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Strength of Short Concrete Filled Steel Tube Columns with Spiral Reinforcement

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Abstract. To further increase the bearing capacity and survivability of reinforced concrete filled steel tube (RCFT) columns, it is offered to supply their concrete core with additional spiral reinforcement. Such reinforcement also has a positive effect on the fire resistance of the columns. The practical use of compressed RCFT elements is restrained by the absence of procedures for determining their bearing capacity. A calculation procedure for determining the strength of short centrally compressed RCFT columns is offered. It is rather easy in terms of application and it allows one to take into account the main features of power resistance of such columns. The results of comparison of the calculated strength with experimental data are presented. The analysis of these results testifies that the accuracy of calculation of RCFT columns strength is sufficient for practice. The offered calculation procedure allows to provide the wider use of RCFT columns in construction practice as heavy loaded bearing elements of buildings and structures. It is recommended to use high-strength longitudinal reinforcement for further increase of the efficiency of these columns.

1. Introduction

One of the main directions of modern building structures development is the reduction of their material consumption and cost, providing the required bearing capacity and high survivability. Concrete filled steel tube (CFT) columns fully meet such requirements, in which the properties of concrete and steel are most rationally combined [1-7]. It is especially effective to use them as short compressed elements, supporting large loads with small eccentricities [8-15].

For the purpose of further increase of bearing capacity and survivability of reinforced concrete filled steel tube (RCFT) columns it is offered to supply their concrete core with additional spiral reinforcement. Such reinforcement also has a positive effect on the fire resistance of the columns, as a spiral, mounted with some distance from the inner surface of the steel pipe, is able to provide significantly longer resistance of the volumetrically compressed reinforced concrete core in fire conditions. The practical use of compressed RCFT elements is restrained by the absence of procedures for determining their bearing capacity. In Russia such structures have not been studied before.

Experimental researches, recently carried out in China and Malaysia [16,17], proved the high survivability of such structures, but they missed the theoretical aspects of the problem at hand. In the joint work of Chinese and Japanese scientists [18] numerical finite element analysis of power resistance of compressed RCFT elements was carried out. In this case the empirical formulas were used for determining the strength of concrete and the lateral pressure of concrete core.

In this paper the procedure for calculating the strength of short centrally compressed RCFT columns of circular cross section, based on theoretically derived formulas, is offered.

2. Calculation procedure

Bearing capacity is dependent on the strength of normal cross sections for a short centrally compressed RCFT column. Using the method of limiting forces this strength can be determined by formula:

$$N = f_{cc}A + \sigma_{pz}A_p + \sigma_s A_s \tag{1}$$

where f_{cc} – strength of volumetrically compressed concrete core; σ_{pz} – compressive stress of axial direction in the steel holder in the limiting state of RCFT element; σ_s – compressive stress in the longitudinal reinforcement in the limiting state of RCFT element; A, A_p and A_s – cross-sectional areas of the concrete core, steel holder and longitudinal reinforcement.

Compressive strength is the most important mechanical characteristic of the reinforced concrete core of RCFT column. In centrally compressed elements of circular cross-section the concrete is in the conditions of triaxial compression by axial stresses σ_{cz} and transversal stresses σ_{cr}, which ensure the uniform lateral compression.

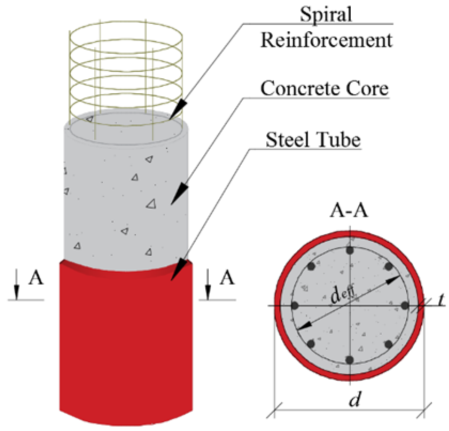

Figure 1. Reinforce concrete filled steel tube column construction.

Inspection of the scheme of the column cross-section (figure 1) shows that reaction lateral pressure acts on the concrete within the diameter of the spiral d_{eff} in the process of power resistance. The reaction lateral pressure is due to the restraining influence of both the outer steel holder and the spiral reinforcement. The principle of superposition for solving physically nonlinear problems is not applicable. Therefore, the essence of the offered calculation procedure comes down to the following.

Initially the power resistance of spirally reinforced concrete element is considered. At the second stage the problem of cooperation of this element and the outer steel holder is solved. Then the averaged values of strength and lateral pressure of concrete over the entire cross-sectional area are determined. When the stress-strain state of the concrete core is known, the compressive stresses in the steel holder and longitudinal reinforcement are calculated. As a result, the strength of column is calculated using the formula (1).

