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Size Effect on the Load Carrying Capacity of Normal and Lightweight Concrete Filled Square Steel Tube Composite Columns

Samoel Mahdi Saleh

Department of Civil Engineering, College of Engineering, University of Basrah, 61004, Basrah, Iraq.

Orcid: 0000-0002-3046-168X

Abstract

An experimental study was conducted to investigate the size effect on the load carrying capacity of concrete filled square steel tube composite columns. Nine column specimens were tested under axial compression; three of them were made from normal concrete filled square steel tubes and another three made from lightweight concrete filled square steel tubes, whereas the last three were tested as bare hollow steel sections. The experimental results were compared with those evaluated according to AISC360-10. It was concluded that the load carrying capacity of the CFST reduced with increase the size of the column specimens, whereas the mode of failure did not affect by the size of the tested specimens. Also, it was found that the load carrying capacity of the composite columns filled by lightweight concrete is more sensitive to the size effect than those filled by normal concrete. Finally, it was observed that the column ductility was also inversely affected by the size of the tested CFST column specimens.

Keywords: Size effect, CFST, Composite column, Lightweight concrete,

INTRODUCTION

The conventional strength of materials predicts that any two structural elements with different sizes will fail at the same stress if they are made of the same material. But there is a deviation that appeared in the nominal strengths of different laboratory tested structural elements having similar geometry but different sizes, with those strengths calculated by the classical theories of structures. This deviation is caused due to that called the size effect, which can be understood as the effect of the characteristic structure size on the structural strength when geometrically similar structures are compared. This effect may be related mainly to one of two causes. The first cause is the randomness of the strength of the material of the structural element itself, whereas the second cause may be related to the material nature and its microstructure and its ability to absorb and release the applied energy.

Research focused on the load carrying capacity of concrete filled steel tube (CFT) composite columns has been extensively carried out, especially after the widely propagation in the use of like these composite structures in the civil engineering. In 1997, Y. M. Hunaiti [1] studied the strength of hollow steel sections filled by foam and lightweight aggregate concrete. He was tested twenty-two of beams and column specimens with square and circular sections. He concluded that the composite columns made from foam concrete are incapable of reaching their analytical strength, whereas the composite columns made from lightweight aggregate concrete developed the ultimate axial capacity and significantly enhance the strength of bare steel sections. On the other hand, he revealed that the filling of both foam and lightweight aggregate concrete developed a significant increase in the flexural capacity of the hollow steel sections for the tested beams. Zhang and Shahrooz (1999) [2] examined the ability of the ACI code and AISC to predict the load carrying capacity of CFT composite columns depending on previously database and three specimens tested by them. The database was included short and slender columns made from normal and high strength steel tubes filled with normal and high strength concrete. The study showed large differences between the capacities as computed from ACI and AISC methods. Ghannam et. al. (2010) [3] tested eight specimens of CFT with normal and lightweight concrete to investigate the behavior of such columns. They concluded that the behavior of CFT columns with both lightweight concrete and normal concrete were very similar. In 2014, Patil and Mohite [4] presented a parametric study for square CFT columns under concentric loading. The main parameters considered in this study were the concrete grade, thickness of steel tube, and the length of column. They concluded that the deformations of the CFT column is inversely proportional to the increase of the steel tube thickness and compressive strength of concrete.

The size of CFT columns may have a significant effect on the load carrying capacity of such columns. This because of the large difference in the nature of their two materials; a ductile behavior for steel tube and a quasi-brittle behavior for concrete. However, the available studies regarding this effect were found very limited. Accordingly, this work has been directed to examine the size effect on the load carrying capacity of composite columns fabricated from square steel tubes filled with normal and lightweight concrete. The experimental results were compared with the theoretical analysis according to AISC360-10.

EXPERIMENTAL WORK

In this study, nine column specimens of square steel hollow sections (SHS), as shown in Fig. 1, were prepared for test under the effect of axial compression. These column specimens comprised three different groups, each consisting of three specimens. The specimens of first group were filled with normal concrete, and the second group specimens were filled with lightweight concrete. For comparison, the third group specimens were tested as bare steel sections. The designation and the dimensions of the column specimens are given in Table 1. The mechanical properties of the steel hollow sections were determined by the tensile test according to ASTM A370-02 [5], from which it was found that the yield stress and modulus of elasticity were equal to 341 MPa and 202 GPa, respectively.

