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Analytical behavior of CFDST stub columns with external stainless steel tubes under axial compression

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ABSTRACT

Concrete-filled double skin steel tubular (CFDST) stub columns with external stainless steel and internal carbon steel tubes can be considered as new types of composite members and expected to combine the advantages of all three kinds of materials. This paper presents non-linear finite element (FE) analysis and design of circular and square CFDST stub columns with external stainless steel under axial compression. FE models are developed, where non-linear material property of stainless steel is considered, and verified through comparisons with experiments in terms of failure modes, load-deformation histories and ultimate strength. Behaviors of stainless steel composite columns are compared with that of columns with both carbon steel tubes. Parametric studies are conducted to investigate the influence of the outer stainless steel tube strength, concrete strength, inner carbon steel tube strength and hollow ratio on structural behavior of axially loaded columns in terms of loading and interaction performance.

1. Introduction

Concrete-filled double skin steel tubular (CFDST) sections, consisting of two concentric steel tubes and concrete-filled in between, have been gaining increasing usage in a variety of engineering practices owing to their load-carrying efficiency and construction cost-effectiveness. Structural behaviors of CFDST sections under axial compressions have been investigated by researchers, such as Zhao and Han [1], Han et al. [2,3], Romero et al. [4], Ren et al. [5], Patel et al. [6], Uenaka et al. [7], Tao and Han [8], Wan and Zha [9] and Li et al. [10]. It is shown that CFDST members provide better structural performance over either conventional concrete-filled steel or double skin hollow steel sections. Compressive strength and stiffness have been enhanced with minimum increase of self-weights. Buckling modes of both tubes have been improved due to existence of concrete infill. Double skin tubes can act as formworks for concrete to reduce construction cost.

In recent years, stainless steel has been increasingly used in engineering applications [11,12]. This is attributed to its unique combination of durability, anti-corrosion, fire resistance, maintenance and mechanical property. Owing to its benefits, it is evident that it plays a significant role in further design of structures, especially when engineers and architects become more aware of the need for life cycle costing [13]. However, extensive applications of stainless steel have been significantly inhibited by its initial high cost. With a cost of about 3–5 times that of mild carbon steel, it is noticeable that more efforts should be made to take full advantages of its properties [14].

One promising means to effectively utilize stainless steel with minimum cost increase is to propose an innovative type of composite section, i.e., a CFDST columns with external stainless steel sections have advantages of resistance to corrosions and esthetics. The composite sections consist of one outer stainless steel tube, one inner carbon steel tube and the void between them filled with concrete, as shown in Fig. 1. Hollow ratio χ has been defined through Eq. (1)

$$\chi = \frac{d}{D - 2t_{so}} \tag{1}$$

in which parameters are illustrated in Fig. 1. It is expected to simultaneously make the optimum use of all three types of materials and have advantages of high bending stiffness inherited from CFDST members [15].

In the past, extensive studies have been carried out on the behaviors of CFDST columns with carbon steel sections, while investigations on CFDST columns with external stainless steel tubes are still limited. Han et al. [15] conducted experimental tests on CFDST stub columns with outer stainless steel tubes and inner carbon steel tubes under axial compression. Typical failure modes are observed outward local buckling on the outer sections and the inward local buckling on the inner ones. Due to existence of concrete infill, load-displacement histories decline in ductile manners. Wang et al. [16] carried out tests on CFDST stub columns with stainless steel outer tubes and high strength steel inner tubes. FE analyses using general purpose finite element (FE)

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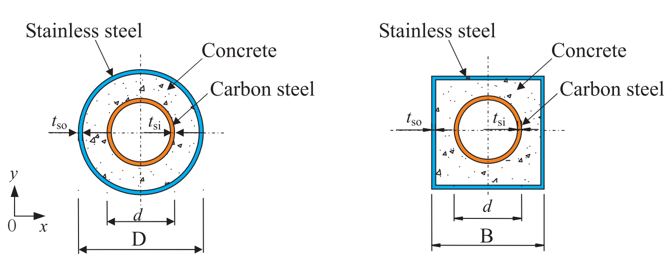
Nomenclature

