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Research paper

Bearing Capacity and Deformability of Three-Component Steel Reinforced Concrete Constructions Made of Lightweight Concrete

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Abstract

The article contains the study of strength and deformability of three-component steel-reinforced concrete structures made of a thin-walled steel shell, light concrete and rigid reinforcement in the form of a light steel thin-walled profile. The results of calculation, simulation and experimental researches of more than 40 steel-concrete elements are presented. The diagrams of the work of these constructions are compared with the comparison of experimental data and numerical modeling, which confirm the correctness of the introduction of the calculation model into the software complex, where special attention was paid to the boundary conditions of the work of the structure. The model with the indication of the concentration of internal stresses and the nature of the deformation of the structure in general, which fully corresponded to the experimental research, was analyzed. An adapted calculation algorithm for three-component steel-concrete constructions is presented, where the coefficients of working conditions for each of the constituent constructions are indicated. The relationship between relative flexibility and the lowering coefficient of operation of a thin-walled cylindrical steel shell is shown. Appropriate conclusions are formulated.

***Keywords**: deformability, flexibility, lightweight concrete, steel-reinforced concrete constructions, strength, thin-walled steel shell/*

1. Introduction

One of the new directions in the development of modern construction are steel reinforced concrete constructions made of lightweight concrete. It is the application of lightweight concrete in little-storey construction is a popular phenomenon, which justifies its use not only as a heater, but as a constructive material. The vivid representatives of this trend can be considered [1,9]. The design of three-component steel reinforced concrete structures made of lightweight concrete consisting of steel clasps, lightweight concrete and rigid armature in the form of light steel thin-walled profile is one of the type of lightweight steel constructions. The efficiency of the combination of these materials [2] in the complex steel-reinforced concrete structure is proved.

Taking into account the features of the work of thin-walled steel structures with lightweight concrete and comparing them with known similar steel-concrete structures, but with heavy concrete, it should be noted the fundamental difference between the work of these structures.

Therefore, as a result, the current issue nowadays is the development of theoretical and practical information about steel reinforced concrete structures made of lightweight concrete. So these studies have been carried out that describe the work of three-component steel reinforced concrete structures made of lightweight concrete in the form of racks working on longitudinal central compression. The work of these structures was verified by experimental tests and simulated in the software complex. Also it is presented the adapted calculation of these structures.

2. Experimental testing of three-component steel reinforced concrete structure made of lightweight concrete

The manufacturing of three-component steel-concrete structures was conditioned:

- the determination of the relationship between flexible and non-flexible patterns;
- the selection of optimal physical and mechanical properties of each component of steel reinforced concrete structure for maintenance of joint work.

By means of experimental tests the physical and mechanical parameters of each component of the steel-concrete structure are determined:

1. The steel shell (t=0.42mm) from galvanized sheet steel S350GD+Z;
2. Lightweight polystyrene density D800
3. Lightweight steel profile ∑50x30mm S350GD+Z.

The research was conducted to determine the nature of the steel shell as a separate structural element. The connection of the sheet steel of the cylindrical shell was due to the combination of the folding and rivet connection.

The samples on which the actual strength of the polystyrene-concrete was determined are shown in Fig. 1.

Fig. 1: Experimental samples of polystyrene concrete

The samples of three-component steel-reinforced concrete constructions CSCS40, CSCS150 made of steel shell, polystyrene concrete and LSTK profile are 400 mm and 1500 mm in length (Fig. 2).

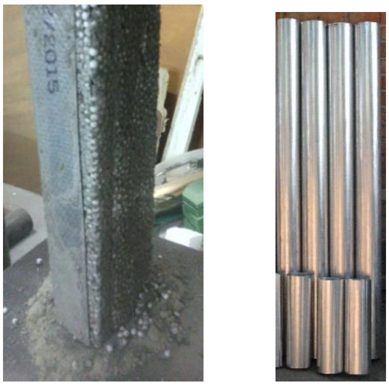


Fig. 2: Experimental samples of the three-component steel reinforced concrete structures: reinforced LSTC profile of open section, steel-reinforced concrete structures CSCS40, CSCS150

The tests on centrifugal compression were conducted in the laboratory conditions. (Fig. 3). Experimental research of reinforced steel LSTC profile of open section with polystyrene concrete showed inefficiency of the design due to the lack of compatible work of profile and polystyrene concrete core.