Figure 1: Details of SHS test specimens

Table 1: Specimens designation and sectional properties

Column Designation	Dimensions of Steel Section (mm)	Column Length (mm)	Concrete Type	Slenderness Ratio
S1NW	150 × 150 × 4.8	900	Normal Concrete	20.8
S2NW	100 × 100 × 3.2	600	Normal Concrete	20.8
S3NW	50 × 50 × 1.6	300	Normal Concrete	20.8
S1LW	150 × 150 × 4.8	900	Lightweight Concrete	20.8
S2LW	100 × 100 × 3.2	600	Lightweight Concrete	20.8
S3LW	50 × 50 × 1.6	300	Lightweight Concrete	20.8
S1BA	150 × 150 × 4.8	900	-------	15.2
S2BA	100 × 100 × 3.2	600	-------	15.2
S3BA	50 × 50 × 1.6	300	-------	15.2

The normal concrete with a mix of ordinary Portland cement, sand, and gravel in the proportions of 1.0:1.5:3.0 with a water cement ratio of 0.46 was used in casting of the first group's specimens. For specimens filled with lightweight concrete (specimens of the second group), a concrete mix of ordinary Portland cement, sand, and gravel in the proportions of 1.0:1.0:2.0 with a foaming agent of 1.7% and superplasticizer of 2% (as liter/kg of cement), and a water cement ratio of 0.28 was used. The casting of concrete and preparing of the column specimens for test are shown in Fig. 2., and the densities and compressive strengths of the used two types of concrete are presented in Table 2.

Figure 2: Casting of concrete and preparing for column specimens

Table 2: Details for casting concrete types

Concrete Type	Average Density (kg/m^3)	Average Compressive Cube Strength, f_{cu} (MPa)	
		7-days	28-days
Normal Concrete	2340	23.6	30.3
Lightweight Concrete	1750	10.5	16.1

All column specimens were tested with a high degree of accuracy under the action of incremental monotonic loading that applied by using universal testing machine (TORSEE) with a capacity that can be adjusted from 20 to 200 tons. Although the ultimate loads were of the major concern, the axial deformations of the column specimens were also measured by dial gauge of 0.01mm precision with the increase of the applied load in order to get the applied axial stress - axial strain curves for these tested specimens as shown in Fig. 3.

Figure 3: Column specimen test setup

THEORETICAL LOAD CARRYING CAPACITY

Several methods are presented by the codes of practice to calculate the ultimate load carrying capacity of the composite column made from hollow steel section filled with concrete. One of these methods that was adopted by AISC360-10 [6], in which the load carrying capacity of a concrete filled square steel tube (CFST) composite column can be evaluated by firstly classified its cross section as compact, noncompact or slender, depending on the mechanical properties and dimensions of the hollow steel section of that composite column. For CFST with compact sections, as the column specimens in present work, the ultimate axial compressive strength (P_n) is: -

$$P_n = P_{no}\left[(0.658)^{\left(\frac{P_{no}}{P_e}\right)}\right] \qquad when \ \frac{P_{no}}{P_e} \leq 2.25$$

$$P_n = 0.877\, P_e \qquad when \ \frac{P_{no}}{P_e} > 2.25$$

$$P_{no} = F_y A_s + 0.85 F_c A_c$$

$$P_e = elastic\ critical\ buckling\ load = \frac{\pi^2 \cdot EI_{eff}}{(L_{eff})^2}$$

$$EI_{eff} = E_s I_s + C_3 E_c I_c$$

$$C_3 = 0.6 + 2\left(\frac{A_s}{A_s + A_c}\right) \qquad \leq 0.9$$

where, L_{eff} is the effective length of composite columns, the parameters A_s, F_y, E_s, and I_s are respectively, the area, yield stress, modulus of elasticity, and moment of inertia for the steel section, and, A_c, F_c, E_c, and I_c are the area, specified compressive strength, modulus of elasticity, and moment of inertia for the concrete, respectively. It must be noted that the specified compressive strength of the concrete is equal to 67% of its cube compressive strength.

RESULTS AND DISCUSSION

The ultimate axial load from the experimental test results and the corresponding values from the theoretical approach (AISC360-10) are summarized in Table 3. One of the main observations that recognized during the tests was all the columns specimens showed approximately the same mode of failure represented by local buckling appeared at the top or bottom of the column, as shown in Fig. 4. This observation may lead to a conclusion that the failure mode does not affect by the size of specimen.

