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Round-ended rectangular concrete-filled steel tubular short columns: FE investigation under axial compression

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ABSTRACT

Concrete-filled steel tubular (CFST) columns with round-ends own the same advantages of typical CFST columns, besides their aesthetical appearance. The smoothness of the cross-section gives the effectiveness to resist running water impact when they are used as piers. Despite these advantages, there are limited researches on the behaviour of round-ended CFST columns. The paper investigates the behaviour of round-ended rectangular CFST (RRCFST) columns. Three-dimensional finite element (FE) models for RRCFST columns are developed using the ABAQUS software. The novelty of this FE model is the consideration of the confinement in the round-ended concrete. The existing experimental behaviour has been captured properly, compared with other previously suggested FE models. After the validation of FE models, a parametric study is generated taking into account wider parameters than those previously considered by other researchers. The results show two different axial load-strain responses based on the B/t ratios of the cross-sections. RRCFST columns with small B/t ratios are found to fail in a ductile manner with large axial strains. The failure of the columns with relatively high B/t ratios has been found to occur suddenly with a rapid reduction in the strength after reaching the ultimate load. The numerical results indicate that the brittle failure is associated with the columns formed from outer slender steel cross-sections. The FE strengths are compared with the available design model which was formulated based on limited research results. This design model is found to predict the strengths unconservatively. A new design model, providing better estimates, has been suggested at the end.

1. Introduction

The concrete-filled steel tubular (CFST) column consists of a hollow steel tube infilled with concrete, from which additional reinforcements or steel section may be added to the core. CFST column has been extensively used in civil engineering projects around the world [1]. From the early days, a greater capacity for the entire CFST section than the sum of the individual capacities of the steel and concrete components was reported [2–3]. In CFST column, the outer steel tube confines the concrete core, while the concrete core prevents the inward buckling of the steel tube. This interaction enhances the overall strength and ductility of this composite section. Hence, it was mainly suggested and used to support high loads that conventional bare steel or reinforced concrete columns cannot support or when they become uneconomical. Circular CFST columns were used, for example, in the SEG Plaza in Shenzhen. Compared with the hollow steel section column, the steel used for the CFST columns was only a half and the designers of the SEG Plaza were able to avoid the use of very thick steel plates [1]. This is mainly attributed to the excellent confinement generated in circular CFST columns. In contrast to encased composite columns, CFST columns have the advantage that they do not need any formwork or reinforcement. In addition, their use in high-rise composite buildings leads to a rapid construction, which can bring significant economic benefits [4]. Despite the fact that the confinement increases the ductility of the concrete core in rectangular CFST columns without increasing their ultimate strengths [5], the rectangular columns also have gained a popular usage in buildings, mainly for the convenience when dealing with the connections [1]. For example, the Ruifeng International Commercial Building built in Hanzhou (China) used square CFST columns. On the other hand, CFST members have also been utilised in many types of bridges to act as piers, bridge towers and arches, and they can also be used in the bridge deck system.

It is worth pointing out that extensive research on the compressive behaviour of circular and square CFST columns has been conducted in literature [1,6]. On the other hand, other cross-sectional shapes that have been suggested for architectural and aesthetical purposes [1], such as the polygonal [7], elliptical [8] and round-ended rectangular [9–11] shapes, have attracted less attention. The current paper, therefore, emphasises on the round-ended rectangular concrete-filled steel tubular (RRCFST) columns shown in Fig. 1. The round-ended rectangular columns own the same advantages of typical CFST columns, besides

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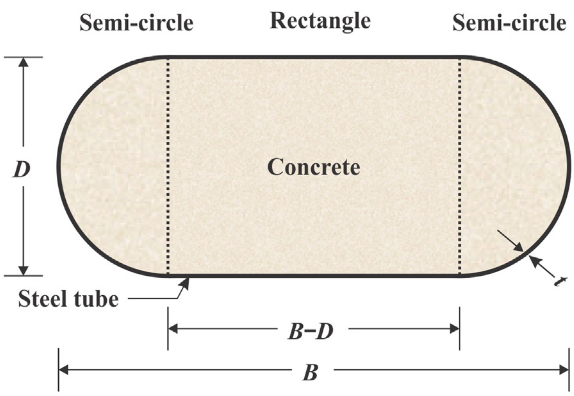

Fig. 1. Cross-section of RRCFST column.

their aesthetical appearance. Additionally, the smoothness of the round-ends of the RRCFST columns gives them the effectiveness to resist running water impact [9]. Hence, in bridges crossing rivers or channels, using RRCFST columns as piers can reduce the impact of water load and increase their life time. Despite these advantages, only one design model for the RRCFST columns can be found in literature as suggested by Ding et al. [10], though Wang et al. [9] suggested predicting their strengths based on the equations of the rectangular CFST columns. As noticed by the current authors, this design model [10] was suggested based on test specimens with round ends of D/t ratios of about 50. Hence, it should be checked further for different D/t ratios representing a wide range of steel confining pressure. Accordingly, due to the limited research in the general behaviour of RRCFST columns despite their advantages discussed above, this paper investigates numerically RRCFST short columns with the main aim of providing their accurate behaviour and design strength.

