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Assessment of the Service Life of Reinforced Concrete and Steel Elements

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Abstract: The article provides information on the service life of metal and reinforced concrete elements, their shelf life, assessment of the technical condition of damaged elements to increase their strength.

Keywords: corrosion protection of structures, steel reinforcement, degree of carbonization of concrete, durability of reinforced concrete structures, effective diffusion coefficient.

Introductions. The need to determine (predict) the service life arises when deciding on the types, volumes and time of performance of work to strengthen, restore and corrosion protection of structures; on the possibility of continuing the operation of the preserved structures for the period of reconstruction and in new operating conditions, etc. Practical methods for predicting the development in time of all signs characterizing the state of reinforced concrete structures have not yet been developed.

Sample models and research methodology. The techniques given in this section make it possible to evaluate the development of the process of loss of protective properties of concrete in relation to steel reinforcement and changes in the bearing capacity of the structure over time. The exhaustion of protective properties by concrete in relation to steel reinforcement is a defining sign of the exit of structures at the considered moment of time from the I category of the state to one of the subsequent categories (II, III, IV and V).

Two ways of determining the expected service life are considered - deterministic and probabilistic. In the deterministic method, the average values of the quantities included in the calculation formulas are used; in the probabilistic setting, the probability is taken equal to 0.95.

With a probabilistic method for assessing durability, after the predicted service life, reinforced concrete structures should be examined, after which the question of the possibility of their further operation without additional protective measures or the time, composition and volume of repair work is decided. These terms must be indicated in the passport for the building or structure [1,2].

The interaction of concrete with carbon dioxide (carbonization) is the most common process for its neutralization. With the combined effect of carbon dioxide and other acid gases (sulphurous anhydride, hydrogen fluoride, hydrogen sulfide, carbon disulfide) on concrete, advanced diffusion of CO_2 takes place. Estimation of the expected depth of carbon dioxide neutralization of concrete, cm, for "new" concrete of reinforced or restored elements for time τ at CO_2 concentration, CO (relative value by volume) is made by the formula:

$$x_{CO_2} = \sqrt{2D^{/} C_o \tau / m_o} \quad (1)$$

where: D - effective diffusion coefficient, cm^2/s;

m_0 - reactivity (volume of gas absorbed by a unit volume of concrete).

The initial data for the calculation is obtained from the determination of the depth of carbonization of concrete in natural conditions or in a chamber with an increased concentration of CO_2. To calculate m0, a sample of the mortar part of the concrete from the carbonized and non-carbonated layer is taken and

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analyzed for CO_2 content. The difference between these values equals the amount of CO_2 absorbed during the carbonization process.
Approximately, the reaction capacity can be calculated by the formula:

$$m_0 = 0{,}4 G_c P_{CaO} f_c \quad (2)$$

where: Gc - is the amount of cement, g, in 1 dm3 of concrete; P_{CaO} - the amount of CaO in calcium-containing compounds in cement in relative terms by weight, for Portland cement can be taken equal to 0,6; f_c - is the degree of carbonization of concrete, equal to the ratio of the amount of CaO bound into carbonate to the total amount of CaO in cement. The f_c value can be taken equal to 0.6.

$$D = (0{,}2\, G_c P_{CaO} f_c x_{CO_2}) / C_0 t_c \quad (3)$$

where: x_{CO_2}' - measured depth of carbonization, cm; C_0 is the concentration of carbon dioxide, in relative units; tc - duration of carbonization, s.
The time during which the concrete will be neutralized to a given depth is determined by the formula:

$$\tau = x^2{}_{CO_2} m_o / 2D' C_o \quad (4)$$

The depth of neutralization of a single section of the exploited concrete is determined by the formula:

$$y_2^{CO_2} = y_1^{CO_2} \sqrt{t_2 / t_1} \quad (5)$$

where: $y_1^{CO_2}$ - neutralization depth after t_1 years of operation according to survey data; $y_2^{CO_2}$ - predicted depth of concrete neutralization after t_2 years of operation, and the duration of neutralization, respectively:

$$t_2 = (y_2^{CO_2} / y_1^{CO_2})^2 \cdot t_1 \quad (6)$$

Taking the normal law of distribution of the value y1 with a security of 0.95, the value:

$$y_2^{CO_2} = \left(y_1^{CO_2} + 1{,}64\, \sigma\, y_1^{CO_2}\right)\sqrt{t_2 / t_1} \quad (7)$$

