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Nonlinear analysis of short concrete-filled steel tubular beam–columns under axial load and biaxial bending

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Abstract

This paper presents a nonlinear fiber element analysis method for determining the axial load–moment strength interaction diagrams for short concrete-filled steel tubular (CFST) beam–columns under axial load and biaxial bending. Nonlinear constitutive models for confined concrete and structural steel are considered in the fiber element analysis. Efficient secant algorithms are developed to iterate the depth and orientation of the neutral axis in a composite section to satisfy equilibrium conditions. The accuracy of the fiber element analysis program is verified by comparisons of fiber analysis results with experimental data and existing solutions. The fiber element analysis program developed is employed to study the effects of steel ratios, concrete compressive strengths and steel yield strengths on axial load–moment interaction diagrams and the C-ratio of CFST beam–columns. The proposed fiber element analysis technique is shown to be efficient and accurate and can be used directly in the design of CFST beam–columns and implemented in advanced analysis programs for the nonlinear analysis of composite columns and frames.

Keywords: Biaxial bending; Composite columns; Fiber element analysis; Nonlinear analysis; Strength

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1. Introduction

Concrete-filled steel tubular (CFST) columns have been widely used in buildings and bridges due to their excellent structural performance such as high strength, high stiffness, high ductility and large strain energy absorption capacities. Columns at corners or with their principal directions different from those of the floor plan or columns resisting earthquake or wind loads are often subjected to axial load and biaxial bending. Design codes usually require that all columns should be designed to resist axial load as well as bending moments [1–3]. This implies that all columns should be treated as beam–columns. High strength concrete and steels are increasingly used in CFST beam–columns in high rise buildings. The analysis of high strength CFST beam–columns under axial load and biaxial bending is complex and current design codes do not provide sufficient specifications for the design of such columns. Experiments can be conducted to investigate the inelastic behavior of CFST beam–columns and to verify numerical methods, but they are highly expensive and time-consuming. These highlight the need for an advanced computational technique for the nonlinear analysis and design of CFST beam–columns.

Experiments on the ultimate load behavior of CFST columns have been conducted by many researchers. Furlong [4] carried out ultimate strength tests on circular and square CFST columns under axial load and uniaxial bending. His studies indicated that for columns in compression, steel and concrete components carried their loads independently. The concrete confinement effect, which increased the concrete strength, was observed in thick-walled specimens only. In thin-walled specimens, steel walls buckled after the yield strain was exceeded indicating the concrete core delayed the local buckling of thin steel walls. The ultimate strength of a CFST beam–column section could be determined by treating the composite section as an ordinary reinforced concrete section. Knowles and Park [5] conducted an investigation into axially and eccentrically loaded circular and square CFST columns with a wide range of slenderness ratios. They reported that all axially loaded columns tested failed by column buckling. No plastic local buckling was observed in all columns while concrete failure only occurred after the maximum load was reached. Moreover, the concrete strength in short circular columns was shown to increase

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due to confinement effect. However, the concrete in short square CFST columns did not show a significant increase in strength. For CFST columns under eccentric loads, the straight-line interaction formula is unsafe for slender columns and conservative for short columns. Experiments on full-scale concrete-filled rolled rectangular hollow-section columns were undertaken by Shakir-Khalil and Mouli [6].

Tomii et al. [7] studied the effects of sectional shapes on the axial load–strain behavior of CFST columns. They reported that at high axial loads, circular and many octagonal steel tubes offered confinement to the filled concrete core and these columns exhibited strain-hardening characteristics. Square steel tubes that resisted concrete pressure by plate bending provided little confinement to the concrete core. As a result, no strain-hardening behavior was observed in square steel tubes filled with concrete. Schneider [8] presented an experimental study on the behavior of axially loaded short CFST columns with depth-to-tube wall thickness ratios between 17 to 50. His study demonstrated that circular CFST columns offered more post-yield axial ductility than square or rectangular CFST columns. All circular CFST columns exhibited strain-hardening characteristics while only square or rectangular CFST columns with $D/t < 20$ possessed this behavior. Significant confinement was not present for most specimens until the axial load reached the 92% of the column yield strength. Local buckling of circular steel tubes occurred at an axial ductility of 10 or more while most local buckling of square and rectangular tubes occurred at ductility between 2 and 8.

