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Axial Bearing Capacity of Elliptical Concrete Filled Steel Tubular Stub Columns

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Abstract. To study the axial bearing capacity of elliptical concrete filled steel tubular (ECFST) stub columns, the calculation theory and accuracy of existing formulas are analysed. The comparison of the calculation results of existing formulas and test results shows that the calculation precision is within the scope of engineering tolerance. Therefore, the existing formulas are proposed for practical project.

1. Introduction

As a new member of concrete-filled steel tubular (CFST) structural families, coupled with their aesthetical appeal and sound structural efficiency in bending, elliptical concrete-filled steel tubes (Fig. 1), referred to as ECFST, has been used as the main axial compression member in airport terminals and bridges. In recent years, the study on static behaviour of ECFST has been a current research focus upon the field of composite structure [1]. The experimental study [2-7], finite element simulation [8-11], and the theoretical analysis [12-14] has been conducted by scholars at home and abroad, they enriched the research achievements one after another. And with the development of the steel processing technology, elliptical concrete-filled stainless-steel tubes [15-17], elliptical concrete-filled steel double-skin tubular columns [18] gradually attract more and more attention.

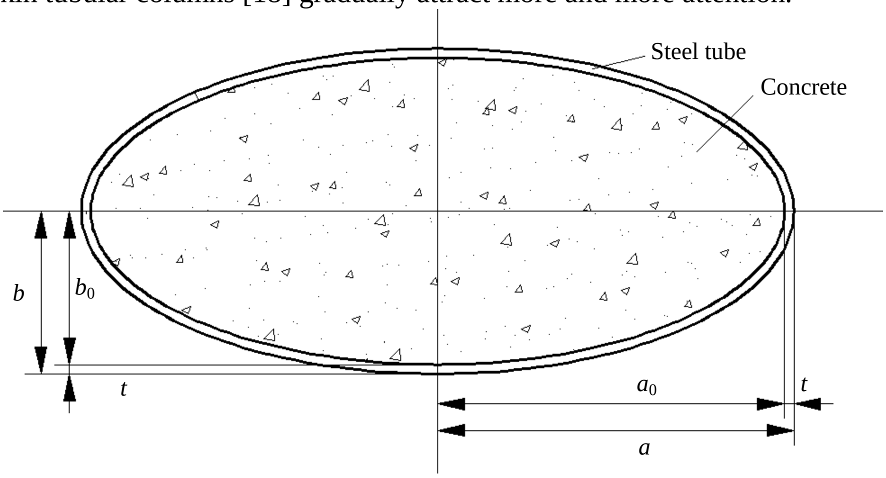

Figure 1. Cross section of ECFST.

Because of the limited researches and parameters on ECFST, no consistently recognitions on some properties of ECFST is reached, and the ECFST is temporarily not included in the design code of CFST structure in all countries. All these lack limit the application of ECFST in engineering practice.

Against this background, this paper presents the current formulas of the axial bearing capacity of ECFST stub columns. In the meantime, calculation for the latest axial loaded specimens is listed before the comparison of computation theory and accuracy of all the formulas. All these jobs can provide advice for structure design and make a little effort to fulfil the theory of ECFST.

2. Existing axial bearing capacity formulas of ECFST

Jamaluddin et al.[5] proposed a formula to calculate the axial bearing capacity N_u of ECFST stub columns based on experiment and the design rules in EC4 [19] for circular CFST,which is given by

$$N_u = \eta_s A_s f_y + \left[1+\eta_c \left(t/D_e\right)\left(f_y / f_{co}\right)\right] A_c f_{co} \tag{1}$$

In which, A_s, f_y and t are the areas, yield strength and thickness of the steel tube respectively, A_c and f_{co} are the areas and cylinder compressive strength of unconfined concrete. The diameter D_e of circular section is taken as the equivalent diameter for elliptical section, η_s is a factor to reduce the tube strength to account for hoop stress, whilst η_c indicates the effect of confinement in the concrete strength. They are given by

$$D_e = 2a^2 / b \tag{2}$$

$$\eta_s = 0.25\left(3+2\lambda\right) \tag{3}$$

$$\eta_c = 4.9 - 18.5\lambda + 17\lambda^2 \tag{4}$$

$$\lambda = \sqrt{\frac{A_s f_y + 0.85 A_c f_{co}}{\left(\pi^2 EI\right)/\left(\mu L\right)^2}} \tag{5}$$

$$EI = E_s I_s + 0.6 E_c I_c \tag{6}$$

In which, EI is the flexural rigidity of the elliptical cross section, λ is the slenderness ratio of ECFST, E_s and I_s are the elastic modulus and inertia moment of the steel tube, E_c and I_c are the elastic modulus and inertia moment of the core concrete, L is the length of ECFST, μ is the effective length factor.

