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

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ABSTRACT

Lean duplex stainless steel material (EN 1.4162) has recently gained significant attention for its higher structural performance and corrosion resistance compared to the austenitic type. Circular lean duplex stainless steel tubes filled with concrete are innovative composite columns which have not been studied experimentally or numerically. This paper presents the fundamental behaviour of circular concrete-filled lean duplex stainless steel tubular (CFSST) short columns under axial compression. Three dimensional finite element (FE) models for CFSST columns subjected to axial compression are developed using the FE package ABAQUS. The lean duplex stainless steel material is modelled using the two-stage constitutive laws while the concrete is simulated using accurate concrete confinement models. The FE models are verified by comparisons with existing experimental results on hollow stainless steel columns, concrete-filled steel tubular columns and CFSST columns. Parametric studies are undertaken to investigate the effects of concrete compressive strength and diameter-to-thickness (D/t) ratio on the behaviour of CFSST columns. The results show that the ultimate axial strength of circular CFSST columns increases with increasing the concrete compressive strength but decreases with an increase in the D/t ratio. Circular CFSST columns with different D/t ratios exhibit the same initial stiffness. The lean duplex stainless steel tubes cannot provide good confinement on the concrete when D/t ratio is large. The ultimate axial strengths of CFSST columns predicted by the FE models are also compared with those calculated by the Eurocode 4, ACI code, the continuous strength method (CSM) by Lam and Gardner and Liang and Fragomeni's design formulas. The comparative study shows that Eurocode 4 and the CSM give good estimates of the ultimate axial strengths of CFSST columns with $D/t < 40$ but overestimates the strengths of columns with $D/t \geq 40$. The ACI code gives too conservative estimates of the ultimate loads of CFSST columns as it does not consider the concrete confinement effects. Finally, it was found that the modified Liang and Fragomeni's design formulas yield the best predictions of the ultimate axial strengths of CFSST columns over the entire range of D/t ratios.

1. Introduction

Nowadays, different stainless steel types can provide a wide range of mechanical properties and material characteristics to suit the demands of numerous construction applications, without the need for surface corrosion protection even in highly aggressive environments. Actually, the austenitic grades, which contain around 8–11% nickel, are the most common stainless steel types that are increasingly used in construction. Nickel stabilizes the austenitic microstructure and consequently contributes to the associated favourable characteristics such as formability, weldability, toughness and high temperature properties. However, nickel represents a significant portion of the cost of austenitic stainless steels. On the opposite, the duplex stainless steels offer higher strength than austenitics along with a great majority of carbon steels with similar or higher corrosion resistance. Accordingly, duplex grades have great potential for expanding future structural design possibilities, enabling a reduction in section sizes and leading to lighter structures. However, duplex stainless steel grades are commonly grouped into different groups, depending on their alloy contents and corrosion resistances as the lean duplex grade being one of them. The lean duplex contains low nickel content (around 1.5%), such as grade EN 1.4162. Hence, significant reduction in both the initial material cost and cost fluctuation can be gained [1–3].

The behaviour of stainless steel material is different from that of carbon steels [1–2]. Stainless steels have a rounded stress–strain curve without well defined yield plateau and low proportional limit stress compared to carbon steel ones. However, despite early applications of lean duplexes (including for example two footbridges

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in Norway and Italy [4]), their structural properties are still to some extent unverified since only limited test results on structural components have been reported. Therefore, research projects are currently underway in different Universities and research centers to address these shortcomings. Lean duplex stainless steel hollow section columns (LDSSHSCs) were investigated experimentally and numerically by Theofanous and Gardner [5] and later on by Huang and Young [6]. In addition, finite element (FE) studies on LDSSHSCs with different cross-section shapes were presented by Patton and Singh [7]. Moreover, Hassanein [8] studied numerically the compressive strength of concrete-filled lean duplex stainless steel tubular stub columns with thin-walled square and rectangular cross-sections. Furthermore, the investigations were extended to lean duplex stainless steel beams [9–11].

It should be mentioned that the previous numerical investigations [5–11] were undertaken using the general purpose FE package ABAQUS [12]. The available test results were used to validate the FE models [5–11], which were thereafter employed in parametric studies. It is worth pointing out that the compound Ramberg–Osgood material model [13], which is a two-stage version of the basic Ramberg–Osgood model [14–15] was used in the numerical analyses [5,9,11]. On the other hand, the two-stage full-range stress–strain relationship for stainless steel developed by Rasmussen [16] was used by the current author [8,10]. The results [5–11] indicate that lean duplex stainless steel members are not completely compliant with the international steel structures codes, based on assumed analogies with carbon steel behaviour, because of their rounded stress–strain curve.

