Energy-efficiency increase of reinforced concrete columns with recessed working fittings

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Abstract. One of the most important ways of increasing the energy-efficiency of the construction industry is the reduction of the material capacity of structures and labour intensity of their manufacturing. Since manufacturing of reinforced concrete structures requires considerable financial and energy expenses, then reduction of technological cycle operations is sure to be the urgent task today. It is well known, that in the recessed reinforced concrete elements the transverse reinforcement is fixed for the purpose of ensuring the longitudinal rods fixity. Besides, the thickness of the protective layer, as a rule, is taken the minimum. The authors proposed to increase the protective layer, and that will reduce the amount of transverse reinforcement rods significantly and will make the technological process of structures manufacturing easier.

1. Experimental section

We carried out the research of reinforced concrete columns without the transverse reinforcement to get experimental data about load bearing capacity, crack resistance and deformation of the following structures.

24 experimental samples were made and tested. The main factors, which influenced on the work of the elements under load, were: thickness of the concrete protective layer α=3 cm, 5 cm and 7 cm; percent of elements reinforcement μ=1.69% (4Ø22 A500) and μ=2.74% (4Ø28 A500); relative eccentricity of external force – e₀/h = 0 – central compression, e₀/h = 0.15 – off-center compression with the application of compressive force at the border of element’s core of the section.

The columns were of the square section with 300 mm high and wide. The length of the element is 1800 mm.

The experimental samples-columns were reinforced with rods, A500 grade, diameter 22 mm and 28 mm. For transverse reinforcement for traditional structures the fittings were used of Bp-500 grade, diameter 6 mm in the form of welded closed clamps. The whole longitudinal reinforcement in the elements of the traditional structures was situated near the elements edges with the protective layer of 3 cm, besides the transverse reinforcement in the form of closed clamps along the whole length of the column was installed. In other experimental structures (with increased protective layer of concrete) the transverse reinforcement was made in the form of nets from fittings Ø6 Bp500 only at the end section of the element. The longitudinal reinforcement (nets and clamps) was made by means of contact welding.
2. Results section

It is necessary to note, that when tested the samples without the transverse reinforcement, the fragile, explosion-like destruction was observed, then with the elements of the traditional structure.

The results of the conducted experimental research allowed to analyze the influence of different factors on the bearing capacity of compressed reinforced concrete elements.

Increasing the eccentricity of external force, the bearing capacity of all experimental elements reduces. At the same time, the degree of the bearing capacity depends significantly on the percent of reinforcement and the thickness of the protective layer of concrete.

The experiments have shown, that the bearing capacity of reinforced concrete bars with the increased protective layer up to 5 cm and without the transverse reinforcement with the central compression of the columns reduced up to 16.2% (with the fittings 4Ø22 A500) and up to 15% (with the fittings 4Ø28 A500). The columns with increased thickness of the protective layer up to 7 cm and without the transverse reinforcement showed nearly a full alignment of the bearing capacity and the traditional structures. The columns, tested by the eccentricity $e_c/h=0.15$, showed the same results. In the bars with $\mu=1.69$% without the transverse reinforcement and with the thickness of the protective layer 5 cm there was a reduction of the bearing capacity for 11%, but with $\mu=2.74$% the reduction was only 7%. (Table 1)

| Samples code | $N_u$,kN | $\frac{N_u}{N_u(T)}$ | $\varepsilon_{bu} \times 10^5$ | $\varepsilon_{b\alpha} \times 10^5$ | $\frac{\varepsilon_{bu}}{\varepsilon_{b\alpha}}$ | $R_b$,MPa |
|--------------|----------|----------------------|-------------------|-------------------|-------------------|----------|
| C3-22-0      | 3700     | 1                    | 241               | 38                | 0.158             | 32.8     |
| C5-22-0      | 3100     | 0.838                | 153               | 89                | 0.582             | 31.6     |
| C7-22-0      | 3680     | 0.995                | 232               | 56                | 0.241             | 33.4     |
| C3-22-0,15   | 2780     | 1                    | 272               | -                 | -                 | 34.1     |
| C5-22-0,15   | 2500     | 0.899                | 189               | -                 | -                 | 32.2     |
| C7-22-0,15   | 2800     | 1.007                | 267               | -                 | -                 | 31.9     |
| C3-28-0      | 4120     | 1                    | 260               | 34                | 0.131             | 33.4     |
| C5-28-0      | 3500     | 0.850                | 180               | 69                | 0.383             | 30.9     |
| C7-28-0      | 4180     | 1.015                | 255               | 47                | 0.184             | 33.2     |
| C3-28-0,15   | 2900     | 1                    | 284               | -                 | -                 | 32.2     |
| C5-28-0,15   | 2700     | 0.931                | 209               | -                 | -                 | 31.8     |
| C7-28-0,15   | 2900     | 1                    | 284               | -                 | -                 | 33.1     |

