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Nonlinear analysis of circular high strength concrete-filled stainless steel tubular slender beam-columns

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ABSTRACT

Concrete-filled stainless steel tubular (CFSST) slender columns are increasingly used in composite structures owing to their distinguished features, such as aesthetic appearance, high corrosion resistance, high durability and ease of maintenance. Currently, however, there is a lack of an accurate and efficient numerical model that can be utilized to determine the performance of circular CFSST slender columns. This paper describes a nonlinear fiber-based model proposed for computing the deflection and axial load-moment strength interaction responses of eccentrically loaded circular high-strength CFSST slender columns. The fiber-based model incorporates the accurate three-stage stress-strain relations of stainless steels, accounting for different strain hardening characteristics in tension and compression. The material and geometric nonlinearities as well as concrete confinement are included in the computational procedures. Existing experimental results on axially loaded CFSST slender columns are utilized to verify the proposed fiber-based model. A parametric study is conducted to examine the performance of high-strength slender CFSST beam-columns with various geometric and material parameters. It is shown that the fiber-based analysis technique developed can accurately capture the experimentally observed performance of circular high-strength CFSST slender columns. The results obtained indicate that increasing the eccentricity ratio, column slenderness ratio and diameter-to-thickness ratio remarkably decreases the initial flexural stiffness and ultimate axial strength of CFSST columns, but considerably increases their displacement ductility. Moreover, an increase in concrete compressive strength increases the flexural stiffness and ultimate axial strength of CFSST columns; however, it decreases their ductility. Furthermore, the ultimate axial strength of CFST slender columns is found to increase by using stainless steel tubes with higher proof stresses.

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1. Introduction

Concrete-filled steel tubular (CFST) slender columns made of carbon steel tubes have been widely used in composite buildings, arch bridges, offshore structures and electricity pylons [1]. Despite the initial high cost of stainless steel, CFSST columns are increasingly used in modern engineering structures in recent years. The reason for this is that CFSST columns not only have the structural advantages of conventional CFST columns, but also possess aesthetic appearance, high corrosion resistance, high durability and ease of maintenance. To reduce the cost of CFSST columns, high-strength concrete can be utilized to construct CFSST columns. However, the performance of eccentrically loaded circular high-strength CFSST slender columns has not been investigated experimentally and numerically. Moreover, design rules for this type of columns have not been provided in international standards, such as Eurocode 4 [2], LRFD [3], ACI 318-11 [4] and AS 5100.6 [5]. Therefore, there is a need for developing an accurate and efficient numerical model that can be employed to simulate the responses of circular CFSST slender columns under eccentric loading.

Experiments on high-strength CFST slender columns have been undertaken by researchers in the past [6–22]. However, experimental studies of circular high-strength CFSST columns are very limited [23]. Young and Ellobody [24] carried out experiments on high-strength square and rectangular stainless steel tubular short columns made of concrete with strengths ranging from 40 to 80 MPa. Circular and square CFSST short columns subjected to axial loading were tested to failure by Lam and Gardner [25]. These CFSST columns were fabricated using normal strength stainless

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steel tubes and concrete with strengths varying from 30 to 100 MPa. Uy et al. [26] described experimental procedures and observations on short circular and rectangular CFSST columns, which were constructed by low strength concrete and normal strength stainless steel tubes and slender columns made of normal strength stainless steel tubes and normal or high strength concrete. Ellobody and Ghazy [27] tested circular plain CFSST short columns and fiber reinforced CFSST slender beam-columns. Experimental studies on rectangular CFSST slender columns under biaxial loads were reported by Tokgoz [28]. It was found that short CFSST columns had typical failure modes of the outward local buckling of stainless steel tubes and concrete crushing while CFSST slender columns generally failed by global column buckling.

Computational models have been presented for the inelastic analysis of eccentrically loaded CFST slender columns fabricated by high-strength materials [29–38]. However, the strength and behavior of eccentrically loaded circular high-strength CFSST slender columns have not been investigated by inelastic analysis procedures. Ellobody and Young [39], Tao et al. [40] and Hassanein et al. [41] utilized commercial finite element analysis software ABAQUS to simulate short circular and square CFSST columns under axial compression. The structural responses of slender circular stainless steel tubular beam-columns filled with fiber reinforced concrete were investigated by Ellobody [42] using ABAQUS. In these studies, either the measured stress-strain curves or the two-stage stress-strain relations given by Rasmussen [43] were used to simulate the material behavior of stainless steels. Quach et al. [44] reported that stainless steel has different strain hardening characteristics in compression and tension [45] and the two-stage stress-strain laws given by Rasmussen [43] were based on the tension coupon test results, which underestimates the ultimate compressive strength of stainless steels. Patel et al. [46] incorporated the accurate three-stage stress-strain relations given by Quach et al. [44] and Abdella et al. [47] for stainless steels in the fiber element modeling of short circular CFSST columns. The numerical solutions obtained were shown to agree well with experimental results.

