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Analysis of circular concrete-filled double skin tubular slender columns with external stainless steel tubes

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ABSTRACT

This paper investigates the strength and behaviour of concrete-filled double skin steel tubular (CFDST) slender columns under axial compression. The lean duplex stainless steel material (EN 1.4162) which has recently gained significant attention is considered herein as the external jacket of such columns. Finite element (FE) analyses of several CFDST columns are conducted. Careful consideration is taken in the modelling for the concrete behaviour, for which both of the compressive and the tensile behaviours and the non-linear behaviour due to cracking are fully considered. The accuracy of the current FE models is ensured through the comparison with the existing columns in literature. A parametric study is then conducted to investigate the behaviour of such columns under different affecting factors; the slenderness ratio, the concrete confinement effect, the hollow ratio, the concrete compressive strength and the thickness ratio. The behavioural differences between intermediate length and very long CFDST columns are carefully addressed. Analytically obtained ultimate strengths are compared with design strengths calculated by European and American specifications. European design strength is found to give better predictions compared to the American specifications. However, it is shown that both strengths cannot be used in design because they overestimate the ultimate strengths and thereby do not satisfy the safety requirements. Therefore, a modification is suggested to the European design model which is shown to be able to estimate the compressive resistance of the CFDST columns more accurately than other methods.

1. Introduction

Steel–concrete composite columns have gained more widespread usage as load bearing constituents in construction. Therefore, considerable research efforts were devoted to investigate the concrete-filled steel tubular (CFST) columns; see Fig. 1(a). By using different rigorous analysis methods (see for example Refs. [1,2]), simplified design approaches have been developed for them. These design approaches were included in modern codes such as EC4 [3] and AISC [4]. To reduce the weight of the CFST columns without affecting the capacity against different loading cases, concrete-filled double skin steel tubular (CFDST) columns were proposed [5]. A CFDST column consists of two concentric steel cylinders with a concrete fill in-between them as can be seen in Fig. 1(b). The cavity inside the internal tube, however, provides a dry atmosphere for possible catering for facilities and utilities such as power cables, drainage pipes and telecommunication lines [5]. In recent times, CFDST columns have been studied extensively in literature [6–11] focusing mainly on *short columns with both carbon steel tubes*.

On the other hand, austenitic stainless steels were used in structural applications for many years as minor elements [12–14] due to their high initial cost. It was found that “nickel” represents a significant portion of the cost of the austenitic stainless steel (around 8–11% of its alloy composition). Consequently, high nickel prices have more recently led to a demand for lean duplexes with low nickel content, such as grade EN 1.4162. Grade EN 1.4162 contains a relatively low nickel content of about 1.5% of its alloy composition. Examples for the structural applications of lean duplex grade EN 1.4162 include the Likholefossen Bridge in Norway and the Siena Footbridge in Italy. Most design codes treat them in the same way as the austenitic stainless steels because most of the existing numerical and experimental results are for austenitic or duplex alloys [13]. On the other hand, the structural behaviour of stainless steel is different from that of the carbon; i.e., stainless steel has no definite yield strength and shows an early departure from linear elastic behaviour with strong strain hardening [12–15]. For carbon steel, the proportional limit is at least 70% of its yield point, but for stainless steel the proportional limit ranges, in average, from 36% to 60% of the yield strength [13,16,17].

The advantages of both the CFDST columns (shown above) and the stainless steel material (i.e., the aesthetic appearance, the high corrosion resistance, the smooth and uniform surface, the high fire resistance, the high ductility and impact resistance, the reuse and

