Behavior of Self-Consolidating Concrete Filled Steel Tube Columns Subjected to High Temperatures

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Abstract

This paper presents the results of an experimental investigation of the behavior of self-consolidating concrete (SCC) filled steel tube columns subjected to high temperatures. Laboratory tests were carried out on 28 composite column specimens to find the temperature distribution during heating, load-deformation relationship, and the residual strengths of SCC filled columns after being subjected to high temperatures. The investigation included finding the effects of several variables including the temperature exposure, concrete compressive strength, steel tube diameter and steel tube wall thickness on the behavior of the composite columns. The test results showed that, in general, the SCC concrete compressive strength and the failure load of the composite columns decreased with the increase of applied temperature. The normal SCC compressive strength decreased by about 39.77 and 64.55% after being subjected to 400 and 600^{o}C, respectively; whereas the high SCC values decreased by 40.86, 74.38 and 89.35% after 400, 600 and 800^{o}C, respectively. The normal and high strength composite columns failure loads decreased by smaller percentages after being subjected to high temperatures, reaching a maximum reduction ratio of 52.36% after 800^{o}C exposure.

Keywords: Self-Consolidating Concrete Filled Steel Tube Columns, Residual Strengths, And Compressive Strength.

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1. Introduction

Concrete filled steel tube (CFST) columns have been used in the construction of framed structures and in high-rise buildings due to their good looking appearance, high bearing capacity, durability, fast construction, and cost saving. Several investigations(1-7) have been published on the behavior of CFST columns exposed to standard fire. The concrete in the CFST columns may be considered as a heat sink for the section. Also, the steel tube can effectively prevent spalling of the concrete in the CFST. The fire endurance of CFST columns is better than that of unfilled tubular columns. Also, self-consolidating concrete (SCC) has been developed and used recently in construction(8-11). There is a good prospect for using SCC in concrete-filled steel tube columns due to the difficulty in compacting concrete by vibration in the steel tube and in columns with congested reinforcement. Little information is available on SCC-filled steel tubes subjected to high temperatures. The investigation reported here aims to illustrate the behavior of SCC-filled columns and their residual strengths after high temperature exposure.

2. Experimental program

2.1. Material properties

2.1.1 Steel

Circular steel tubes were used in the test program. The tube diameters and thicknesses are given in Table (1) and shown in Figure (1).

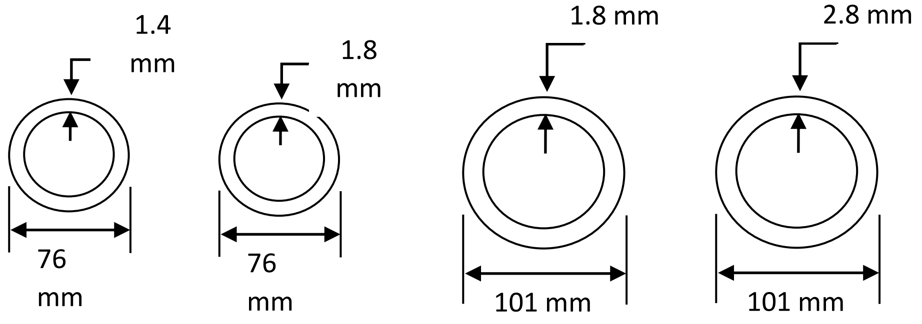


Fig. (1) Details of steel tube column specimens

Table (1) Details of composite column specimens

Group	Sample no.	f'c,MPa	Thickness, mm	Diameter, mm	Temperature,^{0}C
A	CNt_1 D_1 T_1	34	1.4	76	25
	CNt_2 D_1 T_1	34	1.8	76	25
	CNt_2 D_2 T_1	34	1.8	101	25
	CNt_3 D_2 T_1	34	2.8	101	25
	CHt_1 D_1 T_1	43	1.4	76	25
	CHt_2 D_1 T_1	43	1.8	76	25
	CHt_2 D_2 T_1	43	1.8	101	25
	CHt_3 D_2 T_1	43	2.8	101	25
B	CNt_1 D_1 T_2	34	1.4	76	400
	CNt_2 D_1 T_2	34	1.8	76	400
	CNt_2 D_2 T_2	34	1.8	101	400
	CNt_3 D_2 T_2	34	2.8	101	400
	CHt_1 D_1 T_2	43	1.4	76	400
	CHt_2 D_1 T_2	43	1.8	76	400
	CHt_2 D_2 T_2	43	1.8	101	400
	CHt_3 D_2 T_2	43	2.8	101	400
C	CNt_1 D_1 T_3	34	1.4	76	600
	CNt_2 D_1 T_3	34	1.8	76	600
	CNt_2 D_2 T_3	34	1.8	101	600
	CNt_3 D_2 T_3	34	2.8	101	600
	CHt_1 D_1 T_3	43	1.4	76	600
	CHt_2 D_1 T_3	43	1.8	76	600
	CHt_2 D_2 T_3	43	1.8	101	600
	CHt_3 D_2 T_3	43	2.8	101	600
D	CHt_1 D_1 T_4	43	1.4	76	800
	CHt_2 D_1 T_4	43	1.8	76	800
	CHt_2 D_2 T_4	43	1.8	101	800
	CHt_3 D_2 T_4	43	2.8	101	800

