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Strength and stability of a pipe-concrete column of a high-rise building

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Abstract. Reinforced concrete structures are a system consisting of monolithic reinforced concrete, a steel part and connecting elements. In this article, the stress-strain state of the structures of a high-rise building is considered. The domestic experience of research and application of steel-reinforced concrete load-bearing structures is described. The analysis of the strength and stability of the most loaded column of a high-rise building is presented. The columns of the object under study are made using tubular concrete, which is a steel shell pipe working in conjunction with concrete and design fittings. Detailed finite element modeling of each tubular concrete column is labor-intensive and not optimal from the point of view of computing resources. The use of a core model is possible in the case of determining the mechanical characteristics of a tubular concrete column as a core structure. To determine the longitudinal and bending stiffness of columns, it is proposed to use a spatial solid-state model that allows for the joint operation of all these elements. According to the calculation results, the most loaded element is determined, that is, a steel shell pipe. It is shown that the loss of stability of the column as a separate element is impossible with such a configuration of the cross section.

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1. *Introduction*

Modern technologies in the field of construction are designed to ensure high reliability of buildings, reduce construction time, facilitate the development of projects in difficult conditions and make objects much more attractive through the use of individual architectural and planning solutions. When designing unique high-rise buildings, the practice of using steel-reinforced concrete structures is becoming popular. The fundamental design principle of combining functions of various elements is fully and successfully implemented in steel-reinforced concrete structures.

Steel-reinforced concrete is a composite structure that belongs to a special class of structures in modern construction. The composite form of these elements is diverse, therefore, different structural systems can be used. According to the name, it can be concluded that steel-reinforced concrete structures are a system consisting of monolithic reinforced concrete, a steel part and connecting elements. Thus, steel-reinforced concrete is an excellent example of a composite material.

The special properties of steel-reinforced concrete structures are ensured through a joint work of steel and reinforced concrete parts. It is possible to highlight the main advantages of these composites over traditional structural materials. Compared to a reinforced concrete structure, when using steel-reinforced concrete, it is possible to reduce the building's own weight and design sections, and also to accelerate construction. The rate of development of high-rise structures made of reinforced concrete and mixed structures is ahead of the development of high-rise steel structures. The stiffness of the structures under consideration is much higher than steel structures, in addition, the consumption of steel is reduced, which has a positive effect on the cost price. Economic profitability of the steel-reinforced concrete structures is evident at the stage of installation, and subsequently – in the process of maintenance-free operation. One of the most important advantages of the mixed structures is the effective combination of different materials, which is reflected in the safety, durability and stability of high-rise objects not only in non-seismic, but also in seismic areas. Of course, there are some difficulties and disadvantages in using such constructions. In the calculation process, one should take into account the staging of work, the shift of dissimilar materials, specific influences and other factors. Accordingly, a significant amount of studies of structures is required, where two materials of different physicochemical parameters are combined, the process of making steel-reinforced concrete structures is also complicated by the need for connecting elements between steel and reinforced concrete, the active use of prestressing, and the internal static indeterminacy of structures' sections.

The first mention of pipe concrete can be considered the research of J.S. Sewell [1, 2], who filled steel pipes with concrete in order to increase their fire and corrosion resistance. At the same time, the bearing capacity of such a structure turned out to be about a quarter higher than the total of a steel pipe and a concrete core.

The first experience of using pipe-concrete structures in the Soviet Union was the Volodarsky Bridge project across the Neva River, carried out in 1936 under the supervision of engineer G. P. Perederia. To increase the bearing capacity of the arches, G P. Perederiy used for the first time the so-called "cage effect": a large-sized package of 40 pipes with a diameter of 140 × 5 mm was used as the upper parabolic belt of the superstructure. Before the construction of the bridge, a 1/5 life-size model of arched spans was made, which was tested with almost double the design load. The test was conducted with the participation of G.P. Perederia, V.I. Kryzhanovsky, V.K. Kachurin, A.A. Dolzhenko.

