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Performance of lightweight aggregate and self-compacted concrete-filled steel tube columns

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Abstract. The aim of this paper is to investigate the performance of Lightweight Aggregate Concrete Filled Steel Tube (LWCFST) columns experimentally and compare to the behavior of Self-Compacted Concrete Filled Steel Tube (SCCFST) columns under axial loading. Four different L/D ratios and three D/t ratios were used in the experimental program to delve into the compression behaviours. Compressive strength of the LWC and SCC are 33.47 MPa and 39.71 MPa, respectively. Compressive loading versus end shortening curves and the failure mode of sixteen specimens were compared and discussed. The design specification formulations of AIJ 2001, AISC 360-16, and EC4 were also assessed against test results to underline the performance of specification methods in predicting the compression capacity of LWCFST and SCCFST columns. Based on the behaviour of the SCCFST columns, LWCFST columns exhibited different performances, especially in ductility and failure mode. The nature of the utilized lightweight aggregate led to local buckling mode to be dominant in LWCFST columns, even the long LWCFST specimens suffered from this behaviour. While with the SCCFST specimens the global buckling governed the failure mode of long specimens without any loss in capacity. Considering a wide range of column geometries (short, medium and long columns), this paper extends the current knowledge in composite construction by examining the potential of two promising and innovative structural concrete types in CFST applications.

Keywords: lightweight aggregate concrete; self-compacted concrete; concrete filled steel tube column; design specifications

1. Introduction

In structural design, one of the significant challenges is the self-weight of the members, especially if the target is to design members with high strength to weight ratio. There are two possible ways to reduce this weight; using a lightweight material such as lightweight aggregate concrete or employing composite construction. In the composite construction, the beneficial properties of the constituent materials are combined to generate high performance structure with reasonable cost. Recently, the concrete filled steel tube (CFST) columns have found a great use compared to other types of composite construction due to significant advantages. The structural steel and the concrete act together to support the external load, resulting in smaller cross sectional areas for a given load. Also, the existence of the concrete precludes any premature buckling of the structural steel tube section.

The distinguishing properties of the CFST columns motivate the design engineers to deploy these members in high performance structures such as in high-rise buildings, tunnels, bridges, and towers. In earthquake regions, the use of CFST columns is preferred due to the higher energy absorption capacity, stiffness, and ductility properties (Aslani *et al*. 2016, Wang and Chang 2013, Chithira and Baskar 2014, Ekmekyapar 2016). The steel tube works as a permanent formwork for the concrete. Thus, construction time and costs can be reduced. The confinement effect of circular steel tubes on concrete is the most notable characteristic of CFST columns (Giakoumelis and Lam 2004, Han *et al*. 2005a, Han *et al*. 2014, Ekmekyapar and AL-Eliwi 2016).

The promising characteristics of the CFST columns mentioned above are due to the composite action provided between the steel tube and the core concrete. The steel tube act as longitudinal and transverse reinforcement and creates a confining pressure for the concrete core, where the concrete core and steel tube are subjected to triaxial and biaxial stress states, respectively (Yu *et al*. 2007).

CFST columns offer high strength to weight ratio which could be exploited in challenging fields. On the other hand, lightweight aggregate concrete has the potential to increase this strength to weight ratio to further levels which would lead to more efficient structures. There are two general types of lightweight aggregates according to (ASTMC330/C330M-14 2014). The first group includes aggregates prepared by expanding, pelletizing, or sintering the products such as blast-furnace slag, clay, diatomite, fly ash, shale, or slate, and the second group consists the aggregates prepared by processing natural materials, such as

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pumice, scoria, or tuff.

According to the standard, the structural lightweight concrete has to gain a minimum 28-day compressive strength of 17 MPa and a density between 1120 and 1920 kg/m^3 (ACI213R-03 2003). The lightweight concrete is significantly lighter compared to the normal concrete, and its thermal conductivity is about 12% to 33% of the normal concrete (Fu *et al*. 2011a). Also, it has higher strength/weight ratio, superior heat and sound insulation characteristics due to the presence of air voids which also leads to better fire resistance characteristics and low thermal conductivity, (Fu *et al*. 2011b, Fu *et al*. 2011c).

Although the number of the studies on normal CFST columns is significantly high, a survey of the literature reveals few studies on LWCFST columns (Assi *et al*. 2003, Ghannam *et al*. 2004, Mouli and Khelafi 2007, Abdelgadir *et al*. 2011, Fu *et al*. 2011a, Fu *et al*. 2011b, Fu *et al*. 2011c, Ji *et al*. 2013, Chan *et al*. 2015, Yu *et al*. 2016). In this regard, it is appropriate to investigate the potential of LWCFST columns in composite construction.

SCC which was originated in Japan has been proven to be an effective material in structural applications. This type of special concrete promises to ease the burden of compaction in critical regions such as corners and narrow spaces. Using classical concrete requires serious precautions and might lead to surface defects between the steel tube and core concrete. This condition would compromise the composite action and cause unexpected lower compression performances. The fresh properties of the SCC provide the flow of the concrete under its own weight and eliminate the need for vibration. Since the steel tubes have closed sections, SCC would be the most convenient concrete type in CFST applications to ensure that the best compaction is provided. Also, the steel tubes with smaller diameters could also be filled with SCC without any further precautions. Moreover, the bar reinforcement and stiffener applications in CFST columns could be done safely and an appropriate bond between the reinforcing members, steel tube and concrete could be satisfied.

The benign contributions of the SCC in terms of labor, cost and structural performance are well recognized in civil engineering and vast amount of research has been directed to delve into the behaviour of the reinforced concrete members produced using SCC. On the other hand, despite the beneficial properties offered by SCC, the characterization of composite columns manufactured by employing this high performance concrete has not been well established yet. In this regard, a search in the literature shows a small group of study on SCCFST columns (Han and Yao 2004, Han *et al*. 2005a, Han *et al*. 2005b, Lachemi *et al*. 2006a, Lachemi *et al*. 2006b, Zhu *et al*. 2010, Liang *et al*. 2017, Mahgub *et al*. 2017) compared to the huge number of studies conducted on normal CFST columns. Therefore, it is also required to provide more experimental data on the compression behaviour of SCCFST columns to expand the current knowledge and refine the characterization process of such columns for field design purposes.

2. Previous work on LWCFST and SCCFST columns

The state of the art of CFST members was already reviewed by (Han *et al*. 2014). However, since the main focus of the present work is the CFST columns with two different special and promising concrete types, it is convenient to summarize the available content on the associated subjects. Following subsections present the current available research on LWCFST and SCCFST columns.

