EXPERIMENTAL AND NUMERICAL STUDY ON CONCRETE-ENCASED CONCRETE-FILLED STEEL TUBE (CECFST) SHORT COLUMNS UNDER AXIAL LOAD WITH BENDING MOMENT

YOU-XIN MA[1], OU ZHAO[1], KANG HAI TAN[1]

[1]*School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore*

E-mail: YXMA@ntu.edu.sg (You-xin Ma)

E-mail: ou.zhao@ntu.edu.sg (O. Zhao)

Emails: ckhtan@ntu.edu.sg (K. H. Tan)

An experimental study, including 3 eccentrically loaded concrete-encased concrete-filled steel tube (CECFST) short columns, was conducted to investigate the behavior of such columns under axial load with bending moment. The effect of end eccentricities was studied. The failure mode of each specimen, cracking, load-to-deflection, and moment-to-curvature relationships are presented. The eccentric distance could affect the crushing and spalling of the concrete cover and failure mode of the specimens. Furthermore, a numerical model was established and validated against the test results. It was found that the developed FE model in ABAQUS was able to capture the structural performance of CECFST short columns under axial load with bending moment. In the FE model, different material properties were employed to model concrete confined by stirrups and the steel tube. Contact between the steel tube and the concrete was carefully established. In addition, the interface between column ends and the loading plates was also considered in the model to simulate true loading conditions. The design concept per Eurocode 4 for composite columns was evaluated by the test results. The comparison showed that the predicted M–N interaction curve may overestimate the load-carrying capacities of CECFST columns under axial load with bending moment.

Keywords: Composite columns, Eccentric loading, Finite element model, Eurocode 4.

1 Introduction

Concrete-encased concrete-filled steel tube (CECFST) columns have been developed and applied in China and Japan for many years. The inner concrete-filled steel tube core is encased by the reinforced concrete (RC) encasement to prevent outward buckling of the steel tube and improve fire resistance and corrosion resistance, as shown in Fig. 1. Besides, the embedded inner steel tube of composite column allows steel beams to be connected to the column. Due to its good performance, extensive research has been conducted on CECFST columns under different loading combinations. The axial performance of CECFST columns was evaluated by Han and An (2014). It was found that the load-carrying capacities of such columns can be calculated by Eurocode 4. After the initial study of axially-loaded CECFST columns, An and

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Han (2014) conducted a numerical investigation on such columns under axial load with bending moment. A design equation was proposed according to strain compatibility. However, the applicability of plastic stress distribution was not evaluated, which is the basis of designing composite columns in Eurocode 4. Afterwards, the behavior of CECFST short columns under axial load combined torsion was studied by Ren et al. (2017) experimentally and by Li et al. (2018) numerically. They concluded that the CECFST column had ductile behavior in comparison with the RC column.

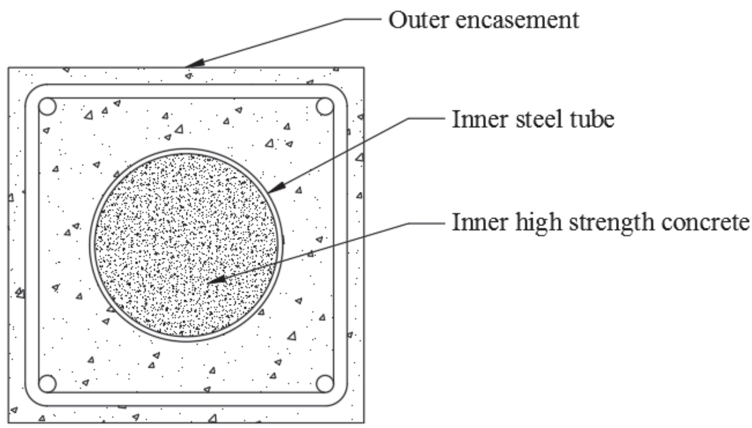


Figure 1. Typical cross-section of CECFST column

A test program including 3 eccentrically-loaded CECFST short columns was conducted. The experimental results, consisting of load-to-deflection curves, end moment-to-rotation curves, failure modes, and load-carrying capacities, are reported in this paper. A numerical model was developed and validated against the test results. Finally, the design concept of Eurocode 4 was examined by comparing the predicted *M*-*N* interaction curve with the test results.

