gamma}{\gamma_0} \right)}{\lambda} \quad (9) \]

Then the term exploitation before overhaul and the period of occurrence of the emergency condition in years from the beginning of exploitation will be expressed accordingly as:
\[ t = \frac{0.162}{\lambda} \]

and
\[ t = \frac{0.43}{\lambda} \]

The term exploitation of the structure in years at the time of the survey; constant depreciation \( \lambda = 0.00256 \), determined when assessing the bearing capacity at the time of the survey. The calculation of the term exploitation before the onset of one of the 5 categories of technical condition is given in Table 1.

| Term of exploitation at the time of survey \( t_F \), in years | Constant depreciation \( \lambda = -\frac{\ln y}{20} \) | Categories of technical condition | Relative reliability \( y = \gamma / \gamma_0 \) | Term of exploitation \( t, \text{year} \) |
|-------------------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1 | 1.00 | 0 |
| 2 | 0.95 | 20 |
| 20 | 0.00256 | 3 | 0.85 | 63 |
| | | 4 | 0.75 | 112 |
| 5 | 0.65 | 168 |

Determination of the service life of the structure, considering the assessment of the technical condition of the structure according to external signs

In the absence of damage, relative reliability \( y = 1 \), damage \( \varepsilon = 0 \); with maximum damage (emergency condition) \( y = 0.65 \) at \( \varepsilon = 0.35 \), that is, the amplitude of the values of relative reliability, which also characterizes also stock level, for the 1st category of technical condition or in the initial period of operation of the structure in relation to its emergency condition is 35%.

In real operating conditions, structural elements of engineering structures are exposed to several effects in different sequences or at the same time [11,14,15,16,17]. As a result, the rates of degradation
processes and the rate of damage accumulation increase. Theoretically, the influence of several factors can be taken into account by the introduction of a multifactorial measure of damage $D$, accepted a priori:

$$ D = \frac{\Delta(x_1, ..., x_i, \sigma, t) - \Delta_0}{\Delta_k - \Delta_0} $$

(10)

where $\Delta_0$ – the value of the damage measure in the initial period of operation $t=0$; $\Delta_k$ – final value of the measure of cumulative damage; $\Delta(x_1, ..., x_i, \sigma, t)$ – current value of the measure at the time the failure occurs over time $t$ depending on the value of the stress, variable factors of loading conditions and operating conditions $x_1, x_2, ..., x_i$. For the initial state of the construction $D=0$, $\Delta(x_1, ..., x_i, \sigma, 0) = \Delta_0$. After completion of operation at the time of failure, when the operating time is equal to the service life $t = T$, $D = 1$ with $\Delta(x_1, ..., x_i, \sigma, t) = \Delta_k$.

As the most representative measure of damage, concrete strength may be suggested. The assessment of durability in such cases is based on the use of the residual strength of concrete, established experimentally or by calculation, using assumptions (Figure 1).

![Figure 1. The distribution function of the service life of a reinforced concrete element on the basis of neutralizing the protective layer of concrete.](image)

The safety characteristic corresponds to a certain value of the specified reliability $P_n$: $\gamma_n = 1,64$ for $P_n = 0,95$ and $\gamma_n = 1,28$ for $P_n = 0,9$.

$$ T_{\text{carb}} = \frac{a^2}{K^2} \times \left( \frac{1 - \frac{1 - \gamma_n^2 \times v_a^2}{1 - \gamma_n^2 \times \gamma_{ke}^2}}{1 - \gamma_n^2 \times \gamma_{ke}^2} \right)^2 $$

(11)

where $a, v_a, K, v_{ke}$ – respectively, the expectation and coefficient of variation of the distribution of the thickness of the protective layer and random value $K$, $v_{ke}$ - characterizes the speed of the carbonization process and depends on the density of concrete, the presence of cracks, temperature, humidity and other operating conditions.

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Taking $t = T_{\text{carb}}$, get the value of the estimated service life of the protective layer of concrete, which should be no less than the normative value $T_n$.

The average value of the thickness of the protective layer is taken equal to the design in accordance with the requirements of regulatory documents. Other data obtained on the basis of statistical analysis of experimental data on the carbonization of the protective layer of concrete of exploited structures and manufacturing conditions (Table 2).

