Experimental Behavior of High Strength Concrete Filled Double Skin Steel Tubular Columns

Dr. Samoel Mahdi Saleh[1] **Dr. Fareed Hameed Majeed**[2]

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Abstract

A series of experimental tests were carried out to investigate the behavior of high strength concrete filled double skin steel tubular (HSCFDST) columns. Fourteen column specimens were tested in the present study, taking into account the effects of the shape of column cross section (circular or square), the hollowness ratio, and the slenderness ratio. For comparison, two of the tested specimens were filled with normal strength concrete. It was seen that the ultimate axial strength of the square HSCFDST columns is greater than that for circular ones, in spite of that the sectional properties were approximately equal. Also, it was found that for both circular and square column specimens, the ultimate axial strength of HSCFDST columns was inversely proportional to their hollowness and slenderness ratios. CFDST column specimens filled with high strength concrete compared with those filled with normal strength concrete increased stiffness and ultimate axial strength, but give unexpected results for the ultimate axial strength, therefore the suitable choice for the section properties of the inner steel tube is required. The experimental results and analytical approach that developed by other researchers shown good agreement.

Key words : CFDST; Hollowness ratio; Composite column; High strength concrete

سلوك الاعمدة الانبوبية الحديدة المزدوجة القشرة المملؤة بالخرسانة عالية المقاومة

د. سموأل مهدي صالح د. فريد حميد مجيد

الخلاصة

تم إجراء سلسلة من الاختبارات التجريبية للتحقيق في سلوك الاعمدة ذات المقاطع الحديدية المزدوجة والمملوءه بالخرسانة العالية المقاومة. تم اختبار أربعة عشر عينة عمود في هذه الدراسة، مع الأخذ بنظر الاعتبار شكل المقطع العرضي للعمود (دائري أو مربع) ونسبة التجويف ونسبة النحافة . ولغرض المقارنة تم ملء اثنين من الاعمدة المفحوصة بالخرسانة ذات المقاومة الاعتيادية. وقد لوحظ أن القوة المحورية النهائية لأعمدة HSCFDST مربع أكبر من تلك التي الدائرية، على الرغم من أن خصائص المقاطع كانت متساوية تقريبا. أيضا، وجد أن كل من الاعمدة الدائرية والمربعة المقطع، كانت القوة المحورية النهائية لأعمدة HSCFDST متناسبة عكسيا مع نسب التجويف و النحافة. وبمقارنة CFDST الاعمدة المملوءه بالخرسانة عالية المقاومة مع تلك التي مملوءه بالخرسانة اعتيادية المقاومة وجد زيادة بالصلابة والقوة المحورية ، ولكن اعطت نتائج غير متوقعة للقوة المحورية، وبالتالي فإن الخيار المناسب مطلوب لخصائص المقطع الحديدي الداخلي. وأظهرت النتائج التجريبية للبحث معالمعادلات التحليلية التي وضعها باحثون آخرون اتفاقا جيدا.

1. Introduction

One of the main characteristics in the construction of the modern buildings and bridges is the widely use of the composite members. The economy, inherent mass, stiffness, and damping of concrete, and the speed of construction, light weight, and high strength of steel represent the main advantages of the composite members that ideally combine both steel and concrete. One of the new creative innovation of composite members is known as concrete-filled double skin steel tubes (CFDST), which represents the new generation of the concrete filled steel tubes (CFST) composite members. This type of composite members consists of two concentric steel tubes with concrete sandwiched

[1] *Lecture at the Department of Civil Engineering, College of Engineering, University of Basrah, Basrah, Iraq.*

[2] *Lecture at the Department of Civil Engineering, College of Engineering, University of Basrah, Basrah, Iraq.*

between them. Circular, square, or rectangular cross section can be used for the inner and outer steel tubes. This may lead to several combinations that may be used to fabricate such composite members, as shown in Fig.1.

