Engineering Structures 124 (2016) 457–472

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Effective stress-strain relationships for analysis of noncompact and slender filled composite (CFT) members

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ARTICLE INFO

Article history:
Received 2 July 2015
Revised 8 April 2016
Accepted 19 June 2016

Keywords:
Concrete-filled steel tube (CFT)
Composite columns
Design
Stress-strain relationships
Noncompact and slender
Finite element
Fiber analysis

ABSTRACT

Fiber-based section analysis methods are widely used to model and predict the fundamental axial force-bending moment-curvature (*P-M-ϕ*) behavior and the strength interaction (*P-M*) of concrete-filled steel tube (CFT) members. The accuracy of these predictions is governed by the uniaxial effective stress-strain relationships assumed for the steel tube and concrete infill of the CFT section. Prior research has developed these effective stress-strain relationships for compact CFT members. This paper presents the development and verification of effective stress-strain relationships for the steel tube and concrete infill of noncompact and slender CFT members. These relationships are developed using results from comprehensive 3D finite element analyses of CFT members with a wide range of geometric and material parameters. The 3D finite element models, which were developed and benchmarked previously by the authors, accounted explicitly for the effects of steel yielding and tube local buckling, concrete cracking and compression inelasticity, and the transverse interaction leading to steel hoop stresses and concrete confinement. As a result, the developed effective stress-strain relationships also accounted (implicitly) for these complexities (yielding, local buckling, confinement, etc.) of behavior. These effective stress-strain relationships are implemented in a nonlinear fiber analysis (NFA) macro model, and used to predict the behavior of noncompact and slender CFT members in the experimental database. The conservatism of the predictions using the effective stress-strain relationships is evaluated.

1. Introduction

CFT members are classified as compact, noncompact or slender depending on the governing (i.e., the maximum) slenderness ratio (λ) of the steel tube walls and the slenderness limits (λ_p, λ_r, and λ_{limit}) specified in AISC 360-10 [1]. The slenderness ratio (λ) is defined as the tube width-to-thickness (b/t) ratio for rectangular CFT members, and the diameter-to-thickness (D/t) ratio for circular CFT members. CFT members with governing tube slenderness ratio (λ) less than or equal to the compact/noncompact slenderness limit λ_p are classified as compact. CFT members with governing tube slenderness ratio (λ) greater than λ_p but less than or equal to the noncompact/slender slenderness limit λ_r are classified as noncompact. CFT members with governing tube slenderness ratio (λ) greater than λ_r but less than or equal to the maximum permitted slenderness limit λ_{limit} are classified as slender.

Fiber-based analysis methods have been used by several researchers [2–6] to calculate the section behavior and strength of CFT members. Several nonlinear structural analysis programs, such as the Drain-2Dx [7] and OpenSees [8], incorporate fiber-based section analysis principles into their beam-column finite element formulation [9]. The accuracy of these fiber-based section analysis or structural analysis programs depends fundamentally on the effective uniaxial stress-strain relationships assumed for the fibers modeling the steel tube and concrete infill of the CFT sections [10].

Researchers in the U.S. and abroad (China, Japan, and Australia among others) have proposed effective uniaxial stress-strain relationships for the fibers modeling the steel tube and concrete infill of CFT members. These relationships were developed considering: (i) experimental observations and results, and/or (ii) results from numerical analysis of detailed 3D finite element models of CFT members. The effective stress-strain relationships were designed to implicitly account for the complexities of behavior including steel material yielding, inelastic hardening, tube local buckling, and concrete confinement if possible.

For example, Varma et al. [11] developed and benchmarked 3D finite element models for predicting the behavior of composite CFT stub (short) columns, and then used these benchmarked models to develop the effective stress-strain relationships for the fibers modeling the steel tube and concrete infill of high strength rectangular

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http://dx.doi.org/10.1016/j.engstruct.2016.06.028
0141-0296/

Nomenclature

A_c	cross-sectional area of the concrete infill
A_s	cross-sectional area of the steel tube wall
D	diameter of circular sections
E_s	steel elastic modulus
F_y	steel yield stress
L	member length
M	bending moment
$M_k^{i,j}$	external moments at station k, see Fig. 13
M_{Fiber}	moment capacity obtained from fiber analysis
M_{FEM}	moment capacity obtained from FEM analysis
P	applied axial load
P_{Fiber}	maximum applied axial load value obtained from fiber analysis
P_{FEM}	maximum applied axial load value obtained from FEM analysis
P_n	axial compressive strength of CFT members
P_i	load increment
Y_k^i	calculated deflections, see Fig. 14
f'_c	concrete uniaxial compressive strength
f'_{cp}	concrete peak stress, see Figs. 6, 9, 11 and 12
t	thickness of steel tube wall
α	axial load ratio, $\alpha = P/P_n$
ε_c	unconfined concrete peak strain, see Eq. (5.b)
ε_y	steel yield strain, $\varepsilon_y = F_y/E_s$
ε_p	steel peak strain, $\varepsilon_p = \sigma_p/E_s$
λ	tube wall slenderness ratio, b/t for rectangular sections and D/t for circular sections
λ_{coeff}	slenderness coefficient, $\lambda_{coeff} = (b/t)/\sqrt{E_s/F_y}$ for rectangular sections and $\lambda_{coeff} = (D/t)/(E_s/F_y)$ for circular sections
λ_{limit}	maximum permitted slenderness ratio
λ_p	slenderness limit for compact/noncompact sections
λ_r	slenderness limit for noncompact/slender sections
ξ	relative strength ratio, $\xi = (A_sF_y)/(A_cf'_c)$
ϕ	curvature
σ_p	steel peak stress, see Figs. 6 and 11
σ_2	steel post-buckling stress at $2\varepsilon_y$, see Figs. 6 and 11

