Journal of Constructional Steel Research 66 (2010) 111–124

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

journal homepage: www.elsevier.com/locate/jcsr

Theoretical study on concrete-filled steel tubes under static and variable repeated loadings

T. Aly [a,*], P. Thayalan [a], M. Elchalakani [b], I. Patnaikuni [a]

[a] Department of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, VIC 3001, Australia

[b] Dubai Men's College, Higher College of Technology, United Arab Emirates

ARTICLE INFO

Article history:
Received 25 February 2008
Accepted 11 August 2009

Keywords:
Analytical models
Circular tubes
Static loading
Variable loading
Concrete strength

ABSTRACT

This paper presents an analytical study for modelling the behaviour of concrete-filled steel tubular (CFST) columns subjected to Static Loading (SL) and Variable Repeated Loading (VRL). The variables considered in this study are concrete strength and load eccentricity. Simple mathematical models are developed and used in the analysis. The analytical results show that the incremental collapse (IC) occurs in high load ranges in CFST columns under VRL and instability failure occurs under SL. The CFST columns with large end load eccentricity were found to fail at a low upper limit load level than that with small eccentricity of loading. The IC failure was found to be unaffected by the strength of concrete infill. The hollow steel tubular (HST) columns showed similar behaviour under SL and VRL protocols. The study showed that the theoretical analyses satisfactorily model the actual behaviour of the columns under SL and VRL protocols.

1. Introduction

The literature review reveals that the theoretical investigations carried out on CFST columns were mainly concerned with the effect of loading protocol [1–4] and confinement [5,6], the effect of local buckling of steel in thin-walled steel tubular columns [7], eccentrically loaded [8–10], and slender columns [11,12]. Although there have been experimental investigations reported on the use of high strength concrete [13] and on the interface bond strength behaviour [14,15] of CFST columns, there are little theoretical studies carried out to incorporate these parameters in the design methods. Kilpatrick and Rangan [13] emphasized the need of developing a mathematical model incorporating all the parameters including the effects of both the short term and long term load deformation response of high strength concrete.

Several design methods incorporating some of the parameters involved in the behaviour of CFST columns have been proposed in the past. At present, no method is available within Australian Standards for the design of CFST while many overseas codes of practice include methods incorporating empirical and semi-empirical formulas with certain limitations such as strength of concrete and the diameter-to-thickness ratio of the steel tube etc. The results of these codes vary considerably. The design codes, Eurocode 4 [16], BS5400 [17], ACI-318-05 [18], AISC-LRFD [19] and others deal with the strength under static loading. Bergmann et al. [20] prepared a design guide which deals with seismically loaded hollow and composite columns.

In a research program at RMIT University, experimental and theoretical investigations were carried out to study the behaviour of CFST and HST columns subjected to SL and VRL. In the experimental study, column behaviour is investigated through testing long CFST and HST columns under SL and VRL [21] and interface bond strength behaviour is investigated through Static and VRL pushout tests [22]. The experimental investigation on the column behaviour revealed that the failure of the columns is due to instability and incremental collapse when subjected to SL and VRL respectively. Theoretical models carried out to simulate the behaviour of CFST and HST columns subjected to SL and VRL are presented in this paper.

2. Scope

In the theoretical study, simple mathematical models have been formulated to analyse the behaviours of CFST and HST columns similar to the columns tested in the experimental study [21,22] under the same loading conditions. The results of both investigations are compared to verify the theoretical models. The variables considered were, strength of concrete infill and end moments.

The dimensions of the steel tubular columns used in this analysis are, 114.3 mm diameter, 3.2 mm thickness and 1200 mm long. Normal and high strength concrete (nominal strengths of 40 MPa and 80 MPa) are used in composite columns. Isolated pin-ended columns are loaded with equal end eccentricities (15 mm or 30 mm) at the ends.

* Corresponding author. Tel.: +61 399259975.
E-mail address: tarek.aly@rmit.edu.au (T. Aly).

