Estimating Durability of Reinforced Concrete

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Abstract. In this article we propose to use the methods of fracture mechanics to evaluate concrete durability. To evaluate concrete crack resistance characteristics of concrete directly in the structure in order to implement the methods of fracture mechanics, we have developed special methods. Various experimental studies have been carried out to determine the crack resistance characteristics and the concrete modulus of elasticity during its operating. A comparison was carried out for the results obtained with the use of the proposed methods and those obtained with the standard methods for determining the concrete crack resistance characteristics.

1. Introduction

Methods and hypotheses of the mechanics of destruction of reinforced concrete are increasingly used in durability calculations [1,2], calculations of bent and eccentrically compressed elements [3-5] for the selection of the concrete composition [6].

The aim of this research study is to work out a proposal of a method for estimating the durability of reinforced concrete structures. The study is based on the proposals of V.Yu. Zaitsev stated in works [1,2]. The method is based on the calculation of crack resistance properties of concrete structures exploited under static loading. The calculated dependencies of the method proposed additionally take into account variation in the strength and elastic properties of concrete.

The methods known for determination of the crack resistance characteristics of concrete in existing structures propose the extraction of a prototype and its subsequent laboratory testing [7-10] that is costly or does not seem feasible in most structures.

On the other hand, the experimental data on the crack extension resistance of concrete refer mainly to the experimental laboratory samples [11,12] and comparison of the results obtained with full-scale structures is difficult in most cases.

2. A corner break-off method for SICF calculation

In order to eliminate the drawbacks, a new method for the stress intensity concentration factor (SICF) calculation was proposed. The devices making it possible to obtain this factor both on the laboratory samples and on existing structures were developed [13]. The method consists of the formation of a stress concentration zone in the corner of the structure (in the form of a corner segment) followed by this concentrator break off.
A corner segment is formed by the formation of longitudinal and transverse cuts (Figure 1). The following reference parameters of the corner segment were assumed: the depth of the longitudinal cuts up to 10 mm; the distance between the transverse cuts up to 50 mm; the distance between the longitudinal cut and the edge of the sample on both facets up to 45 mm. The geometry was chosen based on the largest approximation of the break-off section to the section of the standard sample destruction.

The halves of the samples tested in three-point bending in a standard way were used for testing [14-16]. The tests were carried out with the fixation of the destructive load with the help of a lever fixed dial indicator with 0.001 mm in scale interval. After the break-off, the surface area of the formed corner segment was recorded.

A regression formula was derived for the SICF calculation based on the results of the tests:

\[ K_{IC} = 0.666 + 0.00183M - 5.206b - 4.415l \]  \( \text{MPa} \cdot \text{m}^{0.5} \) \hspace{1cm} (1)

where \( M \) is the moment (N·m); \( b \) is the distance between the transverse cuts (m); \( l \) is the distance between the tips of longitudinal cuts (m).

Two drawbacks of this method should be noted:
- it is applicable only to the corner segments of constructions;
- one sample gives only one SICF experimental value, which corresponds to the initiation of spontaneous crack growth.

3. New methods of the SICF calculation

The schemes and explanations of methods that are free of these drawbacks are shown in Figure 2.

The methods proposed were applied to a flat surface. The relaxation method was used at obtaining the characteristics of crack resistance when several loading and unloading cycles can be carried out on one sample.

The impact of the shape of the segment being break-off on the stress-strain state of the break-off zone was studied on the finite element model. The samples consisted of concrete prisms with 150x150 mm section and 100 mm width. In the lower zone, the prism was fixed. In the upper zone, the cuts 1-7 mm wide of different depths and at different angles were made through the entire thickness. A bar of metal was bonded to the free part of the cut with glue. A single force was applied to the bar.

Prisms were divided into finite elements. At the tip of the cut, the dimensions of the finite elements were 0.2 mm. Figure 3 shows the schemes of the cuts studied.

The effect of the break-off angle is shown in Figure 4. It can be seen that the angle of initial crack inclination should preferably be at least 45°. The increased cut angle above 45° is possible, but can cause the technical problems in cutting. The increased cut width favourably affected the increased stresses and deformations under control.
Figure 2. The schemes of methods for determining surface crack resistance characteristics.