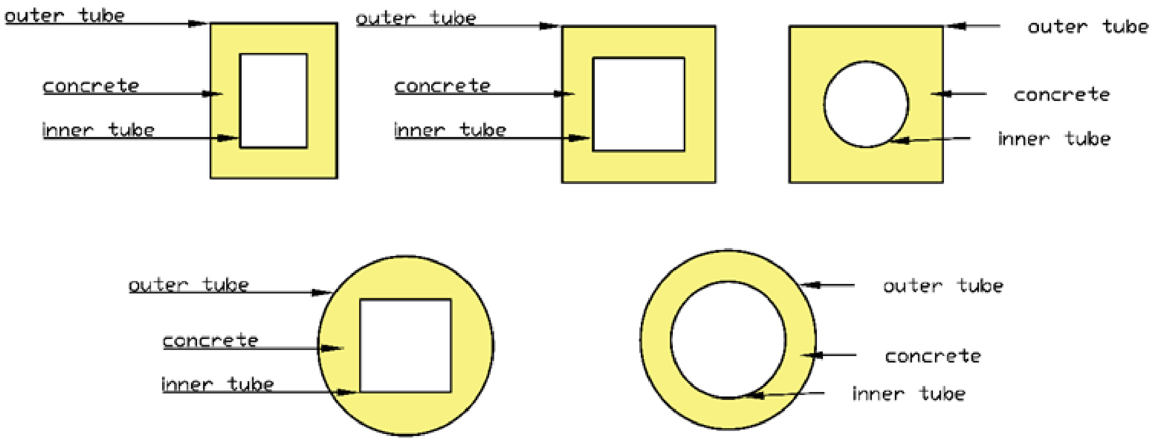

Figure 1: Configurations of CFDST Column Cross Section

In the last few years, the structural behavior of the CFDST members has been investigated by several researchers. In 2004, a series of tests were carried out by Tao et. al. [1] to study the behavior of circular CFDST sub columns and beam-columns. Fourteen sub columns were tested taking into account the effects of diameter to thickness ratio and hollowness ratio, while the effects of slenderness ratio and load eccentricity were taken into account for the tested twelve beam-columns. They developed a theoretical model to establish the carrying capacity of CFDST sub columns and beam-columns that gave good agreement with their experimental results. Han et al., in 2010, [2] suggested a new nonlinear concrete model for the analytical analysis of CFDST columns. They verified their model by comparing their analysis results with the experimental results from other researchers. Also, the analysis results explain why a CFDST column has enhanced strength beyond the sum of the strengths of its component parts, which are an inner tube, an outer tube, and unconfined concrete. Dong and Ho, 2012, [3] experientially investigated, in terms of strength and stiffness, the behavior of CFDST columns with external steel rings under axial compression. They compared their results, like load-displacement curves, Poisson's ratio, axial strength and stiffness with those of CFDST columns without external confinement. They found that the load-carrying capacity, stiffness and ductility were enhanced significantly due to the use of external steel rings with the tested CFDST columns. In 2014, Haas and Koen [4] studied the behavior of CFDST columns under eccentric loading. They tested column specimens with two different lengths and two different hollowness ratios. For each combination of length and hollowness ratio, three test specimens were constructed. The main purpose of this study is to determine whether there exists a trend that could be used to predict the capacities of eccentrically loaded CFDST columns from the calculated concentrically loaded capacities. They showed a clear correlation between the reduction in axial load capacity predicted by simple equations and the length and hollowness ratio of the eccentrically loaded CFDST tested columns. Romero et al. [5], 2015, presented the experimental behavior of six tested circular slender CFDST column specimens filled with normal and ultra-high concrete under room and elevated temperature. They found that the tested specimens at room temperature have approximately the same buckling load, irrespective to the position of the thicker tube (outer or inner). Also, they concluded that the configuration of the tested specimens has a significant effect on their behavior in the fire situation.

This paper studies the behavior of high strength concrete filled double skin steel tubular (HSCFDST) columns. A series of tests were carried out on 14 column specimens considering the effect of the following parameters:

• The shape of column cross section (Circular or Square).

• The hollowness ratio.

• The type of filled concrete (normal or high strength), for comparison.

• The slenderness ratio.

The experimental results were compared with the analytical results that calculated according to a theoretical approach developed by other researchers.

