Thin-Walled Structures 115 (2017) 336–348

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Overall buckling behaviour of circular concrete-filled dual steel tubular columns with stainless steel external tubes

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ARTICLE INFO

Keywords:
Concrete-filled tubes
Dual steel tubes
Finite element analysis
Lean duplex
Stainless steel
Slender column
Axial compression
Ultimate strength
Design

ABSTRACT

Recently, a short composite column consisting of dual steel tubes (external and internal stainless and carbon steel tubes, respectively) with concrete filled in the entire tubular section has been introduced. This column, called as the concrete-filled dual steel tubular (CFDST) column, proved that a lower cost as well as weight can be achieved compared with the concrete-filled stainless steel tubular column (CFSST). This is mainly attributed to the increased strength of the concrete fill, inside the internal tube, that is surrounded by both the external and internal steel tubes. Based on the fact that the columns are generally slender in practice, this paper investigates numerically, by means of finite element (FE) analyses, the axial compressive behaviour of the CFDST slender columns, which has been rarely investigated in literature. The external tubes are currently made of the lean duplex stainless steel material recently attracted the structural community because of its relatively lower cost. The FE models carefully consider the compressive and tensile nonlinear behaviour of the concrete. The FE models are verified for their different material models. This is followed by examining the accurate overall buckling behaviour of the slender columns. This has been made through FE comparisons with tested columns of different cross-section types existing in literature. The fundamental behaviour of the CFDST slender columns under the effect of the slenderness ratio, the concrete confinement effect and the concrete compressive strength is then investigated. The study additionally addresses the differences in behaviour between the intermediate length and long CFDST columns. Moreover, the comparison between the design strengths calculated by Eurocode 4 from one side and the FE and experimental ultimate strengths from the other side shows generally that Eurocode 4 gives unsafe predictions. Accordingly, a modified European design model is suggested at the end to predict accurately the resistance of the CFDST slender columns under axial compression.

1. Introduction

A composite column is a type of column that incorporates two different materials or elements – in this paper the structural steel and concrete. The concrete encased structural steel shapes and the concrete-filled steel sections are the main cross-sectional types of the composite columns [1–8]. Historically, the concrete encasement in the former column type has only been considered as fire and corrosion protection for the steel. In recent years, lateral and longitudinal reinforcements have been added to the concrete encasement, and the strength resulting from the interaction between the embedded steel tube and the surrounding concrete has been used for structural purposes. Alternatively, concrete-filled steel tubular (CFST) columns result from pouring the concrete into the hollow steel tubes. Compared with the concrete encased structural steel columns, the steel tubes act as a formwork for pouring the in situ concrete and thus it eliminates the need of additional formwork and leads to a fast track construction [1–8]. Also, it does not need additional reinforcement. Hence, CFST columns have been extensively used as columns in both medium and high rise buildings [2,3], bridge and large span buildings [2] and as piers [2,9,10].

Both circular and rectangular (including square) CFST columns are the most shapes used in modern construction. Examples of circular- and square-shaped CFST columns [11] are those used in the new VDEh-building in Dusseldorf, Germany, and the University of Winnipeg, Canada, respectively. Circular CFST columns (Fig. 1(a)) own more resistance and ductility compared with the rectangular columns, while

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Abbreviations: CFDST, Concrete-filled dual steel tubular column; CFSST, Concrete-filled stainless steel tubular column; FE, Finite element; CFST, Concrete-filled steel tubular column; RP, Reference point; *STW*, Strength-to-weight ratio of the column; CCR, Concrete contribution ratio

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http://dx.doi.org/10.1016/j.tws.2017.01.035
Received 22 July 2016; Received in revised form 18 January 2017; Accepted 18 January 2017
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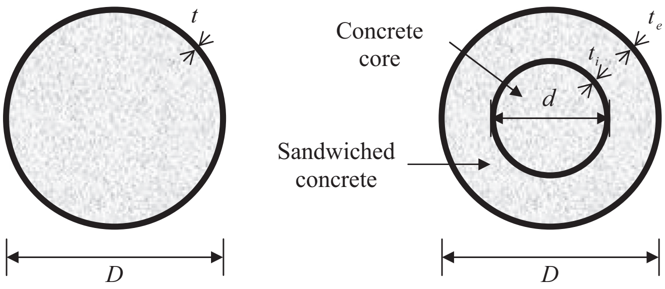
Nomenclature

