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Bearing capacity and rigidity of short plastic-concrete-tubal vertical columns under transverse load

A V Dolzhenko, A E Naumov, A E Shevchenko

Belgorod State Technological University named after V.G. Shoukhov 46, Kostyukov St., Belgorod, 308012, Russia

E-mail: Da7182@mail.ru

Abstract. The results of mathematical modeling in determining strain-stress distribution parameters of a short plastic-concrete-tubal vertical column under horizontal load as those in vertical constructions are described. Quantitative parameters of strain-stress distribution during vertical and horizontal loads and horizontal stiffness were determined by finite element modeling. The internal stress in the concrete column core was analyzed according to equivalent stress in Mohr theory of failure. It was determined that the bearing capacity of a short plastic-concrete-tubal vertical column is 25% higher in resistibility and 15% higher in rigidness than those of the caseless concrete columns equal in size. Cracks formation in the core of a short plastic-concrete-tubal vertical column happens under significantly bigger horizontal loads with less amount of concrete spent than that in caseless concrete columns. The significant increase of bearing capacity and cracking resistance of a short plastic-concrete-tubal vertical column under vertical and horizontal loads allows recommending them as highly effective and highly reliable structural wall elements in civil engineering.

1. Introduction

Modern efficient building methods used in civil engineering, first of all, should meet the needs of the society, and determine the economical efficiency of industry, economic output and economic efficiency of the country in general. Rational building products and technologies, reducing the building costs in civil engineering, are the key factors of steady development of the industry. They allow reducing negative influence of the following production factors on civil engineering economy:

— long-lasting pre-construction activities in general and in some of the stages in particular;
— large amount of manual highly-qualified labour, necessary to meet the required quality of the construction products;
— high costs of prevention and liquidation of production deffects in construction of products;
— high delivery costs of buiding constructions.

Rational design, construction and errection technologies of building elements are the most effective in cost reduction. They should have the following qualities:

— efficient material distribution according to internal stress in the elements under common loads;
— versatility of form-making and space-planning decisions on constructions;
— maximal assembling ability under factory quality inspection;
— archtectonic simplicity and stability even in low-qualified faulty assembling;
— use of widely-distributed, available, cheap resources.

Plastic-concrete-tubal vertical constructions (PCT) meet these criteria to a large extent. They are constructions made of plastic tubes filled with concrete/iron concrete (Fig. 1) and used independently or as frame elements. Two types of plastics were used as a PTC encasement, namely, polypropylene and polyethylene that are the most widely applied in tubes production with a diameter of more than 100 mm.

The advantages of plastics are:
- universal chemical and corrosion resistance;
- strength and elasticity;
- easy coloration process;
- lower thermal conductivity compared with metals.

The disadvantages include:
- decrease in heat resistance;
- flammability;
- aging from ultraviolet rays;
- large (8 times more than steel) coefficient of temperature expansion.

Figure 1. Samples of PTC short columns.

The authors have already tested the central compression resistability of PTC short columns, which are 110 mm in outter diameter and 400 mm in height, filled with concrete of the V15 grade, with manual consolidation of the filling. Samples analysis, received by sawing a PTC short column into thin slices (Fig. 2), showed high density of the concrete core [1, 2, 3].

The vertical load test of PTC short columns showed that concrete cylinders are destructed in a common way [4, 5] (crushing of pier-side areas and longitudinal cracks appear), while the strength of PTC in the polyethylene encasement is higher than that in cubic ones up to 35%, and than that in the polypropylene encasements - up to 15% (table 1).

In order to study the type and the nature of the physical nonlinearity of plastics encasement deformation, the authors determined experimentally the stress-strain characteristics of polyethylene used in PTC tubes on universal hydraulic testing machine WEW-600D. The longitudinal and transverse strains were measured automatically with a 0.01% load step. The results of the tests are shown in Fig. 3. PTC plastics demonstrates a significant physical nonlinearity of stress-strain properties. Stress-strain modulus E reduces from 1200 to 280 MPa with the increase in strains [epsilon] up to 5,3%.

Figure 2. Solid nature of concrete core in tested PTC samples

Table 1. Vertical load test of PTC short columns

No.	Ultimate load, t	Average bearing capacity, t
1	12.25	
2	9.75	10.9
3	10.75	
4	16.5	
5	11.25	14.7
6	16.25	
7	12.75	
8	12.5	12.5
9	12.25	

2. Experimental testing and modeling design diagram

Strength enhancement of short PTC columns during axial compression [1] was confirmed by authors with the help of mathematical modeling of the finite element design diagram, consisting of sample-polyethylene cylinder 400×110 mm with the wall thickness of 5 mm. Non-encased samples of the same concrete type and dimensions were also modeled for the comparison. FEM numerical modeling, carried out according to an exponential stress-strain diagram of the concrete core, and a three-linear stress-strain diagram of plastic (Fig. 5) were based on the experimental studies (Fig. 3).