Fig. 3: Experimental samples of three -component steel-reinforced concrete constructions during testing: reinforced LSTC profile of open section, steel-reinforcment concrete constructions CSCS40, CSCS150

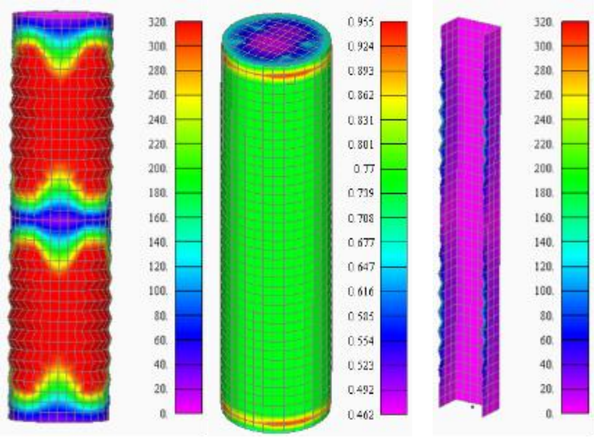
3. Numerical modeling of samples

For numerical modeling of the stress-strain state of three-component steel reinforced concrete structures a software package NASTRAN Femap 10.1.1 SC 32bit (Demo version) is used. It is the creation of a numerical model that would correspond to the actual work of steel structures (8).

Modeling of the finite element model of three-component steel reinforced concrete structure was performed according to the following algorithm:

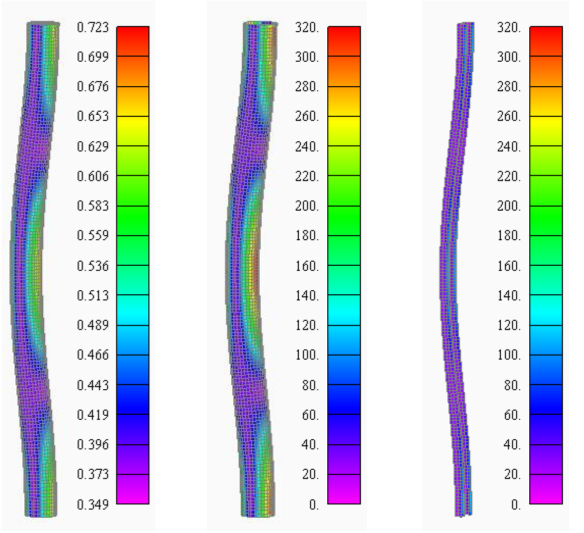
- determination of the relative coordinate system;
- construction, according to the corresponding coordinates, of plane cross sections of each of the elements of complex design;
- the formation of bulky bodies from the given flat geometric forms;
- the physical and mechanical characteristics for each of the materials, the initial data for the introduction of the material chart were taken from experimental tests;
- the choice of finite elements was determined by the following criteria: the time of execution of the calculation, the number of finite elements, the number of vertices of finite elements, the stress in finite elements was defined for the creation of a bulk finite element network of samples to use three-dimensional bulk elements such as a solid hexahedra shape with sides 10mm;
- the definition of boundary conditions;
- the application of loads (the maximum loads were determined by experimental tests);
- the correctness of the created model has been checked;
- the calculation of nonlinear static analysis (the definition and comparison of the stress-deformation state of the models with the experimental tests);
- the calculation of the stability (the determination of the general form of stability loss of flexible elements);
- the analysis of the received data.

The calculation results are shown on Fig 5-6.



a) a steel pipe shell b) polystyrene-concrete core c) the steel profile of the internal reinforcement

Fig. 5: The main stresses of a three-component steel reinforced concrete structure (MPa) and the general form of the deformation of the model elements of 400mm in length



a) polystyrene-concrete core b) a steel pipe shell c) the steel profile of the internal reinforcement

Fig. 6: The main stresses (MPa) and the general form of the deformation of the model elements of 1500mm in length

For the analysis of the obtained results of the calculation the diagrams of work of three-component steel-reinforced concrete structures are presented, in which the dependence of longitudinal forces and relative deformations is indicated.

