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Studies on shear transfer across the cracks in R. C. elements

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Abstract: *The paper gives the results of experimental study of the mechanism of shear transfer across the cracks in reinforced concrete elements. New results has been obtained on ultimate strength and stiffness evaluation of cracked sections.*

Keywords: R.C. elements, cracks, shear transfer, ultimate resistance

1. Introduction

The study of the resistance features of reinforced concrete elements with cracks is associated with great experimental and theoretical difficulties. The presence of cracks significantly changes the relationship between strains and stresses in reinforced concrete, giving it the properties of anisotropy and nonlinearity. 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. In the stage of work with cracks, the anisotropy of the properties of reinforced concrete manifests itself very significantly, causing the appearance of additional stresses along the interacting edges of these cracks. If the edges of such cracks are displaced in a mutually opposite direction, then due to the roughness of the surface of the cracks, forces can be transmitted through them both in the normal and tangential directions. The transfer of forces becomes possible due not only to the engagement of the banks, but also to the presence of reinforcement that crosses the crack at different angles and has axial (taking into account its adhesion to concrete) and tangential (taking into account the compliance of concrete at the edge of the crack) rigidity.

2. Materials and Methods

When calculating reinforced concrete structures with cracks, their non-linear deformation is taken into account by various methods, in which the solution of a non-linear problem is usually reduced to a multiple-iterative solution of a linear one. Modern computer technology and related software open up broad prospects in this direction. In this case, numerical methods of finite differences, variational-difference and finite elements (FEM) are used, which allow at each iteration to implement the following stages of nonlinear calculation: determine the stiffness parameters at the grid nodes or at the finite element; write down the general system of equations; calculate forces and stresses; compare unknowns at adjacent iterations and analyze the convergence of the computational process. As a rule, the convergence of the iterative process is mainly determined by the accuracy of calculating the stiffness values from the forces, which differ significantly for the stages before and after the formation of cracks.

Currently, there are a large number of programs that are effectively used to calculate a wide class of reinforced concrete structures and implement the FEM method, which takes into account mainly the linear elastic properties of materials. To take into account the non-linear properties of reinforced concrete, there is a need for a more accurate assessment of the fundamental properties of reinforced concrete, which determine its behavior and cracking processes under load up to the stage of destruction. In existing FEM programs, this circumstance is taken into account in various ways in the concept of a discrete crack, the development of which at the boundary of finite elements is modeled by breaking bonds at the nodes. The general disadvantages of this approach are: (a) restriction of the direction of crack development of finite element node orientations and (b) neglect of the interaction of crack edges. Partially, this limitation is eliminated by "smearing" cracks over the volume of the element. The surface of "smeared" cracks is assumed to be incapable of transmitting tensile or shear forces. A characteristic of this method is that the directions of principal stresses are assumed to be either parallel or perpendicular to the crack orientation. This automatically excludes any redistribution of forces after cracking, and the shear stiffness modulus G is assumed to be zero. The other extreme, i.e. the maximum shear resistance after cracking is proposed in the EKB-FIP standards [1]. A compromise, apparently, is a solution that would take into account the reduction in the shear stiffness of the element to a certain value, depending on the width of the opening of the cracks formed in it.

The above considerations indicate the extreme importance of any experimental studies of the mechanism of stress transmission through cracks in reinforced concrete elements. The widely used and classic notion of the crack opening width in reinforced concrete is defined as the mutual, equal displacement of its edges in the normal direction. For the general case, when crack faces, along with normal ones, also experience tangential mutual displacements, this concept should include dilatancy, which determines a significant difference in the width of the crack in different sections along its length. We carried out a detailed analysis of the methods for assessing the forces of engagement in cracks, as well as the available studies of the various behavior of cracks in reinforced concrete, which were conventionally divided into the following five groups:

- cracks with a fixed constant opening width;
- cracks with controlled normal displacement a_{crc};
- cracks under normal stress σ_{crc};
- cracks crossed by reinforcement of various sections;
- ratio controlled cracks $\tau_{crc} / \sigma_{crc}$.

An analysis of studies [2–6] representing each of these groups showed that normal crack opening is a key factor in the mechanism of transmission of tangential engagement forces through cracks. It is determined by the intensity of the normal compression of the sample and the transverse (shear) load. The shear displacement, increasing approximately in proportion to the load, sharply increases before failure. The shear stiffness of an element with a crack increases with an increase in the percentage of reinforcement and the more, the higher the strength of the concrete and the better its adhesion to the reinforcement. It is noted that the behavior of specimens with strong “reinforcement” of a crack or high values of σ_{crc} does not differ from the behavior of specimens without cracks. Although the results of these studies are still not comprehensive, there is enough data to conclude that the type of concrete, crack width and normal compression force are the most significant factors. Most of these studies have been carried out on normal heavy concrete.