0143-974X/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jcsr.2009.08.005

Nomenclature

a	Lateral deflection at mid-height
A_c	Cross sectional area of concrete
A_s	Cross sectional area of steel
b_c	Width of a concrete slice
dA_c	Area of a concrete slice
dA_s	Area of a steel element
D_i	Inner diameter of the steel tube
d_n	Neutral axis depth
D_o	Outer diameter of the steel tube
e	Eccentricity of load
E_{c1}	Modulus of elasticity of concrete in compression
E_{c2}	Gradient of the linear inelastic line in compression of concrete
E_{s1}	Modulus of elasticity of steel in compression
E_{s2}	Gradient of the linear inelastic line in compression of steel
E_{s3}	Modulus of elasticity of steel in tension
E_{s4}	Gradient of the linear inelastic line in tension of steel
f_c	Strength of Concrete
f_y	Yield stress of steel
L	Actual height of the column
L_e	Effective height of the column
M_c	Total internal moment in the concrete section
M_{cc}	Moment of P_{cc} about the axis p–p
M_{ct}	Moment of P_{ct} about the axis p–p
M_e	External moment at mid-height
M_e	Total external moment at mid-height due to external load applied
M_{ic}	Total internal moment in the concrete section
M_{is}	Total internal moment in the steel section
M_s	Total internal moment in the steel section
M_{sc}	Moment of P_{sc} about the axis p–p
M_{st}	Moment of P_{st} about the axis p–p
M_t	Total internal moment in the steel section at mid-height
N_c	Total number of concrete elements
n_c	Number of any element from the extreme compressive concrete fibre
n_s	Number of each element from the extreme compressive steel fibre
N_s	Total number of steel elements
$P_c(i)$	Internal force in the n_cth level element in the ith calculation
P_{cc}	Internal force in the n_cth level compressive element
P_{ct}	Internal force in the n_cth level tensile element
P_e	External load applied at equal end eccentricity at both ends
P_{ic}	Total internal force in the concrete section
P_{is}	Total internal force in the steel section
$P_{\max}$	Upper limit load in every load range
$P_{\min}$	Lower limit load in every load range
P_s	Static Collapse load
$P_s(i)$	Total internal force in the two elements at the n_sth level in the ith calculation
P_{sc}	Total internal force in the n_sth level compressive steel elements
P_{st}	Total internal force in the n_sth level tensile steel elements
P_t	Total internal force in a section
t	Thickness of the steel tube
t_c	Thickness of a concrete slice
v	Deflection of the column center line at a distance 'x' from one end
χ	Curvature at mid-height section
ε_{c1}	Elastic limit compressive strain of steel
ε_{c2}	Initial plastic compressive strain of steel
ε_{c3}	Maximum compressive strain of steel
ε_{cc}	Elastic limit compressive strain of concrete
ε_{cf}	Maximum compressive strain of concrete
ε_{co}	Initial plastic compressive strain of concrete
ε_{con}	Strain in the extreme compressive fibre of concrete
ε_{t1}	Elastic limit tensile strain of steel
ε_{t2}	Initial plastic tensile strain of steel
ε_{t3}	Maximum tensile strain of steel
θ	Angle measured from the axis Q–Q to an element
σ_{c1}	Stress corresponds to strain ε_{c1}
σ_{c2}	Stress corresponds to strain ε_{c2}
σ_{cc}	Stress corresponds to strain ε_{cc}
σ_{cf}	Maximum compressive stress of concrete
σ_{co}	Stress corresponds to strain ε_{co}
σ_{con}	Strain in the extreme compressive fibre of concrete

3. Material properties

3.1. Steel

The steel stress–strain constitutive model (virgin curve) shown in Fig. 1 is used in the analysis of static loading cases and consists of a linear elastic third order polynomial inelastic–perfectly plastic stress–strain relationship in both compression and tension. The moduli of elasticity in compression and tension used are different. In the case of VRL, the model is modified by replacing the polynomial curve with a straight line to obtain a trilinear relationship in both compression and tension as shown in Fig. 2. Also, for VRL the moduli of elasticity in compression and tension are assumed to be the same. Compression is taken as positive for convenience.

3.2. Concrete

The concrete stress–strain constitutive model (virgin curve) shown in Fig. 3 is used in the analysis of SL cases and consists of a linear elastic third order polynomial inelastic–perfectly plastic stress–strain relationship in compression. Tensile strength is assumed to be negligible. In the case of VRL, the polynomial curve is replaced with a straight line to obtain a trilinear relationship in compression as shown in Fig. 4. It is considered that the compression is taken as positive for convenience. The modifications in stress–strain curves made for the case of VRL protocol are to further simplify the analysis.

4. Assumptions and limitations

- In-plane analysis for the bending of the beam–columns;
- Single curvature bending;
- Deflected shape of the axis of the column is in the form of a half-sine wave;
- Isolated beam–columns with pin-end conditions;
- Initial imperfections such as out-of-straightness, residual stresses due to welding, for example, are neglected;
- The maximum deflections are small (small deflection theory is used — second order effects are neglected);
- No local buckling of steel occurs;
- Axial force is constant along the height of the column;