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Flexural response of concrete-filled seamless steel tubes

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ABSTRACT

This paper aims to investigate the flexural behavior of concrete filled tubes (CFSTs) made of seamless steel which can handle more pressure than welded steel. Experimental, Theoretical and Finite Element Analyses are utilized for this purpose. The experimental program consists of four-point bending tests of six CFSTs and three hollow steel tubes (STs) for three different Diameter-to-thickness (D/t) ratios of 7.82, 13.5 and 17.5. The test results included are the moment versus displacement and strains, failure modes and ultimate capacities. The contribution of the concrete infill to the flexural capacity was more significant in specimens with higher D/t ratios. All CFST beams exhibited ductile mode of failure with no local buckling. The experimental moments are compared to theoretical nominal moments calculated by well-known international design codes such as the Architectural Institute of Japan (AIJ), the British Standard (BS), the AISC-LRFD, and the Euro code4. Only the AIJ equations predicted non-conservative capacities particularly at the highest D/t ratio. The other codes and standards were more conservative since they did not consider the effect of concrete confinement in their design equations. Finite Element (FE) simulation of the flexural response of CFST is also conducted by developing a nonlinear 3D model considering both material and geometric nonlinearities. The FE model is verified using the present experimental results and a good agreement was achieved in terms of the moment capacity, the failure mode and the moment-mid span deflection curves. In addition, the verified finite element model was used to carry out a parametric study considering wider ranges of D/t ratios and yield strengths.

1. Introduction

Concrete-filled steel tubes (CFSTs) are composite structural members constituting of a steel tube and a concrete infill. Both materials mutually contribute to carrying the load and providing the necessary member stiffness where the steel tube improves the carrying capacity of the concrete and the concrete core delays the global and local buckling of the steel tube [1–3]. In current construction practice, CFSTs are commonly used as columns and braces in tall buildings, bridges and military facilities due to their large axial load capacity, compression stiffness and high deformation capacity [1, 4–7]. The flexural behavior of CFSTs is currently the prompt of much research and investigation. To date, the application of CFST in beams is limited. CFST members are currently employed in lofty structures as well as structures in earthquake-prone areas. Other applications include bridges and piers [1].

CFST members have the potential to combat various limitations of conventional reinforced concrete members. They enhance compression behavior since the concrete infill is well confined inside the steel tube, which allows steel yielding before concrete crushing. The confinement on concrete inside the steel tube also establishes a triaxial state of compression, which results in increased strength and strain of concrete [1]. Moreover, CFST is characterized by high strength and high ductility, which are contributed by the steel, as well as high load-carrying capacity, which is contributed by concrete [8]. Furthermore, the steel tubes readily provide formwork for concrete and hence, no additional formwork is required. This in return accelerates the construction process [9–11].

Considering the aforementioned multiple advantages, CFST is a promising structural element and hence, vast research efforts have been expended to investigate its mechanical properties, as well as its behavior in different applications. More specifically, recent research sheds light on the flexural behavior of CFST, to expand and develop the application of CFST in structures. Han tested 16 CFST beams with square and rectangular cross-sections to study their flexural behavior [3]. The concrete cube strength for these CFST beams ranged from 27 MPa to 40 MPa, and steel yield strength from 294 MPa to 330 MPa. Han also compared experimental ultimate moments of CFST beams with theoretical results calculated by codes equations including the Architectural Institute of Japan (AIJ) [16], the AISC-LRFD [12], the British Standard (BS) [13], and the Euro code [14]. It was found that flexural capacities obtained using these codes were conservative; with >20%

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prediction difference using AIJ and AISC, 12% difference using BS5400 (1979) and around 10% overestimation using EuroCode4. In addition, Han [3] developed two different analytical relationships, one for rectangular and the other for circular cross-sections, based on composite mechanics equations and regression analysis to predict the flexural capacities of CFST beams. It was mentioned that cooling of the weld produces residual stresses which can be up to 20% of yielding stress in the compression zone and full yielding stress in the tension one. All of the theoretical calculations do not account for these residual stresses which will lead to inaccurate flexural capacities. However, seamless tubes considered in this study do not have residual stresses since the steel tube were extracted from steel forms, without any welding.

Probst et al. [4] tested four 6-meter length CFST specimens with rectangular and circular cross-sections, and also with and without shear connections. The D/t ratio for their circular CFST specimens was 36 and the concrete strength was 22 MPa. The experimental ultimate moments for circular CFST beams without shear connection were compared to the AISC and EuroCode4, and both codes were found to be un-conservative. They suspect that the large diameter of concrete is the reason for this deviation from the codes since the effect of concrete shrinkage would be significant. Further research, with various D/t ratios, was recommended to investigate the applicability of AISC and EuroCode4 for calculating the flexural capacity of circular CFST beams.

Elchalakani et al. [15] investigated the flexural behavior of circular CFST beams with a range of D/t ratios between 12 and 110. It was found that local buckling does not occur for CFST specimens that have D/t ratio less than or equal to 40. According to their results, design of CFST using the AISC, AIJ, and EC4 codes was found to be un-conservative for the case of the low D/t ratios 12.8. This could be due to overestimating the CFST flexural capacity when more steel thickness is used.

