Factors determining characteristics of crack resistance of concrete structures

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Abstract. Despite the fact that concrete and reinforced concrete are the main construction materials, to date there is no complete theory of deformation and destruction. Structural concrete is considered at the level of macrostructure, has a number of features that do not allow you to directly transfer some of the provisions obtained for homogeneous materials. Available experimental data on the resistance of the concrete crack propagation relate mainly to the laboratory samples. In the paper, a new method for obtaining the fracture mechanics parameters of concrete, which is one of the most promising areas of research of fracture of composite materials. The study investigates the characteristics of cracks at different parameters of the segment breaks off. The study was carried out on finite element models. The authors studied the influence of the tilt angles formed by the segment on the stress state at the tip of the crack. In addition, the research separately considered the changes in mechanical properties of a break-off segment. As a result, the authors built regression tables and graphs. In conclusion, the research provides recommendations for the implementation of a shape for the break-off segment.

1. Introduction
It is known that the phenomena of deformation and destruction of concrete and reinforced concrete is a complex multistep process, study engineering mechanics of reinforced concrete. A significant contribution to the development of fracture mechanics has been made by Russian scientists A. A. Gvozdev, C. B. Alexanderovsky, N. X. Arutyunyan, V. M. Bondarenko, N. A. Karpenko, S. V. Bondarenko, O.J. Bergh, V. I. Murashov, R. S. Sanzharovsky, M. Kholmyansky, V. I. Rimshin and others. The work of the concrete to a certain level can be considered as a homogeneous medium. After the formation of cracks it is necessary to consider their availability [1-3]. Hence the necessity of studying the concrete and reinforced concrete from the standpoint of fracture mechanics, which in a broad sense this concept includes that part of the science of strength of materials and structures, which is associated with the study of the bearing capacity of bodies, taking into account the initial distribution of cracks [4,5].

Characteristics of fracture toughness of building structures can serve as a criterion of definition of a residual resource of buildings and structures. Characteristics of fracture toughness allow to determine the period of the formation of cracks and their development to a critical size [6-8].

The goal of fracture mechanics is the determination of the conditions of destruction of bodies of various shapes, working under the given loads in certain conditions.
2. Relevance
In reinforced concrete elements cracks can be caused by conditions of hardening and shrinkage of concrete, pre-eccentric compression in the manufacture, the strain of the material during operation due to overload, precipitation and many other reasons. Cracks at the stretched areas of the elements, invisible to the eye, appear even in a perfectly executed reinforced concrete structures. Their formation is due to the small elongation of the concrete, unable to follow for a substantial elongation of the reinforcement at high operating voltages.

Fracture mechanics of heterogeneous bodies is investigated much less than in the case of homogeneous (quasi-homogeneous) materials. Therefore, for the analysis of the development of cracks in concrete involves some additional hypotheses [9,10]. To date no simple experimental method of determination of crack resistance characteristics of exploited elements. In this regard, put forward a hypothetical model of the development of systems of cracks and crack-like defects defects which is the prediction of durability and assessment of technical state of reinforced concrete elements [11].

3. Statement of the problem
Important aspect of fracture mechanics is the formulation of the criterion of local fracture. The analysis shows that the classical methods of calculation of the parts of elastic and plastic States in some cases do not provide a solution to the problem [12]. This situation has led to the development of the theory, which would allow to apply the results obtained in the test samples, design of structures and accurately predict the destructive connection between stress and flaw size. The Objective of this study is to introduce the characteristics of crack resistance of structural materials and to develop testing methods, allowing you to choose the right materials, manufacturing processes and operating conditions by the criterion of fracture toughness.

4. The theoretical part
Most of the ways of experimental determination of characteristics of fracture toughness based on the same principle: in the sample of a certain shape and a certain size is created an artificial crack (notch) having a well defined shape and size. Then the sample is loaded at low speed and record the critical load at which the crack becomes unstable and grows. Then measured the load and deformation and evaluates characteristics of fracture toughness.

Analysis of existing methods of determining characteristics of fracture concrete [13] shows that the existing methods are developed and applicable only in laboratory conditions. Today (GOST 29167-91) recommended definition characteristics of fracture toughness at equilibrium tests on the samples – prisms, tested in three-point bending. The transfer of the values obtained in the laboratory in the design on the actual design who has worked for a long time illegal as mentioned above on the value of fracture toughness provides a large number of factors which are difficult to consider in advance.

The closest analogue of the proposed technical solution is the method of determining characteristics of fracture toughness in the product, namely that in the product of rectangular cross section performs the stress concentration zone, which is loaded to failure, and according to the obtained parameters define the characteristics of fracture toughness. According to the invention (patent RF 2324916), the zone of stress concentration in the product perform in the form of an angular segment at the intersection of its perpendicular faces, load on the surface of the angular segment to its extract, and then measure the failure load and the parameters of the broken-off corner of the segment, and fracture toughness is determined by the derived formula. Therefore, the development of the method of determining Characteristics of fracture toughness in real structures is relevant [14,15].