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Nomenclature

Roman letters

A_{DS}	cross-sectional area of CFDST column
A_s, A_{si}	cross-sectional area of the internal carbon steel tube
A_{ss}, A_{se}	cross-sectional area of the external stainless steel tube
A_{sc}	cross-sectional area of the sandwiched concrete
D	diameter of external stainless steel tube in CFDST
d	diameter of internal carbon steel tube in CFDST
E_0	Young's modulus
E_s	modulus of elasticity of steel
E_c	modulus of elasticity of concrete
$(EI)_e$	effective elastic flexural stiffness of the CFDST columns
f_y	yield strength
f_{yi}, f_{sy}	yield strength of the internal carbon steel tube
f_u (σ_u)	ultimate strength of the carbon steel (stainless steel) material
f_t	tensile strength of concrete
f'_c	compressive strength of concrete cylinder (unconfined concrete strength)
$f'_{rp,ss}$	lateral confining pressure on the sandwiched concrete provided by the outer stainless steel tube
I_{DS}	moment of inertia of the CFDST section
KL, L_e	effective buckling length
$P_{ul,FE}$	ultimate axial strength of the column obtained from the FE analysis
P_s	strength of the column's cross-section
$P_{pl,Rd}$	plastic resistance to axial compression taking into account the concrete confinement
P_{cr}, P_e	elastic critical buckling load
P_{EC4}	ultimate axial capacity of CFST columns according to the EC [3]
$P_{EC4,\ mod}$	the modified EC4 formula for the ultimate axial capacity
P_{AISC}	ultimate axial capacity of the CFST columns according to the AISC [4]
$P_{EC4,cor}$	corrected design strength based on the buckling curves provided in the EC3 for stainless steels
t, t_e	thickness of external stainless steel tube in CFDST
t_i	thickness of internal carbon steel tube in CFDST
u_m	deflection at mid-height of CFDST columns

Greek letters

α	imperfection factor according to EC3 [37]
γ_c	strength reduction factor
γ_{ss}	factor used to account for the effect of strain hardening on the strength of stainless steel
γ_s	factor used to account for the effect of strain hardening on the strength of carbon steel
γ_{sc}	strength reduction factor accounting for the effects of the column size, the quality of concrete and the loading rates on the concrete compressive strength
ε_a	axial strain of CFDST column
ε_l	longitudinal strain
ε_{lc}	longitudinal strain at compression side
ε_h	hoop strain of the stainless steel tube in the compression zone captured at the mid-height section of the CFDST column
ε_y	yield strain of the stainless steel material
ε'_c	strain corresponding to the peak stress of the concrete (f'_c)
λ	column slenderness ratio
$\overline{\lambda}$	column slenderness parameter (relative slenderness)
$\sigma_{0.2}$	0.2% proof stress
χ'	hollow ratio of CFDST column
η_a, η_c	factors related to concrete confinement according to the EC4 [3]
χ	reduction factor for relative buckling mode in terms of the relevant relative slenderness calculated using European strut curves
ρ_s	ratio of the cross-sectional area of the steel tube to the concrete core

Abbreviations

CFDST	circular concrete-filled double skin tubular columns
CFST	circular concrete-filled tubular columns
CFSST	circular concrete-filled stainless steel tubular columns
HSC	high strength concrete
NSC	normal strength concrete
STW	strength-to-weight ratio of the CFDST column
UHSC	ultra-high strength concrete

recycling capability) encouraged Han et al. [18] and Hassanein et al. [19] to investigate the CFDST *short* columns with external stainless steel jackets. As the length of the column increases, a lateral displacement takes place at its mid-height. This lateral displacement has an adverse effect on the ultimate load of the column because it generates a mid-height secondary moment [20]. As the length of the column is further increased, the secondary bending moment increases considerably. This forces the column to fail by bending rather than by compression leading to an instability problem. Hence, the behaviour of slender columns is different from that of short columns. Despite that, the experimental results of circular CFDST *slender* columns with carbon steel tubes are limited in literature with only two replicate columns examined by Tao et al. [21]. It is well known that columns with slenderness ratios (λ) greater than 22 are usually considered as slender columns in design codes. Therefore, this paper is providing new results dealing with the nonlinear analysis, behaviour and design of circular CFDST slender columns with external lean duplex stainless steel tubes. This is made by using the general purpose finite element (FE) package ABAQUS [22]. In this paper, CFDST slender columns are grouped into *intermediate length* columns (i.e., columns failing inelastically) and *very long* columns (i.e., columns failing elastically).

2. Research significance

As seen above, circular CFDST slender columns with external lean duplex stainless steel tubes have never been investigated in literature. On this basis, it is necessary to undertake comprehensive investigations to understand the compressive behaviour of such columns, so that the appropriate design strength can be identified. Accordingly, the contribution of the current paper can be summarised as

(1) Large-scale columns relative to the available experiments of the circular CFDST slender columns with external carbon steel tubes [21] were examined; see Table 1.
(2) The lean duplex stainless steel material was recommended to reduce the cost of such columns compared to other previously used stainless steel materials [18].