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Calculating the Strength of Concrete Filled Steel Tube Columns of Solid and Ring Cross-Section

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Abstract

The authors have carried out experimental and theoretical studies of a new design of concrete filled steel tube (CFST) columns with pressed structure of concrete. The proposed design improvement idea is to make CFST columns with preliminary pressed concrete core. The bearing capacity of centrally compressed samples of CFST has increased by 20 ÷ 25%. The obtained results are explained by a significant increase in the strength of concrete core in such preliminary compressed CFST samples due to the simultaneous manifestation of three effects: long-term compression of concrete mix, preliminary lateral compression of the concrete core and its work under the conditions of volume compression. The calculation of strength of CFST should be carried out on the basis of nonlinear reinforced concrete deformation model. Three-axis tensely-deformed conditions are assumed for the analytical description of work of the concrete core and the external steel holder. The basic dependencies, which allow to carry out such approximate calculations of the ultimate stress of compressed CFST, are resulted, too.

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Keywords: concrete filled steel tube; preliminary pressed; nonlinear deformation model; three-axis tensely; concrete core; external steel holder.

1. Introduction

Concrete filled steel tube columns become more and more popular in modern building, especially at erection of high-rise buildings [1-7]. CFST have a number of essential advantages. The main advantages are the high bearing capacity and operational reliability, the high speed of construction of the frame, the reduction of the consumption of material and financial resources for the manufacturing of CFST [8-15]. However, there are the disadvantages of

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these constructions. One of the most significant constructional drawbacks of traditional CFST is the practical absence of the effect of the holder at operational loadings because of the smaller values of Poisson's ratios of the concrete (compared with the steel), that is why the steel holder tends to break away from the concrete core in the elastic stage. As a result, it is impossible to use effectively the strength properties of concrete core, and it is often difficult to ensure the sufficient adhesion between the concrete core and steel holder in the areas where the loads are transferred from ceiling on a column.

2. The advanced construction of concrete filled steel tube columns

It is offered to make the concrete filled steel tube columns with preliminary pressed concrete core (to improve their construction). The preliminary compression of CFST can be carried out by consecutive pressing of several steel tubules with gradually increased diameters, into concrete mix along the directing core, coaxially located to the external holder [16].

Three steel tubes, which have coordinated diameters of cross-sections, are pressed into the concrete mix through the hole at the top end cap of the sample. The rod, preliminary coaxially installed to the steel holder of the sample, serves as the guide for the first tube. The first and second tubes serve as the guide for the second and third tube correspondingly. The first two tubes have the small holes in the walls. The pressing of concrete mix takes place during the process of pressing the tubes into the mix, and «free» water, not entered into interaction with cement particles, is extracted out of the concrete mix through these holes (the initial W/C decreased from 0,42 to 0,38). The last tube has not any holes in the walls. When the last tube is pressed into the mix, the pressing pressure (in our experiments about 2 ÷ 3 MPa) is transmitted to the inner surface of the steel holder and the preliminary tension of the holder takes place. The last tube is remained as the inner rod of the element after its production, and the guide rod and the tubes with perforated walls are extracted and are used for preliminary compression of the following construction.

The use of long-term compression of concrete mix, carried out with the use of the specially developed technology, allows to improve significantly the quality of the concrete core and to increase its strength approximately by 60%. The thickness of the cement layer between the aggregates is decreased, the fine-grained structure of cement stone of better quality with smaller pore sizes is received during the process of pressing. In addition, the pressing pressure, transferred through the concrete mix, makes the preliminary tensile stresses in the steel holder.

Finally we have got the preliminary compressed concrete of better quality, which has less quantity of pores and greater strength. The constructions of laboratory samples of CFST have the diameter of cross section 219 mm and preliminary compressed core. The inner cylindrical rod has the diameter of 44 mm and the wall thickness of 2,2 mm.

