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Behavior of Reinforced Lightweight Aggregate Concrete-filled Circular Steel Tube Columns Under Axial Loading

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ABSTRACT

The use of lightweight aggregate concrete (LWC) is the most obvious way to reduce the self-weight of concrete-filled steel tube (CFST) columns. This paper reports an investigation of the properties of reinforced lightweight aggregate concrete-filled steel tube (RLWCFST) columns subjected to axial compression. Eighteen specimens with three length-to-diameter (L/D) ratios (short, medium, and long) and two diameter-to-thickness (D/t) ratios (thin and thick) were tested. The LWC compressive strength is 30.58 MPa. The test results are given in terms of the compression loading against end shortening curves, and the failure modes of eighteen specimens are compared and discussed. In addition, the predictions of AISC360-16 and EC4 design specifications were compared to the test results to confirm the predictions of these specifications hold for RLWCFST columns. According to the experimental results, the use of the steel-bar reinforcement improves the mechanical behavior of LWC and increases the compressive strength capacity, toughness, and ductility of the composite column. The failure modes of the columns were affected by the behavior of the reinforced and unreinforced LWC and the geometric properties of the steel tube (L/D and D/t ratios). Steel-bar reinforcement combined with thinner steel tube provided excellent performance and using larger-diameter steel-bars instead of thick steel tube can offer improvement in compression capacity and ductility for short, medium, and long columns.

1. Introduction

Due to their high structural performance, concrete-filled steel tube (CFST) columns have been widely used in different structures such as bridges, offshore structures, and high-rise buildings. They offer desirable characteristics such as high strength capacity, high stiffness capacity, and high ductility, and provide superior structural characteristics for seismic resistance, including large strain energy absorption capacity when compared to bare steel columns and reinforced concrete columns [1–5].

These excellent structural characteristics are due to the composite action between steel tube and concrete core. The steel tube works as a permanent formwork and bears the load during construction before concrete is poured. In return, the presence of concrete core enhances the local buckling of the steel tube and prevents inward buckling of steel tube; hence both construction time and costs are reduced [6–8].

CFST columns have many cross-sectional shapes. Studies have shown that a circular cross-section provides the best confinement to the concrete core compared to rectangular and square sections [1,7,9,10]. In a circular section, the confining stress (σ_{lat}) is distributed uniformly which guarantees the whole section of the core concrete will be confined effectively along the circular CFST specimen [9]. Fig. 1 shows the stress states in circular CFST column under compression. While square and rectangular shapes do not show such behavior [9], square and rectangular sections are still used in construction, as they offer easier beam-to-column connection and may meet certain architectural requirements [1].

Basically, the cross-section of CFST members is smaller than those of reinforced concrete structures, which greatly reduces the self-weight of the member. The use of lightweight aggregate concrete to fill the hollow steel tube columns could further minimize the self-weight of CFST columns, as well as provide improved seismic performance and savings of construction time and cost [11,12].

Lightweight aggregate concrete (LWC) is concrete formed from a lightweight aggregate. There are two main types of lightweight aggregate, that made from natural material such as pumice, scoria, or tuff; and that made from artificial material, such as blast-furnace slag, clay, diatomite, fly ash, shale, or slate [13]. The specification for structural

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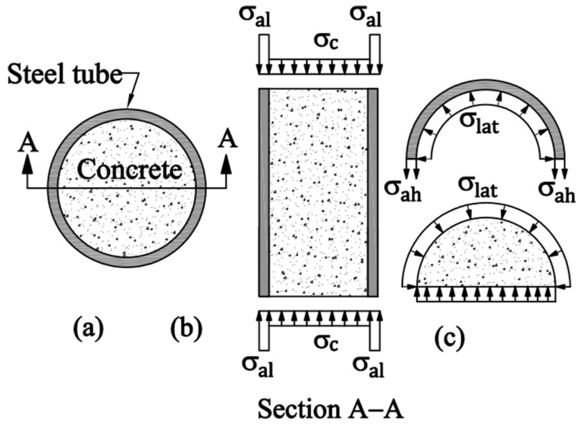

Fig. 1. Stress states of circular CFST column under compression (a) Column cross-section, (b) longitudinal compressive stresses in steel (σ_{al}) and concrete (σ_c), and (c) tensile hoop stress (σ_{ah}) in steel and confinement stress (σ_{lat}) on the concrete core.

lightweight concrete requires it to gain a minimum compressive strength of 17 MPa at 28-day and a density between 1120 and 1920 kg/m^3 [14].

LWC has disadvantages compared to normal weight concrete (NWC), such as high shrinkage, creep deformations, brittle failure, and low rigidity. Despite these disadvantages, the use of LWC offers many advantages. For the same concrete compressive strength, the weight of LWC is 20% to 30% lower than that of NWC. Higher strength-to-weight ratio compared to NWC. LWC also provides low thermal conductivity, about 12% to 33% that of NWC, and offers superior fire resistance; sound and heat insulation, due to the presence of air voids; and anti-seismic performance [11,15,16].

