The Force Transfer in Cracked Reinforced Concrete Elements

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ABSTRACT: Both theoretical and experimental studies on strength resistance of cracked RC concrete elements become complicated due to significant material anisotropy and changes in “stress – deformation” relationship for cracked concrete. Despite the fact that cracks are usually formed normally to principal tensile stresses in concrete, their further opening may not always coincide with their direction, resulting in additional shear stresses and transmission of the forces across the cracks through mechanisms of aggregate interlock in concrete and dowel/tension effects in the reinforcement crossing the crack. A better understanding of these mechanisms may be obtained through the reliable data on the relationship between stresses and displacements in sections containing the cracks.

The paper presents the results of an experimental program on testing of push-off specimens made from normal, lightweight and high strength concrete. Crack behavior have been studied on three series of specimens with regard to the influence of aggregate type, concrete strength, initial crack width and amount of crossing reinforcement on ultimate shear strength and stiffness of specimen. Sets of experimental graphs have been received to show the relation between normal and shear stresses and displacements in crack faces. Working expression has been proposed to approximate experimental data. Experimental study of RC beams of rectangular section without shear reinforcement and the development of the strength model for beams under shear. Equations for ultimate strength assesment of RC beams are given allowing for effects of both aggregate interlock in cracks and dowel action of main reinforcement. The model developed fairly approximates experimental data.

KEYWORDS: Concrete, shear, surface interlock, displacements, reinforcement.

1. INTRODUCTION

The paper presents the results of experimental study on shear transfer across the crack in RC elements. The presence of cracks gives to material additional property of anisotropy and non-linearity, essentially changing the relation between deformations and stresses in reinforced concrete. In spite of the fact that the cracks in RC elements are formed perpendicularly to the direction of the main tension, their opening not always coincides with this direction. For such members the anisotropy is significant, causing additional stresses along interacting surfaces in crack locations. Under shear loading the forces both in normal and tangential direction can be transferred through the cracks due to surface roughness. This is possible not only because of surface interlock, but also because of axial and tangential stiffness of any reinforcement crossing a crack (allowing for crack-softening of concrete at the crack surfaces and bonding/kinking effect of reinforcing bars).

Various methods have been developed for nonlinear design of RC members, in which the nonlinear solutions are usually reduced to the repeatedly iterative linear solutions. Thus the numerical methods of final differences, variational differences and finite elements (FEM) are used. In general, the nonlinearity in numerical methods is introduced by various models representing the development of a discrete crack along the border of finite elements through breaking of the links at the nodes. This approach has common faults, namely: (a) a direction of crack development is restricted by orientation of corners of a finite element and (b) the interaction of crack faces is not considered. Partially “smearing” of cracks over the volume of an element eliminates the restriction. The surface of the "smeared" cracks is supposed not capable to transfer tension or shear forces and the directions of the main stresses are usually assumed either parallel or perpendicular to the cracks orientation. These automatically exclude any redistribution of forces after cracking and thus the module of shear rigidity is accepted equal to zero. Other extreme, i.e. maximum shear resistance after cracking is offered in CEB - FIP code [1]. Compromise decision is the allowance for reduction of shear rigidity to the certain value depending on the width of crack opening.

The above considerations point to the critical importance of any experimental study of the mechanism of stress transfer through cracks in reinforced concrete elements. Widely used and has become a classical notion of the width of the opening of cracks in reinforced concrete is defined as the reciprocal equal to the offset of its banks in a normal direction. For the General case, when the crack banks along with the normal ones experience tangential mutual displacements, this concept should include dilatancy, which determines a significant difference in the crack width at different sites along its length. We have conducted a detailed analysis of methods for assessing the forces of engagement in cracks, as well as existing studies of different behavior of cracks in concrete, which were divided into the following five groups:

- cracks with a fixed constant opening width;
- cracks with controlled normal displacement of a_{crc};
- cracks experiencing the action of normal stresses σ_{crc};

the cracks cross the reinforcement of various sections;

- cracks with controlled ratio $\tau_{crc} / \sigma_{crc}$.

No sufficient explanation of the mechanism of crack resistance to shear displacement is available so far. Therefore it is still assumed in design, that it may be ignored, i.e. only the normal opening of cracks takes place, and the friction in a crack is absent. Widely used classical concept about crack width in RC concrete is defined as equal displacement of crack faces in a normal direction. However, crack opening tends to increase with the slip-shear to be transferred. This defines essential variation in crack width along its length as well as additional stresses in the reinforcement, crossing a crack. Moreover, under service loads the crack width can appear much larger, than it is supposed by design.

