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Nonlinear analysis of biaxially loaded rectangular concrete-filled stainless steel tubular slender beam-columns

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

[a] School of Engineering and Mathematical Sciences, College of Science, Health and Engineering, La Trobe University, Bendigo, VIC 3552, Australia
[b] College of Engineering and Science, Victoria University, PO Box 14428, Melbourne, VIC 8001, Australia
[c] School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

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ABSTRACT

Rectangular concrete-filled stainless steel tubular (CFSST) beam-columns utilized as supporting members for building frames may experience axial compression and biaxial moments. A numerical simulation considering the local buckling effects for thin-walled rectangular CFSST slender beam-columns has not been performed. This paper reports a stability modeling on the structural characteristics of rectangular CFSST slender beam-columns accounting for different strain-hardening of stainless steel under tension and compression. The influences of local buckling are considered in the simulation utilizing the existing effective width formulations. The developed numerical model simulates the strength interaction and load-deflection behavior of CFSST slender beam-columns. Comparisons of computed results with test data provided by experimental investigations are performed to validate the proposed fiber model. The influences of different geometric and material property on ultimate strengths, ultimate pure moments, concrete contribution ratio, strength interaction and load-deflection responses of CFSST slender beam-columns are examined by utilizing fiber model. A design formula considering strain hardening of stainless steel is derived for calculating the ultimate pure moment of square CFSST beam-columns.

1. Introduction

Concrete-filled steel tubular (CFST) beam-columns have been extensively utilized as the compression members for electrical towers, caissons, piles and buildings in many countries [1]. This is attributed to the structural and constructional benefits offered by CFST slender beam-columns. The structural advantages include high elastic stiffness, ultimate strengths, ductility and large energy absorption capacity while the constructional advantages are rapid frame erection, significant reduction in materials, costs and section size and elimination of the plywood formworks [2]. The structural benefits depicted in Fig. 1 shows that the ultimate capacity of composite columns is higher than that of non-composite individual components. The use of stainless steels in CFST beam-columns provides additional advantages, including good corrosion resistance and aesthetic appearance [3–5]. Stainless steel has been used in landmark structures, such as the Hearst Tower in New York, the footbridges in Norway and Italy, the Stonecutters Bridge in Hong Kong and the Parliament House in Canberra [4]. Nevertheless, the initial high cost of stainless steels has restricted their use in general applications such as office or residential buildings. A life-cycle cost analysis needs to be utilized for the general application of concrete-filled stainless steel tubular (CFSST) beam-columns.

Rectangular CFSST beam-columns may experience axial compression and biaxial moments when they are located at the corners in composite buildings. The combined action of biaxial bending may also be caused by different bending moments transferred from the connecting composite beams. The stainless steel plates of biaxially loaded CFSST slender beam-column experience a stress gradient. The thin steel tube walls buckle locally outwards remarkably reducing the capacity of CFST columns [6–8]. The main failure of thin-walled slender CFSST columns can be described by local outward buckling and overall column buckling [9]. No numerical models with local buckling effects have been developed for the simulation of rectangular CFSST beam-columns supporting axial loading or axial compression and biaxial bending.

Extensive research studies have been devoted to the nonlinear characteristic of conventional CFST columns [10–16] while experimental investigations on slender CFSST beam-columns have been relatively limited. Previous studies by Young and Ellobody [17] showed that concentrically compressed rectangular CFSST short columns failed by local buckling of plates and concrete crushing. This test observation agrees with the experimental results reported

* Corresponding author.
E-mail address: Qing.Liang@vu.edu.au (Q.Q. Liang).

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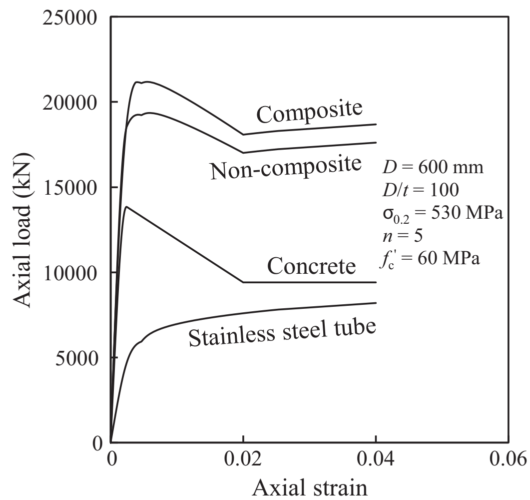

Fig. 1. Component strengths of axially loaded circular CFSST short column.

by Lam and Gardner [18]. Uy et al. [9] tested twelve pin-ended rectangular and square CFSST slender columns under axial compression with different column slenderness ratios and concrete strengths to investigate their performance. As indicated, failure characteristic of slender columns was the global buckling with local buckling at their mid-length. Ellobody and Ghazy [19] tested circular CFSST slender beam-columns under eccentric loading. It was observed that most of the columns failed with gradually increasing the lateral deflections at the mid-length. Tokgoz [20] tested square CFSST slender beam-columns subjected to biaxial loads. Test results indicated that the ductility of high strength concrete was considerably increased due to the confinement offered by stainless steel tubes.

