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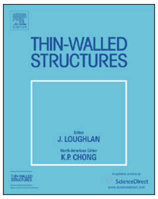

Circular concrete-filled double skin tubular short columns with external stainless steel tubes under axial compression

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ABSTRACT

Lean duplex stainless steel (EN 1.4162) has recently gained significant attention for its higher structural performance, similar corrosion resistance and lower cost compared to the austenitic steel. This paper presents the nonlinear finite element (FE) analysis, behaviour and design of circular lean duplex stainless steel–concrete–carbon steel double skin tubular (CFDST) short columns under compression. The finite element (FE) model for CFDST short columns is developed and validated by comparisons with experimental results available in the literature. The FE model is used to investigate the fundamental behaviour of axially loaded CFDST short columns with various parameters. The results show that the ultimate axial strength of CFDST short columns increases significantly with increasing the concrete compressive strength or with decreasing the hollow ratio. However, increasing the ratio of inner-to-outer thickness or increasing the yield strength of the inner carbon steel tube leads to insignificant increase in the ultimate axial strength of the short column. The accuracy of the design models given in ACI code and by Han et al. (2011) and of the modified continuous strength method (CSM) for CFDST short columns is examined against the FE and experimental results. It is demonstrated that the ACI code and Han et al. model provide conservative strength predictions of CFDST short columns, with a relatively high margin of safety. The ultimate axial strengths of CFDST short columns predicted by the CSM are unconservative. A new design model is proposed and shown to be a reliable predictor of the ultimate axial strength of CFDST short columns under axial loading.

1. Introduction

Composite columns refer to compression members in which a steel element acts compositely with a concrete element, so that both elements resist compressive force. There is a wide variety of composite column types of varying cross-sections, but the most commonly used and studied are encased I-section and concrete-filled steel tubes. In contrast to encased composite columns, concrete-filled steel tubular (CFST) columns (Fig. 1(a)) have the advantage that they do not need any formwork or reinforcement. Concrete-filled columns offer several advantages in terms of structural performance over pure steel, reinforced concrete or encased I-section columns. In addition, the use of CFST columns in high rise composite buildings leads to rapid construction, which results in significant economy [1,2]. Recently, concrete-filled double skin steel tubular (CFDST) short columns have been studied by researchers [3–8]. This composite short column consists of concentric inner and outer steel tubes with concrete filled in between; see Fig. 1(b). The application of CFDST columns was found to reduce the self-weight of the structure due to the hollow inner tubes. CFDST columns have been recognised to have advantages, such as high strength and bending stiffness and fire performance, and favourable construction ability. These columns can be used in seismic resisting structures such as high raise bridge piers under mitigate seismic force against foundation.

Compared to carbon steels, stainless steels have superior characteristics such as intrinsic durability, ductility and formability, improved fire resistance and ease of maintenance [9–11]. As a result, stainless steel tubes have been used to form concrete-filled stainless steel tubular (CFSST) short columns [12–14]. Recently, stainless steel–concrete–carbon steel double-skin tubular (CFDST) short columns have been studied by Han et al. [15]. However, the most commonly employed grades of austenitic stainless steel contain around 8–11% nickel. Although the nickel is added, mainly, to ensure the correct microstructure and mechanical properties of the steel it represents a significant portion of the cost of austenitic stainless steel. As a result, the high nickel prices have recently led to a demand for lean duplexes with low nickel content, such as grade EN 1.4162. The Siena Footbridge in Italy, completed in 2006, is an example to a structure fabricated from lean duplex grade. Such grade was chosen because the structure needed to have a 120-year design life without expensive and disruptive maintenance requirements [11].

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Much of the research work reported in the literature focused on concrete-filled double skin carbon steel tubular short columns [3–8]. However, the behaviour of CFDST short columns with external lean duplex tubes of Grade EN 1.4162 has never been studied. To form composite short columns, the lean duplex stainless steel tubes have only been used in literature by the current authors [16–18]. In this paper, the nonlinear analysis, behaviour and design of circular lean duplex stainless steel–concrete–carbon steel double skin tubular short (CFDST) columns are presented. The finite element (FE) model for CFDST short columns, developed using the general purpose finite element package ABAQUS [19], is described that incorporates material laws for confined concrete [20]. The FE model is verified by existing experimental results and employed to study the behaviour of CFDST short columns with various important material and geometric factors. The design of CFDST short columns is discussed with respect to the ACI code [21], the available design model by Han et al. [15], a modified version from the continuous strength method [22] and the currently proposed design model for CFDST short columns under axial compression. According to the above introduction, the contribution of the current paper can be summarised as

1. Large scale circular CFDST short columns are used relative to experimental results available in literature; see Table 1.
2. The lean duplex stainless steel material is recommended to produce CFDST short columns so that cost of such columns is reduced compared to the use of other stainless steel material as that used in [15].
3. A more accurate confining pressure model for confined concrete in normal, high strength and ultra-high strength concrete circular CFST short columns are used; see Section 2.4.
4. The ultra-high strength concrete (UHSC) is used to increase the range of the concrete strengths in the available CFDST short columns in literature.
5. A new design model is suggested for the design of CFDST short columns under axial compression with a wide range of diameter-to-thickness ratios of the external tube (D/t_e); see Section 5.

