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Study of Joint Work of Shell and Core of Tube Confined Concrete Elements with Strengthened Core

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Abstract. At the present time, it is necessary to strengthen the economy mode, the resources efficiency and reduce the material consumption in construction.

Modern building constructions must meet all the requirements of economy, resource conservation, which are required for construction. The main direction of their development is reducing the cost of steel (14-16%), saving cement (10-12%) and saving forest materials (12-14%). These tasks can be solved, including at the expense of reduction of material content and reduction of the cross-section of structures, due to the rational combination of concrete and steel in their joint work and through the use of high-strength materials. These requirements are satisfied with building constructions from tube confined concrete. With a relatively small cross-section, such structures can withstand significant efforts, while the concrete at the expense of a volumetric stressed state receives stresses that far exceed the prism strength, which saves steel and concrete. Applying high-strength concrete, concrete, compacted by pressing, centrifugation, it is possible to obtain significant cement savings, as due to industrial technological factors of sealing concrete mix significantly increases the concrete strength. It is possible to increase the concrete strength also due to the use of indirect reinforcement, which allows, at low cost of steel, to significantly increase the strength of structures.

Improving the well-known effective methods of strengthening concrete in relation to tube confined concrete constructions with strengthened cores suitable for industrialization is an urgent and important task.

The purpose of the research presented in this paper was the experimental study of tube confined concrete elements with reinforced in different methods concrete cores; the development of methods for calculating the carrying capacity and the stress-strain state of tube confined concrete elements with strengthened cores.

Introduction

The construction industry of Ukraine is experiencing a deep crisis. Given the current state of construction and providing it with resources, the improvement of tube confined concrete structures by strengthening their core is an urgent and important task. As it is known that in compressed tube confined concrete elements, the acting force is perceived both by the tube shell and by the concrete core. If in some way to increase the carrying capacity of the core, it is possible to reduce the consumption of steel to obtain a tube confined concrete element with a predetermined carrying capacity. Therefore, the use of a strengthened core will lead to a significant reduction in steel costs and cost savings during the construction of the structure. However, the question of the joint operation of the steel shell and the concrete core of these structures is not sufficiently studied and has ambiguous estimates.

The purpose of the presented studies is an experimental study of tube confined concrete elements with strengthened cores; the development of methods for calculating carrying capacity and stress-strain state of such elements.

Analysis of research and publications. To date, many buildings have been designed and built with the use of tube confined concrete. Steel tubes filled with concrete are used in China [1, 2, 3], Canada [4, 5], the USA [6]. In the CIS, a number of original structures were built [7, 8, 9]. Tube confined concrete is used even in such responsible structures as bridges [10, 11]. At the same time, for the most part, the research is aimed at the influence of different types of core concrete constitution on the characteristics of structures. The idea of strengthening the core remains beyond the attention of researchers.

Formulation of the Problem.

Due to a number of specific qualities: increased crack resistance, resistance to shock and thermal influences, tube confined concrete is becoming more widespread [12,13, 14], the experiments were aimed at specifying the mechanism of development of a stress-strain state of tube confined concrete elements with a strengthened core for more reliable and specific evaluation of their characteristics.

It is known that in the compressed tube confined concrete elements, the acting force is perceived both by the tube shell and the concrete core [15, 16]. If in some way to increase the carrying capacity of the core, then it is possible to reduce the cost of steel to obtain a tube confined concrete element with a predetermined carrying capacity. Therefore, the use of a strengthened core will reduce the cost of steel and save costs of construction manufacture, which is the main task of the study.

Presentation of the Material and the Results

During the experiments, the following groups and series of samples were tested:

Group I. Samples with high-strength concrete cores;

Group II. Samples with cores reinforced with longitudinal bars;

Group IIIa. With centrifuged core with internal cavity;

Group IIIb. With a centrifuged core with internal cavity filled with concrete;

Group IVa. Double-tube with internal cavity;

Group IVb. Double-tube with internal cavity filled with concrete.

Their geometrical dimensions and design values of the physical and mechanical characteristics of steel and concrete are given in Tables 1-2. The samples are labelled, for example TC-IIa-1, which indicates the characteristics of the taken tube and concrete.

