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Research Paper

Experimental Tests of Eccentrically Compressed Reinforced Concrete Elements Strengthened by Transverse Steel Plates

Engineering

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ABSTRACT

This research paper looks to the Strength of the eccentrically compressed composite reinforced concrete member (reinforced concrete with transverse plates). The results of experimental verification of the criterion equation of the strength of eccentrically compressed composite-element, with transverse plate developed by V.N. Rudakov, by using the generalized criterion of Rankin, within the fracture mechanics of the micro-polarized body.

1. Introduction

We performed experimental and theoretical studies of the strength of eccentrically compressed reinforced concrete elements (ECRCE), strengthened by transverse plates, generalized by Lezer - Shinke, which is one of the components of the target program for the process of the technology safety in the main sectors of the economy [1].

In the new politico-economic environment, the substantial increase in the competitiveness of products and structures, at the expense of their material and energy consumption, is very important factor, in addition to reducing labor costs and other factors. In this case, the advanced technology for design and manufacturing of new types of structures plays a significant role.

One of the effective ways of reducing the mass (but preserving the desirable properties) of the concrete, and composite reinforcement, is reinforcing in form of the transverse plates made from mild steel sheets of lower quality. In such a way reinforced structures working on the axial and eccentric compression, can reduce the consumption of the concrete about 2-3 times, and also reducing the volume of building structures two times, and raising the level of stresses in the longitudinal reinforcement up to 30%.

The massive introduction of the such structures in the building practice is constrained: First of all, the deficiency of the reliable scientific methods of analysis of their strength in the eccentric compression state is due to the presence of physical and geometrical imperfections of the material and structures, installation defects, and lack of the fixation of the load application points, etc. Also, practically, the pure axial loading does not occur.

It is known that many researches and experiments have done for strengthening of reinforced concrete using steel plates, where mainly axially loading was carried out [2, 3], in the present study, we tried to consider the effect of these plates in the case of eccentrically loaded elements.

2. Experimental Work - Sample Dimensions and Materials' Properties

For the study of the behavior of ECRCE, strengthened by transverse plates and short-term loaded, the authors conducted a considerable amount of experimental and theoretical studies on this aspect.

Note that our experiment program included a 1-7 series of samples, four groups (A, B, C, D) of the axial compression, and three (E, F, G) of the eccentrically loaded samples. Each series contains 24 samples (with the triple repetition). The concrete samples which were tested had dimensions: 150x150x600 mm, 150x150x150 mm, 150x150x100 (h) mm and 150x150x75 (h) mm, reinforced concrete, and the reinforced concrete with transvers plates (RCTP): 150x150x600 mm.

The reinforced concrete samples are reinforced with symmetric longitudinal bars of 4Ø12A400C, and the O4Bp-I tie with spacing of 150 mm.

The mechanical characteristics of the longitudinal reinforcement are: yield strength σ_y=40.2kN/cm^2; ultimate strength σ_u = 54.7 kN/cm^2 and relative elongation ε = 0.39.

The main bars used in concrete with transvers plates RCTP was 4Ø12A400C, and transverse plates is 1.8 mm thick. The steel plate's dimensions of 146x146mm are cut from the sheet of the 1250x2500mm of the cold-rolled steel sheet grade 08kp.

Mounting the plate on the longitudinal reinforcement bars is done by sliding the plate on the later, and then will be fixed on the longitudinal reinforcement bars by the welding electrodes of d=3mm. The geometrical form and dimensions of the tested samples for the eccentric loading assumed according to the recommendations of the authoritative scientists [2, 3]. Their difference from standard models is that the application of the eccentrically longitudinal force to the member is possible by using one-sided corbel.

To simplify the preparation of such samples and to prevent the failure of their ends from the local stress concentration, the corbels were designed in the form of the metal end cap, which have a box-shaped cross-section of the channel section No.10 welded together. To ensure the stability of the walls of these channels, under the load application during the test, these walls are strengthened by two stiffeners –80x6mm. For concreting the end cap, sample cavity was filled by concrete.

The length of the cap is equal to the full height of the specimen at the middle part (h=150mm) and the initial eccentricity of e_o. If e_o=15mm, the length of the cap was 180mm, if e_o=25mm, 200mm, and eo=40mm, 230mm, respectively.

