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ScienceDirect
Journal of Constructional Steel Research 63 (2007) 37–44
JOURNAL OF CONSTRUCTIONAL STEEL RESEARCH
www.elsevier.com/locate/jcsr

Experimental study on rectangular CFT columns with high-strength concrete

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Received 3 November 2005; accepted 17 March 2006

Abstract

In the 1999 AISC-LRFD, the in-filled concrete strength (f_c') of concrete-filled tube (CFT) columns is limited to a maximum value of 55 MPa (N/mm^2). That limiting value is raised to 70 MPa in the 2005 AISC-LRFD. This study aims to assess if the LRFD CFT column formulas are applicable to intermediate to long rectangular columns with higher concrete strengths. Twenty four specimens with f_c' varying between 29 and 84 MPa were tested. Various formulas and relevant provisions for CFT columns as specified in the major design codes including AISC-LRFD, EC 4, AS-5100, and CSA S16-01 were examined and compared. The design CFT strength (P_u) predicted by the AISC-LRFD formulas and the test results (P_{test}) were found to be in good agreement. The higher f_c' limiting value of 70 MPa proposed in the 2005 AISC-LRFD appears acceptable. The test results reveal that the 1999 AISC-LRFD design strengths are conservative and tend to penalize these CFT columns with higher concrete strength.

Keywords: Concrete-filled tube; CFT; LRFD; High-strength concrete; Column

1. Introduction

1.1. Current design codes

Concrete-filled tube (CFT) columns are being increasingly used as structural members since filling the steel section with concrete results in an increase in both strength and ductility without increasing the section size. Design criteria for CFT columns are available in various major design codes such as the AISC-LRFD [1], the ACI 318-05 [2], the Architectural Institute of Japan [3], the European Code EC 4 [4], the British Standards BS 5400 [5] and the Australian Standards AS-5100.6 [6]. In the U.S., prior to the publication of the 1986 AISC-LRFD, the design of composite columns referred to the ACI Code. In 1979, the SSRC Task Group 20 [7] proposed a specification for the design of steel–concrete composite columns to be included in the AISC Specifications. Their report was written in the format of the ultimate strength method rather than the original allowable stress method as proposed by Furlong [8].

The 1986 AISC-LFRD specifies strength limits on both steel and concrete. The upper limit for steel strength (F_y) was set at 380 MPa, which corresponds to a concrete strain of around 0.18%. The code also requires that a compressive concrete strength (f_c') of 21–55 MPa be specified. The 1999 AISC-LRFD raised the F_y value to 415 MPa. The new 2005 AISC-LRFD [9] raises the material strengths even higher to $f_c' =$ 70 MPa and $F_y = 525$ MPa. It also modifies the minimum steel wall thickness and contains design provisions for both round and rectangular shapes. For the first time, the 2005 AISC-LRFD adopts the concept of effective stiffness with different adjustment coefficients depending on the situation. It keeps the minimum steel ratio at 4% for regular encased columns, but lowers it to 1% for CFT columns, compared with the 1999 AISC-LRFD. Moreover, it revises the resistance factor to 0.75 from 0.85. The newer design specifications included in the 2005 AISC-LRFD appears meriting from both the 2005 ACI 318 and the 2004 EC 4.

1.2. Previous related studies

A number of experimental and theoretical studies on the related subject have been carried out since the early 1960s. Test variables considered by the previous investigators include sectional dimensions, width-to-thickness ratio (B/t), material strengths (steel and concrete), structural stiffness, percentage of steel area, residual stress, effective length, slenderness ratio, effect of confinement, loading type, and load eccentricity.

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doi:10.1016/j.jcsr.2006.03.007

Nomenclature

A_c	Area of concrete
A_g	Gross area
A_s	Area of the steel section
b	Width in rectangular section
D	Outside diameter of circular hollow section
E_s	Modulus of elasticity of steel (E)
E_c	Modulus of elasticity of concrete
EI_{eff}	Effective moment of inertia rigidity of composite section
f'_c	Specified compressive strength of concrete at 28 days
f_c	Compressive concrete stress before ultimate load is reached
F_{cr}	Critical stress
F_y	Specified minimum yield stress of steel
I_c	Moment of inertia of the concrete section
I_s	Moment of inertia of steel shape
K	Effective length factor for prismatic member
L	Laterally unbraced length of member at the point of load
P_{test}	Test failure load
P_o	Composite compressive strength based on ACI 318-05
P_n	Nominal axial strength based on AISC-LRFD (1999, 2005)
P_u	Design axial strength based on AISC-LRFD (1999, 2005)
r	Radius of gyration
t	Wall thickness of hollow structural steel section
w_c	Weight of concrete per unit volume
λ_c	Column slenderness parameter
ϕ_c	Resistance factor for compression