2. Experimental work

A total of fourteen CFDST column specimens of circular and square steel hollow sections were tested in the present study. Twelve specimens, which filled with high strength concrete, were divided equally into two groups, designated as C for circular specimens and S for square specimens. To consider the effects of hollowness ratio and shape of column cross section, the corresponding specimens were designed so that the hollowness ratio was ranged from 0.0 to 0.749 for each group. One specimen filled with normal concrete was added for each group for comparison. The specimens of each group have three different lengths, 550mm for specimens that designed to investigate the effect of hollowness ratio, and concrete type, and 450mm and 900mm, for specimens that designed to consider the effect of slenderness ratio. The details of those specimens are shown in Fig.2 and Table 1. It must be noted that the hollowness ratio is defined as;

$$\chi = \begin{cases} \dfrac{D_i}{D_o - 2t_o} & for\ circular\ \ CFDST \\ \dfrac{B_i}{B_o - 2t_o} & for\ square\ CFDST \end{cases}$$

where Di and Do are the outer diameter of the inner tube and outer tube of circular columns, respectively, Bi and Bo are the outer dimension of the inner tube and outer tube of square columns, respectively, and to is the wall thickness of the outer steel tube.

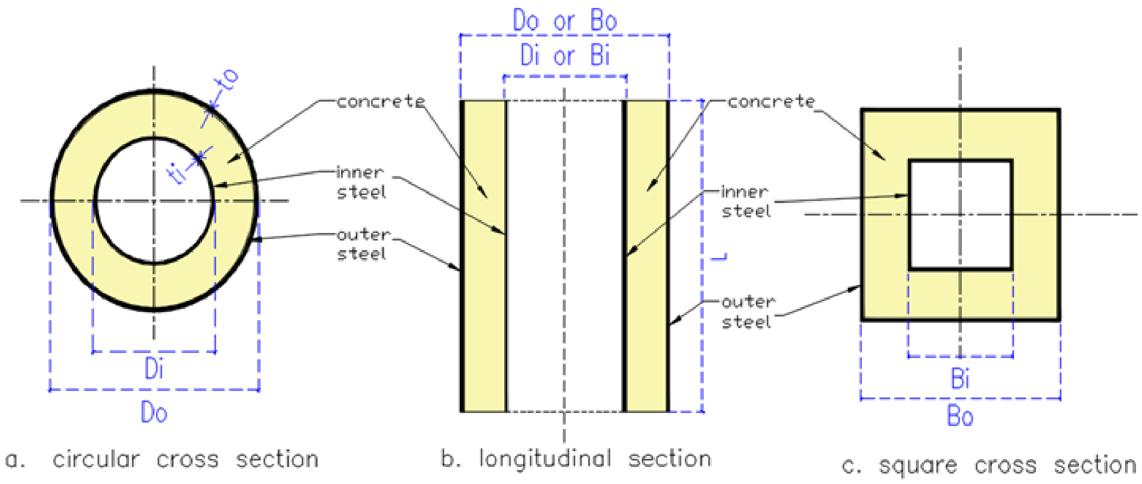

Figure 2: Details of Tested CFDST column specimens

Table 1: Designation and Properties of Tested Column Specimens

Designation	Dimensions of Outer Steel Tube (mm)	Dimensions of Inner Steel Tube (mm)	Concrete Type	Column Effective Length (mm)	Total Steel Area (mm^2)	Slenderness Ratio	Hollowness Ratio
C1L2H	140 × 3.2	100 × 3.0	HSC	550	2289	13.0	0.749
C2L2H	140 × 3.2	75 × 3.2	HSC	550	2097	14.1	0.561
C2L2N	140 × 3.2	75 × 3.2	NSC	550	2097	14.1	0.561
C3L2H	140 × 3.2	40 × 4.0	HSC	550	1829	15.3	0.299
C4L2H	140 × 3.2	--------	HSC	550	1375	15.7	0.0
C5L1H	100 × 3.0	40 × 4.0	HSC	450	1367	17.1	0.426
C5L3H	100 × 3.0	40 × 4.0	HSC	900	1367	34.3	0.426
S1L2H	140×140×3.2	100×100×1.4	HSC	550	2303	11.2	0.749
S2L2H	140×140×3.2	75×75×1.2	HSC	550	2105	12.1	0.561
S2L2N	140×140×3.2	75×75×1.2	NSC	550	2105	12.1	0.561
S3L2H	140×140×3.2	40×40 ×1.0	HSC	550	1907	13.1	0.299
S4L2H	140×140×3.2	--------	HSC	550	1751	13.6	0.0
S5L1H	100×100×1.4	40×40 ×1.0	HSC	450	708	14.6	0.412
S5L3H	100×100×1.4	40×40 ×1.0	HSC	900	708	29.1	0.412

Cold form circular and square steel tubes were used in the fabrication of the column specimens. Both types of steel tubes were produced by the same manufacturer. To measure the material properties, the standard tensile test was conducted by testing three coupons were taken from each type of the steel tube. Table 2 shown the test results and the considered standard.

