Research of the Degradation Process of Reinforced Concrete Structures

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Abstract. The various impact on the durability of concrete and reinforced concrete structures is determined. Three groups of factors are identified that affect the assessment of the durability of reinforced concrete: a) elastic, b) strength, c) crack strength. Based on the analysis, the determining influence of the crack strength factor on concrete degradation was identified. A new method is proposed based on the analysis of existing methods for determining the characteristics of concrete crack strength. The method allows evaluating the crack strength (fracture toughness) of concrete and reinforced concrete structures in any of their conditions. (A method is proposed and a description of samples for implementing the method is given.) Standard formulas were used to evaluate characteristics of crack strength based on prismatic specimens extracted from concrete. Comparative tests of samples were carried out according to the known and proposed method. The obtained characteristics are used to assess the condition and durability of buildings and structures.

1. Introduction

All structures are subject to the destructive effects of the external environment from the moment of their construction. Moreover, three quarters of all structures in the world are affected by an aggressive environment [1]. For underground structures, aggression reaches 90%. Up to 40% of capital investments are spent on the maintenance of structures, the remaining 60% is spent on new construction[2]. Thus, the problem of ensuring the durability of reinforced concrete structures is one of the main ones in construction. The same problem is the assessment of the durability of buildings and structures.

The problem is aggravated by a significant variety of corrosive effects: gas corrosion associated with the release of nitrogen oxide, sulfur dioxide and other gases into the atmosphere by motor vehicles, industrial enterprises; deicing reagents; aggressive action of solutions of salts, acids, etc.; water-air environment, aggressive groundwater, biological corrosion associated with the impact on concrete of microorganisms, molds, plants and animals [3,4]. Corrosion of steel reinforcement significantly reduces the durability of reinforced concrete, reducing the cross-section and adhesion to concrete, changing the properties of steel and reinforced concrete structures. Corrosion of concrete is
closely related to a decrease in the protective properties of concrete most intensely in areas of cracks in concrete. Low and high temperature influences, especially cyclic ones. External influences significantly affect the nature of the concrete deformation diagrams (strength decreases, deformations change), [5, 6]. Frost resistance decreases, the structure loses its density. However, these characteristics are not enough to assess the durability of real structures [7,8]. It is necessary to develop methods for assessing the durability of reinforced concrete structures. The generalization of the research data on the premature destruction of reinforced concrete structures, performed in [1, 9,10], showed that their main causes are: initial defects, insufficient energy efficiency of concrete, increased external influences, poor protection.

Durability is determined by the correspondence of external influences to internal resistance in a certain period of time. The term "durability" in publications is defined by the term "service life". ISO 14 040 – 14 049. The initial theoretical basis and methodological basis for assessing durability is the theory of probability. Initial foundations for calculating the durability of structures N. Streletsky in 1924. The following factors are accepted as determining factors: variability of material properties, load and workmanship. Each of the factors can be taken as random. This approach is still used today and is called the semi-probabilistic method. This approach was developed by A. Gvozdev [11], S. Aleksandrovsky. More general methods were developed by V Bolotin [12], A. Rzhanitsin [13], N Karpenko [14].

2. Theoretical part
The paper [15] highlights the importance of experimental methods in assessing the durability of structures. The durability assessment is based on the Bailey formula:

\[ L = \int_{t_0}^{t_L} \frac{dt}{\tau_L(\omega(t))}, \]  

(1)

where \( t_0 \) and \( t_L \) are the initial and final times \( \omega(t) \), is the fracture factor of the material. (Taken, for example, as the growth of defects from the number of actions).

However, studies of the durability of concrete show that the influence of the parameters of the structure of the material on the applied strength characteristics are in many cases incorrect. [16]. Studies show that the change in strength characteristics and characteristics of crack strength occurs in different ways, often in waves. In this work, the change in long-term characteristics was carried out both by standard methods and methods of measuring the characteristics of crack strength. Comprehensive determination of the characteristics of materials made it possible to predict the performance of the material under load.