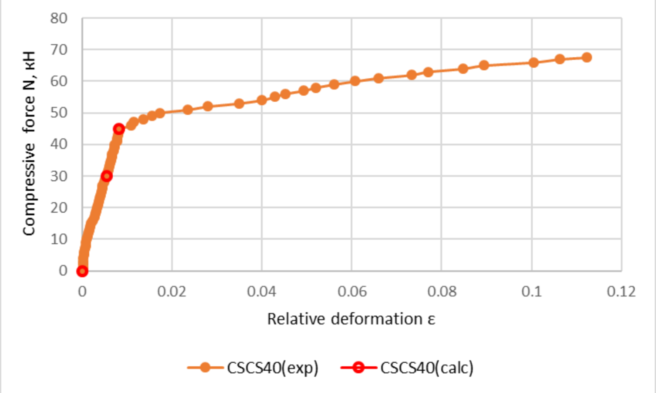


Fig. 7: The graph of short steel reinforced concrete constructions made of lightweight concrete based on experimental tests and numerical modeling.

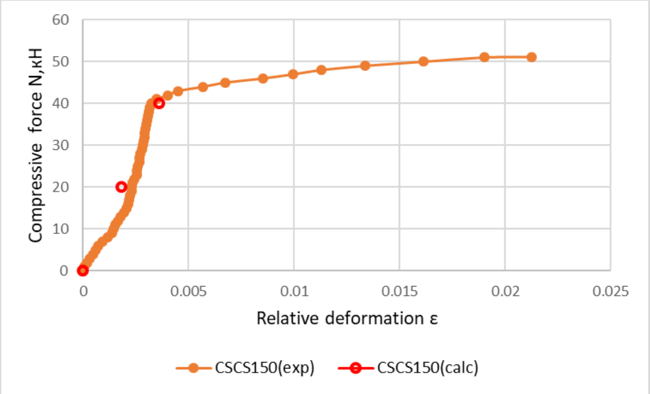


Fig. 8: The graph of work of long steel reinforced concrete constructions made of lightweight concrete based on experimental tests and numerical modeling.

As shown in Fig. 7-8 the deformation of models corresponds to the nature of the destruction of the experimental test samples.

4. The analytical calculation of tested three-component steel reinforced concrete constructions made of lightweight

The experimental research has shown that the loss of the local stable steel shell of closed sections is faster twith lower compressive loads than the loss of the overall stability. Moreover, the steel shell is included in the work, both on the central compression, and on the work of the clips for the concrete core.
The following formulas for calculating of ultra-lightweight steel-concrete structures on light concrete of round and rectangular cross-section are offered.

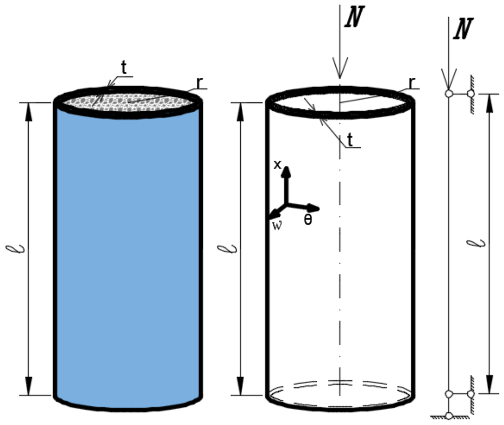


Fig. 9: Design schemes of pipe constructions

The general formula of strength in the central compression:

$$N_{Rd}^{cls} = N_{ls} + N_{lc} + N_{lp}\,, \tag{1}$$

where N_{Rd}^{cls} – the characteristic of the bearing capacity of the light combined section of the steel reinforced concrete structure;
Nls – the characteristic of the bearing capacity of a thin-walled steel shell:

$$N_{ls} = \alpha_s\, f_{yd} A_s, \tag{2}$$

where α – the coefficient, which considers the work of the steel shell, taking into account its stability:

$$\alpha_s = \frac{\sigma_s}{f_{yd}} \tag{3}$$

where As – cross-section area of the steel shell:
fyd – design resistance of steel;
σ_s – stress of the steel shell under central compression:

$$\sigma_s = \sigma_{x,R_d} \tag{4}$$

where σ_{x,R_d} – critical meridional stress of the steel shell under longitudinal bending.

