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Structural behaviour and design of elliptical high-strength concrete-filled steel tubular short compression members

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ABSTRACT

Elliptical concrete-filled steel tubular (CFST) columns have recently attracted significant attention because of their increased strength and stiffness compared with empty elliptical hollow sections (EHSs). As with any new cross-section, there are still many aspects to be investigated to allow for its inclusion in different design specifications. Based on literature survey, this paper investigates the elliptical CFST columns which are filled with high-strength concrete (HSC). Numerical investigations into the structural behaviour of the elliptical CFST columns subjected to pure axial compression and eccentric loading have been performed using the general purpose commercial finite element (FE) software, Abaqus. The validity of the current FE models is examined by comparing their outcomes with those test results in literature. Then, parametric studies are performed considering three main parameters, namely the slenderness of the EHS, the steel yield strength and the concrete compressive strength. This is followed by a discussion of the results, showing in detail the characteristics of their load-strain responses. A comparison of the ultimate strengths with the existing design models is then considered, from which it is found that improved design model could be suggested to save additional weight and reach an optimum design. Hence, a new design formula is presented at the end which considers the effective confined concrete strength. Overall, this investigation expands the available engineering knowledge and assists in utilising the HSC, currently used in a wide range of applications, with the elliptical CFST columns with their favourable aesthetical and structural characteristics.

1. Introduction

Concrete-filled steel tubular (CFST) columns are frequently chosen as building members, bridge piers, transmission towers and offshore structural elements owing to their high strength, stiffness, ductility and energy absorption capacity. Circular or rectangular steel tubes are filled with concrete to form these composite columns. Elliptical CFST columns, a new form of composite columns, are made by filling concrete into elliptical hollow steel tubular column as illustrated in Fig. 1. These elliptical CFST columns have experimentally been investigated by many researchers [1–11]. Since the structural behaviour of elliptical CFST columns is not the same as those of the rectangular and circular CFST columns, further nonlinear analyses are required to examine the performance of such composite members under eccentric loading. The current structural provisions for composite construction, AS5100-2017 [12], AISC 360-10 [13], ACI 318-11 [14] and Eurocode 4 [15], do not specify a methodology for the design of elliptical CFST columns; instead, they recommend to use the rules established for circular or rectangular CFST short columns. On the other hand, the Chinese code GB50936-2014 [16] provides a design guideline to estimate the ultimate capacity of the elliptical CFST columns with different a/b ratios.

A number of experimental researches have been conducted on circular and rectangular CFST short columns [17–25] for predicting the strength, load-strain behaviour and ductility. Research study on hot-rolled elliptical short CFST columns by Yang et al. [1] revealed that the thin-walled elliptical CFST columns fail by outward buckling of the hot-rolled steel tube accompanied by concrete inclined shear crushing. Experimental study on axially compressed elliptical CFST short columns was conducted by Zhao and Packer [2]. They proposed the superposition method for estimating the ultimate strength of elliptical CFST short columns by using an equivalent rectangular section to the original elliptical one. Sheehan et al. [3] investigated experimentally the eccentrically-loaded elliptical short CFST beam-columns. Their results indicated that the tested short beam-columns fail by the local buckling

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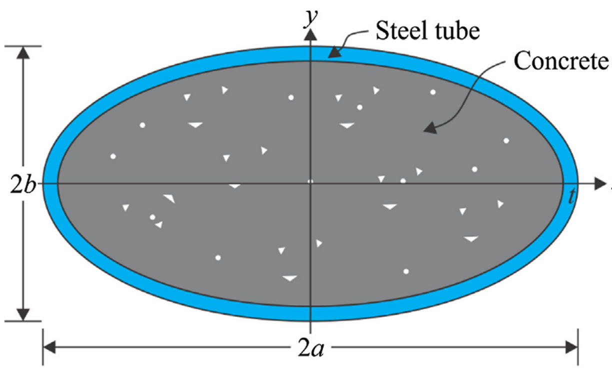

Fig. 1. Cross-section of elliptical CFST column.

of the steel tubes. Jamaluddin et al. [4] tested elliptical CFST short and slender columns subjected to axial loading. It was found that the elliptical tube induces less confinement to the high strength concrete (HSC) due to its low lateral expansion under axial compression. More tests were subsequently conducted by Uenaka [5] on thin-walled elliptical CFST short columns considering a/b ratios ranging between 1.5 and 2.5. Liu et al. [7] experimentally investigated the structural performance of cold-formed elliptical CFST short columns including specimens with a/b ratios varying between 1.5 and 2.5. It was found that the degree of concrete confinement in elliptical CFST columns lies between the circular and rectangular CFST columns.

