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Research paper

Experimental Study on the Multikeyed Joints of Concrete and Reinforced Concrete Elements

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Abstract

The connections ensure teamwork under the load of buildings and structures bearing elements. Joints distraction leads to a change in the structures support conditions and their design schemes. Keyed joints are the most effective under significant shear force action because they have high shear resistance. This makes it necessary to further improve their design solutions. In the article the experimental study results of multikeyed joints two series are presented. The joint models were tested in the department laboratory of reinforced concrete and stone structures and resistance of materials Poltava National Technical Yuri Kondratyuk University. The keyed profile (key's depth to height ratio and load application surface angle), reinforcement (quantity of reinforcement and its location character), seam width, keys number were varied in experiments. Heavy-weight concrete, expanded clay concrete and polypropylene fiber concrete were used for the samples manufacture. In experiments the influence of one of listed factors and their combinations for bearing capacity were studied. The concrete and reinforcement strains, distraction character, the failure load were studied. The influence degree analysis of the factors determining the strength was carried out. The design joints parameters that correspond to maximum strength were determined.

Keywords: *Joint, Connection, Factors of influence, Strength.*

1. Introduction

Load bearing elements joints are the important constituents of the structural system. Keyed joints have an increased shear resistance and they are effectively used in the construction industry.

Such joints are the most common variant of the vertical joints of wall panels. Precast concrete shear wall panels are used extensively in high rise construction. Their popularity is mainly due to the high quality achieved at the factory, as well as the high building construction speed.

Keyed connections are used in noncantilevered joints of beams with columns. If necessary keys are placed in joints of two-branch columns with foundations along the larger sides of branches cross-sections.

In the cast-in-place and precast constructions there are keyed joints (dry contact joint).

Bridges with post-tensioned segmental box girders consists of "small" stressed precast elements. The behavior of such bridges at both serviceability and ultimate strength conditions is dependent on the behavior of the joints between the segments.

For the construction of space structures joints with concrete keys and connection bars are used.

The keyed joints wide use in different construction sectors necessitates their further study.

Numerous experimental and theoretical researches of multikeyed joints are known. The multikeyed joints with different profile configurations, the sizes of keys, reinforcement, the level of compression and the type of concrete were tested [1 – 5].

A series of experiments was carried out to study the shear capacity of the multiple keyed joints currently used in post-stressed horizontal connections for elevator shaft shear wall panels [6]. Seven key connections were tested, which had 5 and 8 keys, including two different key configurations (slope angle ψ of the bearing faces to the horizontal was 7º and 23º, key's width to height ratio l_k/h_k = 0.35 and 0.5). Two levels of compressive stresses, 2 and 4 MPa, were applied normal to the connection. The measured concrete compressive strength ranged between 30 and 50 MPa.

It is known that the average magnitude shear stress across the keyed joints decreases as the keys number increases. Numerical joint models with one, three, five and seven keys were developed [7], and a regression equation for determining shear capacity depending on the keys number and prestressing was presented. The proposed relationships are applicable for prestressing up to 3 MPa and concrete compressive strength up to 50 MPa. It is further concluded that for higher prestressing the joint behavior is independent of the keys number.

Similar questions were considered in [8 – 10]. The most important feature of the developed finite element joint model is that it has been validated with experimental tests on concrete panels which were specifically designed to investigate the shear.

Paper [11] presents a new connection of precast reinforced concrete shear wall elements. The precast elements are connected by a narrow seam grouted with mortar and reinforced with overlapping U-shaped bar loops. Contrary to conventional shear connections, the planes of the U-shaped bar loops are here parallel to the plane of the wall elements. This makes it possible to eliminate the risk of reinforcing bars collision during assembly of the elements. The core of mortar inside each U-shaped bar loop is reinforced with a transverse double T-headed bar to ensure transfer of tension between the overlapping U-shaped bars. The

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joint geometry influence on failure was investigated experimentally. The program included preliminary exploration of 25 specimens. Preliminary 7 specimens were investigated. Specimens with the new design were compared with conventional design specimens with identical geometrical joint properties. The remaining 18 samples were divided into two series which differed in the geometry of the keys. The connections had 3 keys with trapezoidal configuration, key's width to height ratio was l_k/h_k = 0.07 – 0.23, compression strength of mortar was 30.6 – 42.7 MPa, U-shaped bar diameter was 8 mm, U-shaped bar yield strength was f_y = 487 MPa. The key dimensions' significance has been addressed and the key height and depth influence on the failure mode has been outlined.

