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Experimental investigation on octagonal concrete filled steel stub columns under uniaxial compression

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A R T I C L E I N F O

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A B S T R A C T

Concrete filled steel tubes (CFST) have been widely used in modern constructions. The cross-section shapes of circular and rectangular are mostly used. This paper presents an investigation on CFST with a new cross-section shape - octagonal shape which combines both advantages from circular and square cross-sections. In this study, 21 CFST stub columns were tested accompanying with 9 plain concrete columns under uniaxial compression. Three cross-section shapes, octagonal, circular and square sections were considered. In parallel, 10 associated CFST stub columns with octagonal cross-sections from literature were also complied. The measured steel yield strength was between 383 MPa to 485 MPa. Both normal and high strength concrete were used with measured cylinder compressive strengths ranging from 38 MPa to 112 MPa. The key investigation focuses on the relationship between the cross-section shapes and confinement effectiveness which can provide an understanding on the difference in load bearing capacity of CFST with those three section shapes. Design formulae for the cross-section capacity in the current code of practice were assessed by the experimental results and modification was proposed to the existing formula for circular cross-section which could be adopted for the CFST with octagonal cross-section.

1. Introduction

Concrete filled steel tube (CFST) has shown its superiority in structural efficiency and aesthetics in modern construction. The strength of concrete core could be enhanced by the confinement from steel tube whilst the infilled concrete core could delay the appearance of local buckling of the external steel tube. Investigations have been conducted in the past on the effect of confinement in CFST that indicate the key parameters affecting the performance are cross-section shapes [1–5] and material contribution which is related to the material strengths of both concrete and steel and the diameter to thickness ratio [6–9]. Cross-section shapes of concrete columns have a great impact on the confinement effectiveness when the concrete is under confining pressure from steel stirrups or FRP jacket [10,11]. This phenomenon could also be found in the CFST meanwhile the cross-section shapes may also affect the appearance of the local buckling of steel tubes in those CFST with large diameter to thickness ratio.

The commonly used cross-section shapes in CFST are circular and rectangular sections. With circular cross-section, the steel tube can provide a uniform confining pressure to the concrete core which can efficiently confine the infilled concrete to achieve a good strength enhancement. However, poor confinement effectiveness was found in its counterparts, rectangular CFST. The sharp corners of the rectangular section lead to a stress concentration at corner region while the confinement near the flat side is insufficient [12]. However, the advantage of rectangular CFST is the constructability in the beam-column connection where the flat sides allow the bolted connection with end plate to be assembled. To achieve both the structural efficiency and constructability of CFST, octagonal section is suggested which has a better confinement effectiveness than rectangular section and also could provide flat column sides for construction. A number of investigations have been conducted on CFST with octagonal cross-section shapes. Tomii et al. [13] firstly investigated the axial behaviour of octagonal CFST, it is concluded that the confinement effect of octagonal CFST is somewhere between circular and square CFST. Same conclusion was also found in Susantha et al. [2]. Some experimental investigations were also conducted on the polygonal CFST including octagonal CFST [14,15] and hexagonal CFST [5,15]. Cross-section with elliptical shape was also investigated by many researchers [16–18]. Yu et al. [4] then proposed a unified design method to predict the load capacity of the polygonal CFST. However, existing literature on octagonal CFST is still limited especially on the comparison of other CFST with regular circular and rectangular sections.

This paper extends the existing investigations on octagonal CFST with a comparative experimental investigation on circular, octagonal and square CFST. The results extend the existing database of octagonal CFST with high strength concrete which has a cylinder compressive strength of 112 MPa. The experimental results demonstrate the

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difference of confinement effect from those three different sections. Modification was applied to the current design formula of load capacity in Eurocode 4 [19] to provide a design solution for load capacity of the octagonal CFST.

2. Experimental investigation

2.1. Specimens

Twenty-one CFST stub columns with cross-section of octagonal, circular and square shapes were prepared. The cross-sectional dimension has been shown in Table 1 where *D* is the external diameter of the circular section and the external largest width of the octagonal section; *b* is the width of the flat side of the octagonal and square sections excluding corner region; *t* is the thickness of steel tubes and *L* is the length of the specimens (Fig. 1). The steel tubes were fabricated by welding two cold-formed half-sections. To study the effect of confinement, identical hollow steel tubes and plain concrete columns which have the same cross-section shape, cross-sectional dimension and material properties were tested independently to capture a superposition value of load capacity from steel tube and concrete core. The companion experiment tests of the hollow steel tubes have been described in Zhu et al. [20] and average test results for hollow steel tubes are summarized in Table 2. The plain concrete columns were casted with the CFST using the same batch of concrete. Repeated specimens were made and tested for each configuration of specimens to minimize the effect of the discrete outcome. Specimens with normal strength (measured cylinder strength of 38 MPa) and high strength concrete (measured cylinder strength of 80.5 MPa) have 2 repeated specimens while for those specimens with very high strength concrete (measured cylinder strength of 112.1 MPa), the repeated number is 3. The specimens of CFST were labelled as XY-Z, where X stands for concrete grades; Y stands for cross-section shapes where C is for circular section, O is for octagonal section and S is for square section; Z stands for the number of the repeated specimens, the specimens label start with P are the plain concrete columns without any external steel tube.

