Estimation of Carrying Capacity of Eccentrically Compressed Concrete Filled Steel Tube Columns

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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:
CFST columns, carrying capacity, non-linear deformation model, deformation curves, concrete core, steel shell.

ABSTRACT
The article gives practical recommendations for estimation of carrying capacity of eccentrically compressed CFST columns of any flexibility on the basis of non-linear deformation model. Because concrete core and steel shell of CFST columns function in conditions of three-dimensional stress state, there are no these materials’ deformation curves before the calculation. Therefore we suggest that calculation should be performed in two stages. At the first stage one plots a curve of strain of concrete and steel. Then with the help of obtained curves the calculation of carrying capacity is performed.

INTRODUCTION
Modern methods of estimating structural units follow the path of progressively thorough consideration of their functioning actual condition. Becase of that we come across the inevitable necessity for combined recording of geometrical and physical nonlinearity, which allows to get reliable data of all stages of units functioning: from the moment of loading till the carrying capacity failure. This possibility is provided by calculation methods based on non-linear deformation model, theoretical framework of which are presented in some works, for example [1,2].

It is clear that such calculation methods are highly complex. But due to computer technology development they became easy for common use.

Constructional and geometrical features of concrete filled steel tube (CFST) columns predetermine the necessity for using non-linear deformation model for estimating their carrying capacity [3]. Critical force method, mostly used for estimating these columns [4-8], commonly gives acceptable results for cases of short CFST elements axial compression. In case of flexible CFST columns eccentric compression using of the critical force method can lead to a very poor accuracy of calculations [9].

There under this work gives practical recommendations for deformation calculation of carrying capacity of eccentrically compressed CFST columns.

Main part:
Complexity of estimating CFST columns carrying capacity lies in that their concrete cores and steel shells function in conditions of three-dimensional stress state, which constantly changes with increase of external loading level (fig. 1).

We suggest to perform calculation in two stages.

At the first stage one calculates resistibility of short eccentrically compressed CFST column standard section. Flexibility and design eccentricity of external loading application are ignored here.

This stage is necessary for analytical construction of relationships between stress and deformation of axial direction in concrete core “$\sigma_{pz} - \varepsilon_{pz}$” and steel shell “$\sigma_{pz} - \varepsilon_{pz}$” (fig. 2).
Steel is considered to be isotropic material, and concrete is regarded as transversal isotropic material. Connection between deformation and stress for any point of external steel shell at elastic and elastic-plastic stages is described by the system of equations

$$\begin{bmatrix}
\sigma_{pz} \\
\sigma_{pr} \\
\sigma_{pr}
\end{bmatrix} = 
\frac{1}{V_p E_{s,p}}
\begin{bmatrix}
1 & -\mu_p & -\mu_p \\
-\mu_p & 1 & -\mu_p \\
-\mu_p & -\mu_p & 1
\end{bmatrix}
\begin{bmatrix}
\sigma_{pz} \\
\sigma_{pr} \\
\sigma_{pr}
\end{bmatrix}.$$  \hspace{1cm} (1)

In the system (1) $\sigma_{pz}$, $\sigma_{pr}$, $\sigma_{pr}$ are normal (main) stresses in tube in longitudinal, tangential and radial directions; $\epsilon_{pz}$, $\epsilon_{pr}$, $\epsilon_{pr}$ are relative strains of steel shell in corresponding directions; $E_{s,p}$ is an initial modulus of steel elasticity; $V_p$ is steel elastic coefficient; $\mu_p$ is a variable coefficient of tube steel lateral strain.

The system of equations describing connection between stress and strain for any point of transversal isotropic concrete core at elastic and elastic-plastic stages is accepted in the following form:

$$\begin{bmatrix}
\epsilon_{bc} \\
\epsilon_{br}
\end{bmatrix} = 
\frac{1}{E_c}
\begin{bmatrix}
\nu_{\parallel} & -2\nu_{\parallel}\nu_{\perp} & \nu_{\perp} \\
-\nu_{\parallel}\nu_{\perp} & \nu_{\parallel} & -\nu_{\perp} \\
\nu_{\perp} & -\nu_{\perp}\nu_{\parallel} & \nu_{\parallel}
\end{bmatrix}
\begin{bmatrix}
\sigma_{bc} \\
\sigma_{br}
\end{bmatrix},$$  \hspace{1cm} (2)

where $E_c$ is an initial modulus of concrete elasticity (in light of peculiarities of CFST columns stress-strain state, initial moduli of concrete elasticity under volumetric and axial compression can be taken as equal ones).