Higher quality joint can be obtained by replacing the U-shaped bars with high strength looped wire ropes. The wire ropes advantage is their flexibility (they have virtually no bending stiffness) which makes wall elements installation much easier. Loop ropes are usually pre-placed in so-called wire boxes, which are built into precast wall elements. Once the joint is grouted with mortar, the boxes will function as shear keys and the overlapping wire loops will function as transverse reinforcement that replaces the U-shaped bars. The results of studies of such 4 key joints are presented in [12 – 14].

Recently, the demand for record length, height and size of load-bearing structures predetermines the need to develop materials overcoming the limitations of the current high strength concrete. This led to the development of Ultra High Performance Concrete (UHPC) satisfying basic mechanical characteristics. Paper [15] presents the experimental study on the behavior of shear keys according to the curing time of UHPC in joint necessary for the construction of precast structures. In [16, 17] the results of studies of the ratio l_k/h_k, the support surface inclination angle and levels of compressive stresses on the load-bearing capacity of two-keyed joints are presented. In the experiments, the joints bearing capacity increase was recorded with the keys support surface inclination angle increase and the levels of compressive stresses.

2. Experimental Program

At PoltNTU during 1985 – 2017 years, system studies of keyed joints of concrete and reinforced concrete elements were carried out [18, 19]. Seven series of the experimental samples have been made and tested. Description of the results obtained in the first 5 series is given in [20].

According to the received data parameters of both key and seam depend on strength of joints (fig. 1).

The samples code of the sixth and seventh series includes: the code first number is the number of keys in the joint; lettering; joint width t_j (for 6 series); the ratio l_k/h_k ; shape of the profile; concrete type; reinforcement ratio ρ_w ; reinforcement location along the key's height.

The samples sixth series included three-keyed joints (19 samples) with the following variables: the supportting surface angle ψ , seam width t_j and the reinforcement location character placement (fig. 2). The research has been carried out in order to determine the influence of these factors on the experimental sample strength. Ceramsite and polypropylene fibre concrete were used for joints filling.

The seventh series (6 samples) has been made for estimating the irregularity of the tangential stress distribution along the length of the jointing, as well as the influence of keys number and their reinforcement on the strength. This series included contact ceramsite concrete joints with one, three or five keys, and also with cross reinforcement and without it. The parameters of experimental samples are given in the table.

Both moment and momentless loading schemes have been implemented during the testing. Samples were made in two stages from concrete of two different classes. First, external parts of test samples from concrete of higher strength were made. Their lateral faces had a keyway profile. Later, the seam between them was concreted. Samples testing process is described in [21].

