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Tests of self-compacting concrete filled elliptical steel tube columns

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Abstract

This paper presents an experimental study into the axial compressive behaviour of self-compacting concrete filled elliptical steel tube columns. In total, ten specimens, including two empty columns, with various lengths, section sizes and concrete strengths were tested to failure. The experimental results indicated that the failure modes of the self-compacting concrete filled elliptical steel tube columns with large slenderness ratio were dominated by global buckling. Furthermore, the composite columns possessed higher critical axial compressive capacities compared with their hollow section companions due to the composite interaction. However, due to the large slenderness ratio of the test specimens, the change of compressive strength of concrete core did not show significant effect on the critical axial compressive capacity of concrete filled columns although the axial compressive capacity increased with the concrete grade increase. The comparison between the axial compressive load capacities obtained from experimental study and prediction using simple methods provided in Eurocode 4 for concrete-filled steel circular tube columns showed a reasonable agreement. The experimental results, analysis and comparison presented in this paper clearly support the application of self-compacting concrete filled elliptical steel tube columns in construction engineering practice.

Key Words: Self-compacting concrete, elliptical concrete-filled column, experimental study, axial compressive capacity, prediction, comparison.

1 Introduction

Self-compacting concrete (SCC) was originated in Japan and then spread to Europe and South America. It was initially used for concrete slabs and beams, however since the beginning of this century it was increasingly employed in concrete-steel composite members due to its self-compaction performance, higher load capacity, inherent ductility and toughness when they are used as columns in buildings[1]. It can also lead to significant savings in materials and increases in the net floor space [2, 3]. In the past, the most commonly used composite column section shapes were square, rectangular and circular, however, elliptical hollow sections have been recently introduced to the construction market and its application is becoming popular in contemporary building design due to its pleasing appearance.

The behaviour of hollow steel section tube filled with normal concrete has been studied by various researchers [3, 4], who have found that the strength of concrete is increased by the confining effect obtained from the steel tube and the local buckling of the steel wall was delayed by the restraint of concrete. Circular and rectangular tube columns made with SCC have been studied and compared with those using normal concrete, and the results were close. However, very few researchers have investigated SCC-filled elliptical columns [2, 3, 5-7]. Elliptical hollow sections (EHS) can offer greater efficiency than circular ones, particularly when subject to eccentric loading (generating a bending moment about a particular axis) or when differing end restraints or bracings exist about the two principal axes [8]. Unfilled elliptical columns have been used recently in a number of structures including a coach station at Heathrow terminal three in the UK, Sword Airside project in Ireland and the main railway station at Bern in Switzerland. However, the elliptical hollow section is not currently covered by any structural design code [7] . Due to the increasing use of the elliptical hollow section shape, broad studies have been conducted to provide an insight into the behaviour of this form of structure [7- 9]. The compressive behaviour of concrete filled elliptical hollow section stub columns have recently been well established through experimental research, and numerical modelling has also been carried out [7, 10].

Experimental study and numerical modelling of elliptical tube columns have been attempted by other researchers [7-10]; the main areas investigated were geometric features, non-linear material properties and initial geometric imperfections. Several amplitudes of initial geometric imperfection were considered and it was found that the structural behaviour of hollow sections was very sensitive to the degree of imperfection. However, the ultimate load capacity was relatively less sensitive to the amplitude of the imperfection [11, 12]. Parametric studies with different section aspect ratios and varying slenderness for EHS were also carried out following the satisfactory validation of numerical methods against experimental results [13]. An investigation into the local buckling behaviour of EHS columns in compression was performed by using an equivalent circular hollow section (CHS) to model the local and global buckling of EHS. It was confirmed that the use of an equivalent CHS was a reasonably good predictor for the capacity of slender sections [8]. Numerical studies on elliptical concrete filled tube (CFT) columns have been carried out by Dai et al [12] and Dai and Lam [14]; a new confined concrete model was developed for the elliptical CFT columns. However, as for columns with high concrete compressive strength, the confined concrete properties have little effect on the behaviour [9]. This is due to the increment of the compressive strength and the stiffness of high compressive strength of concrete. Moreover, some studies compared and analysed the results against available experimental data to propose a modified stress–strain model. In this model, a ‘quick softening’ section was introduced to consider the effect of the elliptical geometric feature. This modified model has been successfully used in the prediction of axial compressive load and failure modes of stub elliptical CFT columns [9].

In the context of elliptical CFT columns, while the literature is currently fairly limited, as mentioned above, previous experimental studies include compression testing of stub columns, testing of concentrically-loaded slender columns and eccentrically loaded columns with limited numbers of specimens which were smaller section and length than this study [9]. In the present investigation, a series of elliptical tube columns filled with SCC were constructed with different parameters such as length, grade of concrete strength, and section dimensions. The experimental study focussed on the compressive behaviour of these composite columns to assess the adaptability of current design rules provided in Eurocode 4 for circular and rectangular columns.

2 Experimental studies and test set up

2.1 Test specimens

In total, eight SCC-filled elliptical steel tubular column specimens were constructed using commercially available 250x125x6.3 mm and 150x75x6.3 mm elliptical steel hollow sections as shown in Figure 1. Three different lengths (1.5 m, 2.0 m and 2.5 m) were chosen for the 150x75x6.3 mm section, while one length (2.0 m) was used for the 250x125x6.3mm section. Two hollow section columns with the same section sizes described above were also tested for comparison purposes.