Table 1 – The values of the studied samples of groups I and II

Group of samples	Series of samples	Tube external diameter, D, [mm]	Tube wall thickness t, [mm]	Concrete strength fck.prism, [MPa]
I	T-I-1	110,6	2,75	–
	T-I-2	163,0	5,50	–
	T-I-3	204,4	5,20	–
	T-I-11	110,6	2,75	50,0
	TC-I-12	110,6	2,75	64,2
	TC-I-13	110,6	2,75	80,0
	TC-I-21	163,0	5,50	50,0
	TC-I-22	163,0	5,50	64,2
	TC-I-23	163,0	5,50	80,0

	TC-I-31	204,4	5,20	50,0
	TC-I-32	204,4	5,20	54,2
	TC-I-33	204,4	5,20	80,0
II	T-II-1	159,0	4,00	–
	TC-II-11	159,0	4,00	13,9
	TC-II-12	159,0	4,00	24,3
	TC-II-13	159,0	4,00	29,1

Note. Tube confined concrete samples of Group II are reinforced with longitudinal bars 6 ø12 A-III.

Table 2 – The values of the studied samples of groups III and IV

Group of samples	Series of samples	Value of the outer tube D×t, [mm]	Value of the internal tube D_i×t_i, [mm]	Strength of the concrete ring fck.prism1, [MPa]	Strength of the in-fill concrete fck.prism1, [MPa]
III	T-III-1	325,0×8,0	–	–	–
	TC-IIIa-1	325,0×8,0	–	38,9	–
	TC-IIIб-1	325,0×8,0	–	38,9	28,8
IV	T-IV-1/	169,0×6,0	–	–	–
	T-IV-2//	–	89,0×2,8	–	–
	TC-IVa-1	169,0×6,0	89,0×2,8	21,0	–
	TC-IVb-1	169,0×6,0	89,0×2,8	21,0	18,8

Experimental investigations of tube confined concrete elements with high-strength concrete cores have proven that, by the time of the appearance of fluidity in the shell, the latter with concrete core work in parallel. Therefore, when developing a method for evaluating the stress-strain state of such structures, we believe that the tube-shell and the concrete core work in parallel until the fluidity of the tube shell begins (Fig. 1). At a later stage, the concrete core and the shell work together.

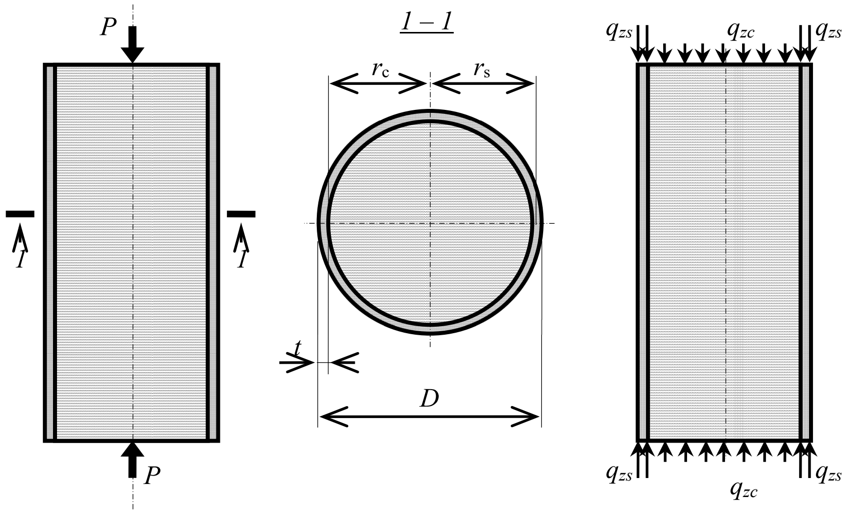

Figure 1 – Design diagram of tube confined concrete element with high-strength concrete core

The peculiarity of the deformation of the studied samples is the symmetry about the central axis. For convenience, the stress-strain state is described using cylindrical coordinates. In this case, the components of the stress-strain state are not dependent on the angle θ (Fig. 2).