Later, G.P. Perederia, based on the experience of designing and building this facility, wrote a monograph in 1945 [3], in which he described the results of the tests and concluded about the effectiveness of using tubular fittings in bridge construction.

In 1938–1940, according to the project of Professor V.A. Rosnovsky [4, 5], a railway bridge was built across the river. Iset in Kamensk-Uralsky with the use of pipe-concrete arches. However, later a problem was identified in the operation of the pipe-concrete elements of the bridge, namely, it was found that the concrete core was detached from the steel pipe.

The main problem when designing buildings and structures using pipe concrete is the complexity of calculations. Modeling with volumetric finite elements of structures from all components of pipe concrete [6–8] leads to high complexity of the model, since the model of only one column of pipe concrete can contain several hundred thousand finite elements, as shown in the current work. Analytical models based on continuum mechanics are labor-intensive and dependent on many mechanical and geometric input parameters [9]. When using rod calculation models, the question arises about the assignment of stiffnesses, the distribution of which directly affects the final design forces. In addition, as for any composite material, the question of the correct stress distribution in the section, which has internal static indetermination, remains open.

Modern computer software systems allow performing calculations in linear and nonlinear formulations. But building structures must be modeled using volumetric finite elements. That is why calculation of a complete building model, as a rule, is not possible due to the lack of computing power, complexity and laboriousness of the modeling process. The solution to this problem can be the use of rod design models, the mechanical characteristics of which are assigned by means of a numerical study of individual elements that have much simpler design models.

The purpose of this study is to determine the possibility of consistently determining the mechanical characteristics of individual steel-reinforced concrete columns for the purpose of their further use in the core model of the building. To achieve this goal, it is necessary to simulate a spatial model of a tubular concrete column, determine the mechanical characteristics of the column as a rod and enter the obtained mechanical characteristics of the rod model into the Scad Office.

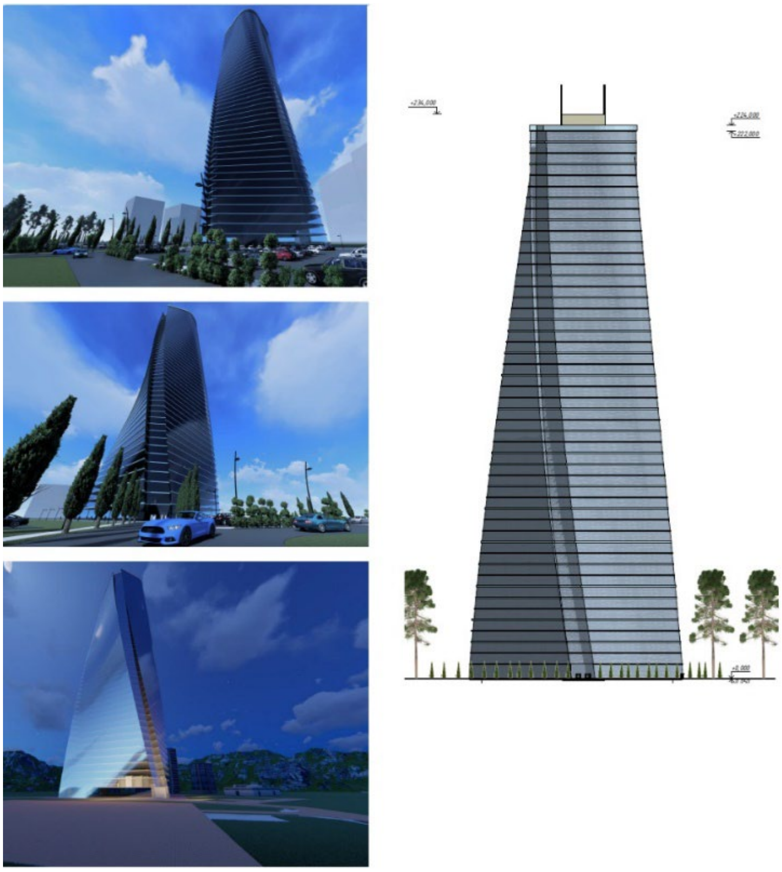

Figure 1. Projected multi-purpose high-rise building.

