Engineering Structures 153 (2017) 732–748

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Behaviour and design of hexagonal concrete-filled steel tubular short columns under axial compression

M.F. Hassanein [a], V.I. Patel [b,*], M. Bock [c]

[a] Department of Structural Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt
[b] School of Engineering and Mathematical Sciences, Bendigo, VIC 3552, Australia
[c] Department of Civil Engineering, University of Wolverhampton, Wolverhampton WV1 1LY, United Kingdom

ARTICLE INFO

Article history:
Received 27 December 2016
Revised 2 October 2017
Accepted 4 October 2017

Keywords:
Concrete-filled steel tubular columns
Hexagonal section
Regular hexagon
Axial compressive strength
Finite element analysis
Stub columns
Design model

ABSTRACT

Concrete-filled steel tubular (CFST) columns have frequently been utilised in the construction of mid-rise and high-rise buildings as they offer smaller cross-sectional size to load carrying capacity ratio than ordinary reinforced concrete or steel solutions. The steel tube component of CFST columns can be shaped into different forms to further increase its strength and this article focuses on hexagonal CFST short columns in compression. Firstly, the literature is revised and it was found that the available experiments on the hexagonal columns cover relatively limited hexagonal dimensions and material properties. Additionally, existing design models were observed to be inaccurate for certain diameter-to-thickness (D/t) ratios of the columns. Accordingly, this paper intends to widen the available pool of data and proposes a new design model to design hexagonal CFST short columns in compression. This is made herein through comprehensive finite element (FE) models by using Abaqus software, carefully validated against experimental results and subsequent parametric studies covering a wide range of hexagonal dimensions of regular cross-section (circular-like). The effect of various D/t ratios, material steel grades and concrete compressive strengths (f'_c) on both the behaviour and strength of the hexagonal CFST short columns is investigated. Based on observations made and conclusions drawn upon analysing numerical data generated, a new design model is presented which provides better strengths compared with available design models and with accurate predictions for the full range of D/t ratios.

1. Introduction

Structural columns made from two different materials or elements such as structural steel and concrete behave compositely. Concrete encased structural steel sections and concrete-filled steel tubular (CFST) sections are the main cross-sectional types of composite columns [1–8]. Concrete-filled steel tubular (CFST) columns result from filling hollow steel tubes with concrete, with the idea traced back to 1879 when the piers of the Severn Railway Bridge in the UK, where made of CFST columns [8] to resist high railway loads. Compared with concrete encased structural steel columns, the steel tubes act as a formwork for casting the in situ concrete and thus it eliminates the need of additional formwork and leads to a fast track construction [1–8]. Furthermore, it does not need additional reinforcement. Therefore, CFST columns have been increasingly employed as columns in medium and high-rise buildings [2–3], bridge and large span buildings [2] and as piers [2,9–10].

Circular and rectangular (including square) CFST columns depicted in Fig. 1 are the most commonly used cross-sectional shapes in modern construction. Examples of circular CFST columns [11] are those used in the new VDEh-building in Dusseldorf, Germany, while square CFST columns [2] were utilised in Ruifeng International Commercial Building built in Hanzhou, China. Circular CFST columns (Fig. 1(a)) own more resistance and ductility compared with their rectangular counterpart columns (Fig. 1(b)). This is because the circular section provides a substantial amount of confinement to the concrete core in CFST columns, whereas this effect is tiny in the case of rectangular hollow sections [7]. Accordingly, the concrete strength increases due to the lateral restrain provided by the surrounding circular steel tube. On the other hand, the ease of connections makes the latter columns preferable in framed structures. Accordingly, circular and rectangular CFST columns were extensively investigated in literature [2,8]. However, the choice of the cross-section of the CFST column for a specific project not only depends on the column efficiency, material availability, cost and construction methods, but also on architectural and aesthetic criteria; see for example Ref. [4]. Some cross-sectional

* Corresponding author.
E-mail address: v.patel@latrobe.edu.au (V.I. Patel).

https://doi.org/10.1016/j.engstruct.2017.10.010

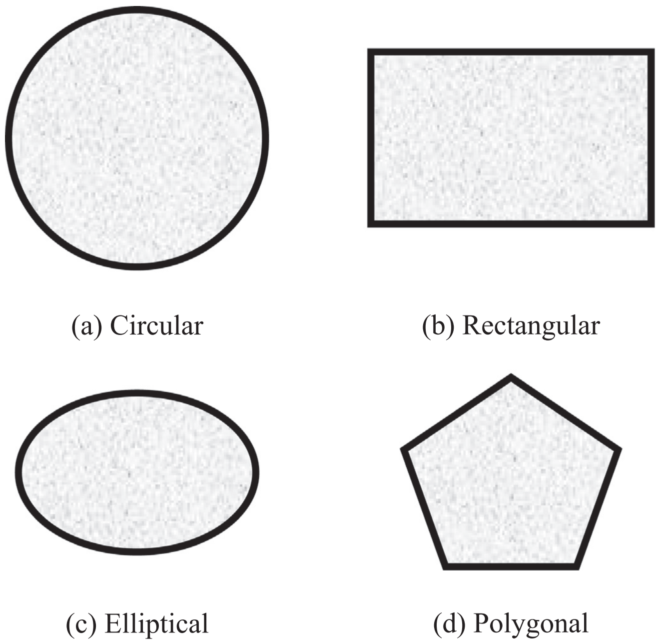

Fig. 1. Different cross-sectional shapes for CFST columns.

shapes that have also been suggested, studied and utilised in practice for aesthetical and architectural purposes are the elliptical [8] and the polygonal [12] shapes, as also presented in Fig. 1, despite their reduced confinement effect compared with the circular hollow sections.

