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Investigation of stress transfer through cracks in reinforced concrete elements

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Abstract. The article presents the results of studies of the mechanism of force transfer through cracks in reinforced concrete elements. New results for estimating the ultimate shear resistance and stiffness of sections with cracks are reflected. Tests of prototypes of the were carried out in a hydraulic press. To install the test sample into the press, without changing the value of the initial crack width obtained as a result of splitting, a special rigid frame made of metal corners was made during the sample turning.

1 Introduction

On one of the side faces, the sample placed in the frame, when splitting, rested against a steel plate, into the drilled sockets of which steel balls were placed, and on the other side rested against four screws, with which it was possible to adjust the initial width of the crack. The sample, together with the frame, was installed in a press, after which steel rod rods were superimposed and tightened on it, and the screws were loosened, during the test, at each stage of the load application, measurements were made of the mutual displacements of the banks and the elongation deformation of the rod rods restraining the dilatation crack opening. The study of the characteristics of the resistance of reinforced concrete elements with cracks is associated with great difficulties of an experimental and theoretical nature. The presence of cracks significantly changes the relationship between deformations and stresses in reinforced concrete, giving it the properties of anisotropy and non-linear. Despite the fact that cracks are formed perpendicular to the direction of the main tensile stresses in concrete, their opening does not always coincide with this direction.

2 Materials and methods

The aim of the study was to obtain new experimental data on the deformation behavior of cracks, taking into account the influence of the type and strength of concrete, the initial crack width, the intensity of external compression and the percentage of reinforcement on the ultimate resistance and rigidity of the engagement mechanism in the crack. In our research, three series of samples were tested, each of which was made of normal heavy (NC), high-strength (HSC) and light (LW) concrete. Natural granite and expanded clay

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gravel of two fractions of 5-10 and 10-20 mm were used as a large filler. To obtain high-strength concrete, a Darex 20 superplasticizer with a content of 3.5% by weight of cement was used. The characteristics of the samples by series and the properties of the materials used are given in Table 1. The test specimens were concreted in a horizontal position in molds inside which reinforcement frames were placed before concreting. The shear and normal displacements in the crack at each load increment were determined according to [1, 2] by taking samples from the reference points that were installed on the sample surface along the crack. The results of the measurement processing showed that, in general, the initial width of the crack opening and the forces in the rods remained approximately constant throughout the loading. Only in some cases, when the initial values of crack opening were large, and the stresses in the rods were small, these parameters changed significantly during loading. In the process of destruction of the samples, staining was observed along the entire plane of the crack with the manifestation of "elastic" shear displacements. Prototypes-disks with an initiated crack were tested for shear in a rigid frame and a hydraulic press according to the scheme in Fig. 1. The values of shear and normal mutual displacements of the banks at each stage of the load were determined by a specially developed technique [3, 4]. Detailed characteristics of the samples by series, as well as the properties of the materials used, given in Table 1.

3 Results and discussion

The test results of samples with different numbers of clamps are shown. As can be seen from the graphs, the rate of increase in crack opening was slower than the change in shear displacements as the load on the sample increased. The measured deformations were used to determine the normal shear stresses that occurred in the clamps. From the characteristics of the tested samples with cracks, it can be seen that when assessing their shear strength, the influence of such factors was studied: the crack opening width and forces normal to the crack plane. The results of the study of shear strength and stiffness are shown in the graphs obtained as a result of testing the first two series of samples on a slice. The most distinct difference in the behavior of the samples of the first and second series can be seen if we compare the test results of all samples. In addition, it should be noted here that, unlike samples with Rb 20 MPa, samples with Rb 20 MPa have fracture of the crack bank surfaces after testing. The influence of the type and number of transverse fittings crossing cracks is very noticeable if we compare samples with a large number of clamps show greater strength and rigidity. In addition, the samples reinforced with reinforcement A-II have a greater tangential stress than similar ones from A-I. This asserts the influence of strength and deformative characteristics on the final value of . The magnitude of the stress difference on the shear displacement for both curves is almost an order of magnitude greater than this difference at 2 mm. In addition, it should be noted that despite the fact that the initial crack opening for heavy concrete is 0.35 mm, the first contact interaction was weaker than the second. The experimental data obtained also indicate the important role played by the crack opening width and the "pseudo-elastic" behavior of the samples of the second series under load. This has been repeatedly pointed out in [5,6] due to the fact that the graphs of the dependencies "τ - δ" obtained from experiments are difficult to interpret without having an idea of the magnitude of "a". For samples with clamps, the work on the dependence "τ - δ" concluded that the shear stiffness increases with the number of clamps, although the values "a" or "$a.$" were not measured. Fig.3 shows a graph showing that samples with stronger reinforcement and greater crack opening show a smaller value of τs shear than samples with less crack opening and the number of clamps. An equally important factor affecting the transmission of forces through the crack in samples of both types of concrete is the normal compression force σ. The analysis carried out for 4 samples of the first series can be illustrated.The sample with a large value of σs shift does not differ significantly in magnitude τ. Figures 1, 2 and 3 show the curves "τ – δ", "τ – a" and "τ – ε" according to the test results of the amplified and non-amplified disk samples. The shear bearing capacity of reinforced samples increased by 7...56% compared to non-reinforced ones. The first series of samples was tested for a cut at fixed values of the initial crack width, regulated by screws on steel rods with a diameter of 20 mm (E = 205 kN/mm2), in which the specified normal tensile stress was controlled by strain gauges during the test. The samples of this series were designed not only to determine the ultimate strength of engagement in cracks experiencing the effect of normal compression, but also to identify the nature of the "τ – δ" invisibility.

