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Behavior of biaxially-loaded rectangular concrete-filled steel tubular slender beam-columns with preload effects

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ABSTRACT

In composite construction, rectangular hollow steel tubular slender beam-columns are subjected to preloads arising from construction loads and permanent loads of the upper floors before infilling of the wet concrete. The behavior of biaxially loaded thin-walled rectangular concrete-filled steel tubular (CFST) slender beam-columns with preloads on the steel tubes has not been studied experimentally and numerically. In this paper, a fiber element model developed for CFST slender beam-columns with preload effects is briefly described and verified by existing experimental results of uniaxially loaded CFST columns with preload effects. The fiber element model is used to investigate the behavior of biaxially loaded rectangular CFST slender beam-columns accounting for the effects of preloads and local buckling. Parameters examined include local buckling, preload ratio, loading angle, depth-to-thickness ratio, column slenderness, loading eccentricity and steel yield strength. The results obtained indicate that the preloads on the steel tubes significantly reduce the stiffness and strength of CFST slender beam-columns with a maximum strength reduction of more than 15.8%. Based on the parametric studies, a design model is proposed for axially loaded rectangular CFST columns with preload effects. The fiber element and design models proposed allow for the structural designer to efficiently analyze and design CFST slender beam-columns subjected to preloads from the upper floors of a high-rise composite building during construction.

1. Introduction

Rectangular concrete-filled steel tubular (CFST) slender beam-columns have been widely used in the construction of modern high-rise composite buildings because of their high strength and stiffness performance. During the construction of a high-rise composite building, hollow steel tubes are subjected to preloads arising from construction loads and permanent loads of the upper floors before infilling of the wet concrete. The stresses and deformations in the hollow steel tubes induced by the preloads might significantly reduce the ultimate strengths of CFST slender beam-columns. Experimental and theoretical studies on biaxially loaded thin-walled rectangular CFST slender beam-columns with preload effects have not been reported in the literature. Therefore, an effective fiber element model for the nonlinear analysis and design of biaxially loaded thin-walled CFST slender beam-columns incorporating preload effects is much needed.

Extensive experimental studies on the behavior of CFST columns without preload effects have been conducted [1–11]. Test results demonstrated that the confinement effect provided by the rectangular steel tube did not increase the compressive strength of the concrete core but considerably improved its ductility [1]. In addition, local buckling of the steel tubes was found to remarkably reduce the ultimate strength and stiffness of thin-walled CFST columns [12–17]. Moreover, Liang et al. [16,17] utilized the finite element method to investigate the local and post-local buckling behavior of steel plates in double skin composite panels and thin-walled CFST columns under axial load and biaxial bending. They proposed a set of formulas for determining the initial local buckling stresses and post-local buckling strengths of steel plates in CFST columns under stress gradients. These formulas can be incorporated in numerical models to account for local buckling effects in the nonlinear analysis of thin-walled CFST columns under biaxial bending. Mursi and Uy [18] conducted tests to study the local and global buckling behavior of square CFST short and slender columns under biaxial bending without preload effects. These specimens were made of high strength steel tubes with yield strength of 701 MPa and low strength concrete. Unique orthogonal knife edge end supports were designed to simulate

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the free rotations in the two orthogonal planes of bending. The depth-to-thickness ratio of the steel tube was varied from 24 of compact sections to 54 of relatively slender sections. This was an important study as it provided test results on biaxially loaded high-strength CFST slender columns made of slender steel sections, which can be used to validate numerical models.

There have been very limited experimental investigations on CFST columns with preload effects. The effects of preload on the ultimate axial strengths of eccentrically loaded circular CFST slender beam-columns were studied experimentally by Zha [19] and Zhang et al. [20]. Han and Yao [21] described experimental investigations on eccentrically loaded normal strength rectangular CFST columns including preload effects. The constant preload was applied to the steel tube by pre-stressing bars before filling the wet concrete. Test parameters included the preload ratio, column slenderness and loading eccentricity. Test results indicated that the preload on the steel tube caused initial deflections which reduced the ultimate axial strengths of CFST beam-columns. Liew and Xiong [22] undertook tests on axially loaded circular CFST short and slender columns with preloads on the steel tubes. Their study showed that the preload on the steel tube might reduce the ultimate axial strength of the circular CFST slender beam-column by 15%, provided that it was greater than 60% of the ultimate axial strength of the hollow steel tube. The strength and behavior of short circular CFST columns were not affected by preloads.

