Advances in Environmental Biology, 8(7) May 2014, Pages: 1991-1994

AENSI Journals

Advances in Environmental Biology

ISSN-1995-0756 EISSN-1998-1066

Journal home page: http://www.aensiweb.com/aeb.html

Strength of Axially Loaded Concrete-Filled Steel Tubular Columns with Circular Cross-Section

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ARTICLE INFO

Article history:
Received 25 March 2014
Received in revised form 20 April 2014
Accepted 15 May 2014
Available online 5 June 2014

Key words:
Key words: concrete-filled steel tubular columns, circular cross-section, прочность, concrete core, steel shell

ABSTRACT

On the basis of known relations of rigid bodies mechanics, researchers obtained a theoretical solving of the task of estimating strength of axially loaded short concrete-filled steel tubular columns with circular cross-section. The article shows derivation of formulas for estimating limit stress in concrete core and axial direction stress in steel shell. The relations that were obtained are universal and can be used for different classes of concrete and steel.

To Cite This Article: Krishan, A.L. and Krishan M.A., Strength of Axially Loaded Concrete-Filled Steel Tubular Columns with Circular Cross-Section. ***Adv. Environ. Biol., 8(7),*** *1991-1994, 2014*

INTRODUCTION

Concrete-filled steel tubular columns (CFST) with circular cross-section under small-scale eccentricities of applying of longitudinal force and little flexibility have high carrying capacity. They are especially efficient in conditions of severe load on vertical support members of buildings and constructions. In these cases practical using of CFST leads to substantial economy of material and financial resources.

Estimation of strength of CFST with circular cross-section can be qualified as a complex problem of calculating strength of a composite element in the form of metal tubing filled with concrete. The main difficulty here consists in necessity for considering three dimensional stress-strain state of concrete core and steel shell. Variants of this problem solution are presented in some works, among which we can mention [1-8]. But all these solutions are based on empirical dependence for estimation of three-dimensionally compressed concrete strength. Therefore the task of developing improved calculation method is of interest at this time.

Main part:

Strength of short axially loaded CFST is usually calculated by the formula which was theoretically obtained by A.A.Gvozdev [9] as far back as in 1935; it can be put down in the following way

$$N = R_{b3}A + \sigma_{pz}A_p, \quad (1)$$

where R_{b3} is limit stress (strength) of concrete core in axial direction;

σ_{pz} is axial direction compression stress in steel shell;

A and A_p are cross-section areas of concrete core and steel shell.

Therefore, for estimating CFST's strength one should first of all calculate values of stress R_{b3} and σ_{pz}. Let's start with showing how these stresses can be found theoretically.

It is known that concrete core of CFST with circular cross-section functions under triaxial compression of the type $|\sigma_1| = |\sigma_2| < |\sigma_3|$. In our case $\sigma_3 = R_{b3}$ and $\sigma_1 = \sigma_{br}$, where σ_{br} is lateral pressure on the concrete from the steel shell.

For finding strength of three dimensionally compressed concrete R_{b3} under element's uniform edging

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draft via stresses $|\sigma_{br}| < |R_{b3}|$ most researchers use a quite simple relation

$$R_{b3} = R_b + k\sigma_{br}, \tag{2}$$

where R_b is concrete's strength under uniaxial compression;

σ_{br} is lateral pressure on concrete core in limit state;

k is lateral pressure coefficient.

For CFST lateral pressure on concrete core in limit state σ_{br} is initially unknown. Its value depends on geometrical and structural parameters of the column under research.

Value of the coefficient k, considering experimental studies [10], is usually taken as constant - k =4.1 or k =4.0. Nowadays it is proved that value of k in the formula (2) is variable and mostly depends on the level of edging draft $m = \sigma_{br}/R_{b3}$ and concrete type.

Our researches showed that in case of CFST concrete core the coefficient k varies within a quite wide range (from 2.5 to 7). Since prior to concrete deterioration the lateral pressure σ_{br} may be 15÷20 MPa and more, even insignificant inaccuracy in estimation of k can lead to essential errors in estimating concrete strength R_{b3} and CFST's carrying capacity. So from now forth in cases of heavy concrete, for finding lateral pressure coefficient, let's use expression theoretically justified by N.I. Karpenko [11]

$$k = \frac{1}{0.1 + 0.9m}. \tag{3}$$

After insertion of expression (3) into relation (2) and algebraic transformations we obtain the following equation

$$R_{b3} = R_b + \left[\frac{\bar{\sigma} - 1}{2} + \sqrt{\left(\frac{\bar{\sigma} - 1}{2}\right)^2 + 10\bar{\sigma}}\right] R_b, \tag{4}$$

in which $\bar{\sigma}$ is a relative value of steel shell's lateral pressure on concrete core σ_{br} in limit state

$$\bar{\sigma} = \frac{\sigma_{br}}{R_b}. \tag{5}$$

The product of expression in square brackets in the right side of the formula (4) by concrete strength R_b equals the product of lateral pressure coefficient k by the value σ_{br} in the formula (2). Therefore when the value of relative lateral pressure $\bar{\sigma}$ is known, there is no need for estimating k, and that is convenient for calculations.