When calculating crack resistance, the conditions for the formation of longitudinal cracks and for the opening of normal cracks are checked.

Condition for the disclosure of normal cracks:

$$a_{cr} \leq \Delta_{cr} \tag{1}$$

where, a_{cr}- crack opening width. Δ_{cr}- permissible crack opening width, 0.02 cm.
The width of crack opening is determined by the formula:

$$a_{cr} = \frac{\sigma_s}{E_s}\psi \tag{2}$$

where, σs- armature voltage;

$$\sigma_s = n'\frac{M}{I_{red}}(h_0 - x') \tag{3}$$

where, E*s*- elastic modulus of reinforcement, 2,1·105
ψ- crack opening coefficient, taking into account the degree of adhesion of reinforcement to concrete, for periodic profile reinforcement:

$$\psi = 1.5\sqrt{R_r} \tag{4}$$

where, R_r- radius of interaction

$$R_r = \frac{A_r}{\sum \beta n d} \tag{5}$$

where, *Ar*- the area of the reinforcement interaction zone with concrete, m2;
β-coefficient that takes into account the degree of adhesion of reinforcement elements with concrete, 1;
n- number of reinforcement elements with the same nominal diameter
The area of interaction is from the ratio:

$$A_r = b(6d + a_s) \tag{8}$$

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$$A_r = 100 \cdot (2.6 + 6 \cdot 1.2) = 9800 \text{ cm}^2,\ R_r = \frac{9800}{12 \cdot 1.2} = 680.56 \text{ cm},$$

$$\psi = 1.5\sqrt{680.56} = 39.13 \text{ cm},$$

$$\sigma_s = 15 \cdot \frac{30.88 \cdot 10^3}{7.18 \cdot 10^{-4}} \left(0.244 - 81.37 \cdot 10^{-3}\right) = 104.92 \text{ MPa},$$

$$a_{cr} = \frac{104.92}{2.1 \cdot 10^5} \cdot 39.13 = 0.0195 \text{ cm}.$$

$0.0195 \le 0.02$. The check is going through.

The calculation of the formation of longitudinal cracks is reduced to the limitation of normal stresses in concrete:

$$\sigma_b = \frac{M}{I_{red}} x' \le R_{bmc} \quad (9)$$

where, R_{bmc}- design resistance of concrete in operation, 14.6 MPa.

$\sigma_b = \frac{30.88 \cdot 10^3}{7.18 \cdot 10^{-4}} \cdot 81.37 \cdot 10^{-3} = 3.50$ MPa. $3.50 \le 14.6$ MPa. The check is going through.

