Engineering Structures 168 (2018) 205–217

Contents lists available at ScienceDirect

Engineering Structures

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

Numerical simulation of high strength circular double-skin concrete-filled steel tubular slender columns

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ARTICLE INFO

Keywords:
Concrete-filled steel tubes
Double-skin
High-strength concrete
Nonlinear analysis
Slender composite columns

ABSTRACT

Circular double-skin concrete-filled steel tubular (DCFST) slender columns made of high-strength concrete are high performance structural members with wide applications in engineering structures. However, research studies on the behavior, load distributions in concrete and steel components and confinement characteristics of such composite columns under eccentric loading have been very limited. This paper describes a new mathematical model that computes the axial load-deflection performance of high-strength circular DCFST slender columns subjected to eccentric loading. The incremental nonlinear equilibrium equations of DCFST slender columns are solved by the developed efficient computational procedure and numerical solution algorithms accounting for initial geometric imperfections and second order effects. The mathematical model incorporates the accurate material constitutive laws of sandwiched concrete, which accurately predict the residual concrete strength and strain in the post-yield regime. The computer program implementing the mathematical model is utilized to quantify the influences of geometric and material properties and concrete confinements on the load-deflection behavior, column strength curves and load distributions in circular DCFST slender columns. It is shown that the mathematical model not only accurately predicts the experimental behavior of circular DCFST slender columns but also effectively monitors the load distributions in concrete and steel components of DCFST slender columns under deflection increments. The proposed mathematical model is an accurate and efficient computational and design technique for circular DCFST slender columns.

1. Introduction

The inner steel tube in a circular DCFST slender column as depicted in Fig. 1 is not filled with concrete, which results in not only a reduction in its weight but also an increase in its stiffness-to-weight ratio, ductility and seismic resistance. However, the ultimate axial strength of the circular DCFST slender column may be lower than that of the concrete-filled steel tubular (CFST) column for the concrete usually shares a large part of the column ultimate axial load. To increase the ultimate axial loads of DCFST columns, high-strength concrete can be utilized to fill the double-skin steel tubes. This leads to high performance DCFST columns. However, only very limited experiments on circular DCFST slender columns have been conducted, such as those by Tao et al. [1], Essopjee and Dundu [2] and Ibañez et al. [3], and no numerical studies on high-strength DCFST slender columns made of carbon steel tubes have been undertaken. Moreover, there is a lack of understanding of the load distributions and concrete confinement characteristics in circular DCFST slender columns. Therefore, an efficient and accurate numerical simulation tool is much needed for investigating the performance, confinement characteristics and load distributions in steel tubes and concrete of DCFST slender columns.

Tests on circular CFST columns were undertaken by Knowles and Park [4], Neogi et al. [5], Rangan and Joce [6], Schneider [7], Giakoumelis and Lam [8] and Portolés et al. [9]. Test results indicated that the performance of the filled concrete in terms of strength and ductility in circular CFST columns with relatively small column slenderness ratios was improved because the circular steel tube confined the concrete infill. Knowles and Park [4] proposed limiting column slenderness for concentrically-loaded CFST circular columns in which the confinement effect should be considered in the design. Liang [10,11] reported that the confinement in circular CFST columns was a function of the tube diameter-to-thickness ratio, eccentricity of applied load and column slenderness. Test results showed that both the inner and outer circular tubes provided confinement to the sandwiched concrete in a DCFST short column, as provided by Tao et al. [1], Wei et al. [12], Zhao et al. [13], Han et al. [14] and Uenaka et al. [15]. However, no investigations have been undertaken on the confinement characteristics of circular DCFST slender columns constructed by carbon steel tubes.

Limited experiments on circular DCFST slender columns subjected to eccentric loading or axial compression were performed in the past

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https://doi.org/10.1016/j.engstruct.2018.04.062
Received 31 January 2018; Received in revised form 29 March 2018; Accepted 16 April 2018

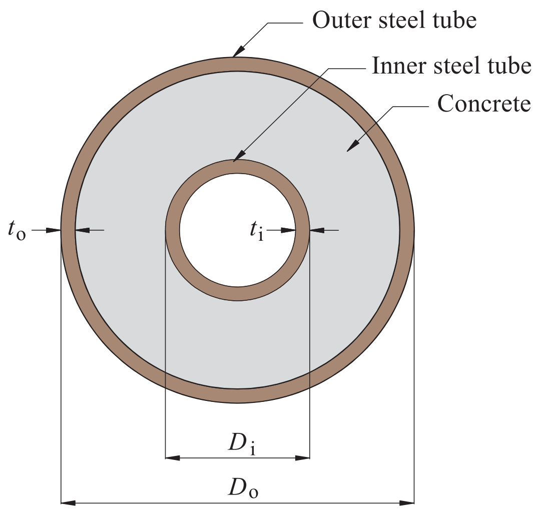

Fig. 1. Cross-section of circular DCFST column.