The main results of the tests of these samples under the influence of short-term compressive stress testify to the fact that there is the noticeable increase of the elastic work limit and of the destructive load for all preliminary stressed samples, compared with the CFST of classic construction. The bearing capacity of centrally compressed samples of CFST has increased by 20 ÷ 25% compared with similar samples of CFST without stress. The level of the limit of elastic work has increased by about 30 ÷ 35%. The bearing capacity has increased from 1,5 to 2,1 times compared with the traditional reinforced concrete elements with similar parameters of concrete and reinforcement.

The received results are explained by the significant increase of the strength of concrete core in the preliminary compressed CFST samples due to the simultaneous display of three effects: long-term compression of concrete mix, preliminary lateral compression of the concrete core and its work in the conditions of volume compression. The strength of the concrete core of concrete filled steel tube elements of the new construction has increased from 2,5 to 4,1 times.

3. The basic information about the calculation of the strength of normal sections

The calculation of strength of CFST, taking into account their cross-section shape, the presence of external reinforcement and the possible use of additional reinforcement of concrete core, including rigid reinforcement, should be carried out on the basis of nonlinear deformation model of reinforced concrete. The features of deformation of the concrete core and steel holder in the conditions of volume stress state should be taken into account. The main dependences, offered for the calculation of the strength, are presented in the work [17].

It is necessary to note that the diagrams of deformation « $\sigma-\varepsilon$ » for the concrete and the steel are the initial basis for the calculation of the strength with using nonlinear deformation model. The main feature of the calculation of compressed CFST elements is the absence of such diagrams for concrete and metal working in the conditions of complex stress state. That is why the strength calculation is offered to carry out in two stages.

At the first stage the dependences between the stresses and deformations of the axial direction in the concrete core and the steel holder under the influence of the centrally applied load at the CFST element are determined. The necessary parameters for these dependencies are calculated from the joint solution of equations, which connect the stresses and deformations of both materials and are written in the form of generalized Hooke's law with variable factors of elasticity and shear deformations. The steel is considered as the isotropic material, and the concrete – as the transversely isotropic material. To solve these systems the equations of deformation compatibility of the concrete core and the steel holder are additionally used the equation of the projections equilibrium of external forces and internal efforts on the longitudinal axis of the element. The solution is made by the method of iterations.

As a result of this calculation we can calculate all the components of the stress state of CFST, including the value of lateral pressure of the steel holder at the concrete σ_{br} at any stage of construction work [18-20]. The parameters of the diagrams « $\sigma_{iz}-\varepsilon_{iz}$ » for the concrete core ($i = b$) and for the steel holder ($i = p$) are largely dependent on this value of lateral pressure of the steel holder at the concrete.

4. The calculation of stresses of transversal direction

The strength of the volume-compressed concrete core is largely dependent on the value of transverse stresses, which take place in it under the load. The tangential stresses $\sigma_{b\tau}$ will be equal to the radial stresses σ_{br} throughout the cross-section of the concrete core in the centrally compressed CFST of round cross-section. The radial stresses σ_{br} are determined by the value of lateral pressure of the steel holder at the concrete, calculated at the point of their contact.

The value of radial and tangential stresses will be changed over the cross section of the construction in the CFST of ring cross-section. The law of its change can be taken from the known solution of the Lame, which is given by the following formula (for thick-walled cylinders, loaded by external pressure σ_{br}^{ext} and located in the elastic stage):

$$\sigma_{br}=\sigma_{br}^{ext}\left(1-r_0^2/r^2\right)/\left(1-r_0^2/r_b^2\right); \qquad (1)$$

$$\sigma_{b\tau}=\sigma_{br}^{ext}\left(1+r_0^2/r^2\right)/\left(1-r_0^2/r_b^2\right). \qquad (2)$$

Obviously, the distribution of radial and tangential stresses in the concrete core of CFST with internal steel rod of ring cross-section will largely be determined by the relations of geometrical and structural parameters of the core and the rod. We will consider the approximate solution of the determination of the stresses in the cross-section of these constructions, loaded by the external pressure.