5. The practical part
In the experimental part of the work carried out research to determine the parameters of fracture toughness of concrete structures operated under static loading with the application of software STARK_ES 2014.
Samples for testing were of the size of the prism 1500x1500x1000 mm of concrete in the upper zone of which the entire thickness made the cuts with a width of 30...200 mm, different depths and at different angles [16]. To free part cutting glued a bar of metal. To the bar on one of the faces of the applied single force. The prism is divided into finite elements. Figure 1 shows schematic cuts of the samples.

![Figure 1. Diagram of cuts and descriptions of the stress state of the fracture tip: N – on the bottom face of the cut at the top edge cutting.](image)

The program for simulation of stress state of massive bodies use modern high-precision volumetric finite elements. Such elements are further conventionally called “3D elements”. Used three types of volumetric finite elements: two types of hybrid finite element and single element type, the method of displacement. When constructing hybrid elements were used, the Reissner functional, and items methods of movement – Lagrange functional. Hybrid elements of type 1 are in equilibrium, and type 2 – non-equilibrium. Elements of the displacements method (type 3) are ISO-parametric. Below is a chart of concrete sample No. 5, the scheme of its loading and diagram, which displays the distribution of stresses and displacements in the sample (figures 2-3).

**Table 1.** Characteristics of samples.

| No. | Thickness, d [m] | Modulus of elasticity, E [kN/m²] | Poisson's Ratio, Mu | The density of the material, Rho [t/m³] |
|-----|-----------------|---------------------------------|-------------------|---------------------------------------|
| 1   | 1               | 3e+007                          | 0.2               | 2.75                                  |
| 2   | 1               | 2.06e+008                       | 0.3               | 8.24                                  |

**Table 2.** The material list of plates.

| Material number | The number of elements | Total area [m²] | Total volume [m³] | Total mass [t] |
|-----------------|------------------------|-----------------|------------------|----------------|
| 1               | 2516                   | 2.229           | 2.229            | 6.129          |
| 2               | 168                    | 0.151           | 0.151            | 1.246          |
| Итого:          | 2684                   | 2.380           | 2.380            | 7.375          |

**Table 3.** Nodal loads of the finite element project

| Loading Node | Px [kN] | Py [kN] | Pz [kN] | Mx [kNm] | My [kNm] | Mz [kNm] |
|--------------|---------|---------|---------|----------|----------|----------|
| 2            | 2611    | 0.000   | 0.000   | 1.000    | 0.000    | 0.000    |

Figure 2 for example shows a diagram of sample number 5, which displays the stress distribution. The strain Distribution over the cross section of the sample shown in Fig.3. A total of 34 experience. The summarized results of the description area of the tip of the crack and deformation of the zone cut are given in table. 4. The influence of the angle of the cutting segment shown in figure 5.
Figure 2. The stress distribution in the sample 5. Min SeM = 0.300935 kN/m², Max SeM = 165.98 kN/m.

Figure 3. The distribution of displacements Max move = 0.00301641 mm

Was carried out 34 experience. The summarized results of the description area of the tip of the crack and deformation of the zone cut are given in table 4.

Table 4. The summary of the test results.

