A Comparative Study on Design Principles of Circular Concrete Filled Steel Tubular Columns

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Abstract- Concrete-filled steel tubular (CFST) structure offers numerous structural benefits, and has been widely used in civil engineering structures. The behavior of circular concrete filled steel tubular (CFST) columns is investigated in this paper. The theoretical equations are used to predict the mechanism of the CFST column subjected to axial loading. This paper attempts to present the analysis of 358 specimens of circular CFST columns subjected to axial load ($L/D \leq 4$). This paper gives the design principles of the British Standards (BS-5400), CECS (Chinese) code and Lu and Zhao (2008) equations. A comparison is made between the predicted axial strength and the corresponding experimental data available from literature.

Keywords: Circular CFST Column, Design Principles, Axial Capacity.

I. Introduction

Concrete Filled Steel Tubular (CFST) Columns are practically used in earthquake resistant structures, piers subject to impact load, columns in high rise buildings and as piles. These columns are a good choice for moment resisting frames. The CFST columns have higher strength to weight ratio. Hence, the rigidity of the CFST columns is comparatively higher than the reinforced concrete columns. The CFST columns can resist reversal load as they possess high ductility and toughness. The load carrying capacity of the CFST columns are higher due to the composite action of steel and concrete. Due to the restraining effect of concrete, the local buckling of the steel tube is delayed and hence, the deterioration of the strength after the commencement of local buckling is reduced. The confinement effect provided by the steel tube plays a major role in increasing the strength of the concrete. The steel ratio in CFST cross section is higher than that in reinforced concrete and concrete encased steel cross sections. The usage of formwork and the reinforcing bars is avoided. The concrete casting is done by pump up methods that lead to savings of human power, construction cost and time. The cost on transportation and assemblage of columns can be reduced, as they are built up by hoisting the empty steel tube first and then, pouring concrete into it.

The application of CFST columns in residential buildings has a greater advantage in that larger span of columns can be adopted and the span of the frame beam is large. The principal advantages when CFST structures are used in bridges is that the load carrying capacity in compression is high and the seismic response is good. The arch bridges can leap across a very large span as the light weight empty steel tube forms the arch rib. Concrete cracking is also diminished. The erection and construction are easy to perform and hence the engineering cost is reduced. Some of the common cross section of concrete filled steel tubular columns are shown in Fig. 1.

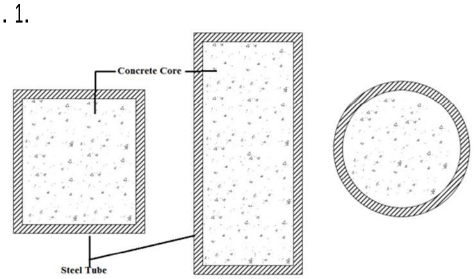

Fig.1 Common Cross Sections of Concrete Infilled Tubular Columns

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Numerous state-of-the-art literatures on concrete-filled steel tubular structures have been published recently, such as Shams and Saadeghvaziri [6] and Shanmugam and Lakshmi [7].Circular tubular columns have a definite advantage over tubular columns with other cross sections when used in predominantly compression members. For a given cross-sectional area the former have a large uniform flexural stiffness in all directions. Filling the tube with concrete will increase the ultimate strength of the member. The main effect of concrete is that it increases the local buckling resistance of the tube wall and, in the restrained state, is able to sustain higher stresses and strains than when it is unrestrained. The use of CFSTs can potentially provide large cost savings by increasing the floor area through a reduction in the required cross-section size. This is very important in the design of tall buildings in cities where space is extremely expensive, and is particularly significant in the lower storeys of tall buildings where short columns usually exist. CFST can provide an excellent monotonic and seismic resistance in two orthogonal directions. Using multiple bays of composite CFST framing in each primary direction of a low to medium rise building provides seismic redundancy while taking full advantages of the two-way framing capabilities of CFSTs (Hajjar 2002). Although CFST columns are suitable for tall buildings in seismic regions, their use has been limited due to a lack of information about the true strength and the in-elastic behavior of CFST composite action.

Several design equations have been developed to find out the ultimate axial capacity of CFST columns (Gardner 1967; Furlong, 1968; Knowles, 1970; Rangan and Joyce 1992). In the proposed equations, the confinement effect of the steel tube on the concrete core was ignored. As a consequence, a close agreement between test results and the predicted ultimate capacities was not achieved. Schneider (1998) investigated the effect of steel tube and wall thickness on the ultimate strength of CFST columns. Different approaches giving significant discrepancies in results (Manojkumar, 2010; Gupta, 2007; Muhammad, 2006) are currently being used for the estimation of the ultimate strength load of composite columns. The above papers predicted the ultimate axial load capacity (UALC) of CFST short columns with normal weight concrete and compared the code predicted ultimate axial strength using the Eurocode EC 4 and the Chinese CECS code specification. This present paper primarily aims to present a comparative study on the International Standard Codes such as the Bridge code (BS 5400) and the Chinese CECS code specifications of the CFST columns and the Theoretical Equations proposed by Lu and Zhao (2008). The experimental data from the literature is used to verify the accuracy of several International code based procedures.