Concrete-filled steel tubular (CFST) short columns are one of the most important structural elements in modern construction around the world in both non-seismic and high seismic zones. The use of CFST columns increases the height of buildings for the effective usage of limited land area. In a CFST, the concrete core prevents the premature local buckling of the steel tube and the steel tube offers the confinement to the concrete core. The confinement effect increases the strength of concrete in circular CFST columns. The high load-carrying capacity of a CFST is accompanied by other good structural performances, such as high ductility and energy dissipation ability, due to the composite action between steel and concrete. Some important findings about the compressive behaviour of CFST columns are summarized as follows:

1. Bradford et al. [17] investigated the local and post-local buckling of circular steel tubes filled by means of a rigid medium, with the emphasis being on the strength of CFST sections. They proposed a cross-section slenderness limit that delineates between a fully effective cross-section and a slender cross-section. This cross-section slenderness is given by $125/(f_y/250)$; where f_y is the steel yield strength.
2. Ding et al. [18] reported that the confinement effect, ultimate capacity and ductility of CFST columns were found to improve with the increase in the steel ratio and yield stress. On the other hand, increasing the concrete compressive strength increases the ultimate load capacity of the column but decreases the ductility of CFST columns.
3. Liang and Fragomeni [19] found that the existing confining pressure models, which were developed based on normal strength materials, generally overestimate lateral confining pressures in high strength circular CFST columns. Therefore, a more accurate constitutive model for confined concrete in both normal and high strength circular CFST columns was proposed. The constitutive relationships for confined concrete can be used in numerical techniques for modelling the nonlinear behavior of circular CFST columns. This proposed design formula can be used by practicing structural engineers to design high strength circular CFST columns, which are not covered by current design codes. Their study demonstrates that increasing the tube diameter-to-thickness (D/t) ratio reduces the ultimate strengths of CFST columns in addition to their section and axial ductility performance.
4. The results of the parametric study conducted by Ellobody et al. [20] showed that the design rules for CFST columns specified in the American Specification [21] and Australian Standards [22,23] are conservative. However, the design strengths predicted by the Eurocode 4 [24] are generally unconservative for carbon steel CFST columns.

To the authors' knowledge, past research on the ultimate axial strengths of circular CFST columns has never considered the lean duplex stainless steels. Hence, in this paper, the ultimate axial strengths and behaviour of concrete-filled lean duplex stainless steel circular tubular short columns of Grade EN 1.4162 (CFSST) are presented. Finite element models are developed using the general purpose FE package ABAQUS [12] and verified by experimental results. The models are than used to investigate the behaviour of circular CFSST short columns with various parameters. The FE results are discussed and compared with current international design codes.

2. Finite element model

2.1. Finite element type and mesh

Owing to the thin-walled nature of the lean duplex stainless steel tubes Grade EN 1.4162, and in line with similar previous investigations [8,25–26], shell elements were employed to discretise the stainless steel tubes. However, the three-node triangular general-proposed shell finite membrane strains element S3 [12] has been utilised in this study.

A convergent study of the mesh had been done by Wu [27] using a range of element sizes for circular CFST columns. It was shown that the results of the circular CFST column with 30 (5×6) elements were almost identical to those with 192 (16×12) elements. Since mesh refinement has very little influence on the numerical results, coarse meshes could be used through the finite element analyses of concrete-filled columns. Accordingly, a mesh of an approximate global size of 25 mm was used in the current modelling for the stainless steel tubes and concrete cores; see Fig. 1(a). For the concrete core and the two cover plates, three dimensional four-node linear tetrahedron solid elements, so called C3D4 [12], were used.

To simulate the bond between the stainless steel tube and the concrete core, 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. In order to construct contact between two surfaces, the slave and master surfaces must be chosen successfully. Generally, if a smaller surface contacts a larger surface, the best is to choose the smaller surface as the slave surface. If the distinction cannot be made, the master surface should be chosen as the surface of the stiffer body or as the surface with the coarser mesh if the two surfaces are on structures with comparable stiffness. The stiffness of the structure and not just the material should be considered when choosing the master and slave surface. Herein, a thin sheet of stainless steel is less stiff than a larger block of concrete core even though the stainless steel material has a higher stiffness than the concrete material. Therefore, the stainless steel surface was chosen as the slave surface whereas the concrete core surface was chosen as the master surface.