For finding value of $\bar{\sigma}$ let's express the right side of the formula (1) via this parameter.

Longitudinal force perceived by concrete in view of the formula (4) will be presented in the following expression

$$N_b = R_b A \left[\frac{\bar{\sigma} + 1}{2} + \sqrt{\left(\frac{\bar{\sigma} - 1}{2}\right)^2 + 10\bar{\sigma}}\right]. \tag{6}$$

Axial direction stress in steel shell σ_{pz} will be expressed from Hencky-Mises yield condition

$$\sigma_{pz} = \sqrt{\sigma_y^2 - 0{,}75\sigma_{p\tau}^2} - 0{,}5\sigma_{p\tau}, \tag{7}$$

where σ_y is the CFST outer shell steel yield limit;

$\sigma_{p\tau}$ is the stress of tangential direction of a short axially loaded compressed steel tubing in limit state.

It should be noted that formula (7) is correct for thin-wall tubes (under $d/\delta \geq 40$, where d and δ are diameter and thickness of a tube's wall). Such tubes are commonly used as steel shell for CFST.

Tangential stress in steel shell for thin-wall tubes can be expressed (with accuracy enough for practical calculations) via lateral pressure with the help of the relation

$$\sigma_{p\tau} = 2\sigma_{br}\frac{A}{A_p}. \tag{8}$$

Then one uses a notion of constructional coefficient of tube confined concrete ρ , calculated by the formula

$$\rho = \frac{\sigma_y A_p}{R_b A}. \tag{9}$$

Considering relations (8) and (9) the stress in steel shell σ_{pz} can be found by the formula

$$\sigma_{pz} = \sqrt{\rho^2 R_b^2 \frac{A^2}{A_p^2} - 3\sigma_{br}^2 \frac{A^2}{A_p^2}} - \sigma_{br}\frac{A}{A_p}. \tag{10}$$

Longitudinal compression force perceived by the steel shell, considering relations (10) and (5), is calculated by the formula

$$N_p = R_b A\left(\sqrt{\rho^2 - 3\bar{\sigma}^2} - \bar{\sigma}\right) \tag{11}$$

So the relation for estimating limit load can be expressed in the following way

$$N = R_b A\left(\frac{1-\bar{\sigma}}{2} + \sqrt{\left(\frac{1-\bar{\sigma}}{2}\right)^2 + 10\bar{\sigma}} + \sqrt{\rho^2 - 3\bar{\sigma}^2}\right). \tag{12}$$

The analysis of the formula (12) testifies that with fixed values of geometrical and constructional parameters (R_b, σ_y, A, A_p) of short axilly loaded CFST the total longitudinal force perceived by concrete and steel shell in normal section depends on relative lateral pressure $\bar{\sigma}$. The following assumption corresponds to the maximum value of longitudinal force

$$\frac{dN}{d\bar{\sigma}} = 0. \tag{13}$$

From there one can put down

$$\frac{d}{d\bar{\sigma}}\left(\frac{1-\bar{\sigma}}{2} + \sqrt{\left(\frac{1-\bar{\sigma}}{2}\right)^2 + 10\bar{\sigma}} + \sqrt{\rho^2 - 3\bar{\sigma}^2}\right) = 0. \tag{14}$$

After estimating derivate and solving the equation that has been obtained we find a formula for estimating steel shell's relative lateral pressure on concrete core in CFST's limit state

$$\bar{\sigma} = \frac{3\rho}{6{,}67 + \rho}. \tag{15}$$

The results of calculations performed via using developed relations [12,13] showed a very high convergence with experimental data that were obtained by different sciences schools before. Moreover, formulas that were developed have been used for calculating strength of preliminarily confined CFST of improved design [14] and also confirmed reasonableness of practical usage.

Conclusion:

On the basis of known relations of rigid bodies mechanics we found a theoretical solution of the task of estimating strength of short axially loaded CFST with circular cross-section. This solution involves actual stress-strain state of concrete core and steel shell and shows a high convergence with experimental data.

Resume:

The current state of the rigid bodies mechanics allows to perform theoretical estimation of power resistance of concrete and steel under combined stress. In the near term we should gradually give up empirical relations which are still often used in estimating steel-concrete constructions. This will allow to make methods of calculation of their strength more multi-purpose.

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