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Strain compatibility method for the design of short rectangular concrete-filled tube columns under eccentric axial loads

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HIGHLIGHTS

- The developed concrete stress-strain model can be used for the strain compatibility method of ACI 318, AISC 360, and Eurocode 4.
- The developed model led to more accurate and consistent prediction of the strength of RCFT columns.
- The structural provisions of RCFT columns in ACI 318, AISC 360 and Eurocode 4 are thoroughly reviewed.
- An updated database is assembled for RCFT columns subjected to eccentric axial loads.

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ABSTRACT

Given that there are few concrete stress-strain models available for rectangular CFT sections with high-strength materials, this study attempts to develop an empirical and practical stress-strain model that can be used in conjunction with the strain compatibility method of the American Concrete Institute Code (ACI 318-14), American Institute of Steel Construction Specification (AISC 360-10), and Eurocode 4. For a better understanding, the structural provisions of rectangular CFT columns in ACI 318-14, AISC 360-10 and Eurocode 4 are comparatively reviewed. Then, an updated database is assembled from previous and recent test results of rectangular CFT columns subjected to eccentric axial loads to evaluate whether the existing provisions and/or stress-strain models for concrete can be used. Finally, a new concrete stress-strain model is proposed that leads to more accurate and more consistent prediction of the P-M interaction strength of rectangular CFT columns under general design conditions.

1. Introduction

Recently high-rise building construction has been rapidly increasing in many countries such as in the U.S., China, and Korea, and steel-concrete composite construction is increasingly popular for those high-rise buildings and mega structures. Among several composite construction types, concrete-filled tube (CFT) columns have superior constructability and structural performance attributes. Concrete is well confined by structural steel tubing, which also functions as column formwork, and at the same time the buckling tendency of steel tubes is restricted by the concrete core. As a result, a CFT column's strength and ductility is substantially enhanced. Such an enhanced performance can be further improved with the use of high-strength materials.

In the codes of both the American Concrete Institute [4] and American Institute of Steel Construction [7], provisions for composite structures (ACI 318-14 Code and AISC 360-10 Specification) exist. Eurocode 4 [9] (Sections 6.7.2 and 6.7.3) is a code used for design of composite steel and concrete structures in Europe. All these codes include the strain compatibility method (SCM) as a design option (the only option in ACI 318-14) for rectangular CFT compact sections. Section 22.2.2.3 of ACI 318-14 states that "The relationship between concrete compressive stress and strain shall be represented by a rectangular, trapezoidal, parabolic, or other shape that results in prediction of strength in substantial agreement with results of comprehensive tests". Section 3.1.5 of Eurocode 2 [8] is referenced in Section 6.7.2 of Eurocode 4, but this is rather for the nonlinear analysis. Section 3.1.7 of Eurocode 2 is generally used for the design of cross-section and allows the use of a parabola-rectangle shaped, bi-linear or rectangular stress distribution of concrete. Though no specific concrete stress-strain models are provided by ACI 318-14 or AISC 360-10, the following modified Hognestad model (1951; also see [27]) is often used. Note that in the Eurocode, the ascending branch of the parabola-rectangle stress-strain diagram is also the same as Eq. (1), except for the peak value.

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$$\sigma = 0.9f'_c\left[\left(\frac{2\varepsilon}{\varepsilon_{co}}\right) - \left(\frac{\varepsilon}{\varepsilon_{co}}\right)^2\right] \quad 0 < \varepsilon \leqslant \varepsilon_{co} \tag{1}$$

$$\sigma = 0.9f'_c - \frac{0.15(0.9f'_c)(\varepsilon - \varepsilon_{co})}{(\varepsilon_{cc} - \varepsilon_{co})} \quad \varepsilon_{co} < \varepsilon \leqslant \varepsilon_{cc} \tag{2}$$

$$\varepsilon_{co} = \frac{1.8(0.9f'_c)}{E_c} \tag{3}$$

$$E_c = 4700\sqrt{f'_c}, \quad \text{where } f'_c \text{ is in MPa} \tag{4}$$

$$\varepsilon_{cc} = 0.0038 \tag{5}$$

where σ is the concrete stress (variable); f'_c is the specified concrete compressive strength; ε is the concrete strain (variable); ε_{co} is the concrete strain at f'_c; E_c is the modulus of elasticity for concrete in MPa per Section 19.2.2.1 of ACI 318-14; and ε_{cc} is the ultimate concrete compressive strain. In the ACI 318-14 (Section 22.2.2.1) and AISC 360-10 (Section I1.2b), the ultimate compressive strain (ε_{cc}) of concrete is assumed to be 0.003, while the value of ε_{cc} is assumed to be 0.0035 for the design using SCM according to Section 3.1.7 and Table 3.1 of Eurocode 2 [8]. Therefore, Eq. (5) needs to be modified for the SCM of ACI 318-14 or AISC 360-10 as follows:

$$\varepsilon_{cc} = 0.003 \tag{6}$$

Eqs. (1)–(6), however, may not reflect all the different conditions of rectangular CFT sections (e.g., high-strength materials, various steel-to-concrete strength ratios and steel tube width-to-thickness ratios, and other unusual dimensions). Commentaries R22.2.2.1 and R22.2.2.3 of ACI 318-14 also indicate that ε_{cc} ranges from 0.003 to 0.004 under usual conditions and from 0.003 to higher than 0.008 under special conditions (e.g., confined concrete). Furthermore, there are few concrete stress-strain models available for rectangular CFT sections with high-strength to very high-strength materials. Given this gap, this study attempts to develop an empirical and practical stress-strain model for concrete in rectangular CFT columns that could be used in conjunction with the SCM of ACI 318-14, AISC 360-10 or Eurocode 4.

