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Behaviour of axially loaded circular concrete-filled bimetallic stainless-carbon steel tubular short columns

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ABSTRACT

Circular concrete-filled bimetallic steel tubular (CFBST) columns are considered as a new type of structural composite members. An experimental investigation has recently been conducted on the performance of these concentrically-loaded circular CFBST stub columns. However, the fundamental response of these columns under axial compression has not been investigated numerically. Therefore, finite element (FE) analysis of axially loaded circular CFBST stub columns is discussed in this paper. An existing concrete constitutive model with the confinement mechanism is modified for the current CFBST columns. The nonlinear stress-strain relationship of stainless steel is utilised in the FE analysis. The current FE model accounts for the influences of initial imperfections, geometric and material nonlinearities. The ultimate strengths and load-strain responses predicted from the analysis are validated against the available test results and observations in literature. The comparisons indicate that the FE model accurately estimates both the ultimate strengths and load-strain characteristics of the concentrically-loaded circular CFBST stub columns. The developed model is then utilised to investigate the effects of the geometric configurations and material properties on the load-strain characteristics, ultimate capacity, ductility and steel contribution ratio of circular CFBST stub columns. The existing design recommendations for conventional circular concrete-filled steel tubular columns are then checked for computing the peak load of the circular CFBST stub columns, and the best strength predictor with the least deviation compared with the experimental values is recommended at the end for design.

1. Introduction

Conventional concrete-filled steel tubular (CFST) columns are utilised for the efficient construction of offshore structures [1]. The marine environments induce corrosion in the external carbon steel tubes in the conventional CFST columns. This corrosion reduces the strength and ductility of conventional composite columns. The barrier to the corrosion agents can be created by replacing the conventional carbon steel tubes with stainless steel ones. However, the initial high costs of the stainless steel greatly reduce its applications in the constructional industry. Therefore, the economical application of the stainless steel can be achieved by using bimetallic tubes filled with concrete. A typical circular concrete-filled bimetallic steel tubular (CFBST) column section is illustrated in Fig. 1. As can be seen, the bimetallic steel tube consists of external stainless steel tube with an inner layer made of carbon steel component. The overall costs of CFBST columns are expected to be lower than those of the conventional CFST columns in the long term, given that maintenance is not required for CFBST columns with their high corrosion resistance of the stainless steel envelopes [2]. The external layer of stainless steel, besides its corrosion and chemical resistances, offers many benefits including high strength, axial stiffness, strain ductility and extended hardening in compression.

The nonlinear characteristics of conventional CFST columns have been experimentally studied by many researchers [3–9]. These studies indicate that the confinement mechanism increases the strain ductility and the compressive strength of the conventional composite section. On the other hand, the stainless steel was recently investigated as an alternative to carbon steel in conventional CFST columns. The experimental studies for predicting the structural performance were conducted for concrete-filled

