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Behaviour of concrete-encased CFST columns under combined compression and bending

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ABSTRACT

The performance of concrete-encased CFST column under combined compression and bending is studied in this paper. A finite element analysis (FEA) model is developed to analyse the behaviour of the composite column, and generally good agreement is achieved between the measured and predicted results in terms of the failure mode, the load-deformation relation and the ultimate load. Typical failure modes, full-range response of load-lateral deflection relation, loading distributions of the inner CFST and the outer RC components, the contact stress between the steel tube and the concrete of the composite columns are analysed. The influence of slenderness ratio and loading paths on the composite columns are also investigated. Influence of parameters, such as the strength of concrete and steel, steel ratio of CFST, longitudinal bar ratio and diameter of CFST on the sectional capacity of the concrete-encased CSFT columns is analysed based on the FEA model. A simplified model is proposed to calculate the sectional capacity of concrete-encased CFST columns under combined compression and bending.

1. Introduction

Concrete-encased CFST (concrete-filled steel tube) has attracted the interests of structural engineers and researchers due to its good structural behaviour [1]. Fig. 1(a) shows a building adopting concrete-encased CFST columns and RC beams under construction, and the typical cross-section of the composite column is shown in Fig. 1(b).

In practice, concrete-encased CFST can be used as the columns in buildings or piers in bridges, which thus may be subjected to combined axial load (N) and moment (M), as shown in Fig. 1(c). Different loading paths may appear in practice, e.g., path I: N and M are applied on the composite column proportionately, such as an eccentrically loaded column; path II: N is applied first and then be kept as constant, after that M is applied until the failure of the column.

There have been some literatures on the studies of concrete-encased CFST columns. Xu [2] and Wang [3] investigated the behaviour of eccentrically loaded concrete-encased CFST columns (loading path I), where the studied parameters included load eccentricity and the diameter of steel tube of the CFST component. The behaviour of concrete-encased CFST columns under constant axial load and laterally cyclic load (loading path II) was investigated by Han et al. [4], Ji et al. [5] and Li et al. [6], where the axial load ratio (=N_0/N_{u0}, where N_0 and N_{u0} are the axial load applied on the tested specimens and the axially compressive capacity of the composite columns, respectively) was analysed. Han and An [1] and An et al. [7] studied the compressive and flexural behaviour of concrete-encased CFST by nonlinear 3-D finite model, respectively. However, there is still limited information on the performance of concrete-encased CFST columns under combined compression and bending based on full-range analysis, and the formulas to predict the sectional capacity of the composite columns also need to be studied further.

This paper presents an investigation on the performance of concrete-encased CFST columns under combined compression and bending. The purposes of this study are threefolds, firstly, to develop a nonlinear 3-D finite model on the composite columns; secondly, to analyse the typical failure modes, the full-range load-lateral deflection response, as well as the loading distribution between the inner CFST and the outer RC components, the contact stress between the steel tube and the concrete of the columns, and the influence of slenderness ratio and loading path on the columns; and thirdly, to present formulas to predict the sectional capacity of the composite columns under combined compression and bending.

2. Finite element analysis (FEA) model

The finite element analysis (FEA) model of concrete-encased CFST column is schematically shown in Fig. 2, which is built based on the software package of ABAQUS/Standard module [8]. The model of concrete-encased CSFT column under combined compression and bending is based on the previous analytical work of such stub columns and beams described in Han and An [1] and An et al. [7], respectively.

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Nomenclature

A	Cross-sectional area of concrete-encased CFST ($=B^2$)
A_{core}	Cross-sectional area of core concrete of CFST
A_l	Cross-sectional area of longitudinal bar
A_s	Cross-sectional area of steel tube of CFST
A_{sc}	Cross-sectional area of CFST ($=A_{core}+A_s$)
A_{out}	Cross-sectional area of outer concrete
B	Sectional width
c	The distance from neutral axis to extreme compressive outer concrete fiber
D	Steel tube diameter of CFST
D/B	Steel tube diameter to sectional width ratio
DI	Ductility index
D_i	Core concrete diameter of CFST
E_c	Concrete modulus of elasticity
f_{ck}	Characteristic concrete strength
f_{cu}	Concrete cube strength
f_c'	Concrete cylinder compressive strength
f_{yh}	Yield strength of stirrup
f_{yl}	Yield strength of longitudinal bar
f_{ys}	Yield strength of steel tube
l_0	Effective column length
M	Moment
M_{cfst}	Moment of CFST component at N_u
M_u	Ultimate moment at N_u
N	Axial load
N_{cfst}	Axial load of CFST component at N_u
N_u	Ultimate axial load
P	Lateral load
t	Wall thickness of the steel tube in CFST
u_m	Later mid-height deflection
u_{mu}	Later mid-height deflection at N_u
α_s	Steel ratio of CFST ($=A_s/A_{core}$)
α_l	Longitudinal bar ratio ($=A_l/(A-A_{sc})$)
λ	Slenderness ratio
ε	Strain
σ	Stress
ξ	Confinement factor of CFST section