The tested column specimens were divided into three series depending on their height, as summarised in Table 1. Series I, II, and III have heights of 1.5, 2 and 2.5

m, respectively. The specimen ID in Table 1 was specified according to the height (1.5, 2, and 2.5), section size (250x125 and 150x75) and nominal concrete strength (low or high). For instance, for CII-150-L-2, the first letter and roman numeral pair, CII, represent a column from series II (column height 2 m). The number in the centre of the ID, 150, represents the major outer diameter of the elliptical steel hollow section. The letter L indicates a low strength concrete used (between 45 to 55.17 MPa), whereas columns with H letter represents high strength concrete (from 85.5 to 103.75 MPa). The letter N indicates columns with no infill concrete. The number at the end of the ID gives the length of the tested column. The imperfections (out of straightness) of a tested column were measured before the test and summarised in Table 1.

Table 1: Geometrical dimensions of elliptical hollow tubes and concrete compressive strength.

	Specimen ID	2a (mm)	2b (mm)	L (mm)	t (mm)	Imperfection (mm)	f_{cu} (Mpa)
Series I	CI-150-L-1.5	150	75	1500	6.88	0	55.17
	CI-150-H-1.5	150	75	1500	6.89	0	85.5
Series II	CII-250-N-2	250	125	2000	6.41	1	-
	CII-250-L-2	250	125	2000	6.3	1	47.5
	CII-250-H-2	250	125	2000	6.3	1	103.75
	CII-150-N-2	150	75	2000	7	1	-
	CII-150-L-2	150	75	2000	6.9	1	45
	CII-150-H-2	150	75	2000	7.1	1	103.2
Series III	CIII-150-L-2.5	150	75	2500	6.88	1.25	55.17
	CIII-150-H-2.5	150	75	2500	6.89	1.25	85.5

where 2a and 2b are the major and minor axis lengths, L is the height, t is the thickness of the column walls, and f_{cu} is the cube compressive strength of concrete.

2.2 Material Properties

2.2.1 Steel properties

The material properties of tube steel were determined by the tensile coupon test. Three coupons were taken from the flatter side of the elliptical profile for each steel hollow section and prepared in accordance with the European Guidelines for Self-Compacting Concrete [15,18]. Table 2 summarises the measured steel properties.

Table 2: Properties of the elliptical steel hollow sections

Sample	Section size	fy (MPa)	fu(MPa)	εy
1	150x75x6.3	431.4	529.4	0.002
2		417.3	504.9	
3	250x125x6.3	388.9	523.3	0.002
4		380.7	512.3	
where fy is the steel yield strength, fu is the ultimate strength and εy is the yield steel strain.				

2.2.2 Concrete properties

SCC was chosen as the infill material for ease of casting as SCC possesses high workability. It also avoids the need for compaction as it can achieve full compaction by self-weight. The raw materials used for SCC are readily available in the UK market. Portland cement (class 52.5 MPa) has been used in accordance with EN 197-1:2011, along with superplasticiser glenium C315, fly ash 450-s, gravel (maximum nominal size 10 mm), and sand.

Tests conducted on fresh and hardened concrete enabled evaluation of the SCC characteristics, and a quality control process selected an acceptable mix specification. Fresh concrete properties were checked by slump flow, V funnels and segregation tests. All of these tests were undertaken according to the European guidelines (2005). Table 3 shows the results obtained in the laboratory, and a summary of the governing parameters adopted for the fresh SCC concrete tests.