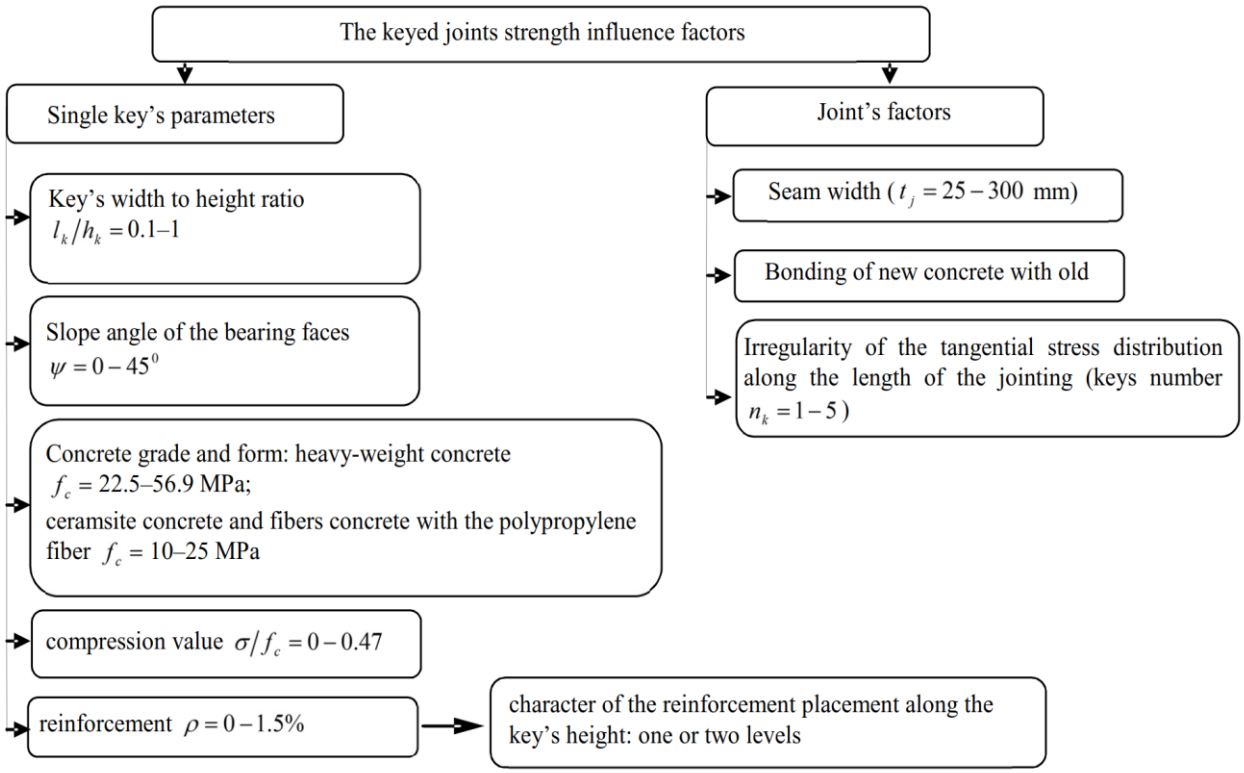


Fig.1: The strength influence factors of the concrete and reinforced concrete keyed joints.

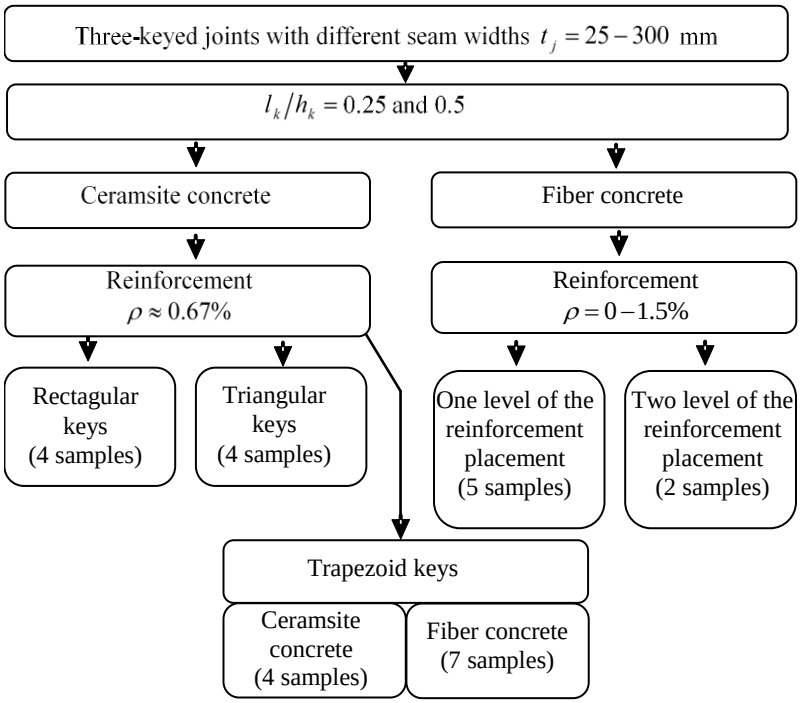


Fig. 2: The experiments program for samples of 6th series.

