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EXPERIMENTAL AND THEORETICAL ANALYSIS OF COMPRESSED REINFORCED CONCRETE ELEMENTS OF ANNULAR SECTION FORCED WITH CARBON FIBER

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Abstract- In modern times, carbon fibers are widely used to strengthen reinforced concrete structures. At this time, carbon fibers play the role of external reinforcement. This type of reinforcement is mainly used to increase the load-carrying capacity of reinforced concrete members working in bending. The fact that carbon fibers have high tensile strength allows the load-carrying capacity of reinforced concrete members working in tension and bending to be sufficiently increased. The use of carbon fibers in reinforcement also simplifies the strengthening technology. The paper describes the results of experimental and theoretical research of compressible reinforced concrete members with annular cross-section and externally forced with carbon fibers. As a result of the conducted experiments, it was determined that the load-carrying capacity of the reinforced concrete members can be sufficiently increased in the strengthening by external winding. This external surface is obtained due to the formation of a grip effect during compression in the reinforced member. The results of the experiments have shown that the load-carrying capacity of the compressed members can be increased many times due to the gripping effect. For the test, members wrapped with carbofibers in one layer, two layers and three layers from the outside were prepared. In the process of preparation, the requirements of normative documents were considered. In order to evaluate the effect of reinforcement, ordinary reinforced concrete elements were also prepared. At the same time, both reinforced and ordinary reinforced concrete elements were tested. The load-carrying capacity of compressed ordinary reinforced concrete elements was determined theoretically based on the method proposed by the authors in previous studies. It is shown that the proposed calculation method allows obtaining results that are consistent with the results of experiments for non-reinforced reinforced concrete elements. Also, as a result of the experiments, it was determined that the number of layers of carbon fibers attached to the outer surface of the compressible element has a serious effect on the load-carrying capacity. However, the number of layers should be up to a certain limit. For example, it was experimentally determined that the ratio of the load-carrying capacities of the elements during additional reinforcement with carbofibers as single, double and triple, respectively, was 1:1.81:2.05. This means that the load-carrying capacity increases by 1.81 during double reinforcement compared to single reinforcement. However, during triple reinforcement, the load carrying capacity increases by 1.13 times compared to double reinforcement. It was suggested that the methodology of calculation of reinforced elements be identified with the methodology of calculation of non-reinforced elements. Just use the reduced value of concrete compressive strength that takes reinforcement into account. As a result of the conducted theoretical calculations, it was determined that it is enough to increase the compressive strength of concrete by 3.1 times to take into account single reinforcement. Accordingly, by increasing the strength of concrete by 6.0 times during double reinforcement, and 7.1 times during triple reinforcement, the results consistent with experiments can be obtained. Of course, this type of calculation methodology requires planned experimental research in this direction, along with simplifications in terms of application. The theoretical calculation methodology proposed in the article should be considered as the first step in this direction. As a result of the analysis, it was determined that carbofibers play an important role in increasing the load-carrying capacity of compressed reinforced concrete elements. It should be noted that while preparing samples for the experiment, samples were prepared to determine the strength characteristics of the concrete and reinforcement used. At this time, concrete cubes were tested for compression and reinforcement bars for tension in anticipation of the requirements of normative documents. During the theoretical calculations, the tested values of the materials were used.

Keywords: Carbon Fiber, Concrete, Reinforcement, Load-Carrying Capacity, Rational Fractional Function, Eurocode (EN).

1. INTRODUCTION

In modern times, carbon fibers and laminates, which are composite materials, are widely used in reinforcing

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reinforced concrete members [1]. The use of these materials in delaying construction structures is justified by the fact that these materials provide conditions for achieving high strength by consuming a small amount of material. It makes it possible to sufficiently increase the load-carrying capacity of construction structures, including reinforced concrete structural members, without changing their cross-sectional areas. This is due to the fact that composite materials have higher strength than concrete and reinforcement. By using very thin winding composite materials, it is possible to increase the load-carrying capacity of reinforced concrete and concrete members in tension, compression and bending.

It should be noted that the application of winding composites, which play the role of external reinforcement in compressible elements, allows for a multiple increase in their load-carrying capacity due to the effect of gripping for compressible members. This is primarily due to the grip effect, which increases the compressive strength of concrete many times compared to ordinary concrete. The main goal of conducting experimental studies was to study the nature of increase in load-carrying capacity during strengthening of reinforced concrete members with an annular cross-section by external wrapping. During the experimental studies, conventional central compression was considered. It should also be noted that the tensile diagram of carbon fiber materials is almost linear up to complete failure. This allows for the maximum use of their reserve of strength. The development of an effective method to take into account the effect of surface reinforcement in compression members in calculations is of practical importance.