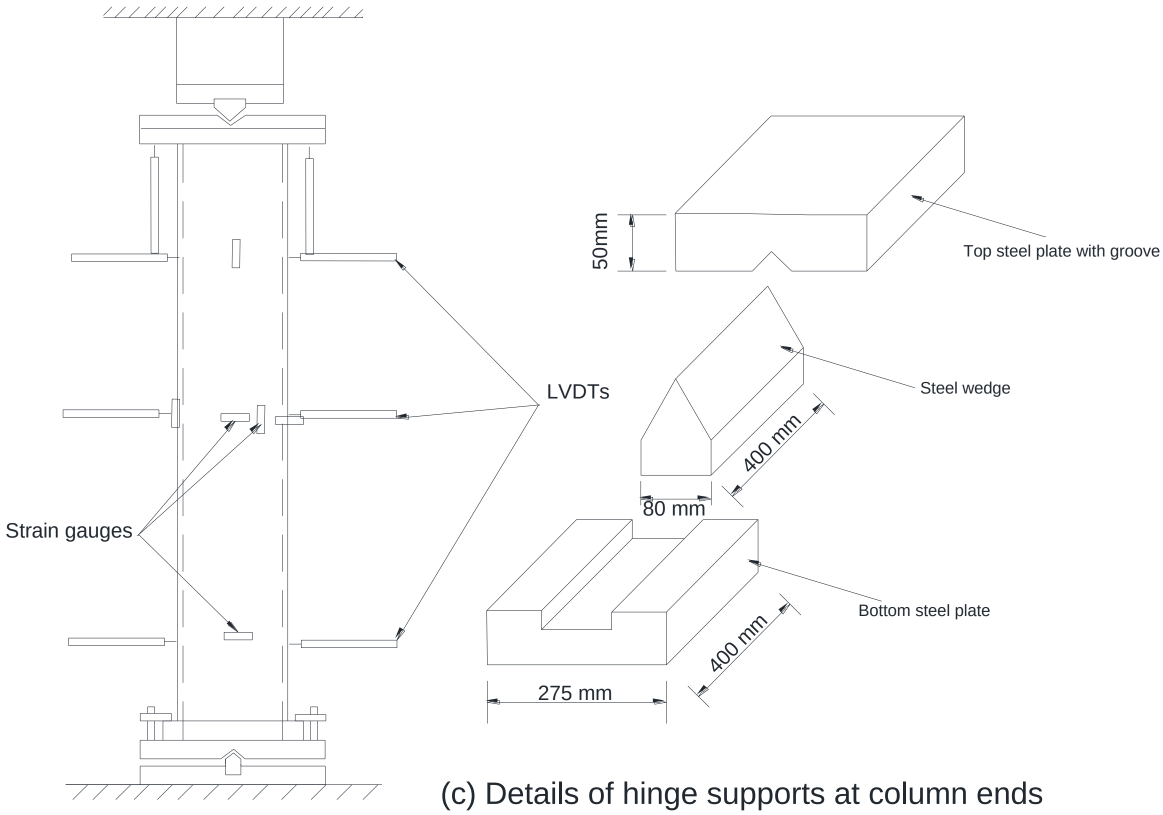
Table 3: Fresh concrete properties

Tests	Lab result		Requirement
	Mix 1	**Mix 2**	
Slump flow	575	750	SF1 class: 550-650 SF2 class: 660-750
T500	1.5	2	Class 1 : ≤ 2
V-funnel	4	6	Class 1 : ≤ 8
Segregation	3.1	2.7	Class 2: ≤ 15%

After the acceptable properties of fresh SCC mix were checked with the European guidelines (2005), the specimen columns were cast and were then tested after 28 days. Six cubes were cast and tested on the same day as the specimen column test, to obtain the compressive strength of the concrete core inside the steel tube. The averaged compressive strengths of the concrete cubes are presented in Table 1. Moreover, three cylinders were cast and tested on the same day to find the relationship between the cubes and cylinders compressive strength.

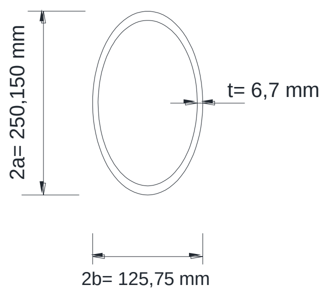
2.3 Test set up

All columns were tested in a vertical position under axial compression as shown in Figures 1 and 2. Pinned end joints were constructed using groove plates and steel knife-edges to allow the free rotation at both ends as shown in Figure 1(c). The reason for using a knife-edge is that the elliptical shape has major and minor axes and global buckling occurs around the minor axis. Therefore, the knife-edge supports ensure that the buckling occurs in the correct direction. Before each test, the top surface of each specimen was levelled and grounded.



(c) Details of hinge supports at column ends

(a) Column in vertical testing position



(b) Column cross section

Figure 1.Test set up

A layer of high strength mortar was capped at the top of concrete core to ensure the axial load is applied to the composite section uniformly.

For all the column specimens, steel plates were welded to the top end of each specimen to facilitate the placing of concrete. After the column was placed in the test rig, a small load was applied to hold the specimen upright and to ensure that the loading was applied concentrically then the specimen was carefully centralised using a plumb bulb and spirit level. The top plate in contact with the jack was fixed by two bars to avoid movement (lateral sway) in the horizontal direction as shown in the Figure 3.

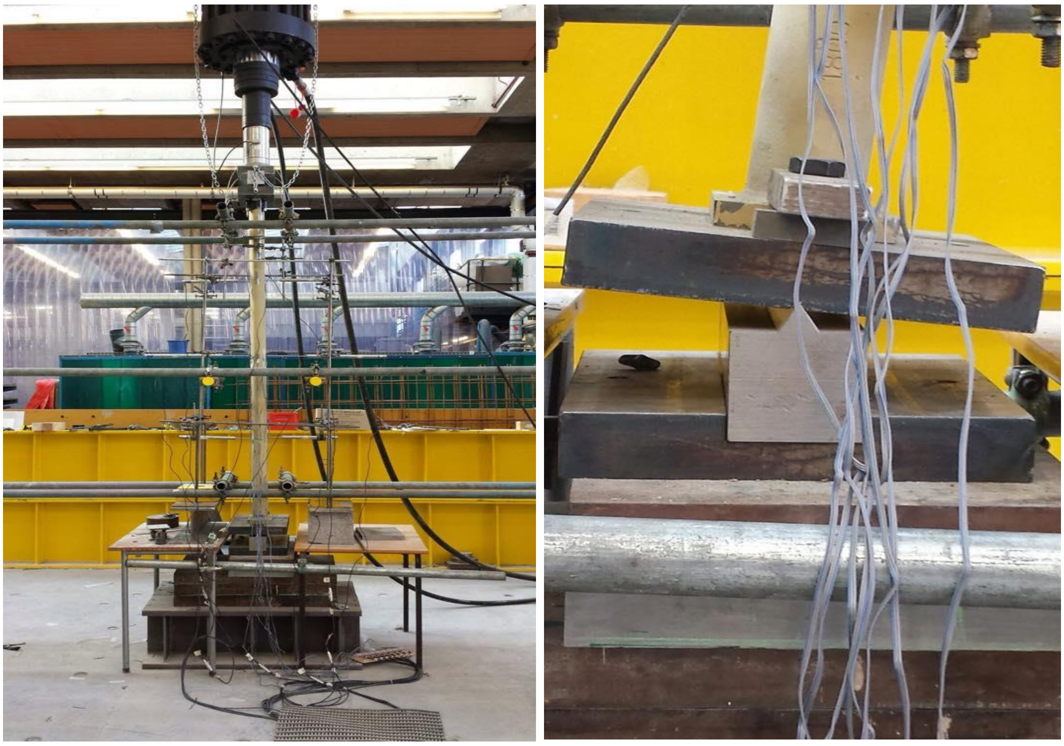


Figure 2. Typical test set up.

