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Effect of Burning By Fire Flame on Load Carrying Capacity of Self-Compacting Concrete Columns

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ABSTRACT
This research presents experimentally investigated the effect of burning by fire flame on the behavior and load carrying capacity of reduced scale SCC column models. Residual ultimate load carrying capacity, load versus deflection curves, maximum crack width, axial deformation and crack pattern for column specimens with and without burning were recorded and discussed.

The reinforced SCC columns were exposed to direct fire fame temperature levels of 752 and 1472^{o}F (400 and 800^{o}C) for 1.5 hour period of exposure at 60 days age.

It was found that the predicted load carrying capacity of SCC columns by three codes (ACI-318/08, BS-8110/97 and Canadian/84), was unconservative after burning except the BS Code equation which was found able to predict load capacity after exposure to high fire temperature levels. Load-deflection curves indicate deleterious response to the fire exposure.
Keywords: *Burning; Fire Flame; Load Carrying Capacity; SCC Columns*

I. INTRODUCTION

Many investigations on self-consolidating concrete (SCC) have been carried out in the last several years and the mechanical behavior of this type of concrete is well understood by now. The fire behavior of this specialized concrete, however, is not fully understood.

Concrete columns are considered to be an important structural element in reinforced concrete structures because they support the structure and transfer the loads to the supports or foundation, so any failure or damage occurs in the column may cause a partial or complete failure of the structure by perhaps chain action.[1] Thus, the aim of this experimental study was to evaluate the effect of fire flame exposure on the behavior of SCC columns.

SCC is defined so that no additional inner or outer vibration is necessary for compaction. It is compacting itself due to its own weight and is de-aerated almost completely while flowing in the formwork. In structural members with high percentage of reinforcement it also fills completely all voids and gaps.

SCC consists of the same components as conventionally normal concrete, which are hydraulic cement, fine and coarse aggregates plus appreciable amount of additives and/or admixtures (fillers and superplasticizers). The high amount of superplasticizer is for reducing the water demand and highly enhancing flowability and overall workability. The high powder content, as well as the use of viscosity modifying agents are to increase plasticity and viscosity of the SCC mix.[2,3]

The effect of sand grading, particle shape and surface texture on the rheology of SCC was studied.[4] They found that increasing the fineness of sand particles and the (fine aggregate / total aggregate) ratio lead to increase the yield stress and plastic viscosity.

The effect of sand-aggregate ratio (S/A = fine aggregate volume to total aggregate volume) on the elastic modulus of SCC was studied.[5] They found that the flow ability of SCC increases with the increase in S/A ratio, meanwhile the modulus of elasticity of SCC is not significantly affected by this ratio when the total aggregate volume was kept constant.

Several test methods are used to evaluate filling ability (flowability), passing ability (passibility), and segregation resistance (stability) of fresh SCC. Among these test methods are the followings:

- Slump flow and T50cm test to evaluate flowability and stability.
- L-box test to assess flowability and passing ability.
- U-box test to measure the filling ability.
- V-funnel test to determine the filling ability.

The residual strength of concrete members after fire exposure investigated,[6] from a batch of traditional (TC = NSC) and self-compacting (SCC) concrete, two cubes were heated for each of the examined temperature levels till 1472^{o}F (800°C). The heating rate was 38.3^{o}F/min (3.5°C/min) and the target temperature was kept constant for 750 minutes. The cubes were cooled in ambient air after removal from the oven. **Fig. 1** shows the mean residual compressive strength immediately after cooling was

68°F (20°C) for TC and 221°F (105°C) for SCC. Both curves were situated around the Euro code curves for normal siliceous concrete.

Studied the behavior of composite beams composed of rolled steel profile concreted between flanges during a fire by conducting a fire resistance test with different cross sections and load ratios, by numerical analysis. The results they obtained are as follows:

1) In steel-concrete composite beams which were simply supported and to which positive bending moment was applied, deformations were downward in the early period of fire, and then the deformation rate decreased once but increased again as heating was continued, leading to the limit of fire resistance.
2) The fire resistance of steel-concrete composite beams increased when the applied bending moment ratio decreased. The fire resistance time was affected by the size of the cross-section, whether steel-concrete composite beams were connected to the reinforced concrete floor or not, as well as by the applied bending moment ratio.[7]

II. RESEARCH SIGNIFICANCE

Numerous investigations studied the effect of fire on concrete, reinforced concrete members is concentrated on exposing such members to high temperatures in special furnaces. Such conditions do not represent the effects due to real fires. In order to simulate this problem to practical site conditions reduced scale column models were cast and they were as close as possible to practical circumstances.