The main purpose of this study is to determine the stress-strain state of the structures of a high-rise building (Fig. 1).

The tasks that are solved in this paper are:

1. Creating a spatial finite element model of a high-rise building.
2. Determination of longitudinal and flexural stiffness of pipe-concrete columns by creating a solid-state model that takes into account the joint work of all elements of a pipe-concrete column.
3. Determination of normal stresses in the body of pipe-concrete columns.
4. Static calculation of a finite element model of a high-rise building to determine the most dangerous combinations of loads, taking into account the obtained equivalent rigidity.
5. Calculation of stability of the most loaded pipe concrete columns in a geometrically nonlinear formulation of the problem.

2. *Materials and Methods*

To perform calculations, a spatial finite element model of the building was created in the SCAD Office using rod (columns) and plate (floor slabs, stiffness core) finite elements (Fig. 2).

The columns of the object under study are made using pipe concrete (Fig. 3), which is a steel shell pipe working in conjunction with concrete and design reinforcement. To determine the longitudinal and bending stiffness of the columns, it is proposed to use a spatial solid model, which makes it possible to take into account the joint work of all the listed elements [10–23]. The model built in the ANSYS software is shown in Fig. 4.

To determine the stiffness characteristics, a cantilever bar loaded with a single concentrated moment is considered (Fig. 5). The displacement of the rod end Δ_A can be determined by the Mohr-Maxwell equation (1), the integral of which is revealed using the Vereshchagin method (2).

$$\Delta_A = \int_0^1 \frac{M_p M_i}{EJ_{eq}} ds; \tag{1}$$

$$\Delta_A = \frac{Ml^2}{2EJ_{eq}}, \tag{2}$$

where: l = 6 m is the rod length; M_p is the moment calculated in each section of the bar with an assigned load M = 1 N·m (Fig. 5); M_i is the moment calculated in each section of the bar with a single force defining the point and direction of displacement Δ_A (Fig. 5); EJ_{eq} is the equivalent bar stiffness; ds is the bar length differential.

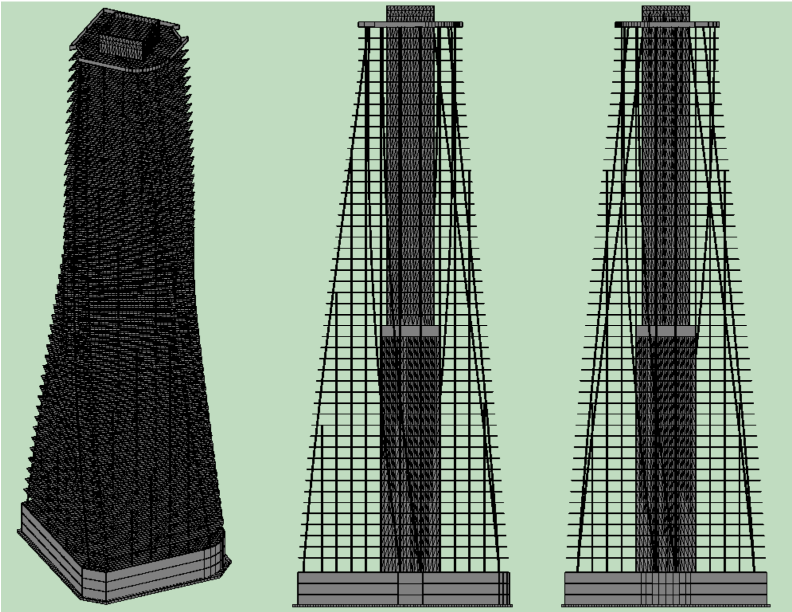

Figure 2. Spatial finite element design model of a high-rise building, built in the SCAD.

