Finite Element Analysis and Theoretical Investigations on Concrete Filled Steel Tubular Columns

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Abstract - This paper presents the behavior and design of axially loaded concrete filled steel tubular (CFST) columns. A numerical investigation on the behavior of concrete filled steel tubular columns loaded in axial compression is presented. Nonlinear finite - element analysis is performed using commercial software ANSYS. The numerical models are used for the computations and the results are validated with the corresponding experimental program from the literature. It is observed that the numerical model is able to map the load deflection response of the CFST specimens. A good agreement is also observed between the experimental and the predicted numerical results. The column strength predicted from the finite element analysis and by using the Lu and Zhao (2008) are compared with the corresponding experimental results obtained from the literature. The comparative results ensured that D/t ratio plays a prominent role on the compressive behavior of the CFST specimens. This paper quantifies the difference between the experimental and numerical results, and the ultimate load of the CFST columns estimated by various International code procedures.

Keywords: CFST Columns, Numerical Model, Nonlinear Analysis, ANSYS, Load Deflection Response, Comparison of International Codes

I. Introduction

CFST columns are often subjected to combined axial load and an extensive research has been conducted on the behavior of CFST columns subjected to axial load. Tests of concrete-filled carbon steel tube columns were conducted by Schneider (1998), Uy (2004), Huang et al (2002), Han and Yao (2003), Mursi and Uy (2003), Uy (2001), Sakino et al.(2004), Giakoumelis and Lam(2004) and many other researchers. These tests were carried out on concrete-filled mild steel and high strength steel tube columns using circular, square and rectangular hollow sections. The experimental study of axially loaded short CFST columns with depth-to-thickness ratio ranging from 17 to 50 was undertaken by Schneider (1998). Fourteen specimens were examined and the effects of steel tube shape and tube wall thickness on the ultimate axial strengths of CFST columns were evaluated. Circular steel tubes possessed higher post-yield axial ductility and strength than square or rectangular concrete-filled tube sections. All circular CFST columns exhibited strain hardening. Strain hardening occurred in rectangular CFST columns with D/t < 20. Sakino et al. (2004) observed early concrete crushing and local buckling for normal strength concrete compared to high strength concrete. Georgios Giakoumelis and Dennis Lam (2004) identified that for high-strength CFT columns, the peak load was observed for small shortening whereas for normal concrete the ultimate load was obtained with large displacement. This paper primarily aims to present a numerical model for the analysis of the CFST columns. The model is validated by comparison with experimental results, from literature. The experimental data from the literature is then used to verify the accuracy of Lu and Zhao (2008) theoretical equation.

II. Numerical Modeling of CFST Columns

The contact between steel tube and concrete causes composite action between steel and concrete in a CFST column. The radial lateral confining pressure exerted by the steel tube on the concrete induces confinement
in concrete. A biaxial state of stress is also induced in steel, which may cause some reduction in its axial load capacity. Thus any numerical model that intends to capture the behaviour of CFST in compression must use suitable constitutive model for the steel tube and concrete. Further, to effectively replicate the inherent advantages of CFST, it is necessary that the composite action between steel and concrete be very carefully modeled.

The uniaxial behavior of the steel is simulated by an elastic-perfectly plastic model. The equivalent uniaxial stress–strain curves for both unconfined and confined concrete are shown in Fig 1, where \( f_c \) is the unconfined concrete cylinder compressive strength, which is equal to 0.8(\( f_{cu} \)), and \( f_{cu} \) is the unconfined concrete cube compressive strength. The corresponding unconfined strain (\( \varepsilon_{cu} \)) is taken as 0.002. The confined concrete compressive strength \( f_{cc} \) and the corresponding confined strain \( \varepsilon_{cc} \) can be determined from the following equations respectively, (Mander et al., 1988) 
\[
f_{cc} = f_{cu} + k_1 \varepsilon_{cc}^\prime + k_2 \varepsilon_{cc}^\prime \]

The coefficients \( k_1 \) and \( k_2 \) are constants and can be obtained from experimental data. Meanwhile, the constants \( k_1 \) and \( k_2 \) were set as 4.1 and 20.5. 

Where:
\[
y_B = \frac{150}{B/t} \quad \text{and} \quad \frac{B}{t} > 0.010085 \]

To define the full equivalent uniaxial stress–strain curve for confined concrete as shown in Figure 1, three parts of the curve have to be identified. The first part is the initially assumed elastic range to the proportional limit stress. The proportional limit stress is taken as 0.5\( f_{cc} \). The initial Young's modulus of confined concrete \( E_{cc} \) is reasonably calculated using the empirical equation by ACI, 1999. The Poisson's ratio \( (\nu_{cc}) \) of confined concrete is taken as 0.2. 

\[
\sigma_{cc} = \frac{f_{cc}}{\nu_{cc} E_{cc}} \quad \text{for} \quad \nu_{cc} \leq 0.5 \quad \text{and} \quad \sigma_{cc} = \frac{E_{cc}}{\nu_{cc}} \quad \text{for} \quad \nu_{cc} > 0.5
\]

While the constants are taken equal to 4 (Ell body et al. 2006), this part starts from 0.5\( f_{cc} \) and progresses to the confined concrete strength \( f_{cc} \). The last part of the curve, the descending line is assumed to be terminated at the point where \( y_B = k_3 f_{cc} \) and \( \varepsilon_{cc} = 0.001885 (B/t) \] for 17 \( \leq B/t \leq 29.2 \) and \( \frac{f_{cc}}{\nu_{cc}} \) for 29.2 \( \leq \frac{B}{t} \leq 150 \). 