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Nomenclature

A_c	Cross-sectional area of concrete section
A_{sc}	Cross-sectional area of carbon steel section
A_{ss}	Cross-sectional area of stainless steel section
A_t	Cross-sectional area of CFBST column section
D	Outer diameter of composite column
D_c	Concrete diameter
E	Young's modulus of materials
E_0	Young's modulus of the stainless steel
$E_{0.2}$	Tangent modulus at the 0.2% proof stress
E_c	Young's modulus of concrete
E_{cm}	Secant modulus of elasticity of concrete
E_s	Young's modulus of carbon steel
$(EI)_{eff}$	Effective flexural stiffness
f'_c	Cylinder strength of concrete
f'_{cc}	Confined concrete ultimate strength
f_{rp}	Confining pressure applied by bimetallic steel tube
$f_{rp.sc}$	Confining pressure applied by carbon steel tube
$f_{rp.ss}$	Confining pressure applied by stainless steel tube
f_y	Yield strength of carbon steel
f_u	Ultimate strength of carbon steel
I_c	Second moment of area of the concrete core
I_{sc}	Second moment of area of the carbon steel tube
I_{ss}	Second moment of area of the stainless steel tube
k_1	Constant which is taken as 4.1
k_2	Constant which is taken as 20.5
L	Length of column
n	Nonlinearity index
N_{cr}	Elastic critical normal force
$N_{\mathrm{pl.Rk}}$	Plastic resistance of the composite section
P_{su}	Load carried by hollow bimetallic tubular column
P_u	Ultimate load of CFBST columns
$P_{u.\mathrm{ACI}}$	Ultimate axial load obtained from ACI design code
$P_{u.\mathrm{cal}}$	Ultimate axial load obtained from the design model
$P_{u.\mathrm{DBJ}}$	Ultimate axial load predicted by the Chinese code DBJ/T13-51-2010
$P_{u.\mathrm{EC4}}$	Ultimate strength obtained from Eurocode 4
$P_{u.\mathrm{exp}}$	Experimental ultimate axial load
$P_{u.\mathrm{FE}}$	Ultimate axial load predicted by the FE model
PI_{ad}	Strain ductility index
t	Thickness of the bimetallic steel tube
t_{sc}	Thickness of the carbon steel tube
t_{ss}	Thickness of the stainless steel tube
$\nu_{e.c}$	Poisson's ratio of carbon steel tubular column filled with concrete
$\nu_{e.s}$	Poisson's ratio of stainless steel tubular column filled with concrete
$\nu_{s.c}$	Poisson's ratio of carbon steel tubular section
$\nu_{s.s}$	Poisson's ratio of stainless steel tubular section
β_{cc}	Factor of concrete stress-strain curve in post-peak range
$\varepsilon_{0.2}$	Strain at the 0.2% proof stress
ε_c	Axial strain in the concrete component
ε'_c	Ultimate strain of unconfined concrete
ε'_{cc}	Confined concrete ultimate strain
ε_{nom}	Nominal strain
ε_{sc}	Axial strain in the carbon steel
ε_{ss}	Axial strain in the stainless steel tube
ε_{su}	Ultimate strain of carbon steel
ε_{ssu}	Ultimate strain of the stainless steel
ε_t	Hardening strain of carbon steel
$\varepsilon_{u.75}$	Strain when the load attains 75% of the peak load in the descending branch
ε_u	Ultimate strain of composite columns
$\varepsilon_{u.90}$	Strain when the load attains 90% of the peak load in the ascending branch
ε^p_{true}	True plastic strain
ε_y	Strain at the yield strength of carbon steel
γ_c	Strength reduction factor for concrete
γ_{sc}	Strength constant for carbon steel tube
γ_{ss}	Strength constant for stainless steel tube
η_a, η_c	Factors related to the confinement of concrete
λ	Material constant for concrete stress-strain curve
$\bar{\lambda}$	Relative slenderness
$\sigma_{0.01}$	0.01% proof strength
$\sigma_{0.2}$	0.2% proof strength
σ_c	Axial stress in the concrete component
σ_{nom}	Nominal stress
σ_{sc}	Axial stress in the carbon steel
σ_{ss}	Axial stress in the stainless steel tube
σ_{ssu}	Ultimate stress of the stainless steel
σ_{true}	True stress
ξ	Confinement factor

stainless steel tubular (CFSST) columns [10–15]. The peak loads and strain ductility of the CFSST columns were found to be higher than those of conventional CFST columns. Unexpectedly, although the CFSST columns offer the above mentioned structural benefits, current international standards in Australia (AS 5100.6-2004 [16]), America (AISC 360-05 [17]), Europe (Eurocode 4 [18]) and China (DBJ/T [19]) do not include any recommendations for the design of such columns.

Liew et al. [20] reported the design of conventional CFST columns with high strength materials. These materials offer various structural benefits in high-rise composite construction such as decreasing the cross-sectional size and subsequently increasing the floor area, but they reduce the ductility of these columns. However, experimental studies on circular CFBST columns with high strength materials have not been investigated yet. Only Ye et al. [2] tested ten axially loaded circular CFBST stub columns with normal strength materials. The test results reported by Ye et al. [2] indicated that the CFBST columns fail by the shear failure of the concrete component and the local buckling of the bimetallic tubes. In addition, CFBST short columns had higher peak strengths compared with the total strength of their individual components. Furthermore, it was found that the strain at the column's ultimate strength is much higher than the peak strain of the individual components.

Extensive numerical investigations were performed in the past to study the structural response of conventional CFST columns [21–26]. However, no numerical model was developed for analysing the fundamental performance of concentrically loaded circular CFBST columns. Ellobody and Young [27], Tao et al. [28], Hassanein et al. [29] and Patel et al. [30] conducted numerical studies on the structural behaviour of CFSST stub columns subjected to axial loading. Their numerical models considered the influences of the confinement mechanism and the extended strain hardening of the stainless steel. The numerical models proposed by these researchers were found to be accurate and computationally efficient.

Literature review indicates that no numerical analysis has been presented for simulating the compressive performance of the CFBST stub columns, as presented in this paper. The finite element (FE) model presented in this paper was developed by using the general-purpose FE code ABAQUS 6.13 [31]. The proposed model considers the influences of the confinement mechanism, high strength materials and stainless steel strain hardening. Its accuracy is verified by comparing the obtained predictions with the existing test results of the circular CFBST stub columns [2]. A parametric