The present work proposes a reinforced SCC column models which resemble the simulation of the state of stress which the reinforced concrete columns are subjected to during fire under loading of different degrees in laboratory. Simulation of real fires in laboratory using a set of methane burners which subjecting the column specimens to real fire flame.

III. EXPERIMENTAL INVESTIGATION

3.1 Materials and Mixes

The properties of materials used in any structure are of considerable importance.[8,9] The properties of materials used in the current study are presented in this chapter. Standard tests according to the American Society for Testing and Materials (ASTM) and Iraqi specifications IQS were conducted to determine the properties of materials.

3.2 Materials

Tasluga-Bazian Ordinary Portland cement (O.P.C) (ASTM Type I). This cement conforms to the Iraqi specification and ASTM C150-05.[10,11] Fine river sand and gravel were used in this study, and **Table 1** contains information about the particle size distribution, specific gravities, and absorption of the aggregates. Both materials were obtained from local sources in Iraq. The sand and gravel were then washed and cleaned with water several times, then it were spread out and left to dry in air, after which it were ready for use. These materials are conformed to the requirements of the Iraqi specification and ASTM C33-03.[12,13] Deformed steel bars of diameters 1/3 and 3/8 in. (Ø8 mm and Ø10 mm) were used as reinforcement and met the ASTM A615 requirements. [14]

A liquid superplasticizer commercially known as [Ura-plast SP] was added to the concrete mix to obtain high workability and fluidity. This superplasticizer can be classified as class F and G according to ASTM C494-99[15] as it has the capability of obtaining more than 12% reduction in mixing water for a given consistency, besides it has a retarding effect to setting. According to trials it was found that the most suitable dose of Ura-plast SP is (4 liters per 100kg of cement). The typical properties of this superplasticizer are listed in **Table 2.**

Limestone powder named locally as "Ghobra" was used filler to increase the amount of powder content (cement + filler) to produce SCC mixes in the present work. The fineness of limestone powder was measured by Blaine method and found to be 1500 cm^2/g. The particle size which is less than 0.125mm acts to increase workability and density of the SCC. This filler conforms to BS 8500-2, 4.4 specifications. The chemical composition of the used limestone powder is given in **Table 3.**

3.3 Mix design and proportions

The Japanese mix design procedure cited by EFNARC[16] was followed to design the mix proportions of SCC. Many trials were made to fix the proportions so as to obtain SCC mix maintaining the ranges and limits of fresh SCC. **Table 4** shows the mix proportions of the SCC mix used in the present study.

3.4 The fresh properties of SCC

The fresh properties of SCC were tested by the procedure of European Guidelines[16] for testing fresh SCC. Four characteristics were achieving by conducting three test which were flowability, was achieved by slump flow test, passibility which was achieved by L box tests, viscosity which was achieved by T50 and V funnel tests, and segregation resistance which was achieved by no halo shape in slump flow test, no visible segregation during handling or testing, and by controlled the average separated diameter of slump to not exceeded the segregation border in slump flow test, **Fig. 2** shows the apparatus of the test.

3.5 Column specimen preparation

The dependent dimensions of the specimens of SCC columns were selected to be 5.9×5.9×39.4 in. (150×150×1000 mm). The mold included: base, sides and sectors for ends. They were made of plywood with a thickness of 0.7 in. (18 mm) to reduce the water effect during the casting process.

The longitudinal and lateral ties reinforcement used is deformed steel bars of diameters 1/3 and 3/8 in. (Ø8 and Ø10 mm) respectively. **Fig. 3** shows the details of the reinforcement of column specimens and Table 5 shows the description and the notation of column specimens.

9 SCC column specimens were cast and cured under laboratory conditions. The casting and curing of the columns were carried out during the period from first of July to the first of November 2012 (4 months period). All specimens were cured in the same method. The specimens in their moulds were covered with a plastic sheet and kept in the casting room at 25(±1) °C for 24 h. These were then demoulded and transferred to the moist curing room at 24(±1) °C and 95(±1) % RH and cured in water where they remained until required for testing.