2.1 LWCFST columns

To the knowledge of the authors, the first research on LWCFST columns was conducted by (Ghannam *et al*. 2004) who studied the behavior of the lightweight and the normal concrete filled steel tube columns in a comparative form. All of the test specimens were long columns with a minimum length to cross sectional dimension ratio of 10. The results showed that both concrete types of infill columns failed by overall buckling, and better ductility was observed in lightweight concrete columns. Mouli and Khelafi (2007) studied the performance of very short rectangular normal and lightweight concrete filled steel tubes columns under axial loading. The test results showed that lightweight aggregate concrete has higher bond strength than normal concrete.

Abdelgadir *et al*. (2011) tested LWCFST columns with different L/D ratios under eccentric loading. The results showed that the impact of L/D ratio is highly visible in the columns with L/D > 3, but for L/D ≤ 3 the influence is negligible. Fu *et al*. (2011a) tested short and slender LWCFST columns. The results presented that the slenderness ratio has a great influence on the behaviour of LWCFST columns and the EC4 prediction method performs better among the assessed prediction methods. Fu *et al*. (2011b) investigated the behaviour LWCFST columns with different concrete strengths and showed that the strength of LWC has a great influence on the failure mode. Fu *et al*. (2011c) tested LWCFST stub columns under axial load. Drum-shaped failure modes were observed with small confinement ratios, while shear type failures were captured in the columns with greater confinement ratios. Ji *et al*. (2013) showed that the elastic instability dominates the behaviour of long LWCFST columns which have slenderness ratios ($\lambda = 4L/D$) greater than 80.0.

Chan *et al*. (2015) examined the behaviour of circular and elliptical LWCFST stub columns under axial compression. The results presented that the cold form processing which was used to produce elliptical sections decreases the capacity and ductility. Furthermore, it was shown that and EC4 method could be adopted to predict the compression performance of LWCFST columns. As a result of experimental study, (Yu *et al*. 2016) underlined the lower performance of LWCFST columns in terms of strength and ductility.

2.2 SCCFST columns

Han and Yao (2004) tested SCCFST stub columns and showed that the use of SCC has significant advantages in composite column applications. Moreover, it was underlined that the various design specification prediction methods could be employed for such composite columns. In a further study (Han *et al*. 2005a) investigated the effect of the parameters of yield strength of the steel tube and cross sectional dimensions on the compression behaviour of the circular and square stub SCCFST columns. They concluded that the existing design specification formulations for normal CFST columns can be used for SCCFST columns as well. Cyclic loading performance of circular and square SCCFST columns was examined by (Han *et al*. 2005b). High levels of energy dissipation and ductility capacity of SCCFST columns were observed in the tests.

Lachemi *et al*. (2006a) and Lachemi *et al*. (2006b) examined the behaviours of SCCFST columns and normal CFST columns in a comparative form. It was stated that the SCC significantly reduces the casting time compared to normal concrete processing. On the other hand, they observed that normal concrete exhibits a superior confinement strength over SCC. They also proposed a formulation to predict the capacity SCCFST columns.

Zhu *et al*. (2010) tested square high strength SCCFST columns reinforced with steel section. The assessed parameters for the columns were concrete strength, width to thickness ratio, length to width ratio and the ratio of the steel section. As a result of the experimental program they concluded that the presence of the embedded steel section precludes the generation of the shear cracks in the SCC and improves the post-yield behaviour of the column. Liang *et al*. (2017) conducted an experimental program on the performance of the stiffened SCCFST columns. The contributions of the various stiffening configurations to the compression capacity and the ductility were discussed. A superior interaction between the steel tube and core concrete was also observed due to the presence of stiffeners. Mahgub *et al*. (2017) tested the behaviour of SCCFST slender elliptical columns. Since the examined columns were slender, overall failure modes observed in the compression tests. The appropriate behaviour of the SCC in providing the composite action was underlined and it was shown that EC4 method exhibits reasonable predictions.

3. Aim and significance of research

The aim of the CFST column is to bear the load, and the parameters are strength, stiffness, and ductility which are mainly provided by the steel tube and its confinement effect (Han *et al*. 2014, Mahgub *et al*. 2017, Ekmekyapar and AL-Eliwi 2017). At an early stage of loading, the confinement is not present due to the difference in the Poisson's ratios between concrete and steel. As is well known, the Poisson's ratio of concrete is typically equal to 0.2 (EC2 2004) which is lower than that of for steel which is typically equal to 0.3 (EC3 2005). When the load is further increased, the concrete core expands and interacts with the steel tube to develop the passive confinement. At greater load levels, the core concrete expands laterally more than steel tube due to the change in the Poisson's ratio of concrete, and hence a radial pressure is developed at the interface between concrete and steel. At this stage, confinement of the concrete core is achieved, and the steel tube works in hoop tension (Johansson 2002, Oliveira *et al*. 2009, Chan *et al*. 2015). A parameter has been adopted in the literature to compare the confinement behaviour of the CFST columns. This parameter is called as confinement index and has been used by several researchers to characterize confinement capability of the CFST columns roughly, (Han *et al*. 2001, Han *et al*. 2005a).

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

where A_s and A_c are the cross sectional areas of the steel tube and core concrete, respectively, f_c is the compressive strength of concrete, and f_y is the steel yield strength.

Recent developments in structural engineering have heightened the need for high performance structural members to circumvent the design and construction challenges of huge structures. In this regard, the last several decades have seen growing trends towards the improvement of the mechanical behaviours of the structural materials and minimizing the construction efforts. LWC and SCC are two of the important outcomes of such research and have been well detailed for reinforced concrete applications. However, as the literature survey reveals, the use of these promising materials in composite column construction has not been well established yet. Due to a small number of test data much uncertainty still exists about the appropriateness of LWC and SCC for composite construction. This study seeks to obtain data which will help to address this research gap. The data obtained from the experimental program also will reveal if these materials are capable of leading to sufficient composite action and generating appropriate confinement effect. Furthermore, the assessments of the design specification prediction methods which were developed mainly for normal CFST columns, against test results will show the effectiveness of the prediction methods for LWC and SCC.