2 Experimental study

To exert purely pin-pin boundary condition onto the specimens, a knife-edge bearing was employed, as shown in Fig. 2. The central deflection was measured by one Linear Variable Differential Transformer (LVDT), and four additional LVDTs were placed onto the bottom endplate of the specimen to record the end rotations during the test. To measure the strain at the mid-height cross-section of the column, strain gages were mounted onto the longitudinal bars, steel tube, and stirrups.

The inner concrete-filled steel tube (CFST) core with a diameter of 144 mm and tube thickness of 4.2 mm was surrounded by the RC encasement with a dimension of 210 mm × 210 mm for all the specimens. The yield strength of inner steel tubes, longitudinal bars, and stirrups are 358 MPa, 558 MPa, and 445 MPa. The inner concrete and outer concrete strength were 40 MPa and 47 MPa, respectively. The end eccentricities were designed as 35 mm, 70 mm and 160 mm for the three test specimens to cover small and large eccentricity ratios. All the dimensions and material properties of the test specimens are summarized in Table 1 and Table 2, respectively.

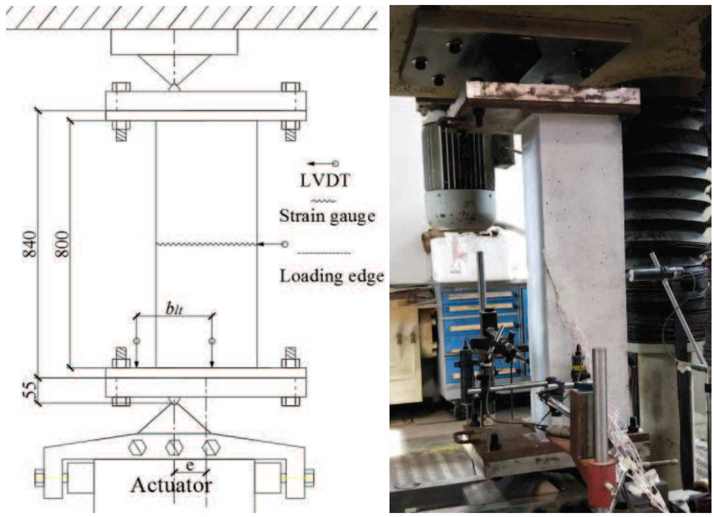


Figure 2. Test-setup and instrumentations

Table 1. Dimensions of the test specimens (in millimeters)

Specimens	Column cross-section	Steel tube	Longitudinal bar	Stirrup	Effective length	Eccentricity
Specimen 1	210 × 210	114 × 4.2	H10	R8@100	950	35
Specimen 2	210 × 210	114 × 4.2	H10	R8@100	950	70
Specimen 3	210 × 210	114 × 4.2	H10	R8@100	950	160

Table 2. Material properties (in MPa)

Material	Inner concrete	Outer concrete	Steel tube	Longitudinal bar	Stirrup
Strength	47	40	358	558	445

3 Test results and numerical model

Experimental results, including load–deflection, and end moment–rotation curves, typical failure modes, and load-carrying capacities are reported and discussed in this section. Furthermore, a nonlinear finite element (FE) model was developed to simulate the behavior of CECFST short columns under eccentric loading. The FE model was validated against the test in terms of load–deflection curves and load-carrying capacities.

3.1 *Experimental results*

The typical failure mode of each specimen is shown in Fig. 3. It was found that the first two specimens with relatively smaller eccentricities failed by concrete crushing at the mid-height section of the columns on the compression side. In contrast, Specimen 3 with a larger eccentricity, which was outside the column cross-section, failed in the tension mode. Several cracks formed along the column at the tension side of Specimen 3.