Varma et al. [9] investigated experimentally the effects of width-to-thickness ratios, yield strengths of steel tubes and the axial load level on the stiffness, strength and ductility of high-strength CFST beam–columns under monotonic and cyclic loads. Their test results indicated that cyclic loading did not have a significant influence on the stiffness and strength of CFST beam–columns, but induced a more rapid decrease in the post-peak moment capacity. The monotonic curvature ductility of high-strength CFST square beam–columns decreased significantly with an increase in the axial load level or the width-to-thickness ratio of the steel tube. However, the yield strength of the steel tube did not have a significant effect on the curvature ductility. Han [10] performed experiments to investigate the effects of constraining factors and the width ratios on the ultimate strength and ductility of short, rectangular CFST columns under axial compression. Experimental results demonstrated that the axial strength and ductility of CFST columns increased with an increase in the constraining factor but decreased with an increase in the width ratio.

Thin-walled steel tubes and high strength concrete have been increasingly used in CFST beam–columns due to their beneficial advantages. However, the use of thin-walled tubes in CFST beam–columns gives rise to local buckling of thin-walled steel tubes. Ge and Usami [11] presented an experimental study on concrete-filled thin-walled steel box columns with and without internal stiffeners under cyclic compressive loads. Experimental results demonstrated that CFST columns offered high strength and high ductility performance compared to hollow steel tubular columns. Local buckling occurred before the maximum load was reached and steel plates buckled outward in all faces of a column. It seems that local plate buckling was induced after concrete was damaged. Bridge and O'Shea [12] performed tests to examine the behavior of axially loaded short thin-walled steel box columns with or without concrete infill. Their tests showed that the infill concrete enhanced the resistance to the local buckling of steel tubes in CFST columns compared to that of bare steel tubes. The strength of thin-walled steel tubes in CFST columns can be determined by using the design provisions in Australian Standards and treating the boundary condition of the square steel plate as clamped.

Uy [13,14] conducted tests on the local and post-local buckling behavior of thin steel plates in concrete-filled welded steel box columns with large width-to-thickness ratios. Test results indicated that local buckling significantly reduced the strength of CFST columns with large width-to-thickness ratios. Wright [15] presented theoretical studies on the local buckling of steel plates in thin-walled composite members using an energy method and derived limiting width-to-thickness ratios for steel plates in contact with concrete. Liang and Uy [16] and Liang et al. [17] investigated the local and post-local buckling characteristics of steel plates in thin-walled CFST columns under axial load and combined axial load and biaxial bending using the nonlinear finite element method. They proposed a set of effective width formulas for the ultimate strength predictions of steel plates in thin-walled CFST beam–columns. Furthermore, Liang et al. [18] reported the local and post-local buckling behavior of steel plates in double skin composite panels under biaxial compression and shear.

Nonlinear analysis methods for predicting the behavior of composite columns have been developed [19]. El-Tawil et al. [20] proposed a fiber element method for the nonlinear analysis of concrete-encased composite columns under axial load and biaxial bending. The concrete confinement effect was considered using the stress–strain model for confined concrete. The results of the fiber analyses were used to evaluate nominal uni- and biaxial bending strengths of composite columns determined on the basic of ACI-318 [2] and AISC-LRFD [3] specifications. El-Tawil and Deierlein [21] employed the nonlinear fiber element analysis technique to investigate the effects of steel ratios, concrete compressive strengths and concrete confinement on the strength and ductility of concrete-encased composite beam–columns. Muñoz and Hsu [22] proposed a fiber element model for the nonlinear analysis of both short and slender concrete-encased composite columns under axial load and biaxial bending. The finite different method in combination with the secant stiffness matrix was used to solve the system of nonlinear equations with an incremental strain procedure. Chen et al. [23] presented an iterative quasi-Newton procedure based on the Regula-Falsi numerical scheme for the sectional analysis and design of short concrete-encased composite columns of arbitrary shapes. In their scheme, stress resultants of concrete were evaluated by integrating the stress–strain curve over the compression zone