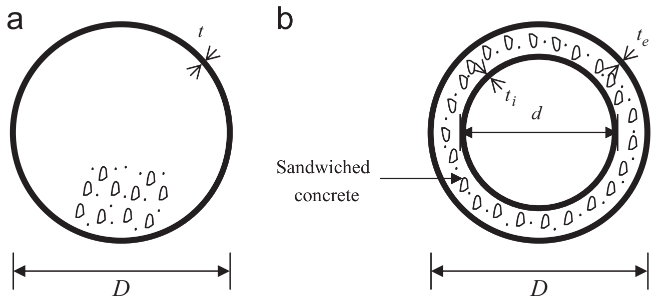

Fig. 1. Types of circular concrete-filled tubular stub columns. (a) CFST or CFSST and (b) CFDST

2. Finite element model

2.1. General

A three dimensional (3D) FE model has been developed for the nonlinear analysis of circular CFDST short columns under axial loading as shown in Fig. 2. Two cover plates were used to cape both ends of the CFDST short column to distribute the axial load evenly on the inner and outer tubes in addition to the sandwiched concrete. Only one quarter of the circular CFDST short column was modelled owing to the symmetry of geometry and loading. Both ends of the short columns were fixed, but the displacement at the loaded end in the direction of the applied load (Z-axis) was allowed. Moreover, the upper and lower bounds of the CFDST short column were restrained to move laterally to prevent the elephant foot buckling at both ends of the column. A uniform distributed load was applied incrementally at the top of the upper cover plate (Fig. 2) using the displacement control approach together with the modified RIKS method available in the ABAQUS library [19]. The non-linear geometry parameter (*NLGEOM) was included to deal with the large displacement analysis.

Typical finite element meshes for CFDST short columns are shown in Fig. 3. As shell elements are generally employed to discretise thin-walled tubes [8,13,16–18,23], the element S3 [19] has been utilised for the external stainless steel and the internal carbon steel tubes. S3 is a three-node triangular general-proposed shell finite membrane strains element. For the sandwiched concrete and the two cover plates, the 3D four-node linear tetrahedron solid elements C3D4 [19] were used. An approximate global size of 25 mm was used in the current modelling for the external and internal steel tubes and sandwiched concrete based on the mesh convergent study made by Wu [23] and Hassanein et al. [18].

Each cover plate was connected with both tubes by “Shell-to-Solid coupling” ensuring that the displacements and rotations of the connected elements to be kept the same in the whole loading process. The 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 to simulate the bond between either the stainless steel tube or the carbon steel tube and the sandwiched concrete. Both the stainless steel and carbon steel surfaces were chosen as slave surfaces whereas the sandwiched concrete surfaces were treated as master surfaces. The friction coefficient between carbon steel tube and the sandwiched concrete was taken as 0.4 as suggested by Hassanein et al. [18], while it was taken as 0.25 between the stainless steel tube and the sandwiched concrete [13].

The effect of initial imperfections on the strength of the CFSCT short columns was not considered in the FE modelling. This is because the strength reduction of the thin-walled hollow tubes is not significant owing to the delaying effect of core concrete on the tube buckling as discussed by Tao et al. [24].

Table 1
Details and FE results of circular CFDST short columns [31]

Column	$D \times t_e$ [mm]	$d \times t_i$ [mm]	L [mm]	f_{sye} [MPa]	f_{syi} [MPa]	$P_{u,FE}$ [kN]	$P_{u,Exp}$ [kN]		$\frac{P_{u,FE}}{P_{u,Exp}}$	
							Case (a)	Case (b)	Case (a)	Case (b)
CC2	180 × 3	48 × 3	540	275.9	396.1	1728	1790	1791	0.97	0.96
CC3	180 × 3	88 × 3	540	275.9	370.2	1570	1648	1650	0.95	0.95
CC4	180 × 3	140 × 3	540	275.9	342.0	1354	1358	1435	1.00	0.94
CC5	114 × 3	58 × 3	342	294.5	374.5	904	904	898	1.00	1.01
CC6	240 × 3	114 × 3	720	275.9	294.5	2386	2421	2460	0.99	0.97
CC7	300 × 3	165 × 3	900	275.9	320.5	3251	3331	3266	0.98	1.00
Mean									***0.98***	***0.97***
Coefficient of variation (COV)									***0.019***	***0.028***