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BEHAVIOR OF EXPANSIVE CONCRETE-FILLED STEEL TUBULAR COLUMNS UNDER AXIAL LOADINGS

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Concrete-filled steel tubes (CFSTs) have been introduced to expedite construction and increase the confinement of concrete by the steel tube. While changing the confinement level through the use of expansive additives (EAs) will have an impact on the performance of CFSTs, limited information is available on the behavior of expansive concrete-filled steel tubular (ECFST) columns. The objective of this study is thus twofold: (i) to experimentally assess the behavior of axially loaded ECFSTs, and (ii) to investigate the correlation between the test results and those obtained from prediction approaches. The experimental program of this study consists of testing four 1500 mm CFST/ECFST columns with 153.6 mm outer diameter and 3 mm thickness. The ECFST specimens are divided into two subgroups with 0% and 12% EA dosage and two concrete mixtures, 16 and 37 MPa. The results indicate that the latter is the most promising mixture since it results in a significant enhancement of 64% in the axial load capacity of ECFST columns compare with CFSTs. The study also recommends employing specific confined concrete models with the existing code prediction approaches to arrive at the best correlation with test results.

Keywords: ECFST, CFST, Confinement, Expansive additives, Testing, Prediction approaches.

1 INTRODUCTION

In recent years, concrete-filled steel tubes (CFSTs) have been increasingly used in high-rise buildings and other types of structures due to their advantages compared with ordinary steel or reinforced concrete columns. The steel tube serves as a form of casting the concrete, which leads to a reduction in manpower, construction cost and project duration. Regarding structural performance, the placement of steel at the perimeter of the section provides the highest contribution to the section flexural capacity and moment of inertia. The concrete core delays the local buckling of the steel tube by preventing inward buckling. The continuous confinement provided to the concrete core by the steel tube effectively enhances the concrete strength and ductility, and hence increases the CFST loading carrying capacity. Therefore, the use of CFSTs increases the usable floor area by a reduction in the required column cross-sectional sizes.

The increase of load-carrying capacity due to the concrete confinement provided by the steel tube depends on several parameters such as the strength and deformability of the materials, diameter-to-thickness ratio (D/t) of the steel tube, its length-to-diameter ratio (L/D), and cross-section shape (Susantha *et al.* 2001, Hu *et al.* 2003, Liang and Fragomeni 2009). Additionally, the concrete shrinkage and bond between the concrete and steel tube play important roles in the axial load capacity of CFST members. The bond strength can be enhanced by adding expansive additives (EAs) into the concrete mix to reduce the concrete shrinkage. This type of CFST member is termed expansive concrete-filled steel tube (ECFST). Although the results of recent studies have indicated that the expansive concrete is a promising technique for improving the performance of CFST columns by increasing confinement and delaying the local buckling of steel tubes, this technique has received little attention (Mwafy *et al.* 2015). There is a pressing need to fill the gaps in knowledge related to the effect of EA and concrete strength on the axial load capacity of ECFSTs, particularly using the EA material commonly utilized in the local construction industry. The main objectives of this study are thus as follows: (i) experimentally investigate the load capacity of concentrically loaded CFST and ECFST columns, (ii) study the correlation between the test results of the present research and previous studies with those obtained from the prediction approaches recommended by design provisions and in previous studies, and (iii) provide recommendations regarding the suitable prediction approaches for estimating the capacity of CFST columns.