In this study, the structural provisions of rectangular CFT columns in ACI 318-14, AISC 360-10 and Eurocode 4 are comparatively reviewed. As noted earlier and in the foregoing section, the strain compatibility methods of ACI 318-14, AISC 360-10 and Eurocode 4 are slightly different from each other in terms of the consideration of steel strain-hardening, confined concrete, ultimate compressive strain, etc., but in this paper, the strain compatibility method in ACI 318-14 is conservatively used and compared. The provisions analyzed include those related to the nominal strength, ultimate compressive strain of concrete, plate slenderness, and the material strength limitations. Then, an updated database is assembled from previous and recent test results of short rectangular CFT columns subjected to eccentric axial loads to evaluate whether the existing stress-strain models for concrete can be used [11,25,26,17,18,10]. Here, the short column is defined as a column having the slenderness ratio (kL/r) of 32 or smaller so that the overall flexural instability including the P-delta effect is not a concern, where k is the effective length factor for columns, L is the unbraced length of a column, and r is the radius of gyration of cross-section. Finally, using the database and analysis of the existing models, a concrete stress-strain model is empirically proposed that, along with the SCM of ACI 318-14, AISC 360-10 or Eurocode 4, can be used for the design of rectangular CFT columns and for the prediction of their flexural and axial strengths. This study is limited to the case of rectangular CFT compact sections, excluding circular and any other sections.

2. Structural provisions for rectangular CFT columns

Since the first inclusion of steel-concrete composite provisions in the standard building regulations for the use of reinforced concrete of ACI [2], significant advances were made until 1983, after which, however, no updates have been made on ACI 318 composite provisions except for the updated load combinations in 2001 [12,13] In contrast, AISC began to recognize concrete slab-steel beam composite configurations in 1961 by adopting the American Association of State Highway Officials Standard Specifications [1], and included composite column provisions in 1986 for the first time based on the [23], which was a joint effort of ACI and AISC [12,13]. Between 1986 and 2005, there were gradual updates to the composite CFT column provisions. In 2010, AISC 360-10 Specification for Structural Steel Buildings related to CFT columns was substantially updated from the 2005 edition of the AISC 360 Specification [6]. For example, pure compressive axial and pure flexural strengths are differently defined for three classifications: *compact sections*, *non-compact sections*, and slender sections, depending on the tube slenderness, to account for the effect of local buckling (AISC 360-10, Sections I2.2b and I3.4b and Commentary I5). In Europe, the European Joint Committee for Composite Construction was formed in 1970s, which published the draft of Eurocode 4 as a book in 1981. The draft had been updated by the Steering Committee as part of the European Commission in early 1980s, and in 1990 the Technical Committee TC250 of the European Committee

Table 1
Limiting material properties and plate width-to-thickness ratios for rectangular CFT columns.

		ACI 318-14	AISC 360-10	Eurocode 4	Proposed
f'_c		N.A	$21 \leqslant f'_c \leqslant 70$ MPa	$f'_c \leqslant 60$ MPa	$f'_c \leqslant 110$ MPa
F_y		N.A	$F_y \leqslant 525$ MPa	$F_y \leqslant 460$ MPa	$F_y \leqslant 830$ MPa
Steel[†]		N.A	$1\% \leqslant \rho_s$	$0.2 \leqslant \delta \leqslant 0.9$	$1\% \leqslant \rho_s$
b/t	Compact/Non-compact	$(b/t) \leqslant 1.73\sqrt{\frac{E_s}{F_y}}$	$(b/t) \leqslant 2.26\sqrt{\frac{E_s}{F_y}}$	$(b/t) \leqslant 1.76\sqrt{\frac{E_s}{F_y}}$	[††]$(b/t) \leqslant 2.26\sqrt{\frac{E_s}{F_y}}$
	Non-compact/Slender		$(b/t) \leqslant 3\sqrt{\frac{E_s}{F_y}}$		
	Maximum Permitted		$(b/t) \leqslant 5\sqrt{\frac{E_s}{F_y}}$		

f'_c = specified concrete compressive strength;
F_y = specified minimum yield stress;
A_s = cross-sectional area of steel section;
A_c = area of concrete;
A_{sr} = area of continuous reinforcing bars;
f_{yr} = yield strength of continuous reinforcing bars;
E_s = modulus of elasticity of steel;
[†] ρ_s [=steel-to-concrete area ratio] or δ [$=(F_yA_s)/(F_yA_s + 0.85f'_cA_c + f_{yr}A_{sr})$];
[††] Only for compact sections.