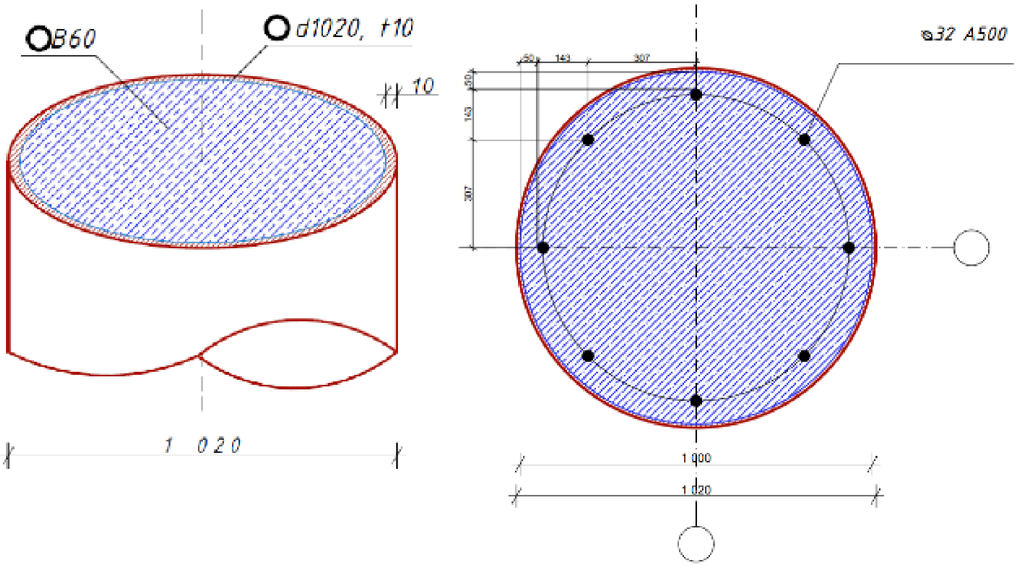

Figure 3. Steel-reinforced concrete column structure.

To determine the equivalent stiffness, the inverse problem is solved, when the displacement of point A is considered known. The displacement value is obtained from the calculation of a spatial finite element model (Fig. 5). The final equivalent stiffness is determined by the equation:

$$EJ_{eq} = \frac{Ml^2}{2EJ_{eq}} = 1.55 \cdot 10^6 \ kN \cdot m^2. \tag{3}$$

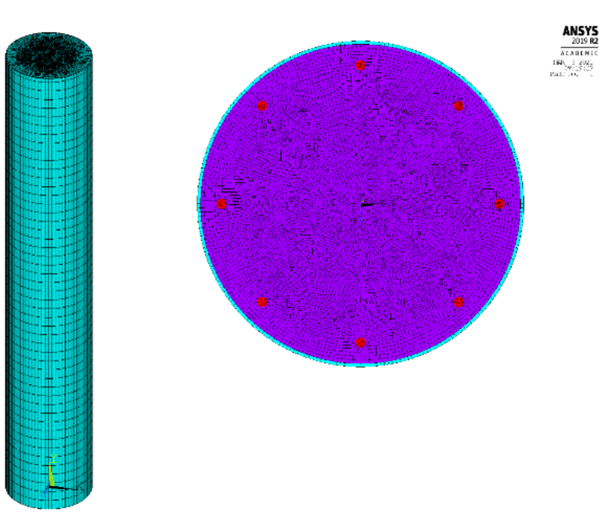

Figure 4. Spatial finite element design model of a steel-reinforced concrete column built in the ANSYS software.