Concrete of the protective layer of reinforced concrete structures operated in aggressive chloride environments must be checked for the presence of chlorides.
Chipped or drilled pieces of concrete should be sawn on a machine with a diamond blade and oil cooling in layers of 3-5 mm thick, parallel to the outside of the structure. Based on the results of the analysis, the depth of the concrete layer is determined, at which the chloride content reaches the maximum allowable – 0,1% of the mass of cement for prestressed structures and 0,4% for structures with conventional reinforcement [3].
The service life of the structure until the maximum allowable chloride content
of the reinforcement is reached:

$$t_2 = \left(Q_{Cl}^{\lim} / Q_{Cl}^{0} + 1{,}06\, h_d / h_{Cl}\right)^2 t_1 \quad (8)$$

where: $Q_{Cl}^{\lim}$ - maximum allowable chloride content at the surface of the reinforcement, % of the mass of cement;
Q_{Cl}^{0} - the content of chlorides in the surface layer of concrete (depth up to 5 mm) at the time of the survey;
h_{cl} - penetration depth of chloride ions into concrete, cm (valid for hcl ≤ hd); hd - the value of the protective layer of concrete.
Quantities Q_{Cl}^{0} and h_{cl} determined according to the graph of the distribution of chlorides in concrete, built according to the layer-by-layer chemical analysis in the coordinates QCl - hd.
If there is condensation moisture on the surface of the structure, it must be removed together with the outer layer of cement stone 0,5-1 mm thick. The law of distribution of the value of hCl, as in the case of the neutralization of concrete with carbon dioxide, is assumed to be normal.
The durability of reinforced concrete structures operating under leaching conditions is characterized by the time of complete loss of strength by concrete of the protective layer, i.e. moment of reinforcement exposure [4,5].
When the structure is washed off with water with a hardness of less than 5 °N, the average service life of the concrete of the protective layer is determined by the formula:

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$$\overline{T}_{mt} = Q_{CaO}^{rel} h_d^5 / k_B D \quad (9)$$

where: Q_{CaO}^{rel} - the relative amount of removed CaO, at which there is a complete loss of concrete strength, is taken equal to 0,3;
h_d - is the size of the protective layer, cm;
D'' - effective diffusion coefficient equal to 3,15 cm^2/year;
k_B = 0,002 for concrete with a cement consumption of 300 kg/m3 or more, with W/C ≤ 0,55; k_B = 0,003 for concrete with cement consumption less than 300 kg/m3 with W/C ≥ 0,6.
The service life of concrete with a level of reliability determined by the safety characteristic γ is determined by the formula:

$$T_\gamma = Q_{CaO}^{rel} h_d^2 / D k_B (1 + \gamma \sqrt{V_D^2 + V_{hD}^2}) \quad (10)$$

where: V_D, V_{hd} - coefficients of variation, respectively, of the coefficient of effective diffusion and the value of the protective layer.
The calculation of the bearing capacity, the width of cracks, deflections of the structure is carried out in accordance with BCandR 2.03.01-84. In this case, instead of the average value of the quantity Q_{SO_3}, value is used:

$$Q_{SO_3}^p = Q_{SO_3} + 1{,}64\,\sigma Q_{SO_3} \quad (11)$$

where: Q_{SO_3} - average content SO_3; σQ_{SO_3} - standard deviation of value Q_{SO_3}.
Damaged concrete is excluded from the calculation (the section of the element is reduced) or a decrease in its strength in depth is taken into account. In the latter case, the section of the structure is conditionally divided into layers, within each of which the values Q_{SO_3} and, accordingly, the strengths of concrete are assumed to be the same.
The assessment of the expected service life of reinforced concrete structures, which are subjected to repeatedly repeated effects of heating and moistening by ground or technical sulfate-containing waters, according to the method given below, is carried out in the case when, due to the complexity of the processes occurring in concrete, they cannot be reduced to one of the types of corrosion (I, II , III).
Scope of the method: the content of ions up to 15 g/l pH of the aquatic environment 6...10 units; maximum heating temperature 90 °C; cycle duration from 2 hours to 2 days; concretes of classes B20 ... B50, grades W4 ... W10 on cements containing C_3S 39...67 %, C_2S - 12...35 %, C_3A - 4...9 %. As the predicted service life of the structure without secondary protection, the time after which the strength of the surface layer of concrete with a thickness of 25-30 mm decreases by 2 times is taken. In this case, as a rule, the protective properties of concrete in relation to reinforcement are exhausted [6,7].
The predicted service life of operating concrete before the selected limit state Tcal is determined by the formula:

$$T_{cal} = f_1 f_2 f_3 f_4 T_s \quad (12)$$

where: f_1 - coefficient taking into account the corrosion state of concrete in the protective layer; f_2 - coefficient taking into account the thickness of the protective layer; f_3 - coefficient taking into account the maximum temperature of the operating medium ($t^0_{\max s}$); f_4 - coefficient taking into account the duration of operation of the structure before the survey.
When predicting the service life of new concrete, the value of the coefficient f_1 is taken equal to 1. For used concrete, f_1 is taken to be the smallest of the values of the coefficients f_{11}, f_{12} and f_{13}, taking into account, respectively, the actual value of the water absorption value (integrated for the entire thickness of the protective layer), pH of the water extract of concrete at the reinforcement level and the number of defective sections of cement stone at the level of reinforcement:

$$f_{11} = 1 - (\omega_r - \omega_0)/(\omega_{adm} - \omega_0) \quad (13)$$

where: ω_0 - normative value of water absorption of concrete in accordance with BCandR 2.03.01-84. The lower limit ωadm is taken equal to 7%. The value of Wτ is equal to the actual value of water absorption for the survey period:

$$f_{12} = 1 - (pH_0 - pH_r)/(pH_0 - pH_{adm}) (14)$$

where: pH_0 =12,5; pH_{adm}=11,5; pH_τ - the actual value of the pH value at the time of the examination:

$$f_{13} = 1 - (L_T - L_0)/(L_{adm} - L_0) (15)$$

where: L_0 - the initial value of the number of defective areas (L_0 = 3%) in the cement stone; L_{adm} = 25% (at $L_{adm} \geq$ 25%, concrete loses its protective properties in relation to reinforcement, and its strength is approximately halved); L_T is the current value of the number of defective sections.