Based on fracture mechanics, dependencies were obtained to assess the durability. [17]. It is assumed that the fracture has the same number of crack lengths both with fast loading and with prolonged loading. The formula describing this assumption looks like: relative ultimate strength:

\[ \eta(t, \tau_1) = \frac{m(t, \tau_1)R(t)}{R(\tau_1)} \left( \frac{1}{1+E(t)C(t, \tau_1)} \right), \]  

(2)

From the dependence it is seen that the long-term strength depends on \( m(t, \tau_1) \) which takes into account the nature of loading, changes in strength, initial modulus and changes in creep. The article concludes that it is necessary to use fracture mechanics to assess durability.

The change in the strength of concrete at the age of 28 days in time is most often described by the dependence:

\[ R1(t)/R28 = log(t)/log(28). \]  

(3)

The study of concrete degradation [18] showed that this process with varying degrees of accuracy can be described by a linear or exponential dependence.

The study of acoustic vibrations during the formation and growth of cracks [19] reveals the following dependence of durability on the acting stresses:

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\[ t = t_0/X^n, \quad X=X = \sigma/\sigma_0 = L/L_0 \quad (4) \]

where \( t \) is the current time, \( t_0 \) is the durability at \( x \rightarrow 1 \), \( \sigma_0, L_0 \) - the ultimate stress or load.

A method for assessing the durability of a material is associated with obtaining the acoustic characteristics of crack growth on a sample and transferring these values when testing a full-scale sample.

In general, considering the problem of assessing durability, it can be noted that in the existing experimental provisions, a set of characteristics is considered: elastic, strength, crack strength. Of all the characteristics noted, only crack strength is a stable characteristic with respect to changes in characteristics.

When considering concrete as a structural material in the general framework of the unified concepts of solid mechanics and fracture mechanics, the critical values of the parameters of the stress-strain state in the sections of structural elements determined from the test results of control samples are used as new characteristics of its crack resistance properties. The introduction of these characteristics into the calculation of concrete and reinforced concrete elements makes it possible to determine the parameters of the bearing capacity in a real stress-strain state in a structure at given load levels.

3. Methods of fracture mechanics

In experimental fracture mechanics, the critical stress intensity factor \( K_{IC} (\text{MPa} \cdot \text{M}^{1/2}) \) and the released elastic energy \( G_i \) are one of the main power and energy characteristics of structural materials. These parameters, characterizing the resistance of concrete to external force effects, are obtained, as a rule, in non-equilibrium tests.

The calculation method is based on the hypothesis of structural capillary - pore defects as cracks, at the tops of which the highest stresses are created due to changing external influences. In mathematical models, invariant energy \( G_i \) and power \( K_c \) are used - parameters of characteristics of concrete structure properties. In the method of calculating the forecast, the classical theory of concrete aging is applied.

However, the determination of \( K_c \) in real structures, calculated on the basis of model schemes of development, association, localization of the system of cracks, their classification by type and relative amount in the volume at an initial concentration that increases to a critical one cannot always be determined with sufficient accuracy under the influence of changing environmental factors.

The method for testing concrete elements was developed in order to obtain data for studying the crack resistance of concrete. Obtaining a deformation diagram with a descending branch is possible only under loading with deformation control. Such loading can be carried out either on rigid testing machines, or on standard machines with loading in parallel with the sample of elastic elements with a selected stiffness, to which the force is gradually redistributed from the sample as it loses its bearing capacity during loading. In the studies carried out, the first scheme was used.

At the moment, the main sample for determining the characteristics of crack strength (fracture toughness) of concrete is a rectangular prism. Figure 1 shows the test scheme for a prismatic sample in accordance with GOST 29167-91. For ordinary concrete, the minimum sample size is 100x100x400 mm. For fine-grained and sandy concrete, the minimum size is 40x40x100 mm.