The scheme of the fixing of the longitudinal reinforcement to walls of the cap is shown in Fig.1.

In Fig. 2 shows the reinforcement of the reinforced concrete and ECRCE, with smooth solid plates and with the plates, which have axial holes of Ø70mm.

The heavy concrete was obtained using cement M500 of the Balakley factory activity

476kg/cm^2, the normal consistency of the cement 28% and a density ρ_c=3.1g/cm^3.

As the coarse aggregate used granite crashed stone of the particle size of 5-10mm, pre-washed in a metal container, and then dried. The density of the coarse aggregate was $\rho_{c.agg}$=2.65g/cm^3, and the bulk density $\rho_{c.agg}^{bulk}$=1.37g/cm^3. The porosity of the granite crashed stone was within 48.3%, moisture content

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0.2%, and water absorption 0.4%.

As fine aggregate used quartz sand from the Bezlyudovsko career with the physical characteristics: density of the sand ρ_s=2.7g/cm^3, bulk density ρ_s^{bulk}=1.40g/cm^3, the porosity of the sand 48%, gradation factor 2.4, and moisture content 3.7%.

The mix of the heavy concrete was designed in accordance with the "Guidelines for the design of the job mix of the heavy concrete" of the Reinforced Concrete (SRIRC) [5] and according to the recommendations of Professor. V. I. Gotz [6]. The refinement of the concrete mix was achived by trial batches.

3. Testing Method

To compare the results of research, as well as to the inspection verification and refinement of the criterial equation of the strength for the 2nd case of the ECRCE (including reinforced plates with an axial hole d=0.5b, where b is the width of the rectangular cross section), developed by V. N. Rudakov, using generalization of the Rankine (maximum normal stress) [7] in the terms of the mechanics of the failure of micro-polarized body, were prepared and tested the concrete, reinforced concrete and ECRCE samples, with the compressive strength of the concrete cube of 20 and 40 N/mm^2 strengrh.

Before loading, the samples were centered so that the initial eccentricities e_o=15mm; 25mm and 40mm are strictly consistent with the application of force, along a common longitudinal axis Y, which coincides with the axis of symmetry along the end cap, and working height of the element (Fig.3-4). Misalignment of axes X_o and X_1 correspond to the initial eccentricity e_o, herewith the tip of the support strictly coincides with the axis X_1.

The samples are tested for compressive strength according to the SRIRC procedure [8, 9]. Loading steps produced approximately equal to 10% of the predicted failure load, with the load stopping at each stage for 10 minutes. And at each stage during the test the deformation of the concrete and reinforcement is measured.

The results of the tests of the concrete samples of series E, F and G are shown in Table 1. It also shows the coefficients of the hardening of the concrete η_h^u for the sample height of h=150mm, 100mm, and 75mm.

Table1. Comparison of the results of tests of short concrete elements of square cross section 150x150 mm groups C, D, E on strength under axial short term compressive load-N_u.

series	Sample No.	Height h, mm	Failure Force kN		Strength MPa		Strength Coefficient $\varsigma_h^u = \frac{\overline{R}_{bh}}{\overline{R}_b}$
			N_u	$\overline{N}_u$	$\overline{R}_b$	$\overline{R}_{bh}$	
C	1.1 1.2 1.3	600	559.17 573.89 588.6	573,89	25.51	-	1
	2.1 2.2 2.3	150	853.47 828.95 824.0	835.49	-	37.13	1.456
	3.1 3.2 3.3	100	1084.0 1152.68 1079.1	1105.26	-	49.12	1.926
	4.1 4.2 4.3	75	1373.4 1402.83 1334.16	1370,16	-	60,9	2,387
D	1.1 1.2 1.3	600	608.22 671.99 671.99	650.74	28.93	-	1
	2.1 2.2 2.3	150	892.71 873.09 878.0	880.45	-	39.13	1.353
	3.1 3.2 3.3	100	1079.1 1152.68 1182.11	1137.96	-	50.58	1.748
	4.1 4.2 4.3	75	1422.45 1437.17 1451.88	1437.17	-	63.87	2.208
E	1.1 1.2 1.3	600	951.57 936.86 912.33	933.58	41.50		1
	2.1 2.2 2.3	150	1187.01 1133.06 1191.92	1170.62	-	52.03	1.254
	3.1 3.2 3.3	100	1574.51 1505.84 1520.55	1533.63	-	68.16	1.643
	4.1 4.2 4.3	75	2099.34 2084.63 2011.05	2065.01	-	91.78	2.212

4. Data Analysis and Discussion

The assumption of the initial eccentricity e_o=0.1h; 0.167h; 0.276h defined by the boundaries of the core section, as well as the known results of the eccentric compressive tests of the mesh reinforced columns conducted in Science-Research Institute of the Reinforced Concrete (SRIRC) [8, 9].