The mechanical properties of the steel were obtained by tensile coupon tests. The measured mechanical properties of the steel tube are given in Table (2).

Table (2) Properties of the steel tubes

Thickness(mm)	Yield Strength(MPa)	Ultimate Strength (MPa)	Elastic E-Modulus (GPa)	Elongation Percentage (%)
1.4	330	358	200	18
1.8	345	361	200	1.8

2.1.2. Self-compacting concrete

The important characteristic of SCC is its high workability in the fresh condition. In order to obtain such high workability, the SCC mix proportions are obtained after several trials. Special test methods are used to check the flow ability of the mix. The two mix proportions of the SCC used in the test program are shown inTable (3).

Table (3) Mix proportions of two SCC

Mix No.	Mix Description	Cement content (kg/m^3)	Sand content (kg/m^3)	Gravel content (kg/m^3)	Water L	S.P L	Lime content (kg/m^3)	Cylinder Compressive Strength fc' MPa (28 days)
1	SCC Normal Strength	400 (1)	797 (1.99)	767 (1.9)	185 (0.46)	7.5	170	34.65
2	SCC High Strength	550 (1)	855 (1.55)	767 (1.39)	165 (0.3)	20	50	43.16

The slump coneT_{50}, and L-Box were used in this investigation. The fresh properties of the SCC mixture are given in Table (4). Concrete cylinders, cubes and prisms were also prepared to determine the compressive strengths of the SCC. Some of the cylinders were cured in standard conditions and tested at the age of 28 days. Other specimens were cured in the same conditions as the CFST specimens were tested. The compressive strength of the concrete at 28 days and at the CFST specimens testing are shown in Table (5).

Table (4) Test results of fresh SCC.

Mix name	Slump flow (mm)	T50 (sec)	L-Box (H2/H1)
LSC	740	2.5	0.98
HSC	670	4.5	0.84
Limits of EFNARC [17]	650-800	2 – 5	0.8 – 1
Limits of ACI-237 [12]	450-760	2 - 5	0.8 - 1

Table (5) Concrete compressive strength results for SCC exposed to high temperatures.

Mix name	f'c(MPa)			
	25 ^{0}C	400 ^{0}C	600 ^{0}C	800 ^{0}C
LSC	44	26.5	15.6	9.7
HSC	49.8	29.45	12.76	5.3

2.1.3. CFST Specimens

Twenty eight SCC filled tube column specimens were prepared. Details of the test specimens and the high temperatures they were subjected to are shown in Table (1). The total length of all the specimens was 500 mm. Several test variables were used such as the temperature, outside column diameter, steel tube wall thickness and concrete compressive strength. Two tube diameters were used.

