PERFORMANCE OF CONCRETE-ENCASED CONCRETE-FILLED STEEL TUBE (CECFST) SHORT COLUMNS UNDER BIAXIAL ECCENTRIC COMPRESSION-AN EXPERIMENTAL STUDY

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The paper presents the results of an experimental study on the behavior of concrete-encased concrete-filled steel tube (CECFST) short columns subjected to biaxial eccentric compression. In practice, theses composite columns may be subjected to biaxial eccentric compression in a building. However, research studies conducted before were all focused on the performance of such columns under axial compression or uniaxial eccentric compression. To fill this technical gap, a total of 3 tests were conducted for such columns under axial load with biaxial bending. Based on the experimental results, the effects of the end eccentricities on failure modes and load–deflection curves of CECFST columns were investigated. Furthermore, the contact behavior between the steel tube and concrete was also discussed. It was found that the steel tube came into contact with the outer concrete encasement initially. Besides, the confinement provided by the inner steel tube was more effective for the specimen loaded with a smaller end eccentricity. Finally, the design concept of Eurocode 4 based on the load contour method for the composite column under biaxial eccentric compression was used to predict failure loads for CECFST columns. At a given load level, it was found that the assumed load contours in Eurocode 4 largely underestimated moment capacities of CECFST columns due to the symmetric cross-section of the column.

Keywords: Composite columns, Biaxial eccentric compression, Contact behavior, Eurocode 4.

1 Introduction

The concrete-encased steel column is one type of composite columns which has been used in practice for many years. The axial-flexural behavior of such columns has been investigated for decades (El-Tawil and Deierlein 1999, Ellobody et al. 2011, Kim et al. 2011). Due to protection of the concrete encasement, the fire and corrosion resistance of such columns are much better than steel columns and concrete-filled steel tube (CFST) columns. In recent years, a new type of concrete-encased steel columns began to attract the researchers' and engineers' attention, which is called concrete-encased concrete-filled steel tube (CECFST) columns. The CECFST column includes two parts, i.e. the outer reinforced concrete (RC) encasement and the

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inner CFST. Compared with conventional concrete-encased steel columns, CECFST columns possess the same fire and corrosion resistance. Besides, high strength concrete can be infilled for inner CFST to enhance the column strength further, and the RC encasement with the inner steel tube can be precast in the factory to promote construction productivity and reduce self-weight onsite. Some research work has been conducted on CECFST columns. Contact behavior between the inner steel tube and the external RC encasement for CECFST columns was initially studied by Han and An (2014). However, numerical studies for columns under axial compression or combined loadings were conducted by An and Han (2014). A design approach was proposed based on the strain compatibility method.

In this paper, a test program including 3 CECFST short columns under biaxial eccentric compression was conducted. The test results, including load-to-deflection curves, contact behavior between the steel tube and the concrete, and failure modes, are reported.

2 Experimental study

The pin-pin boundary condition was applied onto the specimens by a knife-edge bearing, as shown in Fig. 1. The mid-height deflections of the specimen were measured by two Linear Variable Differential Transformers (LVDT). Four additional LVDTs placed on the bottom endplate of the specimen were used to record the end rotations during the test. To study the general behavior of CECFST columns under biaxial eccentric compression, strain gages were mounted onto the specimen. Furthermore, to investigate the contact behavior of steel tube and concrete, strain gages were mounted onto the inner steel tube in both vertical and transverse directions.

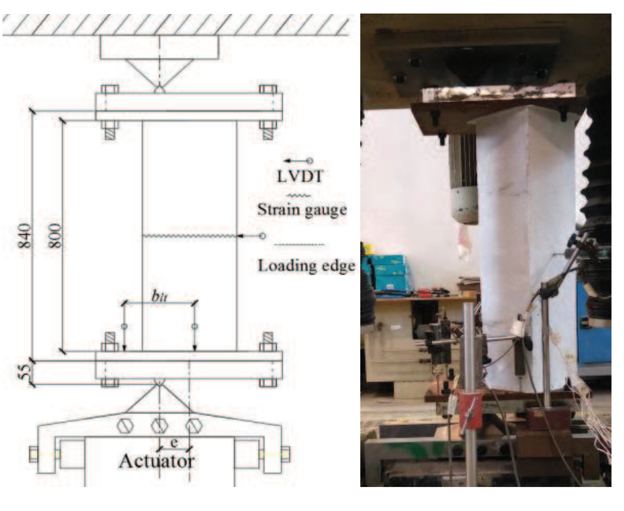


Figure 1. Test-setup and instrumentations

All specimens had an identical cross-section with dimensions of 210 mm × 210 mm and a 114 mm × 4.2 mm embedded steel tube as shown in Table 1. The material properties of the steel tube, reinforcing bars, stirrup, and the concrete are summarized in Table 2. To apply biaxial loading, the specimen was fitted with end plates which were at 45° orientation to the square column axis. The end eccentricities (*e*) were designed as 35 mm, 70 mm, and 155 mm for the three test specimens.

