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Experimental and numerical investigations of the compressive behavior of concrete filled steel tubes (CFSTs)

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ABSTRACT

This paper presents an experimental study to investigate the compressive behavior of circular concrete filled steel tubes (CFSTs) when subjected to pure axial loading at a low rate of 0.6 kN/s. CFSTs of three different diameter-to-thickness ($^D/_t$) ratios of 54, 32, and 20 are considered in this study filled with two concrete's compressive strengths of 44 MPa and 60 MPa. The measured compressive axial capacities are compared to their corresponding theoretical values predicted by four different international codes and standards: the American Institute of Steel Construction (AISC), the American Concrete Institute (ACI 318), the Australian Standard (AS), and Eurocode 4. Result comparisons also included some suggested equations found in the literature. It was found that the effect of ($^D/_t$) ratio on the compressive behavior of the CFST specimens is greater than the effect of the other factors. The underestimation of the axial capacities calculated by most of these codes reduces as the $^D/_t$ ratio increases as verified by the experimental results. A nonlinear finite element (FE) numerical model using the commercial software package ABAQUS is also developed and verified using the presented experimental results.

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1. Introduction

Concrete filled steel tube (CFST) columns are increasingly used in military facilities, tall buildings, bridges, and other structures. They are considered as an advantageous system for carrying large axial load benefitting from the interaction between the concrete and the steel section. The steel tube reinforces the concrete to resist any bending moments, tensile and shear forces. The concrete in a composite column improves the buckling behavior of the steel section in addition to resisting compressive loading. CFST columns have several advantages over structural steel, reinforced concrete or concrete-incased steel members. Earthquake engineers prefer CFST over encased composites because of its enhanced ability to dissipate energy and higher torsional resistance capacity. The tedious process of framework preparation and steel fixing in the RC construction is absent in CFST structures since the steel tube acts as the framework. Thus, less wood is needed for CFST construction which makes it ecologically preferable choice in addition to the fact that it is easier to be reused post demolition (recyclable). The dominant failure mode in bare steel tubes is buckling, but the presence of concrete infill delays failure by forcing it to buckle outwards only resulting in additional capacity to the section. Due to the above-mentioned advantages the cost of using CFST columns in construction makes it more attractive than other alternatives.

Experimental investigations have been performed recently by many researchers to study the effects of various parameters on the overall compressive behavior and failure modes of CFSTs. For example, Sakino et al. [1], developed a design method based on the testing program of the 5 years research on CFST column that was performed as a part of the fifth phase of the U.S.–Japan Cooperative Earthquake Research Program. Four main varying parameters were considered in this phase; the steel tube $^D/_t$ ratio, steel tube tensile strength, steel tube shape and concrete infill strength. It was concluded that the difference between the nominal squash load and the ultimate strength of circular CFST columns can be evaluated through a linear function of the tube yield strength. O'Shea and Bridge [2,3] examined the $^D/_t$ ratios and concrete infill strengths as well, but their focus was on thin walled CFST specimens. The effects of axially loading of the concrete infill only, the steel tube only and the entire CFST specimen were investigated. It was noted that the confinement effects in the CFST specimens were greatest when only the concrete infill was loaded. Yu et al. [4] conducted an experimental study on the behavior of circular CFST columns filled with self-compacting concrete and normal concrete under concentric loading. Their aim was to explore the effect of different measurement methods of the specimens' axial deformation, concrete core compressive strength and loading conditions. It was noted that a significant increase in the section's capacity was associated with the increase of the compressive strength of concrete infill. Gupta et al. [5] studied the effects of not only the $^D/_t$ ratio and the grade of concrete infill but also volume of fly ash in concrete mix and $^L/_D$ ratio on the behavior of axially loaded circular CFST samples. As a bench mark, hollow steel tubes were tested and it was

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noted that their capacity per unit volume decreases with the increase of D/t ratio. Lama and Gardner [6] examined the compressive behavior of concrete filled stainless steel columns with varying concrete infill strengths. The CFST capacities were compared with the ones obtained from stainless steel hollow sections and with existing design rules based on Eurocode 4 [7] and ACI-318 [8]. It was concluded that the current design guides in the codes can be safely used for concrete filled stainless steel tubes despite being somewhat overly conservative.

Most recently, the compressive behavior of CFST columns at high strain rates and temperatures has gained the interest of some scholars. Xiao et al. [9] performed experimental studies on CFSTs under high strain rate loading using split Hopkinson pressure bar. The applied strain rate during the impact test ranged from 81 s^{-1} to 195 s^{-1}. It was noted that the dynamic impact factor (DIF) of CFST specimens was smaller than that of a plain concrete specimen under the same strain rate impact. Huo et al. [10] axially impacted small sized micro concrete-filled steel tubes at elevated temperatures up to 400 °C. Minor load capacity increase was observed for the specimens at ambient temperature after the steel tube yielded, though the specimens at elevated temperatures displayed notable increase in load-carrying capacity. Prichard and Perry [11] investigated the effects of different concrete infill compressive strengths, confining materials and confining tube thicknesses of CFSTs subjected to axial impact loading at different rates. It was concluded that providing additional lateral confinement to the minimum necessary to inhibit the dilation of the concrete will increase the maximum contact force.