Table: Parameters of experimental samples of multikeyed joints

№ series	Samples code	Keys geometric parameters, mm			ψ^0	Concrete strength, MPa		Cross reinforcement		t_j, mm	n_k	V_u^{**}, kN
		h_k	b_k^*	l_k		f_c	f_{ct}	amount	f_{yw}, MPa			
1	2	3	4	5	6	7	8	9	10	11	12	13
6	3KJW-50-0.25-R-C-0.66-1	100	153	25	0	12.9	1.6	3x2Ø8	240	50	3	165
	3KJW-100-0.25-R-C-0.64-1		158							100		160
	3KJW-150-0.25-R-C-0.66-1		152							150		140
	3KJW-200-0.25-R-C-0.60-1		168							200		125
	3KJW-50-0.25-Tr-C-0.64-1		157		17					50		170
	3KJW-100-0.25-Tr-C-0.63-1		160							100		170
	3KJW-150-0.25-Tr-C-0.62-1		162							150		160
	3KJW-200-0.25-Tr-C-0.64-1		158							200		150
	3KJW-50-0.5-T-C-0.64-1		157	50	0	10.4	1.2	3x2Ø8		50		160
	3KJW-100-0.5-T-C-0.69-1		146							100		140
	3KJW-150-0.5-T-C-0.67-1		150							150		130
	3KJW-200-0.5-T-C-0.68-1		148							200		120
	3KJW-100-0.25-Tr-F-0.75-2		150	25	17	9.7	1.36	3x4Ø6		100		153
	3KJW-150-0.25-Tr-F-0.69-2		163							150		142
	3KJW-100-0.25-Tr-F-0.66-1		153					3x2Ø8		100		146
	3KJW-150-0.25-Tr-F-0.64-1		158							150		133
	3KJW-25-0.25-Tr-F-1.48-1		152					3x2Ø12		25		199
	3KJW-150-0.25-Tr-F-1.49-1		151							150		176
	3KJW-300-0.25-Tr-F-1.49-1		151							300		163
7	1KJ-0.3-R-C	90	150	30	0	22.5	1.8	–	–	–	1	92
	3KJ-0.3-R-C										3	212
	5KJ-0.3-R-C										5	265
	1KJ-0.3-R-C-0.7-1							2Ø8	240		1	137
	3KJ-0.3-R-C-0.7-1							3x2Ø8			3	305
	5KJ-0.3-R-C-0.7-1							5x2Ø8			5	370

* – thickness of sample; ** – the value of failure load

3. Results Analysis and Discussion

One of the possible failure schemes of three-keyed joints with $l_k / h_k = 0.25$ and distance between keys that is equal to key's height h_k (fig. 3) has been determined depending on the t_j in the load level $(0.8 - 0.9)V_u$:

– the first case was the shear of three keys by the joint's seam $t_j = 25$ mm; the most downloaded key has been destroyed as the first (lower left or upper right one of the contact joint);

– in the II case (t_j = 25, 50, 100, 150 mm) the most downloaded key has been sheared as the first, and then the vertical crack along the height of the middle key and the inclined crack within the seam of the last key have been formed; the failure of two extreme keys with the appearance of the inclined crack within the limits of the middle one also has been observed;

– the III case can be characterized by the shear of the extreme key with the formation of the inclined cracks inside the joint within the other two keys (t_j = 150, 200 mm);

– by joint's width t_j = 300 mm failure was along the inclined plane within the limits of all the joint (IV case); and keys themselves were not collapsed.

So the joint's width determines failure character and as a result significantly influences the ultimate load. In the conducted experiments the last one decreases to 20% with the increase of t_j for trapezoidal profile.

While studying three-keyed joints with ψ = 0 – 45° the statement has been approved that the triangular keys have the highest strength (fig. 4). Similar results were obtained for joints with different keyed profile in [22, 23].

In the case of inclination of key's loaded surface, the shear dominates over tearing due to the concrete deformations transverse limitation. This limitation is caused by the presence of a horizontal force of the thrust, which arises in trapezoidal and triangular keys. In such joints, the reinforcement begins to perceive the load in the earlier stages of joint operation. The resultant load inclination changes the compressive stresses direction compared to the rectangular key.

Connections with the reinforcement along the height of the key have load bearing capacity slightly more (10%) than similar samples with its location in the middle of the key.

The keys destruction surface under the shear has a curvilinear outline and includes zones of compression and tension. Tension prevails over compression. The tensile zone occupies up to 90% of the keys height.

