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Nonlinear analysis of axially loaded circular concrete-filled stainless steel tubular short columns

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ABSTRACT

Experiments show that the ultimate compressive strength of stainless steel is much higher than its tensile strength. The full-range two-stage constitutive model for stainless steels assumes that stainless steels follow the same stress–strain behavior in compression and tension, which may underestimate the compressive strength of stainless steel tubes. This paper presents a fiber element model incorporating the recently developed full-range three-stage stress–strain relationships based on experimentally observed behavior for stainless steels for the nonlinear analysis of circular concrete-filled stainless steel tubular (CFSST) short columns under axial compression. The fiber element model accounts for the concrete confinement effects provided by the stainless steel tube. Comparisons of computer solutions with experimental results published in the literature are made to examine the accuracy of the fiber element model and material constitutive models for stainless steels. Parametric studies are conducted to study the effects of various parameters on the behavior of circular CFSST short columns. A design model based on Liang and Fragomeni's design formula is proposed for circular CFSST short columns and validated against results obtained by experiments, fiber element analyses, ACI-318 codes and Eurocode 4. The fiber element model incorporating the three-stage stress–strain relationships for stainless steels is shown to simulate well the axial load–strain behavior of circular CFSST short columns. The proposed design model gives good predictions of the experimental and numerical ultimate axial loads of CFSST columns. It appears that ACI-318 codes and Eurocode 4 significantly underestimate the ultimate axial strengths of CFSST short columns.
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1. Introduction

The material constitutive models used in the nonlinear inelastic analysis of circular concrete-filled stainless steel tubular (CFSST) short columns could have a crucial influence on the accuracy of the predicted behavior. The two-stage stress–strain model for stainless steels proposed by Rasmussen [1] assumes that the stainless steel follows the same stress–strain curve in tension and compression. This model developed from tension coupon tests may underestimate the ultimate axial strengths of CFSST columns. The three-stage constitutive model for stainless steels proposed by Quach et al. [2] accounts for different behavior of stainless steels in compression and in tension based on experimental observations. The three-stage material model is believed to be a more accurate formulation than the two-stage one. The inversion of the three-stage stress–strain relationships for stainless steels given by Abdella et al. [3] expresses the stress as a function of strain. This gives a convenient implementation of the material laws in numerical models. The three-stage stress–strain model for stainless steels has not yet been incorporated in numerical techniques for the nonlinear analysis of CFSST columns.

Experimental studies on the behavior of axially loaded circular concrete-filled steel tubular (CFST) short columns have extensively been conducted by researchers [4–7]. However, research studies on circular CFSST short columns under axial loading have been relatively limited. Young and Ellobody [8] conducted tests on the axial strengths of cold-formed high strength square and rectangular CFSST short columns. Their results indicated that the implementation of the material properties of stainless steel obtained from tension coupon tests underestimated the ultimate axial strengths of CFSST columns under axial compression. This is because the strain hardening of stainless steels in compression is much higher than that of stainless steels in tension. Tests on circular CFSST short columns under axial compression were carried out by Lam and Gardner [9]. They investigated the effects of the tube thickness, concrete compressive strength and proof stress on the behavior of CFSST columns under axial loading. Design formulas based on the Continuous Strength Method were proposed for determining the ultimate axial strengths of CFSST short columns. Uy et al. [10] tested circular CFSST columns under axial compression. Both square and circular column sections were tested to study the effects of the tube shape, diameter-to-thickness ratio and concrete compressive

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strength on the behavior of CFSST columns. They compared various design codes for circular CFSST columns. They reported that existing design codes for composite columns provide conservative predictions of the ultimate strengths of CFSST columns.

Numerical models have been developed to study the behavior of circular CFST short columns under axial loading [11–18]. However, there have been relatively limited numerical studies on the behavior of axially loaded circular CFSST short columns. Nonlinear analysis methods for composite columns and structures have been reviewed by Ellobody [19]. Ellobody and Young [20] utilized the finite element analysis program ABAQUS to study the behavior of axially loaded rectangular CFSST short columns. They incorporated the measured tensile material properties in the finite element model and assumed the same material properties of stainless steel in compression. Nonlinear finite element analyses of square CFSST short columns using ABAQUS have been undertaken by Tao et al. [21]. The two-stage stress–strain model for stainless steels proposed by Rasmussen [1] was employed in their study. The true stress–strain curves were used in the finite element model. Recently, Hassanein et al. [22] employed the finite element program ABAQUS to study the inelastic behavior of axially loaded circular lean duplex CFSST short columns. The finite element results were verified against test results presented by Uy et al. [10].

In this paper, the inversion of the three-stage stress–strain relationships for stainless steels [2,3] is incorporated in the fiber element model for simulating the nonlinear inelastic behavior of CFSST short columns under axial compression. The fiber element model accounts for the effects of concrete confinement and high strength concrete. The fiber element analyses are performed to examine the accuracy of different constitutive models for stainless steels. The effects of diameter-to-thickness ratio, concrete compressive strength and stainless steel proof stress on the behavior of circular CFSST short columns are investigated. A design model based on Liang and Fragomeni's formula [16] is proposed for the design of circular CFSST columns and compared with test results and design codes.