All stated above proves both the significance and nesessity of the various experimental data for reliable force transfer analysis based on deformational behavior of the crack. This involves so many different mechanical and geometrical parameters that any comprehensive mathematical model must be based on sound experimental evidence. A considerable number of different direct shear studies are available for this purpose, which can be divided into following broad groups according to the test arrangements made, namely: at constant and variable confinement stiffness (normal displacement controlled, different reinforcement); at fixed constant crack opening (infinite confinement stiffness); at constant confinement action (controlled ratio between shear and normal stresses); at constant crack dilatancy. The analysis of some researches representing each of these groups [2 - 12] has shown, that the crack opening is the key factor in the force transfer mechanism and it is largely dependant on the intensity of both normal confinement and shear loading. The shear displacement, growing proportionally to loading, is sharply increases prior to the failure. Shear stiffness in a crack grows with increase of percentage of reinforcement - the higher concrete strength and bondage, the more the increase. It was noticed, that the behaviour of samples at high "reinforcement" of a crack or high confinement is similar to those without cracks.

2. REASEARCH OBJECTIVES AND TEST PROGRAM

Despite the fact that available test results on shear transfer in concrete is still not comprehensive, sufficient data are available to conclude that the type of concrete, crack opening and normal restraining force are the most significant factors. More experimental studies are needed to assess these factors with particular attention given to former and latter ones. Wast majority of studies were performed on normal densed concrete and only few ones were aiming at other types of concrete barely mentioning the comparisons in behavior. Therefore, the objective of research was to obtain new experimental data on deformational behavior of cracks, with particular aims to evaluate influence of concrete type and strength, initial crack width, external restraint, and percentage of reinforcement on ultimate resistance and stiffness of surface interlock system in crack.

Three series of specimens were tested each one relating to the type of concrete used, namely normal (NC), high strength (HSC) and lightweight (LW). Natural crushed dense (granite) and keramzit gravel (Leca - type lightweight aggregate) were used as coarse aggregates, with two fraction sizes of 5 - 10 and 10 - 20 mm. Normal river sand was used as a fine aggregate with fineness modulus equal to 2.31.

Table 1. Structure and Characteristics of Tested Specimens

Series	**Actual expenditure of materials % by weight**			***W/C***	**Modulus of elasticity *E_c, GPa***	**Cube strength *f, MPa***	**Cylinder strength *f_c, 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

The admixtures used for high strength concrete were superplasticizer (*Darex Super 20*) and silica fume (classified as type F in *ASTM C* 494-92) with content of 2% and 5% respectively of mass of cement. The characteristics of samples in series, and also property of the used materials are given in Tab. 1. The test specimens were cast in a horizontal position in the moulds inside which the reinforcing carcasses were placed prior to the casting, see Figure 1. Prior to the test all specimens were pre-cracked by splitting in horizontal position in hydraulic testing machine.

After splitting the specimen was positioned vertically in order to apply incremental shear load along the plane of the crack. Shear and normal displacements in crack at each load increment were determined according to [11] by developing the gauge readings between stud points, which were stuck on the surface of the specimen along the crack plane. For each type of concrete two groups of specimens were tested.

First group of specimens was tested at the fixed initial crack width, maintained by four external 20 mm diameter steel bolts (E = 205 kN/mm^2) with nuts at each end. The bolts were used to provide external restraint and necessary adjustments of nuts were made in order to give and keep either the desired initial crack width or normal stress. During the test the normal tensile stresses in each of the restraining bolts were monitored by the pair of electric strain gauges attached to the bar at opposite sides of diameter. Thus, at each loading increment besides both crack displacements and shear stresses transferred across the crack, the normal stresses arising from of crack dilatancy were monitored. In each specimen of this group surface interlock failures were always achieved along induced cracks. Samples of this group were intended to determine not only the ultimate resistance of surface interlock in cracks subjected to normal stresses, but also to reveal the character of the relation between shear stresses and crack dilatancy.