Accounting of non-elastic properties of a three-dimensionally compressed concrete core is performed via using variable coefficients of concrete’s elasticity $V_{bij}$ $(j = z, r, i)$ and lateral strain $\nu_{ij}$, $\nu_{rr}$ during the calculation. In case of axial and transversal directions values of elastic coefficients $V_{b\parallel}$ and $V_{b\perp}$ determine values of corresponding diagonal strain (strain of the main main diagonal $\epsilon_{b\parallel}$ and $\epsilon_{b\perp}$, calculated without considering influence of coefficient of lateral strain). Values of coefficients of elasticity $V_{bi}$ and lateral strain $\nu_{ij}$, $\nu_{rr}$ in the system flexibility matrix (2) determine values of strain along one (axial or transversal) direction, conditioned by stress of other direction (transversal or axial correspondingly).

Fig. 1: Stress state of steel tube and concrete core at different stages of loading: a – under $\nu_p > \nu_{bi}$; b – under $\nu_p < \nu_{bi}$

Since these values depend on all components of the concrete core complex stress-strain state, for their estimation we suggest using values of stress intensity $\sigma_{bij}$ and strain intensity $\epsilon_{bi}$.

Experimental researches [9] showed that in compressed CFST elements directions of geometrical axes of symmetry coincide with basic stress areas normal lines, therefore there are no tangential stress and shear strain in matrices of flexibility of concrete and steel.

For calculating coefficients of elasticity and lateral strain of concrete and steel we can take any known relations, providing satisfactory accuracy of unit’s stress-strain state estimation, for example, given in the works [2,9-11]. It must be emphasized that ratio of lateral strain coefficients has considerable impact on qualitative and quantitative pattern of distribution of stress in steel shell and concrete core (see fig. 1).

In the frame of the suggested method all necessary parameters of curves of strain of concrete core and steel shell are estimated via simultaneous solution of equations systems (1) and (2). In these circumstances, loading is considered to be applied for the short moment. For calculation one takes a set of assumptions [9], uses equations of compatibility.
of functioning of concrete and steel, and also equations of equilibrium of projections of external forces and internal forces on the element’s longitudinal axis.

**Fig. 2:** Curves of deformation of concrete (a) and steel (b): 1 – uniaxially compressed concrete; 2 – three dimensionally compressed concrete.

While increasing longitudinal relative strain \( \varepsilon_{bz} = \varepsilon_{pz} \), one performs calculations up to the moment of achieving column’s limit value of axial compression force. Then one refines the concrete core compression relative strain in the curve vertex “\( \sigma_{bz} - \varepsilon_{bz} \)” in longitudinal direction, which has been initially found with the help of the formula suggested by us. All calculations are performed until achieving required accuracy.

Obtained deformation curves are then used at the second stage of the calculation. It is dedicated to estimation of carrying capacity of eccentrically loaded CFST column of the required flexibility. Calculations are performed with the help of known relations of non-linear deformation model, presented, for instance, in the set of rules 63.13330.2012 “Concrete and Reinforced Concrete Structures. Main provisions”.

According to the suggested method, a computer program was developed, and researchers estimated 123 samples of CFST columns, that were tested by different scientists before. Results of comparison of theoretical and empirical values of load at failure speak for their satisfactory match. The maximum difference was +19…-16 % with coefficient of error vector variation \( V_\delta = 0,07 \).

**Conclusion:**

The iterative calculation method we suggested allows to estimate resistibility of CFST column with circular cross-section, considering non-linear functioning and three-dimensional stress state of concrete core and steel shell. Deformation curves one obtains for concrete and steel allow to use main relations of iron concrete deformation model for estimating carrying capacity of eccentrically compressed columns with different flexibility.

**Resume:**

Calculations of CFST columns carrying capacity, based on using of non-linear deformation model, take into account physical and geometrical nonlinearity of construction functioning and thus allow to get the best-attested results. One can perform such calculation only after obtaining deformation curves for concrete core and steel shell under the conditions of combined stress. This work suggests a method of theoretical plotting of such curves.

**REFERENCES**


