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Nonlinear analysis of circular double-skin concrete-filled steel tubular columns under axial compression

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ABSTRACT

The use of the circular hollow steel tube in a circular concrete-filled steel tubular (CFST) column significantly alters the confinement mechanism in the conventional CFST column. The confinement models proposed for conventional circular CFST columns are therefore not applicable to circular double-skin CFST (DCFST) columns. This paper presents a new numerical model for predicting the structural performance of circular DCFST short columns under axial compression. The numerical model incorporates new material constitutive relationships of sandwiched concrete in circular DCFST columns. The confinement effects provided by the outer and inner steel tubes on the sandwiched concrete in circular DCFST columns are taken into account in the numerical formulations. Comparisons with existing experimental results on circular DCFST short columns are made to verify the numerical model developed. The numerical model is used to undertake parametric studies to examine the effects of important geometric and material parameters on the strength and ductility of axially loaded DCFST short columns. It is demonstrated that the numerical model can accurately capture the complete axial load-strain characteristics of circular DCFST short columns under axial compression. A design formula is proposed and found to predict well the ultimate axial loads of circular DCFST short columns.

1. Introduction

A circular double-skin concrete-filled steel tubular (DCFST) column is constructed by filling concrete between two concentric circular steel tubes as depicted in Fig. 1. This type of composite columns is recognized as a new form of double-skin composite panels used in submerged tube tunnels as studied by Wright et al. [1,2] and Liang et al. [3,4]. The use of the inner hollow steel tube in a CFST column not only remarkably reduces the structural weight but also significantly increases the bending stiffness, ductility and seismic performance of the CFST column. In addition, building services can be placed in the inner hollow steel tubes in DCFST columns. However, the use of the circular hollow steel tube in a circular CFST column obviously alters the confinement mechanism in the conventional CFST column. Consequently, the behavior of circular DCFST columns is significantly different from that of conventional circular CFST columns. This highlights the need for experimental studies on this type of composite columns. Extensive experimental studies on the structural performance of conventional circular CFST columns have been conducted in the past few decades [5–14]. However, experimental studies on the performance of circular DCFST short columns under axial compression are very limited [15–19].

Wei et al. [15] tested twenty-six circular double-skin steel tubular short columns filled with polymer concrete under axial compression to study the local instability issue and the strength and ductility enhancement due to the interaction. It was observed that the typical failure modes of DCFST short columns were the local buckling of the outer and inner steel tubes and concrete shear failure in the buckled region. In addition, the DCFST short columns had the ultimate axial strengths of 10–30% higher than the sum of the strength of steel and concrete components. Moreover, the axial strain at the column ultimate load was much larger than the peak point strains of individual components. The test observations demonstrated that the confinement effect increased the strength and ductility of circular DCFST columns.

Experimental investigations into the behavior of six cold-formed circular DCFST short columns under axial compression were undertaken by Zhao et al. [16]. The diameter-to-thickness (D_o/t_o) ratios of the outer steel tubes ranged from 19 to 57 while the diameter-to-thickness (D_i/t_i) ratios of the inner steel tubes varied from 17 to 33. The sandwich between the two steel tubes was filled with concrete with average compressive cylinder strength of 63.4 MPa. However, the ends of all specimens were not strengthened by

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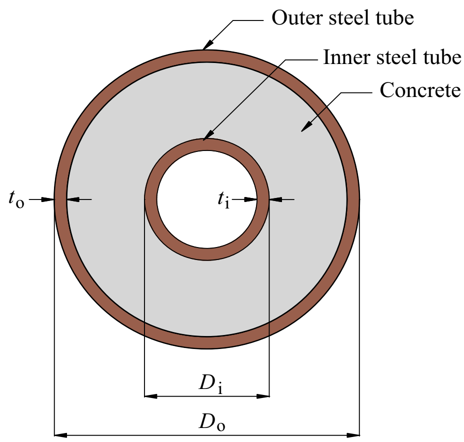

Fig. 1. Cross-section of circular DCFST column.

stiffeners to prevent the ends of the steel tubes from the premature failure. Two typical failure modes were observed, namely the so-called "elephant foot buckling" formed near the ends and the concrete diagonal shear failure. DCFST columns with slender outer steel sections were found to have higher ductility and energy absorption capacity than the hollow outer steel sections.