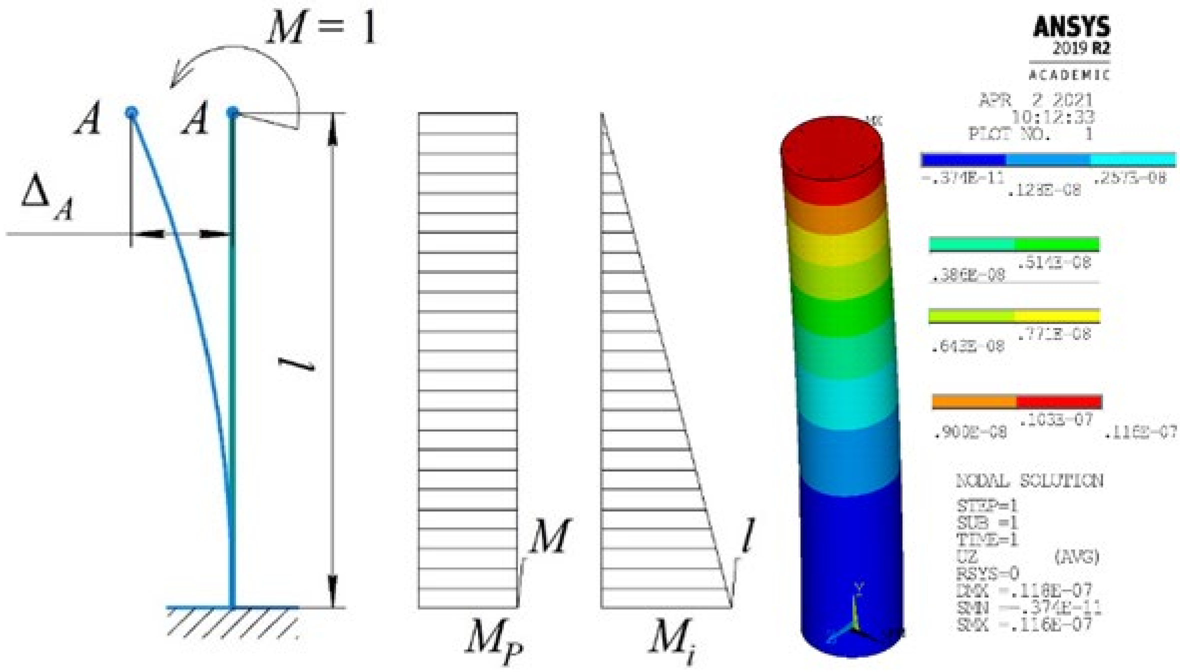

Figure 5. Determination of the bending stiffness of a column.

In this way the bending stiffness was assigned to all types of bars used in the scheme. To determine the longitudinal stiffness, a similar problem is solved, in which the model is loaded with a single longitudinal force.

Then the problem was solved related to the determination of normal stresses in the body of the column [24–31]. For this, the principle of proportionality and the principle of independence of the action of forces (superposition) were used. After assigning the stiffness characteristics to the elements of the rod spatial design model (Fig. 2), a static calculation was carried out, according to the results of which the least advantageous combinations of loadings and design forces were determined. The most dangerous were 2 columns with design forces M = 245 kNm, N = 16675 kN and M = 360 kNm, N = 13035 kN respectively.

The strength of the column elements is checked according to the equation:

$$\sigma_{\max} = \sigma_M^r + \sigma_N^r = \sigma_M M + \sigma_N N \le R_y, \tag{4}$$

where:

σ_M^r, σ_N^r are the normal stresses caused by the calculated value of the moment and the longitudinal force, respectively;

σ_M, σ_N are the maximum normal stresses arising in a column element (shell, concrete or design reinforcement) under the action of a single moment or a single longitudinal force, respectively, determined using a solid design model (Fig. 6, 7);

M, N are the calculated values of the moment and longitudinal force, determined using a spatial bar model (Fig. 2);

R_y is the design material resistance.

To calculate the stability of the column, the calculated values of the moments M were taken, while the value of the longitudinal force was increased gradually. Such a situation can occur when a local load exceeding significantly the calculated value is applied on the floor. The problem, in this case, was solved in a geometrically nonlinear formulation using an iterative load application with control of the current deformed state. The number of steps for iterating the load application was determined automatically, but it could not be less than 50 steps and exceed 150.

