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Experimental behaviour of circular concrete filled steel tube columns and design specifications

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ABSTRACT

This paper presents 18 tests conducted on short, medium and long circular Concrete Filled Steel Tube (CFST) columns. To explore the impact of column parameters and confinement effect three *L/D* ratios, two *D/t* ratios, two steel qualities and three concrete classes were employed. Some specimens have properties within application limits of EC4 and AISC 360-10 whereas others have properties beyond the application limits. Since new, large and efficient structures require adoption of high strength materials, it is compulsory to push the limits of design specifications. It is shown that 56 MPa and 66 MPa concretes provide very smooth and ductile load-shortening curves which imply high deformation capacity of such concrete classes. Brittle nature of 107 MPa concrete is shown by very sharp transitions from pre-peak to post-peak region and sudden discharge of loading in load-shortening curves. Additionally, 239 experimental data were collected from literature to assess EC4 and AISC 360-10 predictions within application limits and beyond application limits. Instead of focusing on a narrow region of configurations, this paper examines the performance of prediction methods on short, medium and long CFST columns. EC4 predictions indicate much better agreement with the test results. However AISC 360-10 predictions are conservative for all combinations of parameters. The application limits of EC4 can be widened to cover solutions of columns with broader properties. Confinement effect should be handled elaborately in AISC 360-10 formulations. *L/D* and relative slenderness are key parameters and have direct impact on column behaviour. However *D/t* does not have direct impact on column behaviour.

1. Introduction

Concrete Filled Steel Tube (CFST) columns have distinctive characteristics which allow use of such compression members in challenging engineering fields. High rise buildings [1,2], deep underground tunnels [3], bridges [4,5] and towers [6] are some examples of structures in which CFST columns are deployed as main load carrying members. High energy absorption capacity, stiffness and ductility of CFST columns motivate engineers to adopt such members in earthquake prone zones [6,7]. The steel tubing serves as a formwork for concrete core, thus construction time and costs can be reduced [7–9]. Further cost savings can be provided since CFST columns cover smaller areas on storeys compared to bare steel and reinforced concrete counterparts [1]. Also the concrete core precludes early local buckling of steel and improves the performance of entire composite cross section [5,10]. The confinement effect of circular steel tubes on concrete is the most prominent characteristic of CFST columns. With proper geometrical and mechanical properties of materials, circular tubes enable concrete core to exhibit higher performance than its characteristic compressive strength [11].

Research into the compression performance of circular CFST columns has been widely carried out in recent decades. Strength of stub CFST columns has attracted the attention of many researchers [1,2,9,12–14]. Considering the practical applications, the behaviour of long CFST columns was also investigated in past [10,15–17]. However a recent paper by Kang et al. [18] reports that a number of experimental studies conducted on long columns is less than the number of studies on stub columns. Also in the same paper, it can be observed that the studied material parameters range is not wide enough to capture underlying mechanics of CFST columns adequately. For example, concrete strength between 80 and 110 MPa was used in 6.6% of circular stub columns. On the other hand just 3.8% of long column tests were conducted using concrete strength between 60 and 96 MPa. The paper presented by Kang et al. [18] reports these statistical information based on the database developed by Tao et al. [19] in 2008. Lots of studies on CFST columns have been published since Tao et al. [19] presented the database. However, there is still need for more experimental studies on long columns and broader material parameters to be able

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to understand the behaviour of circular CFST columns explicitly. The need for more CFST column experimental data to calibrate specification formulations was also highlighted in a document which was published as "Commentary on the AISC 360-10 Specification of Structural Steel Buildings" [20].

Practical formulations of design specifications help engineers predict the capacity of CFST columns. American AISC 360-10 [21], European Eurocode-4 (EC4) [22], Japanese AIJ 2008 [23], Australian AS 5100.6 [24], Chinese DBJ/T13-51-2010 [25] and South African SANS 10162-1 [26] are some specifications which are employed for this purpose. Expected performances of those design specifications differ in predicting the capacity of CFST columns. Several researchers showed that for stub columns AISC 360-10 gives conservative predictions compared to experiments [1,5,9,12,14]. Based on experimental results of short and long columns Oliveira [15] also highlighted conservative predictions of AISC 360-10. On the other hand, capacity prediction of EC4 for stub columns was reported to be unconservative [1,15]. On the contrary, some other experimental results of stub columns were found to be very close to EC4 predictions [9,12,14]. For longer columns Oliveira [15] reported that EC4 predictions are very close to experimental results but still on unconservative side. Dundu [16] assessed EC4 predictions against his experiments on long columns which have *L/D* ratios ranging from 6 to 21.7 and concluded that EC4 predictions are conservative up to 25%. Zeghiche [10] assessed test results of very long CFST columns which have *L/D* ratios greater than 12.5 against EC4 predictions and reported that EC4 predictions are on the safe side. Aforementioned conclusions of specification assessments also denote the need for more experiments to shed light on the behaviour of circular CFST columns. However, to provide new drawbacks novel characteristics are required for new experiments. Significant amount of experiments with mean material and geometrical properties which comply with the applicability limits of the specifications have already been published. Hence, new experiments should push the limits of design specifications.

