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Noncompact and slender rectangular CFT members: Experimental database, analysis, and design

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ABSTRACT

Rectangular concrete-filled steel tube (CFT) members are categorized as compact, noncompact or slender depending on the slenderness ratio (width-to-thickness b/t ratio) of the steel tube walls. International design codes typically focus on the design of compact CFT members with relatively small slenderness (b/t) ratios. The behavior and design of noncompact or slender CFT members is not addressed directly. This paper presents the basis of the current AISC Specification (AISC 360-10) for the design of noncompact or slender rectangular CFT members under axial compression, flexure, and combined axial and flexural loading. The experimental database of tests conducted on noncompact and slender CFT members is reviewed. Design equations are developed based on the experimental results and observations. Detailed 3D finite element method (FEM) models are developed for noncompact and slender CFT members, and benchmarked using experimental results. The benchmarked models are used to address gaps in the experimental database, and further verify the conservatism of the design equations.

1. Introduction

CFT members consist of rectangular or circular steel tubes filled with concrete. These composite members optimize the use of both steel and concrete construction materials as compared to steel or reinforced concrete structures. The concrete infill delays the local buckling of the steel tube, while the steel tube provides confinement to the concrete infill. The behavior of CFT members under axial loading, flexure, and combined axial and flexural loading can be more efficient than that of structural steel or reinforced concrete members. Moreover, the steel tube serves as formwork for placing the concrete, which facilitates and expedites construction while reducing labor costs.

CFT members are used widely around the world in various types of structures. For example, CFT members are used as columns in composite braced frames in: (i) the Two Union Square building in Seattle, Washington, (ii) Casselden Place project in Melbourne, Australia, and (iii) Taipei 101 tower in Taipei, Taiwan. CFT members are also used as columns in composite moment frames, for example in: (i) 3 Houston Center in Houston, Texas, and (ii) Postal Office building in Quanzhou, China. CFT members are used as compression chords in composite bridges, for example, in: (i) the Xialaoxi bridge in Yichang, China, (ii) Jinan East Railway Station bridge in Jinan, China, and (iii) Pudong Canal bridge in Shanghai, China. CFT members are also used as piles, transmission towers, and bracing members in buckling restrained frames.

2. Background

Since the first documented experimental research on CFT columns in 1957 [1], significant research has been conducted to investigate the behavior of CFT members under various loading conditions. For example: (i) axial compression tests, (ii) flexural tests, and (iii) combined axial force and flexure (beam-column) tests have been conducted by researchers in various countries. These studies indicate that the strength of CFT members depends on several parameters, namely, the steel yield stress F_y, concrete compressive strength f'_c, tube wall slenderness (b/t) ratio, column length to depth ratio L/h and composite interaction between the steel tube and concrete infill, etc.

Nishiyama et al. [2], Kim [3], Gourley et al. [4], and Hajjar [5] have independently compiled comprehensive databases of experimental research conducted on rectangular and circular CFTs. The database compiled by Hajjar [5] (previously, Gourley et al. [4]) is the most comprehensive database of experimental and numerical research performed on CFT members, frames, and systems. The database includes all the tests conducted on compact, non-compact, and slender CFT members with a wide range of material, geometric, and loading parameters. However, a significant portion of the database is comprised of tests conducted on compact CFT members. There are fewer, but reasonable number of tests conducted on noncompact and slender CFT members, which are the focus of this paper and research.

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Most design codes specify steel tube slenderness (b/t) ratio limits for CFT members. For example, Eurocode 4 (2004) [6] specifies that the steel tube of rectangular CFT columns in compression should satisfy the limit, $b/t \leq 52\sqrt{235/F_y}$, where F_y is in MPa, to prevent the local buckling. AS 4100 (2012) [7] permits the occurrence of steel tube local buckling, and provides an effective width method to calculate the axial strength of slender CFT members. The Japanese code (AIJ 2008 [8]) classifies rectangular CFTs into three types, i.e., *FA*, *FC*, and *FD* depending on the steel tube slenderness ratio. CFT columns classified as *FC* and *FD* have larger steel tube slenderness ratios and are susceptible to local buckling effects. AIJ 2008 [8] provides an axial load capacity factor to account for the effects of steel tube slenderness (and local buckling) on the axial strength of rectangular CFTs.

Eurocode 4 (2004) [6] specifies that the flexural strength of CFT members can be calculated as the plastic moment resistance over the composite cross-section while using: (i) the yield stress (F_y) for steel in compression or in tension, (ii) the compressive strength (f'_c) for concrete in compression, and (iii) neglecting the contribution of concrete in tension. The Australian and Japanese codes (AS 4100 [7] and AIJ 2008 [8]) specify tube slenderness ratio dependent stress–strain curves for steel in compression that can be used to calculate the flexural strength of rectangular CFT members.

