ISSN 1846-6168
UDK 691.328.001.2

METODOLOGIJA ISPITIVANJA I OSNOVNE ZNAČAJKE PRORAČUNA OŠTEĆENIH TLAČNO OPTEREĆENIH ARMIRANO BETONSKIH STUPOVA

METHODOLOGY OF STUDY AND BASIC CHARACTERISTICS FOR CALCULATION OF COMPRESSED DAMAGED CONCRETE COLUMNS

Yevgeniy Klimenko, Krutko Tatjana, Orešković Matija, Soldo Božo

Prethodno priopćenje

Sažetak: *Aktualni propisi za armiranobetonske konstrukcije koji se koriste u Ukrajini i zemljama EU sadrže određena pravila za proračun ab konstrukcija. Pravila i poglavlja za proračun čvrstoće presjeka bazirana su na dimenzijama najkritičnijeg presjeka elementa. Veličine tamo korištene unificirane su i naširoko prihvaćene. Propisi su većinom, rađeni za elemente punog, gotovog poprečnog presjeka. Postavlja se pitanje provođenja proračuna na elementima oštećenog presjeka, odabira veličina i parametara. U tu svrhu provedena su istraživanja ponašanja armiranobetonskih stupova s "ugrađenim" oštećenjima, pod tlačnim opterećenjem do stanja sloma, te su analizirani najkritičniji presjeci. Izvedeni su preduvjeti za proračun sustava jednadžbi za pronalaženje nepoznatih veličina koje nisu razmatrane u postojećim normativnim dokumentima i propisima.*

Ključne riječi: *ab stup, oštećenje, slom, nosivosti, pravokutni poprečni presjek, kružni poprečni presjek*

Preliminary notes

Abstract: *Current regulations for reinforced concrete structures that are used in countries of EU and Ukraine contain specific rules for the calculation of RC structures. Rules and chapters for strength of cross-section calculation are based on dimensions of the most critical cross-section of the element. Values used there are unified and widely accepted. Regulations are mostly made for the elements of a full, finished cross-section. The question of implementation of calculation on elements with damaged cross-section arises, as well as the selection of values and parameters. For this purpose, research to study the behaviour of reinforced concrete columns with "built-in" damage under compressive load to a state of collapse with the most critical cross-sections being analysed were carried out. The preconditions for calculation systems of equations for finding the unknown parameters that have not been considered in the existing normative documents and regulations are proposed.*

Key words: *rc column, damage, collapse, bearing capacity, rectangular cross section, circular cross section*

1. INTRODUCTION, THE RELEVANCE OF THE WORK

Reinforced concrete is widely used and is perspective construction material for construction of buildings and constructions. In the process of exploitation of construction there is awareness of structure and their elements. To avoid its extremely negative consequences, it is necessary to conduct periodic monitoring of building condition in general (whole construction) and separate designs in particular.

Current regulations [1-2] do not give comprehensive answers regarding some problems in reconstruction. Therefore, the actual problem remains – determination of residual bearing ability of the damaged bearing elements.

The authors examined a specific case of damage – local damage in a part of a section. In such a case, the characteristic of that kind of damaged elements appears when there is damage in plane compressed structures and therefore, an oblique eccentric compression appears, i.e. the case where the force plane does not coincide with any of the main axis of the damaged section. Stress-strain state and bearing capacity of exposed longitudinal compression reinforcement bars also has its own characteristics and they are not included in the existing norms in Ukraine.

2. INVESTIGATED SAMPLES

The research included columns of different sections, rectangular and circular. On the basis of international collaboration, rectangular columns were manufactured and tested in Odessa, Ukraine, by all government regulations and standards, while the circular columns were manufactured and tested in Varaždin, Croatia, unifying the Ukrainian and European standards.

In the Odessa State Academy of Construction and Architecture for the solution of this problem 17 columns of rectangular cross-section with damages were made, and at the same time at University North (Varaždin, Croatia) 15 columns with damages were made.

RC samples have the following geometrical characteristics: the rectangular ones with section size – 200x250 mm; circular ones with section diameter – 300 mm, column height – 1000 mm. Rectangular columns were made of concrete class C15 and reinforced with longitudinal reinforcement 4ϕ16 while the circular ones were made of concrete C25/30, reinforced with 6ϕ12. The difference in concrete class is a result of a different concrete placing technology that is implemented in these countries.