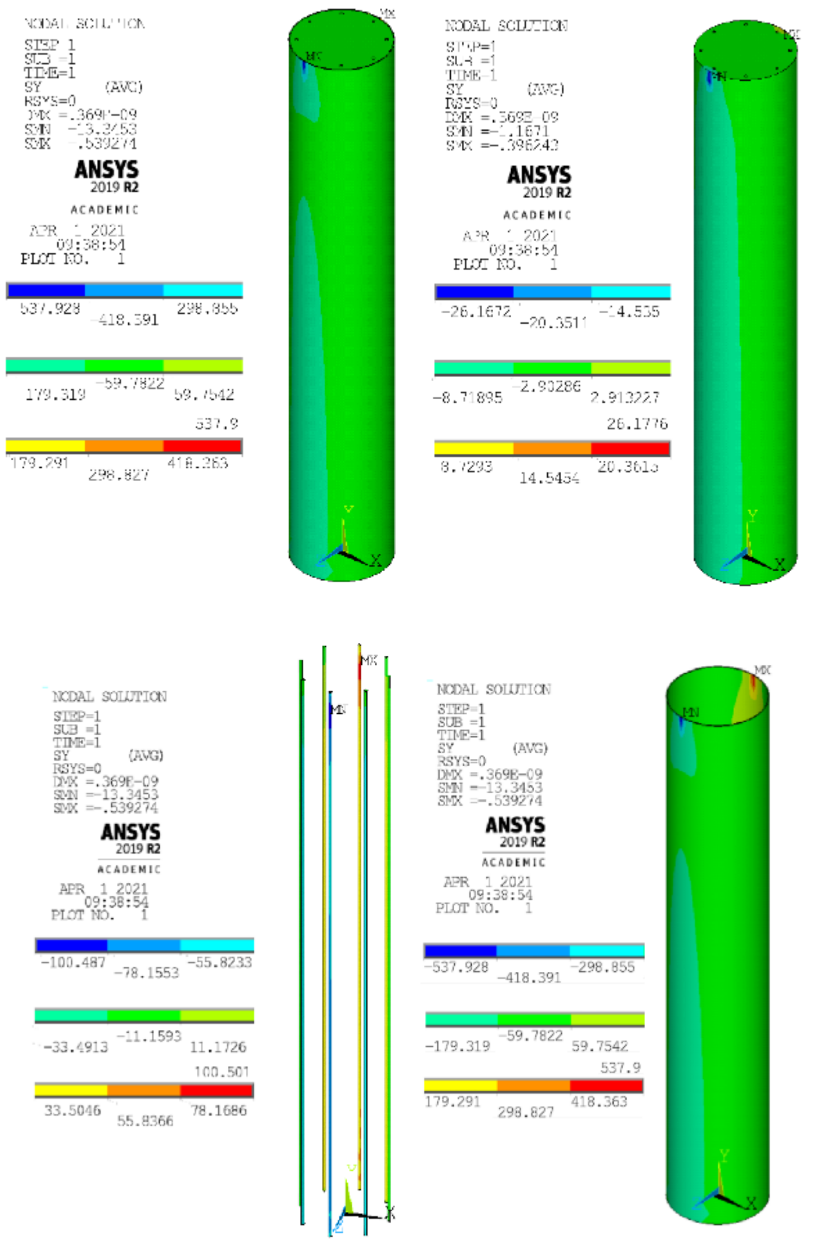

Figure 6. Normal stress (Pa) in the elements of a steel-reinforced concrete column under the action of a single moment.

