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Performance-based analysis of concrete-filled steel tubular beam–columns, Part I: Theory and algorithms

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ABSTRACT

This paper presents a performance-based analysis (PBA) technique based on fiber element formulations for the nonlinear analysis and performance-based design of thin-walled concrete-filled steel tubular (CFST) beam–columns with local buckling effects. Geometric imperfections, residual stresses and strain hardening of steel tubes and confined concrete models are considered in the PBA technique. Initial local buckling and effective strength/width formulas are incorporated in the PBA program to account for local buckling effects. The progressive local buckling of a thin-walled steel tube filled with concrete is simulated by gradually redistributing normal stresses within the steel tube walls. Performance indices are proposed to quantify the section, axial ductility and curvature ductility performance of thin-walled CFST beam–columns under axial load and biaxial bending. Efficient secant algorithms are developed to iterate the depth and orientation of the neutral axis in a thin-walled CFST beam–column section to satisfy equilibrium conditions. The analysis algorithms for thin-walled CFST beam–columns under axial load and uni- and biaxial bending are presented. The PBA program can efficiently generate axial load–strain curves, moment–curvature curves and axial load–moment strength interaction diagrams for thin-walled CFST beam–columns under biaxial loads. The proposed PBA technique allows the designer to analyze and design thin-walled CFST beam–columns made of compact or non-compact steel tubes with any strength grades and normal and high-strength concrete. The verification and applications of the PBA program are given in a companion paper.

1. Introduction

Concrete-filled steel tubular (CFST) beam–columns are efficient structural members which offer high stiffness, high strength, high ductility and large strain energy absorption capacities. They are increasingly used in lateral load resisting systems for high-rise composite buildings. In a CFST beam–column as depicted in Fig. 1, the steel tube completely encases the concrete core and this remarkably increases the ductility of the concrete core. On the other hand, the concrete core effectively prevents the inward local buckling of the steel tube and as a result its local buckling strength is much higher than that of the hollow tube. In addition, steel tubes are utilized as permanent formwork and longitudinal flexural steel reinforcement for the concrete core, offering significant reductions in construction time and costs. There is a growing interest in using thin-walled high-strength steel tubes and high-strength concrete in CFST beam–columns to maximize economical benefits. However, the use of thin-walled steel tubes and high-strength materials in CFST beam–columns gives rise to local buckling and potential ductility problems. The performance-based design of thin-walled CFST beam–columns requires that both the ultimate strength and ductility of column cross-sections are to be determined. Apparently, it is complicated and time consuming to manually calculate the ultimate strength and ductility of thin-walled CFST beam–columns under axial load and biaxial bending. These highlight a need for the development of a performance-based analysis (PBA) technique for the performance-based design of thin-walled CFST beam–columns.

Extensive studies on the behavior of short CFST columns under axial load have been carried out in the last few decades as reviewed by Shams and Saadeghvazir [1] and Shanmugam and Lakshmi [2]. Kloppel and Goder [3] conducted tests on the axial strengths of CFST columns. Furlong [4] performed ultimate strength tests on eight circular CFST columns and five square columns under axial force. Tests indicated that steel and concrete components carried their loads independent of each other. Knowles and Park [5] studied axially loaded circular and square CFST columns with a wide range of slenderness ratios. They reported that the confinement effect increased the concrete strength in short

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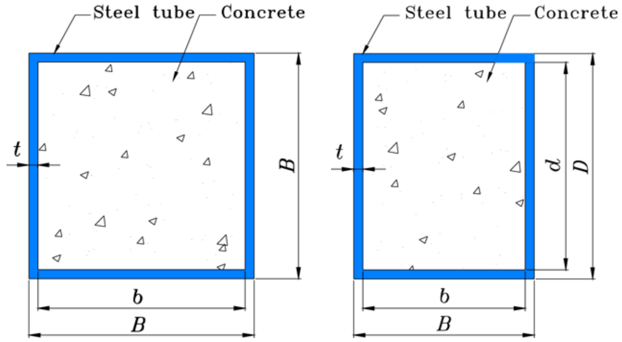

(a) Square section. (b) Rectangular section.

Fig. 1. Thin-walled concrete-filled steel tubular beam–columns.

circular columns but not in short square CFST columns. Tomii et al. [6] studied the effects of sectional shapes on the axial load–strain behavior of CFST columns. They reported that circular and octagonal steel tubes offered confinement to the concrete core at high load and as a result these columns exhibited strain-hardening characteristics. However, square CFST columns did not exhibit strain-hardening behavior. Shakir-Khalil and Mouli [7] presented experimental results of rectangular CFST short columns under axial load. It was observed that at failure steel tube walls were pushed out by the concrete core which took the shape of the deformed steel section.