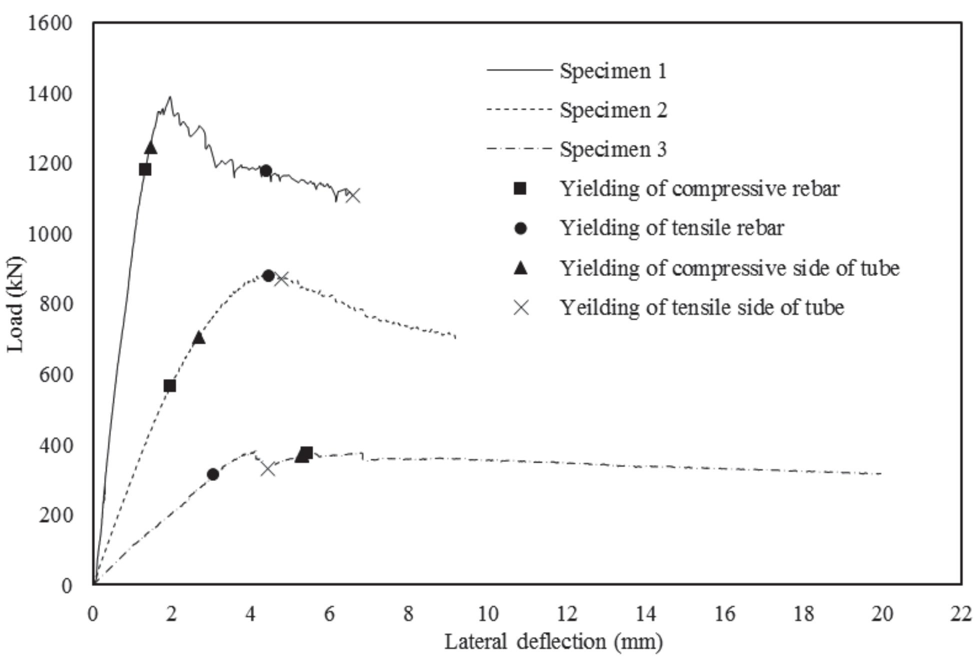
(a)

(b)

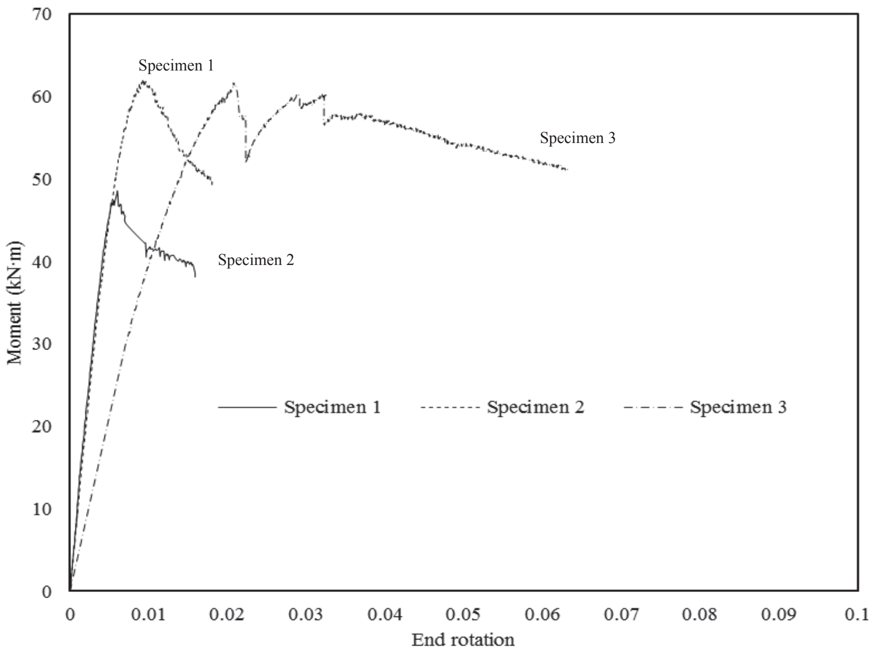
(c)

Figure 3. Failure mode of the test specimens: (a) Specimen 1; (b) Specimen 2; (c) Specimen 3

The load–deflection and end moment–rotation curves of the test specimens are presented in Fig. 4. It was found that the load-carrying capacity of the CECFST short column decreased with an increase of the end eccentricity. On the other hand, the column mid-height deflection corresponding to the peak load tended to increase with an increase of the end eccentricity.