In the paper, it is proposed to identify the method of calculation of reinforced members with the method of calculation of ordinary members [2,15]. At this time, it is proposed to use the reduced value of the concrete compressive strength, which includes the reinforcement, in the calculation of the reinforced members. Because at this time, the calculation of the reinforced compressive member is brought to the calculation of ordinary reinforced concrete members. From this point of view, experimental and laboratory studies on the activation of carbon fibers in compression members should be conducted in the direction of obtaining empirical formulas for determining the reduced strength. The existence of such empirical dependencies allows for the improvement of engineering calculation methods of reinforced compressible members. Reinforced concrete members with annular cross-section are widely used in various fields of construction as the main load-carrying members. The theory of modern reinforced concrete structures is intensively developed in the direction of applying the nonlinear deformation model [3, 4, 10].

The application of the non-linear deformation model makes it possible to determine the state of stress-deformation formed in the cross-sections of the complex element at an arbitrary level of loading. Also, the application of this model makes it possible to determine the load-carrying capacity more accurately and to use the material's strength reserves to the maximum.

The state of stress-deformation and load-carrying capacity of compressed reinforced concrete members depends on many factors. These factors include the percentage of reinforcement, the conditions of fixing the ends of the element, the eccentricity of the compressive force and the flexibility of the member.

Recently, it is preferred to study the state of stress-deformation of forced concrete members with a complex cross-section by applying non-linear deformation diagrams of materials. In [1], the authors investigated the stress-strain state and load-carrying capacity of short reinforced concrete members with unreinforced annular cross-section in compression. It has been shown that the load-carrying capacity of these members is mainly determined by the strength condition. In [5], the author mentioned the fundamental issues that should be taken into account in the creation of the calculation theory of reinforced concrete structures. In [6], the engineering calculation methodology for non-linear version of reinforced concrete members forced with plastic mass materials was developed.

In [8], a calculation method was developed based on the nonlinear deformation model of compressible reinforced concrete members with a circular cross section. In [11], the influence of the flexibility of the element on the performance of reinforced concrete members under load was studied. As research works carried out in this direction, it is possible to mention the application of simplified diagrams of materials proposed by Eurocode to the calculation of compressed reinforced concrete members [7]. In this study, the application of simplified diagrams for materials in the determination of stress deformation state and load-carrying capacity was investigated in terms of accuracy. It is shown that, in some cases, the load-carrying capacity can be determined with engineering accuracy by applying simplified diagrams. In [12], the stress-deformation state of compressed reinforced concrete members with annular cross-section was investigated for certain analytical expressions of deformation diagrams of materials.

The basics of calculation methods based on the non-linear deformation model of reinforced concrete construction members are given in works [9], [10], [13]. In [14], the methodology for determining the state of stress-deformation and load-carrying capacity of tubular-concrete members with a circular cross-section was developed. In [15], the authors developed an effective numerical methodology based on the nonlinear deformation model for determining the stress-deformation state and load-carrying capacity of reinforced concrete members with a compressed annular cross-section. In [16], the load-carrying capacity and collapse mechanism of a reinforced concrete column forced with carbon fiber and laminate were studied. In [17], the authors provided a calculation methodology based on the nonlinear deformation model of reinforced concrete members working in bending during various approximations of deformation diagrams of materials.

In [18], a numerical methodology was developed for determining the stress-deformation state and load-carrying capacity of centrifugally compressed circular cross-section reinforced concrete members by applying the diagram of concrete in compression proposed by Eurocode. In [19], a numerical method of beam calculation was developed by applying non-linear deformation diagrams of materials. The proposed calculation method allows determining the optimal parameters of beams in terms of stress-deformation.

Studied the load-carrying capacity and deformation properties of concrete columns with a square cross-section when reinforced with carbon textile fibers [20]. It has been shown that it is possible to achieve 70% load-carrying capacity increase during the mentioned strengthening. In recent years, research related to CFRP structures has increasingly focused on investigating the contribution of this material to structural strength and durability. Investigations of different types of concrete and cross-layered composite structures have elaborated on the advantages of high-performance structural elements provided by CFRP.