Table 1. Dimensions of the test specimens

Specimens	Column cross-section (mm)	Steel tube (mm)	Rebar (mm)	Stirrup (mm)	*e* (mm)
Specimen 1	210 × 210	114 × 4.2	H10	R8@100	35
Specimen 2	210 × 210	114 × 4.2	H10	R8@100	70
Specimen 3	210 × 210	114 × 4.2	H10	R8@100	155

Table 2. Material properties

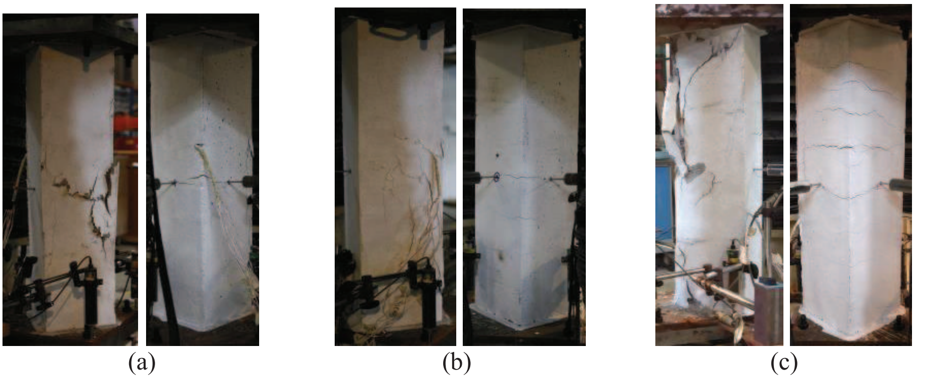
Material	Inner concrete	Outer concrete	Steel tube	Rebar	Stirrup
Strength	47 (MPa)	40 (MPa)	358 (MPa)	558 (MPa)	445 (MPa)

3 Test results

Typical failure modes and load–deflection curves are reported in this section. The main stages of structural behavior of the specimens are represented by yielding points of different materials, such as the steel tube and the longitudinal reinforcement. Furthermore, the contact between the inner steel tube and the concrete is discussed by observing the change of the ratio between the hoop strain and the longitudinal strain of the steel tube.

3.1 *Failure modes*

The crushing region of the compression side and the crack pattern of the tension side for each specimen are shown in Fig. 2. Concrete crushed and several major cracks formed at the column mid-height for Specimens 1 and 2, which were loaded with relatively small end eccentricities. However, for Specimen 3 loaded with a larger end eccentricity, the concrete tended to crush along the column length and many cracks with smaller spacing were formed on the tension side.



(a) (b) (c)

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

3.2 *Load–deflection curve*

The load-to-deflection relationships of three test specimens are shown in Fig. 3. Longitudinal strains of the reinforcement and the steel tube are recorded. Firstly, the compression reinforcing bars yielded for all the specimens due to the flexural loading. However, the middle reinforcing bars only yielded in specimen 1 at the descending part of the curve due to the smallest end eccentricity. For specimen 3, the compressive reinforcing bars and tensile reinforcing bars yielded at the same time in specimen 3, which indicates that this specimen failed by balanced failure mode. It was found that the peak load decreased, and the mid-height deflection corresponding to the peak load increased with an increase of the end eccentricity.