Artificial damage is located in the middle third of element (Fig. 1). Damage depth, angle of a damage and relative force eccentricity varied. Position of the stirrups and their refinement at the column ends as well as the design of damaged part can be seen in Figure 1 ((a) for rectangular sample and (b) for the circular one).

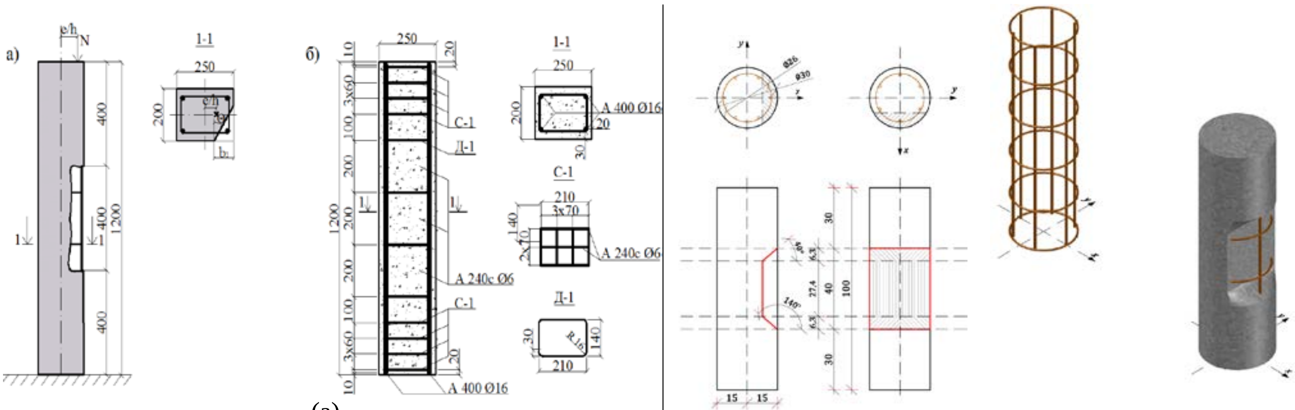

Figure 1 Scheme of column models (samples) with internal reinforcements and designed damage
(a) Rectangular column (Odessa, Ukraine)
(b) Circular column (Varaždin, Croatia)

3. IMPLEMENTATION OF THE EXPERIMENTS

Experiments were conducted on various types of hydraulic presses. Rectangular columns were tested at the press with capacity of 500 t (Figure 2) while the circular ones were tested at the press with capacity of 300 t (Figure 3). Measuring instruments (strain gauges) are glued on each reinforcement bar and along the perimeter of a sample, directly on concrete. All strain gauges were installed in the middle column (the critical section). Three-factor plan was chosen for the experiment, according to which the samples were prepared (Table 1). The force was applied gradually (0.1 F_{max}) while retaining a few minutes at every level of application.

Figure 2 Implementation of experiment on models of rectangular cross section, with oblique damage.

By reviewing and analysing the results, it can be concluded that the capacity of RC elements mostly depends on the eccentricity of applied force. The depth of the damage certainly reduces the element bearing capacity but it is considerably reduced with combination of damage and eccentricity.

Figure 3 Implementation of experiment on model of circular cross section, with oblique damage, model with damaged depth R (radius)

Looking at the rectangular samples, if we compare the case of central load on the sample without damage with the one with highest degree of damage, then the bearing capacity of the damaged model is 0,38$N_{nodamage}$. By moving the applied force to the edge of the element bearing capacity is reduced to 0,19$N_{nodamage}$. By observing same case with elements of circular cross section, in the first case, the ratio is 0,30$N_{nodamage}$, and at the force applied on the edge of a model, it is reduced to 0,25$N_{nodamage}$.

4. BASIC PRECONDITIONS FOR CALCULATION

In the research process, the basic parameters of the stress-strain state were established, which enabled the formulation of the basic premise for calculating the residual load-bearing capacity of elements:

1) The plane sections hypothesis is taken, i.e. after deformation sections remain plane, deformation through the section height changes according to linear dependence.
2) Stresses in the compressed zone are evenly distributed with intensity ηf_{cd}.
3) Concrete capacity in the tensile zone is not taken into account.
4) Tensile stresses in the reinforcement not higher than the calculated tensile strength f_t.
5) Compressive stresses in the reinforcement not higher than the calculated resistance to the compression f_{yd}
6) Damage front has a rectilinear shape
7) Stresses in the reinforcement are determined depending on the relative height of the compressed zone of concrete.
8) Exposures of reinforcing bars is taken into account.
9) A parallelism condition of force planes: point of application of external force (A), resultant force of compressive stresses in the concrete and reinforcement (B) and the point of application of the resultant forces in the tensile reinforcement (C) must lay on a straight line (Figure 4).

