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About The Transmission Of Stress Through Cracks In Reinforced Concrete Elements

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Abstract: The article discusses new mechanisms of nonlinear deformation of reinforced concrete, taking into account the transfer of stresses through cracks. The results of testing and implementation of the model of contact interaction in cracks are presented.

Keywords: ferroconcrete, nonlinear behavior, cracks.

1. Introduction.

The qualitative change in the stress-strain state of reinforced concrete elements after the formation of cracks is associated with a significant anisotropy of the properties of the material, the manifestation of nonlinear deformations, as well as the influence of a number of little-studied features of the joint work of concrete and reinforcement. These factors introduce the greatest uncertainty when calculating reinforced concrete structures that have a complex physical mechanism of destruction, as, for example, occurs during shear or transverse bending. To take into account the nonlinear properties of reinforced concrete, in addition to a more accurate assessment of its fundamental properties, it is necessary to pay attention to the creation of models and methods for calculating reinforced concrete that reflect the actual nature of their behavior under load and the physical essence of the problems that arise.

2. Materials and Methods

When calculating reinforced concrete structures with cracks, numerical finite difference, variation-difference and finite element (FEM) methods are usually used. As a rule, the convergence of the iterative process is determined by the accuracy of calculations based on the forces of the stiffness values, which differ significantly for the stages before and after the formation of cracks. In existing FEM programs, cracking is taken into account using various models of a discrete crack, the development of which at the boundary of finite elements is represented by the rupture of bonds at the nodes. The general disadvantages of this approach are the limitation of the direction of crack development and the orientation of the finite element nodes and the failure to take into account the contact interaction of the crack faces. These limitations are partially eliminated by “smearing” cracks throughout the volume of the element under the assumption that the directions of the main stresses are either parallel or perpendicular to the orientation of the cracks, the surface of which is not capable of transmitting tensile or shear forces. This automatically excludes any redistribution of forces after cracking, and the shear stiffness modulus G is taken equal to zero. The other extreme, i.e., maximum shear resistance after cracking, is proposed in the EKB - FIP standards [3]. A compromise, apparently, is a solution that would take into account a reduction in the rigidity of the element to a certain value depending on the opening width of the cracks formed in it.

The above considerations indicate the extreme importance of research into the mechanism of stress transmission through cracks in reinforced concrete elements. Such studies require the study of various mechanical and geometric parameters, and therefore the development of appropriate mathematical models must be based on adequate experimental data. First of all, this concerns the study of the mechanism and features of the transfer of shear stresses through a crack during the contact interaction of its sides. An important step forward in this direction was the theory of deformation of reinforced concrete with cracks, developed in [4]. In it, reinforced concrete is considered as a physically nonlinear anisotropic material, and the dependencies and computer calculation programs obtained on its basis are confirmed experimentally and are widespread in design practice. If during compression and tension the mechanism of stress transmission through cracks has found sufficient experimental and theoretical justification, then during shearing it has clearly not been sufficiently studied. Here we are talking about new factors that appear in cracks during the mutual displacement of their shores: tangential forces of engagement and dowel action of reinforcing bars. Cracks in concrete, developing, pass through cement stone, aggregate grains and the contact zone, forming two interacting rough surfaces of complex geometry (Figure 1a). They ensure the transmission of shear stresses through cracks by mechanical engagement and friction. Studies have shown [2] that the assumption of complete containment of tangential displacements in cracks with such engagement is not true. Moreover, tangential displacements can serve as a more accurate indicator of the presence of shear stresses in cracks than the crack opening width. The dowel effect of the reinforcement is manifested in local bending, shearing and bending of the rods crossing the crack (Figure 1b).

a)