The failure process under axial compression of the geometrically and physically similar concrete samples is discussed in detail in the works [10,11].

Here, based on the principle of self-modeling [12, 13] provides an analytical solution to the problem for determining the reduction prism strength R_b*, under axial compression as a concrete prism height h<b, and a prism included between the steel plates ECRCE.

Conditions of self-modeling, equivalent to the energetically nonlinear fracture criterion of Rice-Cherepanov (the criterion of J-integral) [6, 14, 15], which takes one of the leading positions in the fracture mechanics of elastic-plastic bodies, for geometrically and physically similar concrete samples followed by the equation

where η_T - theoretical work-hardening coefficient of concrete

$$\eta_T = \frac{R_b^*}{R_b} = \frac{A_{max}^*}{A_{min}^*} \qquad (1)$$

[22,23].

In developing criterial equations of the strength of the eccentrically compressed-

ECRCE, reinforced by symmetric longitudinal reinforcement, for the condition of

$0<e_o<0.5h$, we adopted the following assumptions:

a) The summation of the failure stress σ_u, by the principle of the superposition, is determined by summation of its components: failure stress of the concrete σ^*_{bu} and the failure stress of the longitudinal reinforcement σ^*_{su}, which, in turn, is determined as the summation of their components i.e. the longitudinal force N_i and moment M_i, for Concrete:

$$\sigma_{bu}^* = \sigma_{bN}^* + \sigma_{bM}^* \qquad (2)$$

longitudinal reinforcement:

$$\sigma_{su}^* = \sigma_{sN}^* + \sigma_{sM}^* \qquad (3)$$

b) in equilibrium state (before fracture), the compatibility condition of the concrete and reinforcement, in which $\varepsilon_s=\varepsilon_B$ [6, 23], was observed;
c) in equilibrium state, bearing in mind that $\sigma›_s \geq \sigma_T$ of the concrete acquires the properties of the elastic-plastic material, which allows for the compression (e_o*=0), we assume the unique (fictitious) equivalent of the rectangular diagram, of the total stresses of the core of cross-section of element, with the maximum fiber ordinate (most compressed edge fiber of the face of the concrete) [18], where e_o*=the fictitious eccentricity (Fig. 3);
d) the summation of the internal forces in the longitudinal reinforcement, is uniformly “distributed” across the core of the member cross-section, i.e. for the compression conditions (e_o*=0), the unique equivalent (fictitious) of the rectangular diagram, with the maximum ordinate of the boundary is assumed [17] (Fig. 4);
e) the Rankine’s generalized criterion is applied to assess the strength of the compressed (e_o=0) concrete core and reinforcement, which well known in references as a criterion of the maximum (integral) stress, according to the axial compressive (tensile) testing of the concrete and reinforcement [7].

We note the analysis of the base of the eccentrically compressed steel columns, under combined loading of M and N in the modern methods of analysis [19, 20]. The diagram of the stress distribution in the compressed zone of concrete is taken as triangular, with the maximum ordinate of the boundary σ_b*, or rectangular with a shortened base of C=αλ, where α<1, λ = the distance between the compressed zone of the concrete and the axis of the anchor bolt in the tension zone, and $l>L_{pl}$, L_{pl}= the length of the supporting plate, the coefficient α is given by

$$\alpha = 1 - \sqrt{1 - \frac{2M^*}{R_b^* l^2 B_{pl}}} \qquad (4)$$

$$M^* = N(e_k + \beta) \qquad (5)$$

$$\beta = l - y_{1(2)} \qquad (6)$$

$$y_1^* + y_2^* = h_k \qquad (7)$$

h_k= total depth of the column;

$$e_{oi} = {M}/{N} \qquad (8)$$

B_{pl}=width of the supporting plate;

R_b*= hardening strength of concrete under local compression.

