BUILDING STRUCTURES, BUILDINGS AND CONSTRUCTIONS

UDC 624.016
DOI 10.36622/VSTU.2022.54.2.001

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COMBINED REINFORCED CONCRETE COLUMNS STRENGTHENING WITH STEEL CLIPPING AND CONCRETE SURFACING

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Statement of the problem. The method of strengthening reinforced concrete columns with a steel clipping and the concrete surfacing is investigated. This method allows one to repair the columns with significant defects and damage. The prerequisite for this study was the assumption of strengthening with a steel clipping and the concrete surfacing is an effective way to increase the ultimate limit state of reinforced concrete columns, furthermore, the option of applying the load (only to the concrete core or to the entire section) does not significantly affect the strengthening effectiveness. In this regard, the purpose of the investigation was to identify the need to include the steel jacketing in the work, on the condition the column is coated with concrete along with the entire height.
Results and conclusions. The load transfer method only to the concrete core of the strengthened columns is recognized as rational since the device of the steel clipping head requires the use of complex structural and technological solutions, but at the same time additionally increases the ultimate limit state insignificantly (according to the studies by less than 10 %). Due to the absence of the need to establish structures of the steel jacketing head, the labor intensiveness and terms of work production on strengthening the columns are reduced.

Keywords: columns (structural), reinforced concrete, strengthening (metal), retrofitting, jacketing, compaction, interfaces (materials), load limits, axial loads, strain hardening, stresses.

Introduction. Reinforced concrete columns are structures calling for prioritized attention as a decrease in their performance might to lead to limited or complete failure. Reinforcement of the columns with the device of various clips can considerably increase their load-bearing capacity and restore performance.

Traditionally, reinforced concrete or steel clips are employed. Clips made of various composite materials (carbon fiber, fiberglass, etc.) can also be arranged [11, 16, 21], but such reinforcement methods call for certain conditions and requirements: temperature limitation during operation, protection from ultraviolet rays, and carbon tapes and nets are not allowed to be stuck to the surface with cracks with an opening width of more than 0.2 mm, etc. [5].

In [17], a method for reinforcing reinforced concrete columns with metal meshes is set forth.

Setting up reinforced concrete clips is one of the most basic and reliable design solutions for strengthening reinforced concrete columns. Such clips with a thickness of 60 to 120 mm can be arranged over the entire height of the reinforced column or within the damaged area [22]. However, setting up reinforced concrete cages reinforced with bar reinforcement is laborious and requires developing the solutions ensuring the joint operation of reinforcement with that of the reinforced column.

Reinforcement of columns with a steel cage slightly increases the size of the cross section and enables the column to be used in operational mode immediately following the reinforcement. The effectiveness of strengthening columns with a steel cage has been repeatedly substantiated [9, 13, 14]. E.g., in [6] it was empirically established that as a result of applying this reinforcement method, the load-bearing capacity of a reinforced concrete column increases by at least 20 %. The results are in good agreement with the data provided in [7, 10, 17, 19].

The objective of this study was to identify the need to include the branches of the steel cage in the work on the condition that the column rod is concreted over the entire height. The option of transferring the load only to the reinforced concrete core (directly to the column and concreting) is discussed. This reinforcement option will considerably reduce the labor intensity and the time of work.

1. Influence of accumulated defects on the load-bearing capacity of reinforced columns.

Due to the presence of defects obtained and accumulated during operation, the load-bearing capacity of columns can be considerably reduced, and the technical condition of such columns is evaluated to be inoperable (unsatisfactory).

In [17], two cases of testing reinforced concrete columns reinforced with a steel casing were discussed: in the first one, the samples were not loaded before reinforcement; in the second one, for prototypes in the form of prisms, a preload of 60, 70 and 80 % of the predicted breaking load was created. The test results showed that the presence of preloading before reinforcement — this can be considered as a simulation of the operation of a real structure — causes a decrease in the load-bearing capacity of the reinforced column. Similar data were obtained in [19].

The presence of defects in columns, including cracks, before reinforcement impacts the load-bearing capacity of reinforced concrete columns [7, 18]. The authors of [18] investigated reinforced concrete columns of square, rectangular and round sections, reinforced following the appearance of cracks. A decrease in the load-bearing capacity by 15.7, 14.1 and 13.5 % was observed compared to the samples that did not have cracks at the time of reinforcement. In [7], two options for strengthening samples of reinforced concrete columns of round, rectangular and square cross-section with a steel cage with subsequent concreting are discussed: strengthening immediately following the completion of the hardening process of the sample and strengthening the samples with some defects. In the first case, the load-bearing capacity of the samples went up by 30 % as a result of reinforcement, in the second one (in the pre-sence of defects) — by 20 %. Hence the presence of defects has a considerable effect on the amplification efficiency.