After the complete 60 days age which is the age of fire processing and testing. Fire processing was achieved by subjecting the SCC column specimens to direct fire flame from a network of methane burner. Although the maximum temperatures reached during fires of buildings are in the order of 1832 to 2192^{o}F (1000 to 1200^{o}C)[17,18] such high temperatures occur only at the surface of the exposed members. Considering the relatively small size modeling of the specimens to be tested, it was decided to limit temperature of the specimens to three temperature levels of 752 and 1472^{o}F (400 and 800^{o}C). The dimensions of this burner network are 39.4×3.94 in. (1000×100 mm) (length × width respectively) as shown in **Fig. 4**.

When the target temperature was reached, the temperature of concrete and steel reinforcement was measured at different depths by continuously applying Infrared ray thermometer from about approximately 118.2 in. (3 meters) from the concrete exposed to fire. The measurement device was shown in **Fig. 5**.

3.6 Testing procedure

All the SCC column specimens were white painted to facilitate detection of cracks. The column specimens were tested using a load cell of maximum capacity of (150 Tons) at the age of (60 days). At each test, the first cracking load, midheight lateral deflection, axial deformation, maximum crack width and ultimate load were recorded. The load was applied through a bearing plate for the axially loaded columns, and through a cylindrical roller to simulate line load, attached to the top of bearing plates. The load was applied gradually, the readings were recorded manually. After the first crack appeared on the column surface, the load was applied in small increments up to failure. The specimens were concentrically and eccentrically loaded by eccentricity of 1.77 and 3.55 in. (45mm and 90 mm).

Two dial gauges were fixed at distance 1 in. (25.4 mm) from the nearest edges of these columns to measure the deformation at these edges due to burning. Also, another one was fixed at the centerline of column specimens to measure the axial deformation due to concentric load. The dial gauge was used to measured axial deformation of the specimen having a minimum graduation of 0.001 mm and a maximum needle length of 1.97 in. (50 mm) mounted at the bottom face of the specimens**. Fig. 6** shows the setup of axial deformation measurements mentioned above.

The positions of the visual cracks in the concrete and the loads, at which these cracks were formed, were recorded. The reading of the lateral deflections versus loads was recorded simultaneously for each load increment.

For the SCC column specimens which were subjected to fire flame under loading as shown in **Fig. 7**. The specified (target) fire temperature was reached by mounting the fire subjecting burners by a sliding arm to control the fire distance to the surface of the column specimens, and also by monitoring the fire intensity through controlling the methane gas pressure in the burners. The temperature was measured by infrared rays thermometer continuously till reaching the specified (target) fire temperature. Then, the sliding arm and gas pressure were kept at this position along the period of burning (1.5 hour). The lateral deflection of the column specimens exposed to fire are resulting from loading to 20% of ultimate load before burning, loading 20% and applied fire flame, and loading after burning until failure. While, for specimens without burning the lateral deflection is resulting from applied load only.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Fresh concrete test results

Table 6 gives the experimental results obtained from Slump flow, T50cm, L-box, and V-funnel tests that were conducted throughout the present work. It can be seen that the test results are within the limits of Self-compacting concrete results established in EFNARC 2005[16] which means that the designed concrete mix in the present work conforms to the specifications of SCC.

4.2 Compressive strength results

Table 7 presents cube compressive strength test results for the SCC mix before and after exposure to fire flame at the ages 28, 60 and 90 days. Compressive strength test was conducted by using a standard cubes of dimensions 5.9×5.9×5.9 in. (150×150×150 mm). Each test result represents the mean value of the compressive strength of three cubes. **Fig. 8** reveals the relation between compressive strength and fire temperature. It is obvious from the results that compressive strength decreases significantly with exposure to fire flame.

The percentage of residual compressive strength after burning at 752ºF (400ºC) fire temperature was (84%), while the percentage of the remaining compressive strength was (42%) at 1472ºF (800ºC) fire temperature. In addition, it can be noted that the test results of the residual compressive strength after burning show that, the reduction at 28 days age was more than the reduction at 60 and 90 days. This may be attributed to the fact that hydration of cement paste is more complete at later ages.