The aim of this paper is thus twofold; The first aim is to examine the experimental performance of circular CFST columns which have properties close to the application limits and beyond the limits of the design specifications of AISC 360-10 and EC4. To this end, 18 CFST specimens, including short, medium and long columns were tested to failure under compressive loading. Column lengths were chosen with the intent to observe the confinement effect. Towards this aim, three *L/D* and two *D/t* ratios were considered. Three levels of concrete strength of 56 MPa, 66 MPa and 107 MPa were utilized to assess the effect of concrete strength on column performance. Concrete strengths of 56 MPa and 66 MPa are very close to the applicability boundaries of AISC 360-10 and EC4 specifications. On the other hand, 107 MPa concrete strength is far away from the applicability boundaries of both AISC 360-10 and EC4. Steel tubes with S235 and S355 European steel qualities were used to develop different confinement effects. The above properties enabled the authors to test CFST columns with confinement factors ranging from 0.226 to 1.538 and steel contribution factors (a parameter used in EC4) from 0.185 to 0.606. The second aim of this paper is to make a general assessment of prediction methods of AISC 360-10 and EC4. After detailing experimental behaviour of 18 CFST columns with above properties, 239 additional CFST column data which were collected from literature and cover a relatively wide range of parameters were utilized to make reliable assessments of specifications. Evaluations undertaken on 257 CFST column experiments have the potential to depict the effects of column parameters on compression capacity and prediction capability of design specifications more precisely.

2. Experimental research

2.1. Material properties

Two different steel qualities were employed for CFST column specimens. The first one is European S235 steel, with 235 MPa yield strength and 2.74 mm thickness and the second is European S355 steel, with 355 MPa yield strength and 5.90 mm thickness. The main idea behind the selection of material and thickness properties is to examine behaviours of columns with low and high confinement factors (ξ), Eq. (1). Confinement factor is a practical parameter which has been used by several researchers to roughly characterize confinement capability of the column. This factor can be employed for circular [5,27,28] as well as rectangular [29,30] CFST columns.

$$\xi = \frac{A_s f_y}{A_c f_c} \tag{1}$$

where A_s and A_c are the cross sectional areas of the steel tube and core concrete, respectively. f_y is the yield strength of steel and f_c is the compressive strength of concrete. Also, the values of the above parameters (A_s, A_c, f_y and f_c) directly affect the steel contribution ratio (δ), which is an important parameter in EC4. This parameter is introduced in Section 6 in Eq. (21). The above parameters allow testing columns with steel contribution ratio within and beyond the applicability limits of EC4.

Three different concrete mixes were prepared. Cylinder concrete compression specimens of 100 × 200 mm size were cast from the concrete batch. Considering the small diameter of tubes, coarse aggregate of maximum diameter of 10 mm and fine aggregate (sand) were used in the concrete mix. Moulds were filled in three layers and a shaking table was used to compact the concrete after each layer. Concrete specimens were crushed in accordance with ASTM C39/C39M [31] after curing stage. Measured average compressive strengths of concrete mixes are 56.20 MPa, 66.75 MPa and 107.20 MPa. In the present study, these levels of concrete strengths were deliberately chosen to test columns which have concrete properties close to the upper limits of design specifications and far away from those limits. New, large and efficient structures require the adoption of high strength materials, and thus high strength CFST columns are particularly appropriate for investigation.

2.2. Column specimens

Column specimens were manufactured using 114.3 mm diameter steel tubes. Three *L/D* and two *D/t* ratios were specified for the specimens. These tube properties were selected to allow different types of failure behaviours to take place under compressive loading. Properties of CFST column specimens are presented in Table 1. Employed specimen naming system in Table 1 includes circular tube diameter (*D*), tube thickness (*t*), column length (*L*) and core concrete strength (f_c), respectively. For example, the specimen 114.3-2.74-300-56 represents CFST column with 114.3 mm outer diameter, 2.74 tube thickness, 300 mm length and 56 MPa core concrete strength. The seventh and eighth columns of Table 1 present the confinement factor (ξ) and steel contribution ratio (δ), respectively.

Prior to filling the concrete, the ends of each tube specimen were machined to insure maximum uniformity of contact with the loading heads of the testing machine. Providing the uniformity and flatness of column ends is a crucial step in column testing procedure to obtain reliable test results [32]. The machining process of steel tubes is shown in Fig. 1.

In order to provide appropriate interaction between the steel