Due to the need to restore the surface of the columns for setting up steel clips, combined clips are used, i.e., steel over concrete. For the construction of concrete clips, fibrous concretes are commonly employed using polymer fibers [10]. Combining a concrete cage (heavyweight concrete, fiber-reinforced concrete or another type of concrete) and a steel casing enables one to take advantage of both types of reinforcement. A steel cage with concrete can be arranged in case of considerable destruction of the concrete of the column and corrosion of the reinforcement.

Combined clips are used mainly due to the fact that setting up steel clips involves preliminary preparation of the surface of the reinforced concrete column, particularly, the restoration of the concrete protective layer for reinforcement of the reinforced structure, which in most cases is severely damaged. Fig. 1 shows the characteristic defects of reinforced concrete columns whose technical condition was found to be inoperative according to the results of the survey, and some recommendations were provided for strengthening by the method of steel casing with concreting.

a) b) c)

Fig. 1. Typical defects of reinforced concrete columns:
a) concrete chips, exposure and corrosion of working reinforcement; b) destruction of the section of the column, corrosion and ruptures of working reinforcement; c) concrete chips on the edges, potholes, shells

The major difficulty in reinforcing the method of a steel cage with concrete is the inclusion of the cage branches in the work. It is obvious that the most effective way of loading is to apply a load over the entire section of the column being reinforced, i.e., simultaneously on the concrete core and the steel reinforcement clip through the head. In [22], various options for reinforcing reinforced concrete columns with a steel casing are discussed and it is empirically proven that a rise in the area of steel elements included in the work and the height of the casing has a positive impact on the load-bearing capacity of the reinforced column. There are diverse methods for including the branches of a steel cage into work: the use of screw or hydraulic jacks [2], tightening the branches of the strut.

However, setting up a head of the reinforcement structure (steel cage) is characterized by considerable labor intensity and complexity of its formation. While using the method of tightening the branches of the spacer to create the required prestressing of the steel cage when it is included in joint work with the reinforced column, the calculated elongation of the branches of the spacer, depending on the length of the column, should be 0.6—1.2 mm. Such a slight elongation is technically challenging to implement in the manufacture and to set up elements in actual production conditions.

2. Experimental studies of the work of concrete samples in the form of prisms reinforced with a steel clip. The purposes of the experimental studies are to establish the influence of the loading method on the load-bearing capacity of experimental concrete prisms reinforced with a steel cage; based on xperimental data, we must substantiate the possibility of using finite element modeling to study the influence of the loading method on the load-bearing capacity of reinforced concrete columns reinforced with a steel casing with concrete.

A total of 16 experimental prisms of square cross section (without reinforcement) with the geometric dimensions of 100 × 100 × 600 mm, reinforced with a steel cage, were tested. The longitudinal elements of the cage consisted of equal-shelf corners No. 20 interconnected by transverse bars measuring 100 × 20 × 4 mm using electric arc welding. Also, 8 experimental control prisms without amplification with geometric dimensions similar to the samples with amplification were tested. The tests were performed in the testing laboratory of the quality department of the GUKDPIP "Institute" Mogilevselstroyproekt".

The designs of experimental and control prisms are shown in Fig. 2.

For the preparation of concrete, Portland cement grade 400 was used, the binder consumption was 290 kg/m^3. Granite crushed stone with a fraction of 5—20 mm was used as a coarse aggregate, and quartz sand with a bulk weight of 1520 kg/m^3 and a grain size modulus of 1.61

was used as a fine aggregate. The draft of the concrete mix cone is 4—6 cm, the water-cement ratio W/C = 0.65. Compaction of the concrete mixture was performed on a vibrating platform.