3. Results and Discussions

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 width of the crack, the intensity of external compression and the percentage of reinforcement on the ultimate resistance and stiffness of the engagement mechanism in the crack. In our studies, 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 gravel of two fractions 5–10 and 10–20 mm were used as a coarse aggregate. Normal river sand was used as a fine aggregate with a particle size modulus of 2.31. To obtain high-strength concrete, the Darex 20 superplasticizer was used with a content of 2-5% by weight of cement. 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 of which reinforcing cages were placed before concreting. Prior to testing, all samples were split in a horizontal position in a hydraulic testing machine. After splitting, the sample was installed vertically in the machine to apply a shear load along the crack. Shear and normal displacements in the crack at each load increment were determined according to, by taking readings from reference points that were installed on the surface of the sample along the crack. For each type of concrete, two groups of samples were tested.

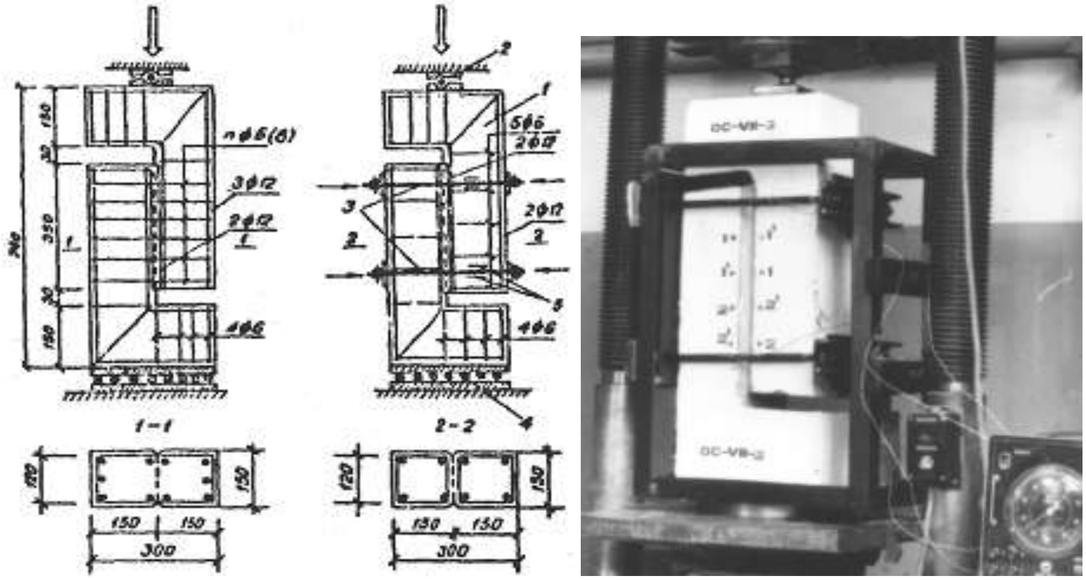
Prototype disks with an initiated crack were tested for shear in a rigid frame and a hydraulic press according to the scheme in Fig. 1. The values of shear and normal mutual displacements of the banks at each load stage were determined according to a specially developed technique [7]. Detailed characteristics of the samples by series, as well as the properties of the materials used are given in Table.1.

The first series of samples was tested for shear at fixed values of the initial width of the crack, adjustable by screws on steel rods with a diameter of 20 mm (E = 205 kN/mm^2), in which the given normal tensile stress was controlled during testing by strain gauges. Thus, at each load stage, in addition to the displacements of the crack edges and the shear stresses transmitted through it, the normal stresses arising from the dilational opening of the crack were controlled in the sample. The samples of this series were designed not only to determine the ultimate strength of engagement in cracks, but also to identify the nature of the dependency "τ - δ".

The test results showed that for a wide range of shear loads, the initial width of the cracks and the normal forces in them practically did not change. Some increase in stress in the rods and opening of cracks was observed at the last load steps.