4.3 First crack load and ultimate load for columns exposed to fire flame

The ultimate load values were recorded for all columns which were tested with or without exposure to fire flame. **Table 8** shows the results of the first crack load and ultimate load values for all columns specimens. From this Table, it can be seen that the values of ultimate load decreases when the column specimen is exposed to fire flame.

At burning temperature 752 and 1472ºF (400 and 800°C), the residual ultimate loads were (86 and 26 %) for concentric loads respectively, while (87, 113.8%) and (28, 39%) for reinforced concrete SCC column specimens loaded at eccentricity of 1.77, 3.55 in. (45, 90mm) respectively.

First crack load which was recorded in this study was represented, the load which caused the visible first crack in the face of column which parallel with the direction of the fire flame and caused by loading operation with respect to the columns which were not exposed to the fire and, which were exposed to fire. Where, the last columns (fired columns) were precracked before the loading operation. From these results, it can be concluded that the first crack load of the reference SCC column specimens decreased with increased amount of eccentricity.

Fig. 9 reveals the effect of fire flame on load carrying capacity with different amount of eccentricities 1.77 and 3.55 in. (45 and 90 mm). From this Figure, it can be noted that the ultimate load capacity had increased in the eccentric columns with 3.55 in. (e=90 mm). This can be explained by the low reduction percentages in tensile and compressive strength of the concrete member at this low fire temperature exposure, on the other hand the expansion happening due to this fire exposure can cause an increase in the axial compressive stress affecting on the eccentric 3.55 in. (e=90 mm) loaded column specimens which raise the moment capacity of the column and consequently the load capacity.

The fire flame temperature applied to concrete column causes evaporation of the free moisture in concrete with continual exposure to fire. The temperature inside the specimen increases and the strength of concrete decreases. This can be attributed to hydration of free lime and deformation of $Ca(OH)_2$ due to absorption of moisture by the effect of fire flame, so expansion takes place, which causes cracking and reduces the ultimate load capacity.

The data of axial deformation was recorded up to 95% of the ultimate load, because the final axial deformation at ultimate load cannot be measured due to the immediate type of failure of concrete column specimens.

Fig. 10 and **11** present the effect of fire flame temperature on the characteristics of axial deformation of the column specimens. From these Figures, it can be seen that the concentric SCC column specimens exhibited a small contraction when loaded to 20% of the ultimate load during 25minutes then remain constant for the later period of this applied load, and then the columns exhibit a sudden increase in contraction which was identified as failure after applied residual load. While, forcolumn specimens exposed to fire flame temperature 752 and 1472ºF (400 and 800°C) also exhibited a small contraction when loaded to 20% of the ultimate load during 25 minutes then remain constant for the later period of this load, thereon noticed a large elongation at the left and right edge of column specimens when exposed to burning, then a sudden contraction was observed when applying the residual load until 95% of ultimate load.

Finally, these Figures present the time versus the vertical displacements in y-direction (expansion or contraction) for column specimens at different stages during burning and loading.

4.4 Effect of fire flame on load-deflection relationship

The midheight lateral deflection of the column specimens which were loaded and exposed to fire flame at the same time was measured during this process. Each column specimen was loaded to 20% of the ultimate load before burning for a period of 25 minute; then exposed to fire flame temperatures of 752 and 1472ºF (400 and 800°C) thereon; the residual ultimate load was applied until failure.

Fig. 12 to 14 showed the load-midheight lateral deflection relationships for columns before and after the exposure to the fire flame, where, columns which exposed to higher fire temperature, gives approximately, the lesser curvature compared with those of the control column specimens and lower burning temperature. This can be attributed to the reduction in modulus of elasticity of concrete and increase in the amount of cracks formation.

These Figures reveal that the load-deflection relation of the column specimens is almost linearly proportional for the two eccentricities 1.77 and 3.55 in. (45 and 90mm) and for temperature exposure 1472ºF (800°C). In addition, it can be noted that the increase in the fire temperature decreases the load carrying capacity and increases lateral deflection in column specimens.

When the fire flame temperature increases to 1472ºF (800°C), the load carrying capacity decreases, and also the deflection values increase rapidly for the same load and eccentricity as shown in these Figures. This can be attributed to the weaker bond strength between the concrete and steel reinforcement. This de-bonding is resulted due to the cracks that formed at surface. They were at locations close to the steel reinforcement. As these cracks propagated and widened, the fire penetrated into the inner part of the column specimens and the steel reinforcement through the "crack opening".