One of the CFST cross-sections that have recently gained significant attention is the hexagonal shape used in Gaoyin Financial Building and Z15 tower in China. Such columns with hexagonal shape were designed to make them easier to connect with the beams of the structural skeleton of the tower [13]. Research on hexagonal CFST available in the literature is relatively scarce and although design approaches have been proposed for various CFST shapes, their suitability for designing the hexagonal CFST requires further investigation. In 2013, Yu et al. [12] suggested a unified design equation to determine the ultimate axial strength for both the circular and regular polygonal CFST columns. This equation was verified for application to octagonal CFST columns using experimental results reported by Tomii [14] but no assessment exists for the hexagonal shape to date. Evirgen et al. [15] conducted experiments on CFST columns of regular hexagonal-shaped cross-sections with small dimensions (see Fig. 2(a)) under axial compression. The behaviour of the hexagonal CFST columns [15] was carefully analysed but their ultimate test strengths were not compared with predictions of the design equation proposed by Yu et al. [12]. More recently, two experimental investigations were conducted on the behaviour and strength of large-diameter hexagonal CFST columns in China by Xu et al. [13] and Ding et al. [16]. The investigation presented in Xu et al. [13] focused on dual-axisymmetric cross-sections in compression (Fig. 2(b)) and concluded that the strengths of such sections are suitably predicted by the equations given in EN 1994-1-1 [17] for rectangular CFST short columns as both of them were observed to have similar confinement effects. Regarding research by Ding et al. [16], they presented the results of an experimental investigation on regular hexagonal shape (Fig. 2(a)) and derived a new design approach that takes into account concrete confinement effects. Additionally, Ding et al. [16] observed that the confinement mechanism in the hexagonal CFST columns is different compared to circular CFST columns. While the circular steel section provides continuous confinement all over the perimeter (see Fig. 2(c)), confinement effects on regular hexagonal CFST were observed to extend from the corner areas of the hexagon to the centre of the concrete core and the length of unconfined parts, as shown in Fig. 2(c), was approximately found to be 60% of the side length of the regular hexagon [16] which leaves a 33% of the total concrete core area unconfined. Accordingly, even if the regular hexagonal section is closer in shape to the circular section than to the rectangular section; the circular section situation cannot be used as a benchmark in the strength calculation of this type of CFST columns. This has recently been confirmed by Ding et al. [16] through proposing a new design model for such hexagonal columns.

In order to complement the few investigations above mentioned and contribute to developing depth understanding of the behaviour of CFST, this article investigates the behaviour and strength of hexagonal CFST short columns in compression on a numerical and analytical basis. Focus has been given to the regular shape as, to the authors' experience; it bears higher axial compression resistance than its dual-axisymmetric counterpart. This is because a regular steel tube shape resembles more closely a circular shape which evenly confines the concrete throughout the perimeter hence enhancing the strength and ductility of the composite tube. Firstly, this article presents a comprehensive assessment of all existing design methods for hexagonal CFST by comparing predicted strengths against all tests found in the literature. Secondly, a comprehensive finite element (FE) model is developed, calibrated and validated against experiments by using Abaqus [18]. Parametric studies are subsequently performed to further investigate the effects of key material and geometrical parameters on the behaviour and strength of hexagonal CFST short columns. Within the parametric study, fully-effective hexagonal tubular sections with a wide range of material properties and diameter-to-thickness ratios D/t are considered to cover ratios that have never been investigated before. The main factors affecting the behaviour of regular hexagonal CFST short columns are presented, carefully examined and a new model allowing for confinement effects is proposed. The numerical strengths of the hexagonal CFST short columns achieved by the models are also analysed and compared against the available design models assessed at the first point of this investigation for comparison purposes. In sight into such design methods is given in the next section.

2. Assessment of available design methods

In this section, the accuracy of available design methods to determine the resistance of regular hexagonal CFST short columns in compression is assessed by comparing their predictions with all experimental data collated from literature [15,16]. Table 1 lists the details of such tests including the specimens' diameter D, thickness t, experimental strength $P_{ul,Exp}$, the average yield strength measured from the tensile coupon tests f_y and the experimental concrete compressive strengths (f'_c) as reported in Refs. [15,16]. The minimum and maximum values of the geometrical dimensions, ratios and material properties are given at the bottom of the table, from which it can be noticed that the available experiments on hexagonal CFST columns cover relatively a limited number of D/t ratios.

To date, there are three equations for determining the strength of hexagonal short CFST columns in compression. The first equation ($P_{ul,Yu}$) considered in this assessment is that suggested by Yu et al. [12] which is a unified equation applicable to both circular and polygonal CFST columns. The second equation is that given in EN 1994-1-1 [17] for rectangular CFST short columns modified by Xu et al. [13] for application to hexagonal cross-sections ($P_{ul,Rec,EC4}$). And finally, the third method is that proposed by Ding et al. [16] ($P_{ul,Ding}$) which allows for confinement effects of the outer