The earlier derived formula [19] is used for determining the strength of volumetrically compressed concrete core, enclosed in spiral reinforcement casing:

$$f_{cs} = f_c \alpha_{cs} \tag{2}$$

$$\alpha_{cs} = 1 + \left\{ 0.5\bar{\sigma}_{sc} + \frac{\bar{\sigma}_{sc} - 2}{4} + \left[\left(\frac{\bar{\sigma}_{sc} - 2}{4} \right)^2 + \frac{\bar{\sigma}_{sc}}{b} \right]^{1/2} \right\} \tag{3}$$

where f_c – unconfined compressive strength of concrete; $\bar{\sigma}_{sc}$ – relative value of lateral pressure of concrete core in the limiting state; b – coefficient of material, which is taken equal to 0.118 for heavy concrete [20].

The value of relative lateral pressure $\bar{\sigma}_{sc}$ is calculated by the formula:

$$\bar{\sigma}_{sc} = \rho_{sc} \frac{\sigma_{sc}}{f_c} \tag{4}$$

where ρ_{sc} – coefficient of confinement reinforcement by spirals; σ_{sc} – tensile stress in the spiral reinforcement, which can be determined from the formula:

$$\sigma_{s,c} = \varepsilon_{sc} E_{s,c} \leq f_{y,c} \tag{5}$$

where ε_{sc} – relative tensile strains of spiral reinforcement; $E_{s,c}$ – modulus of elasticity of steel of spiral reinforcement; $f_{y,c}$ – yield point of steel of spiral reinforcement.

The following formula for calculating the value ε_{sc} is derived in the work [19]:

$$\varepsilon_{sc} = -\frac{\upsilon_{zr}}{q\nu_{cs}E_c} f_{cs} \tag{6}$$

in which,

$$q = 1 - \frac{E_{s,c}}{E_c} \rho_{sc} \left(1 - \upsilon_{rr}\right) \tag{7}$$

where E_c – initial modulus of elasticity of concrete; υ_{zr} , υ_{rr} – coefficients of transverse strains of concrete for the accepted transversal model of concrete stress-strain state; ν_{cs} – coefficient of elasticity at the vertex of the deformation diagram of spirally reinforced concrete, calculated by the formula:

$$\nu_{cs} = \frac{f_{cs}}{\varepsilon_{cs} E_c} \tag{8}$$

where ε_{cs} – relative strain of shortening at the vertex of the deformation diagram of spirally reinforced concrete.

The values of coefficients of transverse strains υ_{zr} and υ_{rr} are calculated depending on the Poisson's ratio of quasi-elastic concrete and the elasticity coefficient ν_{cs} using the formulas given in the work [6]. The formula for determining the strain of volumetrically compressed concrete is also given in [6] :

$$\varepsilon_{cs} = \alpha_{cs}^{2.5} \left[\varepsilon_{c1} - \frac{f_c}{E_c} \left(1 - \alpha_{cs}^{-1.5}\right) \right] \tag{9}$$

in which α_{cs} – coefficient of strength growth of volumetrically compressed concrete, calculated by the formula:

$$\alpha_{cs} = f_{cs} / f_c \tag{10}$$

At the second stage the strength of spirally reinforced concrete core, which has an outer steel holder, is determined f_{cc1}. For this purpose the formulas (2, 3) is used, in the right-hand side of which the value f_{c} is substituted by f_{cs} and the relative lateral pressure of concrete core $\overline{\sigma}_1$, calculated by the formula:

$$\overline{\sigma}_1 = 0.4\exp(-1.5b)\xi_1^{0.8} \tag{11}$$

where ξ_1 – constructional coefficient, calculated by the formula:

$$\xi_1 = \frac{f_y A_p}{f_{cs} A} \tag{12}$$

in which f_{y} – yield point of steel holder.

Outer steel holder lateral pressure acts on the concrete located in the peripheral zone (outside the diameter of the spiral d_{eff}) in the process of power resistance. For this zone the relative value of pressure $\overline{\sigma}_2$ is also determined from the formula (11), but depending on the constructional coefficient ξ_2. This coefficient is calculated by the formula (12), in which f_{cs} is substituted by f_{c}. The strength of concrete of peripheral zone f_{cc2} is determined from the formulas (2, 3), depending on the strength of initial concrete f_{c} and the relative lateral pressure $\overline{\sigma}_2$.

In order to simplify the calculations it is offered to use the averaged design compressive strength of concrete core f_{cc} for the method of limiting forces. It is determined from the formula:

$$f_{cc} = f_{cc2}\left(1 - \beta_c^2\right) + f_{cc1}\beta_c^2 \tag{13}$$

in which the value of coefficient β_{c} is equal to the ratio of the diameter of the spiral d_{eff} to the diameter of the entire concrete core of the element d_{c} ($\beta_{\text{c}} = d_{\text{eff}} / d_{\text{c}}$).