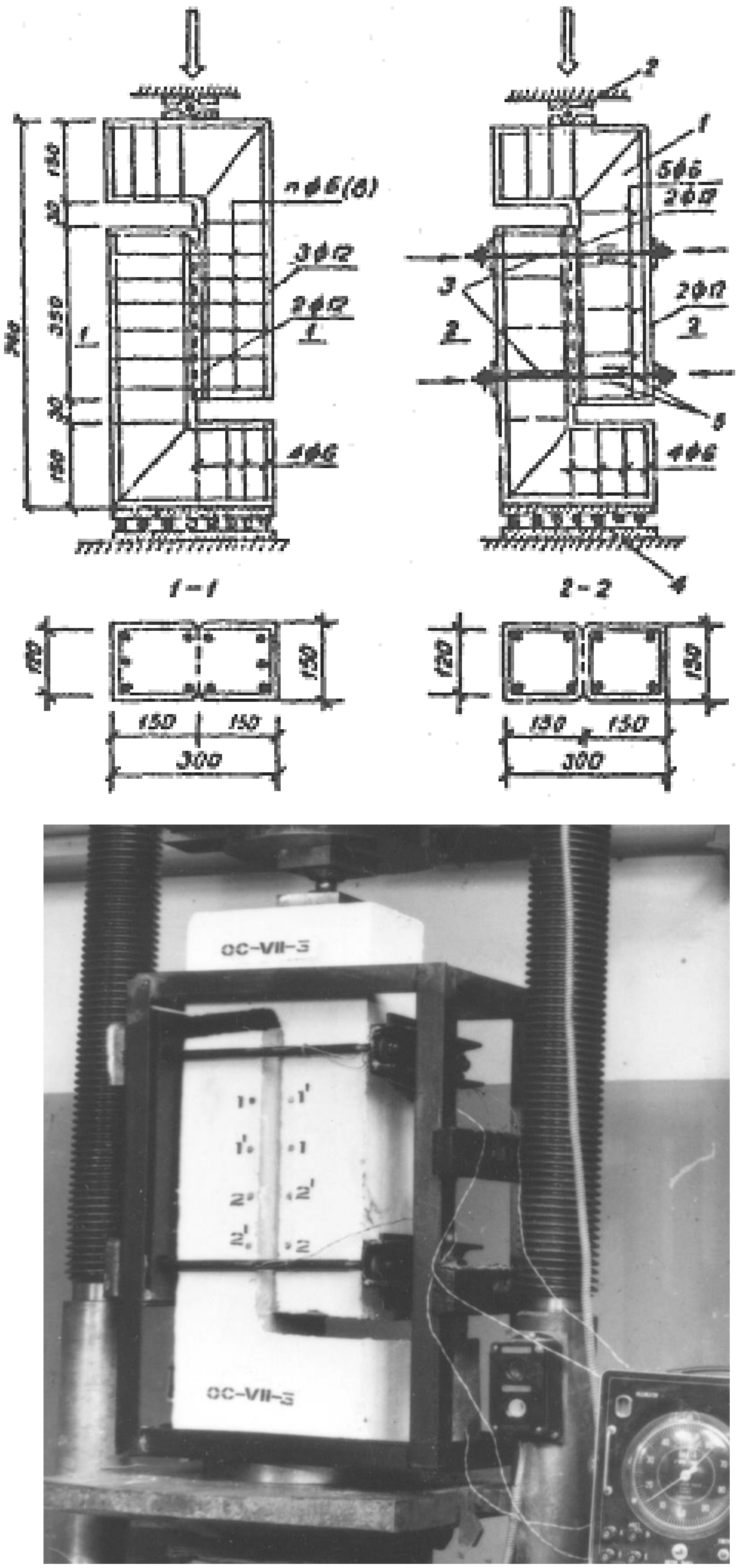

Figure 1. Concrete Specimens, Casting Arrangements and Test Set-up: 1 – Roller Support; 2 - Gauges

The samples of second group were reinforced by links made of 8 mm diameter deformed bars crossing a crack in a perpendicular direction. After splitting the samples were tested under shear. As in the previous group at each increment of monotonously growing loading both the shear and slip deformations in cracks were measured. In addition, the strains in links (ε) were also measured by electric strain gauges, which were attached to the reinforcing bars before casting. Two specimens from this group, namely HSC and LC (both reinforced by six bars), failed at bottom cantilever with the rest showing surface interlock failures achieved along the induced cracks.