4.5 Test observations and mode of failure

During testing of SCC column specimens up to failure, it was observed the cracks appeared on the concentric columns nearly vertical, hairline cracks appeared at the middle portion of columns. More cracks (mostly vertical) continued to appear on the column faces. Also approximately the first twenty five minutes of burning at temperature 1472ºF (800°C), concrete spalling was observed. Scabbing occurred prior to the column failure due to the crushing of the concrete and subsequent buckling of the main reinforcement at later stage. For columns loaded at eccentricity 45 and 90mm on the surface from the tension zone towards the compression zone. Further, flexural cracks were formed progressively and widened as the loading increased. However some of short nearly vertical, hairline cracks were detected on the middle third of the columns.

As exposure to fire flames continued, longitudinal cracks appeared and propagated on all faces of the columns tested. Also transverse cracks during burning, which appeared at locations of ties can be distinguished. Fig. 15 and 16 show these cracks.

As loading increased, the cracks widened and extended to join and form triangular-shaped cracks of 5.3-5.7 in. (135-145 mm) length and 1.57-1.97 in. (40-50 mm) width as shown in Fig. 17.

Generally, runoff water from all surfaces of column specimens in the first few minutes was noticed. This phenomenon was observed at about 12-16 minutes and continued for approximately 11 minutes for all burning temperatures 752 and 1472ºF (400 and 800oC), Fig. 18 show this behavior. This can be attributed to the increase in vapor pressure inside the saturated voids which causes water to escape out from the cracks on the surface generated by fire exposure.

Different modes of failure were observed:

- Compression failure for concentric loaded column specimens.
- Combined flexural and compression failure for eccentric loaded column specimens.

The columns burned at 752ºF (400^{o}C), the type of failure for concentric and eccentric loaded specimens stayed without changes. For columns burned at 1472ºF (800^{o}C), the type of failure also remained constant but scabbing in the concrete cover occurred. This can be attributed to the vapor pressure of the runoff water which exerts internal pressure stresses on the surface layers of concrete which are unconfined by the tie reinforcement resulting in scabbing of these layers.

4.6 General behavior and verification of building code provisions of axially loaded column specimens

The test results were used to verify the recommendations and design simplifications of the various Building Codes Pertaining to axial load capacity (Pn) design, specifically, comments are made on accuracy of strength Predictions. These equations are selected and used in this study for comparison with the results of the experimental work. These equations are outlined in the **Table 9**. **Table 10** presents the comparison between the experimental results with (ACI[19], B.S[20] and Canadian[21]) Codes. To utilize these equations after exposure to fire flame temperatures the relative axial load capacity values (Pu test/Pn calculated) were calculated for the SCC column specimens. The relationship between fire temperature with residual axial load capacity and ultimate load carrying capacity are illustrated in **Fig. 19.**

At burning temperature 752ºF (400°C), the ACI Building Code gave reasonable results to predict axial load capacity, while the (B.S[20] and Canadian[21]) codes gave very conservative values of column capacity. The ratios between the measured and (ACI[19], B.S[20] and Canadian[21]) predicted values were (1.14, 1.91 and 1.74%) respectively.

At burning temperature 1472ºF (800°C), the ACI Code became unable to predict axial load capacity, while the B.S Building codes gave close results, whereas, the Canadian code gave overestimated results to predict column load capacity to predict column capacity. The ratios between the measured and (ACI[19], B.S[20] and Canadian[21]) predicted values were (0.61, 0.98 and 0.83%) respectively.

V. CONCLUSIONS

Based on the results obtained from this work, the following conclusions can be withdrawn:

1. The residual compressive strength ranged between (84-88%) at 752ºF (400ºC), and (42-51%) at 1472ºF (800ºC) burning temperature.
2. In this study, it is observed that the value of longitudinal crack width is less than flexure transverse crack width for columns with or without burning.
3. It is found that the residual ultimate load capacity of SC column specimens decreases significantly when subjected to burning by fire flame.
   - After exposure to fire temperature 752ºF (400^{o}C), the percentage residual ultimate load is 86% for concentric loaded, while 87% and 113.8% for eccentric at 1.77 and

3.55 in. (45 and 90 mm) loaded column specimens respectively.