To determine the compressive stress of axial direction in the steel holder σ_{pz}, Genka-Mises yield criterion for a plane stress state is used. As a result, the following formula is derived:

$$\sigma_{\text{pz}} = f_{\text{c}}\left[\left(\xi_2^2 - 3\overline{\sigma}^2\right)^{1/2} - \overline{\sigma}\right]\frac{A}{A_{\text{p}}} \tag{14}$$

in which $\overline{\sigma}$ – averaged value of relative lateral pressure of concrete core, calculated by the formula:

$$\overline{\sigma} = \overline{\sigma}_1\alpha_{cs}\beta_c + \overline{\sigma}_2\left(1 - \beta_c\right) \tag{15}$$

The compressive stress in the longitudinal reinforcement σ_{s} should be determined from the condition of its combined deformation with the concrete core $\varepsilon_{\text{s}} = \varepsilon_{\text{cc}}$. The strain of concrete core ε_{cc} at the vertex of its deformation diagram is calculated by the formula:

$$\varepsilon_{cc} = \alpha_c^{2.5}\left[\varepsilon_{cs} - \frac{f_{cs}}{E_c}\left(1 - \alpha_c^{-1.5}\right)\right] \tag{16}$$

in which α_{c} – coefficient of strength growth of spirally reinforced concrete, encased in the steel holder, which is calculated by the formula:

$$\alpha_c = f_{cc} / f_{cs} \tag{17}$$

It is recommended to take three- or two-line diagram of reinforcement deformation and use the formulas given in the set of rules 63.13330.2012 for calculation of the stress σ_s.

Thus, all the dependences, which are necessary for calculating the strength of short centrally compressed RCFT column, are offered.

3. Obtained result

The adequacy of the offered calculation procedure was verified by comparing the experimental strength values of centrally compressed RCFT columns Nu^{Exp}, taken upon our researches and the experiments of other scientists [17], with the calculated data Nu^{Th}.

Six series of samples, made of pipes with the diameter of 219 mm, the wall thickness of 5 and 7 mm and the height of 1000 mm, were tested in our experiments. Yield point of pipe steel was 275 MPa. Standard heavy concrete and self-stressing concrete (the series was designated by the letter H) were used. Prismatic strength of concrete was from 25.2 to 58.1 MPa. The spiral was made of wire with the diameter of 5 mm with conventional yield point of 545 MPa. The spiral pitch was 40 mm in the samples of the series I.5, IN.5 II.5, IIH.5 and 30 mm in the samples of the series I.7 and IN.7. 6ø6 A500C steel bars with yield point of 550 MPa were used as longitudinal reinforcement.

The samples, made of pipes with the diameter of 140 mm, the wall thickness of 2.8 mm and the height of 400 mm, were tested in the experiments of Malaysian researchers. Yield point of steel pipe was 355 MPa. The strength of initial concrete of all samples was 46.8 MPa. The spiral was made of wire with the diameter of 3.2 mm with yield point of 340 MPa. The spiral pitch varied from 18.2 to 48.2 mm. 6ø5 B500 steel bars with yield point of 340 MPa were used as longitudinal reinforcement. The samples of CFT series did not have spiral reinforcement.

The results of carried out comparison of theoretical data with our experiments are given in table 1, with the Malaysian researches in table 2. Analysis of the results shows that the accuracy of calculation of RCFT columns strength is sufficient for practice. Maximum deviations of experimental strength from the calculated strength were + 11% / - 5%. Coefficient of variation of the error vector at comparison of theoretical data and analyzed experimental data was 6.5%. The angle of inclination of this vector to the axis with theoretical loads was 46.1º.

Table 1. Comparison of theoretical and experimental strength of samples.

	s, mm	f_c, MPa	f_{cc}, MPa	N_u^{Th}, kN	N_u^{Exp}, kN	$\frac{N_u^{Exp}}{N_u^{Th}}$
I.5	30	26.3	62.6	2858	2983	1.04
IH.5	30	52.1	85.9	3549	3817	1.08
I.7	30	26.3	72.7	3512	3417	0.97
IH.7	30	53.0	94.2	4141	4250	1.03
II.5	40	26.7	62.4	2674	2917	1.09
IIH.5	40	52.4	84.1	3824	3750	0.98

Table 2. Comparison of theoretical and experimental strength of samples.

	s, mm	f_{cc}, MPa	N_u^{Th}, kN	N_u^{Exp}, kN	$\frac{N_u^{Exp}}{N_u^{Th}}$
CFT	-	73.93	1347	1409	1.11
S45	48.2	77.63	1468	1418	0.96
S35	38.2	78.26	1472	1452	0.98
S25	28.2	79.10	1483	1431	0.95
S15	18.2	79.96	1489	1484	0.99

It should be noted that the offered formulas are acceptable for RCFT columns made of both standard heavy concrete and self-stressing concrete. On substituting the corresponding coefficient of material *b* [6] into the dependences (3) and (11), the strength of columns made of fine grained concrete can be calculated.