For example, in [21], embodying the importance of CFRP in infrastructure applications, technical recommendations for the design and experimental study of fiber-reinforced concrete sewer pipes are provided. The study [22] addressed issues related to the compressive behavior of carbon fiber-reinforced polymer steel composite pipes filled with high-performance concrete and examined issues related to the effects of using CFRP to improve durability. A special focus is placed on the design features of precast steel fiber-reinforced concrete airport slabs in analyzing the performance of CFRP under various loads [23]. In [24], reinforcing square steel tubes with carbon fiber-reinforced polymer meshes and testing them under axial loads showed that the durability was increased. In [25], experimental studies were conducted on cylindrical shells damaged by random cuts and cracks.

This confirms that the application of CFRP is an effective solution to improve the durability of damaged structural members. These studies comprehensively evaluated the current status and modern applications of CFRP in concrete structures and laid a good foundation for future engineering applications. [26] The transient deformation states of heterogeneous shells and plates under thermal and thermomechanical loading are studied.

2. PREPARATION OF REINFORCED CONCRETE COLUMNS FEATURING AN ANNULAR CROSS-SECTION FOR EXPERIMENTAL TESTING

Reinforced concrete members featuring a ring cross-section, with outer and inner diameters of 120 mm and 60 mm, respectively and lengths of 700 mm, were prepared in the Central Laboratory of the Production Base of Evrascon LLC. The class of concrete used was B25, and the class of reinforcement was A500 °C. The elements are reinforced with six longitudinal reinforcements with a diameter of 8 mm. Three of these elements are designed as ordinary reinforced concrete elements, while the other three are wrapped externally with single, double and triple composite fibers, respectively.

Before external wrapping, the surface of the elements was cleaned according to the existing technology, after 10-15 minutes of cleaning and processing, MasterBrace P3500 brand primer for different types of bases was applied to the surfaces of the samples. MasterBrace P3500 consists of two components and is available in containers ("A" and "B") of the optimal amount for mixing. Before mixing, the temperature of the components should be between $(+15 \div +25)$ °C.

Component "*B*" is poured into component "A" without any residue in the container and mixed with a screw attachment mixer at low speed $(\sim 300\text{ rpm})$ for 3 minutes until homogenous. After mixing, MasterBrace P 3500 is applied to the concrete surface with a brush or soft roller. During the application of the primer, the temperature of the base and the environment should be between $(+15 \div +30)$ °C. The drying of the primer layer varies depending on the weather conditions and is checked by the formation of stickiness as much as a finger print. At the next stage, a specially prepared layer of MasterBrace 4500 adhesive is applied. This solution acts as the primary adhesive, facilitating the collaboration between the carbon fiber layer and the reinforced concrete component.

After mixing, MasterBrace 4500 consumption is applied by multiplying 2 (two) layers: 1.1 kg/m^2 - first layer, 0.5 kg/m^2 - second layer. During the application of the main layers, the ambient temperature should be between $(+15 \div +30)$ °C. Unlike the primer, you can't wait after the base coat is applied, and the element must be covered with a carbolif layer immediately. After the elements are coated with a layer of carbon fiber, they should be kept in a natural drying strip, and the samples should be tested after they are completely dry. In the current situation, this period is 7 (seven) days. Figure 1 shows some of the stages in the preparation of elements. It should be noted that the strengthening of the elements and their testing were carried out at the test site of the Scientific-Research and Project-Construction Building Materials Institute named after S.A. Dadashov. The thickness of the used dressing materials was 0.167 mm.

(a)

(b)

(c)

Figure 1. Applying Master Brace P3500 primer to the elements

3. EXPERIMENTAL INVESTIGATION OF CARBON FIBER-REINFORCED ANNULAR CROSS-SECTION MEMBERS

After the drying process was completed, each of the annular-shaped reinforced concrete element samples was subjected to a compression test based on GS 10180-2012 in a PK1000 hydraulic compression press. During the test, the maximum load value for the forced concrete members were 23900 kg , 24000 kg and 28400 kg , indicating that the mean compressive strength of the unreinforced concrete elements is (23900+24000+28400)/3 = 25433.33 kg for those tested.

When those elements are reinforced with a single wrap, since the load-carrying capacity of the element in compression is 50000 kg , the load-bearing capacity of the load-carrying capacity of the ring-shaped component, compressed with a single wrap, is enhanced by approximately 1.96 times, which can be considered a very favorable factor for strengthening. Because even with a single winding, the load-carrying capacity of this element is almost doubled. By the same rule, when the element is reinforced with double wrapping, its load-carrying capacity in compression was 90000 kg , which means a 3.53-fold increase in load-bearing capacity compared to an ordinary forced concrete element, and a 1.8-fold increase compared to a single-wrapped member.