4. Experimental research

4.1 Material properties

Three different circular steel tube sections were employed in the experimental program. Two sections have 139.7 mm outer diameter, while the third section has 114.3 mm outer diameter. The larger diameter steel tubes have 3.30 mm and 5.87 mm thicknesses. On the other hand, the smaller diameter steel tube has 3.38 mm thickness. These geometrical properties correspond to three different D/t ratios of 23.80, 33.82 and 42.33. Considering the practical applications of CFST columns, the studied range of D/t ratio is highly representative. Tensile coupon specimens were sectioned from the steel tubes according to (ASTME8/E8M-16 2016) to measure the mechanical properties of the steel tubes, as shown in Fig. 1. The yield strengths were measured to be 290 MPa, 355 MPa, and 420 MPa for 139.7 × 3.30 mm, 139.7 × 5.87 mm, and 114.3 × 3.38 mm tubes, respectively and elastic modulus is equal to 200 GPa. The corresponding ultimate stresses are 377 MPa, 430 MPa and 520 MPa, respectively.

Along with CFST specimen manufacturing, 100 × 200 mm cylinder molds were cast with LWC and SCC. Compression tests of the cylinder concrete specimens were conducted according to (ASTMC39/C39M-03 2003) specification. Average compressive strengths for LWC and SCC were measured to be 33.47 MPa and 39.71 MPa, respectively. Although the compressive strengths of the LWC and SCC are not identical, they are in the same range and can be classified as normal strength concrete.

The main ingredient of the LWC is pumice aggregate with a maximum size of 10 mm. To be able to manufacture LWC with desired structural properties, some additional materials were also utilized. In addition to cement and pumice, also hyperplasticizer, silica fume and fine crushed sand were included in the LWC mix. The dry unit weight of LWC was 1753 kg/m^3.

The manufacturing process of SCC requires further measures to undertake. In this regard, fly ash is a very useful material which has a spherical micro structure and provides high flowability. The ingredients of the SCC are cement, F type fly ash, hyperplasticizer, coarse and fine river aggregates, fine crushed sand and water. The measured dry unit weight of SCC is 2324 kg/m^3. Two tests were adopted to observe the fresh properties of SCC. The first one is the slump-flow test with T_{500} time check to measure the flowability and the flow rate of SCC, and the second one is the V-funnel test to assess the viscosity and filling ability of SCC. The aforementioned tests were conducted in accordance with EN-12350-1 and 12350-2 (EFNARC 2005).

The fresh properties of the SCC mix were as follows:

– Slump flow (mm): 650 mm.
– T_{500} time: 4.5 sec.
– T_v time: 6 sec.

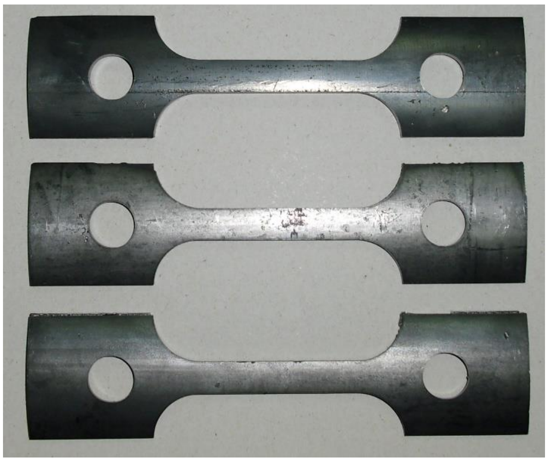

Fig. 1 Tensile coupon specimens

Herein, it is worth to mention that the dry unit weight of the LWC is about 24.57% lower than the SCC. An efficient use of this weight saving has significant potential to improve mechanical and thermal properties of the structures. This weight saving could lead to the minimization of the cross-sectional dimensions of structural members. Furthermore, time and cost savings can be achieved in the erection and handling of the components, so that smaller equipment can be employed or larger precast units can be handled (Chandra and Berntsson 2002). The thermal insulation properties of the structure could also be improved as detailed in previous sections. Moreover, the seismic response of the structure which is related to the mass directly, could be enhanced by employing appropriate LWC (Mo *et al*. 2016).

4.2 Columns specimens

Different geometric properties of steel tube were selected to study various types of failure behaviours. That is to say, it is expected to observe local material failures in short columns and global failure modes in long columns. On the other hand, medium length columns are expected to exhibit the combination of local material failures plus global failure mode. To be able to extend the discussions on a wide range of column properties and observe the differences in behaviours, short, medium and long columns were manufactured. Table 1 shows the properties of CFST columns. The specimen naming system in Table 1 includes concrete type, steel tube outer diameter D, tube thickness t, and the L/D ratio of the column, respectively. As an example, the specimen LWC-114.3-3.38-10.5 refers to the lightweight aggregate concrete core, outer diameter of 114.3 mm, steel tube thickness of 3.38 mm, and L/D ratio of 10.5.

Prior to filling the concrete, the ends of each tube specimen were machined to ensure that the best uniformity of contact between the specimen and testing machine could be provided. To be able to provide an appropriate interaction between the steel and the concrete, the inner surfaces of the steel tubes were cleaned. In order to hold the fresh concrete during the casting the lower ends of the steel tubes were closed with thick mica plates. Silicon was used to connect the mica plates to the lower ends of the steel tubes. The top last 10 mm of steel tubes was left empty and filled with high strength levelling epoxy after completing the curing process. Fig. 2 illustrates the sixteen CFST columns which are ready for testing.

Before the test, mica plates were removed from the bottom ends of the columns, and silicon residues were cleaned. Specimens were carefully centred in the testing machine to eliminate the possibility of eccentric loading and associated bending effect. The specimens were placed into the testing machine and a displacement controlled loading with a rate of 0.5 mm/min was applied to all column specimens up to end of the tests, Fig. 3. Compression loading versus end shortening data of the specimens were recorded to be able to discuss the behaviour of the columns in the pre-collapse and post-collapse regions.