The calculations were done in volumetric nonlinear formulae for finite elements: plastic encasement plates (physically nonlinear universal quadrangular encasement FE) and bulk elements of the concrete core (physically nonlinear trihedral prism) (Fig. 6). The movements of the upper nodes simulated a low-deformative pressing buck. The center-point load in upper nodes corresponded to the ultimate load of 14.7 t that destroyed the PTC sample (table 1).

Analyzing the modeling results, the authors focused mainly on the stresses, equivalent to uniaxial tensile stress in finite elements, obtained according to numerous strength theories. It is assumed that if equivalent stresses $\sigma_e > R_{btn}$ appear in the sections of the concrete sample, cracks are formed and material failure takes place. Accordingly, if equivalent stresses exceed the design concrete tensile strength, it indicates the formation and development of destructive processes in the material and the exhaustion of load capacity of the test sample to an ultimate limit happens.

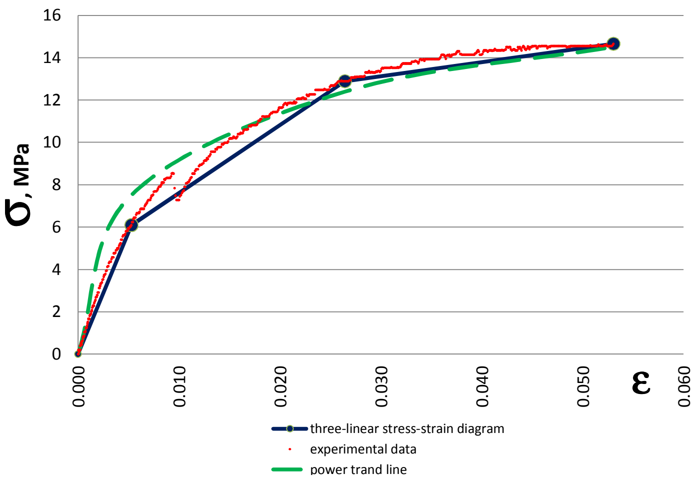

Figure 3. A stress-strain diagram of the encasement plastics (experimental data obtained by the authors).

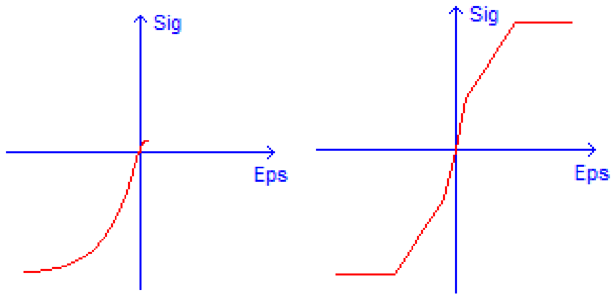

Figure 4. An exponential stress-strain diagram of concrete (left) and a three-linear stress-strain diagram of plastic (right), used in numeric FEM modelling.

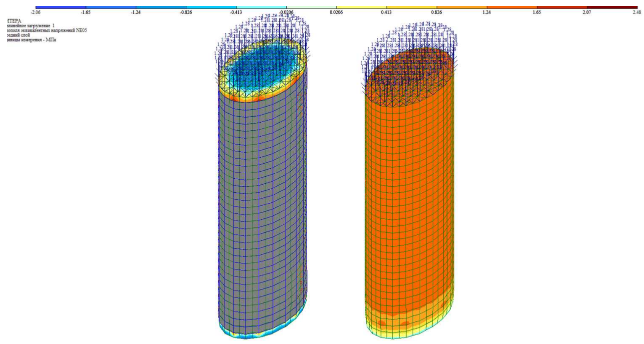

Figure 5. A finite element model of the PTC sample (a non-encased sample of the same concrete type and dimensions for reference are on the right side).

As noted in [6], among numerous strength theories in concrete structures, it is reasonable to use Mohr theory to determine equivalent stresses σ_e. Mohr strength theory does not contain any criterial hypothesis and consists of establishing a definite dependency of the strength properties on the type of the stress state of material [7]. The stress state is generally characterized by the greatest tangential stress and the normal stress with the latter being displayed on the area where the former is effective.