Considering the results of the experimental studies, the general criterial equation of the strength of the ECRCE, can be written as

$$\sigma_u = \sigma_{bu}^* + \sigma_{su}^* \qquad (9)$$

Where

σ^*_{bu}=the fractural stress of the concrete:

Where

$$\sigma_{bu}^* = \sigma_{bN}^* + \sigma_{bM}^* = \frac{N_{bu}}{A_{bef}} + \frac{e_o N_{bu}}{\rho_b A_{bef}} = \eta R_b \qquad (10)$$

N_{bu}= the fractural force of the concrete;

e_o= the initial eccentricity;

ρ_b= the core dimension of the rectangular (square) cross-section:

$$\rho_b = \frac{h_{ef}}{6} \qquad (11)$$

A_{bef} = the working cross-sectional area of the element. Introduced in eq. (10),

$$m = \frac{e_o}{\rho_b} \qquad (12)$$

where m= the relative eccentricity.

And transforming the expression (5) we obtained:

$$N_{bu} = \frac{\eta R_b A_{bef}}{(1+m)} \qquad (13)$$

The fractural stress of the longitudinal reinforcement σ_{su} * can be determined by the formula:

$$\sigma_{su}^* = \sigma_{sN}^* + \sigma_{sM}^* = \frac{N_{su}}{\Sigma A_s} + \frac{e_o \omega N_{su}}{\rho_s \Sigma A_s} = R_s \qquad (14)$$

N_{su} =the fractural force of the longitudinal reinforcement;

ΣA_s= the total cross-sectional area of the longitudinal reinforcement;

ρ_s= the core dimension of the symetrically longitudinal reinforcement:

$$\rho_s = \frac{W_s}{\Sigma A_s} \qquad (15)$$

y_1= the axial distance between the bars of the compressive and tensile zones, along the y axis with respect to the x axis (Fig. 1);

W_s= the section modulus of the reinforcement:

$$W_s = \frac{I_s}{y_1} = \frac{y_1^2 \Sigma A_s}{y_1} = y_1 \Sigma A_s \qquad (16)$$

ω - the coefficient of fullness of the fictitious moment diagram component of the σ^*_{sM} of the fractural stress σ^*_{su};

when $e_o \le [e_o]$, ω = 1, when $e_o > [e_o]$, ω = 0.5. Where $[e_o]$= the initial eccentricity on the boundary of the core of the cross-section;

R_s^*= the strength parameter of the longitudinal reinforcement:

$$R_S^* = f(\sigma_T; \sigma_B) \quad (17)$$

σ_T, σ_B= the yield strength and ultimate strength of the longitudinal reinforcement, respectively.

Empirically established that if forces N_{su} is applied inside of the core section, then

$$R_S^* = 0.5(\sigma_T + \sigma_B) \quad (18)$$

If the force N_{su} is applied at the boundary of the core of the section or outside of it, then

$$R_S^* = \sigma_B \quad (19)$$

After substituting (15) and (16) into (14), and further transformations of the equation (14) takes the form

$$N_{su} = \frac{R_S^* \cdot \Sigma A_S}{(1 + \omega m)} \quad (20)$$

The behavior of the concrete fracture and ECRCE, when e_o>0, is shown in Fig.5, and it is fully consistent with the basic theoretical principles of the fracture mechanics of the micro-polarized body.

Tables (2-4) present the results of the test of the reinforced concrete, and ECRCE of series E, F, and G under eccentric compression with initial eccentricities of e_o=1.5cm, 2.5cm and 4.0cm.

Also, here are presented the theoretical values of the $\bar{N}_{bT}$ $(\bar{N}_{bu})$ and $\bar{N}_{sT}$ $(\bar{N}_{su})$, which are calculated by formulas (13) and (20), and values of the summation of the fractural force are:-

$$\bar{N}_{uT} = \bar{N}_{bu} + \bar{N}_{su} \quad (21)$$

5. Conclusion

It can be noted that the total variance of the experimental results with the theoretical, for the ECRCE samples was +0.77% and +1.54% for reinforced concrete samples.

In addition, the data in Tables 2-4 allows us to conclude, that the concrete in the reinforced concrete sample by longitudinal reinforcement and stirrup, with distance S=b, where b= short side of rectangular section, under compression, is self strengthened by 10-13%. Earlier, similar results were obtained empirically by German scientists [21, 24].