So, we can make a conclusion, that by means of increasing the thickness of the protective layer of concrete, the fixity of the longitudinal rods (keeping the bearing capacity) of the compressed reinforced concrete elements can be provided without the transverse reinforcement.

3. Discussion section

The purpose of the following numerical research is to identify the possibility of optimal location of the longitudinal reinforcement of the reinforced concrete column for providing the maximum strength of the column in the conditions of compression. It is necessary to note, that methods of the reinforcement placement over the section cannot solve the matter, that is why, it is proposed to use the Finite Element Method based on the software package Ansys [15-18]. As the optimality criterion, the
obtainment of the largest ultimate load considering non-linear behavior of the material, as well as the fact of cracking, was chosen.

The reinforced concrete column with the height $L$ (Figure 1, a)) of rectangular transverse section $b \times h$ under central applied vertical load $P$ was examined, transferred through the metal plate on the upper and lower edges of the column. The reinforcement in the form of 4 rods with the diameter $d$ was taken as longitudinal along the whole height of the column. The dimension of the reinforcement protective layer $a$ was a variable parameter of the optimization analysis. The physical properties of materials corresponded to the concrete grades of B25 and B30, A400, A500 reinforcement.

For the description of the column structure behavior in the conditions of the longitudinal compression, the spatial finite-elementary model was realized in the software package Ansys. The concrete is introduced in the form of volumetric elements depending on the modeling character of the structure destruction: cracking with crushing or pseudoplastic destruction, but reinforcement of the column was done with 3D rod element in the conditions of tough connection of the concrete and the reinforcement (Figure 1, b)).

![Figure 1](image)

Figure 1. a) Investigated structure, b) The finite-elementary model of the investigated structure.

The study of fixity with using the Finite Element Method was done by means of method Newton-Rafson with the step loading of the structure and with the performance of the equilibrium iteration.

As the fixity criterion, it is necessary to choose that level of loads, at which the decisions of movement and deformation between the iterations begin to grow. To control the changes of the observed characteristic $E$ near the critical effort, the degree approximation was chosen:

$$
\varepsilon^+pl(P) = \alpha + \beta(P_{kr} - P)^\gamma, \quad \gamma > 0
$$

(1)

The constants of approximation, as well as the dimension $P_{kr}$ were defined by means of changing character $E$, from the solution of non-linear equation on the three consecutive steps of the iteration process:

$$
\frac{\Delta \varepsilon^+pl_n}{\Delta \varepsilon^+pl_{n-1}} = \frac{(P_{kr} - P_n)^\gamma - (P_{kr} - P_{n-1})^\gamma}{(P_{kr} - P_{n-1})^\gamma - (P_{kr} - P_{n-2})^\gamma}
$$

(2)
4. Conclusions
As a result of the analysis it was revealed, that for loads nearly critical, near the edge sections of the column, the following condition is realised \(0 \geq \sigma_1 \geq \sigma_2 \geq \sigma_3\), characterizing the tense condition as “compression-compression-compression”, defining the concrete crushing in the edge zones of the columns. In the central part of the column the following condition is done \(\sigma_1 \geq \sigma_2 \geq 0 \geq \sigma_3\). Besides the cracks formation is happened in the planes, perpendicular to the main tensions \(\sigma_1\) and \(\sigma_2\) (vertical cracks).

The main conclusion of the following numerical research of the finite-elementary model of the reinforced concrete column structure at central applied effort compression is the existence of the optimal dimension of the concrete protective layer, making maximum critical effort and leading to the destruction of the column, for special set of geometric and physical parameter of the model.