Table 2: Tensile Test Results of Steel Tubes

Item	Circular Steel Tube	Square Steel Tube	Average Value (MPa)	ASTM A 36/A 36M Requirements*
Yield Stress (N/mm2)	341	338	340	250 Min
Ultimate Strength (N/mm2)	482	482	482	400-550

* From reference [6]

Two types of concrete mix were designed for a compressive cube strength at 28 days of approximately 30 MPa and 75 MPa for normal and high strength concrete, respectively. The details of the two mixes and the corresponding compressive cube strength are shown in Table 3, were the used materials were ordinary Portland cement (OPC), natural sand (S), crushed gravel (G), water (W), and superplasticizer (SP).

Table 3: Details of Concrete Mixes

Concrete Mix Design	Weight of used materials for 1 m^3 of concrete					Slump Test (mm)	Concrete Density Kg/m^3	Compressive Cube Strength N/mm^2	
	OPC(kg)	S(kg)	G(kg)	W(kg)	SP(kg)			7-days	28-days
NSC	380	650	1250	180	----	125	2370	22.8	28.6
HSC	450	600	1250	115	8	125	2410	68.3	76.4

All the tested specimens were filled by concrete in layers with a manually compaction and placed upright to air-dry for the date of testing, as shown in Fig. 3. A high strength epoxy was used for both concrete surfaces of all tested specimens to prevent the effect of any gap between the steel tubes and the sandwich concrete.

Figure 3: Preparation of Tested CFDST Column Specimens

The column specimens were tested under the action of axial compression that applied by using Universal Testing Machine (TORSEE) with a capacity reached to 200 tons. The load was applied at the top end of the CFDST column specimens by using a thick steel plate to distribute the loading uniformly, as shown in Fig. 4. The applied load was increased incrementally up to failure. The axial displacement was recorded at the end of each load increment by a laser dial gauge of 0.01mm precision.

Figure 4: Column Specimens Test Setup

3. Analytical Analysis

Different analytical approaches were recommended in previous studies to predict the sectional capacity of CFDST columns. Depending on the experimentally recommended assumption that the outer tube of such columns behaves like a tube fully filled with concrete, whereas the inner tube behaves like an empty one but can develop its full yielding strength in the presence of sandwich concrete, Han et al. [as cited in Ref. 7] derived a formula to calculate the sectional capacity of a CFDST column (Nu) by summing the strength (Nosc,u) contributed by the outer tube together with the sandwich concrete and the inner tube capacity (Ni,u), as expressed below;

$$N_u = N_{osc,u} + N_{i,u}$$

in which, ($N_{i,u} = A_{si} f_{yi}$), and Asi and fyi are the cross sectional area and the yield stress of the inner tube, respectively and ($N_{osc,u}$) can be evaluated similar to that of fully concrete filled tubular sections, as presented below;

$$N_{osc,u} = A_{osc} f_{scy}$$

where, ($A_{sco} = A_{so} + A_c$), A_{so} and Ac are the cross-sectional areas of the outer tube and the sandwiched concrete, respectively, and f_{scy} can be evaluated as shown below;

$$f_{scy} = \begin{cases} C_1 \cdot \chi^2 \cdot f_{yo} + C_2(1.14 + 1.02\xi)f_{ck} & for\ circular\ CFDST \\ C_1 \cdot \chi^2 \cdot f_{yo} + C_2(1.18 + 0.85\xi)f_{ck} & for\ square\ CFDST \end{cases}$$

$$C_1 = \frac{\alpha}{1+\alpha}$$

$$C_2 = \frac{1+\alpha_n}{1+\alpha}$$

$$\alpha = \frac{A_{so}}{A_c} \quad and \quad \alpha_n = \frac{A_{so}}{A_{c,nominal}}$$

$$\xi = \frac{A_{so} f_{yo}}{A_{c,nominal} \cdot f_{ck}}$$

The concrete nominal cross sectional area, $A_{c,noinal}$, represents the hollow area of the outer steel tube, whereas the concrete compressive strength, f_{ck}, is equal to 67% of its cube strength in (MPa). The parameter f_{yo}, is the yield stress of the outer steel tube in (MPa).