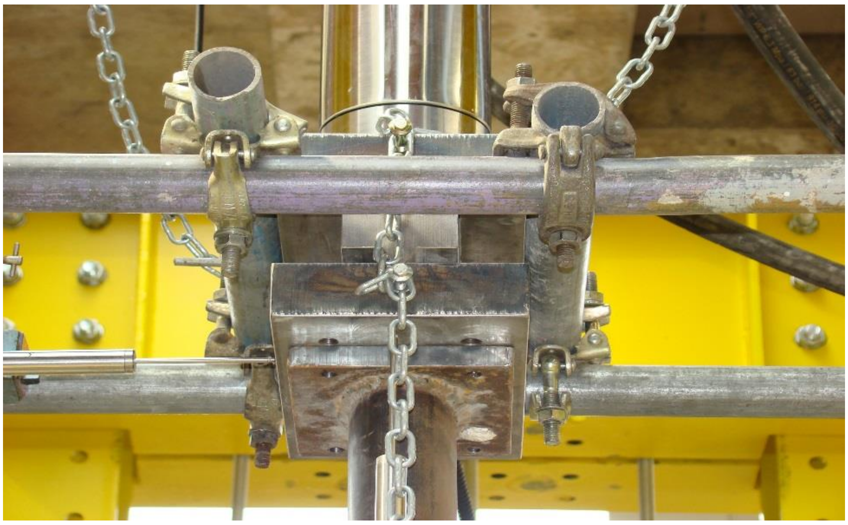


Figure 3. Top plate in contact with the Jack.

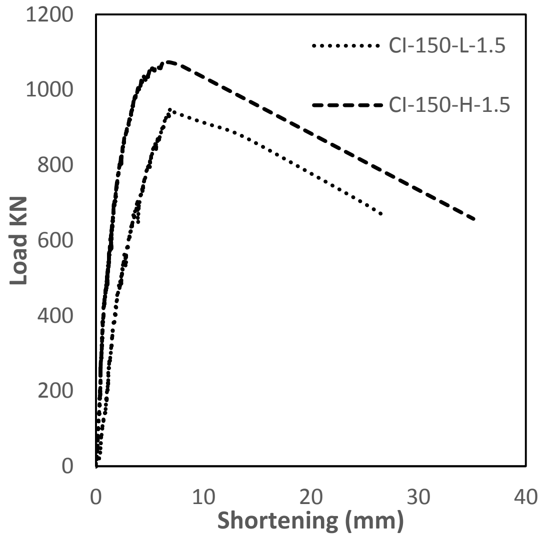
Strain gauges were installed to monitor strains in the steel tube at the top, bottom, and mid-height. The readings from the two strain gauges positioned at the top and bottom of each column were used to ensure the load was applied uniformly. At the mid-height of the column, six strain gages were used in two perpendicular directions to capture the behaviour of composite columns at the expected region of buckling. The failure mode, circumferential strain distribution, load-deformation behaviour and column capacity were, thereby, recorded during the course of the testing. Load control, of a rate of 20 kN/min, was applied up to 80 % of the failure load that was predicted by Eurocode 4. Displacement control with the rate of 0.1 mm/min was, then, applied so that the global buckling behaviour of CFT columns could be carefully observed. Linear displacement transducers (LVDT) were also used to monitor longitudinal shortening and lateral displacement of the test specimens. Six sets of LVDTs were located at various positions along the length of each column, i.e. at the top, mid-height and bottom. Two additional LVDTs were set up at the top of each column to measure the shortening. An extra LVDT was set up at the top plate of the column to check the top sway.

3 Experimental results and observation

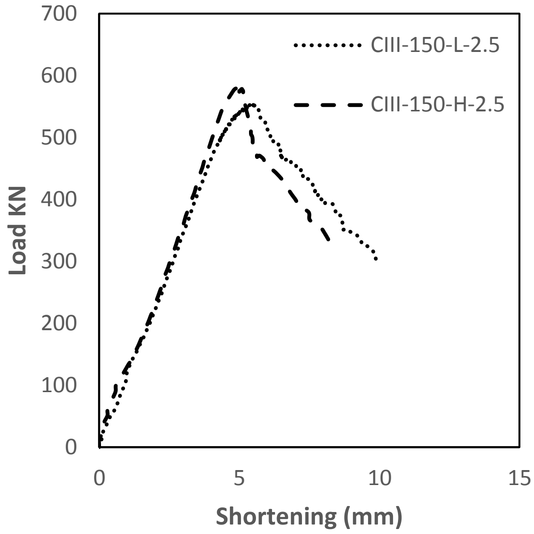
3.1 Axial load capacity

Figure 4 shows the axial compressive load with shortening relationships of the column specimens tested. The column behaved in a stiff manner up until the ultimate load was approached, at which point the curves drop quickly. This signifies the crushing of concrete core followed by global buckling of steel columns. It can be observed from the comparison between the filled and unfilled columns that the CFT columns exhibited a superior performance compared with the steel hollow sections, in terms of both the axial compressive strength and initial stiffness.

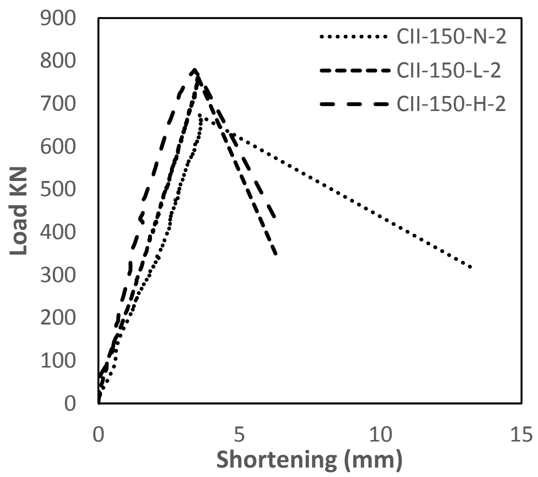
It was noted that for all columns tested, the gradient of the descending branches of the load-shortening curve is very steep after the maximum load is reached. The maximum capacity of the tested columns was governed by the global buckling. It was observed that the global buckling also caused higher stress concentration at the mid-height region, where the lateral deflection and strains increase rapidly as the maximum load is approached. As expected, global buckling deformation was observed in almost all columns tested.