Consider separately the stress-strain state of a *high-strength concrete core and steel shell.*

Concrete core is a solid cylindrical body. With an axisymmetric problem, its stress-strain state is characterized by stresses (σ_r, σ_θ, σ_z, τ_{rz}), deformations (ε_r, ε_θ, ε_z, γ_{rz}) and displacements

(u, w). To find them the equilibrium equation, geometric equations and compatibility equations were used. So the equilibrium equations are:

$$\frac{\partial \sigma_r}{\partial r}+\frac{\partial \tau_{rz}}{\partial z}+\frac{\sigma_r-\sigma_\theta}{r}=0; \quad \frac{\partial \sigma_z}{\partial z}+\frac{\partial \tau_{rz}}{\partial r}+\frac{\tau_{rz}}{r}=0, \tag{1}$$

where σ_r – normal radial stress in the direction of radii; σ_θ – normal tangential stress in perpendicular direction; σ_z – normal longitudinal stress in the direction of the axis *Z*; $\tau_{zr}=\tau_{rz}$ – shear stress in the plane perpendicular to the axis *Z* and the plane parallel to the axis *Z*.

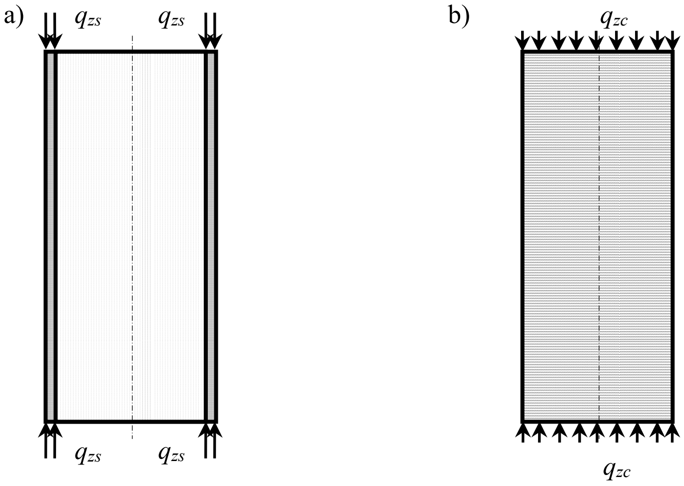

Figure 2 – Design diagram of tube shell (a)
and high-strength concrete core (b)

Dependence between deformations and displacements are related by dependencies:

$$\varepsilon_r=\frac{\partial u}{\partial r}; \quad \varepsilon_\theta=\frac{u}{r}; \quad \varepsilon_z=\frac{\partial w}{\partial r}; \quad \gamma_{rz}=\frac{\partial u}{\partial z}+\frac{\partial w}{\partial r}, \tag{2}$$

where ε_r – deformation in the radial direction; ε_θ – deformation in the tangential direction; ε_z – deformation in the direction of the axis *Z*; u – displacement in the radial direction; w – displacement in the direction of the axis *Z*.

Equations of compatibility in cylindrical coordinates with symmetric distribution of stresses have the form:

$$\begin{gathered}\nabla^2\sigma_r-\frac{2}{r^2}\left(\sigma_r-\sigma_\theta\right)+\frac{1}{1+\mu}\cdot\frac{\partial^2\Sigma}{\partial r^2}=0; \quad \nabla^2\sigma_\theta-\frac{2}{r^2}\left(\sigma_r-\sigma_\theta\right)+\frac{1}{1+\mu}\cdot\frac{1}{r}\cdot\frac{\partial\Sigma}{\partial r}=0;\\ \nabla^2\sigma_z+\frac{1}{1+\mu}\cdot\frac{\partial^2\Sigma}{\partial z^2}=0; \quad \nabla^2\tau_{rz}-\frac{\tau_{rz}}{r^2}+\frac{1}{1+\mu}\cdot\frac{\partial^2\Sigma}{\partial r\partial z}=0,\end{gathered} \tag{3}$$

where $\nabla^2=\frac{\partial^2}{\partial r^2}+\frac{1}{r}\cdot\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}$; $\Sigma=\sigma_r+\sigma_\theta+\sigma_z$ – the sum of stresses.

Thus, equations (1-3) form a system of equations for describing the stress-strain state of the concrete core of the tube confined concrete elements of high strength.

To find a solution to the problem, we apply the stress function φ, which must satisfy the equation

$$\frac{\partial^2\varphi}{\partial r^2}+\frac{1}{r}\cdot\frac{\partial\varphi}{\partial r}+\frac{\partial^2\varphi}{\partial z^2}=0, \tag{4}$$

where φ – arbitrary function.