Table 1. Characteristics of the tested samples

Series	Material consumption in % by weight			*W/C*	E_b, GPa	*R*, MPa	R_b, MPa
	Cement	Sand	Coarse aggregate				
NC	1.00	1.62	2.63	0.45	25.1	39.2	28.3
HSC	1.00	1.33	2.11	0.32	36.2	87.8	76.6
LW	1.00	0.91	0.78	0.50	17.7	33.9	26.5

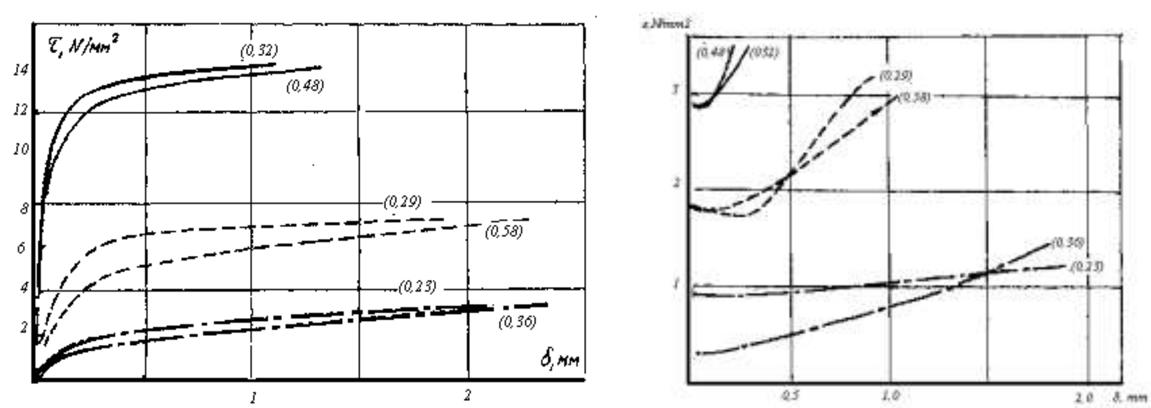


Picture. 1. Scheme of prototypes and their shear test: I - sample; 2 - hinged support; 3 - steel rods; 4 - self-centering device; 5 - strain gauges.

Shear disengagement always occurred along the crack surfaces. At the same time, in specimens made of heavy concrete, a more "plastic" nature of destruction is observed with significant damage to the fracture surfaces. The destruction of expanded clay-concrete samples was of a sudden brittle character.

The second series of samples was reinforced with clamps made of rods of class A-II Ø8 mm, which crossed the crack in a perpendicular direction. After splitting, the samples were tested for shear in a press. As well as in the previous series, shear deformations and crack openings were measured at each loading stage. Deformations in the clamps were measured by strain gauges glued to the rods before concreting. In almost all samples, concrete spalling was observed at the points of engagement of roughness peaks on opposite surfaces of the crack. For samples of heavy concrete, chipping of filler grains from the mortar matrix was characteristic. With significant (over 12 mm) shear displacements, the cracks opened up to such an extent that it was possible to visually observe reinforcing bars bent from the pin effect.

The test results representing the relationship between the shear displacements (δ) and the shear (τ) and normal stresses (σ) caused by them for the first group of samples are given in fig. 2. For each type of concrete, two samples were tested, each of which had different values of the initial crack width, indicated in brackets for the corresponding experimental curve.

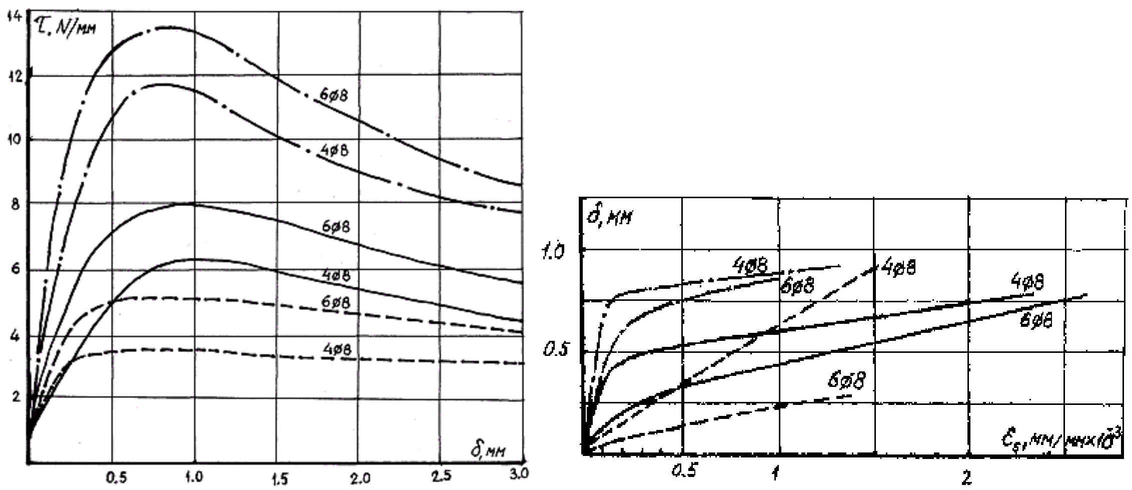


Pic. 2. Test results of the first group of samples: _______ - NC,
___ . ___ - HSC and, _ _ _ _ - LC