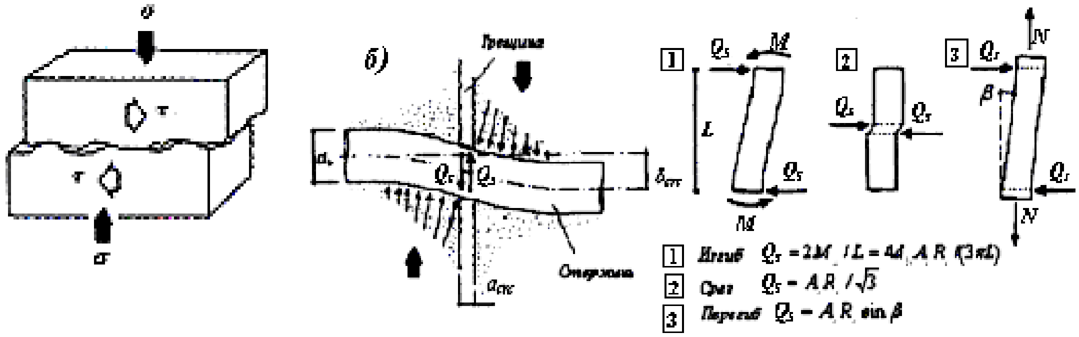

Fig. 1. Mechanisms of engagement of banks in a crack (a) and dowel action of reinforcement (b)

Some underestimation of the role of tangential engagement forces in cracks when designing reinforced concrete structures with relatively dispersed reinforcement, characteristic of shells, box beams and slabs, retaining walls, beam-walls, pressure vessels, etc., is based on the widespread opinion that that friction in a crack is a variable quantity and can be neglected for the sake of safety. However, recent studies [1,2] have revealed the fallacy of this argument. The fact is that with a mutual tangential displacement δ_{crc} of the crack faces, its normal opening a_{crc} (dilatancy) occurs due to the mutual engagement of roughnesses on the crack surfaces (Fig. 2a). Therefore, the width of its opening during the operation stage may turn out to be significantly greater than expected by calculations according to current standards. Typical results of shear testing of reinforced disk specimens (Fig. 2b) showed that significant additional stresses can arise in the reinforcing bars crossing such a crack.

Identification of models for the manifestation of adhesion forces in a crack during shear to predict the rigidity and ultimate resistance of the contact interaction mechanism in cracks requires special research. Such models should reflect the influence of the structural features of concrete and take into account the mechanism of axial and tangential stiffness of the reinforcement crossing the crack. The widely used and classic concept of the opening width of cracks in reinforced concrete is defined as the mutual equal displacement of its edges in the normal direction. For the general case, when the edges of a crack, 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. In the practical use of models of the meshing mechanism, it is necessary to know the dependencies $\tau_{crc}= f(\delta_{crc}, a_{crc})$ and $\sigma_{crc}= f(\delta_{crc}, a_{crc})$ for four variables (Fig. 2c): tangential and normal stresses (τ_{crc} , σ_{crc}) and the corresponding displacements (δ_{crc} , a_{crc}). Such a dependence will reflect one of the fundamental physical and mechanical properties of reinforced concrete as a cracked material, which determine its behavior under load. This makes it the most convenient tool in implementing the concept of "smeared" cracks when calculating reinforced concrete structures using numerical methods.