More recently, Schneider [8] investigated the experimental behavior of axially loaded short CFST columns with depth-to-tube wall thickness ratios ranging from 17 to 50. Test results indicated that circular CFST columns offered more post-yield axial ductility than square or rectangular ones. 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 a ductility ranged from 2 to 8. Han [9] conducted tests to study the effects of constraining factors and width-to-thickness ratios on the performance of rectangular CFST columns. It was observed that the axial strength and ductility of CFST columns increased with an increase in constraining factors but decreased with an increase in width-to-thickness ratios. Sakino et al. [10] investigated experimentally the effects of steel tube shape, steel yield strengths, width-to-thickness ratios and concrete compressive strengths on the axial load–strain behavior of CFST short columns.

When the width-to-thickness ratio of the steel tube wall in a CFST column is large, the steel tube under compression may buckle locally outward. Local buckling of steel tubes remarkably reduces the strength and ductility of thin-walled CFST columns and has been studied by researchers. Ge and Usami [11] tested thin-walled CFST columns with and without internal stiffeners under cyclic loads. It was observed that local buckling occurred before the ultimate load was attained and steel plates buckled outward in all faces of a column. It appeared that local buckling of steel tubes occurred after concrete was damaged. Wright [12] derived limiting width-to-thickness ratios for steel plates in contact with concrete using an energy method. Bridge and O'Shea [13] conducted tests to examine the strengths of axially loaded short thin-walled CFST columns with width-to-thickness ratios ranging from 37 to 130. It was concluded that the strength of thin-walled steel tubes in CFST columns could be calculated by using the effective width formula for clamped steel plates. Uy [14,15] undertook tests on the local and post-local buckling behavior of thin steel plates in welded CFST columns with width-to-thickness ratios ranging from 40 to 100. Test results indicated that local buckling significantly reduced the axial strengths of CFST columns with large width-to-thickness ratios. Liang and Uy [16] and Liang et al. [17,18] investigated the local and post-local buckling behavior of steel plates in thin-walled CFST columns under axial load and biaxial bending and in double skin composite panels using the nonlinear finite element method. They proposed a set of effective strength/width formulas for steel plates in these composite members. It can be seen from above research findings that the effects of local buckling must be taken into account in order to accurately predict the ultimate strength and ductility of thin-walled CFST columns.

The presence of bending moments significantly reduces the ultimate axial strengths of CFST columns and as a result current design codes require that all CFST columns must be designed as beam–columns to sustain axial load as well as bending moments. Furlong [4] tested circular and square CFST beam–columns under constant axial load and increased bending moments. It was concluded that the interaction strengths of CFST beam–column sections could be determined by treating CFST beam–columns as ordinary reinforced concrete sections. Experiments on CFST beam–columns conducted by Knowles and Park [5] indicated that the straight line strength interaction formula was unsafe for slender columns and too conservative for short columns. Shakir-Khalil and Mouli [7] carried out full-scale tests on CFST beam–columns. It was observed that all the tested columns with compact sections failed by overall column buckling with no sign of local buckling. Lu and Kennedy [19] conducted flexural tests to examine the effects of depth-to-width and shear-span-to-depth ratios on the flexural behavior of CFST beams. Experiments on high-strength CFST beam–columns under monotonic and cyclic loads conducted by Varma et al. [20] indicated that 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. Fujimoto et al. [21] investigated the effects of high-strength materials on the flexural behavior of eccentrically loaded CFST beam–columns. It was concluded that the ductility of CFST beam–columns was reduced due to the use of high-strength concrete but increased due to the use of high-strength steel tubes or small width-to-thickness ratios of the steel tubes.

Nonlinear analysis methods for composite columns and structures have been reviewed by Spacone and El-Tawil [22]. Tomii and Sakino [23] presented an analytical elastic–plastic analysis of CFST beam–columns under axial load and uniaxial bending. An elastic–perfectly-plastic stress–strain relationship was used for steel in compression while a tri-linear stress–strain curve was employed for steel in tension and local buckling was not considered. Stress–strain relationships were proposed for confined concrete in CFST beam–columns to account for confinement effects on concrete ductility. El-Tawil et al. [24] and El-Tawil and Deierlein [25] developed a fiber element analysis technique for concrete-encased composite columns under axial load and biaxial bending, which was used 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 [26] 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. [27] proposed 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.

Hajjar and Gourley [28] utilized a fiber element analysis program to generate strength interaction diagrams for CFST beam–columns and proposed strength interaction equations as bounding surface plasticity models for CFST beam–columns. Hajjar et al. [29] proposed a fiber-based distributed plasticity finite