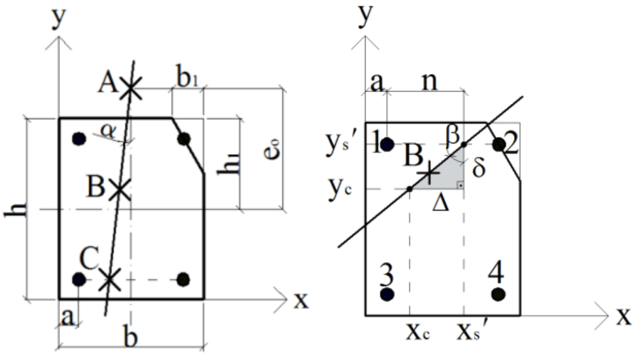

Figure 4 Justification of the precondition 9.

To solve the problem, namely the determination of residual load-bearing capacity of compressed concrete structures damaged during the exploitation, there are five unknown values that we find from five equations:

1. The equilibrium equation regarding the x axis:

$$N - f_{cd} + \sum \sigma_{1-4} \cdot A_{1-4} = 0; \qquad (1)$$

2. The equation of the sum of the moments concerning an axis x:

$$N \cdot e - f_{cd} \cdot A_c \cdot x_c - \sigma_{1-2} \cdot A_{1-2} \cdot h_0 + \sigma_{3-4} \cdot A_{3-4} \cdot a = 0; \qquad (2)$$

3. The equation of the sum of the moments concerning an axis y:

$$N \cdot \frac{b}{2} - \sigma_1 \cdot A_1 \cdot a - \sigma_2 \cdot A_2 \cdot (b-a) + \sigma_3 \cdot A_3 \cdot a + \sigma_4 \cdot A_4 \cdot (b-a) - f_{cd} \cdot A_c \cdot y_c = 0; \qquad (3)$$

4. Static moment relative to compressed area of concrete, the *x* axis (Fig.5(a)):

$$S_{x1} = A_1 y_1 - A_2 y_2; \qquad (4)$$

5. Static moment relative to compressed area of concrete, the *y* axis (Fig.5(b)):

$$S_{y1} = A_1 x_1 - A_2 x_2; \qquad (5)$$

In equations (2-3) stresses in rebars are defined by the expression:

$$\sigma_{si} = \frac{\sigma_{sc,u}}{1 - \frac{\omega}{1,1}} \left(\frac{\omega}{\xi_i} - 1 \right); \qquad (6)$$

where: $\xi_i = \frac{x}{h_{oi}}$, (7)

h_{oi} – distance from the axis passing through the centroid of the observed *i* reinforcing bar and parallel to the line restricting the compression zone, to the most remote point of the compressed zone of the section. We can determine values of h_{oi} from the geometry of the cross section.

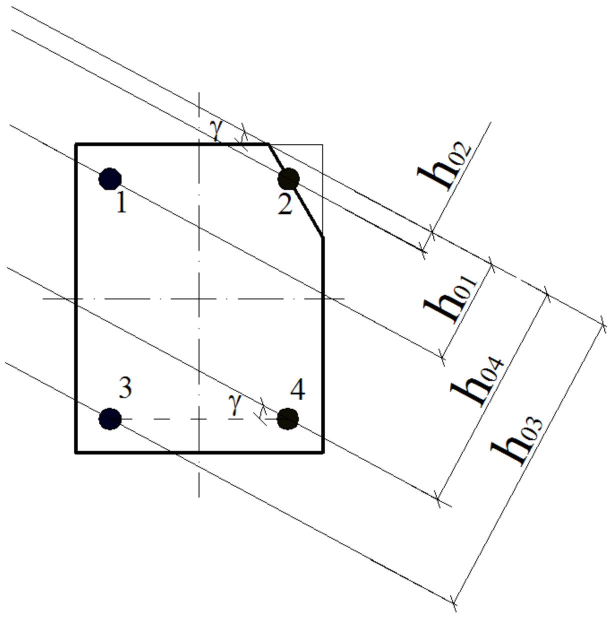

Figure 5 The geometrical position of values h_{oi}.

