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Strength, stiffness and ductility of concrete-filled steel columns under axial compression

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ABSTRACT

Extensive experimental and theoretical studies have been conducted on the compressive strength of concrete-filled steel tubular (CFST) columns, but little attention has been paid to their compressive stiffness and deformation capacity. Despite this, strength prediction approaches in existing design codes still have various limitations. A finite element model, which was previously proposed by the authors and verified using a large amount of experimental data, is used in this paper to generate simulation data covering a wide range of parameters for circular and rectangular CFST stub columns under axial compression. Regression analysis is conducted to propose simplified models to predict the compressive strength, the compressive stiffness, and the compressive strain corresponding to the compressive strength (ductility) for the composite columns. Based on the new strength prediction model, the capacity reduction factors for the steel and concrete materials are recalibrated to achieve a target reliability index of 3.04 when considering resistance effect only.

1. Introduction

Concrete-filled steel tubular (CFST) members have been widely used in routine structural design as piles, building columns and bridge piers. This is due to the great advantages of composite members, including high strength, good ductility, high energy absorption capacity, and rapid construction. From the 1960s, behaviour of CFST members has been extensively investigated [1–4]. Accordingly, many design codes have been developed, such as the Japanese code AIJ [5], Australian code AS 5100 [6], European code EN1994 [7], American codes AISC [8] and ACI [9], and Chinese code DBJ 13-51-2010 [10]. For design purposes, all these codes have provided some limitations on material strengths and section slenderness, as summarised in Table 1. Beyond those limitations, the existing codes might give less accurate strength predictions [11,12]. Even within the limitations, the strength predictions from the existing codes show considerable deviation from the experimental results and the predication accuracy could be further improved [13–15].

In recent years, developments of high strength steel and concrete have progressed in leaps and bounds, and high strength CFST columns have already been used in some building structures. For example, the Latitude Building in Sydney used a steel grade of 690 MPa and 80 MPa strength concrete in box-shaped CFST sections in the two-storey, 7 m deep transfer trusses [16]. In Japan, the Obayashi Technical Research Institute Main Building used CFST columns with a steel grade of 780 MPa and concrete compressive strength of 160 MPa [17]. These applications highlight the urgent need to develop design methods to cope with the development of high-strength materials.

In investigating CFST stub columns under compression, previous studies have mainly focused on their compressive strength. Very little attention has been paid to their compressive stiffness and deformation capacity [18,19]. For structural analysis, compressive stiffness of a member affects the internal force distribution; therefore accurate values should be provided. Meanwhile, designers nowadays are paying more attention to extreme loading, such as seismicity, impact and fire; and other abnormal events. Accordingly, the issue of ductility or deformation capacity is of considerable interests to the designers. The compressive strain corresponding to the ultimate strength to some extent reflects ductility or deformation capacity of an axially loaded CFST column,

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Nomenclature

A_c	cross-sectional area of concrete
A_s	cross-sectional area of the steel tube
B	width of a rectangular cross-section
D	diameter of a circular cross-section
D'	equivalent diameter of a rectangular cross-section
EA	compressive stiffness of a CFST stub column
E_c	elastic modulus of concrete
E_s	elastic modulus of steel
f_c'	cylinder compressive strength of concrete
f_{cu}	cube compressive strength of concrete
f_y	yield stress of steel
f_u	ultimate strength of steel
H	cross-sectional height of a rectangular tube
L	length of a CFST stub column
N_a	strength contribution of the steel tube
N_c	strength contribution of the concrete core
N_u	ultimate strength of a CFST stub column
R^2	coefficient of determination
SD	standard deviation
t	wall thickness of the steel tube
β	reliability index for resistance
ε	strain
ε_c	compressive strain corresponding to the compressive strength
ϕ	capacity reduction factor for steel
ϕ_c	capacity reduction factor for concrete
κ_c	correction factor for the concrete stiffness
μ	average value
σ	stress

Table 1
Strength prediction methods and related limitations.