4. Samples characteristics and test procedure

The minimum dimensions of the samples and the dimensions of the initial cuts are taken depending on the grain size of the aggregate dam. The dimensions of the cuts are shown in the table. 1. The width of the initial notch is taken to be no more than 0.5 dam (maximum aggregate grain size) and no more than 2 mm. Table 1 also shows different ratios of specimen size and initial notches.
Table 1. Dependence of the notch size on the maximum aggregate grain size.

| dam     | b   | a₀   | a₀t  | a_ij | (b - a₀ - a₀t) / b | b / a₀ | b / d_am | a_ij / d_am |
|---------|-----|------|------|------|-------------------|--------|----------|-------------|
| less 1.25 | 40  | 10   | 5    | 25   | 0.625             | 4.0    | 32       | 20          |
| 1.25-5.0 | 70  | 25   | 5    | 40   | 0.571             | 2.8    | 14       | 8           |
| 5.0-10.0 | 100 | 35   | 5    | 60   | 0.60              | 2.9    | 10       | 6           |
| 10.0-20.0 | 150 | 50   | 10   | 90   | 0.60              | 3.0    | 7.5      | 4.5         |
| 20.0-40.0 | 200 | 70   | 10   | 120  | 0.60              | 2.9    | 5        | 3           |
| 40.0-60.0 | 300 | 100  | 15   | 185  | 0.617             | 3.0    | 5        | 3           |
| 60.0-80.0 | 400 | 140  | 20   | 240  | 0.60              | 2.9    | 5        | 3           |

For testing such samples, a special installation was created that allows you to control the deformation process of the experimental element at all stages of its resistance, as well as allows you to get a complete diagram of concrete behavior, including the falling branch. A distinctive feature of our installation from the one proposed by GOST is that it allows using mechanical devices (indications) instead of recorders and excluding elastic elements to obtain fully equilibrium concrete diagrams. In addition, the proposed installation eliminates the influence of the sample's own weight during testing, which presses the sample at the moment of pre-failure. This was achieved by placing the installation in a horizontal plane. Thus, the specimen, the test specimen, perceiving the load in the horizontal direction, is deformed unhindered and is not influenced by its own weight. The schematic diagram of the installation is shown in Figure 1.

![Figure 1. Experimental setup diagram.](image)

1-power frame; 2-screw; 3-pivoting movable support; 4-articulated fixed support; 5-dial indicator; 6-dynamometer; 7-sample; 8-hinge; 9-distribution plate; 10-pallet; 11-balls; 12-support for the dynamometer.

The fundamental difference in the test method is that the tests were carried out according to a "rigid" scheme by specifying the deflection deformations of the test specimen, as well as the load application scheme. The loading step was 0.05 mm with holding at each stage. The criterion for increasing the deformations was the invariability of the readings of the indicators measuring the deflection deformation and the magnitude of the load for 15 sec. The choice of such a loading scheme was caused by the need to obtain a diagram of the behavior of concrete with a falling branch.
5. Results of experimental research;
As a result of equilibrium tests on a new experimental setup, diagrams of the behavior of concrete with a falling branch were obtained (Figure 2).

![Figure 2. Typical test results.](image)

The obtained results of equilibrium tests of the samples were processed according to the method described in GOST 29167-91. The deviation of the obtained characteristics did not exceed 10%.

All known methods make it possible to obtain the characteristics of crack strength only by extracting a prototype, which is very laborious.

To determine the SIF, a method and device was developed that make it possible to obtain this coefficient both on laboratory samples and on existing structures, which consists in the formation of a stress concentration zone in the corner of the structure (Figures 3, 4) to which a moment is applied.

Known hand-held devices for plotting concrete crack resistance diagrams [20]. However, such devices require the manufacture of special samples and are not accurate enough.

The growth of cracks is dangerous not only as a parameter that reduces the strength and durability of buildings, but also as a danger of the emergence and growth of microorganisms in cracks.