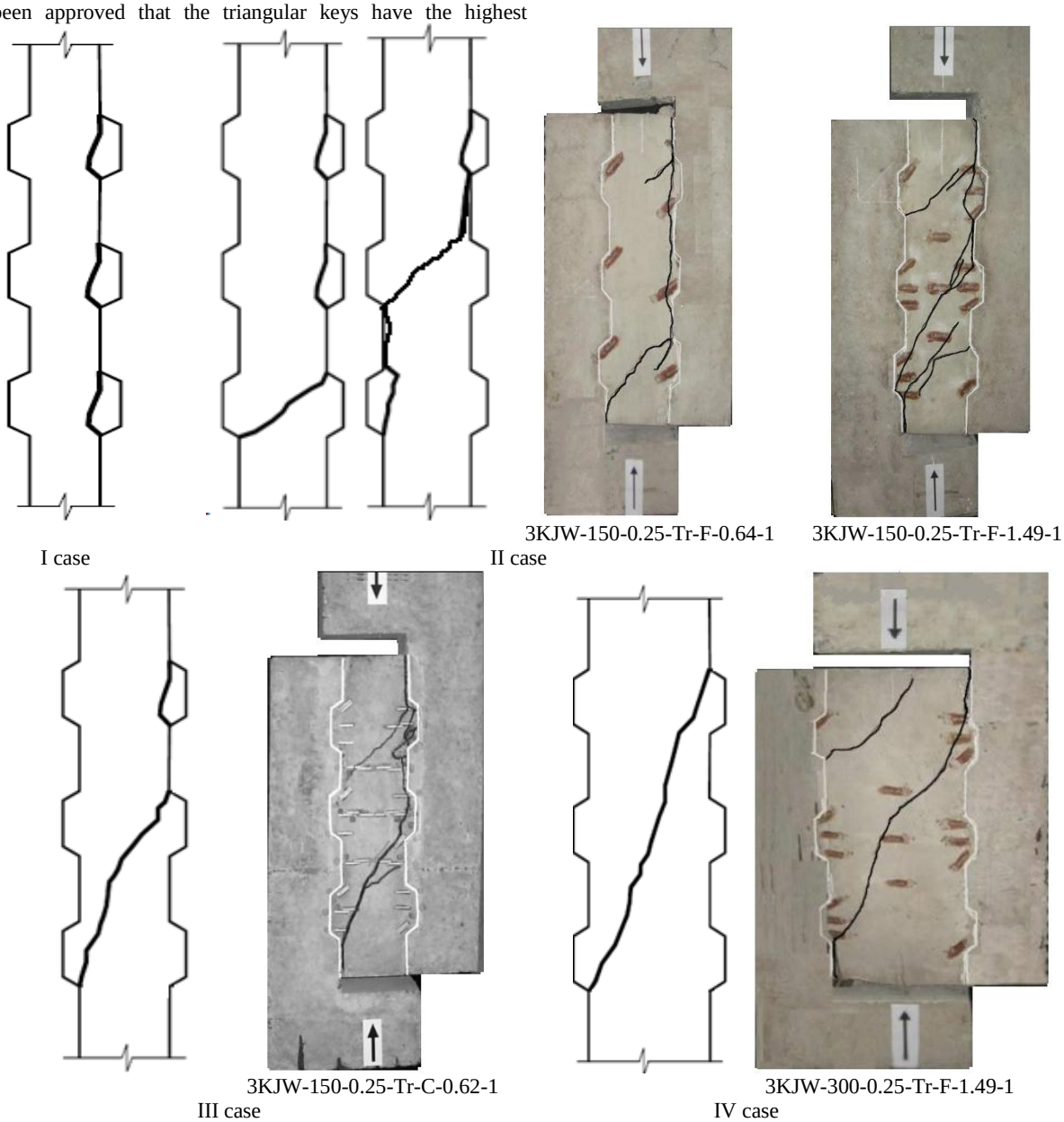


Fig. 3: The failure character of the three-keyed joints made from fibre concrete with the trapezoidal keys.

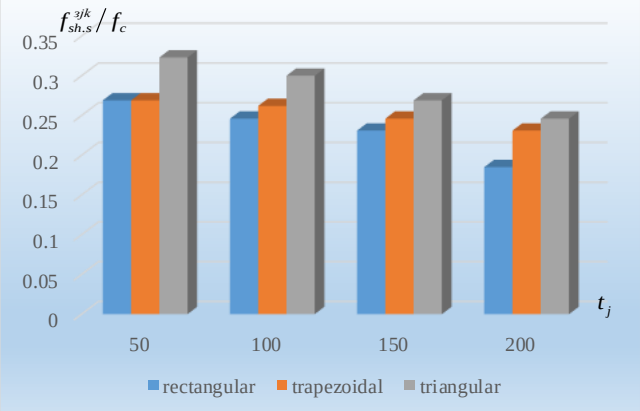


Fig. 4 The strength of three-keyed joints of ceramsite concrete $f_{sh.s}^{3jk}$ on the width of the seam t_j.