Table2. Comparison of the experimental results of the short ECRCE and reinforced concrete elements dimensions of 150x150x600(mm) with symmetric longitudinal reinforcement bars (σ_T=402MPa, σ_u=547MPa, 0.5 (σ_T + σ_u)=474.5MPa) series E under eccentric compression short-term load N_{ex} (the initial eccentricity e_o=1.5 cm), and theoretical (N_{bT}), calculated within the fracture mechanics MEAs.

Sample No.	Steel plates spacing S, mm	Stirrup spacing S, mm	Material Properties							Compressive force, kN				Δ= $\frac{\bar{N}_{ex} - \bar{N}_{uT}}{\bar{N}_{ex}}$ x100%
			Concrete					Reinforcement 4Ø12 A400C		experiment		theory		
			ηR_b, MPa	b_{ef}, cm	h_{ef}, cm	A_{bef}, cm²	m	$\Sigma(A_s + A_s^1)$, cm²	$\bar{N}_{su}$, kN	N_{ex}	$\bar{N}$ ex	$(\bar{N}_{bT})$	$\bar{N}_{uT}$	
6.1 6.2 6.3	150		37.13	15.0	15.0	225	0,6	1.131 x 4 = 4.524	(47.45x 4.524)/1.277 = 168	710 695 655	686.7	522.14	690.14	- 0.50
7.1 7.2 7.3	100		49.12	14.6	13.3	194.18	0.6767			750 720 730	733.33	568.86	736.86	0
8.1 8.2 8.3	75		60.90	13.3		176.89				785 855 815	818.3	641.23	809.23	+1.1
5.1 5.2 5.3	-	150	25.51x x1.13= 28.83	15	15	225	0.6			546.12 573.89 598.41	572.81	405.42	573.42	0

Table 3 Comparison of the experimental results of the short ECRCE and reinforced concrete samples dimensions of 150x150x600(mm) with symmetric longitudinal reinforcement bars (σ_T=402MPa, σ_u=547MPa, 0.5 (σ_T + σ_u)=474.5MPa) series F under eccentric compression short-term load N_{ex} (the initial eccentricity e_o=2.5 cm), and theoretical (N_{bT}), calculated within the fracture mechanics MEAs.

Sa mple No.	Steel plates spacing S, mm	Stirrup spacing S, mm	Material Properties							Compressive force, kN				Δ= x100% $\frac{\bar{N}_{ex} - \bar{N}_{uT}}{\bar{N}_{ex}}$
			Concrete					Reinforcement 4Ø12 A400C		experiment		theory		
			ηR_b, MPa	b_{ef}, cm	h_{ef}, cm	A_{bef}, cm²	m	$\Sigma(A_s + A_s^1)$, cm²	$\bar{N}_{su}$, kN	N_{ex}	$\bar{N}$ ex	$(\bar{N}_{bT})$	$\bar{N}_{uT}$	
6.1 6.2 6.3	150	-	39.13	15.0	15.0	225	1.0	1.131x 4 = 4.524	(54.7x 4.524)/1.463= 169.15	610 608 598	605.33	440.01	609.16	-0,63
7.1 7.2 7.3	100	-	50.58	14.6	13.3	194.18	1.1278			637 640 632	636.33	461.59	630.74	+0.88
8.1 8.2 8.3	75	-	63.87							740 770 735	748.3	582.87	752.02	-0.50
5.1 5.2 5.3	-	150	32.69	15	15	225	1			539.55 547.4 549.36	545.44	367.88	537.03	1.54

Table 4. Comparison of the experimental results of the short ECRCE and reinforced concrete elements dimensions of 150x150x600(mm) with symmetric longitudinal reinforcement bars (σ_T=402MPa, σ_u=547MPa, 0.5(σ_T + σ_u)=474.5MPa) series G under eccentric compression short-term load N_{ex} (the initial eccentricity e_o=4cm), and theoretical (N_bT), calculated within the fracture mechanics MEAs.