We find the static moments (4-5), by dividing the section into simple shapes.

When calculating the model of circular cross section we also follow the same calculation concept, only now with altered basic parameters and taking into account the different geometry of the element and the corresponding primary values (Fig. 5).

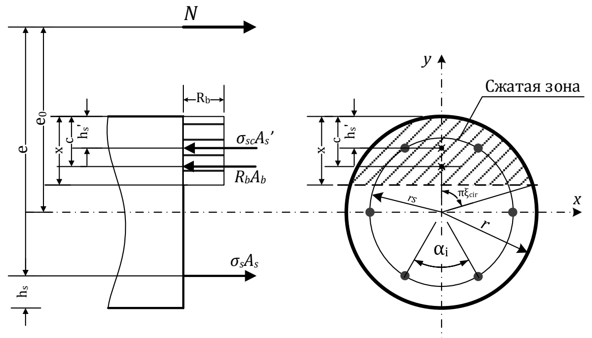

Figure 6 The scheme for the calculation of eccentrically loaded circular cross-section

Calculation of section according to Figure 6, with minimal reinforcement distributed evenly around the circle and including at least 6 bars of longitudinal reinforcement is performed by fulfilling the conditions:

$$M \leq \frac{2}{3} R_b A r_m \frac{\sin^3 \pi\xi_{sir}}{\pi} + R_s A_{s,tot} \left(\frac{\sin \pi\xi_{sir}}{\pi} + \phi \right) r_s, \tag{8}$$

ξ_{cir} - relative area of the compressed zone, defined by solving the equation:

$$\xi_{cir} = \frac{N + R_s A_{s,tot} + R_b A \dfrac{\sin 2\pi\xi_{sir}}{2\pi}}{R_b A + 2{,}55 R_s A_{s,tot}}; \tag{9}$$

Taking into account the part of the section that is defined the angle $\pi\xi_{cir}$, we can introduce an

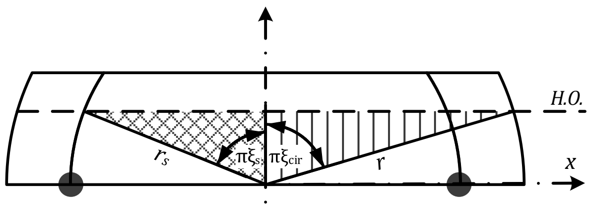

Figure 7 Incised section part with indicated radiuses and angles

analogue value ξ_s, which defines a circle drawn through the centroids of longitudinal reinforcement A_{stot}, that can be expressed using the equation:

$$r_s cos\pi\xi_s = rcos\pi\xi_{cir} \tag{10}$$

Solution is as follows:

$$\xi_s = \frac{arccos\left(\frac{r}{r_s} \cdot cos\pi\xi_{cir}\right)}{\pi} \tag{11}$$

This result in relative value of ξ_s defines the compressive part of reinforcement in the cross-section which does not coincide with the value of ξ_{cir}.

Conditions will prove more complicated in the case of eccentricity and damage, because analogously to rectangular cross-section, as so with circular ones, there is inclination of neutral axis so the compressive zone is at an angle γ. Likewise, stresses in the individual reinforcement bars are parallel to the angle of inclination of the pressure zone so it is necessary to find their distances from the furthest compressive edge of rc element (Fig 8).

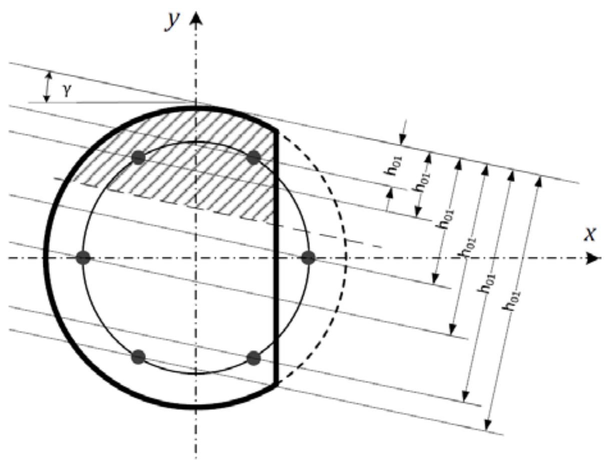

Figure 8 h_{0n} Distance from the compressive edge of element to the centroid of each reinforcement bar.