CFT members (with concrete compressive strength $f'_c = 110$ MPa). The compressive stress-strain relationships for the steel and concrete fibers were developed by idealizing the effective axial stress-strain curves obtained from 3D finite element analyses of the corresponding CFT stub columns. The finite element models explicitly accounted for the effects of local buckling and hoop stresses in the steel tube, and the effects of confinement on the concrete infill. The tensile stress-strain relationships for the steel fibers were bilinear with an elastic branch (slope = E_s), yield stress (F_y), and a post-yield linear hardening branch (slope = 0.01 E_s). The tensile stress contribution of the concrete fibers was conservatively ignored. Huang [12] extended the Varma et al. [5] approach to develop effective stress-strain relationships for the steel and concrete fibers modeling rectangular CFT members made from conventional and high strength materials.

Sakino and Sun [13] used results from experimental investigations (short column tests) to develop effective stress-strain relationships for fibers modeling the steel tube and concrete infill of rectangular and circular CFT members. The stress-strain relationships for steel fibers were bilinear in both compression and tension with an elastic branch (slope = E_s), a post-yield linear hardening branch (slope = 0.01 E_s), and the yield stresses in compression and tension equal to 0.89F_y and 1.08F_y, respectively. The compressive stress-strain relationship for the concrete fibers was a two-parameter curve, which could be determined using the compressive strengths of unconfined (plain) and confined concrete. The tensile stress contribution of the concrete fibers was conservatively ignored.

The Sakino and Sun [13] effective stress-strain relationships were modified and further enhanced by several researchers. For example, Inai and Sakino [3] modified the compressive stress-strain relationship for concrete fibers of rectangular CFT members by removing the increase in strength due to confinement, but retaining the increase in ductility. Sakino et al. [14] modified the compressive stress-strain relationships for steel fibers of rectangular CFT members to a trilinear curve with a post-yield descending branch to account for the effects of tube local buckling. Sakino et al. [14] developed these modified stress-strain relationships for the steel and concrete fibers based on the results from 114 CFT short columns tests.

Han et al. [15] used test results to develop effective stress-strain relationships for the fibers modeling the steel tube and concrete infill of rectangular or circular CFT members. The effective stress-strain relationship for the steel fibers was bilinear with an elastic branch (slope = E_s), yield stress (F_y), and a post-yield linear hardening branch (slope = 0.01 E_s) in both compression and tension. The effective stress-strain relationship for concrete fibers in compression was defined as the function of a confinement factor, ξ, which was the ratio of the steel yield strength-to-concrete compressive strength ($A_sF_y/(A_cf'_c)$ ratio). ξ accounts for the effects of confinement on the compressive behavior of the concrete infill. The tensile stress contribution of the concrete fibers was conservatively ignored. The effective stress-strain relationship for the fibers modeling the steel tube of rectangular CFT members was further improved by other Chinese researchers [16] to account for the effects of local buckling by using the effective width method. The effective width method was also used by several Australian researchers to analyze rectangular CFT members, for example, Uy [17,18], Bridge and O'Shea [19], and Liang [20,21] among others.

Thus, there are several effective stress-strain relationships in the literature that can be used for conducting fiber-based section analysis of CFT members, and for modeling CFT members using fiber-based beam-column finite elements in nonlinear structural analysis programs. These stress-strain relationships focus on compact sections with relatively small slenderness (λ) ratios, i.e., less than or equal to the compact/noncompact slenderness limit λ_p. There are limited stress-strain relationships that can be used for noncompact ($\lambda_p < \lambda \leqslant \lambda_r$) or slender ($\lambda_r < \lambda \leqslant \lambda_{limit}$) CFT members. This paper addresses the limitation by developing effective stress-strain relationships for the fibers modeling the steel tube and concrete infill of noncompact or slender CFT members.

The stress-strain relationships were developed using results from comprehensive parametric studies conducted using detailed 3D finite element models (FEM) developed and benchmarked previously by the authors [22,23] for noncompact and slender CFT members including rectangular and circular cross-sections. The 3D FEM models explicitly accounted for the complexities of CFT behavior including the effects of inelastic local buckling of the steel tubes, concrete cracking and compression inelasticity, and the effects of transverse interaction between the steel tube and the concrete infill resulting in hoop stresses in the steel tube and confinement of the concrete infill. The conservatism of the effective stress-strain relationships was verified by implementing them in a nonlinear fiber-based analysis (NFA) model, and using the model