Sample No.	Steel plates spacing S, mm	Stirrup spacing S, mm	Material Properties							Compressive force, kN				Δ= x100% $\frac{\bar{N}_{ex} - \bar{N}_{iT}}{\bar{N}_{ex}}$
			Concrete					Reinforcement 4Ø12 A400C		experiment		theory		
			ηR_b, MPa	b_{ef}, cm	h_{ef}, cm	A_{bef}, cm²	m	Σ(A_s+ A_s^1), cm²	$\bar{N}_{su}$, kN	N_{ex}	$\bar{N}$ ex	($\bar{N}_{bu}$)	$\bar{N}_{iT}$	
6.1 6.2 6.3	150	-	52.03	15.0	15.0	225	1.6	1.131x 4 = 4.524	(54.7x 4.524)/1.3704 = 180.58	638 642 630	636.7	450.26	630.84	0.92
7.1 7.2 7.3	100	-	68.16	14.6	13.3	194.18	1.8045			666 664 624	651.3	471.93	652.51	0
8.1 8.2 8.3	75	-	91.78		12.0	175.2	2.0			715 718 706	713	536.0	716.58	- 0.15
5.1 5.2 5.3	-	150	41.50x x1.1= 45.65	15	15	225	1.6			541.51 590.56 588.6	573.56	395.05	575.63	0

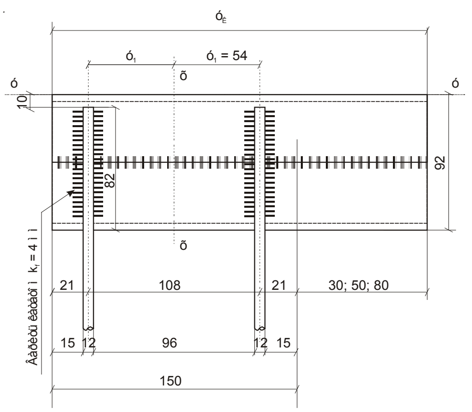
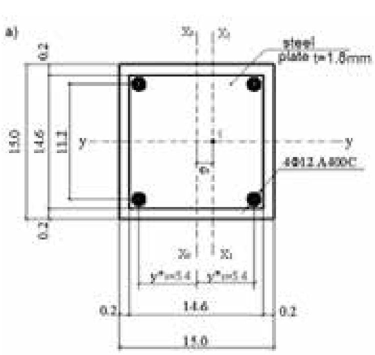


Fig.1 Scheme of the fixing of the longitudinal reinforcement Ø12 to the cap of the member

Fig.2 Reinforcement cages with solid plates and the plates which have axial holes Ø70mm.



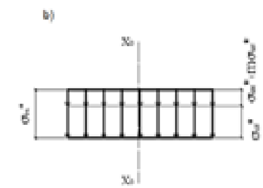


Fig.3 The design scheme of SZHBK element to determine the force (N_{bu}) with eccentric compression (with an initial eccentricity eo = 1.5 ... 4.0 cm): a - normal cross section of ECRCE element with symmetric longitudinal 4 Ø12 A400C and transverse reinforcement plate t =1.8 mm b- average diagram of the total fictitious stress (on the most compressed concrete zone - the edge fibers) at the equilibrium state with the maximum ordinate $\sigma_{bu}{}^* = \sigma_{bN}{}^* + \sigma_{bM}{}^* = \eta R_b$

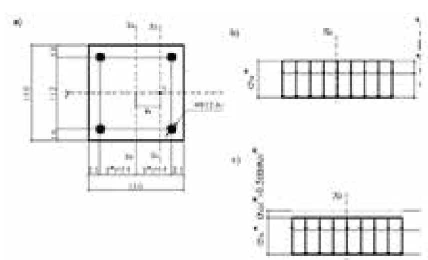


Fig.4 The design scheme for the determination of the maximum longitudinal force in the ECRCE and reinforced concrete elements in the equilibrium state: a – normal section of the element with the longitudinal bars 4Ø12 A400C, and point of application of the force Nae (N_{su}) at C ; b- the equivalent average diagram of the total fictitious stress $\sigma^*_{su}=\sigma^*_{su}+\sigma^*_{sM}=R^*_S$ of the action of the maximal force N_{ae} (N_{su}) when $e_o \le [e_o]$, where $[e_o]$ -eccentricity on the boundary of the core cross section, uniformly distributed over the normal cross-section of the element; c- the same $\sigma^*_{su}=\sigma^*_{sN}+0.5\sigma^*_{sM} =R^*_S$, when $e_o > [e_o]$.

Fig.5 The fractural mode of the ECRCE

REFERENCE

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