Also in the study of the problem we have tested two series of reinforced concrete beams of rectangular cross-section of heavy and light concrete, the destruction of which was assumed by inclined sections. All beams were made of rectangular cross-section with dimensions of 100x400 mm (at h_0 = 370 mm) and loaded with one or two concentrated forces at different values of the relative span of the cut *a/h*. The change in the percentage of longitudinal reinforcement in the beams was achieved by varying the diameter of the rods while maintaining their total number equal to two, and was respectively 1.70%, 1.08% and 0.60%. For the longitudinal reinforcement of experimental beams, fittings A-III with diameters of 12, 16 and 20 mm and A-IV with a diameter of 16 mm were used.

Table 2. General characteristics of experimental beams

Group beams	Beams cipher	*a, мм*	a/h_0	Working armature	μ %	$\sigma_{0,2}$ *MPa*	E_S, *MPa*	R_b, *MPa*	R_{bt}, *MPa*	E_b, *MPa*
Group I	TB-1a	1230	3,32	2∅20, A-III	1,70	441	201	35,13	3,64	28,0
	TB-1в	1230	3,32	2∅16, A-III	1,09	441	201	0,9	3,73	27,0
	TB-1c	1230	3,32	2∅12, A-III	0,61	441	201	27,7	3,41	28,0
	TB-2	2180	5,89	2∅16, A-IV	1,09	649	190	31,4	3,12	27,6
	TB-3	1230	3,32	2∅16, A-IV	1,09	649	190	29,1	3,36	26,1
Group II	LB-1a	1230	3,32	2∅20, A-III	1,70	441	201	23,4	2,19	15,3
	LB -1в	1230	3,32	2∅16, A-III	1,09	441	201	27,2	2,84	16,1
	LB -1c	1230	3,32	2∅12, A-III	0,61	441	201	24,9	2,08	16,0
	LB -2	2180	5,89	2∅16, A-IV	1,09	649	190	23,7	2,48	16,0
	LB -3	1230	3,32	2∅16, A-IV	1,09	649	190	23,1	19,4	16,1

Before testing the beams, the properties of concrete and reinforcement were determined. The General characteristics of the experimental beams are shown in table 2.

Before the destruction of the beams was observed the sudden formation of large critical inclined crack, which was held from the level of the longitudinal reinforcement to the area near concentrated forces. For most beams, the formation of such a crack led to destruction. Two beams (TB-2 and LB-2) were devoted to the study of the influence of the type of concrete on their bearing capacity during the passage of the cut a/h_0 = 5.89, which was achieved by increasing their length to 5 m. they used the same reinforcement and in order to avoid destruction of the normal cross section was used reinforcement 2∅16 a-IV (A_s = 402 mm, μ_s = 1.09). When tested in with a reference zone of these beams formed a comb cracks scheme.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Test results, representing the relationship between crack shear displacement (δ) and resulting shear (τ) and normal (σ) stresses for first group of specimens, are plotted in Figure 2. For every type of concrete two specimens were tested each one having different values of initial crack width denoted in brackets at the relevant experimental curve. All specimens were closely inspected after splitting and before testing under shear with particular attention paid to the formation of crack surface. Visual inspection reviled that the development of tensile cracks resulted in three different types of fracture surfaces, each one being characteristic for the particular type of concrete. For lightweight concrete the main crack surface passed mainly through the coarse aggregate particles.

Test results obtained from the first group of specimens show, that for a wide range of shear loading the initial crack width did not change throughout the test. Some increases (within the range of 3 - 8 %) in both stresses of restraining bolts and crack openings were observed at last few increments of loading. In all specimens local destructions of interlock along the crack surfaces have occurred during their slippage. Generally an overall ductile-type destruction with essential damage around crack surface was observed in normal concrete specimens, while the failure of high strength and lightweight specimens was of sudden, brittle character.

Both graphs on Figure 2 shows that type of concrete have a significant influence on both the ultimate resistance and overall behavior with high strength specimens being the stiffest and the strongest. For each type of concrete the specimens with close average values of crack width show visible difference in resulting normal stress values at equal shear displacement. These demonstrates also a significant increase in stiffness with increase of normal stress. Comparison of these two graphs also shows diverse effect of σ on stiffness for left and right portions of curves separated by boundary values of σ related to δ-value which is approximately equal to 0,5 mm. On the right portion the changes in slippage development for sizable difference in normal stresses are not so much pronounced and, therefore, it may be concluded that the stiffness of specimens are primerily influenced by *a*-

values, but not by σ-values. On the left part of the curves a stiffness changes qute sizeable with changes in normal stress values.