A_c	Cross-sectional area of concrete
A_{ce}	Nominal cross-sectional area of concrete
A_{sco}	Cross-sectional area of the outer stainless steel tube and the sandwich concrete($=A_c + A_{so}$)
A_{si}	Cross-sectional area of inner carbon steel tube
A_{so}	Cross-sectional area of outer stainless steel tube
b	Outer minor axis width of inner round-end rectangular or elliptical carbon steel tube
B	Outer minor axis width of outer round-end rectangular or elliptical stainless steel tube
CFST	Concrete-filled steel tubes
CFDST	Concrete-filled double skin steel tubes
d	Outer diameter of inner circular carbon steel tube, outer major axis length of inner round-end rectangular or elliptical carbon steel tube
D	Outer diameter or width of outer circular or square stainless steel tube, outer major axis length of outer round-end rectangular or elliptical stainless steel tube
$E_{0.2}$	Modulus of stainless steel at 0.2% proof stress
E_c	Elastic modulus of concrete
E_o	Elastic modulus of stainless steel
f_{b0}	Concrete compressive strength under biaxial loading
f_c'	Concrete cylinder strength
f_{ck}	Characteristic concrete strength ($f_{ck}=0.67f_{cu}$ for normal strength concrete)
f_{cu}	Concrete cube strength
f_{syi}	Yield stress of inner carbon steel tube
f_{syo}	Yield stress of outer stainless steel tube
f_y	Yield stress of steel
N_{FE}	Observed ultimate strength of column in FE simulation
N_u	Measured ultimate strength of column
p	Interaction stress
p_u	Interaction stress at ultimate strength
t	Wall thickness of steel tube
t_{so}	Wall thickness of outer steel tube
t_{si}	Wall thickness of inner steel tube
α	Steel ratio ($=A_{so}/A_c$)
α_n	Nominal steel ratio ($=A_{so}/A_{ce}$)
ε_{cu}	Longitudinal strain at ultimate strength
$\varepsilon_{cu,cs}$	Longitudinal strain at ultimate strength for columns with outer carbon steel tubes
$\varepsilon_{cu,ss}$	Longitudinal strain at ultimate strength for columns with outer stainless steel tubes
χ	Hollow ratio, given by d/(D-2t_{so})
ξ	Nominal confinement factor ($=A_{so}f_{syo}/A_{ce}f_{ck}$)
ψ	Dilation angle of concrete
e	Flow potential eccentricity of concrete
γ_c	Poisson's ratio of concrete

package ABAQUS have been conducted by Hassanein et al. [17,18] and Hassanein and Kharoob [19] to study the nonlinear response of CFDST stub and long columns with external stainless steel tubes, respectively. However, features of stainless steel are not fully reflected due to carbon steel material models are used instead and only circular sections have been considered in the analyses [17,19]. The existing international design guidance including ACI-318, EN 1994–1-1 and GB 50936 may provide conservative predictions on cross-sectional strength of CFDST stub columns with external stainless steel tubes due to neglects of strain-hardening properties of stainless steel [13,15,16]. Existing literature indicates that more investigations are needed to capture structural behaviors of CFDST stub columns with outer stainless steel tubes under axial compressions. Only by doing so can rationally understand the composite actions between constituent components.

This paper presents the FE simulation of CFDST stub columns with outer stainless steel tubes (circular or square) and inner normal carbon steel tubes (circular) under axial compressions using ABAQUS, where nonlinear stress-strain model of stainless steel is adopted. The composite actions between the consistent components have been carefully investigated in the FE models. The FE results are verified against the test data reported by Han et al. [15]. Circular and square columns are observed with distinct structural performance in terms of loading and interaction histories. An extensive parametric study is conducted to investigate the effects of stainless steel strength, concrete strength and hollow ratio on column behaviors.



(a) Circular (b) Square

Fig. 1. Schematic view of CFDST with external stainless steel sections.

2. FE modeling and verification

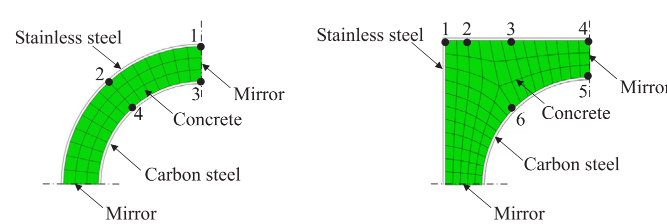
2.1. Introduction

A numerical model using ABAQUS [20] has been developed in conjunction with the experimental studies presented by Han et al. [15]. The FE modeling aims to firstly replicate the full experimental loading-displacement histories, and to generate supplement data for parametric studies thereafter.

2.2. Element, boundary condition and method of loading

Four-noded shell elements with reduced integration (S4R) and eight-noded solid elements (C3D8R) are selected to model steel tubes and concrete infill respectively. Mesh convergence studies are conducted to determine appropriate mesh sizes to achieve reliable modeling with reasonable computational consumptions. According to the mesh convergence studies, element size over the cross-section is taken as D/20 for a circular section or B/20 for a rectangular section, where D and B are defined in Fig. 1. Tao et al. [21] Thai et al. [22] and Hassanein et al. [17] gave similar findings. The numerical meshes for typical members with outer circular and square sections are given in Fig. 2.

Due to symmetry of loading and geometry, only one eighth of a column is modeled as shown in Fig. 3, where the boundary conditions are presented. Displacement is applied at the top of the end plate, stiffness of which is defined infinite to simulate load. Both tubes and



(a) Circular (b) Square

Fig. 2. Schematic view of mesh configurations.