Table 1 Properties of column specimens

Specimen	D (mm)	t (mm)	D/t	L/D	f_c (MPa)	f_y (MPa)	$N_{exp.}$ (kN)
LWC-139.7-3.30-2	139.7	3.3	42.33	2	33.47	290	920.31
LWC-139.7-5.87-2	139.7	5.87	23.80	2	33.47	355	1367.28
LWC-114.3-3.38-2	114.3	3.38	33.82	2	33.47	420	765.96
LWC-114.3-3.38-5	114.3	3.38	33.82	5	33.47	420	774.34
LWC-139.7-3.30-7.5	139.7	3.3	42.33	7.5	33.47	290	855.126
LWC-139.7-5.87-7.5	139.7	5.87	23.80	7.5	33.47	355	1318.2
LWC-114.3-3.38-7.5	114.3	3.38	33.82	7.5	33.47	420	717.39
LWC-114.3-3.38-10.5	114.3	3.38	33.82	10.5	33.47	420	725.81
SCC-139.7-3.30-2	139.7	3.3	42.33	2	39.71	290	989.2
SCC-139.7-5.87-2	139.7	5.87	23.80	2	39.71	355	1554.76
SCC-114.3-3.38-2	114.3	3.38	33.82	2	39.71	420	885.67
SCC-114.3-3.38-5	114.3	3.38	33.82	5	39.71	420	898.47
SCC-139.7-3.30-7.5	139.7	3.3	42.33	7.5	39.71	290	996.38
SCC-139.7-5.87-7.5	139.7	5.87	23.80	7.5	39.71	355	1481.5
SCC-114.3-3.38-7.5	114.3	3.38	33.82	7.5	39.71	420	861.57
SCC-114.3-3.38-10.5	114.3	3.38	33.82	10.5	39.71	420	815.87

Fig. 2 Column specimens

Fig. 3 Column test

5. Test results and discussions

The mechanical behaviours of LWCFST and SCCFST columns with different L/D and D/t ratios will be discussed considering compression loading versus end shortening curves and failure modes.

5.1 Compression loading versus end shortening curves

It is convenient to classify the column specimens considering the L/D ratios. Fig. 4 presents compression loading versus end shortening curves of the specimens which have L/D ratio of 2. It is obvious from this figure that the specimens with 139.7 mm outer diameter and 5.87 mm tube thickness have the greatest performance compared to remaining specimens. It is also clear that the yield strength of the tube has a great influence on this performance. Furthermore, these columns have the greatest initial stiffness. Although the steel tubes with 114.3 mm outer diameter have the greatest yield strength, they exhibit the lower performances in this group due to the smaller cross-sectional area of the columns.

It is expected to observe greater compression capacities from SCCFST columns compared to LWCFST counterparts, since SCC concrete has greater compressive strength. However, it is very interesting to capture different compression behaviours for the LWCFST specimens. The LWCFST column specimens reach the compression capacities at very small levels of end shortenings. That is to say, they experience very little plastic behaviour before reaching the compression capacity, Fig. 4. The end shortening values at the compression capacities also support this behaviour. The specimen LWC-139.7-3.30-2 reaches the compression capacity at 2.18 mm end shortening, whereas the SCC-139.7-3.30-2 counterpart has 3.75 mm end shortening at the level of compression capacity. A 3.15 mm end shortening was recorded for the specimen LWC-139.7-5.87-2 and the corresponding end shortening level for the SCC-139.7-5.87-2 is equal to 7.50 mm. Also, the specimen LWC-114.3-3.38-2 experienced an end shortening of 2.25 mm, where the SCC-114.3-3.38-2 counterpart has 4.52 mm end shortening at the compression capacity. On the other hand, it is also necessary to mention that the initial stiffness of the LWCFST and SCCFST counterparts are not so different. Some greater initial stiffness of the SCCFST specimens could be attributed to the greater strength of SCC.

Moreover, the post-peak behaviour of LWCFST columns are significantly different. A sudden discharge of the loading occurs in LWCFST specimens after achieving the compression capacities, Fig. 4. However, after a level of discharge, the loading in LWCFST specimens gain resistance against the compression loading. On the other hand, the specimens with SCC infill experience a smooth load discharge after the compression capacities. The level of the end shortening and the load discharge behaviour of the specimens with LWC infill reveal that the LWCFST columns exhibit lower ductility behaviour compared to SCCFST columns. These behaviours could be attributed to the physical properties of the lightweight aggregate. Since the lightweight aggregate has a porous structure, when the load reaches the ultimate level the lightweight aggregates crush, resulting in voids in the core concrete. This behaviour leads to sudden load discharges. As a result of continuous displacement controlled loading, the crushed concrete fills the voids and the LWCFST column specimens gain resistance again.

Also Fig. 4 reveals that the yield strength of the steel and the steel ratio have great influence on the ductility. Specimen SCC-139.7-3.30-2 has the smallest yield strength and steel ratio among the SCC filled specimens. As a result,

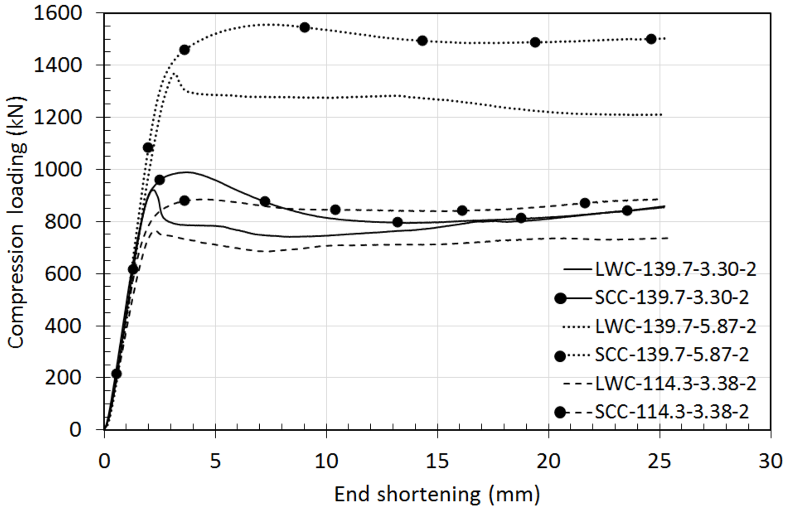

Fig. 4 Compression behaviour of the specimens with L/D = 2

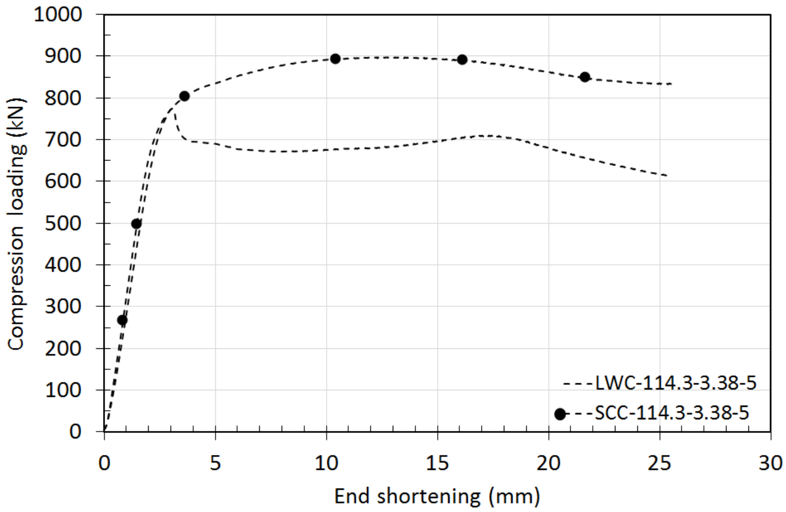

Fig. 5 Compression behaviour of the specimens with L/D = 5

this specimen exhibits a lower ductility behaviour compared to the specimens SCC-139.7-5.87-2 and SCC-114.3-3.38-2, Fig. 4. However, the increment of the yield stress of the steel tube plus the steel ratio significantly improves the ductility (post-peak) behaviour.