Figure 4: Modes of failure for tested column specimens

Table 3: Experimental and analytical results of tested column specimens

Column Specimen	Experimental Ultimate Axial Load, P_{Exp} (kN)	AISC Ultimate Axial Strength, P_{AISC} (kN)	P_{Exp} / P_{AISC}
S1NW	1461.0	1333.3	1.10
S2NW	676.0	592.6	1.14
S3NW	187.0	148.1	1.26
S1LW	1015.0	1146.5	0.89
S2LW	477.0	509.6	0.94
S3LW	135.0	127.4	1.06
S1BA	878.0	935.3	0.94
S2BA	391.0	415.7	0.94
S3BA	99.0	103.9	0.96

The experimental results, as expected, showed that the load carrying capacity of the concrete filled steel tubes (CFST) specimens was significantly improved comparing with that for bare hollow steel tubes (SHS) specimens, irrespective of the concrete type used for filling if it was normal or lightweight concrete. However, by referring to the results of first group's specimens, it can be seen that the load carrying capacity for column specimens S3NW and S2NW are 187 kN and 676 kN, respectively. As specimen S2NW have cross sectional dimensions and length equal to twice of S3NW, theoretically its load carrying capacity must be equal to 4 times that for S3NW. The experimental results showed that the load carrying capacity ratio was only about 3.61 which is 10% less that calculated value from the theoretical analysis. With scaling up the dimensions of the column specimen three times as for S1NW, the expected carrying capacity is equal to 9 times of S3NW based on the theoretical analysis, but the experimental results indicated a ratio of 7.81. This means that the reduction in the load carrying capacity of S1NW is about 13% comparing with S3NW specimen.

The experimental results of the second group's specimens, show the same scenario as in the first group's specimens. It can be concluded that the reduction in the experimental load carrying capacity of the column specimens S2LW and S1LW are about 12% and 16%, respectively comparing with that value for S3LW specimen. This means that the size effect on the strength of the tested column specimens was increased by 20% due to the use of lightweight concrete with compressive strength of about half of that for normal concrete.

For the third group's specimens, the experimental results showed that the reduction in the load carrying capacity of S2BA and S1BA due to size effect, is not more than 2% comparing with that value for S3BA. This may be attributed to the material type of the tested column specimens, in which, in the third group's specimens only a ductile steel material is used, whereas, in the other two groups, the specimens are fabricated from a composition of ductile and quasi-brittle materials [7].

Table 3 also indicated that the values of ultimate axial loads from both experimental results and theoretical analysis are very close with a mean value of the ratio (P_{Exp} / P_{AISC}) equal to 1.07. Moreover, it is hard to find the size effect on the results of AISC approach.

The relations of the applied axial stress with the developed axial strain for the tested groups 1 and 2 are shown in Figs. 5 and 6, respectively. These figures indicate similar behavior at the initial stages of loading regardless the column size. Moreover, the relations are linear which give approximately a constant value of elastic modulus. The values of modulus of elasticity are different for the two groups because of the different material used in filling the columns. After the elastic limit, the curves at each group start to diverge from each other reflecting the size effect on the behavior of such columns.