- After exposure to fire temperature 1472ºF (800^{o}C), the percentage residual ultimate load is 26% for concentric loaded, while 28% and 39% for eccentric at 1.77 and 3.55 in. (45 and 90 mm) loaded column specimens respectively.

4. The experimental results clearly indicate that the crack width in reinforced concrete columns that are subjected to fire flame are higher than the columns that are not burned at identical loads.
5. In this study, it is noticed that the load-deflection relation of rigid beam specimens exposed to fire flame temperature around 1472ºF (800^{o}C) are more leveled indicating softer load-deflection behavior than that of the control beams. This can be attributed to the early cracks and lower modulus of elasticity.
6. The Canadian/84 and ACI Codes predict ultimate load carrying capacity after exposure to 752ºF (400^{o}C) fire flame temperature conservatively.
7. B.S-8110/97 Code give close results to predict ultimate load carrying capacity after exposure to 752ºF (400^{o}C) fire flame temperature.

NOTATION

ACI = American concrete institute
ASTM = American society for testing and materials
An = net concrete area
Ast = total area of longitudinal steel reinforcement
fc' = cylinder compressive strength of concrete
fcu = cube compressive strength of concrete
fcua = cube compressive strength after burning
fcub = cube compressive strength before burning
Fy = yield stress of steel reinforcing bar
NSC = normal strength concrete
LSP = limestone powder
IQS = Iraqi specification limits
Sec. = second
Pu = measured ultimate load
Pn = designed ultimate load
S/A = fine aggregate volume to total aggregate volume ratio
SP = superplasticizer
TC = Traditional concrete

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TABLES AND FIGURES

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Table 1 - Aggregate properties.

Sieve diameter, mm (in.)	Percent passing	
	Coarse	Fine
12.5 (1/2)	100	100
9.5 (3/8)	100	100
4.75 (3/16)	13.4	99.8
2.36 (0.0937)	3	89.6
1.18 (0.0469)	2	71.3
0.60 (0.0234)	—	50.3
0.30 (0.0124)	—	18.4
0.15 (0.0059)	—	4.1
0.075 (0.00295)	—	1.1
0	0	0
Specific gravity, kg/m3(lb/ft3)	2650 (159)	2660 (160)
Absorption, %	2.41	1.78

Note: 1 kg/m^3 = 0.06 lb/ft^3.

Table 2 - Properties of Ura-plast superplasticizer.

Form	Color	Relative density	Viscosity	pH value	Transport	Labeling
Viscous liquid	Dark brown	1.1 at 68°F (20°C)	128 + 3 cps at 68°F (20°C)	6.6	Not classified as dangerous	No hazard label required

Table 3-Chemical composition of limestone powder.

Oxide	CaO	SiO_2	Al2O_3	Fe_2O_3	MgO	SO_3	L.O.I
%	52.76	1.40	0.70	0.17	0.10	2.91	40.60

Table 4-Mix proportions of the SCC mix.

	Mix proportions of specimen materials, lb/ft^3 (kg/m^3)					
W/P ratio	Water	Cement	Sand	Gravel	LSP	SP % by wt. of cement
0.33	12.40 (200)	29.76 (480)	47.12 (760)	52.33 (844)	7.44 (120)	6

Table 5-Description of column test specimens.

Column Notation	C1	C2	C3	C4	C5	C6	C7	C8	C9
Temperature Stage ºF (ºC)	77 (25)			752 (400)			1472 (800)		
Eccentricity of Applied Load in. (mm)	0	1.77 (45)	3.55 (90)	0	1.77 (45)	3.55 (90)	0	1.77 (45)	3.55 (90)

Table 6-Results of fresh properties for SCC.

Type of Test	Flow, in. (mm)	T50cm, (sec.)	V-time, sec.	L-box (H2/H1)%
Values	30.34 (770)	3.1	6.8	0.93
Limits of EFNARC,2005	25.6–31.5 (650–800)	2–5	6–12	0.8–1

Table 7-Test values of cube compressive strength before and after burning.