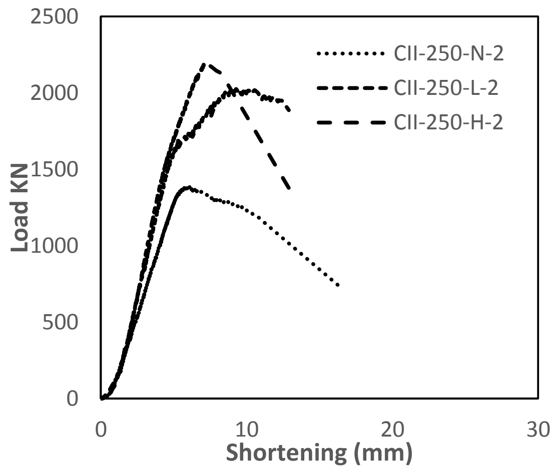
a) L=1.5 m , 150x75



b) L=2.5, 150x75



c) L=2m, 150x75 mm



d) L=2m , 250x125

Figure 4.Load against axial shortening relation of tube columns

(a) Local Buckling for CII-250-N-2 (b) Global buckling for CIII-150-H-2.5

Figure 5.Typical failure modes

3.2 Failure modes

Most specimens tested in this study failed through global buckling, except the empty hollow section column with the larger section size as shown in Figure 5(a), which showed a local buckling failure mode and inward and outward bulge were observed. Figure 5(b) shows the final deformation of a typical concrete filled column after failure load is reached. Obviously the failure mode was dominated by global buckling owing to the large slenderness ratio of the columns tested. However, local buckling of column walls was prevented due to the concrete core. The failure modes observed from this study were similar to those observed by Jamaluddin et al. [9], which clearly demonstrated the composite action of the concrete filled steel tubular columns that the concrete core might eliminate or delay the local buckling occurred before the global buckling and increases the load capacity. Fig 6 shows the concrete core after the steel tube was removed, although tensile cracks were developed in the concrete core, it remained intact due to the constraint and confinement of the steel section.

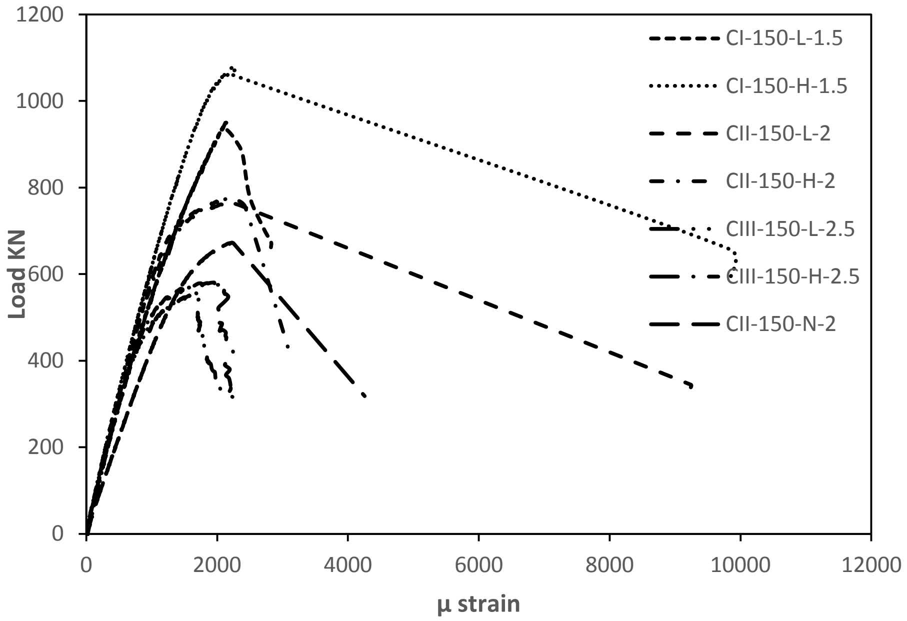
Figure 6. Tensile cracks after removing of steel tube steel