We can designate the modulus of elasticity and Poisson's ratios of the concrete core and the inner cylindrical rod E_c, μ_c and E_p, μ_p correspondingly. Taking into account the (1) and (2) equations for determination of the radial and tangential stresses in the concrete core and the inner rod of ring cross-section we can offer the following dependences:

$$\sigma_{ir}=m_i-n_i/r^2; \qquad (3)$$

$$\sigma_{i\tau}=m_i+n_i/r^2, \qquad (4)$$

in which m_i and n_i − the undetermined constants for the concrete core ($i = b$) and the inner rod ($i = p$).

These constants can be found from the simultaneous solution of the equations (3) and (4) for the concrete core and the inner steel rod taking into account the conditions of their joint deformation.

As a result of this solution [17] the following formulas are received:

$$m_b = \sigma_{br}^{ext} p_0; \tag{5}$$

$$n_b = \left(m_b - \sigma_{br}^{ext}\right) r_b^2; \tag{6}$$

$$m_p = p_1 m_b + p_2 \sigma_{br}^{ext}; \tag{7}$$

$$n_p = m_p r_0^2, \tag{8}$$

in which

$$p_0 = \left(p_5 E_p / E_c + p_2 p_3\right) / \left(p_4 E_p / E_c - p_1 p_3\right); \tag{9}$$

$$p_1 = \left(r_p^2 - r_b^2\right) / \left(r_p^2 - r_0^2\right); \tag{10}$$

$$p_2 = r_b^2 / \left(r_p^2 - r_0^2\right); \tag{11}$$

$$p_3 = \left(1 + \vartheta_p\right)\left(1 - 2\vartheta_p + r_0^2 / r_p^2\right); \tag{12}$$

$$p_4 = \left(1 + \vartheta_b\right)\left(1 - 2\vartheta_b + r_b^2 / r_p^2\right); \tag{13}$$

$$p_5 = \left(1 + \vartheta_c\right) r_b^2 / r_p^2 . \tag{14}$$

The value of the pressure of the steel holder at the concrete core is conventionally accepted 10 MPa. The analysis of the results the calculation of the samples of central compressed concrete filled steel tube column with the diameter of the cross-section 219 mm shows, that the reduction of radial stresses over the cross-section of the concrete core with wall thickness of inner rod ⩾ 2 mm is not more than 10% and can not be taken into account in calculating of the strength of CFST. The reduction of radial stresses is more significant (64%) for wall thickness of inner rod – 0,5 mm.

5. The determination of the strength of concrete core

The stress at the top of the diagram «$\sigma_{bz} - \varepsilon_{bz}$» of the concrete core $f_{ck,c}$ (the standard compressive strength of the volume compressed concrete) for columns of round cross-section (at any point $\sigma_{br} = \sigma_{b\tau} = \sigma_{br}^{ext}$) can be calculated from the known formula:

$$f_{ck,c} = f_{ck} + k\sigma_{br}^{ext}, \tag{15}$$

in which f_{ck} − the standard compressive strength of the concrete to one-axial compression; k − the factor of lateral pressure, which is determined by the following formula [18]:

$$f_{ck,c} = f_{ck}\left[1+\left(0,25\overline{\sigma}+\frac{\overline{\sigma}-2}{4}+\sqrt{\left(\frac{\overline{\sigma}-2}{4}\right)^2+\frac{\overline{\sigma}}{b}}\right)\right], \tag{16}$$

in which

$$\overline{\sigma} = 0,48e^{-(a+b)}\rho^{0.8}; \tag{17}$$

$$\rho = \frac{f_{pk}A_p}{f_{ck}A}. \tag{18}$$

The preliminary compression of CFST is taken into account by the introduction of the initial lateral pressure of the steel holder at the concrete core σ_{br0} in the calculation and by the increase of concrete strength:

$$f_{ck,p} = f_{ck} + \alpha\sqrt{\Delta f \sigma_{bro}}, \tag{19}$$

where $\alpha \approx 1$ – the factor, depending on the composition of concrete mix; $\Delta f = 0,44/\sqrt{f_{ck}}$ – the correction factor for the heavy concrete without plasticizing admixtures.