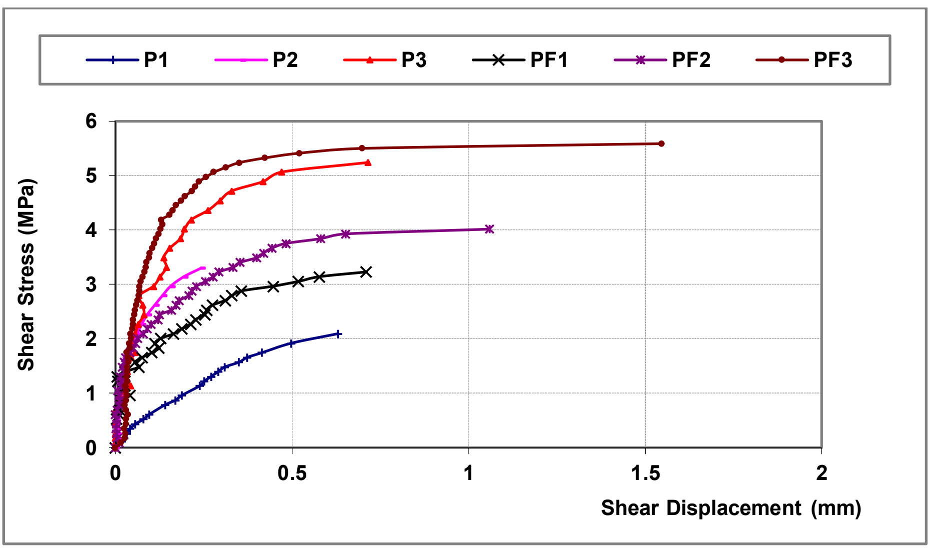

Fig. 1. Dependence "τ – δ" for the P and PF series

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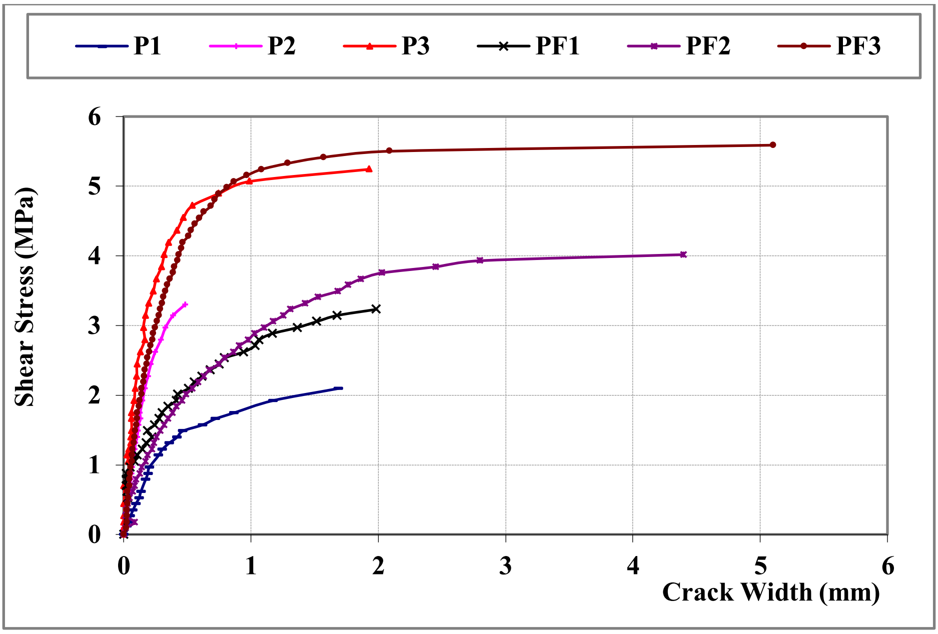

Fig. 2. Dependence "τ – a" for the P and PF series

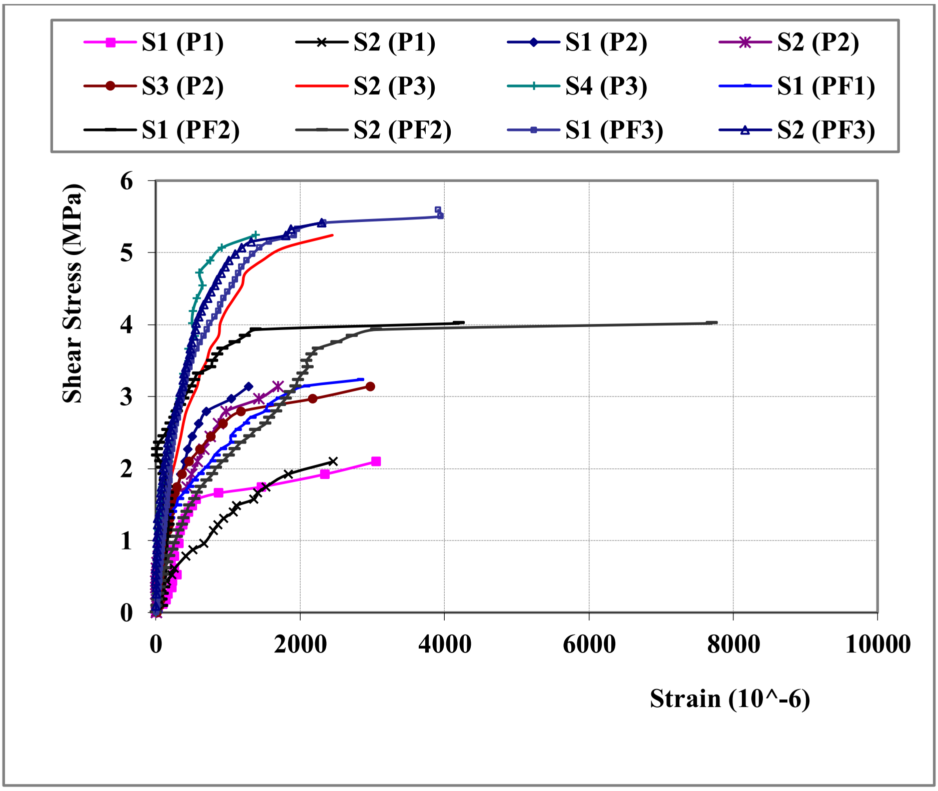

Fig. 3. Dependence "τ – ε" in steel clamps across the cut plane of reinforced (P series) and non-reinforced (PF series) special samples