	Sectional type	Prediction of strength	D/t or H/t	f_y (MPa)	f_cMPa)
ACI	Circular	$N_u = f_y A_s + 0.85 f_c' A_c$	$D/t \leqslant \sqrt{8E_s/f_y}$	–	$f_c' \geqslant 17.2$ MPa
	Rectangular		$H/t \leqslant \sqrt{3E_s/f_y}$	–	$f_c' \geqslant 17.2$ MPa
AISC	Circular	$N_u = \begin{cases} \left[0.658^{(N_0/N_{cr})}\right] N_0 & N_0 \leqslant 2.25 N_{cr} \\ 0.877 N_{cr} & N_0 > 2.25 N_{cr} \end{cases}$ $N_0 = f_y A_s + 0.85 f_c' A_c$ $N_{cr} = \frac{\pi^2}{(KL)^2}(EI_{eff})$	$D/t \leqslant 0.15 E_s/f_y$	$f_y \leqslant 525$ MPa	$21 \leqslant f_c' \leqslant 70$ MPa
	Rectangular		$H/t \leqslant 2.26\sqrt{E_s/f_y}$	$f_y \leqslant 525$ MPa	$21 \leqslant f_c' \leqslant 70$ MPa
AS 5100	Circular	$N_u = \eta_a f_y A_s + f_c' A_c \left(1 + \eta_c \frac{t f_y}{D f_c'}\right)$ $\eta_a = 0.25(3 + 2\bar{\lambda}) \leqslant 1$ $\eta_c = 4.9 - 18.5\bar{\lambda} + 17\bar{\lambda}^2 \geqslant 0$	$D/t \leqslant 82 \times \frac{250}{f_y}$	$230 \leqslant f_y \leqslant 400$ MPa	$25 \leqslant f_c' \leqslant 65$ MPa
	Rectangular	$N_u = f_y A_s + f_c' A_c$	$H/t \leqslant 35\sqrt{250/f_y}$	$230 \leqslant f_y \leqslant 400$ MPa	$25 \leqslant f_c' \leqslant 65$ MPa
EN1994	Circular	$N_u = \eta_a f_y A_s + f_c' A_c \left(1 + \eta_c \frac{t f_y}{D f_c'}\right)$	$D/t \leqslant 90 \times \frac{235}{f_y}$	$235 \leqslant f_y \leqslant 460$ MPa	$20 \leqslant f_c' \leqslant 60$ MPa
	Rectangular	$N_u = f_y A_s + f_c' A_c$	$H/t \leqslant 52\sqrt{235/f_y}$	$235 \leqslant f_y \leqslant 460$ MPa	$20 \leqslant f_c' \leqslant 60$ MPa
DBJ 13-51-2010	Circular	$N_u = f_{sc}(A_s + A_c); \quad \xi = \frac{f_y A_s}{f_{ck} A_c}$ $f_{sc} = f_{ck}(1.14 + 1.02\xi)$ for circular $f_{sc} = f_{ck}(1.18 + 0.85\xi)$ for rectangular	$D/t \leqslant 150 \times \frac{235}{f_y}$	$235 \leqslant f_y \leqslant 420$ MPa	$24 \leqslant f_c' \leqslant 70$ MPa
	Rectangular		$H/t \leqslant 60\sqrt{235/f_y}$	$235 \leqslant f_y \leqslant 420$ MPa	$24 \leqslant f_c' \leqslant 70$ MPa

and simplified equations should be proposed to assist the designers.

A finite element (FE) model was previously developed by Tao et al. [20] for simulating circular and rectangular CFST stub columns under axial compression, which has been verified by a large amount of full-range load-deformation curves. The FE model will be used in this paper to generate simulation data to cover a wide range of parameters, and regression analysis will be conducted to propose simplified models to predict the compressive strength and corresponding strain, and compressive stiffness for the composite columns. Based on the new strength prediction model, the capacity reduction factors for the steel and concrete materials will be recalibrated.

2. Compressive strength predictions based on existing design codes

A database containing test results of 484 circular CFST stub columns and 445 rectangular CFST stub columns was used by Tao et al. [13] to evaluate the applicability of existing design codes, including AIJ, AISC, DBJ 13-51-2003 and EN1994, in calculating the compressive strength. It should be pointed out that the formulae presented in AS 5100: Part 6 are virtually the same as those suggested in EN1994 for compressive strength prediction. Therefore, the predicted results using AS 5100 are similar to those from EN1994. The evaluation conducted by Tao et al. [13] indicates that EN1994 has provided comparable predictions as DBJ 13-51-2003 for rectangular CFST stub columns, but gives better predictions than do the AIJ and AISC. In contrast, EN1994 gives better strength predictions than other design codes for circular CFST stub columns.

Although reasonable strength predictions are given by EN1994, considerable deviation from the experimental results was still reported by Tao et al. [13], Kuranovas et al. [14], and Güneyisi et al. [15]. This is also the case for other design codes. The deviations are mainly caused by unavoidable experimental errors, different specimen end conditions and variations in specimen preparation and quality. The influence of these factors is difficult, if not impossible, to be eliminated in code comparison. Another contributing factor to the variation is the limitations of the design codes themselves. For example, EN1994 considers the local buckling effect for circular thin-walled tubes by limiting the diameter (D) to thickness (t) ratio to $90 \times 235/f_y$ and the cross-sectional