![Figure 3. Test scheme.](image)

1 - metal corner; 2 - lever; 3 - dial indicator;
4 – test specimen (structural element);
5 - longitudinal cuts; 6 - cross cuts.

![Figure 4. Formation of a concentrator in the corner of the structure.](image)

For testing, as well as verification of the data obtained, we used the halves of the tested samples for three-point bending [21-27]. The difference in the results obtained did not exceed 12%. The tests were
carried out with the fixation of the breaking load through a dial indicator with a division value of 0.001 mm, and the surface area of the corner segment breakage was also recorded.

Based on the test results, a regression formula (1) was derived for determining the critical stress intensity factor:

\[ K_{IC} = 0.425 + 0.002M - 5b, \text{ MPa} \cdot \text{m}^{0.5} \]  

(5)

Where \( M \) is the moment (H\cdot m); \( b \) – distance between cross cuts (m)

A more extended dependency is written like this:

\[ K_{IC} = B_0 + B_1 f(M, t/b) + B_2 f(h/b) \]  

(6)

Where \( K_{IC} \) is critical stress intensity factor, MPa\cdot m^{0.5}; \( B_0, B_1, B_2 \) coefficients depending on the type of concrete of the product; The second term is the dependence, determined by the breaking load and the parameters of the broken off corner segment of the product, MPa\cdot m^{0.5}. The third term is the dependence determined by the parameters of the broken off corner segment; \( M \) is breaking load, H\cdot m; \( t \) is the width of the section of the surface of the corner segment break, m; \( b \) is the length of the section of the surface of the corner segment break, m; \( h \) is the height of the lateral surface of the corner segment, m.

According to the claimed method, the coefficients \( B_0, B_1, B_2 \) are obtained empirically and for heavy beton, respectively, are equal to \( B_0 = 0.516, B_1 = -0.02, B_2 = -0.647. \)

Under production conditions, the stress concentration zone in the foundation block was made in the form of an angular segment at the intersection of its perpendicular edges, the formed zone was loaded along the surface of the angular segment until it was broken. The breaking load \( M \) was determined by the product of the concentrated force (N) applied to the lever by the arm (l) of this lever. After breaking off the corner segment, its parameters (b, t and h) were measured. The critical stress intensity factor in the foundation block was determined by the formula:

\[ K_{IC} = 0.516 + 0.02 \]

According to the measurement results: \( b = 0.05 \text{ m}; t = 0.055 \text{ m}; h = 0.045 \text{ m}; \) \( N \) - was in the range 123.7 ÷ 124.7 H; \( l = 0.9 \text{ m}. \)

The critical stress intensity factor in the control samples and in the extracted samples according to the prototype was determined using the force criterion of fracture mechanics in accordance with GOST 29167-91 “Concrete. Methods for determining the characteristics of crack strength (fracture toughness) under static loading. The average test results are shown in Table 2.

| № experiment | Critical stress intensity factor, \( K_{IC}, \text{ MPa} \cdot \text{m}^{0.5} \), in the control sample | in prototype sample | in the sample according to the claimed method |
|--------------|-------------------------------------------------|---------------------|---------------------------------------------|
| 1            | 0.280                                           | 0.221               | 0.279                                       |
| 2            | 0.280                                           | 0.248               | 0.281                                       |
| 3            | 0.283                                           | 0.238               | 0.282                                       |
| Mean         | 0.281                                           | 0.236               | 0.281                                       |

6. Conclusion
The test results given in the table allow us to conclude that the claimed method, in comparison with the prototype, improves the accuracy of determining the critical stress intensity factor in the product by an average of 19%. The scatter of the data obtained by the claimed method was (0.282-0.279) / 0.281 = 0.01, according to the prototype (0.248-0.221) / 0.236 = 0.11 > 0.01, which confirms the higher reliability of the proposed method. At the same time, the proposed method for determining the
critical stress intensity factor in a product, with ease of use, can be widely used not only in laboratory conditions, but also at industrial facilities of operating industries to determine the forecast of durability.

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