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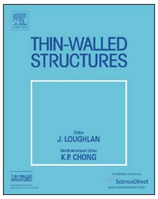

Full length article

Plastic and yield slenderness limits for circular concrete filled tubes subjected to static pure bending

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ABSTRACT

The current slenderness limits in international design codes are often based on certain rotation capacities obtained from plastic bending tests of Concrete Filled Tubes (CFT). In the past, a plastic slenderness limit of $\lambda_s = 188$ was obtained by the first author based on a fracture rotation limit of the steel tube. However, such limit may be questionable being brittle and insufficient for plastic design of CFT members, subassemblies and frames where adequate strain/deformation ductility is required. The main aims of this paper are to present (i) a new method to determine new ductile slenderness limits suitable for plastic design of structures based on the measured strains in plastic bending tests on CFT; (ii) a closed-form solution for the elastic and inelastic buckling strains of CFT under pure bending using a new simplified energy approach employing the well-known Ritz method. The critical strains obtained from such analysis were used to derive new slenderness limits for CFT; and (iii) finite element modelling of CFT and compare the experimental and numerical moment-rotation responses. The effect of concrete filling on the post-buckling strength of restrained tubes is quantified. The current design rules for unrestrained Circular Hollow Sections (CHS) in steel specifications are also compared with the restrained strength obtained from the tests. Two new compact and yield slenderness limits were derived based on the strength corresponds to the appearance of the plastic ripples during the test. The experimentally obtained and the theoretically derived slenderness limits are compared against the available limits in the design codes and standards. The newly derived compact limit of $\lambda_p = 79$ was found in a good agreement with $\lambda_p = 72$ specified for CFT in the ANSI/AISC 360-10 specification. However, the new yield limit of $\lambda_y = 150$ was found considerably lower than $\lambda_y = 254$ for CFT specified in the ANSI/AISC 360-10.

1. Introduction

1.1. General

In general, composite members consisting of circular steel tubes filled with concrete are extensively used in structures involving large rotations, particularly in zones of high seismicity. Composite circular concrete filled tubes (CFT) have been used increasingly as columns and beam-columns in braced and unbraced frame structures [1–3]. Their use worldwide has ranged from compression members in low-rise, open floor plan construction using cold-formed steel circular or rectangular tubes filled with precast or cast-in-place concrete, to large diameter cast-in-place members used as primary lateral resistance columns in multi-story buildings in China [1]. Concrete filled steel box columns fabricated from four welded plates and concrete filled steel fabricated circular sections have been used in some of the world's tallest structures [4,5]. In addition, concrete filling is widely used in retrofitting of damaged steel bridge piers after the 1995 Hyogoken-Nanbu earthquake in Japan and the Northridge earthquake in 1994 in the USA [6].

CFT structural members have a number of distinctive advantages over conventional steel reinforced concrete members. CFT members provide excellent seismic resistance in two orthogonal directions as well as good damping characteristics. These members also have excellent hysteresis behaviour under cyclic loading, compared with hollow tubes [4]. The use of CFT members in moment resisting frames eliminates the use of additional stiffening elements in panel zones and zones of high strain demands. The CFT columns proved to be cost effective in building structures compared to conventional reinforced concrete columns [7]. In general, void filling is an efficient way to delay premature local buckling and to enhance ductility of tubular structures built with cold-formed hollow sections. Concrete filling not only delays local buckling but also prevents the detrimental effect of ovalisation on

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Nomenclature

a	Amplitude of plastic ripples
CHS	Circular hollow sections
D	Outside diameter of CHS
D_i	Inside diameter of the tube
E	Modulus of elasticity of CFT section
E_s	Measured initial Young's modulus of steel tube
E_l	Modulus of steel tube in the longitudinal direction
E_h	Modulus of steel tube in the hoop direction
E_t	Hardening modulus of steel tube in the longitudinal direction
E_c	Predicted elastic modulus of the concrete
f_c	Unconfined strength of concrete
f_{cc}	Confined strength of concrete
f_y	Measured yield stress
f_p	Stress at Proportional limit
f_u	Measured ultimate tensile strength
f_c	Measured ultimate tensile strength
L	Beam length under constant moment
M	Applied moment
M_u	Ultimate moment
M_p	Plastic moment
M_{pc}	Plastic moment of the composite section
M_{ptH}	Plastic moment of the hollow tubes
$M_{concrete}$	Predicted concrete contribution
r	Parameter used in Eq. (20)
R	Mean radius of the tube
S	Shear span
S_H	Plastic section modulus for hollow tubes
Z_H	Elastic section modulus for hollow tubes
t	Thickness of CHS

Slenderness parameter

ε_u	Ultimate strain at fracture
ε_p	Strain at proportional limit
λ_s	Section slenderness defined in AS4100 [39].
λ_{ey}	Yield slenderness limit for compression
λ_y	Yield slenderness limit for bending
λ_p	Plastic slenderness limit for bending
λ_{CFT}	Slenderness limit for CFT
λ_{CHS}	Slenderness limit for CHS
γ_0	Angular location of the plastic neutral axis
σ_{CHS}	Critical buckling stress for CHS
σ_{CFT}	Critical buckling stress for CFT
θ	Relative angle of rotation
θ_{max}	Rotation corresponding to M_u
θ_y	Rotation corresponding to yield of the steel tube

the bending capacity of circular hollow sections (CHS).