The compression loading versus end shortening curves of the specimens with L/D ratio of 5 are presented in Fig. 5.

It is clear that the LWCFST column behaves in a similar manner and a sudden discharge of loading happens at the level of compression capacity. At this compression capacity level LWCFST column has an end shortening value of 3.07 mm. On the other hand, SCCFST column behaves in a more ductile manner and has an end shortening value of 13.32 mm at the level of compression capacity. Examining the stiffness of the columns, it can be deduced that they have close initial stiffness values and the slight difference could be attributed to different concrete strengths.

Fig. 6 illustrates the compression loading versus end shortening curves of the specimens which have L/D ratio of 7.5. It can be observed in this figure that all columns in this group tend to exhibit long column behaviour and the LWCFST columns show more non-linear behaviour before reaching the compression capacity (Comparison of LWCFST column behaviours in Figs. 4-6). However, SCCFST columns have still superior ductility behaviours compared to LWCFST columns. Herein, it should be underlined that the length effect has some influence on the load discharge behaviour of the LWCFST specimens. Comparing the load discharge behaviour of the columns with L/D ratio of 7.5, 5 and 2, it can be concluded that the load discharge behaviour of the LWCFST columns with L/D ratio of 7.5 is more gradual and smoother.

Initial stiffness of the columns in this group are also lower than that of the columns in previous groups, resulting

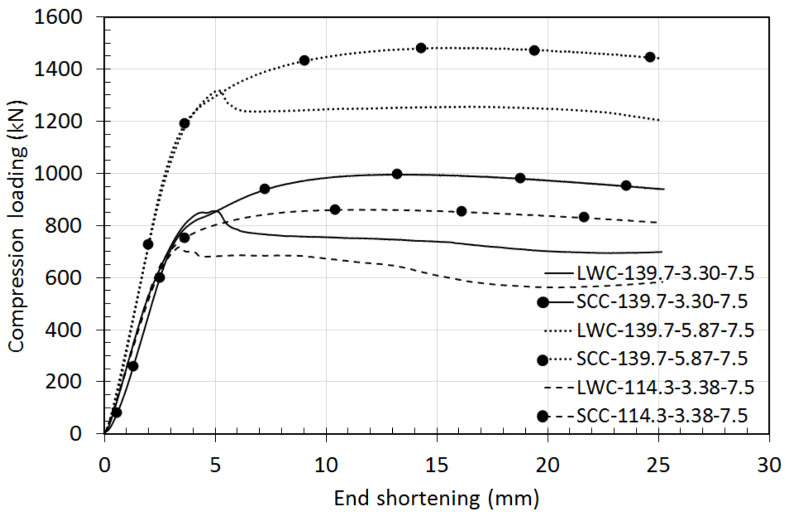

Fig. 6 Compression behaviour of the specimens with L/D = 7.5

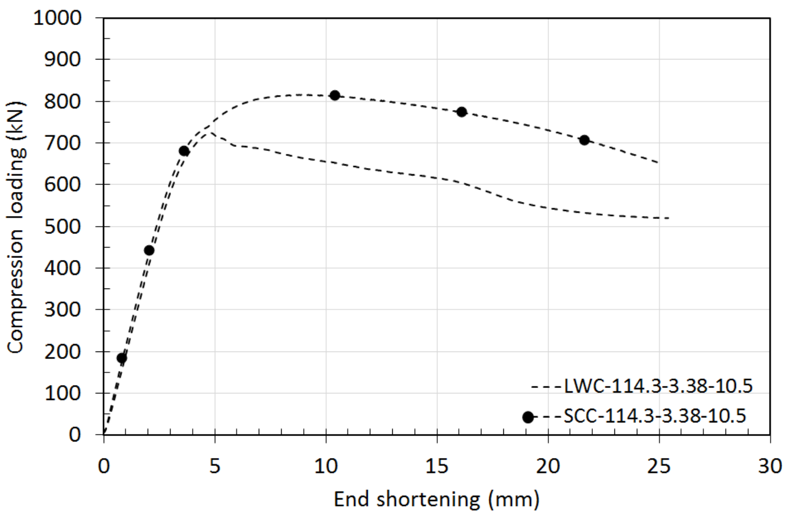

Fig. 7 Compression behaviour of the specimens with L/D = 10.5

in higher end shortening levels at the compression capacities. It is important to mention that the specimens with 139.7 mm outer diameter and 5.87 mm thickness have significantly greater initial stiffness compared to other specimens, Fig. 6. As opposed to the stiffness behaviours of the columns with L/D ratio of 2, greater steel ratio plus greater yield strength lead to perceptible difference in the stiffness behaviour of the columns which have L/D ratio of 7.5.

The compression behaviour of the columns with L/D ratio of 10.5 are shown in Fig. 7. It is crucial here to point that the specimens in this group attain long column behaviour exactly. After the compression capacities have been reached, both LWCFST and SCCFST columns discharge the load quickly but smoothly. This type of response is due to the dominant length effect of a long column which significantly differs from the behaviours of the columns in previous groups. However, in terms of the level of non-linear behaviour before reaching the capacity, the SCCFST column performs better. Nevertheless, as with the previous groups, the initial stiffness of the columns are close to each other, Fig. 7.

5.2 Failure modes

The failure modes of the specimens with L/D ratio of 2 is depicted in Fig. 8. In this figure failure modes of the LWCFST and SCCFST columns are presented in a comparative form. It is clear that the failure modes of LWCFST and SCCFST specimens are similar. Outward local buckling of the steel tubes is followed by local crushing of the concrete and associated shear failure. However, as expected, local material failures have intensified characteristics in the specimens with greater D/t ratio.