| No experience | Voltage zones, KN/m² | Deformation of the side |
|---------------|----------------------|-------------------------|
|               |                      | loaded                  | free                    |
| 1 | 30-0-90 | 4 | 3.9 | 1.1 | 2.2 | - | - | 0.0013 | 0.0016 |
| 2 | 30-5-90 | 5.5 | 5 | 2.4 | 2.5 | - | - | 0.0014 | 0.0015 |
| 3 | 30-15-90 | 8.5 | 7 | 6.7 | 2.8 | - | - | 0.0018 | 0.0015 |
| 4 | 30-30-90 | 6.4 | 9.7 | 23.5 | 4.7 | - | - | 0.0029 | 0.0022 |
| 5 | 30-45-90 | 1.1 | 20.3 | 37.4 | 8.5 | 9.3 | - | 0.0057 | 0.0044 |
| 6 | 30-45-90-2 | 1.2 | 20.3 | 37.4 | 8.5 | 9.3 | - | 0.0018 | 0.0013 |
| 7 | 30-45-90-3 | 1 | 20.3 | 37.4 | 8.4 | 9.4 | - | 0.0021 | 0.0025 |
| 8 | 30-45-45 | 2.5 | 12.7 | 18.2 | 1.26 | - | - | 0.022 | 0.02 |
| 9 | 30-45-75 | 27.3 | 196 | 74.0 | 116 | - | - | 0.0013 | 0.0016 |
| 10 | 50-0-90 | 3.8 | 4.2 | 0.3 | 2.2 | - | - | 0.0013 | 0.0015 |
| 11 | 50-5-90 | 4.5 | 5.5 | 4.0 | 2.7 | - | - | 0.0014 | 0.0015 |
| 12 | 50-15-90 | 7 | 7.7 | 8.3 | 2.9 | - | - | 0.0017 | 0.0015 |
| 13 | 50-30-90 | 0.6 | 12.2 | 16.5 | 5.1 | - | - | 0.0029 | 0.0022 |
| 14 | 50-45-90 | - | 21.5 | 34.5 | 8.4 | 9.3 | - | 0.0015 | 0.0013 |
| 15 | 50-45-45 | 0.7 | 12.1 | 16.6 | 1.3 | - | - | 0.0011 | 0.0014 |
| 16 | 50-45-75 | - | 7.7 | 135 | 31 | - | - | 0.0012 | 0.0014 |
| 17 | 200-0-90 | 5.8 | 4.6 | 2.8 | 3.3 | - | - | 0.0013 | 0.0013 |
| 18 | 200-5-90 | 7.1 | 5.5 | 3.5 | 3.6 | - | - | 0.0013 | 0.0013 |
| 19 | 200-15-90 | 9.6 | 7.0 | 7.3 | 3.8 | - | - | 0.0014 | 0.0015 |
| 20 | 200-30-90 | 5.1 | 8.4 | 16.5 | 6.3 | - | - | 0.0028 | 0.0021 |
| 21 | 200-45-90 | 31.6 | 11.9 | 31.0 | 11.3 | - | - | 0.0020 | 0.0024 |
| 22 | 200-45-45 | 4.4 | 9.8 | 12.7 | 3.5 | - | - | 0.0019 | 0.0015 |
| 23 | 200-45-75 | - | 64.7 | 97 | 71 | - | - | 0.0013 | 0.0016 |
| 24 | 30-0-90* | 4.0 | 3.9 | 1.1 | 2.2 | - | - | 0.0013 | 0.0014 |
| 25 | 30-5-90* | 6.0 | 5.3 | 2.7 | 2.6 | - | - | 0.0013 | 0.0015 |
| 26 | 30-15-90* | 3.8 | 7.0 | 7.8 | 2.7 | - | - | 0.0014 | 0.0015 |
| 27 | 30-30-90* | 6.7 | 10.1 | 27.6 | 4.8 | - | - | 0.0016 | 0.0020 |
| 28 | 30-45-90* | 0.4 | 22.8 | 43.2 | 9.0 | 9.3 | - | 0.0028 | 0.0035 |
| 29 | 30-45-90-2* | -0.4 | 22.8 | 43.2 | 9.0 | 9.3 | - | 0.0055 | 0.0069 |
| 30 | 30-45-90-3* | -0.6 | 22.8 | 43.2 | 9.0 | 12.2 | - | 0.0017 | 0.0021 |
| 31 | 30-45-45* | 2.4 | 15.5 | 24.1 | 2.8 | - | - | 0.0022 | 0.0020 |
| 32 | 30-45-75* | 2.8 | 213 | 12.8 | 218 | - | - | 0.022 | 0.024 |
| 33 | 50-5-90* | 5.1 | 5.8 | 4.3 | 2.8 | - | - | 0.0015 | 0.0015 |
| 34 | 50-45-90* | -6.6 | 24.4 | 39.9 | 8.9 | 11.8 | - | 0.0027 | 0.0035 |
The influence of the angle-cutting segment shown in figure 4. The results presented in table 5 indicate that the angle of the initial cutting cracks it is advisable to perform at least 45°. The increase of the corner cutting more than 45 degrees is possible, but due to technical problems the execution of cut hard.

![Figure 4. The effect of tilt angle on the voltage in the segment](image)

6. Insights
Increase the width of cut is beneficial to increase stress and controlled strain (Figure 5, 14, and 21, table. 4). The change in angle free angle practically does not affect the stress value (POS. 8, 15 and 22 tables. 4).

The point of application of force significantly influenced by the magnitude of the stresses (less than 15%). The change in the modulus of elasticity of the material did not affect the magnitude of the stresses (POS 5, 6, 7 table. 4), indicating the correctness of model building.

It is recommended that the prism with the wide notches with tilt angle-cutting not less than 45 ° and a right angle with the unloaded side.

7. Conclusion
Because of its durability concrete is the main material in the existing structures. Moreover, the volume of concrete structures worldwide is growing. Currently, the monitoring of physical-mechanical condition of reinforced concrete is mainly only by its strength. Moreover control methods to 80% indirect. On the basis of fracture mechanics of concrete at the Department of design of buildings and building constructions, Magnitogorsk state technical University [17,18] was developed "Method of determining the critical stress intensity factor (KKin) in the product" [19]. On the basis of this method was developed the method of assessing KKIN the product and methods of estimation of durability of reinforced concrete structures of buildings and structures. At the moment on this subject in recent years made more than 40 scientific papers. Was conducted further investigation, including modeling of concrete and reinforced concrete. These studies helped to develop the theory of degradation of concrete [20-23]. Getting a new yet unknown characteristics of the structure, working in real conditions will allow to design and to build strong and durable buildings and structures from concrete and reinforced concrete.

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