$$\sigma_{x,R_d} = \chi f_{yk}\,, \tag{5}$$

where f_{yk} - characteristic yield strength of steel:

$$f_{yk} = \frac{f_{yd}}{\gamma_{M0}}\,, \tag{6}$$

where γM0 = 1,00
χ coefficients of weakening the loss of overall stability

$$\chi = 1 \text{ at } \bar{\lambda} \le \bar{\lambda}_0 \tag{7}$$

$$\chi = 1 - \beta \left(\frac{\bar{\lambda} - \bar{\lambda}_0}{\bar{\lambda}_p - \bar{\lambda}_0} \right)^n \text{ at } \bar{\lambda}_0 < \bar{\lambda} \le \bar{\lambda}_p \tag{8}$$

$$\chi = \frac{\alpha}{\bar{\lambda}^2} \text{ at } \bar{\lambda}_p \le \bar{\lambda} \tag{9}$$

The relative flexibility of the elasticity value should be determined by the formula:

$$\bar{\lambda}_p = \sqrt{\frac{\alpha}{1-\beta}} \tag{10}$$

Parameters of the relative flexibility of the shell for different compositional stresses are determined by the formulas:

$$\bar{\lambda}_x = \sqrt{f_{yk} / \sigma_{x,Rcr}}, \tag{11}$$

$$\bar{\lambda}_\theta = \sqrt{f_{yk} / \sigma_{\theta,Rcr}}, \tag{12}$$

The elastic critical meridional tension with its longitudinal bend:

$$\sigma_{x,Rcr} = 0,605 E C_x \frac{t}{r} \tag{13}$$

Substituting these values in the general formula (3) we have the following:

$$\alpha_s = \frac{\sigma_s}{f_{yd}} = \frac{\chi f_{yk}}{f_{yd}} = \chi \tag{14}$$

Nlc – the characteristic of the bearing capacity of lightweight concrete working in volume-tense state:

$$N_{lc} = \beta f_{cd} A_c \tag{15}$$

де β – the coefficient considering the work of concrete in a volume-tense state:

$$\beta = \frac{\sigma_{b,\tau}}{f_{cd}} \tag{16}$$

$\sigma_{b,\tau}$ – stress in the concrete core:

$$\sigma_{b,\tau} = f_{cd} + n\sigma_{\theta,Rd} \tag{17}$$

n – the coefficient of side compression:

$$n = \frac{\nu}{1-\nu} \tag{18}$$

The consolidated formula of the coefficient β :

$$\beta = \frac{f_{cd} + \frac{\nu}{1-\nu}\sigma_{\theta,R_d}}{f_{cd}} \tag{19}$$

ν –Puason coefficient of concrete;

$$\frac{\sigma_{b,\tau}}{\sigma_{\theta,Rd}} \le 1 \tag{20}$$

where σ_{θ,R_d} - the elastic critical stress of the collision compression with its longitudinal bend;
Ac – cross-section area of a concrete core;
fcd – estimated resistance of concrete;
Nlp – characteristic of the LSTC bearing capacity:

$$N_{lp} = \chi f_{ydp} A_{sp} \tag{21}$$

where Asp – cross-section area of the steel profile;
fydp – estimated resistance of the steel profile in the elastic stage of work.
The calculation of the steel shell of cylindrical sheet steel must take into account the loss of the durability of the cylindrical shell to achieve the limit of steel flux, which significantly reduces the strength of such elements. For conventional steel pipe constructions, which work as piping constructions, the lowering coefficient α_s =0.66 for samples of length 400мм, α_s =0.56 for samples of length 1500мм.
The bearing capacity of a concrete core is characterized by a volumetric stressed state that arises at the pressure in a steel cylinder-bearing sleeve. And the lightweight concrete performs a triple function:

- perceives external loads;
- provides stability of the steel profile;
- reinforces the steel shell by limiting the loss of local resistance in the middle of the construction section.