However, as the reinforcement factor increases, the size of the compressed zone increases.

Analysis of compressed zone concrete strain shows that its ultimate magnitude corresponds to strain at the top of the concrete mechanical state diagram, they increase with an increase in the reinforcement ratio and a two-level reinforcement placement.

Rods placed in the tensile area of the samples with the spaced-apart reinforcement along the key's height had deformations 40% more than one-level reinforcement.

In joints with higher reinforcement ratio and two-level reinforcement there were maximum strain. Rods placed in the tensile area of the samples with the spaced-apart reinforcement along of the key's height had deformations 40% more than one-level reinforcement

Rods located in the tensile zone (in incoming corners) at the two-level placement are included in the work in the earlier stages of loading compared with the rods located in the middle. The usage of the fiber reinforced concrete as the material for keyed joints led to changes in the character of the cracking and samples failure. First cracks appeared at more high loading levels comparing to ceramsite concrete jointing. Also failure was more ductile and extended in time.

The strength of multikeyed joints increases nonlinearly with the increase of keys quantity n_k (fig. 5).

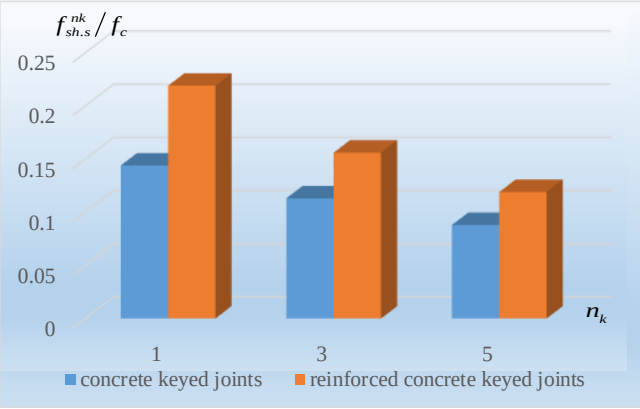


Fig.5: Keyed joints strength $f_{sh.s}^{nk}$ depending on the number of keys.

All samples from the seven series collapsed by the shear (fig. 6).

At loading of $0.7\,V_u$ in the most loaded bottom keys of three- and five-keyed samples cracks appeared near the shear plane. At the loading level of $(0.8–0.9)\,V_u$ the crack width reached 0.7 mm and also new cracks appeared in the middle and top keys.

Failure was followed with the displacement of the side members relative to the middle one. The reinforced joints collapsed under the bigger load comparing with the unreinforced ones.

