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Behaviour of circular concrete-filled lean duplex stainless steel–carbon steel tubular short columns

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ABSTRACT

Recently, a concrete-filled austenitic stainless steel–carbon steel tubular column has been introduced as a new form of composite members. This column is composed of an external stainless steel tube and an internal concentrically placed carbon steel tube with concrete filling in the whole tubular section. However, the excellent performance of such composite columns can additionally be achieved by utilising the low-cost lean duplex stainless steel material. In this paper, the behaviour of circular concrete-filled lean duplex stainless steel–carbon steel tubular (CFSCT) short columns under axial loading is investigated by using the general purpose finite element analysis program ABAQUS. A new constitutive model for the concrete core confined by both the external stainless steel tube and the internal carbon steel tube is proposed and incorporated in the finite element model developed. The accurate two-stage stress–strain relationships are employed to model cold-formed lean duplex stainless steels. The finite element results obtained by the proposed concrete model are shown to be in good agreement with test results. Parametric studies are then conducted to investigate the effects of concrete compressive strength, carbon steel yield stress and cross-section geometry on the behaviour of CFSCT columns. The ACI code is found to significantly underestimate the ultimate axial strengths of CFSST columns. Therefore, a new design model is proposed for CFSCT short columns. It is shown that the proposed design model provides excellent predictions of the ultimate axial strengths of circular CFSCT columns over a wide range of diameter-to-thickness ratios of the stainless steel tubes.

1. Introduction

Concrete-filled steel tubular (CFST) short columns are composite members which are constructed by a steel tube and concrete infill working compositely to support load and provide stiffness as shown in Fig. 1a; where D is the outer diameter of the CFST column and t is the thickness of the tube. CFST columns are recommended structural members because they have several advantages over conventional reinforced concrete or structural steel columns [1]. Compared to conventional reinforced concrete, the concrete core is confined by the steel tube. This results in a tri-axial state of compressive stresses which enhances the strength and ductility of the concrete. Additionally, the concrete infill restrains local and global buckling of the steel tube, and hence increases the deformation capacity of a CFST column compared to a hollow steel tube. Moreover, the combined capacity of the steel tube and the concrete core efficiently provides high stiffness and axial load capacity, which makes them very suitable for columns and other compression members. Furthermore, CFST columns permit rapid construction, because the steel tubes eliminate the material and labour associated with formwork and reinforcement associated with reinforced concrete construction, and the concrete infill is rapidly placed. It should be mentioned that the high load-carrying capacity of a CFST column is accompanied by high ductility and energy dissipation ability, due to the composite action between steel and concrete. However, there has been much research work reported in the literature on the compressive strength of CFST columns formed from carbon steel tubes.

On the other hand, the structural applications of metallic corrosion resistant materials have significantly been increased over recent decades. Most of these materials are stainless steel alloys, which combine high strength, durability, weldability, improved fire resistance, ease of maintenance and an aesthetically clean surface with high corrosion resistance [2–4]. However, the initial high cost associated with stainless steel has significantly limited its structural use. Accordingly, much attention has been paid to make the stainless steel more economical for the use as compression members. As a result, several ideas were recommended in literature *to reduce their amount within the members*, as follows:

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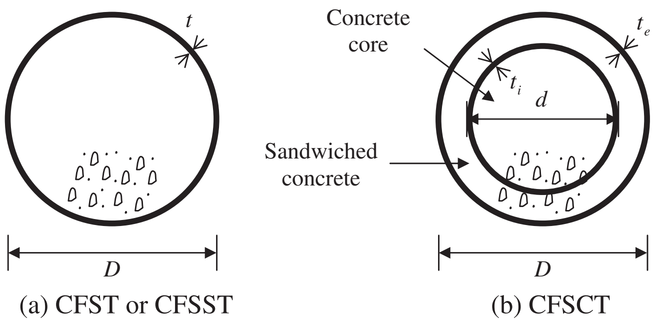

Fig. 1. Types of circular concrete-filled tubular stub columns.

