Engineering Structures 136 (2017) 494–510

Contents lists available at ScienceDirect

Engineering Structures

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

Axial performance of short concrete filled steel tubes with high- and ultra-high- strength materials

Ming-Xiang Xiong [a,b,*], De-Xin Xiong [b], J.Y. Richard Liew [b,c]

[a] School of Civil and Transportation Engineering, Guangdong University of Technology, 100 Waihuan Xi Road, GuangZhou 510006, China
[b] Department of Civil Engineering, National University of Singapore, 21 Lower Kent Ridge Road, Singapore 119077, Singapore
[c] School of Civil Engineering, Nanjing Tech University, No. 30 Puzhu Road(S), Nanjing 211816, China

ARTICLE INFO

Article history:
Received 1 July 2016
Revised 16 January 2017
Accepted 17 January 2017

Keywords:
Concrete filled steel tubes
Short columns
High tensile steel
Ultra-high strength concrete
Eurocode 4
Modifications

ABSTRACT

The use of high strength concrete and steel have significant advantages for composite members subject to significant compression as in the cases of high-rise buildings. Current design codes place limits on the strengths of steel and concrete due to limited test data and experience on the behaviour of composite members with the high strength materials. To extend their applications, a comprehensive experimental program has been carried out to investigate the behaviour of concrete filled steel tubes (CFSTs) with high- and ultra-high- strength materials at ambient temperature. This article presented some new findings on the axial performance of 56 short CFSTs. High tensile steel with yield strength up to 780 MPa and ultra-high strength concrete with compressive cylinder strength up to 190 MPa were used to prepare the CFST test specimens. The key issue is to clarify if the plastic cross-sectional resistance could be used at ultimate limit state as for CFSTs with the normal strength materials. To address this, experimental and analytical methods were adopted where the test results were compared with the predictions by various design codes world widely, and design recommendations were therefore proposed so that the prediction methods could be safely extended to the short CFSTs with the high- and ultra-high- strength materials.

1. Introduction

Steel and concrete are capable to compensate each other meanwhile working together to form composite structural members with expected characteristics. Concrete filled steel tubes (CFSTs), one of the most widely used composite members in high-rise construction in Asia, take the full advantages of the characteristic behaviour of steel and concrete materials. It is well known that the core concrete delays the local buckling and temperature rise of steel tube and in turn enhances the strength and ductility of core concrete. Moreover, the steel tube eliminates the need of formwork for concrete casting and thus leads to fast track construction. The CFSTs have various types of cross-section. Circular, square and rectangular sections are generally used whereas elliptical and polygonal sections could be adopted catering for architectural aesthetics or functional requirements. Conventionally, only plain concrete is infilled to the hollow tubes. Nowadays, the concrete may be reinforced by polymer or steel fibers to enhance ductility and fire resistance, in which cases the workability or the flowablility of the concrete should be carefully controlled if it is pumped into the tubes. Reinforcing steel cages are mainly used to improve the fire resistance, since the steel cages are capable to take over loads when the external tube is sacrificed under fire. For convenience, the steel cage could be replaced by an internal tube to improve the fire resistance as well as the compressive resistance and ductility due to higher confinement provided. Other steel sections, such as solid steel sections or H-sections, can be inserted into the core concrete to further improve the compressive resistance and thus reduce the member size. Nevertheless, the steel cages, internal tubes and inserted sections are less used in practice due to some incurred construction difficulties, such as congesting the concrete casting area and obstructing the inner diaphragm plates at beam-column joints, etc.

With the development of concrete technology and availability of various materials such as silica fume and high-range water-reducing admixtures, the production of ultra-high strength concrete (UHSC) with compressive strength higher than 120 MPa is possible nowadays. However, the UHSC has been limited to some special applications such as marine and offshore structures, pavements, industrial floors, and security barriers, etc. It has not been used in building structures due to concerns on its brittleness and

* Corresponding author at: School of Civil and Transportation Engineering, Guangdong University of Technology, 100 Waihuan Xi Road, GuangZhou 510006, China.

E-mail address: cvexmx@gdut.edu.cn (M.-X. Xiong).

http://dx.doi.org/10.1016/j.engstruct.2017.01.037
0141-0296/

spalling behaviour under fire [1]. To reduce the brittleness, the UHSC may be confined by the steel tubes. As the UHSC is more brittle than normal strength concrete (NSC), high tensile steel (HTS) tubes may be used to provide higher confinement. However current state-of-art design guidelines for CFSTs are only applicable for normal strength concrete and steel. For example, Eurocode 4 [2] method is applicable to composite columns with normal weight concrete cylinder strength from 20 MPa to 50 MPa and structural steel yield strength from 235 MPa to 460 MPa; AISC 360-10 [3] is for composite columns with normal weight concrete cylinder strength from 21 MPa to 70 MPa, light weight concrete cylinder strength from 21 MPa to 42 MPa and structural steel yield strength up to 525 MPa; GB 50936 [4] only applies to composite columns with concrete cylinder strength from 25 MPa to 70 MPa and steel yield strength from 235 MPa to 420 MPa; and AIJ [5] allows the use of high strength concrete with compression strength up to 90 MPa. Therefore, sufficient work should be done to extend current design guidelines to the CFSTs with high strength materials. With regard to this, the axial performance of the said CFSTs were firstly investigated and introduced hereinafter.