Figure 3. The cut schemes. \( h = 240, 270, 300, 330; \delta = 30, 50, 200; b = 210, 240, 300, 360, 420; \beta = 90^\circ, 45^\circ; \alpha = 90^\circ, 95^\circ, 105^\circ, 120^\circ, 135^\circ, 165^\circ \) – on the lower cut edge, on the upper cut edge.

Figure 4. The influence of the angle inclination on the stresses in the corner segment.

The variation of the free angle slope had practically no effect on the stress values at the tip of the crack. The point of force application had an insignificant effect on the stress values at the tip of the crack. A prism is recommended with wide cuts and an angle of inclination from the break off side of no less than 45° and a right angle toward the unloaded side.

The study of the influence of heterogeneity in the concrete body on the distribution of stresses and deformations in this zone showed that the greatest influence of heterogeneity is observed when the zone is located exactly at the centre of the crack tip. Almost immediately after the heterogeneity releasing from the zone of the crack tip, its effect is sharply weakened. To conclude, it is necessary to analyse the fracture zone after having carried out the experiment.

The study of the influence of the trapezoidal zone size on the strain and stress distribution allowed us to conclude that the most rational height of the trapezoidal element is no less than 0.8 of its width.
The study of the zone of direct contact of the metallic element with concrete (Figure 5) indicates the possibility of the SICF calculation by the direct break-off of the metallic element without forming a trapezoidal zone. Provided that the adhesive bond strength will be higher than the strength of concrete.

4. Accounting for modified modulus of elasticity of concrete
In due course, all the dependent properties for concrete are modified [1,2]. It is necessary to take into account the defectiveness of the sample with the old concrete when extracting it from the structure, including the one resulted from stresses and corrosion. The ratio of strength and modulus of elasticity of the old concrete should be different from the same ratio for the standard age of concrete. This should be taken into account both when determining the deformations in the old concrete and when determining the stresses in it.

Different researchers noted a decreased modulus of elasticity of concrete under its cyclic loading [17-19]. This fact is not taken into account in the typical diagrams of concrete deformation and in the theories of its calculation. Previously, we theoretically justified that the modulus of elasticity of concrete should decrease with increasing the defects in it [20,21].

We produced three series of the concrete samples with different coarse aggregate fractions to test the nature of the change in the modulus of elastic deformation. Each series consisted of the samples prisms with 15x15, 10x10; 5x5 cm cross section and 10x10 cm cube cross section.

We used standard steel moulds and a moulding method to make the samples. All series of the concrete samples were made of cement grade M400. Each series was different from the other only in the large aggregate size fraction (5-10mm, 10-12mm, 12-20mm).

The analysis of the deformation graphs obtained allows us to draw the following conclusions:
1. At the first stages of loading, the modulus changes are insignificant with a load of 0.4-0.5; and the change in the modulus of elasticity is not noticeable if the sample is centered before loading - loading and unloading it.
2. The elastic modulus decreases with the level of voltage and with increasing holding time.
3. An increase that was observed in some samples or at some stages of the elastic modulus loading related to the eccentric loading of the samples. When the longitudinal deformations were levelled-off along the faces, the effect of decrease in the modulus of elasticity returned.
4. Deformations could not be fully levelled off in the samples with small dimensions - 5x5x20 cm. This is due not only to external conditions, but also to the heterogeneity of the concrete. Special tools should be used for the small samples.
5. The modulus change in solution prisms was insignificant that is probably due to their small plastic deformations.
5. Conclusions
The material defectiveness is characterized both by plastic and elastic deformations. It is proposed to build the diagram of the concrete behaviour stepwise:
1. The initial module is used to set the loading level.
2. The value of concrete plastic deformation is determined in accordance with a set level of elastic deformations.
3. In accordance with the value of plastic deformation, the modulus of elasticity is specified and the next step of loading is determined.

The variation of the elastic strains can be determined at the first stage in accordance with I. A. Matarov’s formula [19]:

\[
\log \varepsilon_y = a + b \log N
\]  

where \( \varepsilon_y \) is the value of elastic deformations; \( a \) and \( b \) are the experimental coefficients; \( N \) is the loading level.