Finite Element (FE) Analysis was also used by some researchers to investigate the flexural behavior of CFST members. For example, Moon et al. [1] studied the effect of the steel yield stress to the concrete compressive strength ($f_y/f_{c'}$), and the diameter to depth ratios (D/t) on the flexural behavior of circular CFST beams by developing a nonlinear FE model. They concluded that the $f_y/f_{c'}$ ratio improved the flexural capacity, while the D/t ratio has no significant effect. Wang et al. [16] also developed a nonlinear FE model to understand the flexural behavior of rectangular CFST beams. They compared the FE results with the data from previous experimental programs of 70 beam specimens. The moment capacities, the failure modes and the load vs displacement curves predicted by the FE model compared well with their experimental counterparts [16].

A thorough understanding of the flexural behavior of CFST beams is crucial to expand their application. The aim of this paper is to study the flexural behavior of circular CFST beams using seamless steel tubes and also considering a range of low D/t ratios between 7.82 and 17.5. This paper will also investigate the applicability of theoretical results predicted by international design codes such as AIJ, AISC, BS, and EC4, and determine if the conclusions made by the previous studies is applicable for seamless steel tubes. Finally, a three-dimensional finite element model capable of simulating the flexural response and predicting the ultimate capacity of CFST and ST beams will be developed using the commercial software ABAQUS by considering both material and geometric nonlinearities.

2. Experimental program

The experimental program of this study consisted of four-point bending tests of six CFSTs and three hollow steel tubes (STs). All steel tubes had the same diameter of 114 mm and length of 1100 mm; however, their thickness varied from 6.5 mm to 14.5 mm, resulted in three different D/t ratios. The specimens were placed in three groups based on their resulting D/t ratios. At each D/t ratio, two steel tubes were filled with normal concrete and one was left hollow. Fig. 1 illustrates the experimental program matrix used in this study.

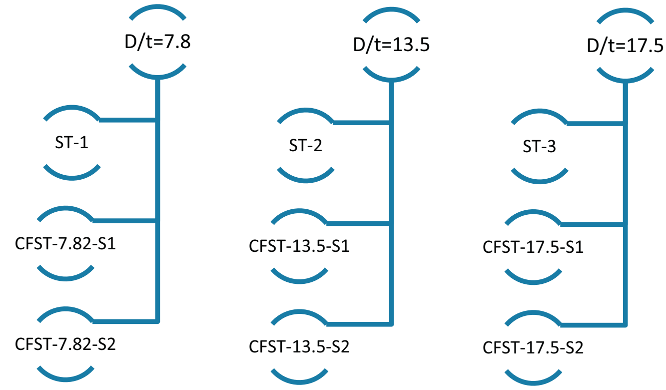

Fig. 1. Experimental program.

Table 1 summarizes the concrete mix propositions used in this study. Three cubes and three cylinders were casted and tested after 28 days curing. The average compressive strength of the concrete infill was 43 MPa for cubes and 39.4 MPa for cylinders.

The steel tubes were readily produced by the manufacturer as seamless tubes. Thus, their diameters and thicknesses were fixed. Coupon specimens were manufactured and tested to extract the tensile stress-strain curve for each tube thickness as shown in Fig. 2. Accordingly, the average yield stress was 245 MPa with a corresponding yield strain of 0.001225 and the modulus of elasticity was around 200 GPa. In addition, the ultimate stress was about 530 MPa, which is more than twice the yield stress. The effect of such high strain hardening on the CFSTs flexural behavior was evident as will be discussed later.

CFST beam specimens were casted and compacted manually to ensure that concrete is distributed throughout the whole beam and is well confined inside the steel tube. The specimens were tested over a 1000 mm clear span in a four-point bending setup with a constant moment region of 400 mm, as shown in Fig. 3. The load was induced using a Universal Testing Machines (UTM), which has a load capacity of 1200 KN, and transferred to two loading points on the specimen through a spreader beam. The load was applied at a constant rate of 2 mm/min.

The mid-span deflection of each specimen was captured throughout the test using a linear variable displacement transducer (LVDT) located at the beam soffit. Strain gauges were also mounted at the center of the beams to measure the strain in both lateral and longitudinal directions. The load, mid-span deflection, and strains were recorded every 0.1 s using a high-speed data acquisition system. Moreover, special supports were used to hold the beams in place. The supports provided good grip of the circular test beams and prevented rotation. Fig. 3-b provides a depiction of the supports employed in this experiment.

3. Results and discussions

The experimental program was capable of capturing the behavior of the seamless CFSTs in term of their moment capacities at yield and at ultimate, their deformation behavior beyond the yield point and their failure modes.

Table 1
Concrete mix proportions.

Concrete type	Mix proportions (divided by the weight of cement)				
	Cement	Fly ash	Coarse aggregates	Fine aggregates	Water
Normal strength concrete	1	0.27	4.4	3.1	0.55