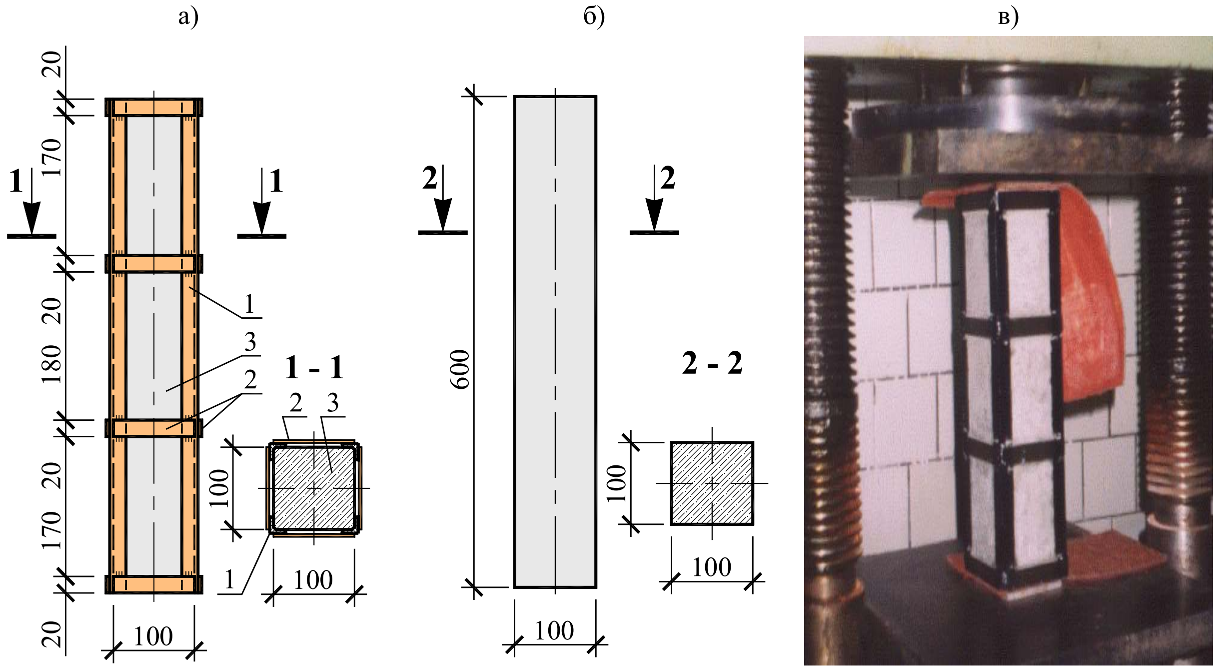

Fig. 2. Testing the experimental and control prisms:
a) experimental prisms reinforced with a steel clip; b) experimental control prisms without amplification;
c) testing a reinforced experimental prism on a hydraulic press;
1 — equal-shelf corner $\llcorner 20 \times 4$; 2 — steel plates of the reinforcement clip (slats); 3 — concrete core

The major characteristics of hardened concrete according to Eurocode 2 (TKP EN 1992-1-1-2009* (02250), EN 1992-1-1:2004) are the following: average compressive strength f_{cm} = 16.85 MPa; the average tensile strength f_{ctm} = 1.2 MPa; the average modulus of elasticity E_{cm} = 28.85 GPa.

The conditions for hardening the concrete mixture are normal: temperature — 18—20 °C, relative humidity — 70—80 %. The tests were performed at the age of 28 days.

The corners and cross plates of the steel cage are made of C245 steel according to GOST 27772-2015 (S235 according to Eurocode 3 (TKP EN 1993-1-1-2009* (02250), EN 1993-1-1:2005, Table 3.1) with mechanical properties (according to the results of the tensile tests): yield strength f_y = 240 MPa; ultimate tensile strength (tensile strength) f_u = 360 MPa; modulus of elasticity E_s = 206 GPa.

The use of steel with a nominal value of the yield strength f_y = 240 MPa for the manufacture of steel clips is substantiated in [15]. Such steel is classified as structural (according to Eurocode 3) and is commonly used for the manufacture of rolled steel profiles for construc-ting clips. A similar steel was used for manufacturing steel clips in the studies [12].

Experimental and control prisms were tested on a hydraulic press. The load on the sample was applied along the physical axis. Loading was performed in steps equalling to approximately 10 % of the predicted breaking load, at a loading rate of 0.2—0.3 MPa per second. At each stage, five-minute exposures were performed.

While loading control prisms, the load was transferred to the entire cross section of the sample. The load on the reinforced experimental prisms was transferred through steel distribution plates in two ways:

- method 1: along the entire cross section of the reinforced prism;
- method 2: only on the concrete core without loading the steel casing.

For experimental concrete prisms reinforced with a steel casing (P-1...P-16), at the start of the loading, the stresses in concrete increased as did the strains and then started decreasing. During the destruction of experimental reinforced samples, stresses in concrete were recorded below the short-term prismatic strength (the falling branch on the deformation diagram). There was a redistribution of forces in the cross section of the experimental reinforced sample from concrete to an elastically working steel reinforcement cage.

The destruction of the experimental prisms (P-1…P-8) during the first loading method (the load was transferred to the samples of columns reinforced with a steel cage over the entire reinforcement section) occurred as a result of crushing of concrete in the middle part of the sample followed by buckling of the longitudinal corners of the reinforcement cage in the area between the crossbars. The deformation of the concrete core of the specimens and the steel reinforcement cage occurred jointly at all the loading stages.

In the second method of loading (the load was transferred to the samples reinforced with a steel cage, only to the concrete core, without loading the steel cage), the destruction of the prototypes (P-9 ... P-16) took place as a result of crushing of concrete in the middle part of the sample followed by deformation in the specified areas of the metal clip of reinforcement.