2. Problem statement

To the best of these authors' knowledge, the finite element (FE) model generated by Ding et al. [10] is the only numerical study in literature to analyse the compressive behaviour of the RRCFST columns. They utilised a unified constitutive concrete model in determining uniaxial mechanical properties of concrete [12–13]. It was derived based on a large number of experimental studies with concrete strengths ranging from 20 MPa to 140 MPa [12], and it has already been validated by simulating CFST columns with different cross-sections; circular, square and rectangular columns. However, the current authors noticed that the FE models of Ding et al. [10] represent well the experimental behaviour of the RRCFST columns with aspect ratios of $B/D \le 1.5$, while they do not accurately predict the behaviour of the column cross-sections having greater aspect ratios ($1.5 < B/D \le 4.0$). It means that the model proposed by Ding et al. [10] suits the behaviour of circular CFST columns and not the behaviour of the RRCFST columns.

A FE model incorporating the accurate constitutive concrete material model is developed for determining the behaviour of RRCFST short columns under concentric loading. This is a step towards conducting a parametric study which provides the behaviour of these columns and to end up with a suggested design model. The idea is to divide the cross-section into two parts (i.e. rectangular and circular parts), and then to apply the proper constitutive concrete model for each one. The model of the circular concrete at both round-ends utilises the increased strength of concrete due to the effective confinement provided by the steel tube, while the middle part of the cross-section (i.e. the rectangular concrete) does not [14–15]. This assumption is, however, supported by the experimental results of Ding et al. [10], at which the local buckling of the steel tubes occurred mainly at the rectangular parts of the RRCFST columns. This indicates that the concrete in the middle rectangular part of the cross-section is partially confined unlike the round-ended concrete which is effectively confined by the circular steel tube. Additionally, the paper investigates the RRCFST columns with low D/t ratios that are characterised by their high confinement of the round-ended steel tubes on the concrete, so that the strengths of the columns could be enhanced.

3. Description of the FE model and validation

3.1. General

In this paper, the software package ABAQUS/Standard [16] is used to develop the FE models of the RRCFST columns. Only short columns are investigated for the sake of providing the fundamental behaviour and strength of such cross-sectional type. The effect of the initial imperfections on the current short columns was checked first by using the experimental results [10]. The initial local geometric imperfection value was taken as the column length over 1000 ($L/1000$) following Tao el al [17]. Despite relating the imperfection to the length of the column as ($L/1000$) [17], the imperfection used in the current RRCFST short columns is still local in nature. This is because such short columns do not represent half-sine (overall) buckling modes. Accordingly, additional values for the initial local geometric imperfection were also considered to confirm the final selected amplitude. Herein, three values of 1, 10 and 100% of the steel tubular section wall thickness (t) were examined as local imperfection amplitudes. Fig. 2 shows the FE load-strain curves of the specimen WST7-A (as sample results) by including and ignoring the initial imperfections, at which it can be recognized that the FE load-strain curves coincide for the models analysed with and without initial imperfections. This confirms the well-known fact that initial imperfections of short CFST columns have insignificant effect on their behaviour and strength [18]. Hence, it has currently been ignored in the FE modelling. The FE modelling consists merely of one step. This step is called the nonlinear analysis, which includes the material plasticity strains, and it uses the displacement contract with Static general method [16].

A Python input script was employed to automatically generate the FE models. The main advantage of the Python input script over the CAE approach is that it generates many FE models for given user's input parameters. Typical FE model for the RRCFST column is shown in Fig. 3. As can be seen, the model does not contain upper and lower end plates, but instead "Rigid body" constraints were used to model the loading plate. Two Reference Points (RPs), one at the centre of each upper and lower cross-section, can be seen in the figure. The boundary conditions were assigned to both RPs, while the load was applied downward on the upper RP. The upper and lower surfaces of

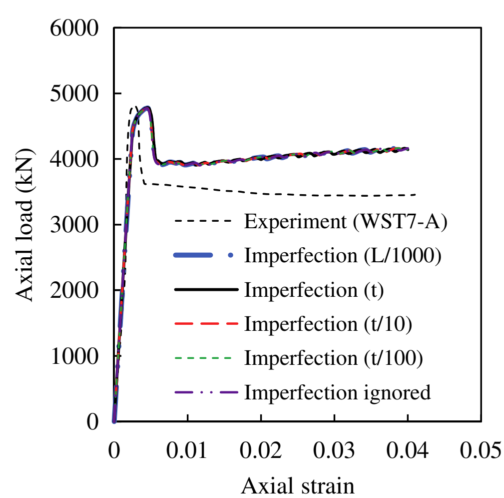

Fig. 2. Effects of initial gometric imperfection for Specimen WST7-A.