For brittle materials with different tensile and compressive strengths, the failure condition is determined according to Mohr theory under the volumetric stress like:

$$\sigma_e = b\times\sigma_{br} - \sigma_{by},$$

where $b = R_b / R_{bt}$,

and Mohr strength condition looks like:

$$\sigma_e \leq [\sigma].$$

What is more, equivalent stresses in prisms determined by the Mohr theory for the state at which cracks are formed in concrete correspond to the tensile strength. This is quite convenient for analyzing strain-stress state of PTC short columns with the concrete core that is a concrete cylinder of a certain class and the corresponding tensile strength.

Comparative estimation of encasement efficiency in PTC short columns under vertical load was confirmed by the ratio of equivalent stresses by Mohr theory in non-encased and encased concrete cores equal to 1.35/1.01.That means that σ_e of the non-encased sample was 1.35 MPa, which is higher than Rbtn of B15 concrete, while σ_e of the PTC sample core was 1.01 MPa, which is less than R_{btn}. It results in the bearing capacity reserve of the estimated PTC column under vertical load to a non-encased sample up to 25%.

In civil engineering, load-carring wall constructions have the largest size, cost, labour contribution, and amenability to production failure. The main loads on the walls constructions are vertical and horizontal ones caused by wind, inequality of loads on the joists and seils, lateral earth pressure on the groundwork, complexity of walls architecture. That is why, the vital task is empirical verification of the assumed PTC short column heavy-duty relatively horisontal loads which could prove their usage as rational frame elements of the walls cladding.

Final element modelling based on tested design models of PTC short columns and on the materials characteristics allowed determining qiantitive indexes of strain – stress distribution during horizontal loads as well as horizontal strucutre rigidity. The horizontal load is applied to the upper joints of the model according to the typical column spacing in wall framing with average wind pressure and soil conditions in the central part of Russia.

Horizontal movements of the model joints were analyzed in two possible structural designs of PTC short columns under horizontal loads: a) a freely deformable shank is rigidly fixed in the basement of the erected building wall under wind pressure (Fig. 6); b) a pin-base shank in the basement of the foundation wall accepting the wind force from the overlying walls and lateral earth pressure 5500 kN/m (Fig. 7).

Horizontal movements of PTC short columns joints in the erected building walls were 8 mm, while those movements of the caseless construction were 9,2 mm. In foundation construction modelling which accepted lateral earth pressure, these movements were 0,93 and 0,99 mm. These results allow estimating the horizontal rigidity reserve of PTC short columns in comparison with caseless columns as 7-15%. In a real building, an average horizontal rigidity reserve of the walls probably will be close to the upper limit as the size of the erected walls is much bigger than the foundation size even in a single-storeyed building.

The internal stress analysis in the concrete core of the PTC short column (a), under the horizontal load (Fig. 6), was carried out according to equivalent stresses of Mohr theory of failure taking into the account strength properties of concrete C15 (Fig. 8).

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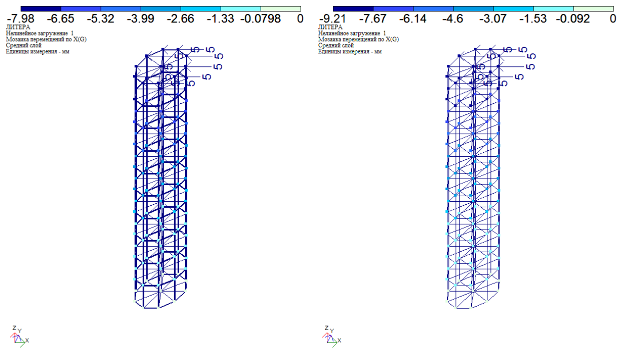

Figure 6. Horizontal displacement of joints in the PTC column (a) — transverse wind load, non-restrained displacements, rigid bottom: the PTC column concrete core is on the left; the non-encased concrete column is on the right.

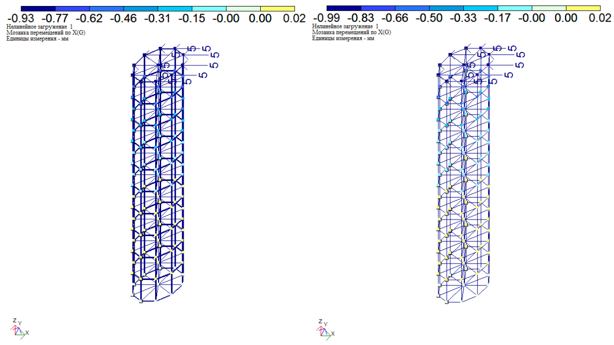

Figure 7. Horizontal displacement of the joints in the PTC column (b) transversion of wind load, pin-base shank, lateral earth pressure (5500 kN/m): the PTC concrete core is on the left; the concrete cylinder test of the non-encased sample is on the right.