III Theoretical Investigations

The data corresponding to experiments collected from the database on the website (http: //web.ukonline. co.uk/asccs2) [2]. The information required and reported for each test is: outer diameter (D) if circular cross-section, or breath (B) and depth (H) if rectangular; the thickness (t) of the steel tube; the steel properties (f_y) and for slenderness columns, modulus of elasticity (E_a); the concrete properties (concrete yield strength (f_{cyl}), and, for long columns, its secant modulus of elasticity (E_c) ;the length (L) of the column; the maximum load achieved by the column in test (N_u= Test failure load).

British Standards-BS 5400:5 (2005)

Code provisions in BS 5400 are based on limit state design with loading factors and material safety factors. The ultimate moment is calculated from plastic stress distribution over the cross-section, and an approximation for the interaction curve for axial load and moment is used. Reduced concrete properties are used to account for the effects of creep and the use of uncracked concrete section in stiffness calculation. This method is applicable to symmetrical sections only (Shanmugam and Lakshmi, 2000).

As per clause 11.1.4, the concrete contribution factor is defined as the ratio of the contribution of strength of concrete to the strength of the composite column. Concrete Contribution Factor (α) = $0.45\ A_c\ f_{cu}\ /\ N_u$ where ,A_c - Cross-sectional area of concrete; f_{cu} = Cube compressive strength of concrete; N_u = Squash load. AISC-LRFD (2010) and Eurocode 4 (2004) provisions do not consider the concrete contribution factor on strength and ductility of the members analysed explicitly. The squash load of concrete in-filled columns is calculated as

$$N_{BS} = 0.91\, A_s f_y + 0.45\, A_c f_{cc} \qquad (1)$$

Where, f_{cc} = enhanced characteristic strength of triaxially confined concrete.

Specification for Design and Construction of Concrete-Filled Steel Tubular Structures in China (CECS 28:90) Methods

The Chinese CECS code depends on unified theory and unified designing formula developed by Harbin University. The ultimate axial load capacity of CFST columns is calculated by

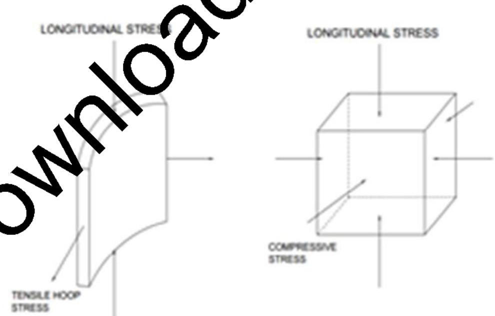
$$N_{CECS} = \varphi_l \cdot \varphi_2 \cdot N_o \qquad (2)$$

$\varphi_l = 1$ for $\left(\frac{l_e}{D}\right) \leq 4$; $\varphi_l = 1 - 0.115\sqrt{\frac{l_e}{D} - 4}$ for $\left(\frac{l_e}{D}\right) > 4$; ϕ_l and ϕ_e are reduction factors which consider the eccentric loading effect and slenderness influence, respectively. For concentric loading $\phi_e = 1$ and l_e = effective length of the columns that is determined by the support conditions.

$N_o = f_c A_c + f_s A_s + \sqrt{(f_c A_c).(f_s A_s)}$; f_c is the characteristic cylinder compressive strength of the concrete, A_c is the area of concrete section, f_y is the yield strength of the steel and A_s is the area of the steel section. The CECS code considers the confinement effect by $\sqrt{(f_c A_c).(f_s A_s)}$.

Lu and Zhao (2008)

It is known that stub columns concentrically loaded on the entire section are significantly affected by the difference between the values of Poisson's ratio of the steel tube, γ_s, and the concrete core, γ_c, (Gardner and Jacobson 1967). In the initial stage of loading, Poisson' s ratio for the concrete is lower than that for steel; therefore, the steel tube expands faster in the radial direction than the concrete core, i.e., the steel does not restrain the concrete core. Provided the bond between the steel and concrete does not break, the initial circumferential steel hoop stresses are compressive and the concrete is under lateral tension, as shown in Fig 2; otherwise, a separation between the steel tube and concrete core occurs. As the load increases and the compressed concrete starts to plasticize, the lateral deformations of the concrete catch up with those of the steel and, with a further increase in load, the steel tube restrains the concrete core and the hoop stresses in the steel become tensile, as shown in Fig 3. At this stage and later, the concrete core is stressed triaxially and the steel tube biaxially. This phenomenon results in an increase of axial compressive load capacity. Because of the presence of the hoop tension, the steel tube cannot sustain the plastic resistance in an axial direction. The bond strength has no effect on structural behavior because there is no relative movement between the concrete core and the steel tube.