Zhao and Packer [6] put the same formula to predict the axial capacity of ECFST stub columns as that of Jamaluddin et al, but they are different in calculating D_e and EI.

$$D_e = 2a\left\{1+\left[1-2.3\left(t/2a\right)^{0.6}\right]\left(a/b-1\right)\right\} \tag{7}$$

$$EI = E_s I_s + E_c I_c \tag{8}$$

In Liu's paper [12]. The distribution rule of interaction force between steel tube and core concrete of ECFST stub columns under axial load was derived by the plastic equilibrium theory, and the lateral stress nephogram of core concrete is obtained using finite element simulation. Then the assumption of effectively confined zone distribution of core concrete is proposed on account of the two results above. Based on the idea of "unified theory" and existing unified formula of axial loading capacity for circular CFST stub columns, a practical unified calculation equation for ECFST stub columns is obtained as follows.

$$N_u = f_{sc}\left(A_s + A_c\right) \tag{9a}$$

$$f_{sc} = \frac{1+1.5\left(b/a\right)^{0.3}\xi}{1+A_s/A_c} f_{ck} \tag{9b}$$

$$\xi = \left(f_y A_s\right)/\left(f_{ck} A_c\right) \tag{9c}$$

In which, f_{sc} is the "unified strength" of CFST, f_{ck} is the axial compressive strength of unconfined concrete, ξ is the factor of confinement effect.

Followed the example of Liu, on the basis of numerical simulation, data fitting and the idea of "unified theory", Shen [11] presented another formula to calculate the "unified strength".

$$f_{sc} = \left(A + B\xi + C\xi^2 + D\xi^3\right) f_{ck} \tag{10}$$

In which, A, B, C and D are the parameters obtained by statistical analyzing, A=1.3625, B=0.7080, C= 0.0624, D=0.0075.

Du [13] analyzed the axial limit stress of three dimensional stress state, with the introduction of the effective constraint factor of the size effect to consider the restraints of steel tube to concrete, also established the formula of ultimate bearing capacity of ECFST stub columns based on the "unified theory",which is given by

$$N_u = A_c f_{co} + \frac{\left(A_c k k_e + A_s \tau\right) f_y t_s}{r_i} \tag{11}$$

In which, k is the factor related to the internal friction angle (β) of concrete, k=3, r_i and t_s are inner radius and thickness of the steel tube respectively of the equivalent circular CFST which has the same area and steel ratio as the ECFST. k_e is the effective restraint coefficient, τ is the factor considering the impact of the intermediate principal stress and the corresponding normal stress.

Wu [14] put forward the design equation for ECFST stub columns by conducting section analysis and introducing an equivalent stress block according to the Chinese code for design of reinforced concrete structures,it's given as follows

$$N_u = \alpha_1 f_{cc} \frac{A_c}{\pi}\left(\theta - \frac{\sin 2\theta}{2}\right) + 0.89 f_y \frac{A_s}{\pi}\left(2\theta - 3\right) \tag{12a}$$

$$M_u = \begin{cases} \frac{2}{3}\alpha_1 f_{cc} A_c b_0 \frac{\sin^3\theta}{\pi} + 0.89 f_y A_s b\left[\sin\theta + \sin\left(3-\theta\right) + 0.24\left(a/b - 1\right)\right]/\pi \\ \text{bend around major axis} \\ \frac{2}{3}\alpha_1 f_{cc} A_c a_0 \frac{\sin^3\theta}{\pi} + 0.89 f_y A_s a\left[\sin\theta + \sin\left(3-\theta\right) - 0.24\left(a/b - 1\right)\right]/\pi \\ \text{bend around minor axis} \end{cases} \tag{12b}$$

In which, θ is the angle corresponding to the height of the equivalent rectangular stress block of the compressive zone. α_1 is used to describe the equivalent rectangular stress block of concrete, $\alpha_1 = 1.17 - 0.25a/b$. The compressive strength of core concrete f_{cc} is given by

$$f_{cc} = \gamma_U f_{co} + k_1 f_l \tag{13}$$

In which, γ_U is the reduction factor of size effect on strength of concrete, $\gamma_U = 1.67\sqrt{a_0 b_0}^{-0.112}$. k_1 is the restraint coefficient and is obtained by test results, $k_1 = 4.1\left(b/a\right)^{1.5}$. f_l is the confining stress of core concrete, obtained by introducing the ratio of the volume of steel tube ρ_s.

$$f_l = 0.095\rho_s f_y \tag{14a}$$

$$\rho_s = \left[1.5\left(a_0 + b_0\right) - \sqrt{a_0 b_0}\right] t \big/ \left(a_0 b_0\right) \tag{14b}$$

3. Comparison of the formulas

Table 1 and Fig.2 show the calculation results of existing specimens [3-6,12,14] by all the formulas, in which, N_{ut} is the experimental result, N_j is the calculation result of paper [5], while N_z for [6], N_s for [11],N_l for [12], N_d for [13] and N_w for [14].