[1–3]. Tao et al. [1] tested twelves pin-ended circular DCFST slender columns where the column slenderness ratios (L/r) varying from 28.3 to 56.5, loading eccentric ratios (e/D_o) ranging from 0.0 to 0.395 and inner-to-outer tube-diameter ratio (D_i/D_o) of 0.509. The experimental results showed that these DCFST slender columns failed by global buckling without any tube local buckling. It was found that the ultimate axial load as well as the flexural stiffness of DCFST slender columns decreased with an increases in the L/r ratio or e/D_o ratio. Specimens with a larger e/D_o ratio exhibited better ductility. Essopjee and Dundu [2] carried out experiments on 32 pin-ended circular DCFST slender columns under axial compression with slenderness ratios (L/r) ranging from 25 to 63.9, the D_o/t_o ratios varying from 46.4 to 55, and D_i/t_i ratio of 38. The failure modes associated with the columns having an L/r ratio of 25 were the yielding and the outer steel tube local buckling and crushing of the sandwiched concrete while other columns exhibited overall buckling behavior without local buckling. Ibañez et al. [3] conducted tests on four eccentrically-loaded circular DCFST slender columns with normal or ultra-high strength concrete. The parameters examined were D_o/t_o and D_i/t_i ratios and concrete strengths.

Computational models that calculated the nonlinear responses of CFST circular columns were developed by Hajjar et al. [16], Susantha et al. [17], Shanmugam et al. [18], Hu et al. [19], Hatzigeorgiou [20], Liang and Fragomeni [21], Portolés et al. [22], Mollazadeh and Wang [23], Kostic et al. [24], Yang and Han [25] and Schnabl et al. [26]. Hu et al. [19] and Liang and Fragomeni [21] developed confinement models for the concrete confined by circular steel tubes, which can be used in numerical analysis procedures. Simulation techniques considering concrete confinement generally provided more accurate results on the performance of circular CFST columns than those ignoring confinement effects [21]. The strength and behavior of circular DCFST short columns were examined by using computer simulations techniques by Tao et al. [1], Wei et al. [27], Huang et al. [28], Hu and Su [29], Pagoulatou et al. [30], Hassanein et al. [31] and Liang [32]. However, the numerical nonlinear analyses of circular DCFST slender columns subjected to eccentric loading have been rare. The only available numerical investigation on circular DCFST slender columns made of carbon steel tubes was conducted by Tao et al. [1]. The material laws of concrete in circular CFST columns were employed in their fiber model, which ignored the confinement caused by the internal tube. Hassanein and Kharoob [33] used the commercial finite element software ABAQUS to study the behavior of circular double-skin concrete-filled tubular slender columns with external stainless steel tubes. They applied the confinement model proposed by Liang and Fragomeni [21] for concrete in CFST columns to the sandwiched concrete in DCFST columns, and did not considered the confinement effect provided by the inner steel tube. Experimental results showed that the stress-strain behavior of stainless steel in compression is significantly different from that in tension [34]. However, the stress-strain laws for stainless steel used by Hassanein and Kharoob [33] in their finite element models did not account for the different strain-hardening characteristics of stainless steel in compression and tension. The confinement effect on the behavior of double-skin concrete-filled tubular slender columns with external stainless steel tubes was investigated. Ky et al. [35] reported on a fiber element model that predicted the inelastic behavior of axially-loaded concrete encased composite short and slender columns considering concrete confinement, the buckling of steel sections and reinforcing bars and initial geometric imperfections.

The confinement effect on the filled concrete in a circular DCFST column is significantly different from that on concrete core in a circular CFST column. Hu and Su [29] proposed a constitutive model for determining the lateral pressures on the concrete sandwiched by both steel tubes in circular DCFST columns. Pagoulatou et al. [30] utilized the confinement model given by Hu and Su [29] in the finite element analysis of DCFST short columns. Liang [32] proposed accurate material constitutive laws for quantifying the post-peak strength and strain of sandwiched concrete confined by circular tubes. The fiber-based technique developed by Liang [32] was found to accurately quantify the experimentally observed behavior of short circular DCFST columns. The load distributions in concrete and steel components of circular DCFST short columns have been investigated by Huang et al. [28] and Liang [32], which gave a better understanding of the load distribution mechanism in DCFST short columns. However, no investigations have been performed on the load distributions in circular DCFST slender columns subjected to eccentric loading.

This paper concerns with the computational simulations of the behavior of eccentrically-loaded circular slender DCFST columns constructed by high-strength concrete for the first time. A new mathematical model is developed to calculate the axial load-deflection responses of circular DCFST slender columns considering geometric and material nonlinearities. The mathematical formulations and computational algorithms that solve the inelastic stability problem of DCFST slender columns are described. The accurate constitutive laws of sandwiched concrete and structural steels considering concrete confinement are presented. The experimental results published are used to verify the mathematical model. A parametric study is given that examines the influences of various geometric and material properties on the load-deflection behavior, column strength curves, load distributions and confinement characteristics of high-strength DCFST slender columns.

2. Mathematical model for DCFST slender columns

2.1. Assumptions

The following assumptions are made in the mathematical formulations of the model:

(1) The bond between the sandwiched concrete and the outer and inner steel tubes is perfect;
(2) Plane sections remain plan after deformation, which results in a linear distribution of strains through the depth of the cross-section as depicted in Fig. 2;
(3) The confinement effect provided by both outer and inner steel tubes is considered by using the stress-strain laws for confined concrete;
(4) The local buckling of circular steel tubes is not taken into account;
(5) Failure occurs when the concrete strain of the extreme compression fiber attains the maximum strain;
(6) The effect of concrete creep and shrinkage is ignored.

2.2. Modeling of cross-sections

The mathematical model utilizes the fiber element method to