Then the stresses are determined by the formulas:

$$\sigma_r = \frac{\partial}{\partial z}\left(\mu\nabla^2\varphi - \frac{\partial^2\varphi}{\partial r^2}\right); \quad \sigma_\theta = \frac{\partial}{\partial z}\left(\mu\nabla^2\varphi - \frac{1}{r}\cdot\frac{\partial\varphi}{\partial r}\right); \quad \sigma_z = \frac{\partial}{\partial z}\left((2-\mu)\nabla^2\varphi - \frac{\partial^2\varphi}{\partial z^2}\right);$$

$$\tau_{rz} = \frac{\partial}{\partial r}\left((1-\mu)\nabla^2\varphi - \frac{\partial^2\varphi}{\partial z^2}\right).$$

In paper [17], it is proposed to use the stress function in the form:

$$\varphi = z\left(C_1 r^2 + C_2 z^2\right).$$

Then the stresses are determined by the formulas:

$$\sigma_r = \sigma_\theta = -2C_1(1-2\mu) + 6\mu C_2; \quad \sigma_z = 4C_1(2-\mu) + 6C_2(1-\mu); \quad \tau_{rz} = 0,$$

where $C_1 = \frac{\mu}{2(1+\mu)}q_z$; $C_2 = \frac{1-2\mu}{6(1+\mu)}q_z$;

q_z – the intensity of the external force along the axis Z at the extreme sections of the concrete core.

After substituting C_1 and C_2, we get stress $\sigma_r = \sigma_\theta = \tau_{rz} = 0$, $\sigma_z = q_z$.

The tube shell represents a field cylindrical body with a thin wall. The transverse deformation along its radius can be neglected. Therefore, to describe the stress-strain state, the shell is replaced by a cylindrical surface passing through the middle radius. The calculation is performed as for a hollow tube according to the method [18].

Tube confined concrete elements with cores reinforced with longitudinal bars.

The peculiarity of this kind of tube confined concrete elements is that the concrete core is reinforced additionally in the longitudinal direction with additional steel bars. That is, in the longitudinal direction the concrete core and steel bars resist, and in the transverse only the concrete core. In order to theoretically describe the work of the bar reinforcement in the tube confined concrete, the fact that the steel bars are arranged evenly in a circle is taken into account. Therefore, in the cross-section, steel bar reinforcement is represented as a conditional ring with the ability of concrete to freely deform (Fig. 3).

The assessment of the stress-strain state of such structures is similar to the method for tube confined concrete elements with a core of high-strength concrete. Only added in the longitudinal direction is the work of additional reinforcement, which works in conditions of uniaxial stress state.

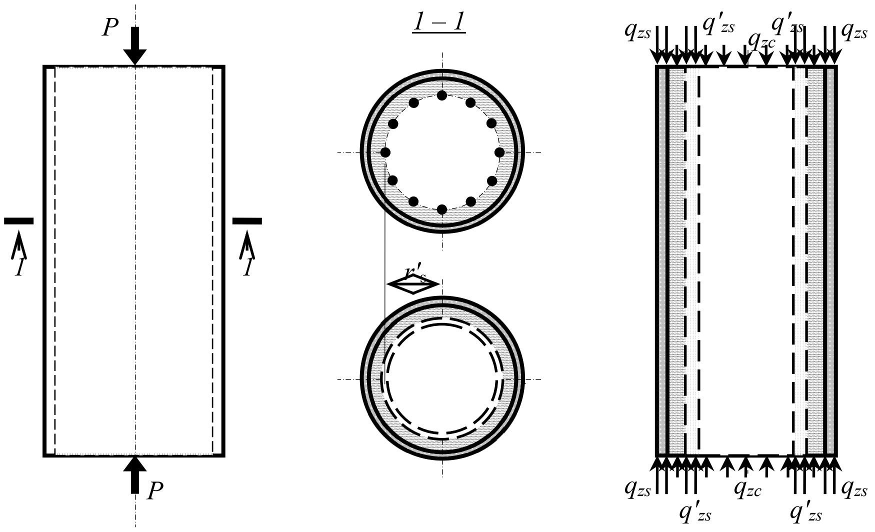

Figure 3 – Design diagram of tube confined concrete element with core of the high-strength concrete reinforced with longitudinal steel bars

Tube confined concrete elements with a multi-layered core.