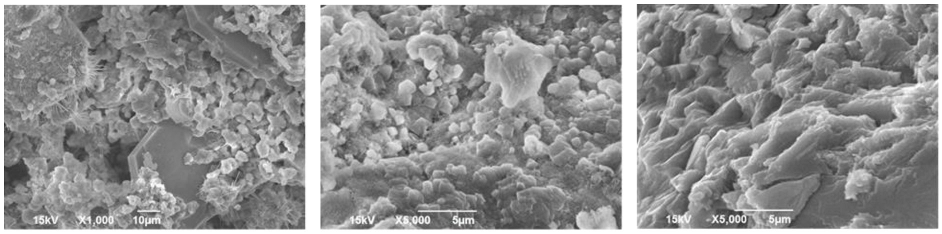
2 EXPERIMENTAL PROGRAM

The experimental program consists of testing relatively long ECFST columns when subjected to increasing axial loads. The concrete of the composite column specimens is mixed in a number of batches with two concrete strength values. An expansive additive in a powder form with both expanding and super-plasticizing actions is used in the present study. To obtain different pre-stressing levels, the EA is added in two dosages relative to the cement weight (i.e., 0% and 12%). The dosages were selected based on the conclusions of a recent study that focused on the behavior of short ECFSTs with four different EA ratios (Mwafy *et al.* 2015). In total, four concrete mixes are prepared. Two mixes are without the EA (M0 and M1) while the other mixes are prepared with 12% EA ratios (i.e., M0-E12 and M1-E12). Average values of the standard cylinder compressive strength at 28 days (f'_c) are presented in Table 1.

Table 1. Details of four CFST/ECFST specimens.

No.	Group	Specimen Concrete mix	Expansive Additive (EA)	f'_c (MPa)	f_y (MPa)	D (mm)	t (mm)	L (mm)
1	A	M0	0%	16	239	153.6	3	1500
2		M1		37	239	153.6	3	1500
3	B	M0-E12	12%	29	239	153.6	3	1500
4		M1-E12		53	239	153.6	3	1500

Two concrete mixing approaches are investigated to verify the effect of the EA mixing on concrete strength. All concrete ingredients are simultaneously mixed with water in the first mixing approach (referred to as MA1). In the second mixing approach (MA2), all ingredients, excluding the cement and water, are firstly mixed together. The water is then added to enable the EA to react with enough water. After 2-3 minutes of mixing, the cement is finally added to the mixture. Scanning Electron Microscope (SEM) is conducted on three samples to identify the main differences in the microstructure between mixtures M1 with no EA, M1-E12 with MA1 and M1-E12 with MA2. Figure 1 shows the SEM micrographs for the three mixtures. For M1, voids with average dimension > 10μm are observed with some calcium hydroxide crystals. For the mixtures with EA, no obvious large voids are observed, indicating more compact microstructure and justifying the obtained higher compressive strength for the EA mixtures. The formation of massive crystalline products due to the inclusion of EA is also observed. As for the comparison between MA1 and MA2, no significant difference is observed except that the sizes of crystals for MA2 are larger than those seen in the MA1 sample. This justifies the slightly higher strength for the MA2 mixtures compare with MA1. It is therefore decided to use MA2 with the specimens studied in the present study.



(a) (b) (c)

Figure 1. SEM micrographs of three mixtures: (a) M1; (b) M1-E12 with MA1; and (c) M1-E12 with MA2.

The hollow steel tubes are cut from 6.0 m long cold rolled circular tubes. A standard tensile test indicates that the yield and ultimate strength are 239 MPa and 303 MPa, respectively. The steel tubes are cut at the shop and fabricated with a lathe to ensure the symmetry of the tube sides. Also, top and base plates were engraved to a depth of 3 mm around the tube and drilled at four corners to place four steel rods, which are used to tie the top and base plates with the tube. The concrete is cast in four layers, and each layer is compacted before casting the following layer. To arrive at an effective pre-stressing action during the hardening process, the two end plates are bolted to each specimen immediately after casting and vibrating concrete using four steel rods. The two end plates are then removed on the test day. The ECFST specimens are cast and cured with the CFST columns (i.e., column specimens with and without EA).