Because the concrete in the CFST columns is usually subjected to triaxial compressive stresses, the failure of concrete is dominated by the compressive failure surface expanding with increasing hydrostatic pressure. Hence, a Drucker-Prager (DP) yield criterion is used to model the yield surface of concrete which assumes an elastic perfectly plastic behavior. The bilinear kinematic hardening model was used to simulate the stress–strain curve of steel and assumed to be an elastic-perfectly plastic material. The bilinear model requires the yield stress \( f_y \) and the hardening modulus of the steel \( E_y \). The constitutive law for steel behavior is 
\[
\sigma = f_y + E_y \varepsilon, \quad \varepsilon_y \leq \varepsilon \quad \text{and} \quad \sigma = f_y + E_y \varepsilon, \quad \varepsilon > \varepsilon_y
\]

Where: \( \sigma \) is the steel stress, \( s \) is the steel strain, \( E_y \) is the elastic modulus of steel, \( E_y' \) is the tangent modulus of steel after yielding, \( f_y=0.01E_y \), \( f_y \) and \( s \) are the yielding stress and strain of steel, respectively.

III. Finite Element Modeling - Ansys

Numerical simulations were carried out with finite element software ANSYS, where the concrete and steel were modeled as following: An eight-node solid element, Solid65, is used to model the concrete. SHELL181 is suitable for analyzing thin to moderately-thick shell structures. All the specimens were modeled as 3D structural elements. The two ends were assumed to be hinged, for modeling. At both the ends, displacement in x, y directions \((U_x, U_y)\) were restrained and translation \(U_z\) as well as rotational degrees of freedom in x, y, z directions were considered to be free. The coefficient of friction between the concrete and
steel surfaces was given by 0.25. Rigid Contact is provided between the two surfaces, that enables the pressure to be transmitted across the two surfaces, only when there is actual contact among them, while causing the surfaces to separate under the influence of a tensile force. Thus, the correct simulation of composite action between concrete and steel tube is achieved successfully in the prediction of the behavior of the CFST column.

Theoretical Investigations - Lu and Zhao (2008)

Lu and Zhao (2008) proposed the axial capacity of CFST columns based on AIJ code. The axial compressive strength of the CFST column is given by:

\[ N_{cu} = A_c f_{cp} (1 + \eta_c) + A_s f_y \]

where, \( f_{cp} \) is the unconfined compressive strength of the concrete; \( f_y \) is the yield stress of the steel tube; \( \eta_c = 0.32 \left( \frac{f_y}{f_{cp}} \right) \) and \( f_{cp} = 1.67 D_{c}^{0.12} f'_{c} \), where, \( f'_{c} \) = the unconfined cylinder compressive strength of concrete; \( D_{c} \) = diameter of the core.

IV. Comparison of Results and Discussion

The estimated capacities of the CFST specimens using the numerical model and the previously described equations are compared to the experimental result from the literature as shown in Table 1.

Results and Validation of the Numerical Model

The numerical model was used to simulate the CFST columns. The accuracy of the numerical model was evaluated based on the difference between the experimental data and ANSYS peak load. The dimensions and other specifications of the CFST columns are shown in Table 1. A comparison of peak load capacity of CFST specimens are presented in Table 1. Figures 2, 3 and 4 compare the experimental and ANSYS load-deflection pattern for circular, square and rectangular CFST columns respectively. The experimental and numerical peak load values also display good agreement with each other. The results show that the numerical model is capable of reproducing the load-deformation behavior. The load capacity \( P_{ANSYS} \) determined numerically is varying within ±10% of the experimental values.

It is observed 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. From Table 1, it is observed that the CFST’s axial capacity decreases as the D/t increases due to the reduction in the confinement provided by the smaller wall thickness. The average value and standard deviation of \( P_{exp}/P_{ANSYS} \) were obtained as 107 and 0.05 respectively, which indicates a good correlation between the experimental and numerically simulated results. Based on the above comparison, it can be concluded that the FE model is sufficiently verified and can be used to conduct further comprehensive studies to investigate the effect of additional parameters influencing the capacity of CFST columns.

Comparison of Results with Lu and Zhao (2008)

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 the equation proposed by Lu and Zhao (2008). Fig 5-7 indicates that the values predicted by this method are in good agreement with the experimental results for circular CFT stub columns. The average value and standard deviation of \( P_{exp} / N_{Lu \ and \ Zhao} \) were obtained as 104 and 0.06 respectively, which indicates a good correlation between the experimental and numerically simulated results.
Table 1. Comparison of Numerical and Theoretical Results with Experimental Results

<table>
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<tr>
<th>Specimen Label</th>
<th>Diameter D (mm)</th>
<th>H (m)</th>
<th>Thickness t (mm)</th>
<th>Length L (mm)</th>
<th>( f_c ) (MPa)</th>
<th>( f_y ) (MPa)</th>
<th>( E_s ) (GPa)</th>
<th>Experimental Load (kN) (Schneider, 1998)</th>
<th>P_{exp}</th>
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V. Conclusions

A nonlinear FEM based model has been developed using ANSYS for the numerical simulation of CFST specimens. The numerical model is validated by comparing its output with the corresponding experimental data available in literature. Good agreement between the experimental data and the model's output in terms of the axial capacity is observed. The established FE model can be used for subsequent parametric studies that would shed more light on additional factors influencing the CFST behaviour. The axial strength of CFST columns are predicted by Lu and Zhao (2008) equation. 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 Lu and Zhao (2008) equation predicted the compression capacity of CFST columns conservatively and can be used to design due to their inherent conservatism. 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.

References