The axial load-moment strength interaction behavior of circular high-strength CFSST slender columns under eccentric loads has not been studied by inelastic analysis techniques. In this paper, an efficient nonlinear fiber-based model is formulated for modeling the load-deflection responses of circular high-strength CFSST slender columns as well as their axial load-moment strength interaction curves. The accurate three-stage stress-strain relations of stainless steels with different strain hardening behaviors in tension and compression given by Quach et al. [44] and Abdella et al. [47] are implemented in the fiber-based model for the first time. The nonlinear fiber-based analysis technique is validated by existing experimental data. The verified fiber-based model is employed to determine the effects of important geometric and material parameters on the performance of eccentrically loaded circular CFSST slender columns of made of high-strength materials.

2. Nonlinear fiber-based model

2.1. Cross-sectional analysis

The fiber element analysis method [34,48] is used in the present study to discretize the cross-section of a circular CFSST column as illustrated in Fig. 1. The method assumes that: (a) there is a perfect bond at the interface between the stainless steel tube and concrete; (b) plane section remains plane after deformation; (c) the local buckling of the stainless steel tube is not included; (d) concrete confinement is taken into account; (e) the effect of concrete creep and shrinkage is ignored.

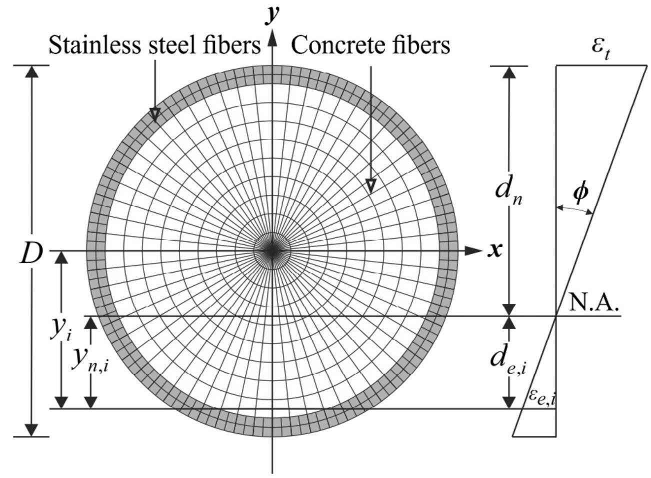

Fig. 1. Typical fiber element discretization of circular cross-section.

The ultimate axial load of a composite cross-section in compression is obtained from its axial load-strain curve simulated by the fiber-based model [48]. The moment-curvature relations of the cross-section are required in the nonlinear analysis of CFSST slender columns under eccentric loading. For a given axial load level, the neutral axis depth (d_n) of the composite section is initialized and the strain (ε_t) at the extreme compressive fiber illustrated in Fig. 1 is computed from the given curvature (ϕ) as $\varepsilon_t = \phi d_n$. The material uniaxial stress-strain relations are used to calculate fiber stresses from fiber strains. The axial force in the cross-section is computed as the stress resultant. The neutral axis depth is iteratively adjusted using the secant method [34,48] or Müller's Method [49,50] until the internal force is in equilibrium with the external axial load. The internal bending moment is then computed as the stress resultant. The above process is repeated until the complete moment-curvature curve is obtained or the stopping criteria are satisfied [34,48]. Fig. 2 presents typical moment-curvature curves for the cross-section of a CFSST beam-column.

2.2. Load-deflection analysis

The present study deals with pin-ended slender beam-columns of length L subjected to axial load (P) with an eccentricity (e) at

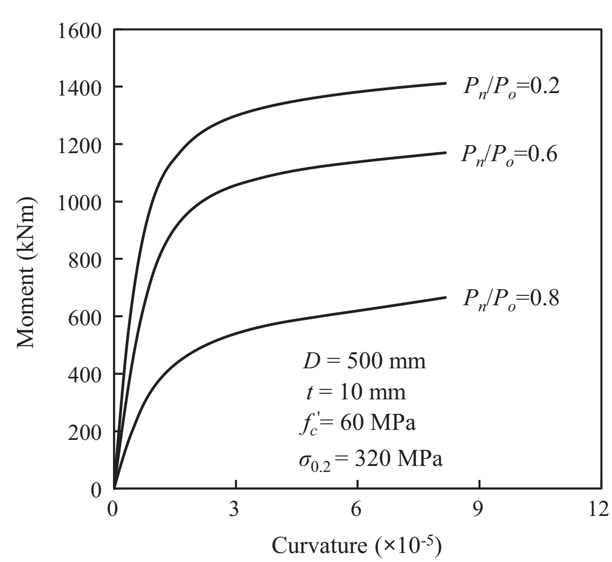

Fig. 2. Moment-curvature curves for the cross-section of a CFSST column.

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