In the *Lira-Windows* software (a block of non-linear calculations), the operation of experimental prisms was simulated using the above loading methods.

The structure of concrete is heterogeneous. Under the action of force, microcracks commonly occur in concrete at the contact of dense coarse aggregate and cement stone. Microcracks develop with a subsequent rise in the load, merge into macrocracks and divide the concrete structure into blocks, which, moving relative to each other, cause a destruction. Due to the complex process of cracking, finite element modeling of the operation of compressed concrete elements cannot reflect the features of their deformation during loading, however, the results obtained under a breaking load have satisfactory convergence with the experimental data.

The results of testing the prototypes, statistical data processing as well as of numerical simulation for experimental prisms are shown in Table.

The analysis of the obtained results showed that the prototypes reinforced with a steel cage have the highest load-bearing capacity when the load is transferred over the entire section (the first loading method). At the same time, the results obtained indicate a high efficiency of strengthening the experimental prisms with a steel cage, even if the load was not transferred to the longitudinal elements of the cage: an increase in the load-bearing capacity by 63 % was noted compared to unreinforced samples.

According to Eurocode (SN 2.01.01-2019, EN 1990:2002+A1:2005), the correctness of numerical simulation using the finite element method to assess the magnitude of stresses and deformations of experimental prisms was assessed (Fig. 3).

Table

Results of compression tests and numerical simulations for prototypes in the form of prisms

Controlled parameters		Loading method		
		Loading of the reinforced prism samples		Loading of the control prism samples with no reinforcement
		along the entire section (method 1)	on the concrete core (method 2)	
Sample code		П-1…П-8	П-9…П-16	ПК-1…ПК-8
Breaking load, kN (average)		366.1	266.0	163.0
Average quadratic deviation S, kN		2.59	1.77	1.41
Variation coefficient V, %		0.71	0.67	0.87
Student's t-test t_p ($P = 0.95$)		2.37	2.37	2.37
Romanovsky criterion t' ($P = 0.95$)		2.51	2.51	2.51
Relarive error in the results Δ, %		4.74	4.46	3.32
Controlled parameters of the concrete under the breaking load	Strains in the concrete σ_c, MPa	16.2…17.2	15.8…17.1	14.8…16.8
	Relative deformations ε_c	$(82…90) \cdot 10^{-5}$	$(74…82) \cdot 10^{-5}$	$(44…53) \cdot 10^{-5}$
Average values of the parameters for a series of samples	Strains σ_{cm}, MPa	16.7	16.5	15.8
	Relative deformations ε_{cm}	$86.8 \cdot 10^{-5}$	$77.4 \cdot 10^{-5}$	$48.0 \cdot 10^{-5}$
Results of the numerical modelling	Strains in the concrete $\sigma_{c,\,cal}$, MPa	16.6	16.4	15.9
	Relative deformations $\varepsilon_{c,\,cal}$	$87.5 \cdot 10^{-5}$	$76.5 \cdot 10^{-5}$	$50.7 \cdot 10^{-5}$

As in the diagram «$r_e - r_t$» (r_e are experimental data, r_t are calculated results), all the points are located close to the straight line $r_e = b \cdot r_t$, and the slope of the straight line is approximately 45° (arctan $b^{(\sigma c)}$ = arctan1.0011 = 45.03°; arctan $b^{(\sigma c)}$ = arctan0.9916 = 44.76°), while the coefficient of variation for the error vector does not exceed 5 % ($V_\delta^{(\sigma c)} = 0{,}84\ \% < 5\ \%$; $V_\delta^{(\varepsilon c)} = 3{,}55\ \% < 5\ \%$), the coefficient of determination R^2 is not lower than 0.9 ($R^{2\,(\sigma c)} = 0.9261$; $R^{2\,(\varepsilon c)} = 0.9909$), thus the applied finite element model can be considered reliable and sufficiently accurate.