To evaluate the member capacity of CFDST columns (N_{cr}), Tao and Yu [8] proposed a stability reduction factor (φ) to use with the sectional capacity of such columns, as follows;

$$N_{cr} = \varphi N_u$$

and,

$$\varphi = \begin{cases} 1 & for & \lambda \le \lambda_o \\ a\lambda^2 + b\lambda + c & for & \lambda_o < \lambda \le \lambda_p \\ \dfrac{d(-0.23\chi^2 + 1)}{(\lambda + 35)^2} & for & \lambda > \lambda_p \end{cases}$$

In which λ is the slenderness ratio of CFDST column, and the parameters λ_o, λ_p, a, b, c, and d can be calculated as follows;

$$\lambda_o = \begin{cases} \pi / \sqrt{\dfrac{420\xi + 550}{f_{scy}}} & (Circular\ CFDST) \\ \pi / \sqrt{\dfrac{220\xi + 450}{f_{scy}}} & (Square\ CFDST) \end{cases}$$

$$\lambda_p = \begin{cases} 1743/\sqrt{f_{yo}} & (Circular\ CFDST) \\ 1811/\sqrt{f_{yo}} & (Square\ CFDST) \end{cases}$$

$$a = \frac{1 + (35 + 2\lambda_p - \lambda_o) \cdot e}{(\lambda_p - \lambda_o)^2}$$

$$b = e - 2a\lambda_p$$

$$c = 1 - a\lambda_o^2 - b\lambda_o$$

$$d = \begin{cases} [13000 + 4657 \cdot \ln\left(\dfrac{235}{f_{yo}}\right)] \cdot \left(\dfrac{25}{f_{ck}+5}\right)^{0.3} \cdot \left(\dfrac{\alpha_n}{0.1}\right)^{0.05} & Circular\ CFDST \\ [13500 + 4810 \cdot \ln\left(\dfrac{235}{f_{yo}}\right)] \cdot \left(\dfrac{25}{f_{ck}+5}\right)^{0.3} \cdot \left(\dfrac{\alpha_n}{0.1}\right)^{0.05} & Square\ CFDST \end{cases}$$

where,

$$e = \frac{-d}{(\lambda_p + 35)^3}$$

4. Experimental Results and Discussion

All tested normal and high strength CFDST column specimens, except C5L3H and S5L3H, were subjected to a typical failure mode represented by outward folding local failure as shown in Fig. 5. This mode of failure is the same as that observed by Tao et. al. [1], Han et al. [9], and Zhao and Grzebieta [10]. As shown in Fig. 6, the global buckling was the mode of failure that the two specimens C5L3H and S5L3H were subjected. This may be related to that two specimens behaved as slender columns due to their slenderness ratios, which were more than 25 [11].

The maximum applied axial load (Nue) obtained for all tested CFDST column specimens are summarized in Table 4. The applied axial load versus axial displacement for circular and square columns specimens having 550 mm length and high strength concrete are shown in Figs. 7 and 8, respectively. It can be seen that the HSCFDST specimens with square sections have an ultimate strength larger than these with circular sections with an increase ratio ranged from 20% to 29% just due to the shape of section irrespective to the other properties which are approximately same. The curves in the Figs. 7 and 8, also show that the failure of circular specimens occurred at axial displacements larger than these measured at the failure of square specimens.

