Technical and economic efficiency of reinforced concrete elements with different types of reinforcement

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Abstract. The article presents data on the bearing capacity of columns with various combinations of prestressed and conventional reinforcement. The areas of the most effective use of such structures with different eccentricities and flexibilities are shown. The ecology of reinforcement steel is an important task that the designers of reinforced concrete structures face. The creation of effective constructive solutions, that allow to combine high technical characteristics with economic use of reinforcement steel, has become urgent and is necessary for today's development of the construction industry.
In the works [1,2,3,4,5] it was shown that the solution of these problems was possible by creating conditions for the full employment of building materials properties - reinforcement and concrete.
The working reinforcement is characterized by its application in the conventional and prestretched forms. At the same time, the works done in the recent years show that reinforcement, subjected to precompression, can be used in the compressed zone [6,7,8].
It is most effective in rigid reinforced concrete columns. Thus, precompression of all longitudinal reinforcement or its part allows to increase the strength of non-flexible columns with not high relative eccentricities of the external longitudinal force. At the same time, in order to obtain the greatest effect caused by the precompression of the reinforcement, certain conditions must be observed.

1 Research objectives and tasks

With the same strength of a centrally compressed column with conventional non-prestressed reinforcement and the column with all precompressed reinforcement, the cross-section areas ratio of longitudinal bars in them is

$$\frac{A_{sc}}{A_s} = \frac{R_{sc}}{R_{sc,c} + \sigma_{spc}}, \tag{1}$$

and the relative decrease in steel consumption by precompression of the high-strength reinforcement

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$$\frac{A_s - A_{sc}}{A_s} = 1 - \frac{A_{sc}}{A_s} = 1 - \frac{R_{sc}}{R_{sc,c} + \sigma_{spc}} = \frac{\sigma_{spc} + R_{sc,c} - R_{sc}}{R_{sc,c} + \sigma_{spc}}, \tag{2}$$

where $R_{sc,c}$ and R_{sc} are the design compression resistance of the precompressed and non-stressed reinforcement;

A_s and A_{sc} – the area of conventional and precompressed reinforcement;

σ_{spc} – the prestresses in compressed reinforcement.

Let us determine the degree of reduction in the reinforcement consumption, due to its precompression. Let us form an equation in which the left side represents the strength of the column N_c, containing the precompressed reinforcement, and the right side - the strength of the columns N without the prestress:

$$R_b A + (R_{sc} + \sigma_{spc})\, A_{sc} + R_{sc}\, A_{s1} = \frac{N_c}{N}(R_b A + R_{sc} A_s\,), \tag{3}$$

it follows that

$$\mu_{sc} = R_b\,(\frac{N_c}{N} - 1) + (\frac{N_c}{N}) R_{sc}\mu_s - R_{sc}\mu_{s1}, \tag{4}$$

where μ_{sc} and μ_{s1} – percentage of precompressed and non-stressed reinforcement in columns containing precompressed reinforcement;

μ_s – percentage of column reinforcement without prestressed reinforcement.

If the precompressed reinforcement A_{sc} and the non-stressed reinforcement A_{s1} have the same value R_{sc} , then

$$\mu_{sc} = K_c\,(\mu_{sc} + \mu_{s1}) \text{ and } \mu_{s1} = (1 - K_c)\,(\mu_{sc} + \mu_{s1}), \tag{5}$$

where K_c – the relative content of precompressed reinforcement in the cross-section.

With the same strength of columns with precompressed reinforcement and columns without prestressing, i.e. at N_c=N

$$\mu_{sc} = \frac{R_{sc}}{R_{sc} + \sigma_{spc}}(\mu_{sc} - \mu_{s1}), \tag{6}$$

Using formula (6), it is possible to determine how many times the percentage of columns reinforcement containing precompressed and non-presstressed reinforcement $(\mu_{sc} + \mu_{s1})$ is reduced in comparison with the percentage of reinforcement of the same equally strong columns, but without prestressed reinforcement.

With central compression and flexibility $\lambda_h \le 25$, it is advisable to have precompression of the reinforcement, which makes it possible to increase the bearing capacity by 250%. The prestretch of the reinforcement, in such structures, can give an effect only with the flexibility of $\lambda_h \le 35$, and the combined prestress - at $15 \le \lambda_h \le 25$.

With off-center eccentricity $\frac{e_0}{h} = 0.3$ the area of efficient precompression of the reinforcement is substantially reduced. This is observed only at $\lambda_h \le 20$. The area of rational prestretching of the reinforcement, on the contrary, extends considerably at $\lambda_h \ge 20$ The area of rational combined prestress $10 \le \lambda_h \le 36$ is also extending.

With an increase in the eccentricity of the longitudinal force $\frac{e_0}{h} > 0.3$, the symmetrical precompression of the reinforcement becomes inadvisable, and the efficiency of the columns with prestretched reinforcement and the columns with combined prestress increases. In compressed elements with prestretched reinforcement with great flexibility, it is possible to achieve a double increase in the bearing capacity, and in columns of medium flexibility with combined prestressing - in 1.3 times [9,10,11].

With the given values of columns flexibility λ_h, the relative eccentricity of the longitudinal force $\frac{e_0}{h}$ and other initial data, the main characteristics on which the efficiency of the compressed elements prestressing depends are the following: prestress levels of the reinforcement and the precompression level of concrete $\frac{\sigma_{\text{bp}}}{R_{bp}}$ (depending on the prestretching force of the reinforcement, and in the case of combined prestressing - on the difference in forces in the prestretched and precompressed reinforcements).