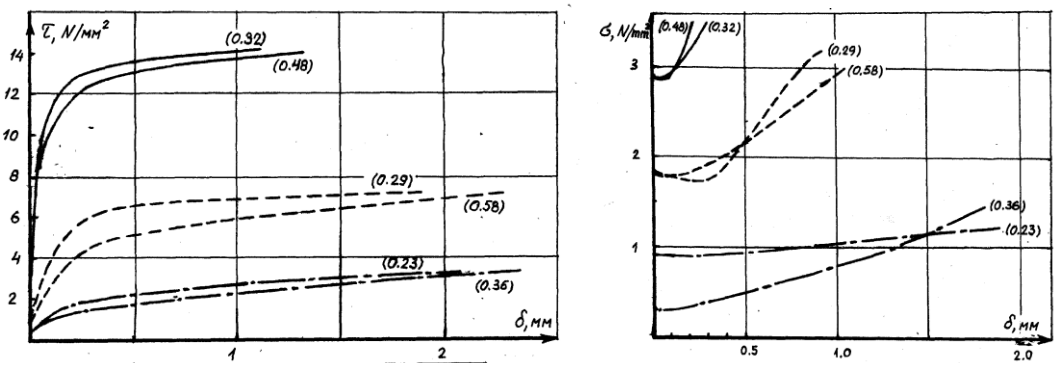

Figure 2. Test Results for First Group of Specimens: —— - NC, —· — - HSC and, ---- - LC

The samples of second group displayed the crumbling of concrete, which occurred at contact points and areas of roughness peaks on opposite surfaces of a crack. Dense aggregate particles, crushed out from mortar matrix, were typical for normal concrete samples. This caused a significant crack openings at large (more than 10 mm) shear displacements so, that it was possible visually to observe reinforcing bars bent due to the dowel action. The relationship between cracks shear displacements (δ), resulting shear (τ) and tensile strains (ε) in reinforcing bars obtained for this group of specimens are plotted in Figure 3. All "$\tau - \delta$" curves have visible peak values with biggest steepness for HSC specimens, more gently sloping for NC specimens and eventually vanishing for LC specimens. A considerable residual stress values for all specimens have been observed after interlock failure. For specimens with identical reinforcement the difference in these values was far less compared with the difference between the peaks on the curves. Crack width remained almost unchanged having approximate values of 1.5mm and 1.3mm - for HSC, 1.4mm and 1.0 mm - for NC and, 0.9mm and 0.5mm - for LC specimens, the first and the second number being related to the specimens with four and six bars respectively. Small increases (within 10 - 20% range) in a crack width values were observed at last increments of loading. Close proximity of these two values leads to the assumption that the overall stiffness of the specimens increases with the increase of reinforcement, which crosses the crack. The results have also shown, that the smaller shear stiffness have been observed in specimens with the greater crack openings and larger reinforcement percentages than in specimens with small crack width and lower rate of reinforcement. This contradicts to a popular belief in absolute growth of shear rigidity with increase of percentage of the reinforcement.