(a)



(b)

Figure 4. Test results: (a) Load–deflection curve; (b) End moment–rotation curve

The yield points of the inner steel tube and longitudinal bars during the test are shown in Fig. 4(a). Generally, the compressive rebar yielded before the tensile rebar for Specimens 1 and 2, followed by yielding of the compressive side of the inner steel tube. However, due to the large eccentricity, the tensile rebar and the tensile side of the tube could yield before the compressive rebar and compressive side of the tube. Besides, due to sudden spalling of the concrete cover at the compression side of Specimen 3, sudden drops were observed in both curves for this specimen.

3.2 *Numerical study*

Finite element (FE) models were established to further study the behavior of CECFST short columns under axial load with bending moment. The modeling approach is illustrated in Fig. 5, in which the column cross-section was divided into the tube confined concrete, the outer effectively confined concrete, and the outer most unconfined concrete consisting of concrete cover. Different compressive stress-strain relationships need to be applied to different types of concrete due to different confinement conditions. A tube confined concrete model proposed by Tao et al. (2013) was used herein for the inner concrete. The model used for outer effectively confined concrete and unconfined concrete was obtained from Legeron and Paultre (2003) and Attard and Setunge (1996), respectively. The tensile behavior of the concrete was modeled by Hordijk (1992).

Besides, hard contact was employed for the interface between the concrete and the inner steel tube. To model the true loading conditions during the test, the rigid loading plates were modeled onto the column ends. The steel tube was tied to the plates, and hard contact was applied to the interface between the concrete and the loading plates. The boundary conditions were applied on two reference points, which was coupled with the surfaces of the loading plates.

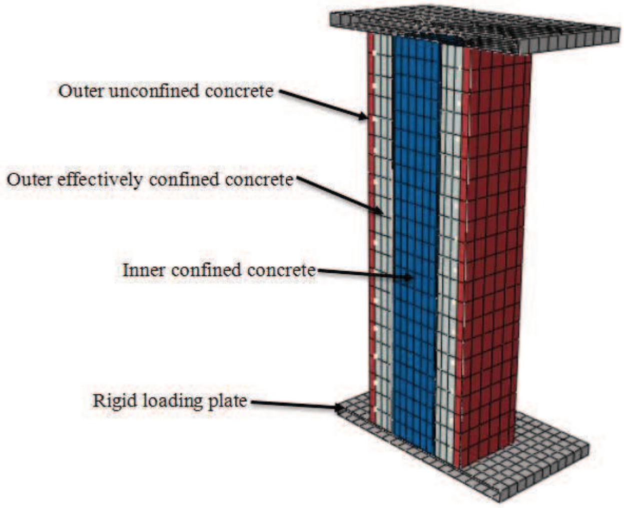


Figure 5. Modeling approach

The developed FE models were validated against the test results, as shown in Fig. 6. It can be seen that the developed FE models could capture the general behavior and the load-carrying capacities of the CECFST short columns under uniaxial eccentric loading.

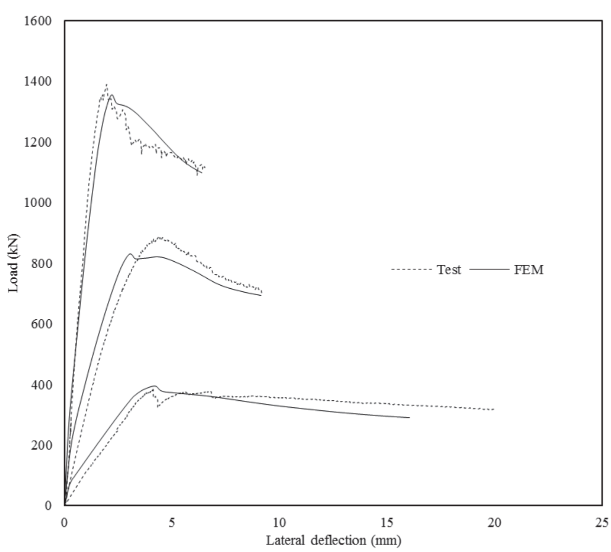


Figure 6. Comparison of the FE and experimental results

4 Evaluation of the design approach in Eurocode 4

Plastic stress distribution method is the basis of designing of concrete-encased steel section columns under combined loading, as shown in Fig 7, in which the concrete stress is assumed to be a stress block and inner steel section and longitudinal bars are assumed fully yielded. According to the same concept, the moment capacities of the CECFST columns under certain load levels can be obtained by the predicted *M*-*N* curve. The moment capacities predicted by the *M*-*N* curve were compared with the test results as, shown in Table 3. It was found that the design approach in Eurocode 4 could result in unconservative predictions. This is because crushing of the concrete cover is not considered in Eurocode 4.