In spite of the bulk literature written over the last five decades on the techniques of concrete filling of circular steel tubes, little was devoted, specially theoretical studies, to the large deformation flexural behaviour of these members as noted by [2]. In the past, CFT beams were studied under 3-point bending by Kilpatric and Rangan [8] and 4-point bending by [9], Hosaka et al. [10]. CFT stub columns were first studied by Furlong [11], Schneider [12], Uy [13], Bridge and O'Shea [14], Tao et al. [15], and more recently by Portolés et al. [16]. CFT beam-columns were investigated by Liang [17], Prion and Boehme [18], Neogi et al. [19], Tomii [20]. Bond between concrete and steel tubes stub columns have been experimentally studied by Shaker-Khalil [21]. Han et al. [1] provided a state-of-the art review, where the results of research on CFT members under monotonic and cyclic loading over the last five decades were summarised.

The plastic slenderness limits are widely used in current design rules to classify the cross sectional behaviour subjected to pure bending. Three types of sections are commonly used in this classification, namely, compact, non-compact and slender. The plastic D/t-limits are used to identify a compact and a non-compact sections suitable for plastic design of frames. Table 1 shows that there are large differences in the D/t limits for CFT members among the available design codes and standards. The variations in the plastic D/t limits among the codes and other factors such as shear-span to depth ratio (S/D), concrete strength (f_c) and yield strength (f_y) cause considerable discrepancies between the available design rules to predict the ultimate bending strength of CFT. It is worth noting that

Table 1

The current D/t-limits for circular CFT members in international codes.

Country (1)	Code for CFT structures (2)	CFT member type (3)	CFT symbol (4)	CFT formulae (5)	CFT D/t-limit (f_y=350 MPa)[a] (6)	CFT λ_{CFT} (D/t).(f_y/250) (7)	CFT λ_y/λ_{ey} (8)	$\lambda_{CFT}/\lambda_{CHS}$[*] (9)
Japan	AIJ [22]	Columns	λ_{ey}	$1.5^{*}[240/(F^{\#}/98)]$	117.2	164.1	–	1.5
	ANUHT [23]	Columns	λ_{ey}	$1.5^{*}(23{,}500/F^{\#})$	117.1	164.0	–	1.5
China	GB50017-201x [28]	Columns	λ_{ey}	$135^{*}(235/f_y)$	90.6	126.9	–	1.35
		Beams	λ_y	$177^{*}(235^{*}/f_y)$	118.8	166.4	1.31	1.77
	GB50936-2014 [27]	Columns	λ_{ey}	$135^{*}(235/f_y)$	90.6	126.9	–	1.35
		Beams	λ_y	$177^{*}(235^{*}/f_y)$	118.8	166.4	1.31	1.77
	JGJ138-2012 [29]	Beams, columns	$\lambda_{ey}=\lambda_y$	$100^{*}(235/f_y)$	67.1	94.0	1.0	1.0
USA	ANSI/AISC 360-10 [24]	Beams, compact	λ_p	$0.09^{*}(E_s/f_y)$	51.4	72.0	–	1.25
		Beams, non-compact	λ_y	$0.31^{*}(E_s/f_y)$	177.1	254.0	1.67	1.0
		Columns	λ_{ey}	$0.19^{*}(E_s/f_y)$	108.6	152.0	–	1.73
Europe	Eurocode 4 [25]	Columns, beams	$\lambda_{ey}=\lambda_y$	$90^{*}(235/f_y)$	60.4	84.6	1.0	1.0
	CIDECT [26]	Columns, beams	$\lambda_{ey}=\lambda_y$	$90^{*}(235/f_y)$	60.4	84.6	1.0	1.0
Australia	Present paper	Beams, compact	λ_p	$79^{*}(f_y/250)$	56.4	79	–	1.58
		Beams, non-compact	λ_y	$150^{*}(f_y/250)$	107.1	150	1.20	1.25
	Bradford et al. [37]	Columns	λ_{ey}	$125^{*}(f_y/250)$	89.3	125	–	1.52

[a] Nominal properties of cold-formed CHS: f_y=350 MPa, f_u=430 MPa and E_s=200,000 MPa.

[#] F (in MPa) is the lesser of $0.7f_u$ and f_y.

[*] The limit λ_{CFT} is the one listed for CFT in Column 7 of this table. The limit λ_{CHS} is corresponding one for CHS in the corresponding steel design code.