Analytical and numerical models have been developed for simulating the nonlinear inelastic behavior of CFST columns without preload effects [23–25]. A semi-analytical model was presented by Lakshmi and Shanmugam [26] that simulates the behavior of CFST slender columns under axial load and biaxial bending. A generalized displacement control method was employed in the model to solve nonlinear equilibrium equations. Mursi and Uy [27] developed a numerical model for the nonlinear analysis of biaxially loaded CFST short and slender columns incorporating local buckling effects. Their work was a good attempt to address the local and global interaction buckling problem of CFST slender columns under biaxial loads. In their model, the elastic local buckling of steel plates under stress gradients was considered, but the post-local buckling strength of plates was determined by the effective width formulas for steel plates under uniform compression. In addition, the progressive post-local buckling of steel tubes has not been modeled by redistributing the stresses on the steel tube walls. Moreover, the unconfined concrete model adopted in their study did not account for the confinement effect on the concrete ductility while the confined concrete model used was shown to give a significant increase in the strengths. Furthermore, the numerical solution method has not been described in their paper. Liang [28,29] developed a performance-based analysis (PBA) technique for predicting the ultimate strength and ductility of biaxially loaded thin-walled CFST short beam-columns without preload effects. The PBA technique incorporated effective width formulas proposed by Liang et al. [17] to account for the effects of progressive local buckling. Moreover, numerical models that do not consider preload effects were developed by Patel et al. [30,31] and Liang et al. [32] that simulate the load–deflection responses and load–moment interaction diagrams of high strength thin-wall rectangular CFST slender beam-columns under combined axial load and bending.

Xiong and Zha [33] utilized the finite element analysis ABAQUS program to study the behavior of eccentrically loaded circular CFST slender beam-columns considering preload effects. It was observed that the ultimate axial strengths of CFST columns decreased with increasing the preloads on the steel tubes. They proposed a simplified formula for calculating the ultimate strength of CFST beam-columns subjected to axial or eccentric loading. However, their model and formula are applicable only to circular CFST slender beam-columns. Liew and Xiong [22] proposed a design method for determining the strength of axially loaded circular CFST slender columns incorporating preload effects. However, their model yields very conservative prediction of axially loaded rectangular CFST columns with preload ratio greater than 0.4. A numerical model was proposed by Patel et al. [34] for predicting the load–deflection behavior of eccentrically loaded circular CFST slender beam-columns accounting for the effects of preloads, initial geometric imperfections, concrete confinement and second order.

The above literature review clearly shows that there have been very limited experimental and numerical studies on the behavior of uniaxially loaded rectangular CFST slender beam-columns with preloads effects. No investigations have been reported on biaxially loaded rectangular CFST slender beam-columns considering the effects of preload and local buckling. In this paper, a fiber element model developed for the nonlinear analysis of biaxially loaded rectangular CFST slender beam-columns incorporating the effects of preload and local buckling is briefly described. The fiber element model is verified by comparisons with existing test results and used to investigate the behavior of biaxially loaded CFST slender beam-columns with various important parameters. A design model for axially loaded rectangular CFST columns considering preload effects is proposed and compared with the design method given by Liew and Xiong [22].

2. Fiber element model

2.1. Fiber element method

The inelastic behavior of the cross-section of a CFST beam-column is modeled by the fiber element method [28]. The column cross-section is divided into fine fiber elements as shown in Fig. 1. It is assumed that the plane section remains plane after deformation. This results in a linear strain distribution throughout the depth of the section as depicted in Fig. 1. Each fiber element can be assigned either steel or concrete material properties. Fiber stresses are calculated from fiber strains using material uniaxial stress–strain relationships. Axial forces and bending moments carried by the cross-section are determined as stress resultants in the composite section.

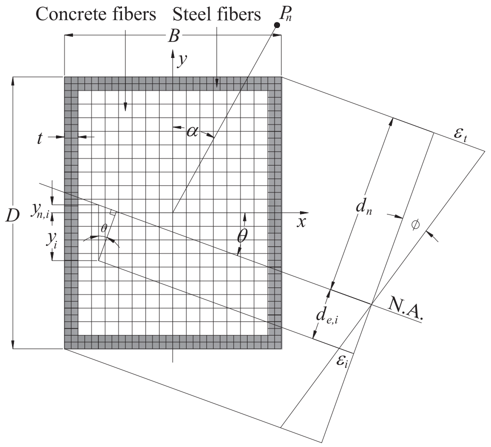

Fig. 1. Fiber strain distribution in CFST beam-column section under axial load and biaxial bending.