Specimens were tested 28 days after casting of concrete in the laboratories of the United Arab Emirates University (UAEU). To enable measuring both longitudinal and transverse strains at different locations, five sets of uniaxial strain gauges are bonded to the exterior tube surface of each of the specimens. Each of the used sets includes three strain gauges that are located at 0.25, 0.5 and 0.75 of the specimen height/length. The vertical strain gauge sets are used to measure the longitudinal strains at different points in the same level of the ECFST specimen. A set of horizontal strain gauges measures the circumferential strains for each specimen. A 2000 kN reaction steel frame and 2000 kN Enerpac® hydraulic jack with a maximum stroke of 156 mm are used for testing the column specimens (Figure 2). Four steel stub columns are used to reduce the frame height to the required length of the long column specimens. A thick steel plate is fixed to the concrete strong floor to support the column specimens. A magnetic base fixed at the base plate of the specimen is used to secure the linear variable displacement transducers (LVDTs) during testing. Four LVDTs (TML® CDP-100) are placed symmetrically around each of the specimens to measure the deformations along the specimens. The applied load, strains, and longitudinal deformations are recorded in real-time using a 30-channel static/dynamic digital strainmeter (TML® DRA-30A). With all instrumentations connected to the data logger, the load is applied and monotonically increased up to failure, and the test data are recorded.

3 RESULTS AND DISCUSSION

The results shown in Figure 3 are for the load-deformation/strain relationships of the ECFST and CFST specimens. It is shown that the increase in the ECFST strength is more pronounced for the LM1 column with the unconfined concrete compressive strength of 37 MPa. The increase in the axial load capacity of LM1-E12 column compared to that of LM1 is 64%. The results also show that the behavior of ECFST columns has higher strength degradation compared with that of CFSTs, particularly for the specimen with high strength concrete (HSC).

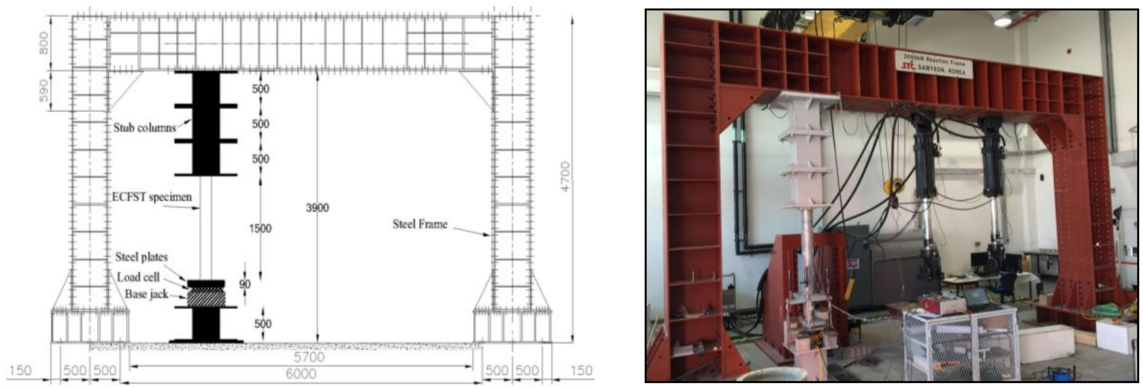


Figure 2. Test setup of ECFST specimens.

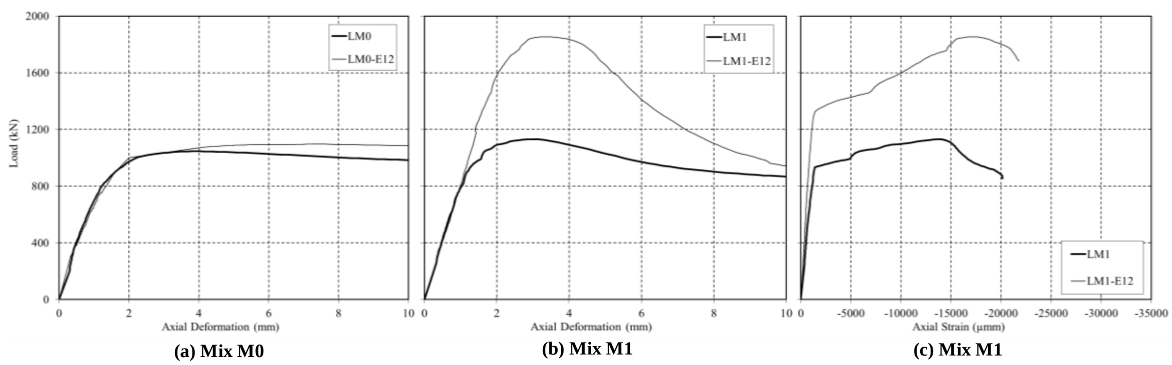


Figure 3. Load-deformation/strain relationships of ECFST specimens.