Table (6) Details of test composite columns and their exposure temperature

Test specimen		f'c,* (MPa)	Thickness, (mm)	Diameter, (mm)	Temperature, ^0C
1	$CNt_1\ D_1\ T_1$	44	1.4	76	25 (Control column)
2	$CNt_1\ D_1\ T_2$	26.5	1.4	76	400
3	$CNt_1\ D_1\ T_3$	15.6	1.4	76	600
4	$CNt_2\ D_1\ T_1$	44	1.8	76	25 (Control column)
5	$CNt_2\ D_1\ T_2$	26.5	1.8	76	400
6	$CNt_2\ D_1\ T_3$	15.6	1.8	76	600
7	$CNt_2\ D_2\ T_1$	44	1.8	101	25 (Control column)
8	$CNt_2\ D_2\ T_2$	26.5	1.8	101	400
9	$CNt_2\ D_2\ T_3$	15.6	1.8	101	600
10	$CNt_3\ D_2\ T_1$	44	2.8	101	25 (Control column)
11	$CNt_3\ D_2\ T_2$	26.5	2.8	101	400
12	$CNt_3\ D_2\ T_3$	15.6	2.8	101	600
13	$CHt_1\ D_1\ T_1$	49.8	1.4	76	25 (Control column)
14	$CHt_1\ D_1\ T_2$	29.45	1.4	76	400
15	$CHt_1\ D_1\ T_3$	12.76	1.4	76	600
16	$CHt_1\ D_1\ T_4$	5.3	1.4	76	800
17	$CHt_2\ D_1\ T_1$	49.8	1.8	76	25 (Control column)
18	$CHt_2\ D_1\ T_2$	29.45	1.8	76	400
19	$CHt_2\ D_1\ T_3$	12.76	1.8	76	600
20	$CHt_2\ D_1\ T_4$	5.3	1.8	76	800
21	$CHt_2\ D_2\ T_1$	49.8	1.8	101	25 (Control column)
22	$CHt_2\ D_2\ T_2$	29.45	1.8	101	400
23	$CHt_2\ D_2\ T_3$	12.76	1.8	101	600
24	$CHt_2\ D_2\ T_4$	5.3	1.8	101	800
25	$CHt_3\ D_2\ T_1$	49.8	2.8	101	25 (Control column)
26	$CHt_3\ D_2\ T_2$	29.45	2.8	101	400
27	$CHt_3\ D_2\ T_3$	12.76	2.8	101	600
28	$CHt_3\ D_2\ T_4$	5.3	2.8	101	800

*Tested at the age of 240 days

3. Experimental Procedure

Initially, the steel tubes were cut to the specified lengths. In order to measure the temperatures in the specimens, two thermocouples were installed in each specimen. The positions of the thermocouples in the specimen are shown in Figure (2). One was located at the center of the section and the second was located at the half distance between the center and the outer surface of the section. The steel tube was fixed vertically on a steel plate. Then, the self-consolidating concrete mixture was placed into the steel tube from the top without any vibration.

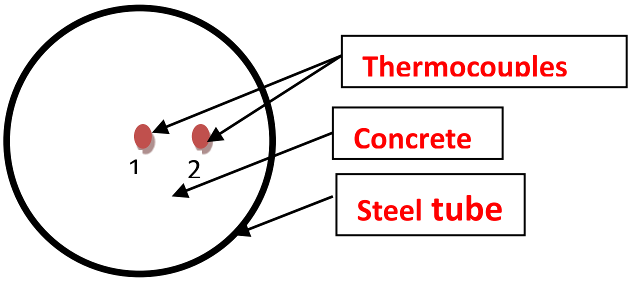


Fig. (2) Thermocoples locations into the composite column

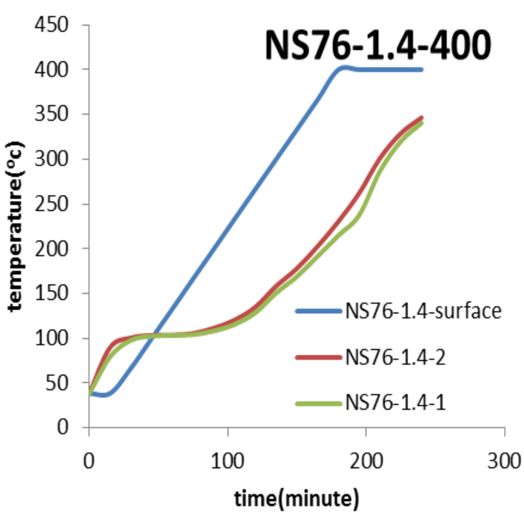
The CFST specimens were tested in the Civil Engineering Laboratory at Al-Nahrain University. A specially designed and manufactured electrical furnace with control unit and data recording system. The control system controls the temperature inside the furnace according to the designated values. The temperatures were recorded by the data acquisition system.

The cast specimens were left in the laboratory for 243 days when they along with the control specimens were placed inside the furnace which was switched onafter and the door closed. Then, the furnace was switched on after choosing the temperature setting required. When the furnace temperature reached the specified value, it was maintained constant for one hour, and then the furnace was switched off and allowed to cool to the laboratory temperature. The specimens were then placed in the testing machine and the load was applied at load increments until failure, during which the load and the corresponding deformation were recorded.