Further element calculation will be carried out according to (1…5) by adjusting all the parameters and conditions of equilibrium to the geometry of the circular cross-section.

The system of equations (1-5) can be solved by Newton's method (the method of successive iterations). Thus, we obtain the value of the five unknown values. By knowing the height of the compressed zone of *x*, we find the value of stresses, existing in reinforcement bars by (6). If the stress greater than the limiting $\sigma_{si} \leq f_{yd}$, then we take $\sigma_{si}=f_{yd}$, and recalculate with this correction. It is also necessary to take into account that the values of *N*, *x*, δ are positive values and cannot be less than zero, therefore from the obtained we must choose the appropriate one.

The value of residual bearing capacity for the elements of rectangular cross section obtained by the above method is shown in Table 2. Calculation method is quite accurate and can be used to calculate the damaged compressed elements with error about 10,66%.

Table 2. Bearing capacity of the samples

№	Marking of the sample	N_{exp}, T	N_{theory}, T	N_{theory} / N_{exp}
1	-1-1-1	65.20	65.10	0.9984
2	-1-1 1	14.00	17.10	1.2214
3	-1 1-1	30. 0	29.56	0.9853
4	1-1-1	81.10	82.00	1.0110
5	-1 1 1	7.90	8.07	1.0215
6	1-1 1	14.5	10.68	0.7365
7	1 1-1	55.2	50.58	0.9163
8	1 1 1	12.3	13.82	1.1235
9	1 0 0	23.3	21.81	0.9360
10	-1 0 0	15.1	14.40	0.9536
11	0 1 0	21.3	20.47	0.9610
12	0-1 0	31.35	29.77	0.9496
13	0 0 1	12.67	10.82	0.8539
14	0 0-1	60.9	61.54	1.0105
15	0 0 0	22.8	23.50	1.0307
16	0 0 0	23.1	23.50	1.0173
17	0 0 0	21.9	23.50	1.0730

5. CONCLUSION

The article describes the concept and methodology of testing and examination of reinforced concrete columns of two most common cross-sections for the purpose of analysing their residual capacity. The columns are modelled with damages that are most commonly encountered in exploitation of structures and buildings. The examination demonstrated a significant reduction of element bearing capacity and a dependence of the residual capacity with three different factors, mostly with eccentricity of applied force, has been confirmed. A similarity was determined depending on the given parameters (depth of damage, angle of applied force and its eccentricity) in both examinations.

The basic parameters of the stress - strain state are obtained by calculation that enabled to formulate the basic premise for calculating the residual load-bearing capacity of elements, set of equations for determing the bearing capacity of the damaged element. Thus, it is possible to extend the existing standards [1] to the case where part of the cross section of the compressed element is damaged.

With further analysis it is necessary to determine basic parameters for the calculation of damaged rc elements with circular cross-section. The basic elements of calculation will be the equilibrium equations as with rectangular cross section, but the difference certainly occurs due to the cross-sectional geometry and different types of damage.

6. REFERENCES

[1] Бетонні та залізобетонні конструкції (II-а ред): ДБН В.2.6.-2009. – [Чинний від 2011-06-01]. – К.: МІНРЕГІОНБУД України, 2009. – 101 с. (Державні будівельні норми України).

[2] Eurocode 2: Design of concrete structures - Part 1: General rules and rules for buildings, European Committee for Standardization, 2001.

[3] Пособие по проектированию бетонных и железобетонных конструкций из тяжелых и легких бетонов без предварительного напряжения арматуры (к СНиП 2.03.01-84), М.: Госстрой СССР, 1986. – 194с.

Author’s contact:

The Odessa State Academy of Building and Architecture
Ukraine, Odessa, Didrihsona 4 str., 65029

Yevgeniy Klimenko, doctor of technical sciences, professor
klimenkoev@mail.ru

Krutko Tatjana, postgraduate
krutko-tatjana@mail.ru

Orešković Matija, postgraduate
matias.oreskovich@mail.ru

Soldo Božo doctor of technical sciences, professor
bsoldo@gmail.com