Knowles and Park [10] studied 12 circular and 7 square columns by considering various D/t and l/d ratios. Their results demonstrated that concrete confinement increases the structural capacity of circular tubes. However, this beneficial effect was not noted in square or rectangular shapes. The SSRC Task Group 20 [7] proposed a design specification for steel–concrete composite columns to be included in the AISC Specifications, which was based on the ultimate strength design format. Shakir-Khalil [11–13] conducted a series of tests of CFT rectangular columns on compression and bending from 1989 to 1996. The experimental results indicated that BS 5400 gave safe capacity prediction for the CFT columns subjected to axial loading or uniaxial bending about the major axis. Kenny et al. [14] examined the limiting steel yield stress (F_y) of 380 MPa as specified in the 1986 LRFD Specification. They reported that the 380 MPa yield limit could be increased to 550 MPa. Bradford [15] proposed a design model for calculating the design strength of slender rectangular CFT columns. Schneider [16] tested 14 specimens with various shapes and investigated the effects of steel tube shape and wall thickness on the ultimate strength of composite columns. They also addressed the concrete confinement effect. Kilpatrick and Rangan [17] tested 41 CFT columns with high-strength steel tubes ($F_y > 400$ MPa) filled with concrete with a compressive strength of 58 and 96 MPa to investigate the single and double curvature bendings. Zhang and Shahrooz [18] provided the measured results from past studies and from their own specimens, where they gave the comparison between ACI and AISC for CFT columns. Shanmugam and Lakshmi [19] gave a review of the research carried out on composite columns with emphasis on experimental and analytical work. Han [20] studied 24 short axially-loaded CFT rectangular specimens considering the two major parameters, constraining factor and tube width limit. By comparison, he reported that the loading capacity of the concrete-filled rectangular stub columns could be conservatively predicted by using the AISC-LRFD, AIJ, EC 4, and GJB4142 [21] recommendations. Mursi and Uy [22] studied 3 slender CFT square columns filled with high strength concrete ($f'_c = 65$ MPa), and 3 HSS columns. They made a comparison of the design recommendations for the strength evaluation of slender composite columns with thin-walled steel sections. Liu et al. [23] studied 22 CFT rectangular stub columns ($F_y = 550$ MPa, and $f'_c = 70$–82 MPa) subjected to concentric loading. They further compared the ultimate loads obtained from experiments with the values calculated based on the EC 4, the AISC-LRFD and the ACI. Their comparison shows that the EC 4 closely predicts the ultimate load with a difference of 6%, while the AISC-LRFD and the ACI underestimated the critical load by more than 14%. Viest [24] reviewed the historical development of the design requirements of composite structures made of steel and concrete.

Melcher and Karmazinova [25] presented the analysis of CFT columns with high strength concrete. Sakino et al. [26] studied 114 specimens to investigate the behavior of centrally-loaded short CFT columns, and proposed the formulae for estimating the ultimate axial compression capacities of CFT columns. Liu [27] studied 22 CFT rectangular stub columns filled with high-strength concrete. His comparison indicates that the current ACI and AISC specifications conservatively estimate the failure loads of the specimens by 9% and 11%, respectively. The EC 4 method gives a close and conservative estimate of the ultimate capacities with a difference of 1%.

1.3. Current study

The recently developed high strength concrete has lured industrial enterprises and researchers into the field of high strength composite construction. The high strength concrete offers benefits in both strength and stiffness. The majority of the previous studies focus on circular and square sections with lower concrete strength. Research work related to rectangular sections with higher concrete strength is still limited and therefore deserves further investigation. This study examines the ultimate strength of CFT rectangular columns under axial compressive loading experimentally. The following various concrete compressive strengths (f'_c) were considered: 29, 63, 70, and 84 MPa, while the average steel yield stress was kept at