4. Test Results

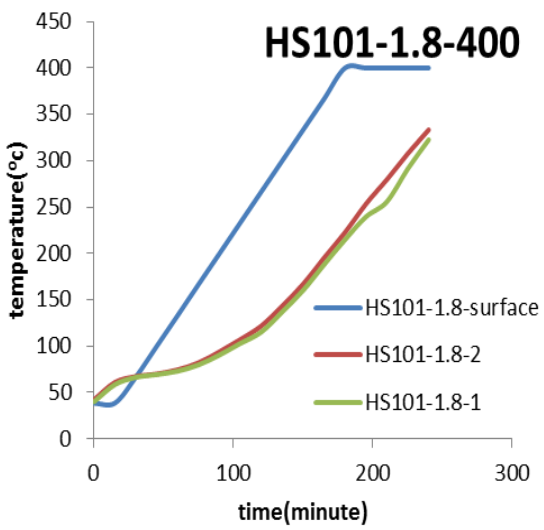
4.1. Temperatures

The temperature in the CFST specimens was measured using thermocouples installed inside the specimens. The positions of thermocouples are shown in Figure (2). Typical temperature-time curves for the composite columns are shown in Figure (3). As noticed from the figure, the concrete temperature increases with the increase of furnace temperature and exposure time. Also, the temperature at the inner point is less than that at the outer point.