1. It was *firstly* suggested to fill the stainless steel hollow tubes with concrete to develop the concrete-filled stainless steel tubular (CFSST) short columns [5–7]. By doing so, the resulting columns possess higher corrosion resistances compared to conventional CFST columns. In their CFSST columns, Young and Ellobody [5,6] used the duplex and the high strength austenitic stainless steels, while Uy et al. [7] used the austenitic stainless steel material.
2. To gain further benefit from the stainless steel, different types of stiffeners were *then* added to the tubes of the CFSST columns by Ellobody [8] and Dabaon et al. [9,10]. It was shown that the stiffened CFSST columns [8–10] offer a considerable increase in the column strength and ductility than the unstiffened CFSST columns. This was attributed mainly to the high average of increase in the confinement of the concrete core in stiffened CFSST columns compared to that of the unstiffened ones [10].
3. *Recently*, lean duplex stainless steels with reduced nickel content have been used as structural materials [4]. It is commonly known that nickel represents a significant portion of the cost of austenitic stainless steels. The lean duplex (Grade EN 1.4162) contains a relatively low nickel content of about 1.5% of its alloy composition, while it is around 10% in the austenitics. Accordingly, they are very competitive within the stainless steel grades due to the strong fluctuations in nickel price and better mechanical properties than those with austenitic alloys. This encouraged the first author to investigate the circular CFSST short columns utilising such relatively low-cost material [11].
4. *More recently*, a concrete-filled austenitic stainless steel–carbon steel tubular (CFSCT) column has been introduced as a new form of composite member [12] to benefit from the lower cost upcoming from combining the advantages of the stainless steel and the CFST columns as illustrated in Fig. 1b; where the diameter of the internal tubes, thickness of the internal and external tubes are d, t_i and t_e, respectively. The CFSCT column has a hollow cross section consisting of an external stainless steel tube and an internal concentrically placed carbon steel tube with concrete filling in the whole tubular section. Chang et al. [12] used *the high strength austenitic stainless steels* with an ultimate strength of about 700 MPa as well as *high strength concrete* with unconfined cubic compressive strengths of 56.3 MPa and 65 MPa. However, this austenitic stainless steel is very expensive as it costs five times the carbon steel [12]. Additionally, they did not use the actual stainless steel material curve (they used the elastic–plastic material model with strain hardening which merely suits the carbon steel [2–4]).

The above literature review indicates that there have been very limited studies on the behaviour of circular concrete-filled stainless steel–carbon steel tubular (CFSCT) short columns and the research on CFDCT columns made of lean duplex stainless steel tubes has not been reported in the literature. This paper studies the behaviour of circular concrete-filled lean duplex stainless steel–carbon steel tubular (CFSCT) short columns under axial loading by using the general purpose finite element analysis program ABAQUS [13]. A three-dimensional finite element model is developed for CFSCT short columns, incorporating the new constitutive model proposed for the concrete core confined by both the external stainless steel tube and the internal carbon steel tube. A parametric study on the behaviour of CFSCT columns with various important material and geometric factors is conducted by using the verified FE model. The FE results are compared with the ultimate axial strengths calculated by the ACI code [14] and by the proposed new design model for CFSCT columns under axial compression.

2. Finite element model

As found by Chang et al. [12], the confinement effect on the concrete core in CFSCT columns is more significant than that in conventional CFSST columns. Accordingly, the confined concrete strength (f'_{cc}) and the corresponding strain (ε'_{cc}) proposed by Mander et al. [15] were modified by Chang et al. [12] to increase the confinement provided by the external stainless steel tube on the internal carbon steel tube. However, the confining pressure model used by Chang et al. [12] was previously found by Liang and Fragomeni [16] to generally overestimate the lateral confining pressures in high strength circular CFST columns. Consequently, a more accurate confining pressure model for confined concrete in both normal and high strength circular CFST columns was proposed [16]. Therefore, the confining pressure model given by Liang and Fragomeni [16] is used herein to model the concrete in CFSCT columns with high strength materials.

The details of the FE model of the current CFSCT emphasising on the material models of the stainless steel, carbon steel and confined concrete are described in the following sections.

2.1. Finite element type and mesh

Due to the symmetry of geometry and loading, only one quarter of the circular CFSCT column was modelled in the analysis. Typical finite element meshes for CFSCT columns are shown in Fig. 2a. Owing to the thin-walled nature of both the external stainless steel and the internal carbon steel tubes, shell elements were employed to discretise both tubes [6,10–12,17]. However, the three-node triangular general-proposed shell finite membrane strains element S3 [13] has been utilised. Although Wu [17] found that mesh refinement has very little influence on the numerical results of CFST columns, further sensitivity analyses were undertaken to investigate the mesh effect on the ultimate axial strengths of CFSCT short columns. A CFSCT column with an external stainless steel tube of $D \times t_e$ = 480 × 10 mm and an internal carbon steel tube of $d \times t_i$ = 240 × 10 mm was considered for such analyses. The value of the concrete compressive strengths was (40 MPa) and the steel grade of the internal carbon steel tube was S355. The results of the sensitivity analyses are shown in Fig. 3 where each data point represents the equivalent mesh size. It can be seen from Fig. 3 that an approximate global size of 25 mm provides accurate results with reasonable computation times. Therefore, the element size of 25 mm was used in the current modelling for the external and internal steel tubes and concrete cores; see Fig. 2a. Three dimensional four-node linear tetrahedron solid elements C3D4 [13] were used to model the sandwiched concrete, the concrete core and the two cover plates.

To simulate the bond between each steel tube and the concrete, a surface-based interaction with a contact pressure–overclosure model in the normal direction, and a Coulomb Friction Model in the directions tangential to the surface, were used; more