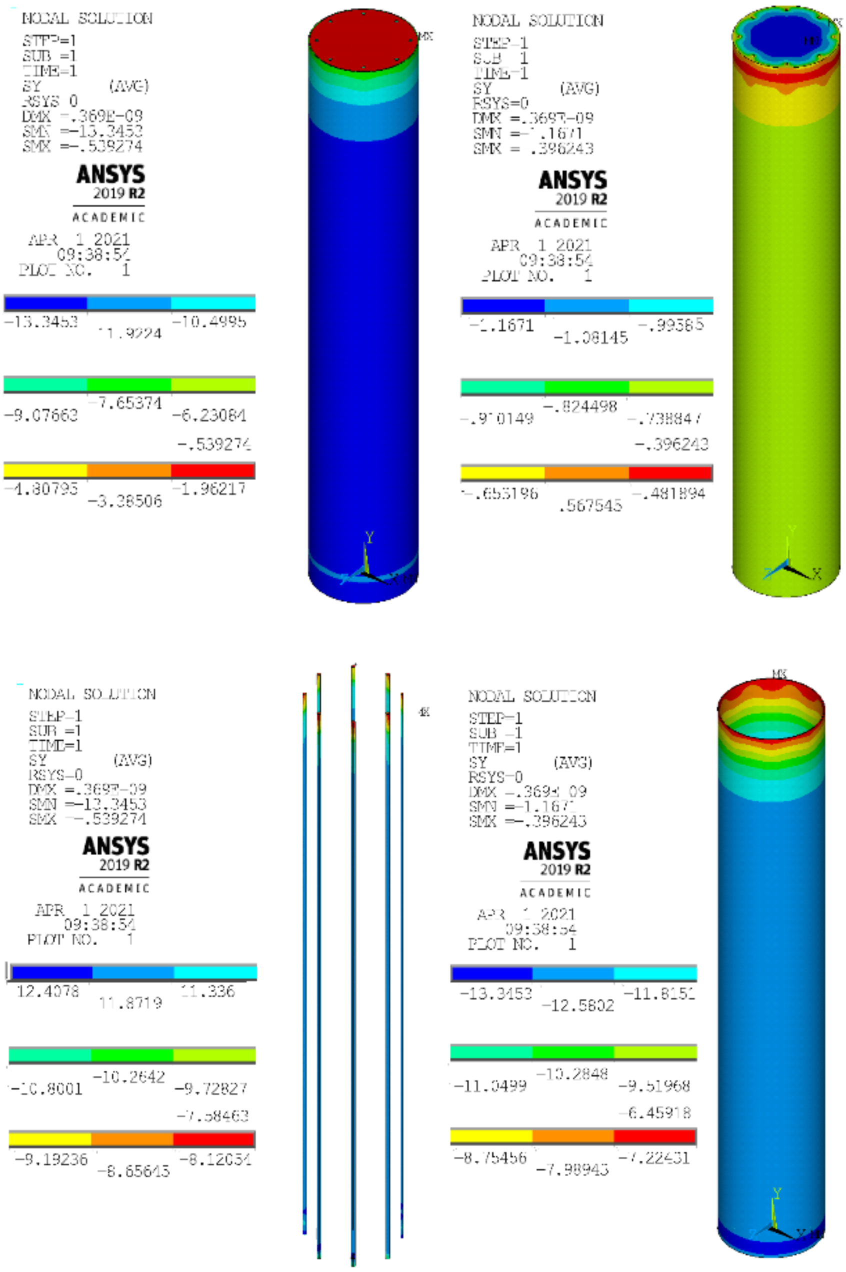

Figure 7. Normal stress (Pa) in the elements of a steel-reinforced concrete column under the action of a single longitudinal force.

To control the convergence of the solution, the ANSYS software package allows the user to track the magnitude of the current displacements and load values in the object model. If the indicators of current displacements and load values exceed the set critical values (limits), then the ANSYS software package decreases the load increment at an iteration step increasing the number of load increment steps. If the number of steps in this case exceeds the maximum set by the user, the ANSYS displays a message about the impossibility of solving the problem in the specified number of steps, which gives the right to conclude that the solution is not convergent. In this study, the divergence of the solution allows us to conclude about the loss of stability of the column.

3. Results and Discussion

The results are summarized in Table. 1. Based on the results of the performed calculation, it can be concluded that the strength of the column is ensured. At the same time, the maximum safety factor, equal to 48 % and 56 %, respectively, with combinations of forces 1 and 2, arises in the reinforcing bars, while the most loaded is the steel shell pipe, the safety factor in which is about 5 %. To rationalize the result, the adopted section can be corrected (Fig. 3), followed by the refinement of the stiffness characteristics and design forces.

According to the current regulatory documents, in order to ensure full bearing capacity, in addition to the strength, it is necessary to check the stability of the element. Issues of ensuring stability of compressed and compressed-bendable elements are of special attention [32–39], and the monograph by V.V. Katyushin [32], published in 2005, is considered one of the leading works by the scientific community in this respect.

