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A theoretical axial stress-strain model for circular concrete-filled-steel-tube columns

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ABSTRACT

Concrete-filled-steel-tube (CFST) columns are widely adopted in many structures nowadays attributed to the superior behaviour developed by the composite action. However, the composite action cannot be fully developed because of different dilation properties of steel tube and concrete in the elastic stage. Moreover, due to the inelastic outward buckling of steel tube, CFST columns may suffer serious degradation. To overcome these problems, external confinement, such as rings, ties, spirals and FRP wraps have been studied recently and proven experimentally to have potential in improving the uni-axial behaviour of CFST columns. In this paper, an experimental database containing 422 uni-axial compression test results of unconfined and externally confined CFST columns has been assembled. In addition, a theoretical model has been proposed for predicting the uni-axial behaviour of circular CFST columns. This model consists of mainly three components: (1) Constitutive model of confined concrete modified from Attard and Setunge's actively confined concrete model. (2) Constitutive model of steel tube under complex stress-state using Prandtl-Reuss theory. (3) The interaction among external confinement, steel tube and core concrete based on new a hoop strain equation. The validity of the proposed model has been verified by comparing the predicted results with the experimental database.

1. Introduction

Concrete-filled-steel-tube (CFST) column, which consists of a hollow-steel-tube (HST) column in-filled with concrete, is widely adopted in many structures nowadays attributed to the superior behaviour by the composite action [1–3]. In CFST columns, due to the supporting effect provided by the core concrete, the inward buckling of steel tube can be prevented, resulting in higher buckling resistance [4,5]. Moreover, the steel tube can act as both longitudinal and transverse reinforcement, which provides both axial resistance and confining pressure. The uniform confining pressure can improve the strength and ductility of core concrete much more effectively than stirrups in traditional reinforced concrete columns [3]. Besides, it saves construction materials and shortens construction cycle time because the steel tube can serve as permanent formwork [6]. Despite the above advantages, CFST columns have the following drawbacks. During the initial elastic stage under compression, the confining pressure may become negative (i.e. hoop compressive stress) due to the different dilation of steel tube and concrete [7,8]. This will reduce the strength, elastic stiffness and ductility of CFST columns [9,10]. The confining pressure will be activated only when the micro-cracking of concrete starts to form and the expansion of concrete exceeds that of steel tube. On the other hand, degradation of confining pressure, strength and ductility will occur beyond the elastic stage due to the inelastic outward buckling of steel tube. These problems are more prominent when thin-walled steel tube with high-strength-concrete (HSC) is adopted, as reported by a lot of research studies [11–13].

To overcome the deficiencies and fully utilise the potential of composite action, various types of external confinement have been proposed for circular CFST columns: rings [7,10,14–16], ties [9,14], spirals [17] and FRP wraps [11,18–23]. In confined circular CFST columns, attributable to the additional confining pressure provided by additional confinement, the steel–concrete interface bonding has been improved and the inelastic outward buckling of steel tube has been prevented or at least delayed, resulting in superior uni-axial behaviour of CFST columns.

Although previous studies have demonstrated the beneficial effects by adopting external confinement, limited theoretical models have been proposed for predicting the true structural behaviour of confined CFST columns. Several analytical studies have been