Figure 5: Mode of Failure for All Specimens Except (C5L3H and S5L3H)

Figure 6: Mode of Failure for Specimens C5L3H and S5L3H

Table 4: Loads results of CFDST column specimens

Designation	Experimental Load (kN)	Analytical Load (KN)	Nominal Load (kN)	P_{Exp} / P_{Ana}	P_{Exp} / P_{Nom}
C1L2H	1052	1089	1092	0.97	0.96
C2L2H	1246	1223	1202	1.02	1.04
C2L2N	980	903	893	1.09	1.10
C3L2H	1385	1315	1271	1.05	1.09
C4L2H	1360	1244	1181	1.09	1.15
C5L1H	796	765	754	1.04	1.06
C5L3H	709	687	754	1.03	0.94
S1L2H	1273	1209	1183	1.05	1.08
S2L2H	1493	1399	1338	1.07	1.12
S2L2N	1174	964	945	1.22	1.24
S3L2H	1790	1566	1476	1.14	1.21
S4L2H	1880	1607	1504	1.17	1.25
S5L1H	732	664	640	1.10	1.14
S5L3H	640	602	640	1.06	1.00

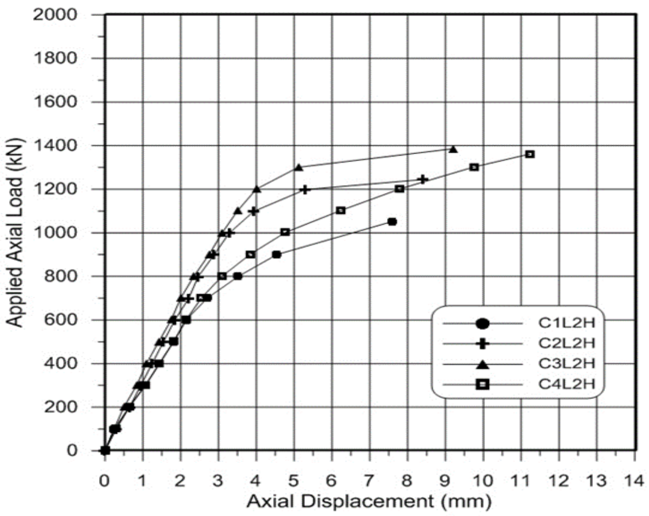

Figure 7: Applied Axial Load – Axial Displacement Relationships for Tested HSCFDST Circular Specimens

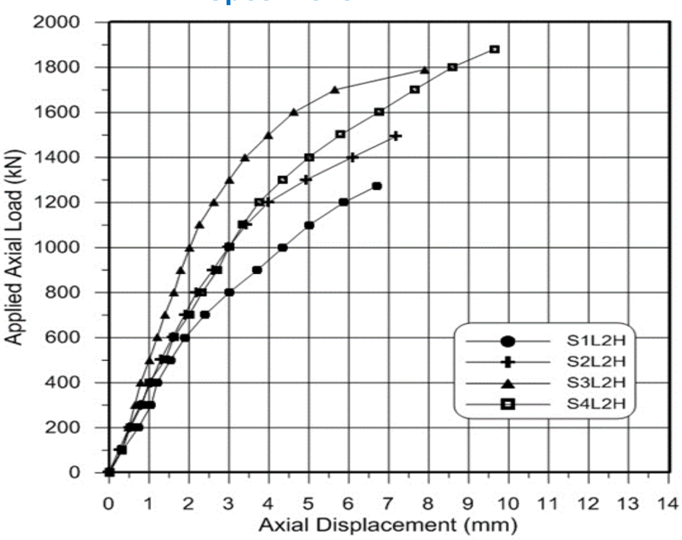

Figure 8: Applied Axial Load – Axial Displacement Relationships for Tested HSCFDST Square Specimens

The effect of hollowness ratio on the behavior of HSCFDST columns is also shown in in Figs. 7 and 8. It can be seen that the curves of tested specimens with different hollowness ratio show the same changing trend as that with zero hollowness ratio, which represents the conventional concrete filled steel tube column. On the other hand, it can be found that the ultimate axial strength for both circular and square HSCFDST column specimens was increase with the decrease of the hollowness ratio. Fig. 9 shows the variation of the normalized axial strength with the hollowness ratio for the tested circular and square HSCFDST column specimens. The normalized axial strength is represented as the ratio of the experimentally measured to nominal ultimate axial strength (N_n), which represents the sum of the strengths of inner tube, outer tube, and concrete alone of the tested specimens [12], as follows;

$$N_n = A_{so}f_{yo} + A_c f_{ck} + A_{si}f_{si}$$

where the nominal ultimate axial strength (N_n) of the experimentally tested HSCFDST column specimens are also shown in Table 4. It can be seen form this figure that the variation of the ultimate strength with the hollowness ratio is approximately same, whether the tested specimens were circular or square columns.