2.2. Material

The material properties were collected and based on the tensile coupon tests conducted in Zhu et al. [20]. The coupon tests were conducted in accordance with EN ISO 6892-1 [21], for octagonal and square section, coupons were extracted from different locations such as flat side and corner. The material properties from different locations in each hollow section were weighted by their cross-sectional area to obtain an average value for each section. The weighted yield stress of the section is normally larger than that obtained from tensile coupon extracted from flat side which does not consider the strain hardening from the cold forming process. Table 3 shows the material properties from the flat side and the weighted averaged results. $\sigma_{0.2}$, σ_u and *E* are the 0.2% proof stress, the ultimate stress and the elastic modulus of steel respectively. $\sigma_u/\sigma_{0.2}$ ratio fulfills the requirement in Eurocode 3 [22] ($f_u/f_y > 1.05$). The concrete was commercially sourced and Table 4 shows the mix proportions for each concrete grade. The concrete properties were assessed by the compression tests on standard concrete cylinders and cubes. The dimension of the concrete cylinder was 150 mm diameter × 300 mm height while that of the concrete cube was 150 × 150 × 150 mm. The concrete material tests were conducted within the same week of the main tests on CFST and the test procedure was in accordance with EN 12390-3 [23]. For batches with concrete grades of C25/30 and C50/60, three cylinders and three cubes were tested. Five cylinders and five cubes were tested for the concrete with grades of C80/95 to avoid high standard deviation due to the brittleness of very high strength concrete. The results of concrete tests were shown in Table 5, where f_{co} and f_{cu} are the cylinder strength and cube strength of concrete respectively, ε_{co} is the axial strain at maximum stress which was measured by the strain gauges with 2% strain limits, *E* is the elastic modulus of concrete and υ is the Poisson ratio. It can be found that the commercial concrete with a certain grade provides a higher cylinder strength which are 38.0, 80.5 and 112.1 MPa for concrete grade of C25/30, C50/60 and C80/95 respectively. These deviations may be caused by a longer curing age (44, 84 and 93 days for C25/30, C50/60 and C80/95 respectively) and a safety margin from the concrete supplier. The strains at maximum stress of C25/30 and C50/60 concrete are 0.0023 and 0.0026 respectively while that in C80/95 concrete is slightly higher (0.003). The elastic modulus was calculated by regression analysis on the region where axial stress ranges from $0.1f_{co}$ to $0.3f_{co}$ which is in accordance with EN 12390-3 [23]. Lateral strain was also measured in the test to capture the Poisson ratio in the mentioned region of the stress-strain curves. Fig. 2 shows the stress-axial strain relationship of concrete with different grades. The concrete with measured cylinder strength of 80.5 MPa and 112.1 MPa show a brittle failure within the elastic zone. For normal strength concrete with measured cylinder strength of 38 MPa, the softening behaviour could be observed.

Table 1
Cross-sectional dimension of the specimens.

Cross-section	*D* (mm)	*B* (mm)	*b* (mm)	*t* (mm)	*L* (mm)	*D*/*t* or *b*/*t*
Octagonal	178	73.7	60	5.6	695	31.8 or 10.7
Circular	200	–	–	6.0	695	33.3
Square	–	200	179	6.0	695	29.8

2.3. Stub column tests

Stub column tests were conducted under a compression machine with 1000 tons load capacity. Strain gauges were attached at the middle of the stub columns to capture axial strain and lateral strain of the column under compression. For circular CFST, the strain gauges were attached at the locations 90° apart while in octagonal and square CFST, strains at corner and flat side were recorded. Four LVDTs were mounted around the specimens to record the end-shortening. Fig. 3 shows the arrangement of the instrumentations and test set up. Same instrumentations were applied to the plain concrete stub column which has the same section size as the corresponding CFST specimens but without any external steel tube. Steel ring was installed at each end of the CFST specimen to avoid the premature failure at column ends [36]. Fig. 4 shows the steel ring at the column end.

2.3.1. Load-end shortening curves and load capacity

There are three types of load-end shortening curves of CFST under axial compression which were illustrated by Han et al. [24]. In Fig. 5, experimental data collected from current tests show those three types of load-end shortening curves. In all types of load-end shortening responses, a transition zone could be found after the elastic stage because of the yielding of material. Different behaviour shows after the transition zone. Under a high level of confinement, a hardening behaviour was found after the transaction zone. As the level of confinement decreases the hardening stiffness decreases and the post-transition curve becomes a flat line. Below a certain level of the confinement, the softening behaviour occurs with a decreasing softening stiffness. The confinement ratio ξ is used to indicate the level of confinement in Han et al. [24] to differentiate hardening and softening behaviour of CFST and the boundary value ξ_o is 1.12 and 4.5 for CFST with circular and rectangular cross-section shapes respectively. The definition of confinement ratio ξ is shown as follows:

$$\xi = A_s f_y / A_c f_{co} \quad (1)$$

where A_s and A_c are the cross-sectional area of steel tube and concrete core respectively, f_y is the yield stress of steel tube and f_{co} is the cylinder