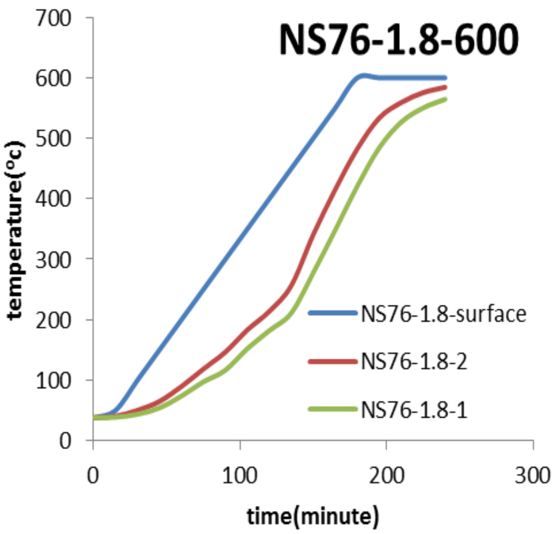
a) Diameter =76 mm,

steel thickness =1.4 mm



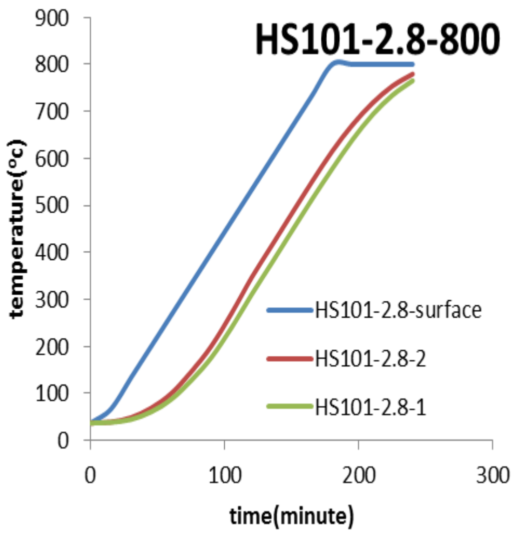
b) Diameter =101 mm,

steel thickness =1.8 mm



c) Diameter =76 mm,

steel thickness =1.8 mm



d) Diameter =101 mm,

steel thickness =2.8 mm

Fig.(3) Temperature -time curves for high strength composite columns

Table (7) Summary of test results of SCC composite column specimens

Specimen no.		Age at time of testing, days	f_c' (MPa) at time of test	Failure load (kN)	Shortening, mm	Mode of failure
1	$CNt_1\ D_1\ T_1$	240	44	474.4622	10.51259	third length break concrete ,steel yield
2	$CNt_1\ D_1\ T_2$	240	26.5	377.9518	11.98958	Break top concrete, steel yield
3	$CNt_1\ D_1\ T_3$	240	15.6	289.3893	15.98609	Concrete failure, steel yield half length
4	$CNt_2\ D_1\ T_1$	240	44	436.9935	11.06333	Break in top concrete, steel yield,
5	$CNt_2\ D_1\ T_2$	241	26.5	402.931	10.56829	Break in top concrete, steel yield
6	$CNt_2\ D_1\ T_3$	242	15.6	381.1097	15.24674	Concrete failure, steel yield +buckling
7	$CNt_2\ D_2\ T_1$	242	44	707.2227	15.56603	concrete failure ,steel yield full length
8	$CNt_2\ D_2\ T_2$	242	26.5			Break in top concrete ,steel yield +buckling
9	$CNt_2\ D_2\ T_3$	243	15.6	588.0039	19.40487	Steel yield full length
10	$CNt\ D_2\ T_1$	243	44	790.1081	15.86751	Steel yield full length
11	$CNt_3\ D_2\ T_2$	243	26.5	649.3164	22.05239	Buckling in steel
12	$CNt_3\ D_2\ T_3$	243	15.6	587.4362	18.53605	Break in top concrete, steel yield full length
13	$CHt_1\ D_1\ T_1$	244	49.8	520.4466	12.59775	Top concrete break, steel yield
14	$CHt_1\ D_1\ T_2$	244	29.45	422.2331	13.03214	Break in top concrete, steel yield
15	$CHt_1\ D_1\ T_3$	244	12.76	330.2643	13.64031	Concrete failure, steel yield full length +buckling
16	$CHt_1\ D_1\ T_4$	244	5.3	247.9466	15.11234	Steel yield+ buckling
17	$CHt_2\ D_1\ T_1$	245	49.8	534.0716	13.023365	Top concrete break, steel yield & buckling
18	$CHt_2\ D_1\ T_2$	245	29.45	391.0091	12.33709	Concrete failure, steel yield & buckling
19	$CHt_2\ D_1\ T_3$	248	12.76	354.1081	15.44353	Concrete failure, steel yield & buckling
20	$CHt_2\ D_1\ T_4$	248	5.3	266.681	14.33537	Concrete failure, steel yield &bucking top
21	$CHt_2\ D_2\ T_1$	248	49.8			concrete break, steel yield
22	$CHt_2\ D_2\ T_2$	248	29.45	736.4865641	16.60729311	concrete break, steel yield
23	$CHt_2\ D_2\ T_3$	249	12.76	601.6289	18.10339	concrete break, steel yield
24	$CHt_2\ D_2\ T_4$	249	5.3	454.0247	23.81651	Concrete failure, steel yield & buckling
25	$CHt_3\ D_2\ T_1$	249	49.8	826.4414	17	Top concrete break
26	$CHt_3\ D_2\ T_2$	249	29.45	784.431	18.56403	Top concrete break, steel yield
27	$CHt_3\ D_2\ T_3$	249	12.76	672.5925	17	Top concrete break, steel yield + buckling
28	$CHt_3\ D_2\ T_4$	249	5.3	557.3477	20.1645	Top concrete break, steel yield + buckling

4.2. CFST Columns under axial load

After heating and cooling the CFST column specimens, loading tests were conducted to evaluate the effects of high temperature exposure on the behavior of the composite columns. For every test, there was a control column specimen placed at laboratory temperature of 37 ^{0}C. Table (7) shows a summary of the properties, concrete strengths, failure loads, and modes of failure of the specimens tested.

5. Parametric Study

The fire behavior of CFST columns depends on a number of factors such as the load level, cross-sectional dimensions, concrete type and type of aggregate used.

The parameters that were investigated included the temperature, outside diameter, steel wall thickness and the concrete strength.

The outside diameters of the steel tube of CFST columns were 76 and 101 mm, the steel wall thicknesses used were 1.4, 108 and2.8 mm. All the column specimens had a constant length of 500 mm. The effect of concrete strength was investigated using two concrete strengths, normal and high strength. The applied temperatures were 25, 400, 600, and 800^{o}C.

In the following, the effects of the various factors that influence the high temperature behavior of CFST columns will be further discussed.

5.1. Effect of Column Diameter

From the experimental results, it is noticed that the heat transferred from the surface to the center of the composite column is slower if the diameter of composite column is increased.

For example, for the normal SCC composite column with 1.8 mm wall thickness and subjected to 400^{o}C, the heat transferred in the 101 mm diameter is smaller than that in the 76 mm diameter, as shown in Figure (4). This is due to the longer path in the larger diameter specimen.