Let's consider the characteristic of the Nlp profile, which is located inside the lightweight steel shells. Given the nature of the destruction of three-component ultra-lightweight steel-smelting samples that describe the loss of overall stability of the profile, it can be assumed that although the profile is thin-walled, the work includes the entire section of the profile. Reinforcement of polysilicon concrete with complete concrete eliminates the loss of local stability, even the finest profile of that determination Aeff is not need.
Further calculation is made in accordance with [7].
It should be noted that the dependence of the decreasing coefficient χ (9) has the same relation to the relative flexibility for cylinder-drill shells up to 400 cm in radius up to 20 cm with a steel thickness of 0.4 mm to 1 mm. This dependence is depicted as a diagram (Fig. 10). This diagram is based on theoretical calculations for meridional axial compression.

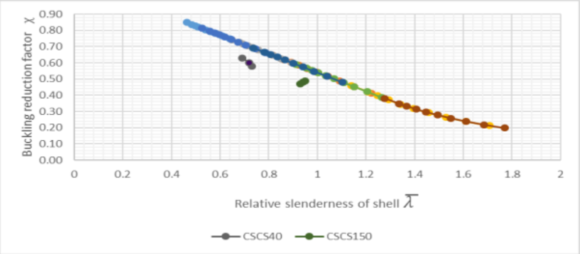


Fig. 10: The diagram of the dependence of the coefficient t χ on the reliability flexibility

Also, the feature of the calculation of these constructions is to take into account the strength of the connection of the steel element. Moreover, the relationship between the maximum stresses of the connection and the concrete core are interconnected, because concrete works in volume- tense state. It is proposed to establish an appropriate relationship between these stresses:
- if the stress in the concrete core along the whole element or in the most stressful place will be less than the maximum stress in the connection, then the calculation is taken without taking into

account the strength of the connection of the steel shell;
- if the stress in the concrete core along the whole element or in the most stressful place will be bigger than the maximum stress in the connection, the calculation of the steel shell will include the strengthening of the existing connection or replacing it for the stronger one.

All samples presented in the experimental research corresponded to the case when the stress in the seam of the steel shell is less than the maximum stress in the concrete core. When calculating the connections of a steel shell, it is most expedient to use the stresses which appear from the action of a concrete core in a critical volume-tense state. The stresses that occur in the connection of a shell of a circular cross section are shown in Fig. 11.

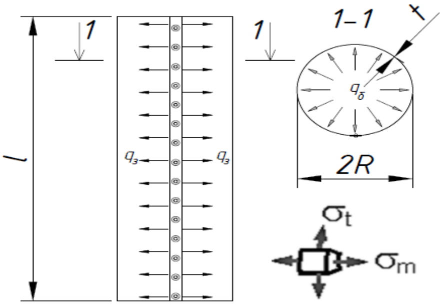


Fig. 11: Distribution of stresses in cylindrical tubular elements

The maximum stresses for each axis are as follows:

$$\sigma_m = \frac{\sigma_{b,\tau} R}{2t}, \tag{22}$$

In this case $\sigma_{b,\tau} = q_б$.

$$\frac{\sigma_m}{\sigma_{\theta,Rd}} \leq 1 \tag{23}$$

where σ_m – the critical stress in the transverse direction relative to the connection of the steel shell;

$q_б$ – uniformly distributed load on a steel shell in a cross section from the action of a concrete core in a volume-tense state;

R – radius of the steel shell;

t – thickness of the steel shell;

$$\sigma_t = \frac{\sigma_{b,\tau} R}{t}, \tag{24}$$

$$\frac{\sigma_t}{\sigma_{\theta,Rd}} \leq 1 \tag{25}$$

where σ_t – critical stresses in the longitudinal direction relative to the connection of the steel shell.

5. Conclusions

Comparison of the results of the experimental tests and numerical modeling of three-component steel reinforced concrete structures, which have a difference of up to 8%, confirms the correctness of the calculation model of this type of construction.

The adapted engineering calculation of three-component steel-reinforced concrete structures made of lightweight concrete taking into account the peculiarities of the joint work of each of the materials is given.

A generalized diagram of the dependence of the relative flexibility $\bar{\lambda}$ to the lowering coefficient of work of the steel thin-walled cylindrical shell χ (Fig. 10) is derived.

Analyzing the graph of Fig. 10 it can be concluded that the analytical calculations describe the actual work of steel-concrete structures made of lightweight concrete and have a discrepancy with the experimental research up to 10%.

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