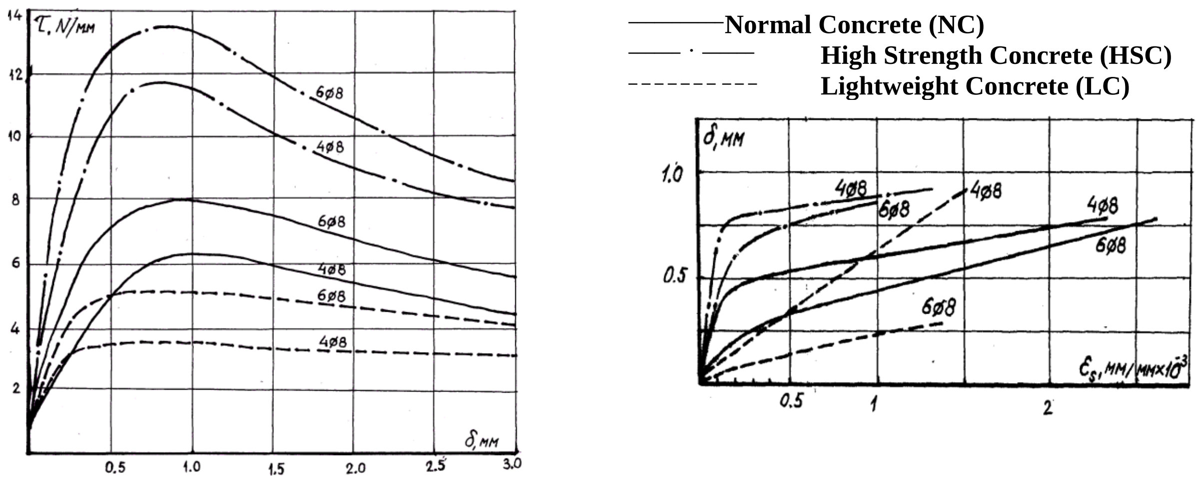

Figure 3. Test Results for Second Group of Specimens

4. CONCLUSIONS

New experimental data on deformational behavior of cracks has been obtained showing that the surface interlock has a great influence on normal/shear displacements and utimate resistance of cracks and may be considered as a key factor in force transfer mechanism for all types of concrete used in the study. Basic roughness of crack surfaces plays a significant role in surface interlock capacity defining the magnitude of normal and shear stresses unduced in the crack.

Crack width may be considered as a principal parameter affecting both ultimate resistance and deformational behavior of the crack under shear; the stiffness of the force transfer mechanism decreases with increase of the crack width. However the role of crack width is less pronounced under significant external confinement. An overall stiffness as well as an ultimate resistance of the specimens increased with the increase of reinforcement, which crosses the crack for all types of concrete used in the current study.

5. ACKNOWLEDGMENT

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REFERENCES

1. Comite Euro-International du Beton. (1990). *CEB – FIP Model Code 1990, First Draft*. CEB, Paris, Sept. 1990, Bulletin d'Information 195.
2. Millard, S. G. and Johnson, R. P. (1984). Shear Transfer Across Cracks in Reinforced Concrete due to Aggregate Interlock and Dowel Action. *Mag. Conc. Res*. 36, No. 126, Mar., pp. 9 – 21.
3. Walraven, J. C. and Reinhardt H. W. (1981). Theory and Experiments on the Mechanical Behavior of Cracks in Plain and Reinforced Concrete Subjected to Shear Loading. *Heron Journal*, 26, No. 1A, Dept. of Civil Engineering. Delft University of Technology, Delft.
4. Houde, J. and Mirza, M. S. (1981). A Finite Element Analvsis of Shear Strength of Reinforceed Concrete Beams. ACI Special Puhlication SP42, Detroit, pp. 103-128.
5. Paulay, T. and Loeber, R. J. (1974). *Shear Transfer by Aggregate Interlock*. ACI Special Publication SP42, Detroit, pp. 1-15.
6. Daschner F. and Kupfer H. (1982). *Tests on Shear Transfer Across Cracks in Normal and Light Concretes* (in German), Bauingenieur 57, pp. 57-60.
7. Divakar, M. P. *et al*. (1987). Constitutive Model for Shear Transfer in Cracked Concrete. J. Struct. Engng, Am. Soc. Civ. Engrs, 113, No. 5, May, pp. 1046-1062.
8. Nishimura, A. *et al*. (1982).Shear Transfer at Cracked Section in Reinforced Concrete. *Transactions of the Japan Concrete Institute*, 4, pp. 257-268.
9. Taylor, H. P. J. (1975). *The Fundamental Behaviour of Reinforced Concrete Beams in Bending and Shear*. ACI Special Publication SP42, Detroit, pp. 43-77.
10. Dei Poli, S. *et al*. Dowel Action as a Means of Shear Transmission in R/C Elements. (in Italian), *Studi e Recerche*, 9/87. School for the Design of R/C Structures, Politecnico di Milano, Milan, pp. 217-303.
11. Ashrabov, A. A. and Samarin, A. V. (1984). On Evaluation of Aggregate Interlock Component in Determination of Shear Capacity of RC Beams. (in Russian), *Transactions of Leningrad Institute of Civil Engineers*, No. 106, pp. 64-68.
12. Sagatov B.U. "*About transfer of effort through cracks in ferro-concrete elements*" "European science review." № 7–8. July–August. Vienna-2016. Pag.: 222-224
13. Teacher S. B. U. S. STUDY OF SHEAR FORCES AND STRAINS IN INCLINED CRACKS OF REINFORCED CONCRETE BEAMS Sagatov BU (Republic of Uzbekistan) Email: Sagatov455@ scientifictext. ru.