None of these international codes specify tube slenderness (b/t) ratio limits to classify rectangular CFT members into noncompact or slender CFTs. They also do not have different slenderness (b/t) ratio limits for rectangular CFTs subjected to different loading conditions (axial or flexural loading). The AISC 360-05 [9] specification also specified the tube slenderness (b/t) ratio limits only for compact CFTs, and did not include any provisions for classifying or calculating the strength of noncompact or slender CFTs subjected to different loading conditions (axial or flexural loading). As a result, the design and use of noncompact or slender CFT members in the US was limited in scope.

This paper presents the development of the AISC 360-10 [10] specification that includes provisions for classifying and calculating the strength of noncompact and slender CFTs subjected to different loading conditions. It is based on the work done earlier by the authors (referenced in AISC 360-10 [10]), and enhanced herein to further confirm the conservatism of the design provisions. This paper focuses on rectangular CFT members. The development of the AISC 360-10 specification for (noncompact and slender) circular CFT members and the confirmation of their conservatism is presented elsewhere in [11].

The outline of this paper is as follows. The paper first presents the AISC 360-10 [10] slenderness (b/t) ratio limits used to classify rectangular CFT members as compact, noncompact, or slender depending on the loading (axial or flexural). It discusses the basis and reasoning for these limits, and the associated strength equations in AISC 360-10 [10]. The experimental database of tests conducted on noncompact and slender rectangular CFT tests subjected to different loading conditions (axial compression, flexure, combined axial force and flexure) are presented. The conservatism of the AISC 360-10 [10] design equations are established by using them to predict the strength of CFT members in the experimental database. 3D nonlinear inelastic finite element models are developed and benchmarked for predicting the behavior and strength of noncompact and slender CFTs in the experimental database. The benchmarked models are used to address gaps in the experimental database, and further confirm the conservatism of the AISC 360-10 [10] design equations.

3. Slenderness limits for rectangular CFT members—axial compression

The behavior of CFT members is fundamentally different from that of hollow structural shape (HSS) members. The concrete infill changes the buckling mode of the steel tube by preventing it from buckling inward, as shown in Fig. 1. The post-buckling behavior of CFT members is more ductile than that of equivalent HSS members due to the larger wavelength of the buckling mode, spreading of plastic deformation, and slight increase in the moment of inertia of the steel tube due to the outward buckling shape. The elastic local buckling behavior of the steel tube walls of rectangular CFT members subjected to axial compression was investigated analytically by Bradford et al. [12] using the Rayleigh–Ritz method. The assumed local buckling mode shape accounted for the effects of concrete infill, i.e., no inward displacements as shown in Fig. 1.

The resulting equation for local buckling is shown in Eq. (1). In this equation, F_{cr} is the critical stress for elastic local buckling, E_s is the modulus of elasticity of the steel tube, ν is the Poisson's ratio for steel, and b/t is the governing (larger) slenderness ratio. The parameter k accounts for the local buckling mode. Bradford et al. [12] showed that k was equal to 10.6 for the mode shape shown in Fig. 1. The critical buckling stress F_{cr} simplifies to $9.6E_s/(b/t)^2$ after substituting the values of k equal to 10.6, and Poisson's ratio for steel equal to 0.3. The critical buckling stress (F_{cr}) reaches the yield stress (F_y) when the slenderness ratio (b/t) becomes equal to $3.10\sqrt{E_s/F_y}$.

$$F_{cr} = \frac{k\pi^2 E_s}{12(1-\nu^2)\left(\frac{b}{t}\right)^2} \tag{1}$$

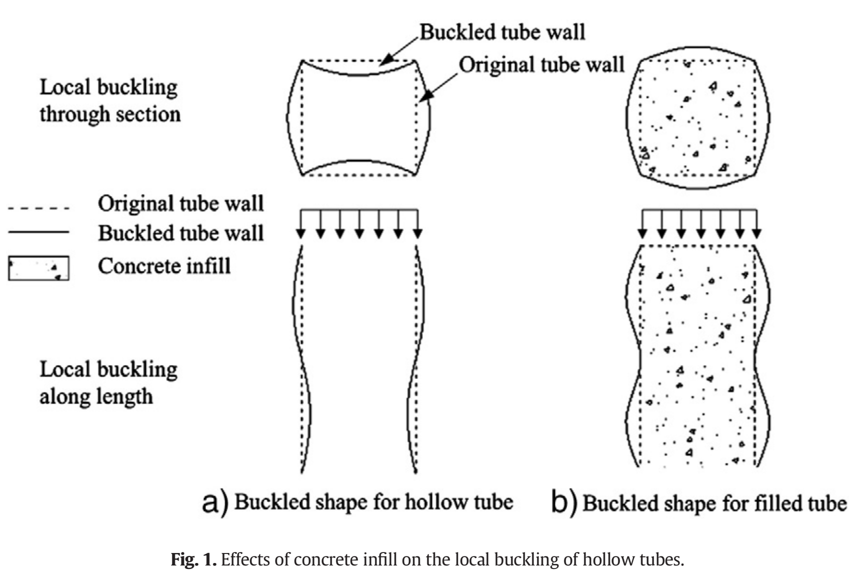

Fig. 1. Effects of concrete infill on the local buckling of hollow tubes.