Fig. 8 Failure modes of the specimens with L/D = 2. (a) LWC-139.7-3.30-2, (b) LWC-139.7-5.87-2, (c) LWC-114.3-3.38-2, (d) SCC-139.7-3.30-2, (e) SCC-139.7-5.87-2 and (f) SCC-114.3-3.38-2

Fig. 9 Failure modes of the specimens with L/D = 5. (a) LWC-114.3-3.38-5 and (b) SCC-114.3-3.38-5

Fig. 9 presents the failure modes of the specimens with L/D ratio of 5. Both specimens' failure modes were dominated by a coupled instability which includes local and global modes simultaneously. Therefore, it can be deduced that these columns exhibit the behaviour of a medium length column. On the other hand, it is important to note that local buckling of the steel tube is more obvious and severe in LWCFST column, Fig. 9.

It is very interesting to observe that local material failures are still dominant in the failure modes of the LWCFST column specimens with L/D of 7.5, Fig. 10. The evidence of the global mode is minimum in these columns. On the other hand, all of the SCCFST columns in this group exhibit global failure mode due to length effect, resulting in a superior performance. A very important conclusion can be drawn from this observation. As a result of the porous

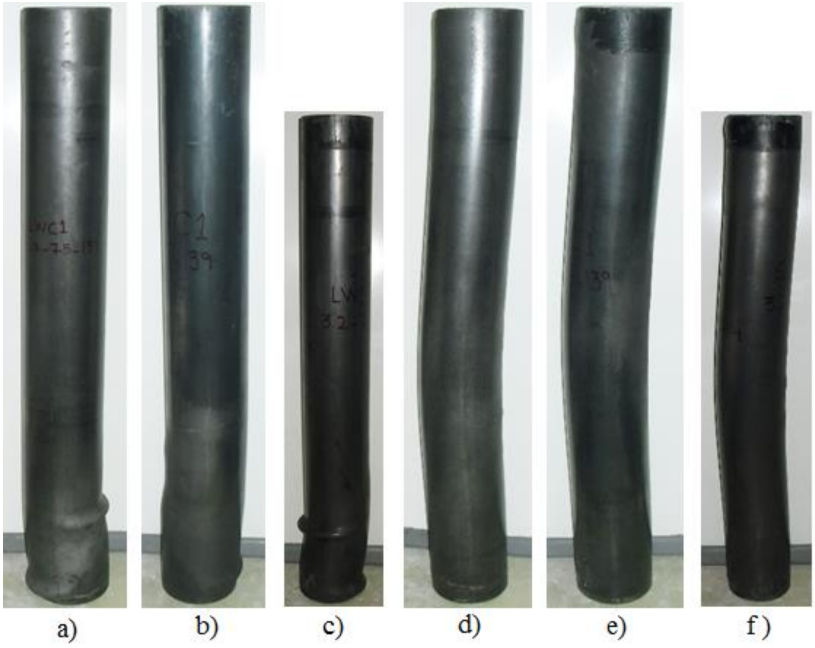

Fig. 10 Failure modes of the specimens with L/D = 7.5. (a) LWC-139.7-3.30-7.5, (b) LWC-139.7-5.87-7.5, (c) LWC-114.3-3.38-7.5, (d) SCC-139.7-3.30-7.5, (e) SCC-139.7-5.87-7.5 and (f) SCC-114.3-3.38-7.5

Fig. 11 Failure modes of the specimens with L/D = 10.5. (a) LWC-114.3-3.38-10.5, and (b) SCC-114.3-3.38-10.5

structure of the lightweight aggregate, LWC core is not able to provide a complete inward support to the steel tube. Thus, it means that local crushing of lightweight aggregate occurs before the column achieves its compression capacity. This behaviour is dominant in the LWCFST column even with D/t ratio of 23.80 (specimen LWC-139.7-5.87-7.5). It is not desired to obtain such a behaviour in the design of composite columns which have this level of L/D ratio.

As discussed in previous sections, columns with L/D ratio of 10.5 are expected to be under control of global mode of failure, since these columns can be classified as long columns. This expectation was somewhat satisfied in both LWCFST and SCCFST columns with L/D ratio of 10.5, Fig. 11. However, it can be observed in Figure 11 that local mode of failure has also a significant role in the failure behaviour of LWCFST column. Even with this level of L/D

Table 2 Strength index SI of CFST column

Specimen (LWCFST)	*SI*	Specimen (SCCFST)	*SI*
LWC-139.7-3.30-2	1.14	SCC-139.7-3.30-2	1.12
LWC-139.7-5.87-2	1.10	SCC-139.7-5.87-2	1.19
LWC-114.3-3.38-2	1.02	SCC-114.3-3.38-2	1.11
LWC-114.3-3.38-5	1.03	SCC-114.3-3.38-5	1.12
LWC-139.7-3.30-7.5	1.06	SCC-139.7-3.30-7.5	1.13
LWC-139.7-5.87-7.5	1.06	SCC-139.7-5.87-7.5	1.13
LWC-114.3-3.38-7.5	0.95	SCC-114.3-3.38-7.5	1.08
LWC-114.3-3.38-10.5	0.96	SCC-114.3-3.38-10.5	1.02

ratio LWC could not help the composite column to develop a complete global failure. Nevertheless, SCCFST column performed better and exhibited a complete global mode of failure, Fig. 11.

5.3 Strength index (SI)

Strength index is also an appropriate measure which has been used to quantify the strength enhancement due to concrete confinement and composite action in a CFST column (Han *et al*. 2005a, Han *et al*. 2014, Chan *et al*. 2015, Ekmekyapar and AL-Eliwi 2016). (*SI*) is defined as follows

$$SI = \frac{N_u}{A_s f_y + 0.85 A_c f_c} \tag{2}$$

where N_u is the axial capacity of a composite column section, determined by experiment or design specifications. The denominator in Eq. (2) is called as the squash load of a section.

Generally, as expected strength index of the column decreases as the column length increase. However, there are a few exceptions in Table 2 which contrast this behaviour.

These results could be attributed to the uncertainty inherent in the concrete compressive strength. The *SI* values of the LWCFST specimens range from 0.95 to 1.14, while for the SCCFST specimens range from 1.02 to 1.19. These results give an indication that the composite action between the steel tube and the SCC is better and a confinement effect is provided with SCC core even in the long columns.

There are two values of *SI* less than 1.0 (0.95, and 0.96) for the LWCFST specimens. This reduction in strength is attributed to the premature crush of lightweight aggregate at local buckling region and gives the same indication that the LWC is not suitable for long CFST columns and provides no confinement in long columns. The presented failure modes in previous subsection also verify this conclusion. The unexpected local buckling behaviour in long columns with L/D ratios of 7.5 and 10.5 compromise the composite action between the LWC and the steel tube.