For the high strength concrete (HSC) used in short CFSTs, there were researches in the available literature done by Han et al. [6] and Liu et al. [7][8] where the concrete strength reached 106 MPa. The test results were compared with the predictions based on the EC 4 approach, showing that the EC 4 approach overestimated the ultimate axial resistance. However, different conclusions were drawn by Lue et al. [9] and Yu et al. [10] based on their tests where the concrete strength was close to 120 MPa. It is found that the EC 4 approach actually provided conservative predictions. For the high tensile steel (HTS) employed for the short CFSTs, Uy [11] carried out an experimental investigation on box CFSTs where the yield strength of the HTS was approximately 750 MPa. The comparisons with the EC 4 predictions showed that the EC 4 approach overestimated the ultimate resistance. A 5 year research on centrally loaded stub CFSTs was carried out under the U.S.–Japan Cooperative Earthquake Research Program [12]. A total of 114 specimens was tested and the steel strength reached 853 MPa. The test results were used to form the design basis of the AISC Standards for the CFSTs. Again similar research was done by Aslani et al. [13] and the yield strength of HTS reached 700 MPa. Test results were compared with the predictions by Australian Standards, Eurocode 4, and AISC. The comparisons showed conservative predictions, implying applicability of the said codes to the short CFSTs with the HTS.

The foresaid studies have provided significant contributions to the research progress in developing cross-sectional resistance of the short CFSTs using the HSC and HTS. However, the work is insufficient, especially for CFSTs with the UHSC of compressive strength higher than 120 MPa and the HTS of yield strength greater than 460 MPa as shown in Fig. 1. Therefore, more investigations should be carried out to assess their potential applications in high-rise construction. This paper presented the test data and code predictions on the short CFSTs under concentric compression to evaluate the cross-sectional resistance. Design recommendations were then proposed for the relevant design approaches. It should be mentioned that this is a supplementary and summary work to the preliminary and incomplete research introduced in Ref.[14]. In this article, all the test data on short CFSTs were covered, and the detailed test program and test results were described and discussed.

2. Eurocode 4 approach for short CFSTs under compression

According to Eurocode 4 [2], the characteristic plastic cross-sectional compressive resistance of a CFST without reinforcing steel is calculated by

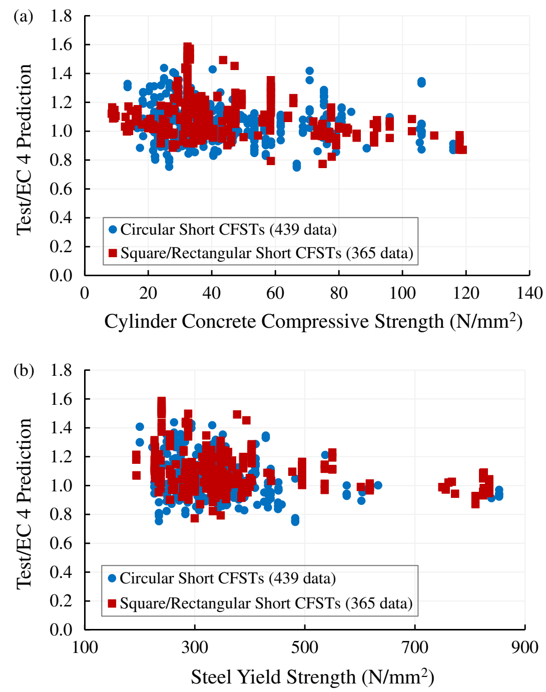

Fig. 1. Database of tests on short CFSTs.

$$N_{pl,Rk1} = A_a f_y + A_c f_{ck} \tag{1}$$

where A_a and A_c are the cross-section area of steel and concrete section, respectively; f_y and f_{ck} are the characteristic yield and cylinder compressive strength of steel and concrete, respectively. Confinement effect may be considered for circular CFSTs with non-dimensional slenderness ratio $\bar{\lambda} \leqslant 0.5$ and the ratio of load eccentricity to diameter $e/d < 0.5$, where $\bar{\lambda}$is the non-dimensional slenderness ratio = $\sqrt{N_{pl,Rk1}/N_{cr}}$, $N_{cr}$is the Euler buckling force of the CFST. The cross-sectional compressive resistance is then calculated by

$$N_{pl,Rk2} = \eta_a A_a f_y + A_c f_{ck}\left(1 + \eta_c \frac{t}{d}\frac{f_y}{f_{ck}}\right) \tag{2}$$

where t and d is the wall thickness and diameter of the steel tube; η_a and η_c are given by the following expressions:

$$\eta_a = 0.25(3 + 2\bar{\lambda}) + (1 - 0.25(3 + 2\bar{\lambda}))(10e/d) \tag{3}$$

$$\eta_c = (4.9 - 18.5\bar{\lambda} + 17\bar{\lambda}^2)(1 - 10e/d) \tag{4}$$

The Euler buckling force N_{cr} is formulated as

$$N_{cr} = \frac{\pi^2 (EI)_{eff}}{L^2} \tag{5}$$

where

$$(EI)_{eff} = E_a I_a + 0.6 E_{cm} I_c \tag{6}$$

L is column length; E_{cm} and E_a are the test elastic moduli of concrete and steel; I_a and I_c are the second moment of area of steel and concrete sections, respectively.

3. Discussion on confinement effect

According to Eq. (2), there is an increase of concrete strength for circular CFSTs due to confinement effect which is normally ignored for the other shapes of sections. The level of confinement is related to the steel yield strength and concrete compressive strength. Basically, the level of confinement is represented by the ratio of