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Nonlinear analysis of rectangular concrete-filled double steel tubular short columns incorporating local buckling

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ABSTRACT

Rectangular concrete-filled double steel tubular (CFDST) columns with inner circular steel tube possess higher structural performance than conventional concrete-filled steel tubular (CFST) columns. However, the local buckling of the outer steel tube of thin-walled rectangular CFDST columns has not been accounted for in the existing fiber element models and design codes that may overestimate the column ultimate axial strengths. This paper describes a computationally efficient fiber-based modeling technique developed for determining the behavior of concentrically-loaded rectangular CFDST short columns including the local buckling effects of the external steel tube and the confinement offered by the internal circular steel tube. The effective width concept is used to simulate the post-local buckling of the outer steel tube. Comparative studies are undertaken to verify the fiber-based model with the relevant test results. The computational model is then employed to investigate the axial load–strain responses of rectangular CFDST short columns with various key design variables. A design equation is developed for computing the ultimate axial loads of short rectangular CFDST columns and compared with design methods given in several international design codes. It is shown that the fiber-based modeling technique and the proposed design model predict well the structural performance of short CFDST columns.

1. Introduction

The rectangular concrete-filled double steel tubular (CFDST) column is a high performance composite column, which is constructed by an outer rectangular steel tube and an inner circular steel tube filled with concrete as depicted in Fig. 1. Experiments conducted by Knowles and Park [1], Tomii et al. [2], Schneider [3] and Sakino et al. [4] indicated that the rectangular or square steel tube provided little confinement to the filled concrete while the circular steel tube offered a significant confinement to the concrete infill. The addition of a circular steel tube to the rectangular concrete-filled steel tubular (CFST) column remarkably improves the column structural performance. The circular steel tube provides confinement to the core concrete, which increases the strength and ductility of the core concrete and thereby improves the ultimate axial loads, stiffness, ductility, shear-resistance and fire-resistance of CFDST columns. The concrete within the inner circular steel tube not only prevents the local buckling of the inner steel tube but also increases the overall buckling strength and fire-resistance of the inner hollow steel tube. Therefore, thin-walled rectangular CFDST columns are utilized in high-rise composite steel-concrete buildings, industrial buildings and bridges to support heavy loads. The CFDST columns are characterized by the outward local-buckling of the external rectangular steel tube. However, the local buckling effects have not been incorporated in the fiber-based analysis models for thin-walled CFDST columns and in international design codes including Eurocode 4 [5], ACI 318-11 [6], AISC 360-16 [7] and AIJ [8]. A fiber element simulation technique considering the local buckling effects and concrete confinement is much needed for accurately predicting the axial load-strain responses of rectangular CFDST columns with thin-walled sections.

Computational and experimental investigations on the responses of circular short CFDST columns subjected to axial loading have been undertaken by researchers, such as Peng et al. [9], Hassanein et al. [10], Wan and Zha [11], Xiong et al. [12], and Ekmekyapar and Al-Eliwi [13]. These studies showed that the core concrete was confined by both the inner and outer circular steel tubes, which increased both the ductility and capacity of circular CFDST columns. Ahmed et al. [14] proposed confinement models for the core concrete in short CFDST circular columns based on available test results while the confinement model presented by Hu et al. [15] was adopted to compute the

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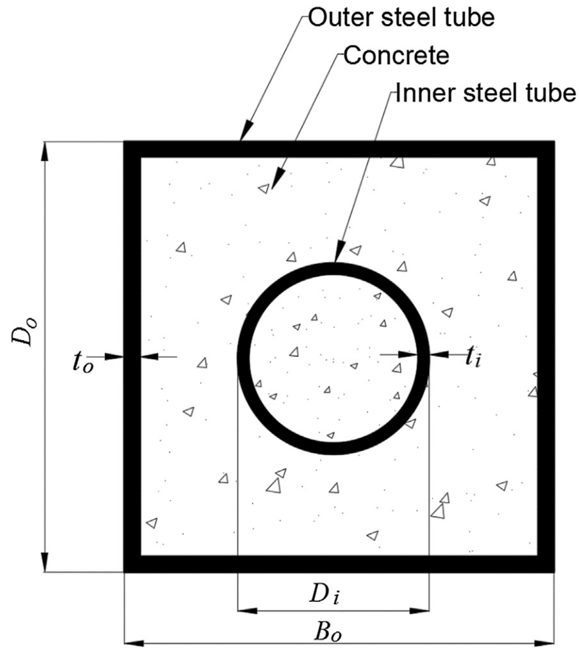

Fig. 1. Cross-section of rectangular CFDST column with inner circular steel tube.

maximum compressive strength of the concrete between the two tubes. The fiber technique implementing these confinement models was shown to capture well the behavior of circular CFDST short columns.