Nonlinear simulations have been employed in literature to obtain the structural behaviour of axially compressed circular and rectangular CFST short columns [26-32]. However, the numerical studies on the elliptical short CFST beam-columns under eccentric studies have relatively been limited. A finite element (FE) analysis was firstly conducted by Dai and Lam [33] to examine the performance of elliptical short CFST columns. The confining pressure model, verified by using the experimental test results of Yang et al. [1], was suggested by Dai and Lam [33] for elliptical CFST columns made of hot-rolled steels. Additionally, numerical simulation using both FE and fibre element techniques was performed by Patel et al. [34] to obtain the performance of elliptical CFST columns. Furthermore, Liu et al. [7] used the FE simulation to obtain the inelastic response of elliptical short CFST columns with a/b ratios varying from 1.5 to 2.5. They, however, did not consider the nonlinear strain hardening of the hot-rolled steel in their FE model. The first FE analysis of the elliptical short CFST members under eccentric loading was presented by Sheehan et al. [3], from which a numerical procedure for computing the axial load-moment interaction diagram was presented.

As noted above, most of these numerical studies have only investigated the elliptical CFST columns under axial compression. Only Sheehan et al. [3] developed the FE model, using Abaqus software, to examine the structural behaviour of elliptical short CFST members under eccentric loading. Therefore, there is a need to develop numerical simulation for the elliptical short CFST members under eccentric loading. This paper, therefore, presents the numerical simulation of axially- and eccentrically-loaded elliptical short CFST beam-columns using FE analysis. Comprehensive comparisons of the computational predictions are made with various experimental results for elliptical short CFST beam-columns. At the end, a simple calculation model is developed based on the computational results and verified against the experimental data.

2. Assessment of available experiments

In this section, the experimental specimens available in literature [1,2,4,5] concerning elliptical CFST short columns are collected and their geometrical and material properties are evaluated. It was firstly found that the length-to-depth ($L/2a$) ratios varied from 1.0 to 3.3 [1,2,4,5], in which $2a$ represents the major axis diameter (Fig. 2). However, Tao et al. [28] previously found that the ultimate strength of the CFST columns decreases significantly when the length-to-depth ratio increases from 1.0 to 1.5 owing to the fast diminishing end effects. On the opposite, when the length-to-depth ratios lie in the range of 2.0–5.0, the columns exhibit identical load-deformation curves [28]. Accordingly, the specimens having $L/2a < 2.0$ ratios which were tested by Uenaka [5], despite their valuable contribution to the topic, were ignored in the current assessment. Table 1 provides the minimum (Min) and maximum (Max) limits of the geometrical and material properties available in Refs. [1,2,4]. From this table, it can be noticed that the available elliptical CFST columns had depth-to-width ratios of 2.0. The yield stress (f_y) of the steel tubes varied between 355 MPa and 425 MPa, while the compressive strength of the concrete (f_c') was on the range 30–100 MPa.To get an in-depth view to the distribution of the yield stress (f_y) of the steel tubes and the compressive strength of the concrete (f_c') against the slenderness of the cross-section, Fig. 2 is presented. The slenderness considered is given as $(a + b)/t$ typical to that suggested by Patel et al. [34]. As can be seen in Fig. 2(a), the distribution of the the yield stress (in between 355 MPa and 425 MPa) and the $(a + b)/t$ ratios (from 16 to 29) of the available 15 specimens is regularly covered. On the opposite, the available columns are not covering the compressive strength of the concrete (f_c') evenly with respect to the $(a + b)/t$ ratios, at which it can be seen that only a few columns had $f_c' > 70$ MPa.Based on the above discussion, this paper substitutes the lack of the available results of the elliptical CFST short columns filled with concrete ranging with strength between $70\text{ MPa} \leqslant f_c' \leqslant 100$ MPa; see the red[1] dashed rectangle in Fig. 2(b). The limited test results in this range would be verified firstly by using the f_{rp} stress of Patel et al. [34]. It is worth pointing out that the steel material is currently constrained to the used grades in the tested elliptical CFST short columns (i.e. 355–425 MPa) [1,2,4]. This is because the steel in these limits were used in proposing the confining pressure (f_{rp}) [34].

3. FE model

3.1. Basic concepts

The FE code ABAQUS [35] was employed to obtain the structural performance of elliptical CFST short columns loaded concentrically and eccentrically. The influences of material and geometric nonlinearities were incorporated in the numerical investigation. This simulation predicts the failure modes, ultimate axial strengths, axial load-strain responses and stress contours for a CFST short column. One way to conduct this parametric study was to recreate the columns many times. Every time the cross-sections, loads and constraints were to be applied. An efficient way to perform the same task was to develop a script with material and geometric parameters assigned as variables. The script can be rerun in the loop many times by changing the concrete compressive strengths, dimensions of the elliptical section and steel yield strengths [36]. Therefore, A Python script was developed to simulate the FE models in the parametric study.

3.2. Finite elements and interactions

The solid elements (C3D8R) with 8-node linear brick incorporating reduced integration were utilised to divide a steel tube and concrete core. This element represents larger deformation, geometric and material nonlinearities and provides accurate solution for the behaviour of CFST columns [33]. It should be noted that the selection of the shell element (S4R) or solid element (C3D8R) for the steel component does not affect the compressive behaviour of CFST columns [33]. However,

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.