Ultimately, the load-carrying capacity of the element reinforced with a triple wrap reached 102,800 kg, which is roughly 4.04 times that of the forced concrete element, 2.06 times that of the element with a single wrap, and 1.14 times that of the element with a double wrap, representing an overall increase of 14%. This once again shows that when reinforcing compressed reinforced concrete elements with carbon fibers, their optimal thickness should be used. It should be noted that compression reinforced concrete elements reinforced with carbon fibers work in triaxial tension even in uniaxial compression due to the griping effect compared to ordinary elements. This factor is what leads to the enhancement of load-carrying capacity.

Overall, the calculation approach for reinforced concrete components strengthened with carbon fiber wraps should incorporate the triaxial stress condition. However, these calculation methods are quite intricate and challenging to apply in engineering assessments. Consequently, one of the most practical approaches for engineering calculations is to utilize the modified strength properties of concrete, considering the impact of the gripping effect during reinforcement with wraps, as outlined in the construction standards. For this, of course, sufficient tests should be conducted and methods of determination of transformed characteristics should be developed. Test images are shown in the images below. Tensile tests of three armature bars were also conducted in the testing laboratory.

Figure 2. Testing moment of a double carbon fiber clad element

Figure 3. Visual analysis of the post-disintegration condition of a triple carbon fiber-clad element

4. THEORETICAL STUDY OF LOAD-CARRYING CAPACITY OF CARBON FIBER-FORCED ANNULAR CROSS-SECTION MEMBERS

In [14], the authors formulated an effective approach for calculating reinforced concrete elements with annular cross-sections under compression. This methodology does not consider the behavior of concrete in tension, and the performance in compression is represented by the fractional rational function outlined in Eurocode [3, 4].

By assuming that the reinforcement bars exhibit identical tensile and compressive resistance, and using a bilinear model with a defined yield zone for these bars, the problem presented in [14] was reduced to solving the following system of nonlinear equations.

$$2R^2 \times R_b \times N_b^*(\beta,\zeta) + N_s^*(\beta,\zeta) = P$$
$$2R^3 \times R_b \times M_b^*(\beta,\zeta) + M_s^*(\beta,\zeta) = P(e+f) \tag{1}$$

where,

$$f = \rho_* \frac{\beta}{\xi}; \quad \rho_* = \frac{\varepsilon_R \times l_0^2}{\pi \times R^2} \tag{2}$$

$$N_b^*(\beta,\xi) = \begin{cases} Y_{Nb}(\beta,\xi,-1,1) - Y_{Nb}(\beta,\xi,-\gamma,\gamma); \text{if } \xi \geq 2 \\ Y_{Nb}(\beta,\xi,1-\xi,1) - Y_{Nb}(\beta,\xi,-\gamma,\gamma); \text{if } 1+\gamma \leq \xi < 2 \\ Y_{Nb}(\beta,\xi,1-\xi,1) - Y_{Nb}(\beta,\xi,1-\xi,\gamma); \text{if } 1-\gamma \leq \xi < 1+\gamma \\ Y_{Nb}(\beta,\xi,1-\xi,1); \text{ if } 0 < \xi < 1-\gamma \end{cases} \tag{3}$$

where, $Y_{Nb}(\beta,\xi,a) = \int_a^b f(\beta,\xi,\overline{z}) \times \sqrt{a^2 - \overline{z}^2} \times d\overline{z}$

Let's theoretically calculate reinforced concrete elements based on the methodology developed in [14]. Three cubes were prepared and tested after 28 days to assess the cubic compressive strength of the concrete used, based on laboratory evaluations carried out at the Evrascon testing center. As a result of these tests;

$$R = \frac{37.5 + 37.0 + 36.9}{3} = 37.13 \text{ kN/mm}^2 = 37.13 \text{ MPa}$$

Was obtained for the average value of cubic strength of $B\,25$. If we accept 70% of its cubic strength for the prismatic strength of concrete in compression, we get. $R_{bn} = 25.99$ MPa. The calculated resistance is $R_b = \frac{R_{bn}}{\gamma_b} = \frac{25.99}{1.3} = 19.99$ MPa considering the reliability factor. The calculation results are presented in the table below.