The recommended values of these parameters for reinforced concrete columns with symmetrical reinforcement and steady section prestress have been developed. They are determined on the basis of generalization and analysis of numerous experimental data on the influence of the main factors on the load-bearing capacity of reinforced concrete columns [12, 13].

These recommendations are aimed at the most complete and effective use of reserves in prestressed elements, provided that the requirements of the first group of limit states are met. Considering, however, that the requirements of the second group of limit states must also be satisfied simultaneously, the recommended values of the characteristics are given in different ranges, that allow them to be chosen in such a way that the construction would meet all the requirements [12,13,14].

The reinforcement of centrally compressed columns with the flexibility of $\lambda_h < 30$ only by prestretched reinforcement is not effective. However, if in the elements of this flexibility the part of the longitudinal reinforcement is subjected to precompression, then the condition for increasing the strength corresponds to the columns in which $\frac{\sigma_{\text{bp}}}{R_{bp}}$ is not more than 0.1. This condition at $\lambda_h \leq 15$ also corresponds to columns in which $\frac{\sigma_{\text{bp}}}{R_{bp}} \leq 0$, i.e. the concrete is prestretched and the reinforcement is precompressed.

With the flexibility of $\lambda_h = 30...35$, the level values of recommended concrete precompression in the elements with small eccentricities at combined prestressing and with prestretched reinforcement are close, but in the latter values they are limited on both sides, and in the elements with combined prestress they can even be negative.

The columns containing precompressed reinforcement, with flexibility of $\lambda_h = 35$ and any eccentricity of longitudinal force, are not effective, therefore the developed recommendations cover only the elements with flexibility of λ_h up to 35. To increase their load-bearing capacity with greater flexibility of columns, the reinforcement should be subjected to prestretching.

In centrally compressed columns $(\frac{e_0}{h} = 0)$ with flexibility of $\lambda_h \leq 15$, it is advisable to use only the precompressed reinforcement - all or part of it. It should be kept in mind that with the increase of reinforcement precompression, the strength of columns increases. In the same direction, the increase of the values of precompressive stresses in the elements with flexibility $\lambda_h \leq 22$ also influences. The minimum value of $\sigma_{\text{spc}} = 150$ MPa is set based on the fact that, firstly, the total losses of the precompressive stresses are practically zero and, secondly, taking into account that even with this prestress value, the strength of the columns significantly increases (up to 10 ... 20%).

With $\frac{e_0}{h} = 0$ and with the flexibility of the columns $15 \le \lambda_h \le 25$, columns with precompressed reinforcement, as well as with combined prestresses are effective. In this case, the level of concrete precompression is not high, because in the columns of this flexibility its increase leads to a decrease in the relative bearing capacity.

In centrally compressed elements with the flexibility of $\lambda_h \ge 25$, the use of only reinforcement precompression is not practical, it should be used only for a part of the reinforcement with the other part's simultaneous stretching of the longitudinal reinforcement. In this case, it is possible to obtain a positive effect for the column with a flexibility of λ_h up to 35 at a precompression level of concrete less than 0.15.

If the flexibility of the element λ_h is about 35, then in the centrally compressed columns it is advisable to combine the prestressing or only the prestretching of all or part of the longitudinal reinforcement. The level of concrete precompression in these cases should not be more than 0.1 ... 0.15.

With the off-center compression of the columns where the eccentricity is $0.075 < \frac{e_0}{h} \le 0.3$ and flexibility is $\lambda_h \le 20$, the positive effect can be achieved both with precompression of the reinforcement and with combined prestressing. With the same values of eccentricity and flexibility $\lambda_h > 20$, the use of only precompression of the reinforcement does not give an effect, in these cases it should be used either a combined prestressing $20 < \lambda_h \le 35$ or only prestretching of the reinforcement.

With $\frac{e_0}{h} > 0.3$, columns in which the reinforcement is only subjected to precompression are not rational with any of their flexibility. With such eccentricities, a combined prestressing (at $10 < \lambda_h \le 35$) or only a prestretched reinforcement (at $\lambda_h > 20$) should be used.

The level of concrete precompression $\frac{\sigma_{\mathrm{bp}}}{R_{bp}}$, providing an increase in the load-bearing capacity of prestressed columns in comparison with non-stressed, with combined prestressing and with reinforcement of columns only with prestretched steel is different, especially in the case of the off-center compression, which is due to the presence of precompressed reinforcement in the combined prestressing.

2 Conclusions

It should be noted that the performed studies and analysis of physical and numerical experiments results have made it possible to develop recommendations for facilitating the search for optimal solutions in the design of compressed elements. It is shown that each of the possible types of reinforcement and prestressing of columns under certain conditions can provide the greatest increase in bearing capacity in comparison with columns without prestressed reinforcement. Thus, columns having only precompressed reinforcement can be effective with flexibility $\lambda_h \le 25$ and eccentricity $\frac{e_0}{h} \le 0.3$. Columns with combined prestresses are advisable with flexibility λ_h from 10 up to 35 and eccentricity $\frac{e_0}{h}$ from 0 up to 0.7, and columns with only prestretched reinforcement - at $\lambda_h > 30$ and $\frac{e_0}{h} \geq 0$, as well as at $\frac{e_0}{h} > 0.4$ with any flexibility.

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