Relatively limited investigations on the behavior of square CFDST columns under static loading were conducted by researchers [16–20]. Lu and Zhao [16] presented a numerical method for computing the load-deflection relationships of eccentrically-loaded square slender CFDST columns with various width-to-thickness, loading eccentricity and column slenderness ratios. Pei [18] performed experimental investigations on short and slender square CFDST columns subjected to axial and eccentric loading and used the finite element software ANSYS to analyze square CFDST short columns. The effects of the inner circular tube with various thicknesses, diameters and steel yield stresses on the performance of CFDST columns were examined. The 23 square short CFDST columns under axial compressive loads were tested to failure by Qian et al. [19]. The experimental results indicated that the local buckling of the square steel tube occurred outwardly while the sandwiched concrete near the buckled regions crushed. However, these square CFDST columns still could withstand about 70% of the ultimate axial loads and had the ultimate axial strains ranging from 0.09 to 0.11. The finite element software ABAQUS was utilized by Qian et al. [19] to analyze short square CFDST columns including local buckling effects. Wang et al. [20] undertook tests on 12 square cold-formed thin-walled CFDST short columns with stiffeners under axial compression. It was reported that the failure mode of all CFDST columns was the outward local buckling of the external square steel tube. The outer steel tube at the stiffeners buckled locally outward because the sandwiched concrete crushed and the stiffeners buckled. No local buckling of the inner circular steel tube was observed so that the core concrete was effectively confined by the internal tube, which improved the column ultimate load and ductility. The finite element software ABAQUS was employed by Wang et al. [20] to study the behavior of short CFDST columns.

It should be noted that at the early loading stage, the inner circular steel tube does not provide confinement to the core concrete because the Poisson's ratio of the concrete is less than that of the steel. When the axial compressive stress in concrete is greater than its unconfined compressive strength, the sandwiched concrete crushes and separates from the inner steel tube. Under this high axial compressive stress, the core concrete expanses and eventually inserts a lateral pressure on the inner steel tube so that the inner circular steel tube confines the core concrete. In the numerical analysis, the confinement effect is considered in the stress-strain model for concrete in circular steel tubes when the axial compressive stress in the concrete is greater than its unconfined compressive strength as discussed by Liang [21].

The dynamic and impact responses of CFDST columns and double-skin concrete-filled steel tubular (DCFST) columns have been studied in recent years. Han et al. [22] developed a fiber element model for determining the cyclic behavior of square and circular DCFST beam-columns with inner circular tubes. Simple models were proposed that compute the moment-curvature and lateral load-deflection responses of DCFST beam-columns under cyclic lateral loads. The seismic performance of high-strength square CFDST columns with various geometric parameters and axial force levels were experimentally investigated by Qian et al. [23]. It was observed that the sandwiched and core concrete crushed and the outer square steel tube buckled locally outward. Wang et al. [24] employed ABAQUS software to quantify the effects of impact height as well as geometric and material properties on the behavior of circular DCFST columns under lateral impact. They reported that the hollow ratio had a significant effect on the dynamic resistance of DCFST columns, which should account for the dynamic increase factor when the confinement factor is greater than 1.03. The blast resistance of square DCFST columns made of high performance steel-fiber reinforced concrete was studied experimentally and numerically by Zhang et al. [25]. The experimental results showed that square DCFST columns could resist a large blast load without failure. Aghdamy et al. [26] utilized the finite element software LS-DYNA to investigate the effects of load-related parameters on the behavior of circular DCFST columns under lateral impact. Large-scale tests and numerical analyses on the flexural behavior of square DCFST members under blast loads were conducted by Ritchie et al. [27]. Their study indicated that increasing the width of the inner steel tube increased the ultimate moment capacity of DCFST columns and the width and thickness of the outer tube had a significant effect on the ductility of DCFST columns.

The local buckling of the external steel tube is one of the main failure modes associated with rectangular CFDST short columns with inner circular steel tube. The local buckling of thin steel plates restrained by concrete was studied previously by researchers [28–33]. Liang and Uy [31] derived effective width models for calculating the post-local buckling strength of steel plates in rectangular CFST columns based on finite element analyses. Liang et al. [32] utilized these effective width models in the inelastic analysis of rectangular short CFST columns. Liang et al. [33] also investigated the local and post-local buckling strengths of steel tube walls of rectangular CFST columns under biaxial loads and developed expressions for determining initial local and post-local buckling strengths of clamped steel plates. The expressions were implemented in the fiber based models to include local buckling in the inelastic simulations of CFST columns subjected to biaxial loads by Liang [34,35].

Although the local buckling of the external rectangular steel tube in CFDST columns could be considered in the finite element analysis using commercial programs, the nonlinear inelastic finite element analysis of CFDST columns is highly time consuming and expensive. This paper presents a computationally efficient fiber-based modeling technique for the simulation of rectangular CFDST short columns including the effects of the progressive local and post-local buckling of the outer rectangular steel tube. The fiber-based analysis technique incorporates the confinement to the core concrete offered by the inner circular steel tube. The model validation is performed by comparing the predicted ultimate axial strength and load-strain relationships with the corresponding test results. The developed computer program is then used to evaluate the influences of important variables on the ultimate load and behavior of short CFDST columns. A design formula is developed for rectangular short CFDST columns considering the concrete confinement and local buckling and verified by independent test results as well as design codes.