The sample results presented in Figure 3(c) show the axial load-strain relationships of the ECFST and CFST columns. In CFST columns, the steel tube expands faster than concrete in the initial stage of loading because of its larger initial Poisson's ratio. Hence, the concrete in CFST specimen is subjected to small tensile radial stresses from the steel tube until the bond between the steel tube and the concrete breaks down. The concrete of ECFST specimen is subjected to radial compression from the steel tube in the initial stage of loading resulting from using EA. The bond between the steel tube and concrete is sufficient to delay cracking of concrete and enhance the stiffness of the specimens. When the axial strain of specimen reaches the cracking limit, the concrete starts to dilate significantly and faster than the steel tube, and it pushes the steel tube outward. This behavior results in a confining pressure at the interface and hoop tensile stresses in the steel tube. Hence, the steel tube of ECFST more effectively constrains the lateral expansion of the concrete. The strain hardening of the LM1-E12 is much higher than LM1. This is because the ECFST column capacity improves after the first concrete cracking due to the confining pressure from steel tube when using EA. The results generally indicate that most promising concrete mixture is M1 (i.e., with concrete strength of 37 MPa), which results in a significant enhancement in the confining pressure and axial load capacity (i.e., LM1-E12).

4 COMPARISON OF TEST RESULTS WITH PREDICTION APPROACHES

The test results obtained from the present study, the results of testing a set of CFST and ECFST short columns conducted by the Authors (Mwafy *et al.* 2015), and those collected from the literature are verified with the prediction approaches suggested by other researchers, namely Susantha *et al.* (2001), Hu *et al.* (2003) and Liang and Fragomeni (2009). Moreover, the prediction approaches recommended by design codes, namely AISC (2005) and Eurocode 4 (CEN 2006), are also compared with the test results, as shown in Figures 4 and 5.

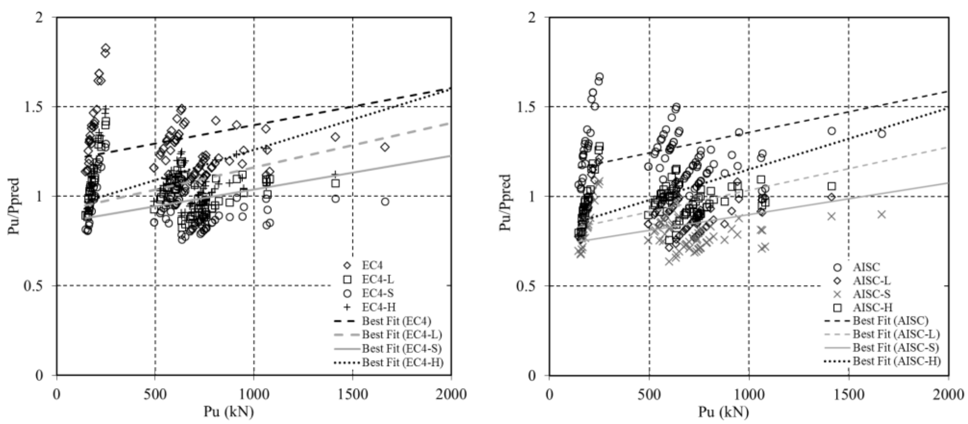


Figure 4. Comparison of all CFST results with EC4 (CEN 2006) and AISC (2005) prediction approaches (L: (Liang and Fragomeni 2009); S: (Susantha *et al.* 2001); H: (Hu *et al.* 2003)).