Table 1. Strength check of column elements.

Combination of forces		Element	σ_M, Pa	σ_N, Pa	σ_M, Pa ($\cdot 10^6$)	σ_N, Pa ($\cdot 10^6$)	σ_{max}, *Pa* ($\cdot 10^6$)	R_y, Pa ($\cdot 10^6$)	Reserve
M, Nm	N, kN								
245000	$1.668 \cdot 10^6$	Concrete	20.36	1.16	4.99	19.3	24.3	33.0	26%
		Armature	78.17	12.41	19.2	207	226.2	436	48%
		Pipe	179.32	12.58	43.9	210	253	265	5%
360000	$1.304 \cdot 10^6$	Concrete	20.36	1.16	7.33	15.1	22.8	33.0	31%
		Armature	78.17	12.41	28.1	162	190.1	436	56%
		Pipe	179.32	12.58	64.6	164	228.6	265	14%

Fig. 8 shows a diagram that visualizes the percentage of material utilization of various column elements for each of the considered stress combinations.

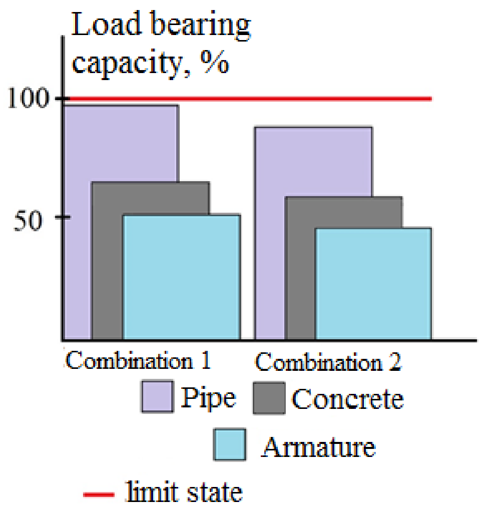

Figure 8. Chart visualizing the percentage of material utilization of various column elements.

Similar methods for determining the mechanical characteristics of individual parts, based on a spatial finite element model of these elements, are used in many problems of continuum mechanics, including the mechanics of civil structures. However, a similar method in relation to structures made of tubular concrete is not sufficiently presented in the literature.

The published works [40] present the results of field experiments on the operation of tubular concrete under axial compression, analyze the data of theoretical calculations of the maximum bearing capacity in accordance with various applicable codes of practice: EC4, NBR 8800, AISC and GB50396-2014. In many works, the greatest efficiency of tubular concrete is determined, and the issues of operation of non-centrally compressed tubular concrete elements are discussed by both domestic [41–43] and foreign [44–50] scientists. Insufficient amount of work has been devoted to the calculation of buildings and structures in general, the elements of which are tubular concrete elements.

4. Conclusions

1. The mechanical properties of the column can be obtained from the ANSYS spatial model.
2. A spatial finite element model of a high-rise multifunctional building using rod and plate finite elements was created in the SCAD Office.

3. From the calculation of the spatial finite element model, the displacements necessary for calculating the equivalent longitudinal and bending stiffness of columns are obtained.
4. A static calculation of the spatial finite element model was carried out and the most dangerous combinations of forces 1 and 2 were identified.
5. As a result of calculating the strength of a pipe-concrete column, it was revealed that the steel shell pipe is the most loaded. At the same time, reinforcing bars have a large margin of safety. This suggests that it is necessary to adjust the parameters of the section.
6. Since it was not possible to achieve the loss of stability of the column, it can be concluded that the loss of bearing capacity at given cross-sections and design characteristics of the column elements is possible only when the stresses reach values that exceed the design resistance of materials. Thus, the local stability of the column is ensured under any loads. However, it is necessary to perform a calculation of the overall stability of the entire building as a whole, which is beyond the scope of this study.
7. As a result of the performed studies of the strength and stability, it can be concluded that the bearing capacity of the studied column is provided.

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