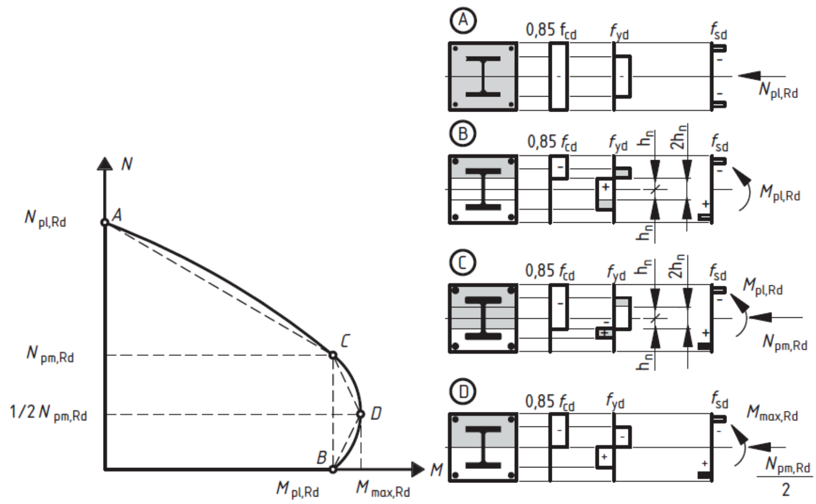


Figure 7. Design of concrete-encased steel section columns under combined loading (Eurocode 4)

Table 2. Comparison between predicted and test results

Specimen	Predict	Test	Predict/Test
Specimen 1	59.5 kN·m	51.3 kN·m	1.16
Specimen 2	72.0 kN·m	65.9 kN·m	1.09
Specimen 3	67.5 kN·m	63.3 kN·m	1.07

5 Conclusions

In this paper, a test program including 3 eccentrically loaded specimens has been conducted to study the behavior of CECFST short columns under axial load with bending moment. It was found the end eccentricity could affect the failure mode. Besides, a numerical study has been performed to simulate such columns under combined loading. It demonstrated that the developed FE models could capture the general behavior of the CECFST columns under eccentric loading. Finally, the design approach in Eurocode 4 was examined by the test results, which showed that the plastic stress distribution method in Eurocode 4 could over-predict the moment capacities of CECFST columns under certain load levels.

References

LI, S., HAN, L.-H. & HOU, C. Concrete-encased CFST columns under combined compression and torsion: Analytical behaviour. *Journal of Constructional Steel Research,* 144**,** 236-252, 2018.

REN, Q.-X., HAN, L.-H., HOU, C., TAO, Z. & LI, S. Concrete-encased CFST columns under combined compression and torsion: experimental investigation. *Journal of Constructional Steel Research,* 138**,** 729-741, 2017.

HAN, L.-H. & AN, Y.-F. Performance of concrete-encased CFST stub columns under axial compression. *Journal of Constructional Steel Research,* 93**,** 62-76, 2014.

AN, Y.-F. & HAN, L.-H. Behaviour of concrete-encased CFST columns under combined compression and bending. *Journal of Constructional Steel Research,* 101**,** 314-330, 2014.

TAO, Z., WANG, Z.-B. & YU, Q. Finite element modelling of concrete-filled steel stub columns under axial compression. *Journal of Constructional Steel Research,* 89**,** 121-131, 2013.

LEGERON, F. & PAULTRE, P. Uniaxial confinement model for normal-and high-strength concrete columns. *Journal of Structural Engineering,* 129**,** 241-252, 2003.

ATTARD, M. M. & SETUNGE, S. Stress-strain relationship of confined and unconfined concrete. *Materials Journal,* 93**,** 432-442, 1996.

HORDIJK, D. A. Tensile and tensile fatigue behaviour of concrete; experiments, modelling and analyses. *Heron,* 371992.