All specimens were carefully examined after splitting and before shear testing, paying special attention to the formation of crack surfaces. Visual inspection of the specimens after failure revealed that the development of a crack during splitting led to the formation of three different types of fracture surfaces, each of which was characteristic of one or another type of concrete. For lightweight concrete, the crack passed mainly through coarse aggregate particles. The test results of the first group of samples showed that for a wide range of shear loads, the initial crack width did not change during the entire test. Some increase (about 3 – 8%) both stresses in both clamping bolts and crack opening took place at the last load increments. In all samples, as a result of friction and engagement, local fractures appeared along the crack surfaces. In general, the destruction of samples from heavy concrete had a viscous character with significant damage in the area of the crack surface, while the destruction of samples from high-strength and lightweight concrete was of a sudden, brittle nature.

Both graphs in Pic.2 show that the type of concrete has a significant influence both on the ultimate resistance and on the overall behavior of the samples, among which the samples from high-strength concrete were the most rigid and strong. For each type of concrete, samples with close average crack widths showed a noticeable difference in the final values of normal stresses at equal shear displacement. This also indicates a significant increase in stiffness with increasing normal stress. A comparison of the two plots also shows the effect of σ on the stiffness for the left and right sides of the curves, separated by the boundary values of σ associated with a δ value of 0.5 mm. On the right side, the increase in displacements with a significant change in σ is not so pronounced and, therefore, we can conclude that the stiffness of the samples is mainly determined by the influence of the values of a, and not σ. On the left side of the curves, the change in the stiffness of the samples as the normal stresses change is quite pronounced.

Samples of the second group showed chipping of concrete at the points of contact and at the peaks of roughness on opposite surfaces of the crack. Dense aggregate particles spalled from the mortar matrix were typical of normal concrete specimens. This caused a significant crack opening at large (more than 10 mm) shear displacements so that it made it possible to visually observe the reinforcement bars bent under the action of the pin action. The dependences between shear displacements in cracks (δ) and the stresses (τ) caused by them and tensile strains (ε) in the rods obtained for this group of samples are shown in Pic.3. All "τ – δ" curves have visible peak values with a maximum steepness for the HSC series specimens, a flatter slope for the NC series specimens, and eventually a vanishing steepness for the LC series specimens.



Pic. 3. Test results of the second group of samples: —— - NC;
—·— - HSC; ---- - LC

In all samples after the destruction of the system of engagement in cracks, significant values of residual stresses were observed. For samples with identical reinforcement, the difference in these values was much smaller compared to the difference between the peaks on the curves. The crack width remained almost unchanged: 1.5 mm and 1.3 mm for HSC specimens, 1.4 mm and 1.0 mm for NC specimens, and 0.9 mm and 0.5 mm for LC specimens (the first and second values refer to specimens with four and six reinforcement bars, respectively).). A small (within 10 - 20%) increase in the width of the crack opening was observed at the last steps of the load increment. The closeness of these two values leads to the assumption that the total of specimens increases with the increase in reinforcement that crosses the crack. The results also showed that lower shear stiffness occurred in specimens with larger crack openings and reinforcement percentages than in specimens with smaller crack widths and lower reinforcement percentages. This contradicts the generally accepted opinion about the absolute increase in shear stiffness with an increase in the percentage of reinforcement.

4. Conclusions

Thus, new experimental data on the deformation behavior of cracks have been obtained, showing that the mutual engagement of crack surfaces has a great influence on their normal and shear displacements and ultimate resistance and can be considered as a key factor in the mechanism of force transmission through cracks for all types of concretes studied. The roughness of crack surfaces plays a significant role in the manifestation of the engagement forces, determining the magnitude of the normal and shear stresses arising in the crack. The width of the crack opening can be considered as the main parameter affecting the ultimate resistance and deformation behavior of the crack under shear; the rigidity of the force transfer mechanism decreases with increasing width, but this effect is less noticeable with significant external compression. The overall stiffness as well as the ultimate resistance of specimens of all types of tested concretes increased with the increase in reinforcement crossing the crack.

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