Many previous studies have been carried out on plain lightweight aggregate concrete-filled steel tube (LWCFST) columns, but are still fewer in number than reports on normal CFST columns. Ghannam et al. [17] compared the behavior of long circular, rectangular, and square CFST between LWC and NWC; the results showed that both columns types fail by global buckling, and ductility was observed in LWCFST columns. Mouli and Khelafi [18] studied the behavior under axial loading of short rectangular hollow-tube columns filled with NWC and LWC. Their results showed that lightweight aggregate concrete has higher bond strength than normal concrete.

Fu et al. [16] tested LWCFST stub columns under axial loading. Drum-shaped failure modes were observed with small confinement ratios, while shear-type failures occurred in columns with larger confinement ratios. Fu et al. [11] examined the performance of LWCFST columns with concretes of various compressive strength and concluded that the strength of LWC has a significant effect on the failure mode of LWCFST columns. In addition, they concluded that the EC4 estimation method gives better results than other design codes. Fu et al. [19] investigated the impact of LWCFST column length on behavior, finding that the slenderness ratio has a significant effect on the behavior of composite columns. In the same area, Ji et al. [20] showed that elastic instability governs the behavior of long LWCFST columns which have a slenderness ratio ($\lambda = 4L/D$) > 80.0. AL-Eliwi et al. [21] investigated the performance of LWCFST columns and compared their behavior with that of self-compacted concrete-filled steel tube (SCCFST) columns under axial loading. The results showed differences in performance between LWCFST and SCCFST columns, especially in their ductility and failure modes.

Concrete-filled steel tubes with longitudinal steel-bar reinforcement have been used in bridge erection to improve their strength and ease connection with other elements. Despite its general recognition as an excellent structural engineering solution, few experimental studies have examined the performance of reinforced CFST columns [22,23].

In reinforced CFST columns, the existence of the longitudinal steel reinforcement and the lateral reinforcement which works as a steel cage increases the confinement effect on the concrete core. Where the presence of the longitudinal steel reinforcement not only decreases the propagation of cracks and prevents sudden loss of strength, it also improves the mechanical properties of the concrete core, such as its strength, toughness, and ductility. Additionally, the fire and seismic resistance of CFST columns increase significantly [2,24–27].

A group of studies [24,26,28,29] have shown that reinforced CFST columns have even better compression capacity, toughness, and ductility, in addition to improved anti-seismic response compared to unreinforced CFST columns. The basic motivation behind reinforced CFST is to combine the abilities of reinforced concrete columns and CFST columns; however, all previous improvements in the response of CFST columns using steel-bar reinforcement have increased the difficulty of construction and increased its cost. Since use of LWC as filling material for hollow steel tube columns significantly enhances the LWC characteristics [16], the use of reinforced LWC in LWCFST columns should help further improve the performance of these composite columns.

Previous research in this area has dealt only with plain LWCFST columns; to our knowledge, no study has been done on the properties of steel-bar reinforced lightweight aggregate concrete-filled steel tube (RLWCFST) columns. Therefore, this study aimed to provide data to help fill this gap by: (1) exploring the experimental behavior of RLWCFST circular columns with three different L/D ratios, two different D/t ratios, and two different diameters of longitudinal steel-bars; (2) comparing the response of RLWCFST columns to that of corresponding LWCFST columns; (3) investigate the appropriateness of the AISC360-16 and EC4 design codes for predicting the compression capacity of RLWCFST columns.

2. Experimental work

An experimental study was carried out to explore the performance of reinforced lightweight aggregate concrete-filled steel tube (RLWCFST) columns under axial compression loading. Eighteen circular specimens were categorized into three groups according to the length of the specimen. Each group consisted of three specimens with the same thickness and with three different reinforcement conditions.

2.1. Material properties

The steel tube specimens were prepared from 6-m-lengths of circular hollow steel tube; all steels used were mild steel. Two different cross-sections, outer steel tube diameter (D) × steel tube thickness (t), 114.3 × 3.21 mm and 114.3 × 5.80 mm, were used. The tensile coupons specimens were prepared and tested according to the ASTME8/E8M-16 [30] specification to determine the mechanical properties of the steel tubes. The yield strengths were 465 MPa and 440 MPa for 114.3 × 3.21 mm and 114.3 × 5.80 mm tubes, respectively, with an elastic modulus of 200 GPa. The longitudinal steel-bars were deformed bars 8 mm and 12 mm in diameter, respectively, with yield strength values of 534 and 470 MPa. The transverse steel-bars were deformed bars 5.5 mm in diameter with a yield strength of 520 MPa.

Lightweight aggregate concrete, pumice type, with a maximum aggregate size of 10 mm, was used to produce lightweight aggregate concrete LWC. In addition to cement and pumice aggregate, hyperplasticizer silica fume was used to improve workability and facilitate concrete pouring inside the steel tube, and fine crushed sand were included in the LWC mix. The dry unit weight of LWC was 1753 kg/m^3. The standard cylinder specimens 100 × 200 mm were cast and tested according to the ASTMC39/C39M-15 [31] specification. According to the compression test, the average compressive strength of LWC was 30.58 MPa.