Theoretical Investigations on Design Approaches of Concrete Filled Steel Tubular Columns

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Abstract- Concrete filled steel tubular (CFST) structures have been used widely in high-rise buildings and bridges due to the efficiency of structurally favorable interaction between the steel tube and the concrete core. This paper represents the analysis of experimental data corresponding to 358 specimens of concentrically loaded CFST columns ($L/D \leq 4$). Test results are compared with International design code Eurocde 4 (EC4) and American Concreete Institute/Australian Standards (ACI/AS) specifications and the theoretical equations proposed by Giakoumelis and Lam(2004) and Mander, Priestley and Park's (1988) method for determining the load-bearing capacity of these composite elements. For circular cross-section columns, there is a good agreement between the test failure load and the EC4 calculation. In this paper, the influence of relative slenderness on the axial capacity of concentrically loaded circular CFST specimen is discussed.

Keywords: Design Approach, EC4, ACI and AS, Theoretical Equations, Relative Slenderness.

I. Introduction

The concrete filled steel tube (CFST) columns are widely used in construction. This type of structural elements is favored in practice because of its small cross sectional area to load carrying capacity ratio. Hence, mega - concrete columns, in the lower floors of tall building structures, can be substituted by smaller cross sections of CFST columns. Moreover, CFST elements can be used as piers for bridges in congested areas. Therefore, such structural elements should be thoroughly investigated before their use in critical structures. Extensive parametric studies were performed to fully understand the nature of CFST columns. The important decision that a structural designer should make is the selection of the materials used for civil engineering construction. The central goal is to achieve an economic structure with good performance. In civil constructions, concrete and steel are used widely. Both the materials are complementary. Concrete is very stiff, inexpensive and has good fire resistance whereas steel is strong, ductile and lightweight. The combination of these two materials results in a system with a much higher efficiency and performance than that of the individual components.

Here short circular CFT columns are considered. These offer much more post-yield axial ductility than rectangular, square, and octagonal tube sections (Schneider 1998), and are more commonly used in many modern structures. Fourteen short CFT columns subjected to axial loads were tested by Schneider (1998) to investigate the effect of the tube shape and steel tube plate thickness on the composite column strength. Sakino, Nakahara, Morino and Nishiyama (2004) studied the effect of steel tube tensile strength and concrete strength on the behavior of composite columns. Giakoumelis and Lam (2004) carried out 15 tests on circular CFT columns and investigated the effects of the steel tube thickness, the bond between the steel tube and concrete, and the concrete confinement on the behavior of these columns. The data corresponding to experiments collected from the database on the website (http://web.ukonline.co.uk/asccs2) [5]. This paper primarily aims to present a comparative study on the International Standard Code specifications of the CFST columns and the Theoretical Equations proposed by Giakoumelis and Lam(2004) and Mander, Priestley and Park (1988). The model is validated by comparison with experimental results, from literature. The experimental data from the literature is used to verify the accuracy of several International code based procedures.

II. Theoretical Investigations

Several theoretical approaches and equations were proposed over the years to calculate the axial capacity of CFST columns. Some of them accounted for the increase in the infill concrete strength while others, conservatively, ignored it. For instance, the American Concrete Institute (ACI-318-11) [1] and Australian Standard (AS 3600 – 2009) [9] use the typical concepts of reinforced concrete design in their formulation without any consideration to the confinement effects on concrete. On the other hand, the derivation procedure of the American Institute of Steel Construction (AISC) code equation was based on the same concept used in structural steel design [2]. The Eurocode (EC4) which is exclusively used for composite elements design combines both these approaches [3]. 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}), (f_{ck} in EC4)) and, for long columns, its secant modulus of elasticity (E_c) to (0.4 f_{ck})); the length (L) of the column; the maximum load achieved by the column in test (N_u= Test failure load).