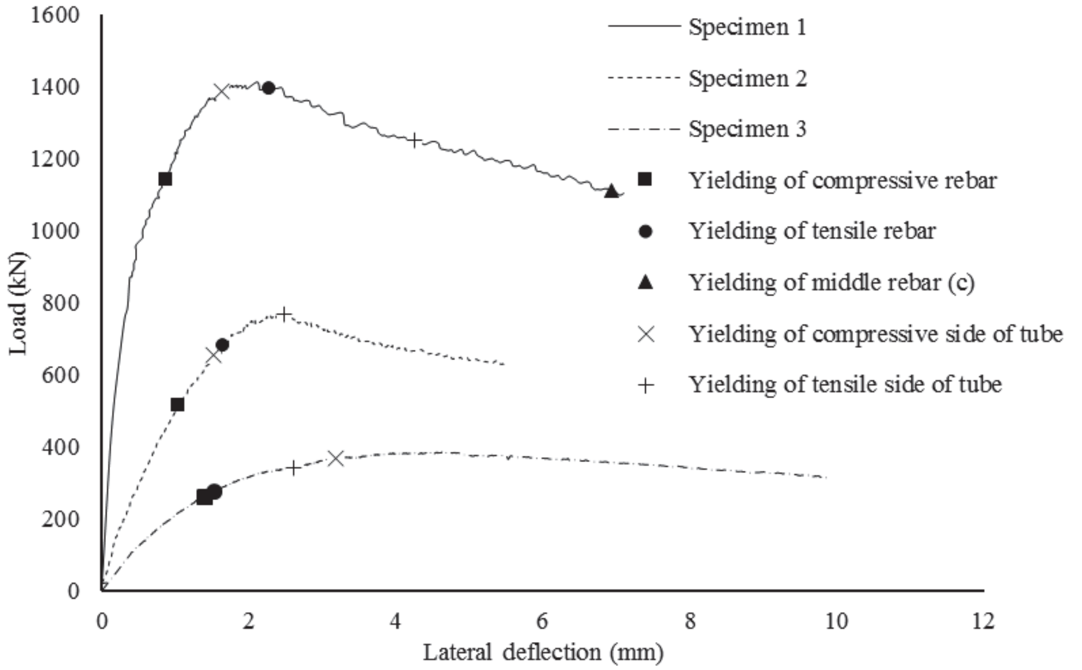


Figure 3. Load–deflection curve

3.3 *Contact behavior*

Contact between the inner steel tube and the surrounded concrete and the innermost infilled concrete could be observed by the ratio (ν) of the hoop strain and the longitudinal strain of steel tube. Due to damage of the transverse strain gage in specimen 1, values of v for specimens 2 and 3 were plotted with mid-height deflection as shown in Fig. 4. Values of v when the specimens reached their peak loads were indicated by solid points in the figure.

When v was equal to Poisson's ratio of the steel tube (0.3), there was no contact between the steel tube and the concrete encasement or between the infilled concrete and the steel tube. From Fig. 4, it was found that the value of ν for specimen 1 was smaller than 0.3 before lateral deflection reached around 2 mm and then it increased sharply. This means that the steel tube contacted the outer concrete first since the Poisson's ratio of the steel tube (0.3) is larger than that of the concrete (0.2). However, with increasing load, the inner concrete dilated and contacted with the steel tube, which began to mobilize the confinement effect for the inner concrete. For specimen 3, the value of v was larger than 0.2 but smaller than 0.3, which indicates that the steel tube contacted with the outer concrete but was separated from the innermost concrete infill until lateral deflection reached 8 mm.