Table 2. The values of the coefficients for various operating conditions of reinforced concrete structures.

| No. | Type of construction and conditions of its operation | Expected value $K$ $\text{mm/m}\text{year}^{1/2}$ | Variation coefficient $v_{\text{ke}}$ | $v$ |
|-----|--------------------------------------------------|-----------------------------------------------|------------------------------------|-----|
| 1   | Structures operated in the open air (coating plates, walls, etc.) | 1.5-2.5 | 0.15-0.25 | 0.1-0.255 |
| 2   | Structures operated indoor                        | 1.5-3.0 | 0.1-0.25 | 0.1-0.25 |
| 3   | Constructions operated in environments with varying degrees of aggressiveness: | | | |
|     | a) low degree of aggressiveness                   | 2-3 | 0.1-0.25 | 0.17 |
|     | b) medium degree of aggressiveness                | 3-5 | 0.1-0.3 | 0.17 |
|     | c) high degree of aggressiveness                  | 5-6 | 0.1-0.3 | 0.17 |

The relevance of solving the probabilistic calculation of the thickness of the protective layer is justified by the fact that in real structures, significant actual deviations of the thickness of the protective layer are observed in comparison with the design values: up to 2 ÷ 3 times with the coefficient $v_a = 0.1 \div 0.25$.

A quantitative characteristic of the corrosion process is the depth of neutralization of the concrete of the protective layer of the reinforced concrete structure with an aggressive substance for a certain period. The criterion for the onset of the limiting state is the condition, that destruction occurs at a moment of time, when the depth of the damaged layer exceeds the thickness of the protective layer, as further development of the process will be characterized by depassivation (depassivation - the release of metal from a passive state; depassivation is associated with the destruction of the passivating layer on the metal surface) reinforcement and its corrosion initiation.

In this formulation, the following problems are solved: a) for given parameters of the protective layer, find the distribution functions and the distribution density of carbonization time; b) what is the required thickness of the concrete protective layer, if the service life and the probability of destruction are specified. When solving the first problem in a probabilistic setting, the purpose of the calculation is to find the time during which with confidence probability $P_n$ the protective layer will not be neutralized. The probability of complete neutralization of the protective layer. The probability of complete neutralization is $1-P_n$ and depends on the purpose of the construction.

Calculation of probable service life.

Example: thick reinforced concrete slab 220mm. The front of the impact of an aggressive environment on the surface of the plate is distributed over the surface, limited in size $a$ and $b$.

Determine the time of carbonization of the protective layer of concrete in the center of the field at the coordinate $x = a / 2$, $y = b / 2$ with the following initial data:

The average thickness of the protective layer of concrete $a = 25 \text{mm}$; safety characteristic at the standard value of the probability of reliable (safe) operation of the structure $P_n = 0.9$; $\gamma_a = 1.28$; coefficient of variation of the thickness of the protective layer as for a structure operated in an aggressive environment $v_a = 0.17$ (medium degree of aggressiveness); mathematical expectation of
the rate of carbonization $K = 2.5 \text{mm/year}^{1/2}$; coefficient of variation of the rate of carbonization $v = 0.2$.

The calculation is performed using the safety characteristic according to the formula:

$$T_{\text{carb}} = \frac{25^2}{2.5^2} \cdot \left( \frac{1 - \sqrt{1 - (1 - 1.28^2 \cdot 0.17^2) \cdot (1 - 1.28^2 \cdot 0.2^2)}}{1 - 1.28^2 \cdot 0.2^2} \right)^2 = 51.1 \text{year}$$

The average carbonization time of the protective layer of concrete at $\gamma_v = 0$ is equal to $T = 25^2 / 2.5^2 = 100 \text{year}$. The results of calculating the plate for durability in different operating conditions are shown in Table 3.

| Operating environment                                      | The carbonization time of the protective layer of concrete, years | The average carbonization period of the protective layer of concrete, years |
|----------------------------------------------------------|------------------------------------------------------------------|--------------------------------------------------------------------------|
| Indoor Operated                                           | 86.17                                                            | 156.25                                                                   |
| Operated in environment of low degree of aggressiveness   | 51.1                                                             | 100                                                                      |
| Operated in environment of medium degree of aggressiveness| 18.62                                                            | 36.06                                                                    |

4. Conclusions
The work considers the existing methods for determining the technical condition and physical deterioration of the building as a whole and its individual structures using precast concrete structures as an example.

Statistical data are presented, such as the average physical depreciation of buildings on the example of Moscow, the increase in physical depreciation over a decade, etc., graphs and functions of physical depreciation are given.

Factors affecting the performance of reinforced concrete structures, such as aggressive environments, are considered.

The calculations for predicting the service life of structures and for determining durability are analysed.

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