4 Discussion of the behaviour of SCC filled steel tube columns

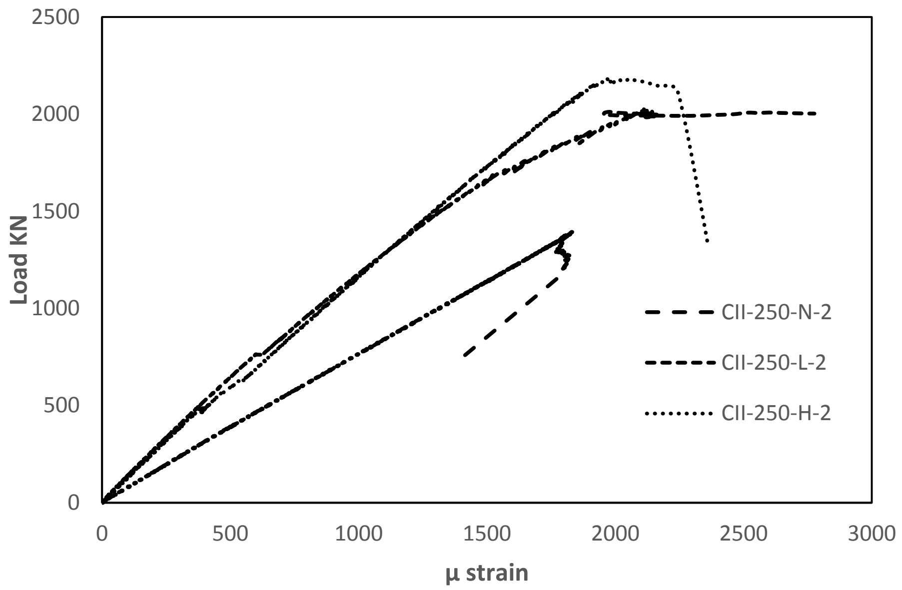
4.1 Effect of concrete strength

The concrete infill substantially contributes to the load capacity of the concrete filled columns. In comparison to the load capacity of the steel hollow section columns, the load capacity of the filled columns in Series II is nearly 15 % higher for the 150x75 mm columns, and over 45 % higher for 250x125 mm columns. The columns filled with high strength concrete, exhibited a smaller confinement effect due to the low dilatation of concrete, which prevented the development of the confinement effect. Confinement is only achieved when the micro cracking of concrete core sufficiently increases to enable the concrete infill to expand and exert lateral compressive stress on the steel tube. However, with the increase in concrete strength, the stiffness of concrete also increases, resulting in less lateral expansion, and therefore the confinement gives little effect to the high strength concrete infill.

The influence of concrete strength on the longitudinal strain can be seen from the load curves in Figure 7. In general, the strength and stiffness of elliptical columns increase as the concrete strength increases. As expected, specimens with higher strength concrete have larger elastic rigidity in the elastic stage as the initial elastic modulus of concrete increases with the concrete strength. The presence of concrete infill also increases the flexural rigidity as shown by the slope of the curves. It can be seen from Figure 7(a) that change in a column’s height can affect the longitudinal strain.



(a) 150 x 75 x 6.3, low and high compressive strength

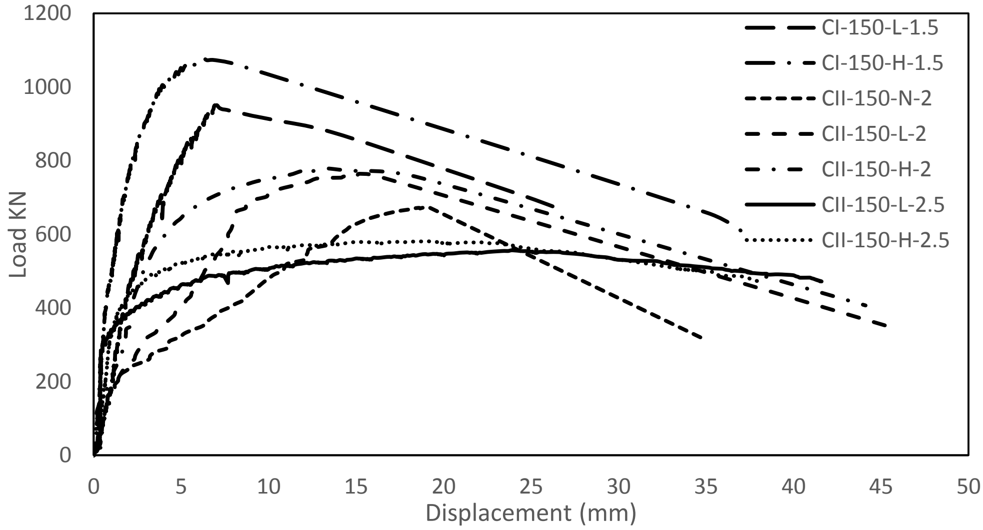


(b) 250 x 125 x 6.3, low and high compressive strength

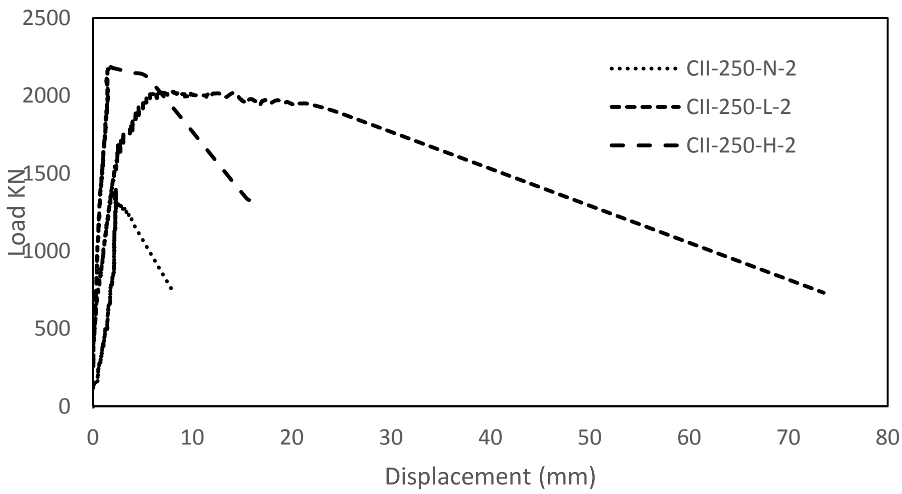
Figure 7.Load vs longitudinal strain

4.2 Effect of column slenderness

Figure 8 shows the load vs lateral displacement relationships of columns with high slenderness ratio tested in this study. The tested columns with larger slenderness ratio were found to have greater flexibility, which resulted in larger mid-height lateral displacement and lower stiffness. As the height of the column increases, the columns with larger slenderness had a lower load capacity than columns with lower slenderness, and the load reduced quickly once the ultimate load was reached. All concrete filled columns in this study with limited high slenderness ratio failed with global buckling about the minor axis. However, it must be pointed out that concrete filled steel tubular columns with a lower slenderness ratio than this study might have different failure mode, such as local buckling or concrete core crushing etc. The failure mode is consistent with the measured hoop strains at the major axis vertices being larger than those at the minor axis vertices. After maximum load was achieved, significant lateral displacement was observed.