As we can see, the formula of paper [5] gives the most accurate prediction, but the formulas of paper [13] and [14] are more conservative and secure for design.

Table 1. Statistical Analysis of Selected Specimens

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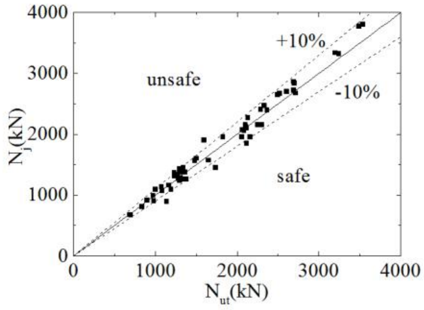
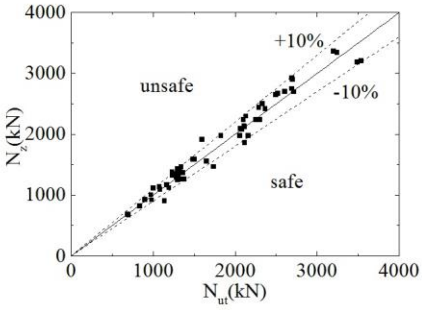
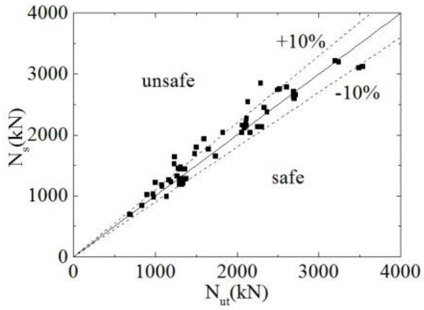
	N_j/N_{ut}	N_z/N_{ut}	N_s/N_{ut}	N_l/N_{ut}	N_d/N_{ut}	N_w/N_{ut}
Mean	1.006	1.011	1.022	0.971	0.917	0.849
SD	0.069	0.070	0.096	0.078	0.076	0.071
COV	0.069	0.069	0.094	0.080	0.083	0.084



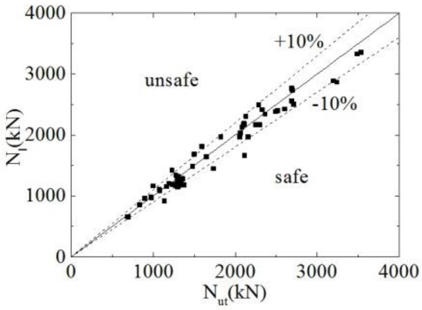
(a) comparison of N_j and N_{ut}



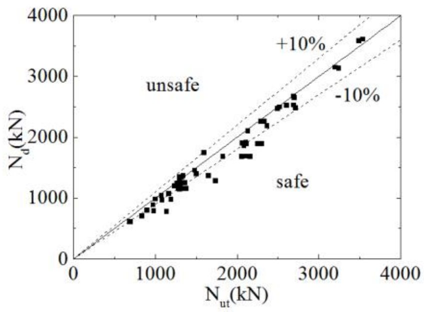
(b) comparison of N_z and N_{ut}



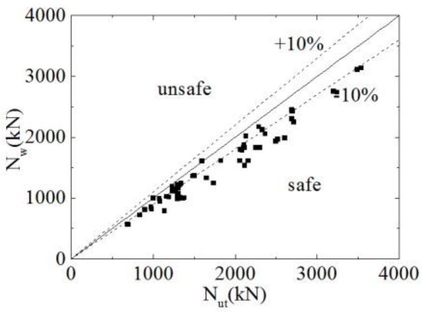
(c) comparison of N_s and N_{ut}



(d) comparison of N_l and N_{ut}



(e) comparison of N_d and N_{ut}



(f) comparison of N_w and N_{ut}

Figure 2. Comparisons between calculation and test results.

4. Summary

In a word, all the formulas above can meet the tolerable error of engineering, the formulas of paper [5] and [6] provide the most accurate predictions for the axial bearing capacity of ECFST stub columns. The formulas of paper [11] and [12] can also give reasonable predictions, and the calculation procedure are more simple. Though the formulas of paper [13] and [14] show the larger error, but the predictions are most conservative.

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