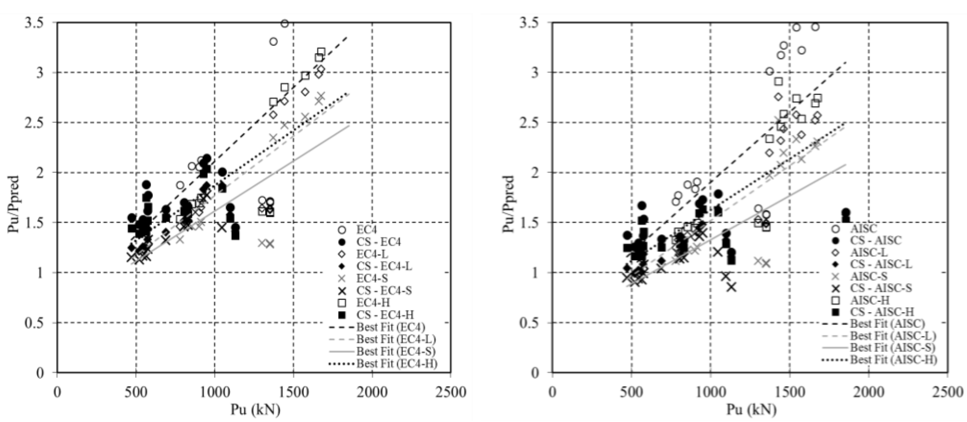


Figure 5. Comparison of all ECFST results with EC4 (CEN 2006) and AISC (2005) prediction approaches (CS: Current Study; L: (Liang and Fragomeni 2009); S: (Susantha *et al.* 2001); H: (Hu *et al.* 2003)).

The results indicate that the design code approaches do not provide a realistic prediction for the axial capacity of CFSTs. The average difference percentage between the ultimate axial capacity observed from testing (Pu) and that predicted by the EC4 and AISC codes (PPred) is 30% and 26%. This is mainly attributed to the constant factor adopted by the design codes to account for the increase in axial load capacity due to the concrete confinement. On the other hand, the prediction approaches suggested by previous researchers provide a better prediction of the confined concrete compressive strength, f'_{cc}, taking into consideration the specimen diameter and length, tube thickness, and concrete strength (Susantha *et al.* 2001, Hu *et al.* 2003, Liang and

Fragomeni 2009). Hence, adopting f'_{cc} predicted by the studies mentioned above to calculate the axial capacity of CFST reduces the dispersion in the predicted capacity compared with test results. As shown in Figure 4, the predicted axial capacity of CFSTs by EC4 (CEN 2006) using the Susantha *et al.* (2001) approach for calculating f'_{cc} results in the best correlation with test results (i.e., 13% average difference percentage). Moreover, the predicted axial capacity of CFST by AISC (2005) using the Liang and Fragomeni (2009) prediction approach for calculating f'_{cc} results in the best correlation with previous tests (i.e., 14% average difference), as shown in Figure 4. Moreover, the collected results from the present study and literature for ECFST are compared with the prediction approaches in Figure 5. The results indicate that the prediction approaches of the design codes, as well as those suggested by previous researchers, underestimate the axial capacity of the ECFST (i.e., 59% average difference).

5 CONCLUSIONS

This study assessed experimentally the behavior of concentrically loaded CFST and ECFST columns with different concrete mixing approaches, concrete strength levels and EA ratios, and compared the test results of the present research and previous studies with those obtained from prediction approaches. Test results indicated that increasing the concrete strength significantly increased the axial capacity of CFST columns by up to 64%. The behavior of ECFST columns was less ductile compared with that of CFST. Using EA with a concrete strength of 37 MPa led to the most notable enhancement in the confining pressure and axial load capacity. The axial capacity of CFST columns predicted by EC4 using the Susantha *et al.* (2001) approach for estimating the confined concrete led to the best correlation with test results with 13% average difference percentage. The axial capacity of CFST columns predicted by AISC (2005) using the Liang and Fragomeni (2009) concrete model led to the best correlation with test results with 14% average difference percentage. Test results indicated that the prediction approaches recommended by the design codes and previous studies underestimate the axial capacity of the ECFST columns. Hence, a prediction approach specifically for ECFST should be developed to account for the higher confinement provided by steel tubes when the EA is used.

Acknowledgments

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