(a) 150 x 75 x 6.3



(b) 250 x 125 x 6.3

Figure 8. Load vs Lateral displacement (mm)

5 Comparison of experimental results with Eurocode 4

Currently, the design calculation of concrete filled elliptical tube columns is not covered by Eurocode 4. The calculation provided in EC 4 covers the design rules for encased, partially encased and concrete-infilled columns with circular, square and rectangular sections.

The simple design and calculation method provided in EC4 for concrete filled columns with circular sections was used in this study to assess its applicability to elliptical CFT composite columns with the buckling curves given in Eurocode 3 (EC3) for steel columns [16]. The resistance of the cross section is calculated by assuming it is fully plastic, and the load is distributed reasonably between the steel and concrete core.

The compressive resistance of concrete filled steel tubes, as stated in EC4, is given by Eq (1). This expression is usually applied to circular, square and rectangular tube columns; but in this study, it is used for elliptical tube columns filled with SCC.

$$N_{ed} = \chi \; N_{Pl,Rd} \tag{1}$$

where $N_{Pl,Rd}$ is the plastic resistance of the composite section, and χ is the reduction factor for the relevant buckling mode. χ is a function of slenderness, which can be obtained from Eq (2),

$$\chi = \frac{1}{\varphi + \sqrt{\varphi^2 + \lambda^2}} \leq 1, \tag{2}$$

where

$$\varphi = 0.5[1 + \alpha(\lambda - 0.2) + \lambda^2] \tag{3}$$

The imperfection factor, α**,** corresponds to the relevant buckling curve as given by Eurocode 3 [16,17]. The relative slenderness, λ for the plane of bending being considered is given by:

$$\lambda = \sqrt{\frac{N_{pl,Rd}}{N_{cr}}} \quad (4)$$

The reduction factor, χ, based on the EC4 method is dependent on the relative slenderness, λ, of columns and on their imperfections. It should be noted that EC3 shows these five buckling curves to reflect the differences in imperfections. These can include geometric imperfection, lack of verticality, straightness, flatness and accidental eccentricity of loading. As most of the experimental failure load points lay above the EC3 buckling curve "a", using these buckling curves for the slender elliptical CFT composite columns is conservative. Table 4 shows the values of χ and λ that are used for Figure 9. $N_{Pl,Rd}$ can be calculated from Eq (5).

$$N_{Pl,Rd} = 0.85\ A_c\ f_c + A_s f_s \quad (5)$$

where A_c is the cross-sectional area of concrete, f_c is the compressive concrete cubes strength, A_s is the cross-sectional area of steel tube, and f_s is the yield strength of steel. N_{cr} is the critical elastic normal force for the relevant buckling mode, which may be calculated from the effective flexural stiffness $(EI)_{eff}$ and the actual effective height L:

$$N_{cr} = \frac{\pi^2\ (\mathrm{EI})_{eff}}{L^2} \quad (6)$$

where:

$$(EI)_{eff} = E_a\, I_a + E_s\, I_s \quad (7)$$

I_a and I_s are the second moments of inertia of the structural steel section and the un-cracked concrete section, respectively; while E_a and E_s are the elastic modulii of the structural steel section and the un-cracked concrete section, respectively.

The predicted load-carrying capacities (P_{EC4}) calculated using the method provided in Eurocode, as described above, are compared with test results (P_U) in Table 4.

Table 4 compares the load capacities of tested column specimens obtained from experimental study against those predicted using the method provided in EC4 for circular and rectangular column sections. It can be seen that the average load ratio is 1.07, with a coefficient of variation COV of 0.069. For all specimens, the load capacities predicted by EC4 are lower than the load capacities obtained from experimental tests, apart from specimen CII-150-L-2 whose measured load capacity is 8 % lower than EC4 prediction. In general, EC4-predicted results are fairly close to those measured in the current experimental study.

Table 4: Comparison of load capacity predicted by EC4 method and obtained from experiments

Specimen ID	P_u	P_{EC4}	$\frac{P_u}{P_{EC4}}$	$\bar{\lambda}$	χ
CI-150-L-1.5	949.85	928.6	1.01	0.904	0.73
CI-150-H-1.5	1076.4	988.9	1.06	0.945	0.7
CII-150-N-2	672.84	575.5	1.04	1.087	0.6
CII-150-L-2	763.93	651.6	0.92	1.17	0.55
CII-150-H-2	778.53	725.1	1.17	1.29	0.47
CII-250-N-2	1392.13	1315.9	1.17	0.626	0.88
CII-250-L-2	2023.1	1947.1	1.07	0.716	0.84
CII-250-H-2	2184.4	2382.3	1.02	0.815	0.79
CIII-150-L-2.5	556	485.6	1.09	1.49	0.37
CIII-150-H-2.5	580.54	500.3	1.14	1.57	0.34
		Average	1.07		
		COV	0.069		

Figure 9 compares the experimental results against the non-dimensional slenderness and the buckling curves given in EC3. It can be seen that the

EC3 buckling curves generally provide a lower bound to the experimental results. Almost all experimental points lay above the buckling curves, indicating that the buckling curves are deemed safe for elliptical CFT columns, particularly for columns with higher slenderness. For concrete filled tube columns, buckling curve ‘a’ with the imperfection factor α = 0.21 is used. Further analysis shows that the column curve is reliable in determining the influence of slenderness. Buckling curve ‘a’ agrees reasonably well with the experimental data.