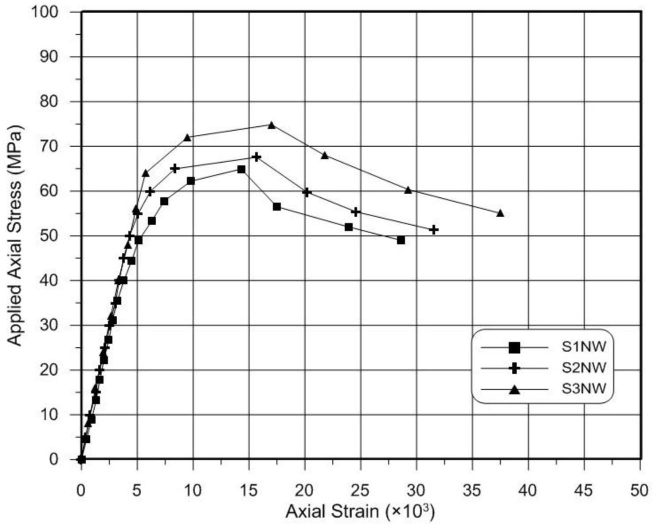

Figure 5: Structural response of column specimens filled with normal concrete

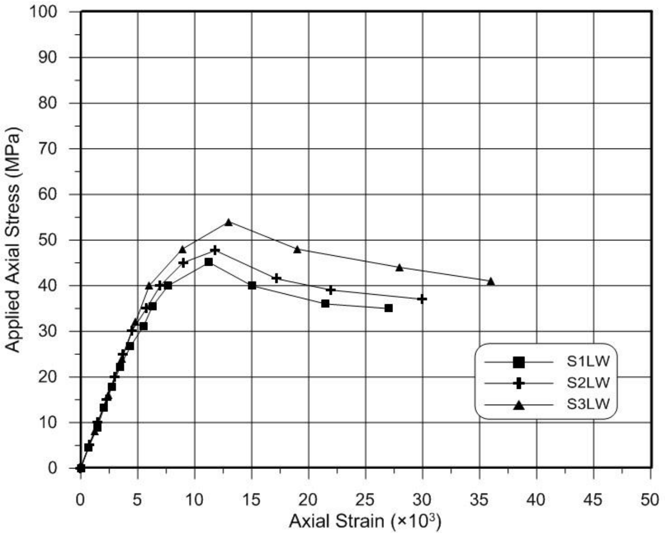

Figure 6: Structural response of column specimens filled with lightweight concrete

To investigate the size effect on the ductility of CFST column section, the ductility index that presented by Han [8] for composite columns was adopted in this study. The ductility index DI can be defined as the ratio of the axial strain when the load falls to 85% of the ultimate load ($\epsilon_{85\%}$) to the axial strain at the ultimate load (ϵ_u). Using this definition, the values of DI are calculated for specimens of groups 1 and 2 and presented in Table 4. The values of DI indicate high ductility of small size specimens. The ductility behavior of same size column specimens from the three tested groups is shown in Fig. 7. It is clear that the concrete filled steel tube sections have more ductility than the bare section. This behavior was also recognized by Hanbin and Usami in 1991 and 1994 [9, 10].

Table 4: Ductility index for tested CFST specimens.

Column Specimen	ϵ_u **(× 10^3)**	$\epsilon_{85\%}$ **(× 10^3)**	**DI**
S1NW	14.30	19.50	1.364
S2NW	15.70	22.70	1.446
S3NW	17.00	27.40	1.612
S1LW	11.26	17.50	1.554
S2LW	11.83	19.00	1.606
S3LW	13.00	23.50	1.808

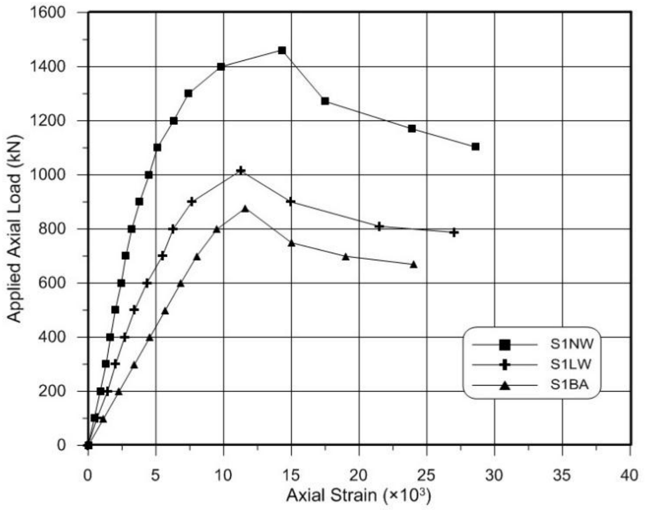

Figure 7: Comparison of structural response of CFST and SHS column specimens

CONCLUSION

Nine column specimens were tested under axial compression to consider the size effect on the behavior of concrete filled square steel tubes composite columns. Three of these specimens were made from normal concrete filled square steel tubes and another three specimens made from lightweight concrete filled square steel tubes. The last three specimens were tested as bare hollow steel sections. It was concluded that the load carrying capacity of the CFST is reduced with increase the size of the column specimens, whereas the mode of failure does not affect by the size of the tested specimens. Also, it was found that the load carrying capacity of composite columns filled with lightweight concrete is more sensitive to the size effect than those filled by normal concrete. Finally, it was observed that the column ductility was also inversely affected by the size of the tested CFST column specimens.

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