Euro Code 4

In order to estimate the CFST specimen's axial capacity, Eurocode 4 [3] adopted two approaches, the general method and the simplified method. EC4 covers concrete encased and partially encased steel sections and concrete-filled sections with or without reinforcement. EC4 uses limit state concepts to achieve the aims of serviceability and safety by applying partial safety factors to load and material properties. EC4 is the only code that treats the effects of long-term loading separately. The axial capacity of the CFST column can be predicted based on the Eurocode 4 equation as follows:

$$N_{EC4} = \chi[\eta_a A_s \frac{f_y}{\gamma_{ma}} + A_{sc}\frac{f_c'}{\gamma_c}\left[1 + \eta_c \frac{t\, f_y}{D\, f_c'}\right]] \quad (1)$$

Where γ_{ma} and γ_c are the partial safety factors for structural steel and concrete material, taken as 1.0 and 1.3, respectively. Because of the pure axial loading of the CFST members tested in this study, the coefficients η_a and η_c are given as:

$$\eta_a = 0.35(3.2\bar{\upsilon}) \le 1 \quad (2)$$

$$\eta_c = 4.9 - 18\bar{\upsilon} + 17\,\bar{\upsilon}^2 \ \ge 0 \quad (3)$$

Where, $\bar{\upsilon} = \sqrt{\frac{f_c' A_c + f_y A_s}{N_{cr}}}$; is the relative slenderness ratio. $N_{pl,R} = f_c' A_c + f_y A_s$; is the plastic strength of the composite column. $N_{cr} = \frac{\pi^2 (EI)_e}{l^2}$; is the Euler buckling strength of the column. $EI_e = A_s E_s + 0.6 A_c E_{sm}$; E_{sm} = Secant modulus of the concrete. The buckling strength reduction factor $\chi = \frac{1}{\Phi+\sqrt{\Phi^2-\bar{\upsilon}^2}} \le 1$;
Where $\Phi = 0.5\,[1 + 0.21(\bar{\upsilon} - 0.2) + \bar{\upsilon}^2$.

ACI and AS codes

The ACI and Australian Standards use the same formula for calculating the squash load. Neither code takes into consideration the concrete confinement. The limiting thickness of steel tube to prevent local buckling is based on achieving yield stress in a hollow steel tube under monotonic axial loading, which is not a necessary requirement for an in-filled composite column. The axial capacity of the CFST column is given by

$$N_{ACI/AS} = 0.85\, f_c' A_c + f_y A_s \quad (4)$$

Giakoumelis and Lam equation - Modified ACI/AS Method

Giakoumelis and Lam (2004) concluded, after comparisons with their experimental results, that the ACI and AS codes are overly conservative in their estimation of axial load capacity of CFST specimens. Hence, they proposed a new equation as a modification for the ACI and AS equations to predict the axial capacity of CFST members as shown below:

$$N_{Geo} = 1.3\, f_c' A_c + f_y A_s \qquad (5)$$

The 0.85 coefficient shown in ACI/AS equation was replaced by 1.3 in Giakoumelis and Lam's expression to account for confinement effects. This formula was derived based on regression analysis of their experimental results and it does not consider the composite section's geometry.

Mander et al. Equations

Mander et al. [6] considered the confinement effects on the infill concrete compressive strength (f_{cc}') which is determined using a constitutive model that contains a unique ultimate strength surface for multi-axial compressive stresses. Mander's expression was derived by modifying the theoretical equation by replacing f_c' with f_{cc}' to take into consideration the confinement effects.

$$N_{Mander} = f_{cc}' A_c + f_y A_s \qquad (6)$$

In the concrete filled steel tubes, the confining steel tube imposes tri-axial compression on the concrete core with equal effective lateral confining stresses from circular hoops. The confined compressive strength (f_{cc}') is given by:

$$f_{cc}' = f_c' \left(-1.254 + 2.254 \sqrt{1 + \frac{7.94\, f_1}{f_c'}} - 2\frac{f_1}{f_c'} \right) \qquad (7)$$

$$f_1 = \frac{2\, \sigma_\theta\, t}{D} \qquad (8)$$

Where, f_1 is the effective lateral confining stress on the concrete and $\sigma_\theta = 0.1 f_y$ is the lateral stress imposed by the steel tube.