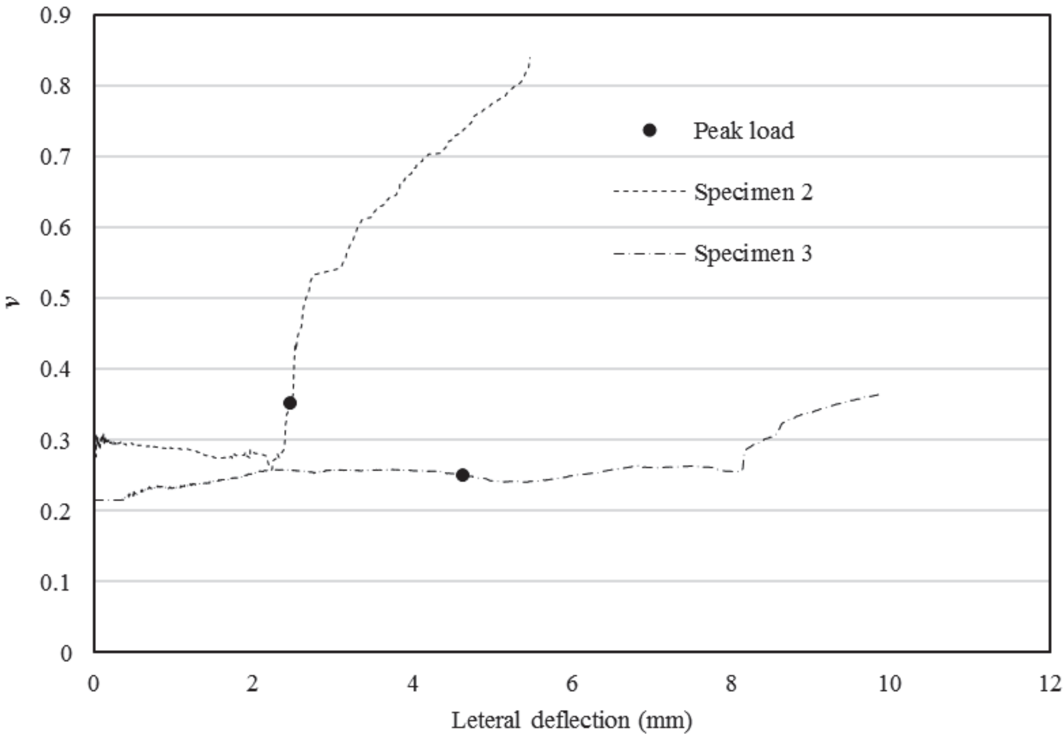


Figure 4. Contact between steel tube and concrete

When the innermost concrete infill contacted the steel tube, the former was under triaxial stress state due to the hoop stress provided by the steel tube. For specimen 2, contact between the inner concrete and the steel tube happened before the column reached its load-carrying capacity. In contrast, contact happened after the peak strength of the column for specimen 3 loaded with large end eccentricity, indicating lower effectiveness of confinement on the inner concrete compared with specimen 2.

4 Assessment of the design approach in Eurocode 4

For the design of composite columns under axial load with bi-axial bending moments, load contour method from Eurocode 4 was employed. This approach could trace the real load contour for a certain load level N_0 by a straight line formed by the uniaxial moment capacities (M_{x0} and M_{y0}) of the columns (under N_0) for both principal axes, as shown in Fig. 5.

To assess the design method of Eurocode 4, the predicted moment capacities of the test specimens were compared with the test results as shown in Table 2. It can be found that the design approach in Eurocode 4 could give very conservative predictions due to the low accuracy of the assumed load contour.

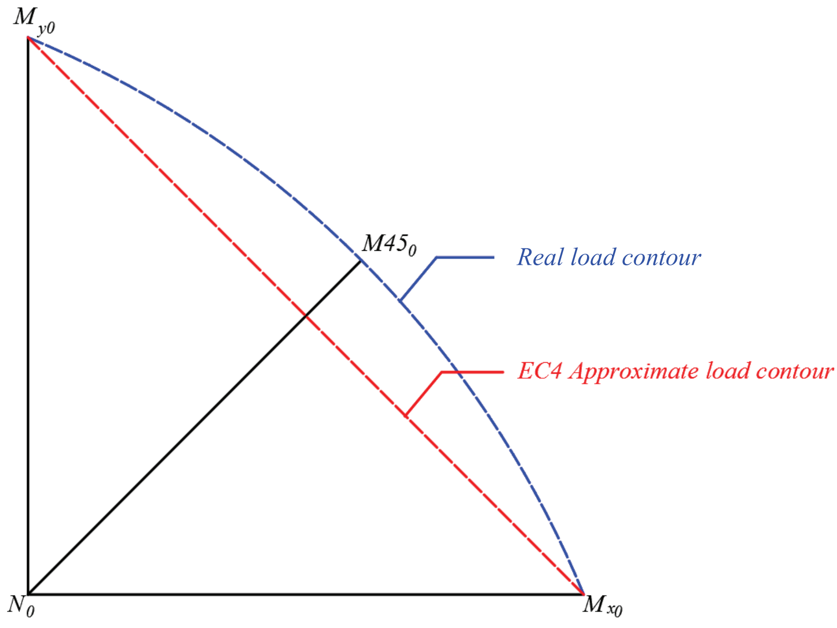


Figure 5. Design of composite columns under biaxial eccentric compression (Eurocode 4)

Table 2. Comparison between predicted and test results

Specimen	Load level	Prediction	Test result	Prediction/Test result
Specimen 1	1415.1 kN	41.3 kN·m	53.9 kN·m	0.77
Specimen 2	773.6 kN	51.3 kN·m	56.9 kN·m	0.90
Specimen 3	385.5 kN	47.4 kN·m	62.3 kN·m	0.76

5 Conclusions

In this paper, the test results of 3 concrete-encased concrete-filled steel tube columns were presented. The key findings were briefly presented herein. Concrete at the compression side of the column tended to crush along the column length when the end eccentricity was large. The load-carrying capacity decreased, and the mid-height deflection corresponding to the peak load increased with an increase of end eccentricity. Initially, the inner steel tube contacted the outer concrete due to different Poisson's ratios of both materials. The confinement effect from the steel tube on the inner concrete could be weaker with an increase of end eccentricity. The design approach in Eurocode 4 for composite columns was assessed by comparing the predicted moment capacities to test results for certain load levels. It was shown that the design approach in Eurocode 4 could result in large conservative predictions.

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