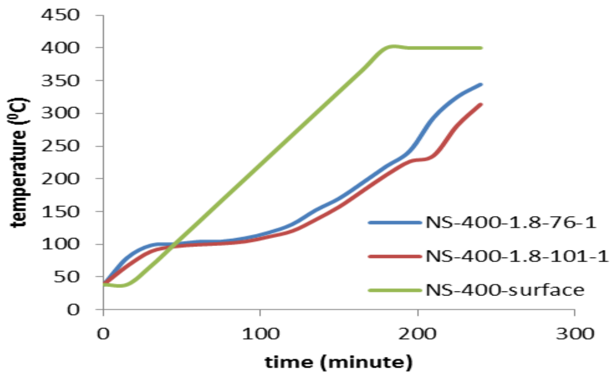


Fig. (4) Effect of diameter of composite column on heat transfer

5.2. Effect of Steel Wall Thickness

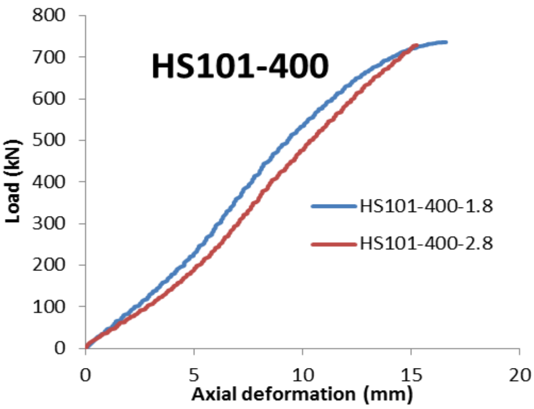
The effect of steel wall thickness on the ultimate load of CC composite columns is shown in Table (8) and Figure (5), respectively.

Table (8) Effect of steel wall thickness on ultimate load and axial deformation of SCC composite column specimens.

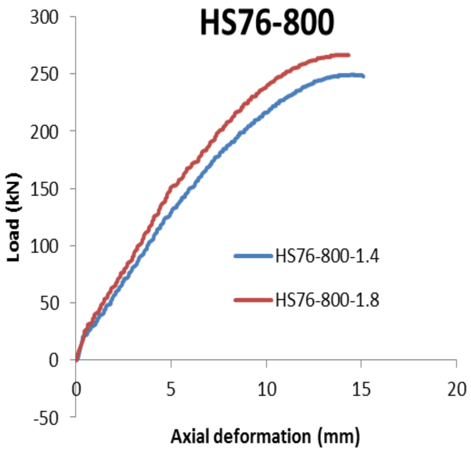
Temperature (^{0}C)	Type of concrete	Diameter (mm)	Steel wall thickness (mm)	Failure load (kN)	Axial Deformation (mm)
25	NS	76	1.4	474.4622	10.51259
25	NS	76	1.8	436.9935	11.06333
400	HS	101	1.8	736.4866	16.60729
400	HS	101	2.8	784.431	18.56403
600	NS	101	1.8	588.0039	19.40487
600	NS	101	2.8	587.4362	18.53605
800	HS	76	1.4	247.9466	15.11234
800	HS	76	1.8	266.681	14.33537

From these results, it is noted that at high temperatures, the increase in the steel wall thickness leads to a small increase in the ultimate loads.

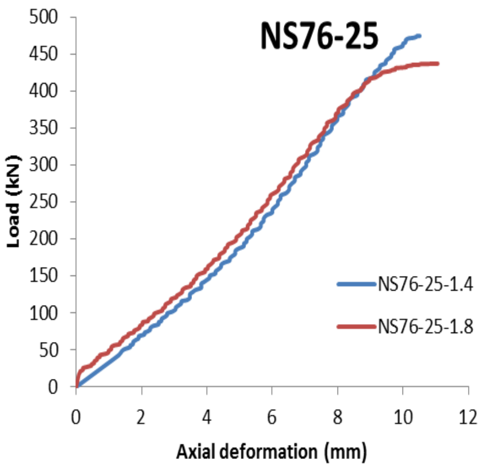
For example, in the high strength composite column of 76 mm diameter and subjected to a temperature of 25^{o}C, increasing the steel wall thickness from 1.4 to 1.8 mm leads to an increase in the ultimate load of 2.62 %



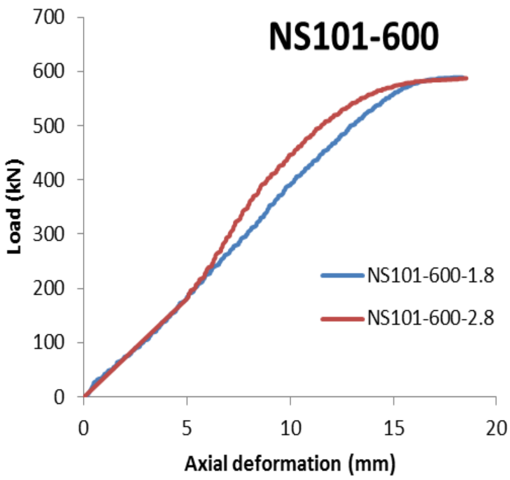
a) High strength concrete, diameter=76 mm and temperature=25 ^{0}C.



b) High strength concrete, diameter=76 mm and



c) Normal strength concrete, diameter=76 mm and



d) Normal strength concrete, diameter=76 mm and

Fig. (5) Effect of steel wall thickness on ultimate load and axial deformation of composite column specimens.