In the SCCFST specimens, all of the *SI* values are greater than 1.0, even for long columns. This behaviour is desired for design purposes and means that SCC has great potential to be adopted for composite applications.

6. Design specifications against experiments

(AISC360-16 2016), (EC4 2004) and (AIJ 2001) are the design specification methods which are employed in this paper to perform some assessments. The AISC 360-16 is the specification for steel structures in the United States, the EC4 is the European code for composite structural design, and the AIJ 2001 is the Japanese guide for steel reinforced concrete structures.

The presented formulations in AIJ 2001 are based on the allowable stress design which considers the elastic analysis of the structures and EC4 adopts the limit state design to provide for serviceability and safety, by employing some partial safety factors to load and material properties. On the other hand, the AISC 360-16 procedure which is based on structural steel design, allows the use of either the limit state or the allowable stress design. In this section it is intended to employ these design specification formulations to assess the relationships between the design specification formulations and experimental results for LWCFST and SCCFST columns.

All codes apply some limitations on geometrical properties of the columns and mechanical properties of the materials. It is worth to note that there exist significant differences in the limitations of the design specifications.

Table 3 shows the limitations of the aforementioned design specifications.

In Table 3 E_s refers the elastic modulus of the steel tube, K is the end fixity coefficient of the column, λ refers the relative slenderness and δ is the steel

Table 3 Limitations of design specifications

Parameter	AIJ 2001	AISC 360 – 2016	EC4
f_y (MPa)	$235 \le f_y \le 355$	$f_y \le 525$	$235 \le f_y \le 460$
f_c of NW (MPa)	$f_c \le 60$	$21 \le f_c \le 70$	$20 \le f_c \le 60$
D/t	$\le 1.5(23500/f_y)$	$\le 0.31(E_s/f_y)$	$\le 90(235/f_y)$
Steel amount	-	$\ge 1\%$ of gross area	$0.2 \le \delta \le 0.9$
Slenderness	-	$KL/r \le 200$	$\lambda \le 2$

Table 4 Elastic modulus of the concrete

Specification	E_c (MPa)	Details
AIJ 2001	$3.35\times10^4(\gamma_c/2400)^2(f_c/60)^{\frac{1}{3}}$	γ_c : Concrete density (NC, and LWC) kg/m^3
AISC 360-16	$0.043w_c^{1.5}\sqrt{f_c}$	w_c : Concrete density (NC, and LWC) $(1500 \le w_c \le 2500\,\text{kg/m}^2)$.
EC4	$22000((f_c+8)/10)^{0.3}$	NC
	$(22000((f_c+8)/10)^{0.3})(\rho/2200)^2$	LWC, ρ : LWC density, kg/m^3 According to EC2 EN 1992-1-1

Table 5 Capacity formulations of the design specifications

Specification	Compression capacity of CFST column
AIJ 2001	$N_{AIJ-1} = r_{uc} f_c A_c + (1+\eta) f_y A_s;\ (l_k/D \le 4)$ $N_{AIJ-2} = N_{AIJ-1} - 0.125(N_{AIJ-1} - N_{AIJ-3})(l_k/D - 4);\ (4 \le l_k/D \le 12)$ $N_{AIJ-3} = N_{crc} + N_{crs};\ (l_k/D \ge 12)$
AISC 360-16	$P_{AISC} = p_{no}\left[0.658^{\frac{p_{no}}{p_e}}\right] \quad \frac{p_{no}}{p_e} \le 2.25$ $P_{AISC} = 0.877 p_e \quad \frac{p_{no}}{p_e} \rangle 2.25$
EC4	$N_{EC4} = \eta_a A_s f_y + A_c f_c(1+\eta_c \frac{t}{D}\frac{f_y}{f_c})$

contribution ratio defined in EC4

$$\delta = \sqrt{\frac{A_s f_y}{N_{pl,Rd}}} \tag{3}$$

Elastic modulus of the concrete, E_c, is calculated in each specification as presented in Table 4.

For the sake of brevity, the design specification formulations are not presented here in detail. However, to be able to reflect the differences in the capacity calculations, the approaches are summarized in Table 5.

In Table 5 for the AIJ 2001 l_k is the effective length of CFST column, η is the confinement factor for circular section only and equal to 0.27. This parameter is independent of the material properties and dimensions of

Table 6 Experimental results versus design specifications predictions

Specimen	$N_{exp.}$ (kN)	$N_{exp.}/N_{AIJ}$	$N_{exp.}/P_{AISC}$	$N_{exp.}/N_{EC4}$
LWC-139.7-3.30-2	920.31	1.00	1.08	0.81
LWC-139.7-5.87-2	1367.28	0.92	1.07	0.75
LWC-114.3-3.38-2	765.96	0.86	0.98	0.70
LWC-114.3-3.38-5	774.34	0.87	1.00	0.82
LWC-139.7-3.30-7.5	855.126	0.97	1.03	0.93
LWC-139.7-5.87-7.5	1318.2	0.93	1.06	0.94
LWC-114.3-3.38-7.5	717.39	0.85	0.95	0.86
LWC-114.3-3.38-10.5	725.81	0.92	0.99	0.96
SCC-139.7-3.30-2	989.2	1.00	1.06	0.81
SCC-139.7-5.87-2	996.38	1.00	1.14	0.82
SCC-114.3-3.38-2	885.67	0.95	1.06	0.77
SCC-114.3-3.38-5	898.47	0.96	1.09	0.89
SCC-139.7-3.30-7.5	1554.76	1.04	1.10	0.98
SCC-139.7-5.87-7.5	1481.5	1.00	1.12	1.00
SCC-114.3-3.38-7.5	861.57	0.96	1.06	0.96
SCC-114.3-3.38-10.5	815.87	0.98	1.04	1.00
Average		**0.95**	**1.05**	**0.87**

the column and r_{uc} which is equal to 0.85 is the reduction factor for concrete strength. N_{crc} and N_{crs} are buckling strength of a concrete column and buckling strength of a steel tube column, respectively.

For the AISC 360-16 calculations, p_{no} is the nominal compressive capacity of the composite section and p_e is the Euler critical load. The nominal compressive capacity of the column is calculated according to the type of the section which might be compact, non-compact or slender.

In EC4 calculations η_a is the steel reduction factor and η_c is the concrete enhancement factor due to confinement effect. These parameters depend on the relative slenderness of the column ($\bar{\lambda}$) and the confinement effect is ignored beyond a relative slenderness value of 0.5.