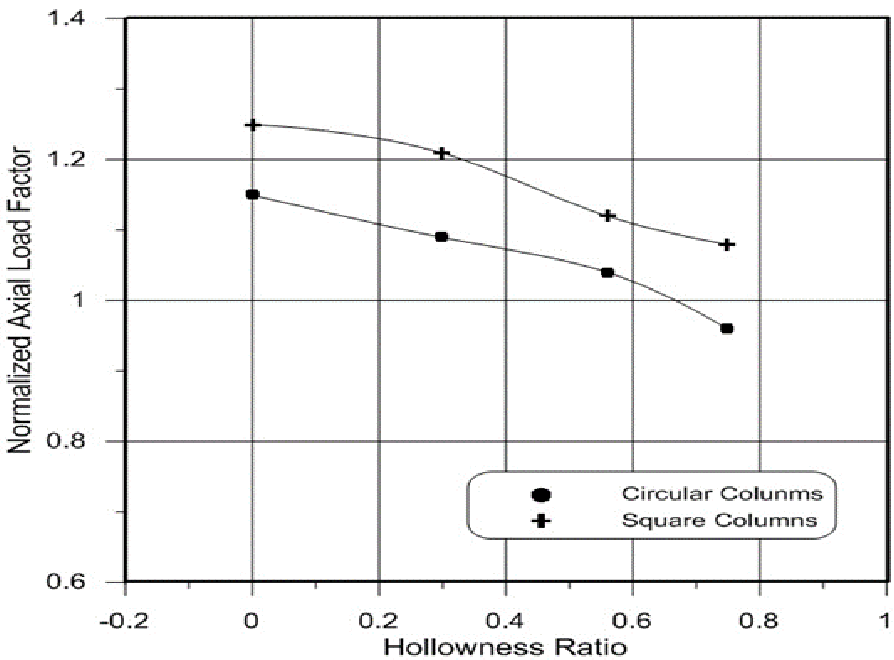

Figure 9: Variation of Normalized Axial Load Factor with the Hollowness Ratio of Tested HSCFDST Specimens

The effect of the type of sandwich concrete on the behavior of the tested CFDST specimens is shown in Figs. 10 and 11. It can be seen that both the stiffness and ultimate axial strength were increased with change of the sandwich concrete from normal to high strength and for both shapes of specimens. But, and as shown in Table 4, the increase in the ultimate axial strength was only about 27%, despite of the increase of the concrete strength which about 170%. This may be related to that the inner steel tube has not sufficient thickness to prevent its failure before the outer steel tube, and then leading to change the sandwich concrete in the tested CFDST specimens from the confined state to the unconfined state [2].

Figs.12 and 13 show the effect of the slenderness ratio on the behavior of the tested circular and square HSCFDST column specimens, respectively. As clearly shown, the effect of the slenderness ratio is approximately same on the overall behavior of both circular and square test specimens and appeared after the linear stage of these behaviors. On the other hand, and as expected, the ultimate axial strength of the tested HSCFDST column specimens decreased with the increase of their slenderness ratio. Where, the tested specimens were lost about 11-12.5% from their ultimate strength just due to increase their length from 450mm to 900mm. Also, this effect is appeared after the linear stage of the behavior of the tested HSCFDST column specimens.