4. Discussion

Carried out researches have shown that the use of the method of limiting efforts for determining the strength of short centrally compressed RCFT columns can produce acceptable results for practice. However, this method has a significant drawback. It does not make possible to limit the longitudinal strains of columns. Meanwhile, the examined columns differ in increased deformability even in comparison with CFT columns, which do not have spiral reinforcement. The value ε_{cc} can reach 1 ÷ 1.5% and more for these columns. It is hardly possible to use the columns of buildings with such strains.

More acceptable procedure for calculating RCFT columns should be based on nonlinear deformation model. It requires the development of special computer programs [6]. The offered calculation procedure, based on the method of critical forces, is perfectly acceptable for the approximate evaluation of strength, which is often in demand at the stage of feasibility study of project.

Analysis of the results of carried out calculations shows that because of the increased deformability of the examined samples it becomes possible to make the best use of high-strength longitudinal reinforcement in them. This fact should be referred to the advantages of RCFT columns and it should be taken into account in design practice.

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References

[1] Liang Q Q and Fragomeni S S 2010 Nonlinear analysis of circular concrete-filled steel tubular short columns under eccentric loading *J. of Constructional Steel Research* vol 66 pp 159–69
[2] Popovics S 1973 A numerical approach to the complete stress-strain curves of concrete *J. Cement and Concrete Research* **3(5)** pp 583–659
[3] Fafitis A and Shah S P 1985 Lateral reinforcement for high-strength concrete columns *ACI Materials J.* **87(12)** pp 212–32
[4] Fattah A M 2012 *Behaviour of concrete columns under various confinement effects* (Kanzas, USA: Kanzas State University) p 399
[5] Shams M and Saadeghvaziri M A 1999 State of the art of concrete-filled steel tubular columns*ACI Structural J.* **94** S51 pp 558–71
[6] Krishan A L, Astafieva M A and Sabirov R R 2016 *Calculation and construction of concrete filled steel tube columns* (Saarbrucken, Deutschland: Palmarium Academic Publishing) p 261
[7] Nesvetaev G V and Rezvan I V 2011 Evaluation of strength of pipe concrete *Fundamental sciences* **12** pp 580–3
[8] Han L H, He S H and Liao F Y 2011 Performance and calculations of concrete filled steel tubes (CFST) under axial tension *J. of Constructional Steel Research* **67(11)** pp 1699–709
[9] Han L H and An Y H 2014 Performance of concrete-encased CFST stub columns under axial compression *J. of Constructional Steel Research* **93** pp 76–92
[10] Imran I and Pantazopoulou S J 1996 Experimental study of plain concrete under triaxial stress *ACI Materials J.* **93(6)** pp 562–73
[11] Krishan A L and Krishan M A 2014 Strength of axially loaded concrete-filled steel tubular columns with circular cross-section *Advances of Environmental Biology* **8(6)** pp 1991–4
[12] Nishiyama I, Morino S, Sakino K and Nakahara H 2002 *Summary of Research on Concrete-*

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Filled Structural Steel Tube Column System Carried Out Under The US-JAPAN Cooperative Research Program on Composite and Hybrid Structures (Japan) p 176
[13] Sakino K, Nakahara H, Morino S and Nishiyama A 2004 Behavior of centrally loaded concrete-filled steel-tube short columns *J. of Structural Engineering ASCE* **132(1)** pp 123–33
[14] Uy B, Tao Z and Han L H 2011 Behaviour of short and slender concrete-filled stainless steeltubular columns *J. Constr Steel Res* **67(3)** pp 360–78
[15] Nesterovich A P 1987 *Strength of concrete filled steel tube elements of 500 mm and more diameter at axial compression* (Moscow) p 236
[16] Lai M and Ho J 2014 Confinement effect of ring-confined concrete-filled-steel-tube columns under uni-axial load *Engineering Structures* **67** pp 123–41
[17] Hamidian M R, Jumaat M Z, Alengaram U J, Ramil Sulong N H and Shafig P 2016 Pitch spasing effect on the axial compressive behavior of spirally reinforced concrete-filled steel tube (SRCFT) *Thin-Walled Structures* **100** pp 212–23
[18] Xiamuxi A and Hasegawa A 2012 A study on axial compressive behaviors of reinforced concrete filled tubular steel column *J. of Constructional Steel Research* **76** pp 144–54
[19] Krishan A L 2014 Power resistance of compressed concrete elements with confinement reinforcement by means of meshes *Advances of Environmental Biology* **8(6)** pp 1987–90
[20] Karpenko N I 1996 *General models of reinforced concrete mechanics* (Moscow: Stroyizdat) p 416