Nonlinear analysis methods have been employed to model the performance of CFST columns [21–32]. Nevertheless, a relatively limited number of studies have been devoted to the numerical simulation of CFSST beam-columns. The finite element analyses were performed by Ellobody and Young [33], Tao et al. [34] and Hassanein et al. [35,36] to determine the deflections and strengths of square and circular CFSST short columns subjected to concentric loading. Although stainless steel has different strain-hardening behaviors in tension and compression, most of the analysis techniques employed material constitutive laws based on coupon tension tests to model the compressive behavior of CFSST columns. Ky et al. [37] developed a mathematical programming based algorithm utilizing the fiber element formulation and Müller's method for the inelastic analysis of axially loaded concrete encased composite short and slender columns. The mathematical model was shown to give good predictions of the behavior of concrete encased composite columns. Patel et al. [38,39] reported that the material models of stainless steel in tension incorporated in the analysis underestimate the strengths of axially compressed CFSST short columns. Tokgoz [20] employed the fiber analysis technique to analyze biaxially loaded CFSST slender beam-columns with compact sections of stainless steel tubes.

The previous research studies indicate that limited experimental studies on rectangular CFSST slender beam-columns with biaxial loads have been performed. There have been few computational analyses on biaxially loaded CFSST slender beam-columns. Local buckling and different strain-hardening of stainless steel under compression and tension were not considered in the existing studies of rectangular CFSST slender beam-columns. A fiber model for analyzing the strength interaction and load-deflection behaviors of CFSST slender beam-columns is described herein. This model incorporates the influences of local buckling and strain-hardening of stainless steel tubes. Computational solutions are compared against test data published by independent investigators. The influences of local buckling, concrete strengths, stainless steel strengths, depth-to-thickness ratios, slenderness ratios, eccentricity ratios and applied load angles on the nonlinear characteristic of CFSST beam-columns are discussed in detail. A simple formula is given for computing the ultimate pure moment of square CFSST beam-columns.

2. Material stress-strain relations

2.1. Concrete in compression

The concrete confinement increases the overall ductility of rectangular CFSST columns without increasing the strength. The increased ductility in the confined concrete is considered to accurately capture the performance of CFSST beam-columns. The constitutive law of concrete is represented by the nonlinear stress-strain relationship depicted in Fig. 2. This relationship contains a parabolic curve up to the concrete effective compressive strength f'_{cc}, a constant portion at f'_{cc}, a linear descending branch beyond f'_{cc} and constant residual strength after strain 0.015.

The four-stage stress-strain relations of concrete under compression illustrated in Fig. 2 were proposed by Liang [7] and are expressed by

$$\sigma_c = \begin{cases} \dfrac{f'_{cc}\lambda(\varepsilon_c/\varepsilon'_{cc})}{\lambda-1+(\varepsilon_c/\varepsilon'_{cc})^{\lambda}} & \text{for } 0 \leqslant \varepsilon_c \leqslant \varepsilon'_{cc} \\ f'_{cc} & \text{for } \varepsilon'_{cc} < \varepsilon_c \leqslant 0.005 \\ \beta_c f'_{cc} + 100(0.015-\varepsilon_c)(f'_{cc}-\beta_c f'_{cc}) & \text{for } 0.005 < \varepsilon_c \leqslant 0.015 \\ \beta_c f'_{cc} & \text{for } \varepsilon_c > 0.015 \end{cases} \tag{1}$$

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

$$E_c = 3320\sqrt{\gamma_c f'_c} + 6900 \text{ (MPa)} \tag{3}$$

$$\varepsilon'_{cc} = \begin{cases} 0.002 & \text{for } f'_{cc} \leqslant 28 \text{ (MPa)} \\ 0.002 + \frac{f'_{cc}-28}{54000} & \text{for } 28 < f'_{cc} \leqslant 82 \text{ (MPa)} \\ 0.003 & \text{for } f'_{cc} > 82 \text{ (MPa)} \end{cases} \tag{4}$$

$$\beta_c = \begin{cases} 1.0 & \text{for } \frac{B_s}{t} \leqslant 24 \\ 1.5 - \frac{1}{48}\frac{B_s}{t} & \text{for } 24 < \frac{B_s}{t} \leqslant 48 \\ 0.5 & \text{for } \frac{B_s}{t} > 48 \end{cases} \tag{5}$$

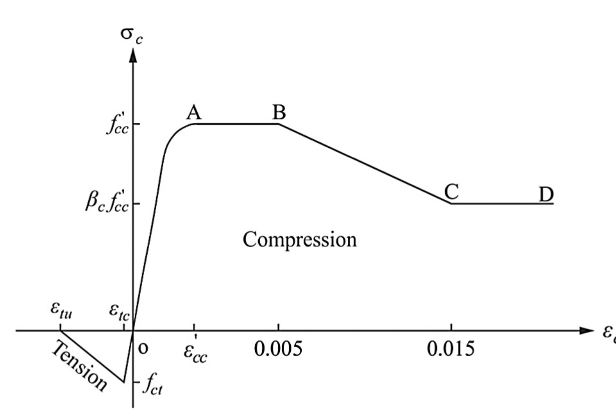

Fig. 2. Typical stress-strain curves for concrete.