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Flexural behavior of lightweight concrete and self-compacting concrete-filled steel tube beams

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ABSTRACT

The study presents a comparative experimental analysis of the flexural behavior of lightweight concrete and self-compacting concrete filled square steel tube beams subjected to pure bending. A total of 20 specimens including eight lightweight concrete-filled steel tube (LWCFST) beams, eight self-compacting concrete-filled steel tube (SCCFST) beams, and four hollow steel tubes were tested. The main parameters varied during the experiment include (1) type of concrete core, lightweight concrete (LWC), and self-compacting concrete (SCC); (2) width to thickness ratio; and (3) confinement factor (ξ). The flexural capacities, flexural stiffness, ductility, failure modes, deflection curves, and bending moment versus mid-span deflection curves were examined. Several performance indexes were used to discuss the flexural strength, stiffness, and ductility of the tested beams. The test results revealed that LWC and SCC significantly improved the overall flexural behavior of square hollow steel tubular sections. The results indicated improvements in flexural strength, stiffness, and ductility. Furthermore, a comparison was performed, and the findings indicated that LWCFST beams exhibit increased flexural stiffness, comparable moment resistance, and lower ductility when compared to SCCFST beams. The moment capacities and flexural stiffness were compared with the predicted values by using various design codes, and the comparisons indicated that all the design codes are conservative with respect to the estimation of the moment capacity. However, all the design codes are not conservative with respect to the prediction of the serviceability level flexural stiffness. The test results and comparisons motivate application of LWCFST and SCCFST beams as a potential alternative for normal weight CFST beams.

1. Introduction

Concrete filled steel tube (CFST) members are widely utilized in different structural applications including high rise buildings, bridges of several typologies, towers, and bracing systems [1–6]. Specifically, CFST members display several advantages including high load carrying capacity, stiffness, significant ductility, and energy absorption ability [7–10]. The infill concrete core delays and even precludes local buckling of the confining steel tube, and this significantly increases strength and ductility [11]. On the other hand, the steel tube provides continuous longitudinal and lateral reinforcement for the concrete core in addition to effective confinement [9].

Lightweight aggregate concrete (LWC) is a structural material with several advantages including higher strength/weight ratio, excellent thermal and sound insulation, and fire resistance characteristic due to air voids in the lightweight aggregate [12–14]. The LWC is approximately 20% to 30% lighter when compared with normal weight concrete (NWC). However, LWC exhibits lower compressive strength, lower elastic modulus, higher brittleness, and significantly lower ductility when compared to NWC [14–18]. The lower compressive strength of lightweight aggregate concrete is due to the mechanical properties of the main component which is the lightweight aggregates. Lightweight aggregates are characterized by their brittle, weak, and porous structure that leads to decreases in the compressive strength of these aggregates and consequently decreases the compressive strength of the LWC. Thus, the AISC 360-16 limits the allowable compressive strength of LWC in CFST members within the range of 21 MPa – 42 MPa (normal strength concrete only).

Lightweight aggregate concrete-filled steel tube (LWCFST) beam is a combination of a hollow steel tube with the lightweight concrete core. The composite member represents an economical alternative to other types of construction [12]. With respect to the CFST beams and specifically those with a large span, the self-weight of the beam adversely affects the moment carrying capacity. Hence, LWCFST beams with lighter weight characteristics may replace normal weight CFST beams (NWCFST). This increases the crossover ability of the beams and potentially decreases the height of the beam section and the cost of foundations [12, 19, 20]. Recently, LWCFST members are successfully used as a main composite girder beam for railway bridge systems in Japan

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[4, 6]. In a manner similar to NWCFST, the steel tube confines the lightweight concrete core due to the composite action of LWCFST, and thus the strength, ductility, and stiffness increase. On the other hand, the infill concrete supports the steel tube and postpones or even prevents local buckling.

Self-compacting concrete-filled steel tube (SCCFST) beam represents a hollow steel tube filled with self-compacting concrete. Self-compacting concrete (SCC) discharges under its weight and fill in the formwork without the need for any compaction efforts and results in a decrease in construction time and labor cost [21]. Research on SCCFST beams and columns indicated that the structural behavior of these composite members is similar to that of NWCFST members [22, 23].

Currently, different design codes and specifications are employed to only predict the flexural strength and flexural stiffness of NWCFST members. They include the American specification AISC 360-16 [24], European code EC4-2004 [25], Chinese specifications DBJ/T13-51-2010 [26], Australian standard AS 5100.6-2004 [27] and the Japanese standard AIJ-2001 [28]. However, it should be noted that among all these codes, only the AISC-360-16 and EC4-2004 permit the use of LWC in CFST members albeit with a specific limitation on concrete strength and density. For example, the AISC 360-16 limits the compressive strength of the normal weight concrete and lightweight aggregate concrete in the range of 21–70 MPa and 21–42 MPa, respectively. Whereas, it limits the concrete density in the range of 1500–2500 kg/m^3. Therefore, it is extremely important to investigate the feasibility of these design codes to predict the flexural strength and stiffness of LWCFST beams and SCCFST beams.