It is possible to form multi-layered sections of compressed tube confined concrete elements in different ways. Therefore, it is worth highlighting common in all these cases. So the concrete core in the general case is a hollow thick-walled cylinder. Depending on the design, this cylinder can be loaded not only from the extreme sections, but also from the sides.

We find the stress in the concrete core. In the most generalized form, such a core is represented in the form of a cylindrical body with a cavity inside (Fig. 4). A uniform pressure on four surfaces acts on this element: the pressure on the inner side – q_a; pressure from the outside – q_b; pressure on the upper and lower bases – q_z.

As a function of stress, we accept a polynomial of the third degree. In paper [17], it is indicated that such a function satisfies the equation (4).

$$\varphi = C_1 \cdot z \cdot \ln r + C_2 \cdot r^2 \cdot z + C_3 \cdot z^3, \tag{5}$$

In this case, the stresses are:

$$\sigma_r = \frac{C_1}{r^2} - 2C_2(1-2\mu) + 6\mu C_3; \; \sigma_\theta = -\frac{C_1}{r^2} - 2C_2(1-2\mu) + 6\mu C_3;$$

$$\sigma_z = 4C_2(2-\mu) + 6C_3(1-\mu); \qquad \tau_{rz} = 0.$$

To determine the coefficients C_1, C_2 and C_3, we set the conditions on the surface. On the lateral surfaces and on the bases, the tensile stresses are zero. But normal stresses on these surfaces differ from zero. So on the lateral surfaces:

$$\sigma_{r(r=a)} = -q_a; \; \sigma_{r(r=b)} = -q_b.$$

On the base $\sigma_z = -q_z$,

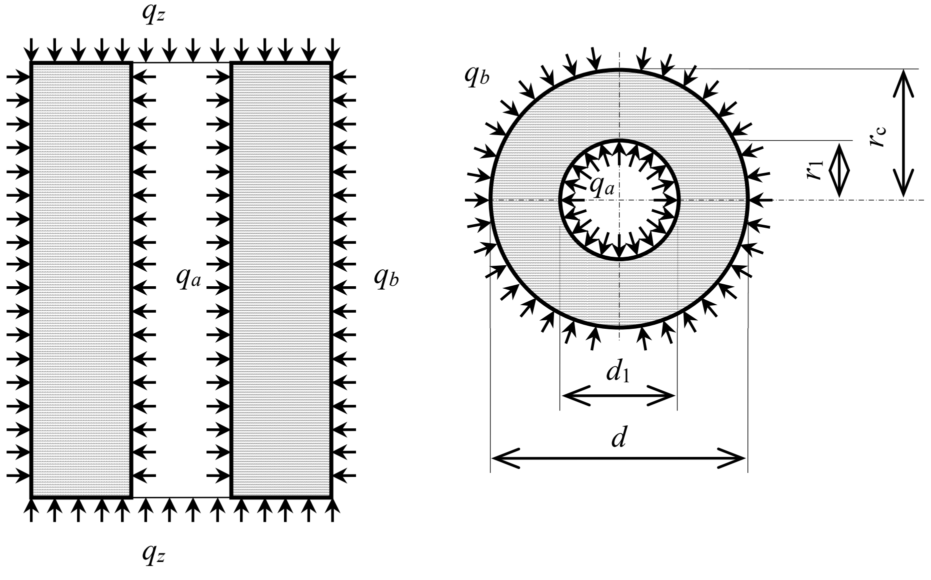

Figure 4 – Design diagram of the concrete core of the circular cross-section in multi-layered tube confined concrete elements

Thus three equations for finding unknown coefficients C_1, C_2, C_3 are obtained:

$$\frac{C_1}{r_a^2} - 2C_2(1-2\mu) + 6\mu C_3 = -q_a; \; \frac{C_1}{r_b^2} - 2C_2(1-2\mu) + 6\mu C_3 = -q_b; \; 4C_2(2-\mu) + 6C_3(1-\mu) = -q_z;$$

After the solution of these equations, the coefficients are obtained:

$$C_1 = \frac{-r_a^2(q_b + q_a)}{\left(1 + \frac{r_a^2}{r_b^2}\right)}; \qquad C_2 = \frac{1}{(2-\mu)\left(1 + \frac{1}{9(1-\mu)}\right)} \left[\frac{\mu q_z}{(1-\mu)} + \frac{r_a^2(q_b + q_a)}{r_b^2\left(1 + \frac{r_a^2}{r_b^2}\right)} - q_b \right];$$

$$C_3 = -\frac{q_z}{6(1-\mu)} - \frac{2}{3(1-\mu)\left(1+\frac{1}{9(1-\mu)}\right)}\left[\frac{\mu q_z}{(1-\mu)} + \frac{r_a^2(q_b+q_a)}{r_b^2\left(1+\frac{r_a^2}{r_b^2}\right)} - q_b\right];$$

