Journal of Constructional Steel Research 92 (2014) 183–194

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Numerical analysis of high-strength concrete-filled steel tubular slender beam-columns under cyclic loading

Vipulkumar Ishvarbhai Patel [a], Qing Quan Liang [a,*], Muhammad N.S. Hadi [b]

[a] College of Engineering and Science, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia
[b] School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

ARTICLE INFO

Article history:
Received 9 January 2013
Accepted 8 September 2013
Available online 8 November 2013

Keywords:
Concrete-filled steel tubes
Cyclic loading
High strength
Local and post-local buckling
Nonlinear analysis
Slender beam-columns

ABSTRACT

The effects of cyclic local buckling on the behavior of concrete-filled steel tubular (CFST) slender beam-columns under cyclic loading were approximately considered in existing analytical methods by modifying the stress–strain curve for the steel tube in compression. These methods, however, cannot simulate the progressive cyclic local buckling of the steel tubes. This paper presents a new efficient numerical model for predicting the cyclic performance of high strength rectangular CFST slender beam-columns accounting for the effects of progressive cyclic local buckling of steel tube walls under stress gradients. Uniaxial cyclic constitutive laws for the concrete core and steel tubes are incorporated in the fiber element formulation. The effects of initial geometric imperfections, high strength materials and second order are also included in the nonlinear analysis of CFST slender beam-columns under constant axial load and cyclically varying lateral loading. The Müller's method is adopted to solve nonlinear equilibrium equations. The accuracy of the numerical model is examined by comparisons of computer solutions with experimental results available in the published literature. A parametric study is conducted to investigate the effects of cyclic local buckling, column slenderness ratio, depth-to-thickness ratio, concrete compressive strength and steel yield strength on the cyclic responses of CFST slender beam-columns. It is shown that the numerical model developed predicts well the experimentally observed cyclic lateral load–deflection characteristics of CFST slender beam-columns. The numerical results presented reflect the cyclic local and global buckling behavior of thin-walled high strength rectangular CFST slender beam-columns, which have not been reported in the literature.

1. Introduction

High strength thin-walled rectangular CFST slender beam-columns have increasingly been used in composite buildings and bridges in seismic regions due to their high structural performance such as high strength, high stiffness, high ductility and large energy absorption capacity. In seismic regions, thin-walled CFST slender beam-columns may be subjected to a constant axial load from upper floors and cyclically varying lateral loading due to the earthquake. These cyclically loaded beam-columns may undergo cyclic local and global interaction buckling, which makes the predictions of their cyclic performance highly complicated. Cyclic local buckling reduces the strength and ductility of thin-walled CFST slender beam-columns. It is therefore important to incorporate cyclic local buckling effects in nonlinear analysis techniques so that the cyclic performance of thin-walled CFST slender beam-columns under cyclic loading can be accurately predicted.

Experimental studies on the ultimate strengths of CFST columns under monotonic axial load or combined monotonic axial load and bending have been very extensive in the past [1–12]. However, only limited tests have been conducted on CFST beam-columns under cyclic loading. Experiments on square CFST beam-columns under axial load and cyclic lateral loading were performed by Varma et al. [13,14]. These test specimens were made of high strength concrete of 110 MPa and steel tube with yield stress ranging from 269 MPa to 660 MPa. Their studies indicated that the cracking of the infilled concrete and local buckling of the steel tubes reduced the flexural stiffness of CFST beam-columns. Han et al. [15] investigated experimentally the effects of the depth-to-thickness ratio, concrete compressive strength and axial load level on the cyclic behavior of square and rectangular CFST beam-columns. They reported that the local buckling of CFST beam-columns occurred after the steel yielded. Tests on normal strength square CFST beam-columns under cyclic loading were undertaken by Wu et al. [16]. It was observed that the steel tube walls buckled outward after the concrete was damaged.

Various nonlinear analysis techniques for predicting the cyclic responses of CFST beam-columns have been reported in the literature. Varma et al. [13] developed a fiber element model for rectangular CFST beam-columns under cyclic loading. The uniaxial cyclic stress–strain relationships for steel and concrete were derived from the nonlinear finite element analyses of CFST beam-columns. The stress–

* Corresponding author. Tel.: +61 3 9919 4134.
E-mail address: Qing.Liang@vu.edu.au (Q.Q. Liang).

0143-974X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jcsr.2013.09.008

strain curve for steel in compression was modified to approximately account for the effects of local buckling. Gayathri et al. [17,18] proposed an efficient fiber element technique for the nonlinear analysis of CFST short and slender beam-columns under monotonic and cyclic loading. Their technique was formulated for normal strength CFST beam-columns where local buckling effects were not included. Chung et al. [19] presented a fiber element model for the analysis of cyclically loaded square CFST beam-columns. The effect of local buckling was approximately taken into account in the model by modifying the stress–strain curve for steel in compression. However, their model did not consider concrete tensile strength and high strength materials. Zubydan and ElSabbagh [20] proposed a mathematical model for the nonlinear analysis of normal strength rectangular CFST beam-columns where local buckling was approximately considered by modifying the stress–strain curve for steel in compression. The fiber element model presented by Wu et al. [16] could be used to analyze normal strength square CFST beam-columns, provided that the steel sections are compact. It should be noted that the modified stress–strain curve method used in the abovementioned models might overestimate or underestimate the cyclic local buckling strengths of steel tubes under stress gradients. This is because they cannot model the progressive cyclic local buckling of the steel tube from the onset to the post-local buckling, which is characterized by stress redistributions within the buckled tube wall.