Symbols are ordered by appearance in the paper

D	Diameter of the external stainless steel tube
d	Diameter of the internal carbon steel tube
t_e	Thickness of the external tube
t_i	Thickness of the internal tube
P_{ul}	The column strength
λ	The slenderness ratio of the column
L_e	Effective buckling length of the column
I_{DS}	Moment of inertia of the CFDST section
A_{DS}	Cross-sectional area of the CFDST column
λ_r	The limiting slenderness ratio differentiating between intermediate length and long CFDST columns
f_y, $f_{sy,i}$	Yield stress of the carbon steel tube
f'_c	The unconfined concrete cylindrical compressive strength
P_{uo}	The short column strength
λ_p	The limiting slenderness ratio delineating between short and intermediate length CFDST columns
L	Physical length of the column
$\sigma_{0.2}$	0.2% proof stress of the stainless steel material
E_{ss}	Young's modulus of the stainless steel tube
f_u	Ultimate strength of the carbon steel tube
E_s	Young's modulus of the carbon steel tube
P	Stress of the concrete material
ε_h	Strain of the concrete material
K	The ratio of the second stress invariant on the tensile meridian to that on the compressive meridian, which is used in defining the "Concrete Damaged Plasticity" model in the FE models using Abaqus
$f'_{cc,\mathrm{mod}}$	The confined concrete strength of the concrete core
$f'_{rp,s}$	Lateral confining pressure provided by the carbon steel tube on the concrete core
k	Confinement amplification factor for the concrete strength taken as 4.1
$f'_{rp,ss}$	Lateral confining pressure provided by the stainless steel tube on the sandwiched concrete
β_c	A factor reflecting the confinement effect on the concrete ductility
f'_{cc}	Confined concrete strength
f_t	The tensile strength of concrete
γ_c	A strength reduction factor for the concrete strength
ε_{lc}	Strain at the confined concrete strength (f'_{cc})
u_m	Mid-height deflection of the columns
$P_{ul,Exp}$	Column strength predicted by the experimental testing
$P_{ul,FE}$	Column strength predicted by the current FE modelling
P_{cr}	Elastic critical normal force for the flexural buckling mode
$P_{pl,Rd}$	Plastic resistance to compression
A_{sc}	Cross-sectional area of the sandwiched concrete
A_{cc}	Cross-sectional area of the concrete core
I_{ss}	Moment of inertia of the outer stainless steel tube
I_s	Moment of inertia of the inner carbon steel tube
I_{sc}	Moment of inertia of the sandwiched concrete
I_{cc}	Moment of inertia of the concrete core
E_{sc}	Young's modulus of the sandwiched concrete
E_{cc}	Young's modulus of the concrete core
ε_a	Average strain calculated as the end shortening divided by the column length
ε_l	Longitudinal strain value measured at the external surfaces of the tubes at the mid-height sections
$\bar{\lambda}$	Non-dimensional slenderness, given as the square root of the characteristic value of the plastic resistance to compression to the elastic critical normal force for the flexural buckling mode
γ_{ss}	Factor used to account for the effect of strain hardening on the strength of stainless steel tube
γ_s	Factor used to account for the effect of strain hardening on the strength of carbon steel tube
P_s	Cross-section strength suggested by Hassanein, et al. [29]
ε_h	The hoop strains of the stainless steel tube in the compression zone
ε_{lc}	The longitudinal strains of the stainless steel tube in the compression zone
$f'_{c,sc}$	The unconfined concrete strength of the sandwiched concrete
$f'_{c,cc}$	The unconfined concrete strength of the concrete core
P	Axial load applied to the column
χ	Reduction factor for the relevant buckling curve
ϕ	Global initial sway imperfection
α	An imperfection factor corresponding to the appropriate flexural buckling curve
$\bar{\lambda}_o$	The limiting non-dimensional slenderness of the member to avoid flexural buckling (i.e. $\chi = 1.0$)
$P_{ul,EC4}$	Design strength according to EC4 [34]
$P_{ul,EC4,m}$	Currently modified EC4 strength
P_{Design}	Original ($P_{ul,EC4}$) or modified ($P_{ul,EC4,m}$) EC4 design strength
$f_{sy,e}$	Yield stress of the external carbon steel tube of the columns tested by Romero, et al. [30]

the ease of connections makes the latter columns more popular in framed structures. Accordingly, circular and rectangular CFST columns were extensively investigated in literature [2,8]. However, the choice of the shape of the CFST column for a specific project not only depends on the column efficiency, material availability, cost and construction methods, but also on architectural and aesthetic criteria; see for example Ref. [4–7]. Accordingly, the concrete-filled stainless steel tubular (CFSST) columns have recently been suggested because they mix the advantages of both the CFST columns and the stainless steel material with its architectural and aesthetical appearance [12–21]. In the past, using structural members made of stainless steels in conventional constructions was limited because of their high initial material costs besides the lack of knowledge about their properties among designers and architects [12–15]. However, recently, the wide section availability and the introduction of different design manuals have contributed in spreading the structural use of the stainless steels globally in conventional structures. The durability of the stainless steels and their higher fire resistance are additional factors that increased their applications in construction in comparison with carbon steels [12–15].



(a) CFST or CFSST (b) CFDST

Fig. 1. Typical cross-sections of circular concrete-filled tubular columns.

Different buckling behaviours of CFST columns have comprehensively been studied for decades, with more emphasis has been given to

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