5.3. Effect of Concrete Compressive Strength

The effects of concrete compressive strength (f'c) on the ultimate failure load of SCC composite columns tested are shown in Table (9) and Figure (6), respectively.

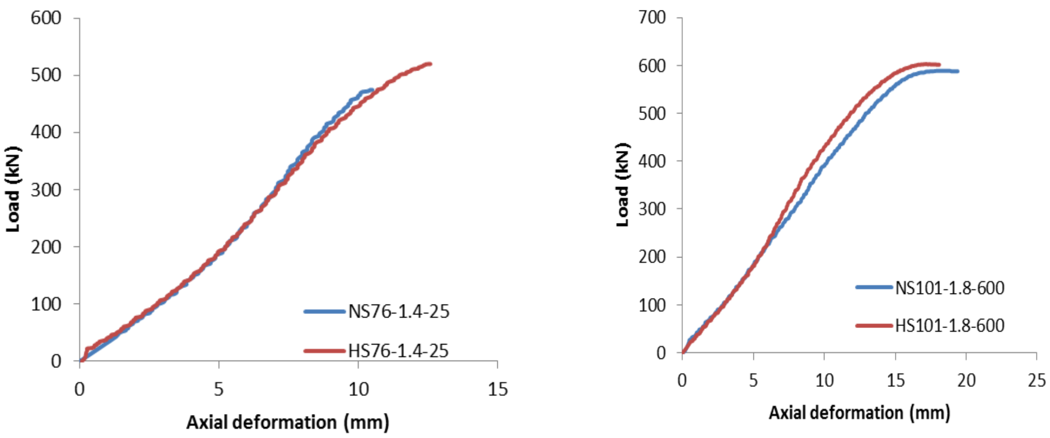
Two SCC compressive strengths (normal and high)of 44 and 49.8 MPa, respectively, were used in this research.

Table (9) Effect of concrete compressive strength on failure load of SCC column specimens

Temperature, ^{0}C	Tube diameter, mm	Thickness of tube, mm	Failure load with Normal Strength concrete (kN)	Failure load with High strength concrete (kN)	Increase in Failure Load due to increasing f'c, %
25	76	1.4	474.4622	520.4466	+9.7
25	76	1.8	436.9935	534.0716	+22.2
25	101	2.8	790.1081	826.4414	+4.56
600	76	1.4	289.3893	330.2643	+14.19
600	101	1.8	588.0039	601.6289	+2.31
600	101	2.8	587.4362	672.5925	+14.48

From these results, it is noted that the increase in (f'c) values leads to a significant increase in the failure load at same temperature.

For example, the ultimate failure load for the high strength SCC composite column of 76 mm diameter and 1.8 mm wall thickness at 25 ^{o}C, is higher than that with normal strength with the same specification. Increasing the concrete compressive strength by 13% leads to an increase in the failure load of the composite column by 22.2%.



a)Diameter =76mm, Tube thickness =1.4mm

b) Diameter =101 mm, Tube thickness =1.8 mm

Fig. (6) Effect of concrete compressive strength on failure

5.4. Effect of Temperature on Ultimate Failure Load

The effects of the high temperatures on the ultimate load of SCC composite columns tested are summarized in Table (10) and shown in Figure (7).

Table (10) Effect of Temperatures on Failure Load and Axial Deformation of Composite Columns**.**

Temperature (^{0}C)	Type of concrete	Tube diameter (mm)	Steel Wall thickness (mm)	Failure load (kN)	Axial Deformation (mm)
25	NS	76	1.4	474.4622	10.51259
400	NS	76	1.4	377.9518	11.98958
600	NS	76	1.4	289.3893	15.98609
25	HS	76	1.4	520.4466	12.59775
400	HS	76	1.4	422.2331	13.03214
600	HS	76	1.4	330.2643	13.64031
800	HS	76	1.4	247.9466	15.11234

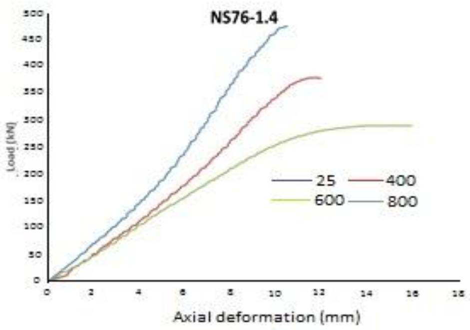
From the results, it is noted that the increase in temperature values leads to a significant decrease in the failure loads and an increase in the axial deformations

For example, in a normal SCC composite column with 76 mm diameter and 1.4mm wall thickness, raising the temperature from 25 to 400 ^{0}C leads to a decrease in the failure load of 20.34 % and an increase in the axial deformation of 14.05 %.