It is obvious in Table 5 that AIJ 2001 proposes three different capacity calculations according to the slenderness of the column with the objective of including length effect. In this regard, AISC 360-16 employs two formulations. The first AISC 360-16 formulation in Table 5 corresponds to capacity calculation of short and medium columns whereas the second formulation is devoted for long columns in which the Euler buckling behaviour is dominant. On the other hand, EC4 has a single formulation for the capacity calculation of CFST columns. To be able to include the length effects, EC4 utilizes the relative slenderness ratio ($\bar{\lambda}$) and according to the value of this ratio steel reduction factor, η_a , and concrete enhancement factor, η_c , vary.

In order to assess design specification prediction methods for LWCFST and SCCFST columns, experimental results were employed. Such comparisons are very useful in generating the sense for design purposes. Also, it is very critical to examine the performance of the methods in predicting the capacity of the composite column filled with LWC, since LWC is not the main focus of the design specification prediction methods. Table 6 presents the ratios of the experimental results to the column capacities obtained by employing the prediction methods.

A ratio of the experimental result to specification prediction smaller than unity refers an unconservative prediction. On the other hand, if the ratio is greater than unity, it refers a conservative prediction. The ratio of the experimental result to specification prediction ranges from 0.85 to1.04 for AIJ 2001 method. The average of the ratios for the entire experimental set is equal to 0.95 which means that AIJ 2001 generally overpredicts the column capacities by approximately 5%. However, consideration of separate examinations for the LWCCFST and SCCFST reveals that the averages of the ratios for LWCCFST and SCCFST columns are equal to 0.92 and 0.99, respectively. These results suggest that AIJ 2001 is very successful in predicting the compression performance of the SCCFST columns. Although the prediction performance of the AIJ 2001 method deviates more for LWCFST columns compared to SCCFST columns, this method has moderately good performance for LWCFST columns with an average deviation of 8%.

The ratios of the experimental results to AISC 360-16 predictions lie between 0.95 and 1.14. The average of the ratios for the entire experimental set is equal to 1.05. Therefore, it can be deduced that AISC 360-16 generally leads to conservative predictions which are on the safe side for design purposes. Examining the performance of the AISC 360-16 for LWCFST and SCCFST columns separately, it can be specified that the averages of the ratios for LWCFST and SCCFST column are equal to 1.02 and 1.08, respectively. These results suggest that AISC 360-16 predictions agree satisfactorily well for LWCFST columns with an average 2% difference on the safe side. On the other hand, the performance of the AISC 360- 16 method for SCCFST columns is much more conservative by 8%.

Considering the EC4 method, the ratios of the experimental results to design specification predictions are between 0.70 and 1.0 with an average of 0.87 for the entire experimental set. Consequently, it can be deduced that EC4 generally leads to unconservative predictions on average by 13 %. The average of the ratios for the EC4 predictions for LWCFST columns is equal to 0.85 which means that EC4 predictions deviate more for LWCFST columns with 15%. On the other hand, the average of the ratios for SCCFST columns is equal to 0.90. That is to say, EC4 overpredicts the SCCFST column capacity on average by 10%.

7. Conclusions

Composite construction finds a great use in high rise buildings, bridges, underground tunnels and towers which require to be designed against severe loading actions. CFST members offer discernible properties compared to other types of structural members, thus has a pioneering role in the composite structural member family. As a result, extensive studies regarding the performance of CFST columns were carried out over the last several decades. However, the most majority of the studies focused on the normal CFST columns. For the civil engineering industry to continue to flourish on composite construction, such investigations should never just be conducted on traditional normal concrete. The research should also be directed towards the innovative concrete types which offer superior engineering properties. In this regard, LWC and SCC are two innovative and highly engineered concrete types which have significant potential to ease the composite construction and advance the CFST column concept. However, the challenge here is to find a path from concept to design. To be able to circumvent this challenge, it is required to obtain a significant amount of experimental data on the performance of the steel hollow section columns filled with LWC and SCC. This is devoted to exploring the performance of LWCFST and SCCFST columns under compressive loading. Instead of focusing on a single type of column length, test column L/D ratios were chosen with the intent to observe the short, medium and long column behaviours within the same research. Based on the test results following conclusions could be derived:

- LWC offers significant reduction of the own weight of the structure and leads to the increment of the strength to weight ratio. This property of the LWC concrete could be fully exploited in huge structures and the static, dynamic and thermal characteristics of the structure would be improved. On the other hand, SCC has significant potential to ease the construction process by eliminating the need for compaction. This property of the SCC is very useful, especially in CFST applications due to the closed sections of the steel tubes.
- LWCFST and SCCFST short columns experienced local material failures as expected. However, LWCFST short columns exhibited less ductility and presented sudden discharge of the loading after achieving the compression capacity.
- Medium length SCCFST column with L/D ratio of 5 showed an interaction of local and global failures. Although this type of combined failure was observed in LWCFST column, local failure was much intensified in this column. All of the SCCFST columns with L/D ratio of 7.5 exhibited global failure modes with very small local effects. On the other hand, corresponding LWCFST column failure modes were again dominated by local buckling of the steel tube plus local crushing of the concrete and the effect of global mode was minimum. Sudden discharge of the loading for the LWCFST columns with L/D ratio of 7.5 is not severe as it was with L/D ratios of 2 and 5.
- Long SCCFST column experienced a complete global failure mode, while interestingly the long LWCFST column showed evidence of interaction of local and global failure modes.
- The primary complication with employing the pumice type of lightweight aggregate is that this type of the aggregate led local mode of failures to dominate the collapse behaviour of the columns, even with the long columns. This adverse effect could be minimized either by utilizing steel bar reinforcement or by using artificial lightweight aggregate which has no or less porous physical structure.
- All of the SCCFST columns, including the long ones have *SI* values greater than unity which means that this type of concrete is relatively appropriate for composite construction. On the

other hand, LWCFST columns provided *SI* values greater than unity with L/D ratios of 2 and 5. It is worth to note that for these columns provided *SI* values are generally smaller than the *SI* values of SCCFST counterparts. Also, long LWCFST columns with L/D ratio of 10.5 have *SI* values smaller than unity.

- AISC 360-16 provided the best capacity predictions for the LWCFST columns with an average 2% conservative deviation from the experimental results. On the other hand, for the SCCFST columns AIJ 2001 design specification exhibited the best performance with an average unconservative deviation of 1%. Considering the EC4 method, it can be concluded that EC4 solutions lead to average unconservative deviations of 15% and 10% for LWCFST and SCCFST columns, respectively.

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