III. Comparison Results and Discussions

The estimated capacities of the CFST specimens using the International codes and equations are compared to the experimental result from the literature as shown in the dispersion plots of Fig 1 to Fig 4. Fig-5 represents the Ratio Test Results/EC4 vs concrete compressive strength. For high strength concrete, EC4 code predicted conservative results. The best estimation of EC4 is achieved for circular columns filled with concrete. The maximum P_{exp}/N_{EC4} (P_{exp}= Experimental Load (kN)) for circular columns is found to be 1.70. It is clear that EC4 can reliably predict the axial capacity of CFST columns as it possesses a mean value of P_{exp}/N_{EC4} = 1.48. It is inferred from Fig 2-3 that the ACI and AS appeared to be very conservative, due to the fact that concrete confinement was ignored in the estimation of their axial load capacity. However, in ACI/AS the maximum difference is up to 51%, because there is no consideration for the effect of confinement or L/D ratio. The axial load ratio estimated by Giakoumelis and Lam (2004) has an average of 1.65 and N_{Geo} (Modified ACI/AS) has an average of 1.31. Fig 6 and Fig 7 illustrate Ratio Test Results/ACI-AS vs compressive strength of concrete. A significant feature observed is that the improvements in the axial capacity of CFST specimens are more affected by the change in the D/t ratio of the steel tube. The CFST's axial capacity decreases as the D/t increases due to the reduction in the confinement provided by the smaller wall thickness. Fig-4 represents the comparison between test and predicted results from Mander equations and Fig-8 represent the ratio of test/Mander vs compressive strength of concrete. The axial load estimated by Mander (1988) has an average of 1.33.

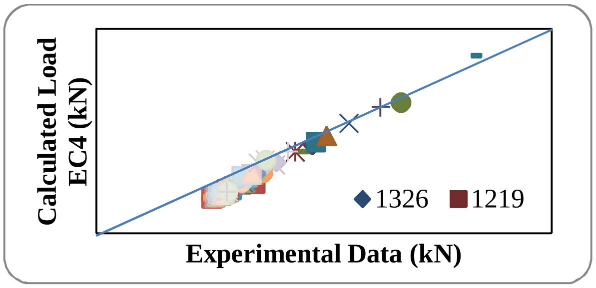

Fig 1. Experimental Results Compared with EC4

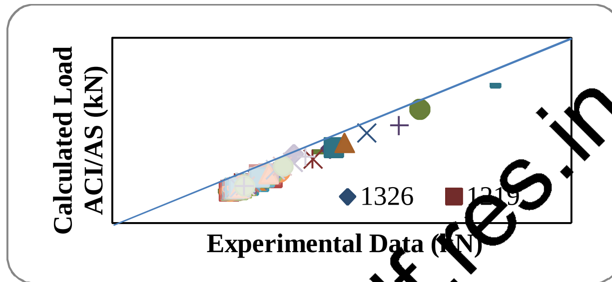

Fig 2. Experimental Results Compared with ACI/AS

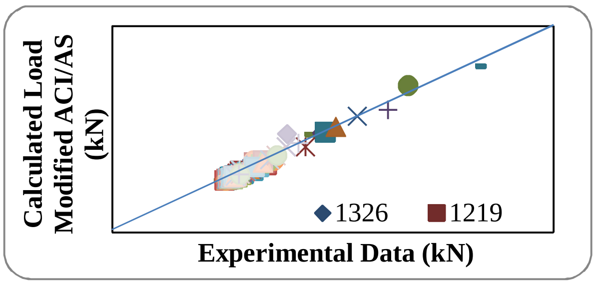

Fig 3. Test Results Compared with Modified ACI/AS

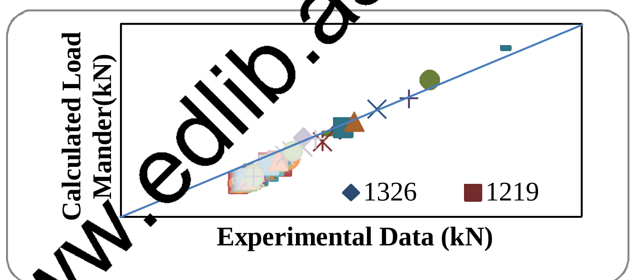

Fig 4. Test Results Compared with Mander (1988)