The value of L is determined by the planimetric method of optical microscopic analysis and is equal to the percentage of corrosion products, cracks, pores in a transparent plane-parallel section (r ≥ 10-5 m).

The coefficient f_2, which takes into account the effective thickness of the protective layer, is determined by the formula:

$$f_2 = h_d^{obs} / h_d^h (16)$$

where: h_d^{obs} - the average actual thickness of the protective layer in the surveyed area; h_d^h - thickness of the protective layer in accordance with BCandR 2.03.11-85.

Service factor f_3 depends on the maximum heating temperature $t^o_{\max}$ in cycle:

$$f_3 = 2,0 \begin{cases} 0,3 = 60^0 C \langle\ t^o_{\max} \leq 90^0 C \\ 1,6 = 40^0 C \langle\ t^o_{\max} \leq 60^0 C \\ 0,3 = t^o_{\max} \leq 40^0 C \end{cases}$$

Coefficient f_4 takes into account the duration of operation before the survey (T_{ser}), years:

$$f_4 = \begin{cases} 0,3 = T_{ser} \leq 10 \\ 0,7 = 11 \leq T_{ser} \leq 15 \\ 1 = 16 \ \langle\ T_{ser} \leq 20 \\ 1,4 = T_{ser} \ \rangle\ 20 \end{cases}$$

In the absence of information about the initial state of concrete, the predicted service life is determined in the range of T_{cal1} and T_{cal2}, which are recommended to be calculated using the formula:

$$T_{cal,j} = \eta_j T_{ser} / (1 - \eta); \quad j = 1,2 \ (17)$$

where:

$$\eta_j = S_{gen,j} / K_{ser,j} \qquad (18)$$

Here, $S_{gen.j}$ - generalizing parameter of the corrosion state of concrete, $k_{ser.j}$ - coefficient of operating conditions, taking into account the limits of change in the parameters of the initial state of concrete. Value $S_{gen.j}$ depends on the resource of concrete in terms of permeability, reactivity, the presence of clinker residues in the cement stone and the smaller of the values is taken:

$$S_{gen_1} = \frac{|\omega_t - \omega_{adm}| \cdot |pH_t - pH_{adm}| \cdot |V_t - V_{adm}|}{\omega_{adm} \cdot pH_{adm} \cdot V_{adm}} (19)$$

$$S_{gen_2} = \frac{|\omega_t - \omega_{adm}| \cdot |L_t - L_{adm}| \cdot |V_t - V_{adm}|}{\omega_{adm} \cdot L_{adm} \cdot V_{adm}} (20)$$

Here V_t - the amount of clinker residues in the cement stone of concrete,%, at the time of the survey, the value of V_{adm} = 20%. The value of V_t and V_{adm} is determined by the planimetric method of optical-microscopic analysis of transparent plane-parallel sections.

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Results of experiments and their analysis. The decrease in the cross section of steel reinforcement with uniform corrosion (after the concrete has exhausted the protective properties) occurs at an average rate given in Table. 1.

The degree of aggressive impact of the environment	Corrosion rate, mm/year	The degree of aggressive impact of the environment	Corrosion rate, mm/year
non-aggressive	0,025	Medium aggressive	0,2
Slightly aggressive	0,075	Highly aggressive	0,5

The assessment of the possible service life of load-bearing steel structures is associated with the establishment of a weakening of the section of structural elements as a result of the development of corrosion damage. Average corrosion penetration depth t_{mt} on each side of the structural element surface:

$$t_{mt} = \sum_{i=1}^{q} k\tau_t^b \quad (21)$$

where: τ_i - service life of structures with destroyed anti-corrosion protection; q - is the number of protection renewals; k, b - empirical parameters.

For operational environments, except for highly aggressive ones, characterized by increased relative humidity, the presence of sulfur dioxide, as well as dust deposits containing mainly iron compounds, which occurs at most objects of ferrous metallurgy enterprises, the values of b ≈ 0,5. For the same conditions, the values of k, mm/year, established with a confidence probability of 0,95, turned out to be 0,075 for non-aggressive environments, 0,15...0,3 for slightly aggressive environments, and 0,5 for moderately aggressive environments. In this case, these values represent the mathematical expectation of the depth of continuous uneven corrosion for a vertical single structural element of an open section. For these media with a highly aggressive degree of impact, the values of b and k turned out to be 0,67 and 0,8 mm/year, respectively [8].

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