Several international codes (e.g., AISC [12], ACI 318 [8], AS [13] and Eurocode 4 [7]) provided guidelines and procedures to estimate the compressive capacity of CFST columns. However, most of these codes are overly conservative in their estimation because they neglect the contribution of concrete confinement on the overall axial capacity of CFST columns. For this reason, recent studies focused on developing new equations to predict the CFST element's capacity taking into consideration the confinement of concrete caused by the steel tube. For example, Mander et al. [14] developed a stress–strain model for confined concrete by transverse steel reinforcement based on the energy balance approach. This model can be applied to CFST columns utilizing the defined effective lateral confining stress that depends on the structural steel dimensions. Giakoumelis and Lam [15] performed linear regression analysis using their experimental results on CFST columns to propose a correction to the ACI code equation by replacing the 0.85 reduction factor with a magnification coefficient of 1.3 to the concrete compressive strength.

Finite element analysis has been used frequently in previous researches to predict the behavior of CFST using available commercial finite element software like ANSYS [16] and ABAQUS [17]. Hu et al. [18] developed a nonlinear FE model to simulate CFST columns, and verified it against experimental data extracted from the literature. However, the definition of the lateral confinement stress on the concrete was based on regression analysis using their experimental results. Hence the post ultimate behavior was not fully captured. Ellobody et al. [17] investigated the behavior and design of axially loaded circular CFST columns computationally using an ABAQUS based FE model. The model's results were compared with the results of the tests conducted by Giakoumelis and Lam [15] and Sakino et al. [1]. Nevertheless, the type of elements used in the mesh analysis was not appropriate for the steel tube and the concrete infill of the CFST specimen.

The aim of the presented research is thus threefold: first, to conduct an experimental testing program to study and monitor the performance of concrete-filled steel tubes considering two compressive strengths of the concrete infill and three D/t ratios of the steel tubes. Second, to validate the accuracy of the available design codes as well as some of the newly suggested equations by direct comparisons with the proposed experimental results. Third, to develop a robust and well-calibrated nonlinear FE model using the commercial software package ABAQUS. The model would be taking into consideration the nonlinear behavior of both steel and concrete.

2. Experimental program

The experimental program presented in this article provides important results regarding the compressive capacity of 16 CFST specimens under pure axial loading. All samples were filled with plain concrete cast from two batches, eight of which were filled with normal strength concrete (44 MPa) and the remaining eight with high strength concrete (60 MPa). The proportions of both concrete mixes are shown in Table 1. The length-to-diameter (L/D) ratio was kept at 2 for all samples as suggested in the literature [11]. The experimental program includes additional axial loading tests performed on hollow steel tubes (ST). All the CFST and ST samples were prepared from three hollow steel tubes of 6 m length each. Three D/t ratios of 20, 32 and 54 are considered in this study, which were obtained by either varying the section's outer diameter (D) or the tube thickness (t). Specimens with $D/t = 20$ and 32 have similar outer diameter of 114 mm, but tube thickness of 5.6 mm and 3.6 mm, respectively. On the other hand, specimens with $D/t = 54$ have an outer diameter of 167 mm and tube thickness of 3.1 mm. A schematic layout of the experimental program for testing CFSTs and STs is presented in Fig. 1.

Details of the geometric description of the CFST specimens as well as the characteristics of parameters investigated in this study are summarized in Table 2. Herein, $t_{3.1}$, $t_{3.6}$ and $t_{5.6}$ stands for tube thickness of 3.1 mm, 3.6 mm and 5.6 mm, D_{114} and D_{167} refer to tube outer diameter of 114 mm and 167 mm, and f_{60} and f_{44} relate to concrete infill compressive strength of 60 MPa and 44 MPa, respectively.

After cutting the steel tube into the desired dimensions, the CFST specimens were cast and manually compacted. Concrete cubes and cylinders were prepared from each batch. After 28 days of curing, the average compressive strengths of high and normal strength cubes were found to be 70 MPa and 53 MPa, respectively. On the other hand, the concrete cylinder results indicated that the compressive strengths of these two batches are 60 MPa and 44 MPa, respectively. The difference between the two tests is in the order of 5–25% which is in agreement with the provision of British Standards Institute Draft for Development [19]. It should be noted that the concrete cylinders were tested not only in the same day as CFSTs but also under the same loading conditions as well. Fig. 2 shows the load–displacement diagrams of concrete cylinders from both concrete types. The stiffness of high compressive strength concrete is slightly larger than that of normal strength. Due to the brittle nature of concrete, the nonlinear regions in the two curves are minimal. Coupon tests were also conducted on the steel material at a relatively low strain rate. The average yield stress for the steel tubes was around 300 MPa and the modulus of elasticity was about 200 GPa.

Load was applied to all CFST and ST specimens using a 3000 kN-capacity universal testing machine (MTS, Servo Hydraulic Compression Model YAW4306). The load was applied at a constant rate of 0.6 kN/s until the sample reaches its ultimate load capacity. Once softening (or unloading) is detected, the machine holds a constant

Table 1
Concrete mix proportions.

Concrete type	Mix proportions (divided by weight of cement)				
	Cement	Coarse aggregates	Fine aggregates	Water	Plasticizer
Normal strength concrete	1	3.4	2.9	0.62	–
High strength concrete	1	3.2	2	0.41	1.1%

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