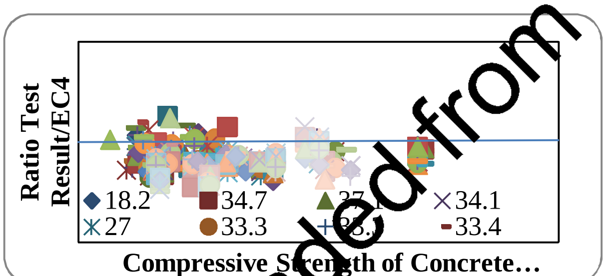

Fig 5. Ratio test/EC4 Vs Concrete Strength

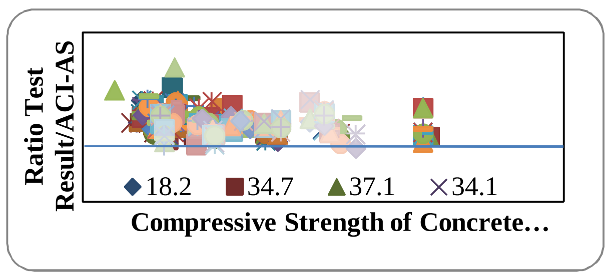

Fig 6. Ratio Test/ACI-AS Vs Concrete Strength

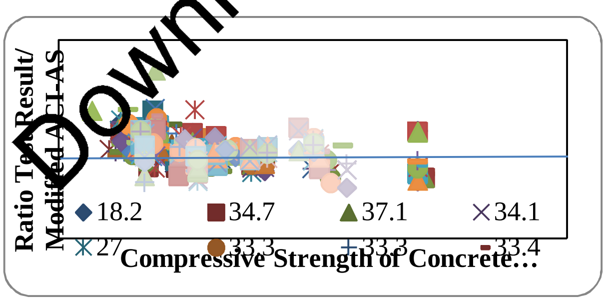

Fig 7. Ratio Test/N_{Geo} Vs Concrete Strength

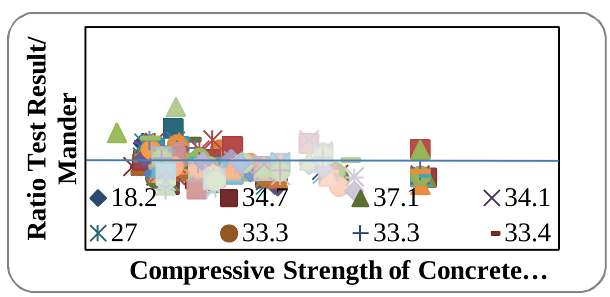

Fig 8. Ratio Test/Mander Vs Concrete Strength

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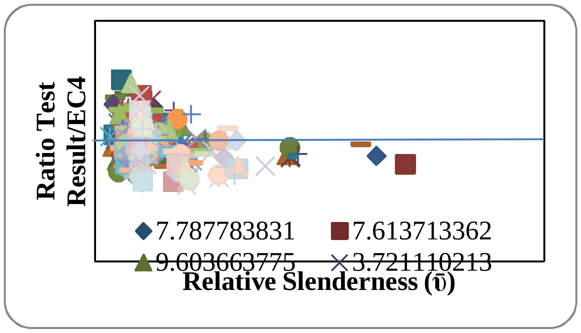

Fig 9. Ratio test/EC4 Vs Relative Slenderness (ῡ)

Fig-9 presents Ratio test results/EC4 Vs relative slenderness (ῡ). For higher relative slenderness the EC4 predicts results conservative. The code is conservative but it need not be economical in many cases.

IV. Conclusions

This paper summarizes equations and formulae are investigated to estimate the axial strength of CFST columns. A comparison of the experimental results with the numerical analysis and theoretical results is presented in this study. From the observations made, it is observed that the EC4, Mander (1988) ACI/ AS, and Modified ACI/AS have underestimated the compression capacity of CFST columns, thus these codes are fairly conservative and can be used to design due to their inherent conservativeness. The deviations of the estimates from the results may be attributed to the influence of D/t ratio of the columns. It is observed that at high D/t ratio there is a reduction in confinement effect. Thus, this paper provides a comprehensive summary of the various International code procedures and a comparative study used to estimate the capacity of CFST columns.

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