Concrete Core Strength and Deformability in Prestressed Concrete Filled Steel Tube Columns

E P Chernyshova¹, V E Chernyshov², A I Sagadatov³

¹Associate Professor of Design Department, Nosov Magnitogorsk State Technical University, 11 Uritsky Str., 455000, Magnitogorsk, Russia
²Student, Saint-Petersburg Mining University, 21 line, 2, Vasilievsky Island, 199106, Saint-Petersburg, Russia
³Associate Professor, Department of Building Design and Constructions, Nosov Magnitogorsk State Technical University, 11 Uritsky Str., 455000, Magnitogorsk, Russia

E-mail: ep.chernyshova@gmail.com

Abstract. The article reviews efficient methods of accomplishing stronger bonds between concrete and outer steel shell through transverse prestressing of the concrete core. Load-strain diagrams are provided for concrete subject to uniaxial and triaxial compression. The authors describe formulas of the basic parametric point, a vertex, of a deformation curve of triaxially compressed concrete. When making estimations using these formulas, the following is considered: long-term stressing of concrete, specifics of its behavior under triaxial compression, and whether it was prestressed.

1. Introduction
Concrete filled steel tube columns (CFST) offer significant design, technological and economic advantages [1-5]. That is why they are becoming more common in construction practice. Reliable steel tube and concrete core interaction at operation loads should be ensured when producing CFST [6-9].

Transverse prestressing of a concrete core is effective for providing stronger bonds between outer steel shell and concrete. The estimates suggest that satisfactory shearing resistance could be ensured at 1-3 MPa stressing even with zero bond between concrete and steel.

Suggested methods of concrete core prestressing are described in study [9]. According to the analysis found in that same study, long-term stressing of ready-mix concrete proves particularly useful. It improves concrete core structure. Stressing helps to reduce width of a concrete layer between pieces of aggregate creating a fine-grained structure of a cement stone with higher quality and distinctly smaller pores. As a result, strength of the source concrete improves. In the experiments [9], the stressing value was 2-3 MPa. At the same time, concrete strength increased by approximately 50-60%. Besides, being transferred through the concrete mix, stressing creates circumferential pre-tensile stress within a steel shell. Triaxial compression of a concrete core could be subsequently enabled at any level of its external loading.

Another method of concrete core prestressing is realized through self-stressing concrete energy [9-11]. This method is the simplest in terms of column production technology. However, it provides a less significant increase in concrete strength.
In the work [12], it is shown that the most reliable method of determining CFST column carrying capacity is based on estimations using a stress-strain model of reinforced concrete. These estimations are based on diagrams of materials deformation. The most challenging task consists in plotting a diagram of concrete core deformation. What is more, concrete stress-strain behavior constantly changes with external compressive load increase.

Concrete deformation diagram is a descending curve. Numeric plotting of this diagram could be done with a multipoint method [9]. It is apparent that design parameters of a concrete deformation diagram determine, largely, the vertex coordinates – strength of three-dimensionally compressed concrete $f_{cc}$ and relative strain $\varepsilon_{cc}$ (figure 1).

![Concrete Deformation Diagrams](image)

Figure 1. Concrete Deformation Diagrams:
1 – Source concrete subject to uniaxial compression, 2 – Concrete subject to triaxial compression

To determine the strength of stressed concrete, the authors propose to use the following formula obtained in the work [13]:

$$f_{cp} = f_c \left( 1 + 0.3\alpha \sqrt{P} \right) \quad (1)$$

where $f_c$ is ultimate strength of concrete at axial compression,
$\alpha \leq 1$ is concrete composition-dependent factor,
$P$ is a value of effective stressing calculated using a formula

$$P = \Delta f \cdot \sigma_{co}, \quad (2)$$

where $\sigma_{co}$ is an estimated pressing value,

$\Delta f$ is a reduction factor, which makes allowance for decline in long-term stressing efficiency with increasing source concrete strength, found through an empiric formula

$$\Delta f = 4.4f_{c}^{0.4}. \quad (3)$$
In formulas (1)-(3), $P$, $\sigma_{co}$ and $f_c$ assume values in MPa. These formulas were practically tested for concretes of grades C20-C50. Value of the factor $\alpha$ should be revised on completion of testing of standard specimens of source and stressed concrete using formula (1).

Note that for self-stressing concrete $f_{cp} = f_c$ should be adopted.