2. Nonlinear analysis

2.1. Assumptions

The nonlinear analysis of CFSST columns under axial compression is based on the fiber element method. The following assumptions are made in the fiber element formulation:

- The bond between the stainless steel tube and the concrete core is perfect.
- The passive confinement provided by the stainless steel tube increases the compressive strength and ductility of the concrete core.
- The stress and strain of fibers are uniformly distributed on the cross-section.
- Strain hardening of stainless steels in compression is considered.
- Failure occurs when the concrete fiber strain reaches the maximum axial strain.
- Local buckling of the stainless steel tube is not considered.
- The effects of concrete creep and shrinkage are not considered.

2.2. The fiber element method

The fiber element method is an accurate numerical technique for determining the cross-section behavior of steel–concrete composite columns [14,15,23–25]. In the fiber element method, a circular CFSST column cross-section is discretized into fine fiber elements as depicted in Fig. 1. Each fiber element represents a fiber of material running longitudinally along the column and can be assigned either stainless steel or concrete material properties. The fiber stresses are calculated from fiber strains using the material uniaxial stress–strain relationships. Although the discretization of a CFSST column under axial compression is not

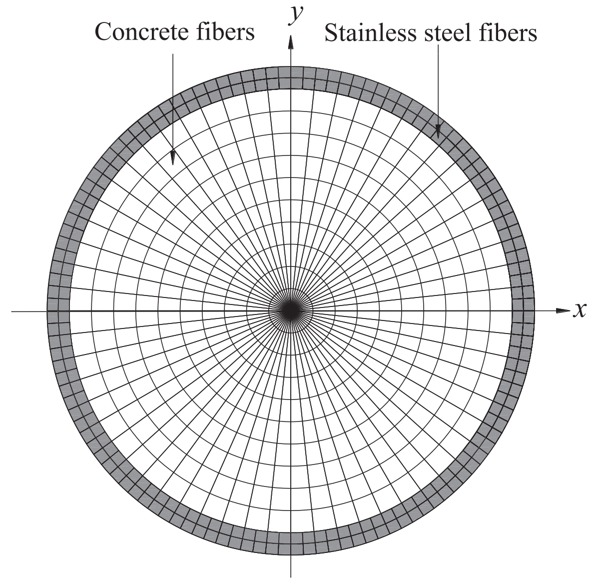

Fig. 1. Fiber element discretization of circular CFSST section.

required, it is a prerequisite for the nonlinear analysis of CFSST short columns under eccentric loading or CFSST slender columns [26,27]. The present study is part of a research program on the nonlinear analysis of CFSST slender columns so that the composite section is discretized using the fiber element method. However, the size of fiber elements does not affect the ultimate axial strength and behavior of CFSST short columns.

2.3. Material model for stainless steels

The inversion of the full-range three-stage stress–strain relationships for stainless steels presented by Abdella et al. [3] is based on the equations proposed by Quach et al. [2], which is implemented in the present fiber element model. The three-stage stress–strain curve for stainless steels in compression is shown in Fig. 2. In the first stage ($0 \le \varepsilon_s \le \varepsilon_{0.2}$) of the stress–strain curve, the stress is expressed by

$$\sigma_s = \frac{E_0\,\varepsilon_s\left[1 + C_1\left(\frac{\varepsilon_s}{\varepsilon_{0.2}}\right)^{C_2}\right]}{1 + C_3\left(\frac{\varepsilon_s}{\varepsilon_{0.2}}\right)^{C_4} + C_1\left(\frac{\varepsilon_s}{\varepsilon_{0.2}}\right)^{C_2}} \tag{1}$$

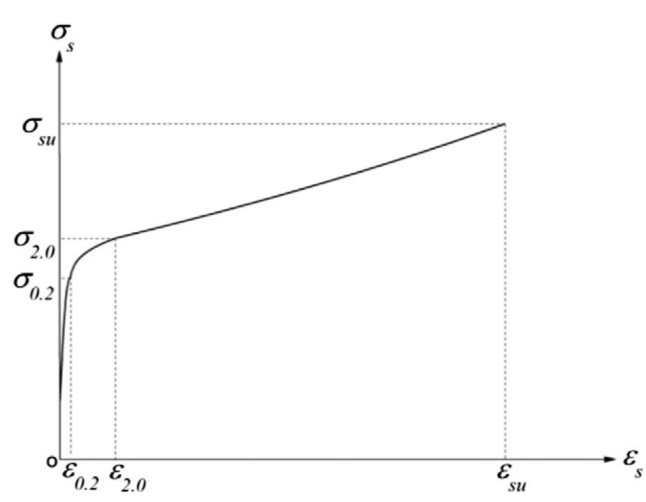

Fig. 2. Stress–strain curves for stainless steels in compression.

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