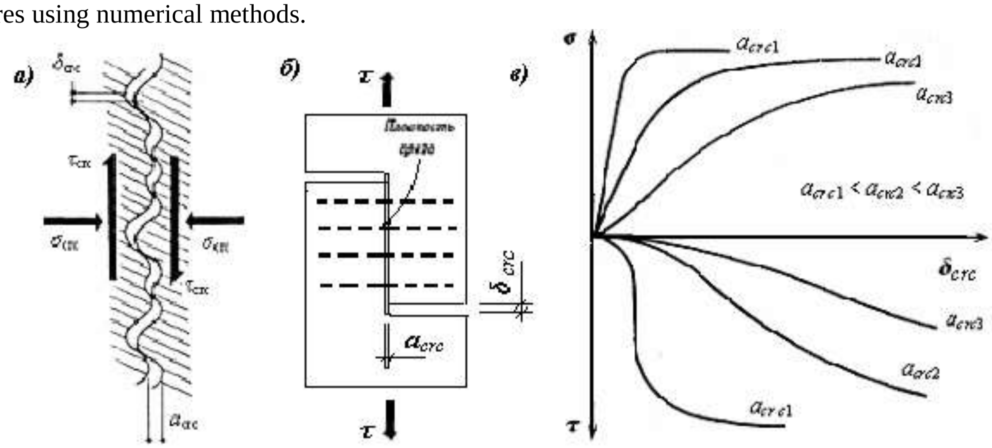

Fig. 2. Contact interaction in cracks during shear (a), typical samples for shear tests (b) and graphs of displacements in a crack versus stress (c)

In [1, 2], a detailed analysis of studies was carried out to assess the adhesion forces in cracks, which can be conditionally divided into groups with the following characteristic test conditions (Fig. 3a, b, c, d): with external connections (rods) of constant rigidity; with internal "reinforcement" of variable stiffness; with constant controlled crack opening (a_{crc}); with constant controlled normal compression σ_{crc}; at a fixed constant crack opening width with a controlled ratio τ_{crc} / σ_{crc} = const. A similar analysis of studies of the dowel action of reinforcement allowed us to identify the following groups (Fig. 3e, f, g, f): direct shear tests on disk samples; testing beam fragments; testing of full-scale beams with dowel liners; testing of sample blocks.

Analysis of the research results showed that normal crack opening is a key factor in the mechanism of transmission of tangential engagement forces through cracks. Shear stiffness in a crack increases with increasing percentage of reinforcement and the higher the strength of concrete and the better its adhesion to reinforcement. It was noted that the behavior of samples with powerful "reinforcement" of a crack or high values of σcrc was practically no different from the behavior of samples without cracks.

In the studies carried out on the mechanism of stress transmission through cracks [2], prototype disks with an initiated crack were made of light, heavy and high-strength concrete and tested for shear according to the scheme in Fig. 2b. The first series included samples without transverse reinforcement with free normal displacement of the crack edges. The second series of samples was tested at fixed values of the initial crack width, which was adjusted by screws on steel rods with controlled normal tensile stress. Thus, in addition to shear stresses, normal stresses arising from dilatational crack opening were monitored. The samples of this series were intended not only to determine the ultimate adhesion strength in cracks experiencing normal compression, but also to identify the nature of the "τ_{crc} - δ_{crc}" relationship. The third series of samples was reinforced with rods of classes A-I, A-III and A-IV. For each series of samples, a family of experimental curves $\tau_{crc}= f(\delta_{crc}, A_{crc})$ and $\sigma_{crc}= f(\delta_{crc}, A_{crc})$ was obtained, taking into account the influence of the type and strength of concrete, the crack opening width, the value of σ_{crc} and the percentage of transverse reinforcement (Fig. 2c).