It should be noted, that increase of the critical load, by means of the optimal location of the reinforcement on the section of the column in comparison with the variant for minimum possible value of the protective layer similar with the reinforcement, diameter 22 mm, is from 30 to 40 %.

Since increasing the height of the column, the optimal value keeps the same at slight changing of the character of the behavior of the critical effort. Since reducing the height of the column, there is a significant increase of the critical load value, the law of its changing according to the parameter \(a\) has a tendency to periodicity.

From the analysis of spatial the Finite Element Method model of the structure at the central compression by means of the behavior character of main tensions \(\sigma_1\) and \(\sigma_2\), in the plane of normal section of the column, undergone the deformation of the distension, there is a conclusion about the dependence of the tension intensity level in the section, developing at the increase of the load, at special location of the reinforcement. As a result, finite-elementary model of flat deformation of normal section of the column \(S_{xz}\) as follows:

\[
S_{xz} : \{x \in [0, b/2], z \in [0, h/2]\}, \quad S_{xz} = S_B \cup S_A,
\]

(3)

On the lines \(x=0, z=0\) the normal stretching distributed efforts on the law \(P(z)\) and \(P(x)\) respectively (figure 2)

On the lines \(x=b/2, z=h/2\) – conditions of symmetry of columns section deformation:

\[
\begin{align*}
  u_x\big|_{x=b/2} &= 0, \\
  u_z\big|_{z=h/2} &= 0
\end{align*}
\]

(4)

Figure 2. Flat deformation of normal column section model.

For the choice of the applied load \(P(x)\) the movements in the middle section of the column of the spatial model at the level of vertical compressed effort 0.7 from the critical one. Closeness of the diagrams of movements distribution on the section in both flat and spatial models allowed to make a conclusion about the possibility of seeing the case of constant efforts \(P(x) = \text{const}\).
Further research of choosing the optimal reinforcement location on the column section was based on the analysis of the tension intensity $\sigma$ in accordance with the value of the concrete protective layer $a$:

$$\sigma_i = \frac{1}{\sqrt{2}} \left( (\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right)^{1/2}$$

(5)

It was defined, that the most sensitive characteristic of changing the reinforcement location is the concentration of the tension on the border between reinforcement and concrete. The analysis of the reinforcement location on the section is possible by using the effective modules of resilience for transversal isotropic material. The effective module of resilience $E_{22}$ has the form:

$$E_{22} = (1 - \delta)E_B + \delta E_A + \frac{4 \delta (1 - \delta) (\nu_A - \nu_B)^2 \mu_B}{(1 - \delta) \mu_A / (k_A + \mu_A / 3) + \delta \mu_B / (k_b + \mu_B / 3) + 1}$$

(6)

$$\nu_{12} = (1 - \delta)\nu_B + \delta \nu_A + \frac{\delta (1 - \delta) (\nu_A - \nu_B) \mu_A / (k_A + \mu_A / 3) - \mu_B (k_b + \mu_B / 3)}{(1 - \delta) \mu_A / (k_A + \mu_A / 3) + \delta \mu_B / (k_b + \mu_B / 3) + 1}$$

(7)

Here $\delta$ - the volume fraction in the structure; $E_{A,B}, \mu_{A,B}, k_{A,B}$, $V_{A,B}$ - modules of resilience and Poisson coefficient of the reinforcement and the concrete.

To take into account the reinforcement location on the section of the column, let us use the mechanism of the repeated averaging. For this, at the first stage, the area of a square configuration, covering the reinforcement in the section and distributing till the edge of the field $S_{xy}$. The reinforcement is situated in the center of the received square. The calculation of the effective modules is done for defining the field. The volume fraction of the reinforcement here can be rather high at minimum $a$. At the second stage, there is a repeated usage of formulae for the section on the whole.

Further research is done on conducting the finite-elementary modeling of the special structure to get transversal isotropic material. In Figure 3, there is a dependence of the optimal value on the chosen criteria of the protective layer $a$, at the changes of the square section sizes of the column $b$.

![Figure 3](image_url)

Figure 3. Dependence of chosen criteria optimal value of the protective layer $a$ by changing the sizes of the square section of the column $b$.

It is seen, beginning with the size of the section $b=0.5$, the location of the optimal $a$ is stabilized in the frames of the specified computational error and is 11 cm.

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