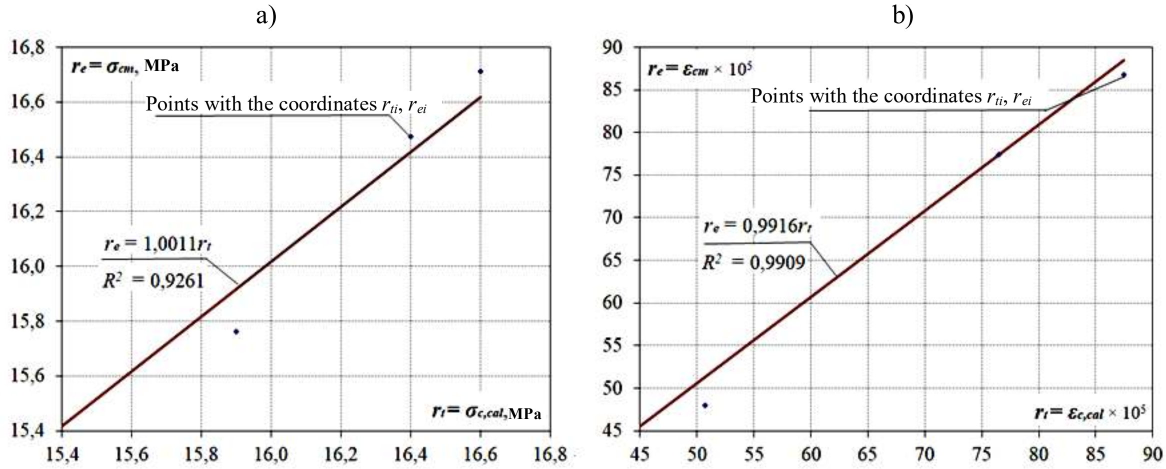

Fig. 3. Diagram «$r_e - r_t$»:
a) for the strains; b) for the relative deformations

The possibility of using finite element modeling of the operation of reinforced concrete columns reinforced with a steel cage is also experimentally substantiated in [6].

3. Simulation of the operation of columns reinforced with a steel casing with concrete. In the technical literature [1–4], there are no data available on the degree of influence of the loa-ding method on the load-bearing capacity of a reinforced concrete column. In the presence of the head of the reinforcement structure, the load on the reinforced concrete column being reinforced can be transferred over the entire cross section of the reinforced column, and in the absence of the head, only on the cross section of the reinforced column and concreting (concrete core).

The premise of theoretical studies was the assumption that the reinforcement of a steel casing with concrete is an effective way to increase the load-bearing capacity of reinforced concrete columns, and the option of applying the load — only to the concrete core or to the entire section — does not considerably impact the effectiveness of the reinforcement.

The problem was solved by means of the finite element method making it possible to consider the design and technological features, the nature of the interaction between the reinforcement elements and the reinforced column, and the redistribution of loads between them. The solution is implemented in PC *Lira-Windows* (a block of non-linear calculations). The problem was solved in a contact formulation considering he elastic-plastic characteristics of the materials. In order to eliminate the need to identify the internal forces in the system transmitted between its elements and create adequate loading, finite element models formed by solid elements were used. For comparing the results, a model of a reinforced concrete column was also designed, reinforced only by concreting. In this case, the cross section of the concreted column is assumed to be of equal strength.

In order to identify the stress state of elements, the theoretical values of equivalent stresses and resulting strains were calculated for the models of reinforced concrete columns with the following characteristics. The geometric dimensions of the reinforced concrete column being reinforced are 400 × 400 mm, height is 3600 mm. The concrete clip is 60 mm thick. The dimensions of the concrete core are 520 × 520 mm. Column concrete characteristics according to Eurocode 2: concrete class — C30/37 (B35 according to SP 63.13330.2018); standard resistance to axial compression f_{ck} = 30 MPa; standard resistance to axial tension f_{ctk} = 2 MPa; design compressive strength f_{cd} = 20 MPa; design tensile strength f_{ctd} = 1.33 MPa; modulus of elasticity of concrete E_{cm} = 33 GPa; transverse strain coefficient (Poisson) ν_c = 0.2; density ρ = 2400 kg/m^3. The column reinforcement characteristics according to Eurocode 2 are the longitudinal reinforcement class — S500, standard resistance f_{yk} = 500 MPa, design resistance f_{yd} = 435 MPa; transverse reinforcement class — S240, design resistance f_{ywd} = 174 MPa; elasticity modulus of reinforcement E_s = 200 GPa. Characteristics of the reinforcement cage steel according to Eurocode 3: f_y = 240 MPa; f_u = 360 MPa; E = 206 GPa. Concreting of the reinforcement structure is designed from concrete similar to the concrete of the reinforced column. The value of the adhesion strength of steel with concrete is 1.4 MPa.