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Nomenclature

ΔR	virtual displacement	f_{ccp}	confined peak concrete stress
ε_{cc}	strain corresponding to confined peak concrete strength	f_{cu}	unconfined concrete cube strength
ε_{co}	strain corresponding to unconfined peak concrete strength	f_r	total confining stress
$\varepsilon_{s\theta}$	hoop strain of the steel tube	f_{rE}	confining stress of external confinement
ε_{sr}	radial strain of the steel tube	f_{rS}	confining stress of steel tubes
ε_{ssE}	hoop strain of external confinement	F_c	axial load of confined concrete
ε_{sz}	axial strain of the steel tube	F_s	axial load of steel tube
σ_E	stress provided by external confinement	F_t	axial load of CFST column
$\sigma_{s\theta}$	hoop stress provided by the steel tube	G	shear modulus of steel tube
σ_{sr}	radial stress provided by the steel tube	H	height of the steel tube
σ_{sut}	ultimate tensile stress of the steel tube	HSC	high-strength concrete
σ_{ssE}	yield stress of external confinement	HSCFST	high-strength concrete-filled-steel-tube
σ_{sy}	uni-axial yield stress of the steel tube	HST	hollow steel tube
$\sigma_{sy,b}$	elastic buckling stress of steel tube	i	increment number
σ_{syc}	compressive yield stress of the steel tube	K	bulk modulus of steel tube
σ_{syt}	tensile yield stress of the steel tube	LS	parameter reflecting the effect of external confinement
σ_{sz}	axial stress of the steel tube	LVDT	linear variable differential transducer
v_s	Poisson's ratio of steel tube	m	parameter considering the effect of concrete grade
ω	hardening parameter	n	number of external confinement
A_c	contact concrete area	N_{exp}	ultimate strength
A_s	contact steel area	NSC	normal-strength concrete
CFST	concrete-filled-steel tube	NSCFST	normal-strength concrete-filled-steel-tube
d	diameter of the rings	R	radius of internal steel tube
D_o	outer diameter of the steel tubes	S	spacing of the rings
E_c	elastic modulus of concrete	S_θ	deviatoric stress in hoop direction
E_s	elastic modulus of steel tubes	S_r	deviatoric stress in radial direction
E_{ssE}	elastic modulus of external confinement	S_z	deviatoric stress in axial direction
f_c'	unconfined concrete cylinder strength	t	thickness of the steel tube
f_{cc}	confined concrete stress	t_{frp}	thickness of FRP wrap
		UHSCFST	ultra-high-strength concrete-filled-steel-tube

developed for unconfined CFST columns [18,24–32]. A brief overview of the previously proposed models is given herein. Most of the studies [24–30] were based on the assumption that the confining pressure provided by the steel tube was constant throughout the loading history. With this assumption, the actively confine concrete model could be directly applied with a certain confining pressure [33–35]. However, it is obvious that the core concrete is subjected to continuously changing confining pressure during uni-axial compression [11,32]. Thus, the assumption with constant confining pressure would result in significant error, especially for high-strength steel tube and CFST columns with external confinement. The model of Han et al. [31] was derived based on the direct interpretation and regression analysis from test results and the accuracy of this model depends on the versatility of the database and the representation of the chosen parameters. Moreover, Han et al. [31] did not consider the complexity of the stress-state of steel tube in which the hoop stress varies continuously. These are also the drawbacks in most other models. In the model proposed by Johansson [32], the validity of the volumetric strain model for concrete was questionable [36]. Though the model of Teng et al. [18] could predict the behaviour of CFST columns filled with normal-strength concrete (NSC) well, the validity of this model in high-strength concrete (HSC) is questionable. Moreover, in this model, the steel tube was assumed to be in plane stress state. This assumption is reasonable for CFST columns with relatively thin-walled steel tube. However, to confine HSC, thicker steel tube was expected [7]. Thus, three-dimensional stress-strain relationship of steel tube should be used when dealing with thicker steel tube.

In order to predict the structural behaviour of confined CFST columns well, accurate equations for predicting the behaviour of confined concrete, steel tube and steel-concrete interaction are pre-requisite. By adopting the path-independence assumption [18,32,37,38], the behaviour of confined concrete could be modelled based on a model for actively confined concrete [35,39] by continuously updating the confining pressure. The steel tube could be modelled as linearly-elastic-perfectly-plastic material: Generalized Hooke's Law was applied to the linearly elastic part and Prandtl-Reuss theory to the perfectly-plastic part. By introducing von Mises' failure criterion, three dimensional stress-strain behaviour of steel tube could be simulated. The steel-concrete interaction could be evaluated using free body diagram or virtual work principle for confined CFST columns.

In this paper, an experimental database containing 422 test results of unconfined and externally confined CFST columns is presented. Then, the analytical modelling of confined CFST columns is introduced: (1) The new hoop strain equation is discussed. (2) The behaviour of confined concrete is described. (3) Modelling of steel tube, additional confinement and the confining mechanism of confined CFST columns are clearly interpreted. (4) The generation of axial stress-strain curves is explained. Finally, the predicted results using the analytical model are compared with the experimental database and close agreements have been obtained.

2. Experimental database

In this paper, an experimental database of unconfined and externally confined CFST columns, which includes the test results of the authors' previous research [7,9,10,14–17,40] and other researchers' studies [2,11,12,24,26,32,41–61], is employed herein. To ensure the reliability and consistency of the database, the selection criteria are listed below: (1) Only monotonic uni-axial