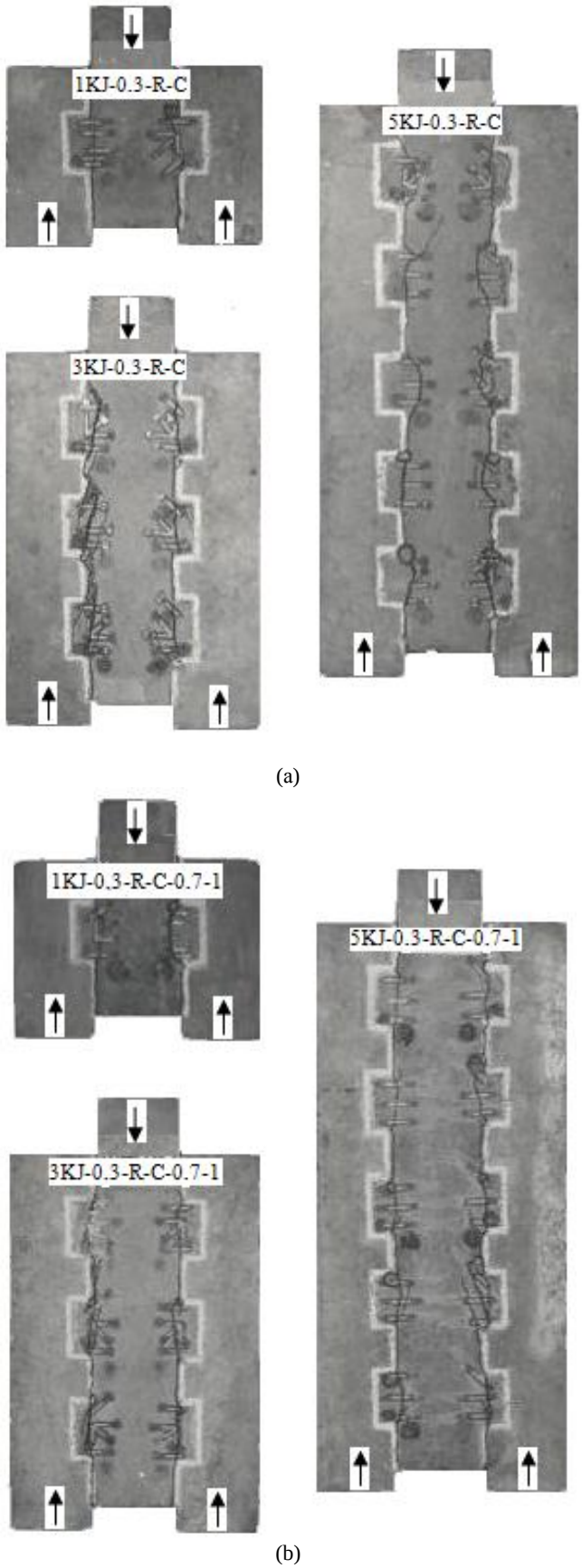


Fig. 6: The failure character of the samples with different number of keys: (a) concrete keyed joints samples; (b) reinforced concrete keyed joints samples.

It happened when reinforcement stress in more tensioned keys reached the yield point. Irregularity of the concrete and reinforcement deformations has been noticed along the length of

the multikeyed joins (fig. 7). It increases with the decrease of the seam's width.

The research allowed to establish qualitative and quantitative influence of separate factors on the joints strength and to receive new information about their combination.

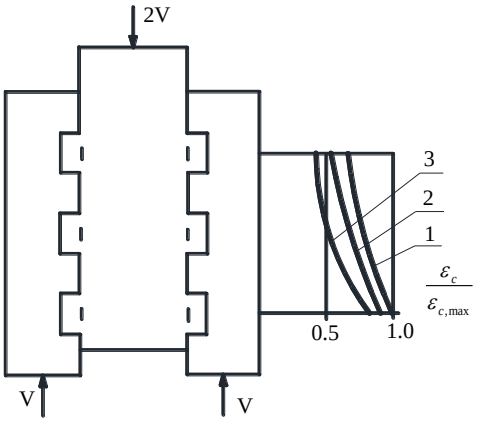


Fig. 7: Concrete strain distribution along the joint length in the sample 3KJ-0.3-R-C-0.7-1: 1 – $V/V_u = 1$; 2 – $V/V_u = 0.87$; 3 – $V/V_u = 0.79$.

4. Conclusion

The received data allow to make the following conclusions:

1. For three-keyed joints next variants are possible: shearing of the three keys, shearing of the two keys and seam failure in the limits of the third key, shearing of one of the keys and seam failure in the limits of other ones, failure over the seam.
2. With the increase of the seam's width its strength decreases.
3. The irregularity of key's work was noticed along the joint in the multikeyed joints. For example, the ultimate load of the five-keyed joints only 3 times more than of the one-keyed. So dependency of the ultimate load on the number of keys is not linear. The actual number of keys with reduction factors must be given in design of multikeyed joints strength.
4. The reinforced concrete multikeyed joints strength with triangular keys is higher than strength of rectangular keys to 15% when the keys support surface is 45°.
5. In the experimental studies an increase of reinforced joints load-bearing capacity up to 2.5 times in comparison with concrete joins was established.
6. In addition to increasing of the strength by 1.1 times, the reinforcement displacement to the key incoming corners leads to an increase in the concrete plastic properties with an increase in the strain value by a factor of 1.5.
7. Before the joint destruction, the strain of the concrete and reinforcement significantly increased. The yield of the reinforcement is fixed at the failure time at a reinforcement percentage of up to 1%.
8. The joints crack resistance and strength is increased when using fiber-reinforced concrete on polypropylene fibers for the joint grouting. Also, the distraction nature changes to more plastic.

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