Strength of triaxially compressed concrete is defined using a formula

$$f_{cc} = \alpha_c f_{cp};$$

(4)

where $\alpha_c$ is a coefficient that incorporates increasing strength of concrete subject to triaxial compression. Coefficient $\alpha_c$ is determined using a formula

$$\alpha_c = 0.5 + 0.75\bar{\sigma} + 0.25\sqrt{(\bar{\sigma} - 2)^2 + 16\bar{\sigma}/b}$$

(5)

Formula of relative lateral pressure of a steel shell on a concrete core in CFST limit state obtained through re-expression is written as

$$\bar{\sigma} = 0.48e^{-(a+b)} + 0.8\sigma_{co}/f_c$$

(6)

where $a$, $b$ are material factors determined through experiments (for heavy-weight concrete $b=0.096$ and $a=0.5b$);

Then we use a value of structural factor of steel tube confined concrete $\xi$, calculated using a formula

$$\xi = \frac{\sigma_{yp} A_p}{R_b A}.$$  

(7)

where $\sigma_{yp}$ is yield strength of steel of STCC outer shell, $A$ and $A_p$ are cross-section areas of a concrete core and steel shell.

The other vertex coordinate of a concrete core deformation diagram is a relative longitudinal deformation $\varepsilon_{c1}$ (see figure 1). Value of this concrete core shortening deformation is determined with regard to a three-dimensional stress state. The obtained formula is written as

$$\varepsilon_{c1} = E_c \varepsilon_{c1} \alpha_c^{m} \left[ 1 - \frac{f_c}{E_c (1 - \alpha_c^{-m})} \right],$$

(8)

where $E_c$ is a tangent concrete modulus of elasticity,

$m$ is an exponent quantity (statistical analysis has shown that best conformity with experimental data is achieved when $m=2.5$).

2. Summary

To conclude, formulas of the basic parametric point, a vertex, of a deformation curve of triaxially compressed concrete are proposed. These formulas make allowance for long-term stressing effect of concrete, and consider the specifics of its behavior under triaxial compression, including prestressing.

References

[1] Nishiyama I, Morino S, Sakino K and Nakahara H 2002 Summary of Research on Concrete-Filled Structural Steel Tube Column System Carried Out under the US-JAPAN Cooperative Research Program on Composite and Hybrid Structures (Japan) p 176
[2] Dundu M (2012) Compressive Strength of Circular Concrete Filled Steel Tube Columns Thin-Walled Structures № 56 pp 62-70

[3] Fattah A M (2012) Behaviour of Concrete Columns under Various Confinement Effects: A dissertation doctor of philosophy (Kanzas, USA: Kanzas State University) p 399

[4] Yamamoto T, Kawaguchi J and Morino S (2002) Experimental Study of the Size Effect on the Behavior on Concrete Filled Circular Steel Tube Columns under Axial Compression J. of structural and Construction Engineering № 561 pp 237-44

[5] 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

[6] Huang C K and Liu Y (2007) Expansive Performance of Self-Stressing and Self-Compacting Concrete Confined with Steel Tube J. of Wuhan University of Technology № 22 (2) pp 341-45

[7] Chang X, Lin H X and Huang C K (2009) Experimental Study on Shear Resistance of Self-Stressing Concrete Filled Circular Steel Tubes J. of Constructional Steel Research № 65(4) pp 801-07

[8] Zhu M C, Liu J X, Wang Q X and Feng X (2010) Experimental Research on Square Steel Tubular Columns Filled with Steel-Reinforced Self-Consolidating High-Strength Concrete under Axial Load Engineering Structures № 32 (8) pp 2278-86

[9] Krishan A L, Astafyeva M A and Sabirov R R 2016 Calculation and Designing of Concrete Filled Steel Tube Columns (Saarbrucken Deutschland: Palmarium Academic Publishing) p 261

[10] 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 № 66 pp 159-69

[11] Xu L, Zhou P, Chi Y, Huang L, Ye J and Yu M (2017) Performance of the High-Strength Self-Stressing and Self-Compacting Concrete-Filled Steel Tube Columns Subjected to the Uniaxial Compression International J. of Civil Engineering https://doi.org/10.1007/s40999-017-0257-9

[12] Krishan A L and Astafyeva M A 2014 Strength of Axially Loaded Concrete-Filled Steel Tubular Columns with Circular Cross-Section Advances of Environmental Biology № 8 (7) pp 1991-94

[13] Krishan A L and Troshkina E A 2005 Steel Pipe-Concrete Columns with Preliminary Pressed Core Application of Codes, Design and Regulations. Opportunities: Proceedings of the International Conference (Scotland, UK: University of Dundee) pp 725-33

Acknowledgments
This article was prepared by results of implementation of the scientific project within the state task of the Ministry of Education and Science of the Russian Federation No. 7.3379.2017/4.6.