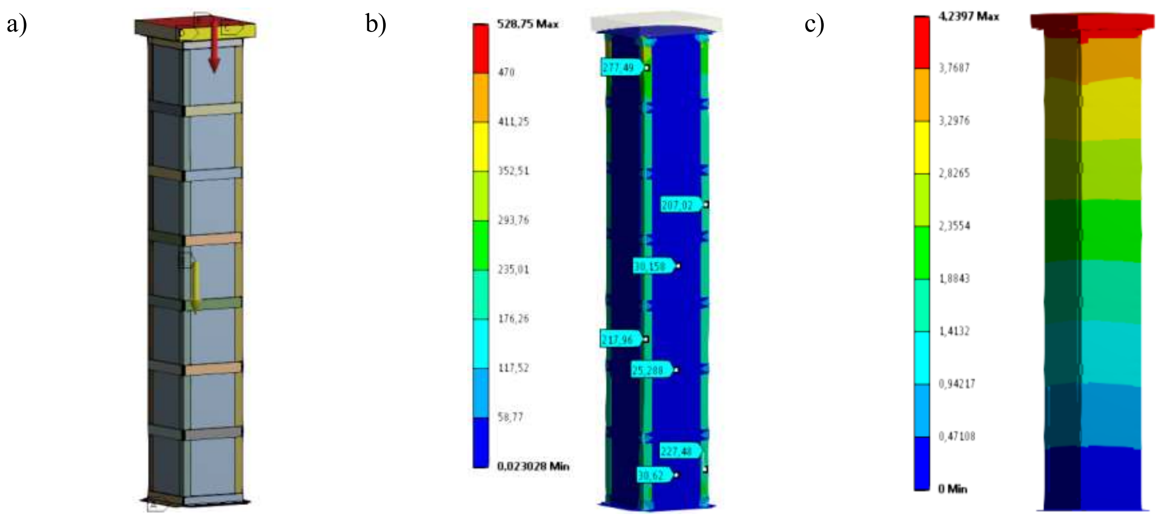

Fig. 4. Loading scheme and distribution of equivalent stresses and resulting strains while loading a column model reinforced with a steel casing with concrete, over the entire section (method 1): a) loading scheme; b) equivalent stresses, MPa; c) resulting deformations, mm

The loading of a model of a reinforced concrete column reinforced with a steel casing with concrete was performed in two ways. Method 1: loading a model of a reinforced concrete column, reinforced with a steel casing with concrete, over the entire section (Fig. 4). Method 2: loading a model of a reinforced concrete column, reinforced with a steel casing with concrete, on a concrete core without loading the steel reinforcement casing (Fig. 5). For comparing the studied data, a model of a reinforced concrete column, reinforced only by concreting, with similar geometric and strength characteristics was also loaded (Fig. 6).

Based on the simulation results (Fig. 4, 5), it can be seen that for columns reinforced with a steel casing with concrete, the largest resulting deformations are noted at the head, the smallest — at the support. From the head to the support along the length of the column, the deformations decrease evenly. At the same time, an abrupt change in the transverse deformations of the concrete core was noted associated with the formation of microcracks and their subsequent merging into macrocracks. The resulting deformations of the steel cage and the concrete core at all the loading stages had comparable values, which confirms the assumption that the steel cage and the concrete core work together (reinforced column and concreting concrete).

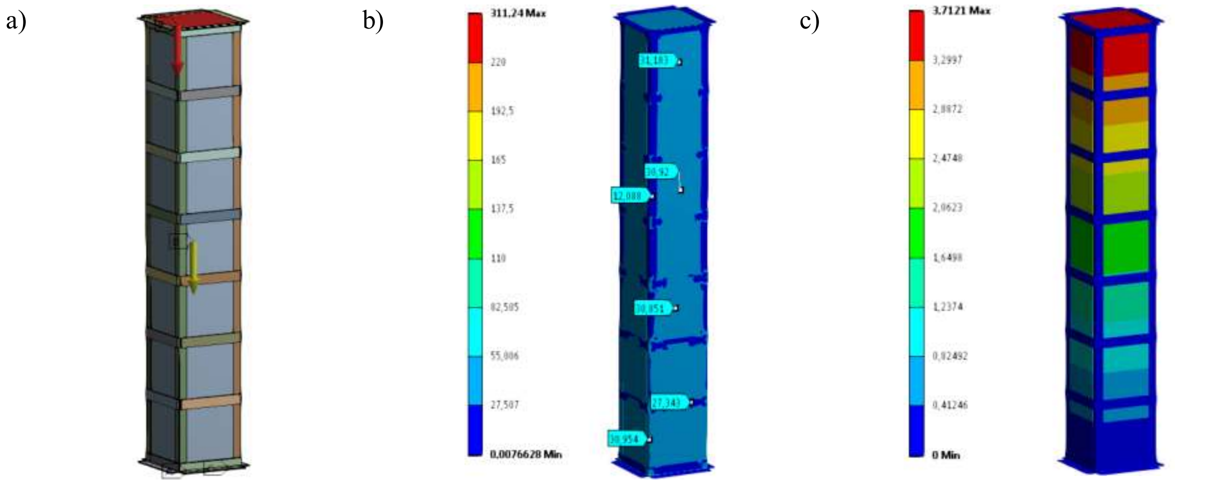

Fig. 5. Loading scheme and distribution of equivalent stresses and resulting strains while loading a model of a column reinforced with a steel casing with concrete, on a concrete core (method 2): a) loading scheme; b) equivalent stresses, MPa; c) resulting deformations, mm