Comparative estimation of efficiency of the encasement in PTC short columns under transverse load is confirmed by the ratio of equivalent stresses by Mohr theory in non-encased and encased concrete cores equal to 1.78/1.48. That means that σ_e of the non-encased sample was 1.78 MPa, while σ_e of the PTC sample core was 1.48 MPa. It results in the bearing capacity reserve of the estimated PTC column under transverse load to the non-encased sample up to 20%.

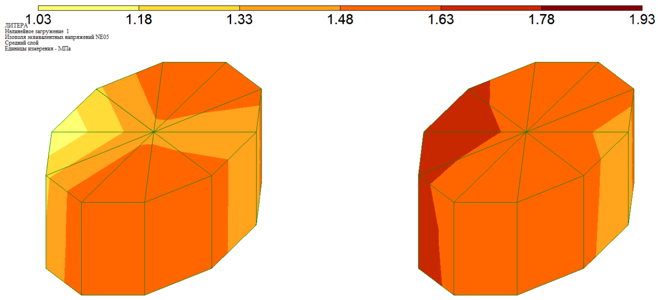

Figure 8. Equivalent stresses σ_e in the middle concrete core section according to Mohr theory: the PTC column (a) is on the left; the non-encased sample is on the right.

Significant variations in the origin and the crack formation character of the tested samples under horizontal load were identified in mathematic modeling of the foundation work (fig. 9). In the PTC short columns concrete core, the crack formation is concentrated mostly near butt ends, which is caused by harder contacting of turning pressure tension of the presssing bucks into destroying tension. Crack formation on the lateral surface of the core at the given load does not happen, which is caused by triaxial concrete compression appearing in the case and rational distribution of the internal stresses in the core. In the caseless concrete column, the cracks actively appear and develop on the lateral surface of the core as the stresses in the tensioned concrete overcome the value of R_{btn} at the initial stage of horizontal loading. Crack formation is the most intensive in the upper third of the column, which is typical of stress-strain state concrete columns, which a tested column represents.

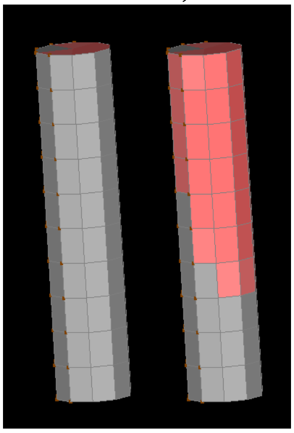

Figure 9. Cracks formation under transverse load restricted with soil resistance (5500 kN/m): the PTC column (b) – on the left; the non-encased sample – on the right; crack formation zones are highlited with pink.

Difference in crack formation allows formulating one more positive constructional feature of PTC short columns used in the underground walls under horisontal pressure. They are significantly resistant to crack formation. The following is especially important for underground constructions, which must be cracking resistant because of foundation constructions:

a) active contact with underground waters;

b) not accessibility of the apearing cracks for conducting the maintanance and repair works.

The combination of isolating properties of the plastic cases with high cracking resistance allows recommending PTC short columns as the most rational and effective constructions for underground frameworks and foundations in civil engineering.

3. Conclusion

The determined relative decrease in the equivalent stresses of PTC that entails an increase in its load capacity with respect to a purely concrete structure is due to the redistribution of stresses in PTC elements during their joint operation. It allows increasing the PTC load capacity of the concrete core in a more rational way. It has been determined that bearing stength capacity of PTC short columns is 25% higher, rigidity capacity is 15% higher than those of the caseless concrete column of the similar size. Crack formation in the core of PTC short columns happens under greater horisontal loads and in a lesser amount of concrete than in caseless concrete columns. Effectiveness improvement in bearing capacities and cracking resistence of PTC short columns under vertical and especially under horizontal loads allows recommending them as highly effective and reliable structural wall elements. Taking into account the low cost of a polymer tube, the use of PTC is a cost effective alternative to traditional structural solutions applied to frame elements in low-rise housing construction.

4. Acknowledgment

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