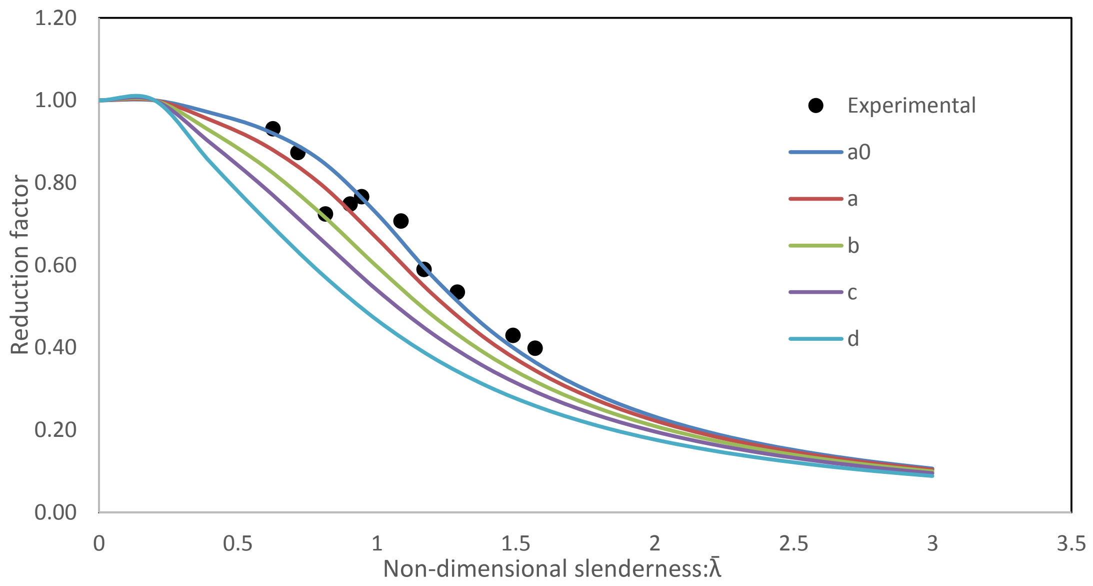


Figure 9. Comparison of normalised experimental load to the EC buckling curves.

The maximum loads (Pu) obtained from experiments and those predicted by EC4 ($PEC4$) are compared in Figure 10, where the solid line represents a gradient of 1.0. The other two dotted lines represent gradients of 1.0 ± 10 %. From Figure 10, it can be seen that the ratio of the tested specimens are in the range of 1.0 to 1.0+10 %, indicating a good agreement between EC4 predictions and the experimental load capacities.

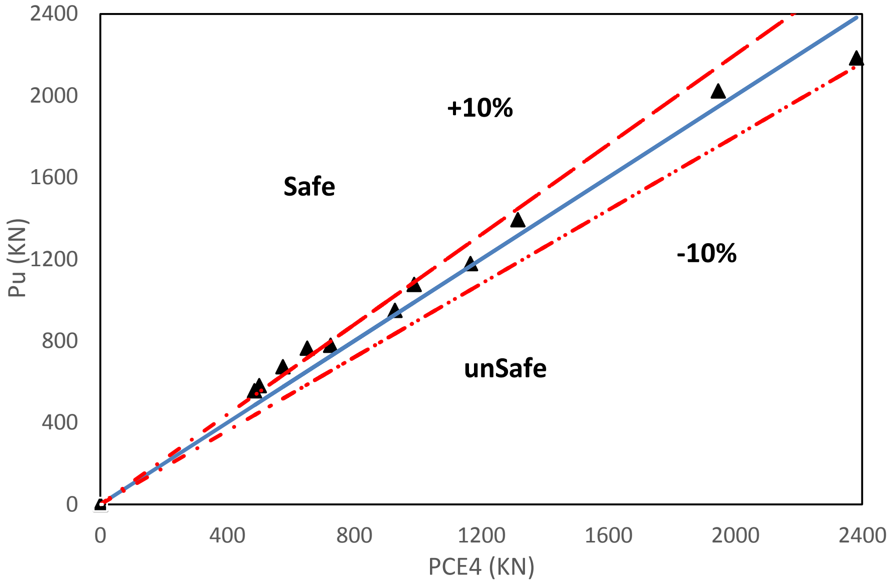


Figure 1.Comparison of experimental ultimate load and EC4 predicted loads

6 Conclusions

This paper presents an experimental study on elliptical steel tube columns filled with self-compacting concrete under axial compressive loads. The influence of several parameters including concrete strength, column section dimensions and columns height on the structural behaviour were investigated. According to the experimental results, the following conclusions may be drawn:

1) The confinement that steel hollow sections provide to concrete core enhanced the axial compressive capacity of composite columns by delaying the occurrence of global buckling and eliminating tube wall local buckling.

2) The axial compressive load capacity of composite columns increases with an increase in SCC compressive strength, and decreases with the increased slenderness ratio.

3) The failure modes were characterised by the overall global buckling for most of tested columns due to the larger slenderness ratio adopted.

4) The EC4 method displays reliable results as the confinement effect was considered. The European buckling curves for steel columns can therefore be considered as the basis of elliptical CFT column design as was also found by other investigations with different elliptical tube columns section and length.

5) Due to the limited range of high slenderness ratios of test specimens in the current study, further experimental and numerical investigations on concrete filled elliptical steel tube columns are needed to further verify and extend findings.

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