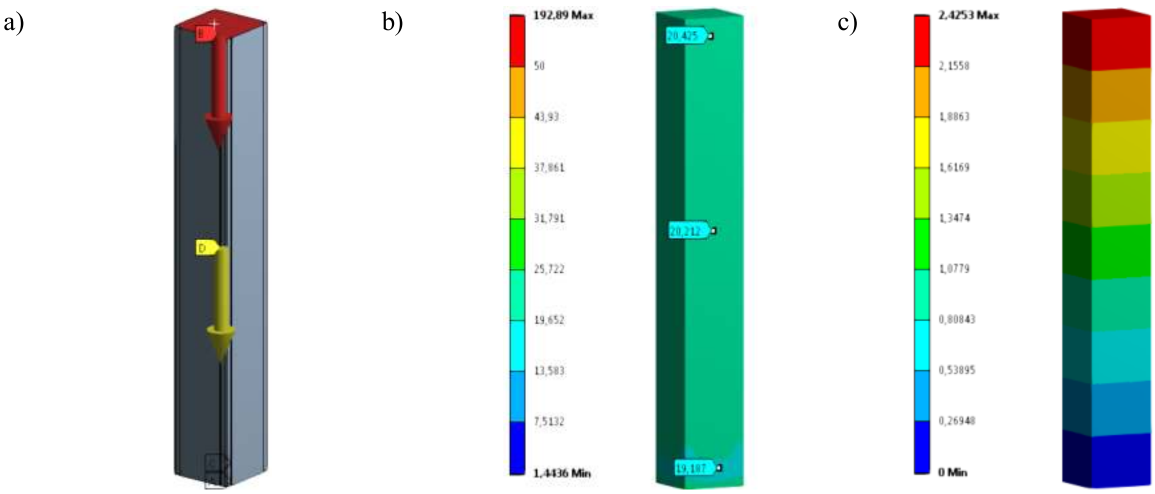

Fig. 6. Loading scheme and distribution of equivalent stresses and resulting strains while loading a column model reinforced only by pouring: a) loading scheme; b) equivalent stresses, MPa; c) resulting deformations, mm

4. Results of modeling the operation of columns reinforced with a steel casing with concrete. Fig. 7 shows the results of modeling the operation of reinforced concrete columns: while reinforced only by concreting, the breaking load is $N_{u,0}$ = 5200 kN; while reinforced with a steel cage with concrete and transferring the load to the entire section $N_{u,1}$ = 9050 kN; while reinforcing a steel cage with concrete and transferring the load to the concrete core without loading the branches of the steel cage $N_{u,2}$ = 8450 kN. The graphs shown in Fig. 7 also clearly indicate that in the case of reinforcement of columns with a steel casing, the nature of the destruction is more plastic compared to the reference reinforced concrete sample.