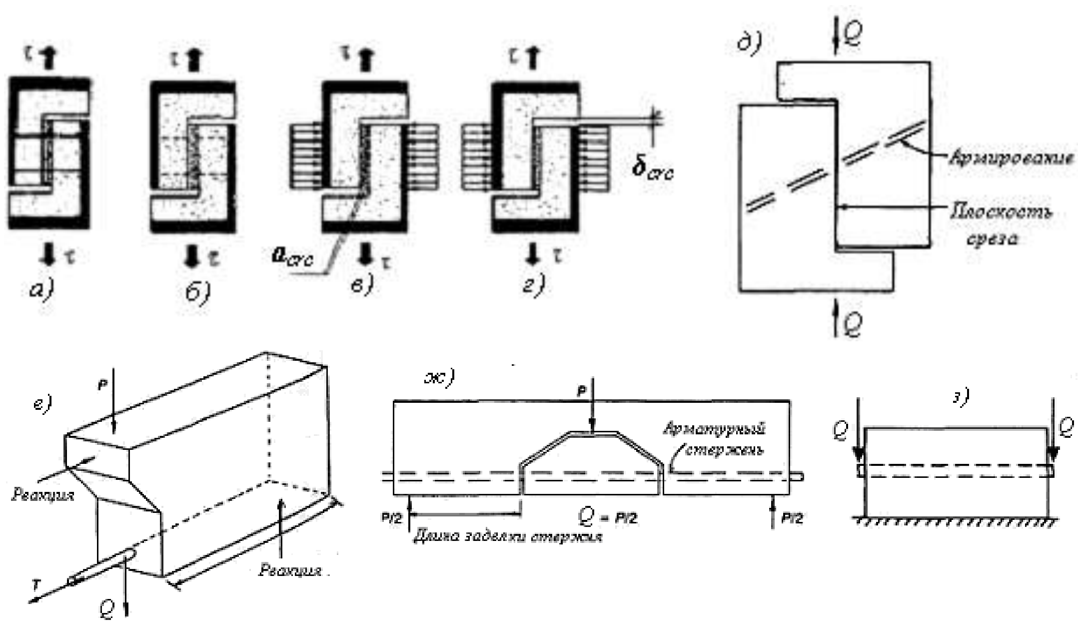

Fig. 3. Test schemes for studying tangential engagement forces (a-d) and dowel action of reinforcement (e-h)

3. Results and Discussions

Test results showed that the type of concrete affects both the ultimate shear strength and the deformation behavior of the samples. Despite the different behavior under load, each type of concrete is characterized by its own shear strength limit, which for expanded clay concrete turned out to be significantly lower than for heavy concrete, even with a significantly smaller crack opening width. With large crack openings in samples with a large number of reinforcing bars, lower shear stiffness was observed in these sections. The average crack opening width in expanded clay concrete samples of the second series turned out to be almost the same, but despite the fact that the value a has a scatter of 55%, the stiffness of the samples turned out to be almost the same.

To describe the processes of contact interaction in shear cracks, simulation modeling was used, based on stereological analysis of crack surfaces and material structure. As a starting point, we considered a concrete structure model in which dense aggregate inclusions are randomly distributed in the mortar matrix. The development of shear strains manifests itself due to plastic deformation of the material in the contact zones of the protrusions along the entire surface of the crack. The projection of the mutual contact area in orthogonal directions for a given type and volumetric content of aggregates is a function of δ_{crc} and a_{crc}. Using statistical analysis methods, the probable number of particles of a certain size that were intersected by a crack at a unit length was calculated. The possible distribution of filler grain sizes, being a continuous function, was considered on the basis of the experimental sieving curve and the probability density function was used to describe it. The most probable general line of contact interaction was obtained by integrating over the entire range of changes in the diameters of distributed inclusions. The graphs of the dependences $\tau_{crc}= f(\delta_{crc}, a_{crc})$ and $\sigma_{crc}= f(\delta_{crc}, a_{crc})$ obtained when implementing the model approximated the experimental curves quite closely. Integration of the obtained expressions for the mutual contact area was carried out using a special program, which is easily combined with commercially available programs for calculating reinforced concrete structures using the FEM method and other numerical methods.

Subsequently, models for the development of critical inclined cracks in reinforced concrete beams of rectangular and T-sections were developed for experimental and computational assessment of the main components of their shear resistance. Based on the conditions of equilibrium of internal forces, analytical expressions were obtained that evaluate the shear stiffness in cracks of beams by using experimental values of dilation displacements of their banks.

4. Conclusions

To test the theoretical principles, a test program was carried out on reinforced concrete rectangular and T-beams made of heavy and expanded clay concrete, the results of which revealed: the levels of destructive load and the nature of destruction of the beams; deformations in concrete along the height of the section and deflections of beams; relative deformations in longitudinal and transverse reinforcement; dilation and shear displacements of crack banks using a specially developed technique; Compressive deformations in inclined concrete strips of T-beam ribs. Calculations of the load-bearing capacity of beams during transverse bending showed satisfactory agreement with the test data of experimental beams.

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