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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.

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

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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 250×125×6.3 mm and 150×75×6.3 mm elliptical steel hollow sections as shown in Fig. 1. Three different lengths (1.5 m, 2.0 m and 2.5 m) were chosen for the 150×75×6.3 mm section, while one length (2.0 m) was used for the 250×125×6.3 mm 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 (250×125 and 150×75) 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 45–55.17 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.

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.

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.

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 Figs. 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 Fig. 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.

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 Fig. 3.

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.