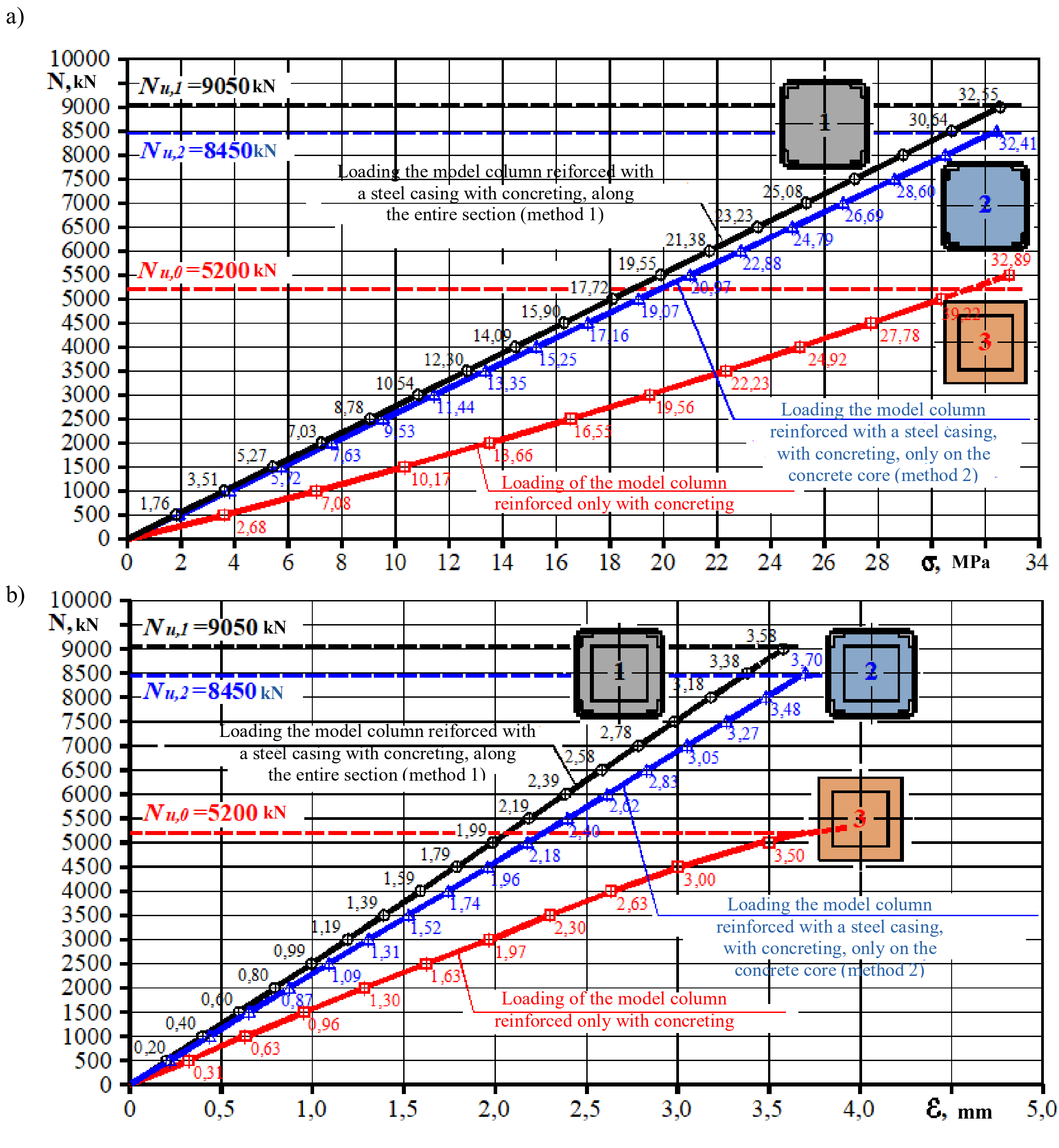

Fig. 7. Change in resulting strains and equivalent stresses with an increasing load under various loading methods: a) for equivalent voltages; b) for the resulting deformations

This effect was also observed in [6, 7, 10]. According to the research results, it is obvious that the highest load-bearing capacity of reinforced concrete columns was observed in the case of transferring the load to the entire section: to the concrete core and to the branches of the steel cage ($N_{u,1}$ = 9050 kN). At the same time, the limiting stress-strain of reinforced columns when the load is transferred only to the concrete core (reinforced column and concreting concrete) occurs at a load value of $N_{u,2}$ = 8450 kN, which indicates a sufficiently low — less than 10 % — efficiency of transferring the load to the entire section including steel cage legs (Δ % = [9050 − 8450] / 8450 · 100 % = 7.1 %). On top of this, setting up a steel head is a labor-intensive and material-intensive process conducted in cramped conditions for the production of works typical for the reconstruction and modernization of buildings.

Therefore when the load is transferred to the entire section (including the elements of the steel cage), the load-bearing capacity of the reinforced column increases by less than 10 % compared to the case of loading only the concrete core. It thus seems appropriate to abandon setting up the head of the steel cage, which will significantly reduce the complexity and time of work and simplify the constructive solution for reinforcing reinforced concrete columns using the steel cage with concreting.

In addition to the function of increasing the load-bearing capacity, the concreting device also performs the functions of restoring the performance of reinforced concrete columns. This makes it possible to offset the effect of surface defects and damage accumulated in the column by the time of reinforcement on the effectiveness of strengthening the steel casing: in [7, 18] it has been empirically proven that the use of steel casings for damaged columns is much less effective than for columns without defects.

Conclusions

1. Reinforcement of reinforced concrete columns with a steel cage with concrete surfacing can considerably increase the load-bearing capacity of the operated columns. This method can be used to strengthen columns whose technical condition is assessed as inoperable (unsatisfactory), i.e., those that have numerous considerable or critical defects and damage by the time of reinforcement.

2. Based on the experimental and numerical studies, the option of transferring the load only to the concrete core (the existing column and concreting) without loading the branches of the steel cage is considered more rational as it enables one to considerably increase the load-bearing capacity of the reinforced column and, at the same time, to abandon setting up the head of the steel cage, which is a labor-intensive process requiring the use of complex design and technological solutions.

3. The greatest increase in the load-bearing capacity of the columns as a result of strengthening the steel casing with concrete was observed when the load was transferred to the entire section of the reinforced column (the existing column, concrete and steel casing branches). At the same time, the load-bearing capacity of the reinforced column increases by no more than 10 % compared to the one achieved when only the concrete core of the reinforced section is loaded.

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