The test results showed that for a wide range of shearing loads, the initial width of cracks and normal forces in them practically did not change. A slight increase in the stresses in the rods and the opening of cracks was observed at the last stages of the load. Disruption of engagement during shear has always occurred along the crack surfaces. At the same time, in the samples of heavy concrete, a more "plastic" nature of destruction was observed with significant damage to the fracture surfaces. The destruction of expanded clay-concrete samples was of a sudden fragile nature.The stiffness of the reinforced samples was higher than that of the non-reinforced ones, except for the PF2 sample. The stiffness of the P2 sample was higher than that of the PF2 sample, which is explained by a smaller initial crack opening width. With an increase in the percentage of internal reinforcement, there was no significant difference in the shear and normal displacements of samples P1and P3 under destructive load. As shown in Fig. 3, the dependence "τ–δ" shows the same behavior for amplified and non-amplified samples. It was revealed that the deformations of the reinforcement in the samples reinforced with TCM, at the same load level, reached a lower value than in the non-reinforced ones, which is explained by the presence of external reinforcement from TCM. In the steel clamps of reinforced samples, under the breaking load, the denormalization reached a maximum and in the samples of the P series varied from 2447 με to 3052με, while in the PF series it increased from 2805με to 7770 με. The increase in the load increased the values of the displacements δ and a in the reinforced samples. The deformation in the steel clamps did not exceed the limit value. The proposed theoretical model. In [7-9] and [10-18], equations for calculating the shear resistance of a special sample based on analogy with the theory of shear friction are proposed. From the table 1 it can be seen that the proposed equation gives results close to the experimental values.

Table 1. Comparison of theoretical and experimental results of non-reinforced and reinforced disk samples

Sample Details	Asv (mm2)	f_y (MPa)	Cutoff voltage υ_{uf}		$\frac{\upsilon_{uf,\exp}}{\upsilon_{uf,the}}$
			theoretical (MPa)	experimental (MPa)	
P1	56.55	660.82	1.28	2.09	1.63
PF1	56.55	660.82	3.20	3.32	1.04
P2	113.09	660.82	2.56	3.30	1.28
PF2	113.09	660.82	4.34	4.10	0.95
P3	169.65	660.82	3.84	5.24	1.36
PF3	169.65	660.82	5.48	5.58	1.02

4 Conclusion

When calculating reinforced concrete structures with cracks, their non-linear deformation is taken into account by various methods, in which usually the solution of a nonlinear problem is reduced to a multiple-iterative solution of a linear one. Currently, there are a large number of programs that are effectively used for calculations of a wide class of reinforced concrete structures and implement the FEM method, which mainly takes into account the linear elastic properties of materials. To take into account the nonlinear properties of reinforced concrete, there is a need for a more accurate assessment of the fundamental properties of reinforced concrete that determine its behavior and processes of cracking under load up to the stage of destruction. In the existing FEM programs, this circumstance is taken into account by various ideas about a discrete crack, the development of which at the boundary of finite elements is modeled by the rupture of connections in nodes. The common disadvantages of this approach are: (a) limiting the direction of crack development of the orientations of the nodes of the finite element and (b) not taking into account the interaction of the crack banks. This limitation is partially eliminated by "smearing" cracks in the volume of the element. The surface of the "smeared" cracks is assumed to be unable to transmit tensile or shear forces. Characteristic of this method is that the directions of the main stresses are assumed to be either parallel or perpendicular to the orientation of the cracks. This automatically eliminates any redistribution of forces after cracking, and the shear stiffness modulus G is assumed to be zero. The other extreme, i.e. maximum resistance to the cut after cracking is proposed in the ECB - FIP and ASI standards [8]. A compromise, apparently, is a solution that would take into account the reduction of the shear stiffness of the element to a certain value, depending on the width of the cracks formed in it. Based on experimental and theoretical studies of beams and special samples, the following conclusions were made. The results of the disk samples showed that orthotropic sheets increase their load-bearing capacity. At the same time:

- the bearing capacity when cutting reinforced special samples increased by 7-56% compared to non-reinforced ones;
- the deformation curves of steel clamps of reinforced special samples are similar to the curves of non-reinforced special samples;

The nature of the dependence "$\tau - \delta$" of reinforced and non-reinforced disk samples is the same. The proposed theoretical expression for calculating the shear stress of reinforced disk samples can be used provided there is sufficient correlation with experimental results. For a wider application of the proposed equation, further research is needed.

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