Concrete samples were produced for the comparative tests. The raw materials for the sample production were portland cement of M400 grade as a binding substance, quartz sand of fraction 0-5 mm (Mk = 2.9) as a fine aggregate, the porphyritic gravel of the Magnitogorsk granite quarry of fraction 5-20 as a coarse aggregate. Concrete prisms were produced with size of 100 \( \times \) 100 \( \times \) 400 mm. The concrete were cut through by the disc cutter to initiate cracks.

The dimensions of initiating cracks were accepted taking into account the recommendations of the standard methods [7]: the upper one was 5 mm; the lower one was 35 mm and 40 mm.

In order to determine the SICF in the remaining halves of the prisms tested in three-point bending, longitudinal and transversal cuts were made by the diamond disc cutter. The depth of the longitudinal cuts was 10 mm. The distance from the sample edge to the longitudinal cut was \( h = 25 \) mm.

One half of the prism was tested with the corner zone break off, the second one – with fracture of the trapezium on the surface area (method 1). Figure 6 shows the characteristic load-displacement diagrams. The test results processed are shown in the Table 1.

\[\text{Figure 6. Completely balanced diagram.}\]
Table 1. Results of the determination of the crack resistance characteristics of concrete by different methods.

| Test | Wm, N·m | We, N·m | Wl, N·m | Wui, N·m | Wce, N·m | Gi, N/m | Gf, N/m | Gce, N/m | Ji, N/m | Klc, MN/m$^{3/2}$ |
|------|---------|---------|---------|---------|---------|--------|--------|--------|--------|----------------|
| 5-35 | 0.09    | 0.37    | 0.80    | 0.32    | 0.04    | 76.32  | 195.44 | 6.52   | 22.57  | 0.54          |
| 5-40 | 0.10    | 0.24    | 0.64    | 0.18    | 0.04    | 55.11  | 145.50 | 7.48   | 25.29  | 0.57          |

The test result of the angle segment 0.56

The test results of the trapezium break-off

|   | Wm, N·m | We, N·m | Wl, N·m | Wui, N·m | Wce, N·m | Gi, N/m | Gf, N/m | Gce, N/m | Ji, N/m | Klc, MN/m$^{3/2}$ |
|---|---------|---------|---------|---------|---------|--------|--------|--------|--------|----------------|
| 1 | 0.06    | 0.16    | 0.76    | 0.12    | 0.06    | 46.68  | 121.67 | 7.10   | 16.87  | 0.57          |
| 2 | 0.10    | 0.35    | 0.80    | 0.21    | 0.04    | 70.98  | 193.58 | 7.00   | 36.73  | 0.56          |
| 3 | 0.12    | 0.43    | 0.74    | 0.28    | 0.03    | 77.75  | 166.72 | 6.96   | 37.33  | 0.55          |
| 4 | 0.10    | 0.23    | 0.62    | 0.20    | 0.04    | 43.19  | 134.51 | 7.20   | 16.98  | 0.59          |
| 5 | 0.08    | 0.18    | 0.67    | 0.13    | 0.03    | 38.95  | 142.54 | 6.86   | 23.96  | 0.55          |
| 6 | 0.13    | 0.21    | 0.57    | 0.17    | 0.04    | 57.27  | 147.06 | 7.40   | 22.83  | 0.55          |
| Average | 0.10 | 0.26    | 0.69    | 0.19    | 0.4     | 55.80  | 151.01 | 7.08   | 258    | 0.56          |

6. Conclusion

The data in the table shows that the characteristics of the concrete crack resistance obtained by the standard and proposed methods almost coincide. A new method for determining the crack resistance characteristics of concrete makes it possible to obtain not only the SICF, but also a number of other characteristics of the concrete crack resistance. Therefore, the methods proposed for determining the crack resistance characteristics of concrete can be used to evaluate the reinforced concrete durability.

Eventually, a new method has been developed that allows the determination of the SICF of concretes on flat surfaces of exploiting elements of reinforced concrete structures under static load. This method consists in a trapezoidal segment formation with the use of a diamond disk and its subsequent break-off.

We propose to determine the concrete durability with the use of the methods developed for determining the concrete characteristics.

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