The local buckling problem of thin-walled CFST columns has been studied experimentally by various researchers [21–24]. Liang et al. [25] proposed a fiber element model for the nonlinear analysis of thin-walled CFST short columns under axial compression, accounting for progressive local buckling effects by using effective width formulas. Liang [26,27] developed a numerical model for simulating the axial load–strain responses, moment–curvature relationships and axial load–moment interaction diagrams of high strength rectangular CFST short beam-columns under axial load and biaxial bending. The effects of local buckling of steel tube walls under stress gradients were incorporated in the model by using initial local buckling equations and effective width formulas proposed by Liang et al. [28]. Patel et al.[29,30] and Liang et al. [31] extended the numerical models developed by Liang et al. [25] and Liang [26,27] to the nonlinear analysis of eccentrically loaded high strength thin-walled rectangular CFST slender beam-columns considering the effects of local buckling, geometric imperfections, second order and high strength materials.

The above literature review indicates that research studies on the fundamental behavior of cyclically loaded high strength rectangular CFST slender beam-columns with large depth-to-thickness ratios have been relatively limited. In this paper, a numerical model is developed to simulate the cyclic performance of high strength thin-walled rectangular CFST slender beam-columns incorporating cyclic local buckling effects. Comparative study is undertaken to verify the numerical model. The fundamental cyclic behavior of CFST slender beam-columns under constant axial load and cyclically varying lateral loading is investigated using the computer program developed and the results obtained are discussed.

2. Material constitutive models

2.1. Cyclic constitutive models for concrete

The confinement effect provided by the rectangular steel tube on the concrete ductility is considered in the cyclic stress–strain curves schematically depicted in Fig. 1. The cyclic stress–strain relationships also account for the effects of stiffness degradation and crack opening and closing characteristics of concrete under cyclic loading. The envelope curve for the concrete under cyclic axial compression can be characterized by the monotonic stress–strain curve of the concrete as shown in Fig. 1. The longitudinal compressive concrete stress for the

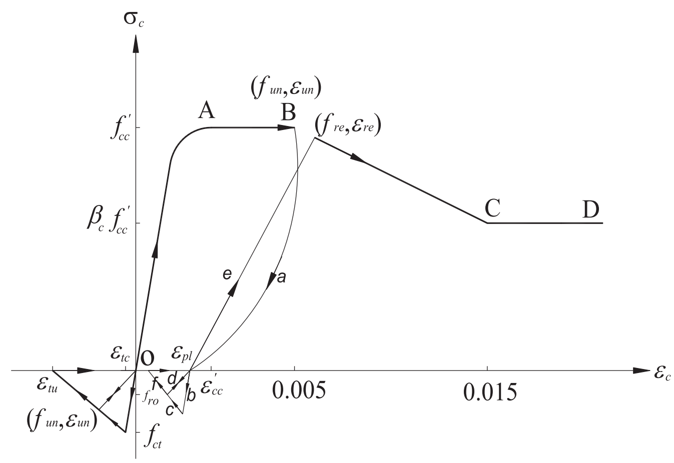

Fig. 1. Cyclic stress–strain curves for concrete in rectangular CFST columns.

ascending part from O to A is calculated based on the equation given by Mander et al. [32] as:

$$\sigma_c = \frac{f'_{cc}\lambda\left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)}{\lambda - 1 + \left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)^{\lambda}} \tag{1}$$

$$\lambda = \frac{E_c}{E_c - \left(\frac{f'_{cc}}{\varepsilon'_{cc}}\right)} \tag{2}$$

where f'_{cc} is the effective compressive strength of concrete, ε_c is the longitudinal compressive strain of concrete, ε'_{cc} is the strain at f'_{cc} and E_c is the Young's modulus of concrete which is given by ACI 318-11 [26,33]. The effective compressive strengths of concrete (f'_{cc}) is taken as $\lambda_c f'_c$, where λ_c is the strength reduction factor proposed by Liang [26] to account for the column size effects and is expressed by $\lambda_c = 1.85 D_c^{-0.135}$ $(0.85 \le \lambda_c \le 1.0)$ where D_c is taken as the larger of $(B-2t)$ and $(D-2t)$ for a rectangular cross-section. In the numerical model, the strain ε'_{cc} corresponding to f'_{cc} is taken as 0.002 for the effective compressive strength less than or equal to 28 MPa and 0.003 for $f'_{cc} > 82$ MPa. For the effective compressive strength between 28 and 82 MPa, the strain ε'_{cc} is determined by the linear interpolation.

The parts AB, BC and CD of the stress–strain curve for concrete in CFST columns as shown in Fig. 1 are defined by the following equations given by Liang [26]:

$$\sigma_c = \begin{cases} f'_{cc} & \text{for } \varepsilon'_{cc} < \varepsilon_c \le 0.005 \\ \beta_c f'_{cc} + 100(0.015 - \varepsilon_c)\left(f'_{cc} - \beta_c f'_{cc}\right) & \text{for } 0.005 < \varepsilon_c \le 0.015 \\ \beta_c f'_{cc} & \text{for } \varepsilon_c > 0.015 \end{cases} \tag{3}$$

where β_c was proposed by Liang [26] based on experimental results presented by Tomii and Sakino [34] as follows:

$$\beta_c = \begin{cases} 1.0 & \text{for } B_s/t \le 24 \\ 1.5 - B_s/(48t) & \text{for } 24 < B_s/t \le 48 \\ 0.5 & \text{for } B_s/t > 48 \end{cases} \tag{4}$$

in which B_s is taken as the larger of B and D for a rectangular cross-section.

The concrete under compression is initially loaded up to an unloading strain and then unloaded to a zero stress level. The reloading of the concrete from the zero stress up to the envelope curve is characterized by the linear stress–strain relationships. For the unloading