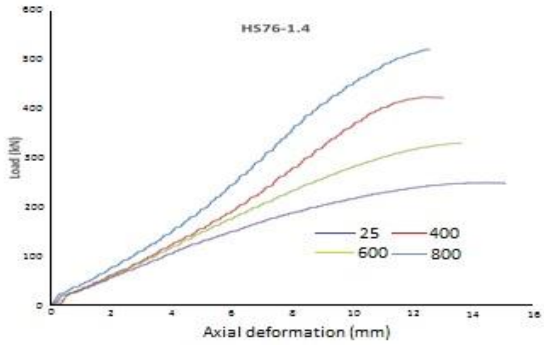
Also raising temperature from 25 to 600 ^{0}C leads to a decrease in the ultimate load of39 % and an increase in the axial deformation of 52.07 %.

6. Failure Mode

After testing the composite column specimens to failure, they were examined to find the failure mechanism. The tested specimens shown in Figure (8) indicates that there are outward bulges on the face of the tested steel tubes. Figure (9) shows that the concrete has crushed at the mid height of the specimens and cracks appeared on the concrete surface after cutting the steel tube.



a) Normal strength concrete, diameter=76 mm and tube thickness=1.4mm



b) High strength concrete, diameter=76 mm and tube

Fig. (7) Effect of high temperature on ultimate load and axial deformation of composite column specimen.

Fig. (8) Failure modes in tested CFST column specimens.

Fig. (9) Crushing of concrete at bulge regions of CFST

7. Conclusions

The behavior of SCC filled steel tubes columns exposed to high temperatures was investigated experimentally. From the results obtained, the following conclusions are made.

1. The behaviors of high and normal SCC- filled steel tube composite column specimens are similar.
2. The self-consolidating concrete compressive strength decreases significantly with the increase in temperature. For normal strength concrete, it deceased by 39.77 and 64.55% when subjected to 400 and 600^{o}C, respectively; whereas for the high SCC, the strength was deceased by 40.86, 74.38 and 89.35% when subjected to 400, 600 and 800^{o}C, respectively.
3. The failure load of the composite columns is decreased with the increase in temperature. The failure load of the normal strength composite columns decreased by 20.34 and 39% when subjected to 400 and 600^{o}C, respectively. The high strength SCC column failure load decreased by 18.87, 36.54 and 52.36% when subjected to 400, 600 and 800^{o}C.
4. The increase in the SCC compressive strength of 13% caused a significant increase in the failure column load of 22.2% at normal temperature.
5. The increase in the steel tube wall thickness led to a decrease in the composite column failure load at normal temperature, but changed to an increase at the high temperatures.

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سلوك الاعمدة الانبوبية الحديدية المملوءة بالخرسانة ذاتية الرص المعرضة للحرارة العالية

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المستخلص

يقدم هذا البحث نتائج دراسة عملية حول سلوك الاعمدة الانبوبية المملوءة بالخرسانة ذاتية الرص المعرضة للحرارة العالية. اجريت فحوصات مختبرية على 28 نماذج اعمدة لايجاد التوزيع الحراري خلال تسخينها،علاقة الحمل المسلط مع الازاحة، المقاومة المتبقية للاعمدة المملوءة بالخرسانة ذاتية الرص بعد تعرضها للحرارة العالية. تضمن البحث ايضا ايجاد تاثيرات عدة متغيرات منها درجة الحرارة المسلطة، مقاومة انضغاط الخرسانة، قطر الانبوب الحديدي وسمكه على سلوك الاعمدة المركبة. اظهرت نتائج الفحوصات بشكل عام ان مقاومة انضغاط الخرسانة ذاتية الرص وحمل الفشل للا عمدة المركبة ينخفضان بزيادة درجات الحرارة المسلطة. فللخرسانة ذاتية الرص العادية انخفضت مقاومة انضغاطها بنسب 39.77 و 64.55 % بعد تعرضها الى 400 و خ600 م على التوالي، بينما كانت نسب الانخفاض للخرسانة ذاتية الرص ذات المقاومة الاعلى هي 40.86 و74.38 و 89.35%بعد تعرضها الى400 و 600 و 800 ^{o}م على التوالي. كذلك انخفضت قيم احمال الفشل للاعمدة المركبة بنسب اقل حيث وصلت اعلى نسبة انخفاض لها الى52.36% بعد التعرض الى 800 ^{o}م .

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