2. Research background, significance, and objectives

Over the past decades, several researchers focused on the experimental flexural behavior of NWCFST beams [7, 9, 29–34]. However, there is a paucity of studies on the flexural behavior of LWCFST and SCCFST beams. In the field of LWCFST members, several studies concentrated on the compressive performance of LWCFST columns under concentric and eccentric compression loadings [12–14, 18, 19, 35–37]. However, extremely few studies examined LWCFST beams [20, 35, 38]. Therefore, studies on LWCFST beams are currently in the initial phase worldwide. The scarcity of information on LWCFST beams reveals the necessity for increased research to fill the gaps in the field.

Similarly, with respect to the SCCFST members, most studies examined SCCFST columns with different configurations [21, 23, 39–41]. Conversely, only a few studies focused on SCCFST beams [22, 41, 42], and this indicates the need for additional research in this area. Given the aforementioned points, the following conclusions are reported: (1) there is evidently a significant lack of studies and test data on the flexural behavior of LWCFST and SCCFST beams. The research in the domain is still in the primary stage, and more experiments are required to shed light on the structural performance of these composite beams. (2) A few extant studies compared the performance of LWCFST or SCCFST members relative to those of NWCFST members. However, to the best of the authors' knowledge, there are no studies that examine the behavior of LWCFST beams relative to SCCFST beams.

There are three main goals of the study. First, to generate a set of new test data on LWCFST beams and SCCFST beams. Second, to investigate the experimental flexural behavior of the LWCFST beams relative to SCCFST beams with respect to the strength, stiffness, ductility, failure modes, deflection, and failure process. Finally, to examine the feasibility of different current design codes and specifications including the AISC 360-16, EC4-2004, DBJ/T13-51-2010, AS 5100.6-2004, and AIJ-2001 to predict the flexural strength and stiffness of LWCFST and SCCFST beams.

3. Experimental program

3.1. Material properties

3.1.1. Lightweight concrete (LWC)

The coarse aggregate of the LWC is pumice with a maximum aggregate size of 10 mm. The fine aggregate was crushed sand with a maximum size of aggregate of 4 mm. The target concrete compressive strength was set as 30 MPa. The design proportions of the LWC mix are summarized in Table 1. Six standard concrete compression specimens (100 mm × 200 mm) were cast from the concrete batch. After the curing stage, the concrete cylinder samples were tested based on the ASTM C39/C39M standard [43]. The workability properties of the LWC mixture with respect to the slump test results were as follows: slump of 250 mm and slump flow of 480 mm. Furthermore, a LWC density of 1806 kg/m^3 was approximately 76% of that of the self-compacting concrete 2377 kg/m^3.

3.1.2. Self-compacting concrete (SCC)

The coarse aggregate utilized in the mix included river gravel with a maximum size of 14 mm. The fine aggregate is a mixture of river sand and crushed sand with maximum sizes of 4 mm and 2 mm, respectively. The mix proportions of the SCC are shown in Table 2. In a manner similar to LWC, the concrete compressive strength of the SCC was set as 30 MPa. In order to evaluate the concrete compressive strength, six standard cylinders (100 mm × 200 mm) were cast from the concrete batch without any compaction. The workability characteristics of the SCC mixture are shown in Table 3 based on the EFNARC committee [44] recommendations.

3.1.3. Steel

A total of four different square seam welded steel sections were used with cross-sectional dimensions of 100 × 100 × 4.54 mm, 100 × 100 × 2.71 mm, 120 × 120 × 4.69 mm, and 120 × 120 × 2.80 mm. In order to determine the material properties of these sections, tensile coupon tests were performed based on the recommendations of the ASTM E8 [45]. Thus, three coupons were obtained from each steel tube in the longitudinal direction. The average values of the yielding strength (f_y) and ultimate tensile strength values (f_u) obtained from the tests are reported in Table 4.

3.2. Specimen preparation

In the study, a total of 20 CFST beam specimens were prepared to conduct the experimental investigation including eight LWCFST beams, eight SCCFST beams, and four hollow steel tubes. Each composite beam specimen exhibited a duplicated specimen with the same properties and loading configurations. The main testing parameters for the tested CFST beam specimens were as follows: (1) Type of concrete core (LWC and SCC) with compressive strengths (f_c) of 30.65 MPa and 37.21 MPa (normal strength concrete), respectively; (2) width to thickness ratio (B/t) ranging from 22.03 to 42.86 (compact sections); (3) steel yielding strength (f_y) ranging from 261 to 392 MPa (normal strength steel sections); (4) steel ratio (α) ranging from 0.10

Table 1
Mix proportions and properties of lightweight aggregate concrete (LWC).

Cement (kg/m^3)	Silica Fume (kg/m^3)	Lightweight aggregate (kg/m^3)	Crushed sand (kg/m^3)	Water (kg/m^3)	Super plasticizer (kg/m^3)	f_c (MPa)	Density (kg/m^3)
650	150	318	613	200	11	30.65	1806