Tao at al. [17] conducted experiments to investigate the effects of the diameter (D_i/D_o) ratio of the inner-to-outer steel tubes and the diameter-to-thickness ratios of both steel tubes on the behavior of circular DCFST short columns. Twelve cold-formed circular DCFST short columns under axial compression were tested to failure. The D_i/D_o ratio of these tested specimens ranged from 0.267 to 0.778. The D_o/t_o ratios of the outer tubes ranged from 38 to 100 while the inner tubes had D_i/t_i ratios varying from 16 to 55. Test results showed that the outer steel tubes buckled locally outward while the inner steel tubes could buckle locally inward depending on the D/t ratios of the tubes. Further tests on DCFST short columns under axial loading were conducted by Uenaka et al. [18]. They observed that the confinement effect existed in circular DCFST columns.

The behavior of conventional circular CFST columns has been studied analytically and numerically by researchers [7,9,10,20–36]. Kostic et al. [37] developed a concentrated plasticity beam-column model based on the generalized plasticity material model for CFST beam-columns. The axial force and bending moment interaction, gradual yielding and strain hardening of material and nonlinear geometry under large displacements were taken into account in the model. The proposed model was shown to be accurate and computationally efficient. However, there are very few numerical models developed for simulating the performance of circular DCFST short columns [17,38–41]. The analytical model proposed by Wei et al. [38] for double-skin polymer concrete-filled steel tubular columns considered the confinement effect. The material stress-strain relationships of confined polymer concrete were a function of the effective lateral confining stress, which was determined by using an iterative procedure. Tao et al. [17] developed a fiber element model for the nonlinear analysis of axially loaded circular DCFST columns. The material constitutive model for confined concrete in conventional circular CFST columns was used in the analysis of circular DCFST columns and the effect of the inner steel tube on the concrete confinement was not considered. They recognized that the fiber element model needs to be improved in order to accurately predict the post-peak behavior of DCFST short columns. The commercial finite element program ABAQUS was used by Huang et al. [39] to simulate the responses of DCFST short columns under axial loading. The stress-strain relationship for confined concrete in conventional circular CFST columns given by Han et al. [42] was used to model the material behavior of sandwiched concrete in circular DCFST columns.

Hu and Su [40] proposed three lateral confining pressure models based on experimental results presented by Tao et al. [17] and finite element analysis results for confined concrete in circular DCFST columns. In these models, the lateral confining pressure was expressed as a function of the geometric parameters of the outer and inner steel tubes or combined geometric parameters and yield strength of steel tubes. A material degradation factor was also proposed for modeling the post-peak behavior of the confined concrete. The proposed model and material degradation factor were used in the stress-strain relationship for sandwiched concrete in DCFST short columns. The models proposed by Hu and Su [40] were employed by Pagoulatou et al. [41] in the finite element models developed for the nonlinear analysis of DCFST short columns under axial loading. The results showed that the confining pressure models by Hu and Su generally yielded more accurate predictions of the structural performance of DCFST columns than the ones for concrete in conventional CFST columns.

It should be noted that the confinement model proposed by Hu and Su [40] was based on limited test data. Further evaluations of their lateral confining pressure models are necessary. Moreover, new models need to be developed to accurately determine the post-peak behavior of the sandwiched concrete confined by the outer and inner steel tubes. This paper presents accurate constitutive models developed based on the previous work for simulating the material behavior of confined concrete in circular DCFST columns. The new material constitutive relationships are incorporated in the numerical model based on the fiber element formulation to predict the behavior of DCFST short columns under axial compression. The accuracy of the lateral confining pressure models given by Hu and Su [40] is examined. The numerical model is used to investigate the effects of various geometric and material parameters on the strength and ductility of circular DCFST short columns. A design model is proposed for the design of circular DCFST short columns.

2. The numerical model

2.1. General

There are three numerical models that can be used to undertake the nonlinear inelastic analysis of composite columns, including the continuum finite element model, fiber element model and inelastic beam-column model [37,43–46]. In the finite element modeling, the column is divided into three dimensional elements with many degrees of freedom along its length. In addition, contract elements need to be used to model the interaction between the steel tubes and the sandwiched concrete. Because there are many degrees of freedom in a finite element model, the computational cost of the nonlinear finite element analysis is very high compared to the fiber element model, where the discretization of the column along its length is not required. In this paper, therefore, the numerical model is formulated based on the fiber element method. The typical fiber element discretization of the cross-section of the circular DCFST column is illustrated in Fig. 2. The outer steel tube, the inner steel tube and the sandwiched concrete can be assigned different material properties. The material uniaxial stress-strain relationships are used to calculate fiber stresses from fiber strains. The axial force acting on the cross-section is determined as the stress resultant.

2.2. Stress-strain relationships for sandwiched concrete

The confinement mechanism in circular DCFST short columns is different from that in conventional circular CFST short columns

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