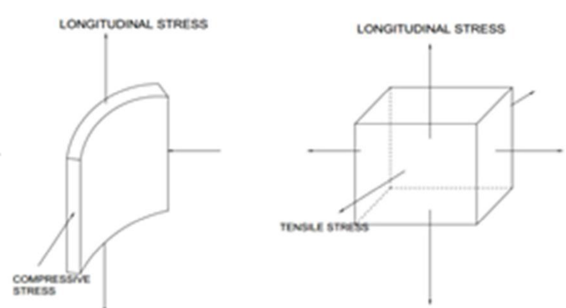


Fig. 2 Stress conditions in steel tube and concrete core $\gamma_s > \gamma_c$ Fig. 3 Stress conditions in steel tube and concrete core $\gamma_s < \gamma_c$

Lu and Zhao (2008) proposed the axial capacity of CFST columns based on AIJ code. A composite structural system using concrete and steel tube is called 'steel reinforced concrete' (SRC) in Japan. The allowable stress design is primarily employed, in which working stresses are calculated based on the elastic stiffness of members and allowable strength by the superposed strength formulae (Shanmugam and Lakshmi, 2000).The axial compressive stength of the CFST column is given by;

$$N_{cu} = A_c f_{cp}(1 + \eta_c) + A_s f_y \quad (3)$$

Where, η_c is the coefficient of confinement of concrete, $\eta_c = 1.25\frac{t}{D}(f_y/f_{cp})$ and f_{cp}= unconfined compressive strength of concrete, $f_{cp} = \Upsilon_c f_c' = 1.67\, D_c^{-0.112} f_c'$, where, Υ_c = strength reduction factor introduced to the scale effect into consideration; f_c'= the unconfined cylinder compressive strength of concrete; D_c= diameter of the core.

III. Results and Discussions

The calculated load using BS code is shown in dispersion plot in Figure 4. It observed that BS Code underestimates the capacity of in-filled composite columns with high-strength concrete. The predicted results have underestimated the results by maximum of 70%. The calculated load using CECS code is shown in dispersion plot in Figure 5. The Chinese code over predicts the results for Circular CFST columns with an average value (P_{EXP}/N_{BS}) of 0.875. The CECS code overestimates the results by a maximum of 30% with a standard deviation of results with (P_{EXP}/N_{CECS}) 0.13. The calculated load using Lu and Zhao (2008) equation is shown in dispersion plot in Figure 5. A decrease of confinement of concrete is observed when the diameter-to-thickness ratio is small, and it tends to be moderate when the diameter-to-thickness ratio D/t is greater than 60. The concrete confinement increases linearly when the yield stress of the steel tube increases, and it decreases as the unconfined compressive strength of the concrete core increases, respectively. The Lu and Zhao (2008) equation underpredicts the results for Circular CFST columns with an average value($P_{EXP}/N_{LU\ and\ ZHAO}$) of 1.33. The Lu and Zhao (2008) equation underpredicts the results by a maximum of nearly 30% with a standard deviation of results with 0.19.

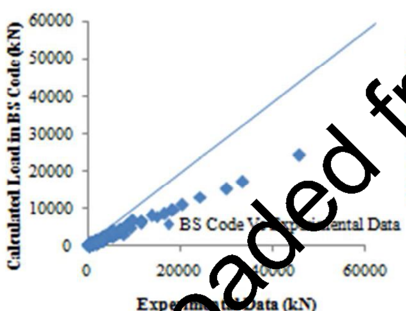


Fig. 4. BS Code Vs Experimental Data

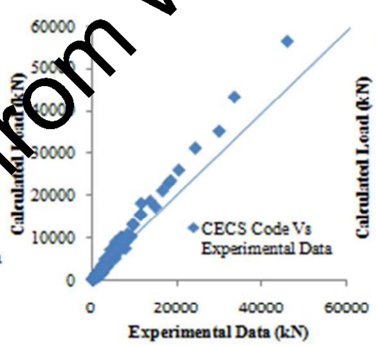


Fig. 5 CECS Code Vs Experimental Data

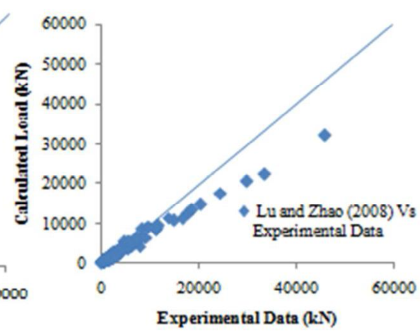


Fig. 6. Lu and Zhao(2008) Vs Experimental Data

IV. Conclusions

This paper gives a comprehensive summary on the comparative study on the British Standards code, the Chinese CECS code and the Lu and Zhao (2008) equation. The BS Code underestimates the capacity of in-filled composite columns with high-strength concrete whereas the CECS code over predicts the axial capacity of CFST columns. The scale effect on the strength of the filled concrete and the enhancement of CFT columns due to the composite action between steel tube and concrete core are taken into account in Lu and Zhao (2008) formula. Hence, it gives more reliable results and the values predicted using the present formula are in good agreement with the experimental data for circular CFT stub columns not only within a large range of diameter-to-thickness ratios but also with normal-strength of concrete and steel tubes and high-strength of concrete and steel tubes.

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