2.1. General description of the FEA model

(1) Material model
Elastic plastic model and damage plastic model are used for the steel and concrete material in the FEA model, respectively. The five-stage and bi-linear stress–strain relations provided by Han et al. [9] and Zhao et al. [10] are used to describe uniaxial stress–strain relations of steel tube and rebar, respectively. The elastic modulus and Poisson's ratio of steel are taken as 206,000 N/mm^2 and 0.3, respectively.
The elastic modulus and Poisson's ratio of concrete are taken as 4 730$\sqrt{f_c'}$ according to ACI 318-11 [11] and 0.2, respectively. The stress–strain relations provided by Attard and Setunge [12], Han and An [1], and Han et al. [9] are used to describe the uniaxial compressive stress–strain relations of outer unconfined concrete, outer confined concrete and core concrete in the inner CFST (as shown in Fig. 2(b)), respectively. For concrete in tension, the cracking strength of concrete σ_t is $0.3\cdot(f_c')^{0.67}$ according to Model Code 2010 [13]. The stress–strain relation introduced in An et al. [7] is used herein to describe the post-failure behaviour of the concrete in tension.

(2) Element type, mesh and boundary conditions
Half of the composite column is modeled due to symmetry of cross-section as shown in Fig. 2(b) and loading conditions along the loading lines. The concrete, the steel tube and the rebar are simulated by eight-node brick element, four-node shell element and two-node truss element, respectively. A mesh convergence study has been performed to identify an appropriate mesh as shown in Fig. 2.
The load is applied on the loading plate, which is assumed to be a rigid block as shown in Fig. 2(a). Along the loading line of the bottom loading plate, all freedom degrees except the rotation around x axis are constrained, whilst at the loading line of the top loading plate, an appointed displacement is applied along z axis, and the displacements along x and y axes and rotations along y and z axes are constrained. Pin-ended conditions are used, and the load eccentricity (e, the distance from the loading line to the center line of the column) at the two ends are the same. The above boundary conditions are used for the simulations of the loading path I as shown in Fig. 1(c). The boundary condition for loading path II is that the constant axial load (N) is applied in the loading plate first and then the appointed lateral displacement is applied step by step to the failure of the composite column.

(3) Concrete–steel interface
Surface interaction with hard contact in the normal direction and the Mohr–Coulomb friction model in the tangential direction between the steel tube and the concrete had been used to simulate concrete-encased CFST subjected to axial compression or bending [1,7]. These models are also used in the current FEA modeling. The rebar is connected to the outer concrete by embedded element technique, where the translational degrees of freedom at the rebar node are eliminated as described in Han and An [1].

2.2. Verifications of the FEA model

The collected testing data of concrete-encased CFST columns under both loading paths I and II are used to verify the FEA model. Tables 1 and 2 give the collected testing specimens of the concrete-encased CFST columns under the two kinds of loading paths, respectively, where B is the sectional wide of the composite columns; D and t are the diameter and thickness of the steel tube of the CFST; A_{lt}, A_{lc}, A_{lw1} and A_{lw2} represent the longitudinal bars in tension side, compression side, web below mid-line and web up mid-line, respectively; f_{ys} and f_{yl} are the yield strength of the steel tube and the longitudinal bar, respectively; $f_{cu,core}$ and $f_{cu,out}$ are the cube strength of the core concrete in CFST and its outer concrete, respectively. For the testing specimens presented by Li et al. [6], the yield strength of the longitudinal bar with diameter of 12 mm was 405 N/mm^2 and that with diameter of 5 mm was 350 N/mm^2, respectively.

The failure modes, the axial load (N) versus extreme fiber strain of the steel tube at mid-height (ε_s) and the ultimate strength between predicted and measured columns under loading path I are compared. The distributions of the crushed concrete and the cracks between measured and predicted specimens Z4 and Z6, whose failure modes are balance failure and tension-controlled failure according to Wang [3] are compared in Fig. 3. Concrete is crushed in the compression zone and horizontal cracks distribute uniformly in the tension zone in the specimens. Generally good agreement is obtained between the predicted and measured N–ε_s for eccentrically loaded columns, as shown in Fig. 4. The predicted ultimate axial loads (N_{uc}) agree well with the measured ones (N_{ue}), as shown in Fig. 5. The mean value and the standard deviation of N_{uc}/N_{ue} are 0.979 and 0.108, respectively.

Fig. 6 gives the comparisons of lateral load (P)–lateral displacement (Δ) relations of the composite columns under loading path II, where the measured P–Δ relations are the envelop curves of the composite columns under cyclic loading, and it can be found that good agreement has been achieved. The predicted ultimate lateral loads (P_{uc}) agree