The relation of compressive stresses $\sigma_{br} < \sigma_{b\tau} < f_{ck,c}$ is characteristic for centrally compressed concrete filled steel tube elements of ring cross-section. Taking into account the small influence of the intermediate stress $\sigma_{b\tau}$ on the strength of volume compressed concrete [21], it is recommended to calculate the strength, using the averaged compressive strength of the concrete core, determined according to the corresponding value of lateral pressure σ_{brm}.

The averaged over the normal cross-section of CFST lateral pressure can be found by dividing the longitudinal force in the concrete core N_c, calculated by taking into account the variable over the cross-section of the element value of lateral pressure σ_{br}, by the area of the concrete core. The factor of lateral pressure is considered constant for the given construction. The longitudinal force in the concrete core N_c for CFST with the internal steel rod of the ring cross-section is determined by the following formula:

$$N_c = \int_{r_p}^{r_b} (f_{ck} + k\left(m_b - n_b/r^2\right))2\pi r dr. \tag{20}$$

The averaged value of lateral pressure is determined by the following formula:

$$(\sigma_{pz}-\sigma_{p\tau})^2 + (\sigma_{p\tau}-\sigma_{pr})^2 + (\sigma_{pr}-\sigma_{pz})^2 = f_{pk}^2 \tag{21}$$

in which the parameter K_r is determined by the geometrical and deformation characteristics of the concrete core and the steel rod

$$K_r = p_0(1-2\ln\frac{r_b}{r_p}) + 2\ln\frac{r_b}{r_p}, \tag{22}$$

and the parameter p_0 are determined by the formula (10).

The calculated compressive strength of the concrete $f_{cd,c}$ is determined by dividing of the corresponding standard value of compressive strength $f_{ck,c}$ by the factor of reliability for the concrete at its compression γ − partial safety factor.

6. The stress condition of the steel holder

The steel holder is in the complex stress condition in the centrally compressed column. The components of the stress condition of the steel holder in the limiting equilibrium are connected by the condition of yielding of Hencky-Mises:

$$(\sigma_{pz} - \sigma_{p\tau})^2 + (\sigma_{p\tau} - \sigma_{pr})^2 + (\sigma_{pr} - \sigma_{pz})^2 = f_{pk}^2. \qquad (23)$$

The stress σ_{pz} in the middle cross-section of the holder can be received from the formula (23).

$$\sigma_{pz} = f_{ck}\left(\sqrt{\rho^2 - 3\bar{\sigma}^2} - \bar{\sigma}\right)\frac{A}{A_p}. \qquad (24)$$

7. The approximate calculation of the strength of CFST

It is recommended to carry out the approximate calculation of the strength of the normal sections of CFST on limiting efforts at the stages of choosing of the constructive solution and rough design. In this case the strength condition of compressed CFST element is:

$$N = mm_e\phi\left(f_{ck,c}A + \sigma_{pz}A_p\right), \qquad (25)$$

where m – the factor of working conditions. It is equal to 0,95, when the diameter of the element is $d \leq 150$ mm, in other cases, $m = 1$; m_e − the factor, with the help of which the influence of the initial eccentricity e_0 of the applying of compressive force on the strength of CFST is taken into account; φ − the factor, depending on the effective flexibility λ_{eff} .

$$m_e = 1 - \left(\frac{e_0}{2r_b}\right)^{0,5}. \qquad (26)$$

$$\varphi = 1 - 3 \cdot 10^{-6}\lambda_{eff}. \qquad (27)$$

8. Conclusions

The new construction of CFST with the preliminary compressed concrete core is worked out and the method of its production is offered. The calculation of CFST strength is offered to be carried out by the iteration method on the basis of the nonlinear deformation model, considering the heterogeneity of the stress condition and the physical nonlinearity of the concrete core and the steel holder.

The basic dependences, which allow to carry out the approximate calculations of the strength of compressed CFST on limiting efforts, are resulted.

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