Then the stress is equal to:

$$\sigma_r = -\frac{r_a^2(q_b+q_a)}{r_b^2\left(1+\frac{r_a^2}{r_b^2}\right)} - \frac{\mu q_z}{(1-\mu)} - \frac{2}{\left(1+\frac{1}{9(1-\mu)}\right)}\left[\frac{(1-2\mu)}{(2-\mu)} + \frac{2}{1-\mu}\right]\left\{\frac{\mu q_z}{(1-\mu)} + \frac{r_a^2(q_b+q_a)}{r_b^2\left(1+\frac{r_a^2}{r_b^2}\right)} - q_b\right\};$$

$$\sigma_\theta = -\frac{C_1}{r^2} - 2C_2(1-2\mu) + 6\mu C_3;\ \sigma_z = -q_z;\ \tau_{rz} = 0.$$

Substituting the stress equation in the Hook equation, the relative deformations along the axis Z are found:

$$\varepsilon_z = \frac{\partial u}{\partial r} = \frac{1}{E}\left[\sigma_z - \mu(\sigma_r + \sigma_\theta)\right].$$

Steel shells in multi-layered tube confined concrete elements can be located both externally and additionally inside. Fig. 5 shows the design diagrams of steel tubes in the conditions of multi-layered tube confined concrete elements.

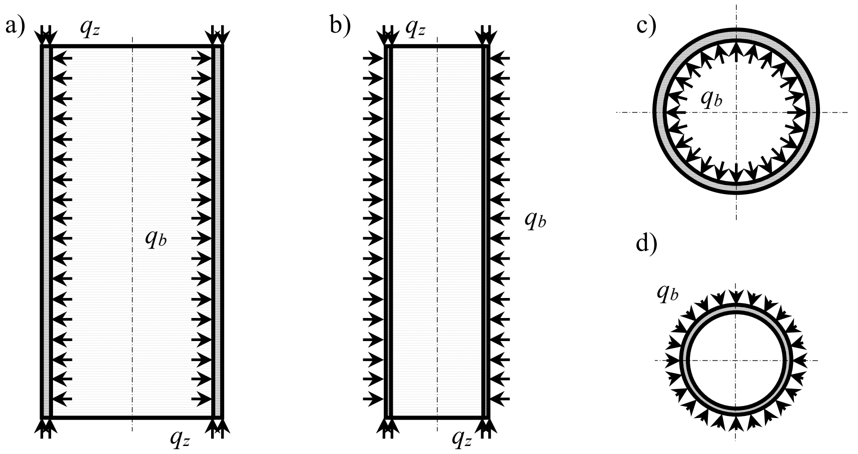

Figure 5 – Design diagram of tube shell in multilayered tube confined concrete elements:
a – external tube-shell; b – internal tube shell; c – cross-section of the external tube-shell; d – cross-section of the internal tube-shell

To make it possible to build a method for estimating the stress-strain state of a steel pipe, several factors must be taken into account: the calculation of the tube confined concrete is performed by an iterative procedure with a change in the elastic parameters; within the separate calculation stage, the operation of a steel pipe is considered to be elastic; the stress-strain state of the pipe is considered as the sum of states under simple loads. So as simple downloads we take: longitudinal compression; uniform internal compression; uniform external compression.

Summary

According to the carried out experimental study of the mechanism of development of the stress-strain state of the tube confined concrete elements, reliable and more accurate data on their properties was obtained. The obtained calculations give an opportunity to investigate the features of changes in the parameters of the bearing capacity and the stress-strain state in the tube confined concrete elements with the strengthened core of different types: the core of high-strength concrete and steel shell, the core reinforced with longitudinal steel bars, the multilayered core. These data make it clear that the application of these methods can contribute to the improvement of the construction of various structures due to better conservation of resources and increase the reliability of the structures themselves. The problem elucidated in the work has further perspectives and needs further study.

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