As can be seen from the table, as a result of the calculations, the limit value $P = 223.78$ kN was obtained for the considered shaft, which is $\frac{254.33 - 223.78}{254.33} \times 100\% = 12.01\%$ less than the average value obtained in these experiments. This once again shows that the developed numerical calculation methodology allows obtaining results that agree with the results of experiments with engineering accuracy.

To compare the results obtained from the compression of annular elements reinforced with fibers using an analytical approach, we will again apply the methodology proposed in [14] for determining the stress and deformation state as well as the load-carrying capacity of reinforced concrete elements, along with the software module that supports this methodology. We will adapt the calculation of reinforced elements to fit the context of reinforced concrete elements.

To achieve this, we will define a reinforced concrete element that is equivalent to an element enhanced by adjusting the compressive strength and modulus of elasticity of concrete operating under the influence of the grip effect. For this purpose, let's show the strength in compression and modulus of elasticity of concrete for the reinforced element in the form of $R_{b,red} = \lambda \times R_b$ and $E_{b,red} = \lambda \times E_b$, and we determine the value of the entered dimensionless parameter λ on the condition that the load-carrying capacity of the forced element is equal to the load-carrying capacity of the forced concrete member in the reduced values of the concrete strength limit and the modulus of elasticity.

Using the aforementioned software module, the outcomes of the calculations for various values of the λ parameter are presented in Table 2. It can be seen from the table that the results obtained when the parameters of concrete are increased by about three times during single reinforcement are about $\frac{490.33 - 476.90}{490.33} \times 100\% = 2.74\%$ smaller than the results of the experiment, and the results of experiments and calculations are about $\frac{882.60 - 862.52}{882.60} \times 100\% = 2.28\%$ when the parameters of concrete are increased by six times

Specific expressions of functions $N_b^*(\beta,\zeta), N_s^*(\beta,\zeta)$, $M_b^*(\beta,\zeta)$, $M_s^*(\beta,\zeta)$ are given in [14]. For example, the internal normal force formed from compressive stresses in concrete depending on the position of the neutral axis [14].

Figure 4. Condition of the tested elements after disintegration

in the double reinforced element. And finally, when increasing the parameters of concrete in a triple reinforced element by about seven times, the results of calculations are obtained about $\frac{1008.12-991.28}{1008.12}\times 100\% = 1.67\%$ smaller than the results of the experiment.

This indicates that in the future, with an increase in the number of experiments, the calculation method for reinforced concrete elements enhanced with carbon fibers could be simplified to the calculation method for reinforced concrete elements by incorporating adjusted parameters for concrete.

Table 1. Parameters characterizing the stress deformation state of the reinforced concrete element

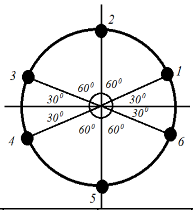
β	f, mm	P, kN	Stresses in armature bars, σ_j, MPa 					
			σ_1	σ_2	σ_3	σ_4	σ_5	σ_6
0.1	0.06	37.05	30.96	36.58	30.96	19.72	14.19	19.72
0.2	0.13	67.78	61.22	72.89	61.22	37.86	26.19	37.86
0.3	0.20	93.61	90.85	108.97	90.85	54.61	36.50	54.61
0.4	0.27	115.54	119.94	144.84	119.94	70.13	45.22	70.13
0.5	0.35	134.45	148.53	180.52	148.53	84.54	52.54	84.54
0.6	0.42	150.59	176.68	216.04	176.68	97.97	58.61	97.97
0.7	0.51	164.71	204.45	251.41	204.45	110.52	63.55	110.52
0.8	0.59	177.06	231.86	286.65	231.86	122.28	67.49	122.28
0.9	0.68	187.90	258.96	321.77	258.96	133.35	70.54	133.35
1.0	0.77	197.46	285.79	356.79	285.79	143.79	72.80	143.79
1.1	0.86	205.91	312.37	391.71	312.37	153.69	74.35	153.69
1.2	0.95	213.41	338.73	426.55	338.73	163.09	75.27	163.09
1.3	1.05	217.60	36.93	4.5	363.93	169.90	72.88	169.90
1.4	1.15	220.33	388.67	435	388.67	175.67	69.17	175.67
1.5	1.25	222.50	413.30	435	413.30	181.19	65.13	181.19
1.6	1.36	223.78	435	435	435	186.18	60.42	186.18
1.7	1.47	221.87	435	435	435	189.55	53.64	189.55