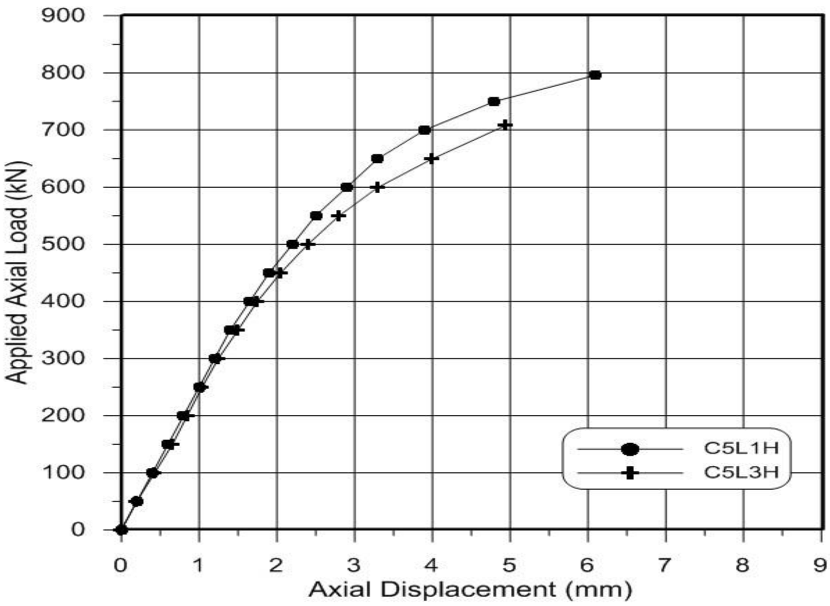

Figure 12: Effect of the Slenderness Ratio on the Behavior Tested Circular HSCFDST Column Specimens

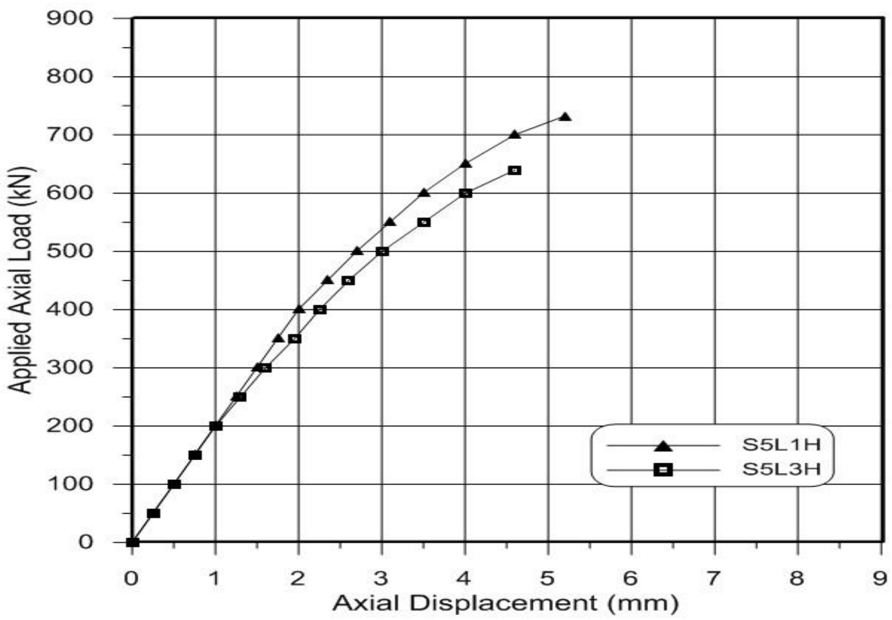

Figure 13: Effect of the Slenderness Ratio on the Behavior Tested Square HSCFDST Column Specimens

5. Analytical Results and Comparison

The predicted ultimate axial strength values from the experimental and analytical investigations of the HSCFDST column specimens was compared. It was found that the results of both approaches are very close with a mean value of the ratio (P_{exp} / P_{anal}) equal to about 1.04 for circular column specimens and about 1.12 for square column specimens. Also, it can be noted that the analytical results were almost lower compared to that of the experimental results.

6. Conclusions

A series of tests including fourteen columns was conducted to study the behavior of high strength concrete filled double skinned tubular (HSCFDST) columns. The mean parameters that considered in this study were the shape of column section (circular or square), hollowness ratio, type of concrete (normal and high strength), and the slenderness ratio. The following points can be concluded from the present study;

1. With same section properties, except the shape, the square HSCFDST columns have an ultimate strength greater than the circular ones with a ratio reached to 29%.
2. The ultimate axial strength of HSCFDST columns inversely proportional to the hollowness ratio, irrespective to the section geometry of the tested column specimens.
3. Both the stiffness and ultimate axial strength were increased for CFDST column specimens filled with high strength concrete compared with these filled with normal strength concrete.
4. The use of high strength concrete may not give the expected results for the ultimate axial strength of CFDST columns without suitable choice for the section properties of the inner steel tube.
5. As expected, the ultimate axial strength of the HSCFDST columns is significantly affected by the slenderness ratio of these columns.

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