Table 2. Reducing carbon fiber-reinforced elements to a reinforced concrete element

Element reinforced with monolayer carbon fibers		Element reinforced with double carbon fibers		Element reinforced with triple carbon fibers	
Load-carrying capacity according to the test result $P_{eks} = 490.33$ kN		Load-carrying capacity according to the test result $P_{eks} = 882.60$ kN		Load-carrying capacity according to the test result $P_{eks} = 1008.12$ kN	
λ	P_{ult}, kN	λ	P_{ult}, kN	λ	P_{ult}, kN
2.5	413.03	4.5	669.41	7.0	991.28
2.7	438.57	5.0	733.78	7.1	1004.15
3.0	476.90	5.5	798.14	7.2	1017.02
3.1	489.67	5.7	823.89	7.5	1055.65
3.2	502.45	6.0	862.52	8.0	1120.04

The conducted experiments also showed that there is an optimal number of layers of carbon fibers for each element. For example, if we took single-layer reinforcement as the basis, the load-carrying capacity ratio for the tested elements was $1:1,8:2,06$ depending on the number of layers.

Based on the experimental results, the possible applications of the high load-carrying capacity of concrete elements reinforced with carbon fibers in high-stress environments, such as infrastructure objects exposed to seismic loads, were investigated. For example, when carbon fibers are applied to the outer surface of ring-section concrete structures, these structures are shown to be more resistant to local pressures and dynamic loads. Additional experimental analyses confirmed the potential impact of this strengthening technology in underground traffic tunnels, bridge abutments, and building structures in seismically active regions. These practical examples highlight the wide application potential of carbon fiber reinforcement in the field of engineering by providing high stress resistance and long-term strength.

5. CONCLUSIONS

Through experimental studies, the effectiveness of utilizing the nonlinear deformation model for calculating compressed reinforced concrete elements with annular cross-sections has been demonstrated. Based on laboratory tests, the load-carrying capacity of the reinforced concrete element can be significantly enhanced by wrapping the outer surface of these annular cross-section elements.

The increase in load-carrying capacity varies with the number of wrapping layers, and the experimental results indicate that double wrapping is the most effective approach for the tested elements. This study demonstrates a significant increase in the load-carrying capacity of carbon fiber-reinforced ring-section reinforced concrete structures, revealing the wide application potential of this technology in the field of engineering. The use of different composite materials in this strengthening technology, as well as the evaluation of the durability of concrete under different environmental conditions (high humidity, saline environment, and temperature changes), are suggested as future research directions. Such research will further strengthen the scientific basis for the wider application of carbon fiber reinforced concrete in engineering practice. The results of this study can have a significant impact on the development of future construction technologies, making important contributions to the creation of long-lasting and stable structures under seismic effects and heavy loads.

NOMENCLATURES

Symbols / Parameters

R : outer diameter of the cross section of the element,

R_b : compressive strength of concrete

ε_b : deformation of concrete on the compressive face of the most stressed section

ε_R : deformation corresponding to the maximum of the "stress-strain" diagram of concrete in compression

$\beta = \frac{\varepsilon_b}{\varepsilon_R}$: the level of deformation on the compressive face of the most stressed section

ε_R : the height of the compressive zone of the section at the most stressed section

l_0 : the effective length of the compressed element

P : the force compressing the element

e : eccentricity of compressive force

f : deflection of the most stressed section

ρ_* : dimensionless coefficient

$2R^2 \times R_b \times N_b^*(\beta,\zeta)$: the internal normal force formed by compressive stress in concrete at the most stressed section

$2R^3 \times R_b \times M_b^*(\beta,\zeta)$: the internal bending moment formed by the compressive stress in the concrete at the most stressed section

$N_s^*(\beta,\zeta)$: the internal normal force formed from stresses in the reinforcement bars in the most stressed section

$M_s^*(\beta,\zeta)$: the internal bending moment formed from the stresses in reinforcement bars in the most stressed section

γ : the ratio of the outer radius of the cross-section of the element to the inner radius

σ_j : the tension in the j armature bars

λ : reducing coefficient

$R_{b,red}$: compressive strength of concrete

$E_{b,red}$: reducing strength of concrete in compression

R_{bn} : normative strength of concrete

γ_b : working condition coefficient of concrete

P_{eks} : load-bearing capacity of the element obtained from the experiment

P_{ult} : load-bearing capacity of the element determined as a result of calculations

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