Age at exposure (days)	Cube compressive strength psi (MPa)			(fcua/fcub) Ratio	
	Temperature ºF (ºC)				
	77 (25) (a)	752 (400) (b)	1472 (800) (c)	b/a	c/a
28	6090 (42)	5119 (35.3)	2552 (17.6)	0.84	0.42
60	6670 (46)	5800 (40.0)	2871 (19.8)	0.87	0.48
90	6960 (48)	6119 (42.2)	3553 (24.5)	0.88	0.51

Table 8-Test results of the first crack load, ultimate load, axial deformation and maximum deflection for reference columns and columns exposed to fire flame.

Column Notation	Temperature Level ºF (ºC)	First Crack Load lbf (kN)	Ultimate Load lbf (kN)	Percentage Residual Ultimate Load (%)	Axial Deformation in. (mm) at Centerline	Maximum Deflection at Midheight in. (mm)
C1	77 (25)	41026 (182.5)	219854 (978)	100	0.126 (3.2)	----
C2		32371 (144.0)	147918 (658)	100	----	0.23 (5.83)
C3		10678 (47.5)	52154 (232)	100	----	0.346 (8.72)
C4	752 (400)	Precracking	189282 (842)	86	0.173 (4.4)	----
C5		Precracking	129035 (574)	87	----	0.248 (6.3)
C6		Precracking	59347 (264)	113.8	----	0.362 (9.20)
C7	1472 (800)	Precracking	57549 (256)	26	0.243 (6.18)	----
C8		Precracking	42038 (187)	28	----	0.272 (6.9)
C9		Precracking	20457 (91)	39	----	0.350 (8.9)

--- No measured value

Table 9-Summary of formulas for predicting axial load column capacity.

Method	Equation	EQ. NO.
ACI-318M-08 Code	$\mathbf{P_n = 0.85f'_c A_n + f_y A_{st}}$	1
B.S 8110-97 Code	$\mathbf{P_n = 0.4f_{cu} A_n + 0.75f_y A_{st}}$	2
Canadian Code-1984	$\mathbf{P_n = 0.51f'_c A_n + f_y A_{st}}$	3

Table 10-Comparison of the load carrying capacity test results with that obtained from (ACI[19], B.S[20] and Canadian[21]) codes of SCC column specimens at age of 60 days.

Column Notation	Compressive strength (MPa)		F_y (GPa)	Ultimate load (kN)				$\frac{P_{u\,test}}{P_{n\,ACI}}$	$\frac{P_{u\,test}}{P_{n\,B.S}}$	$\frac{P_{u\,test}}{P_{n\,Cand.}}$
	F_{cu}	F'_c		Test	B.S	ACI	Cand.			
C1	42.0	35.7	540	978	500.3	843.3	547.5	1.16	1.96	1.78
C4	35.3	30.0	540	842	440.8	735.8	484.0	1.14	1.91	1.74
C7	17.6	14.96	453	256	260.8	421.6	308.8	0.61	0.98	0.83

Notes: 1 MPa = 145 psi; 1 GPa = 145.04 ksi, 1kN = 224.8 lbf

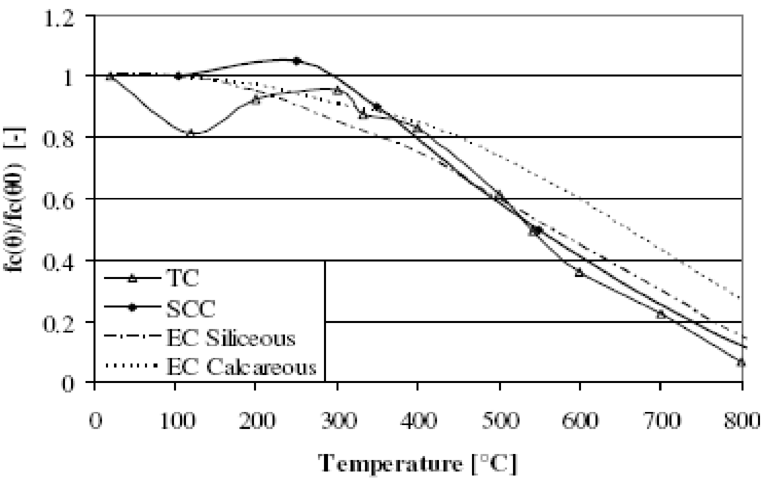

Fig. 1-The residual compressive strength.[6] Note: tC = (tF – 32)/1.8

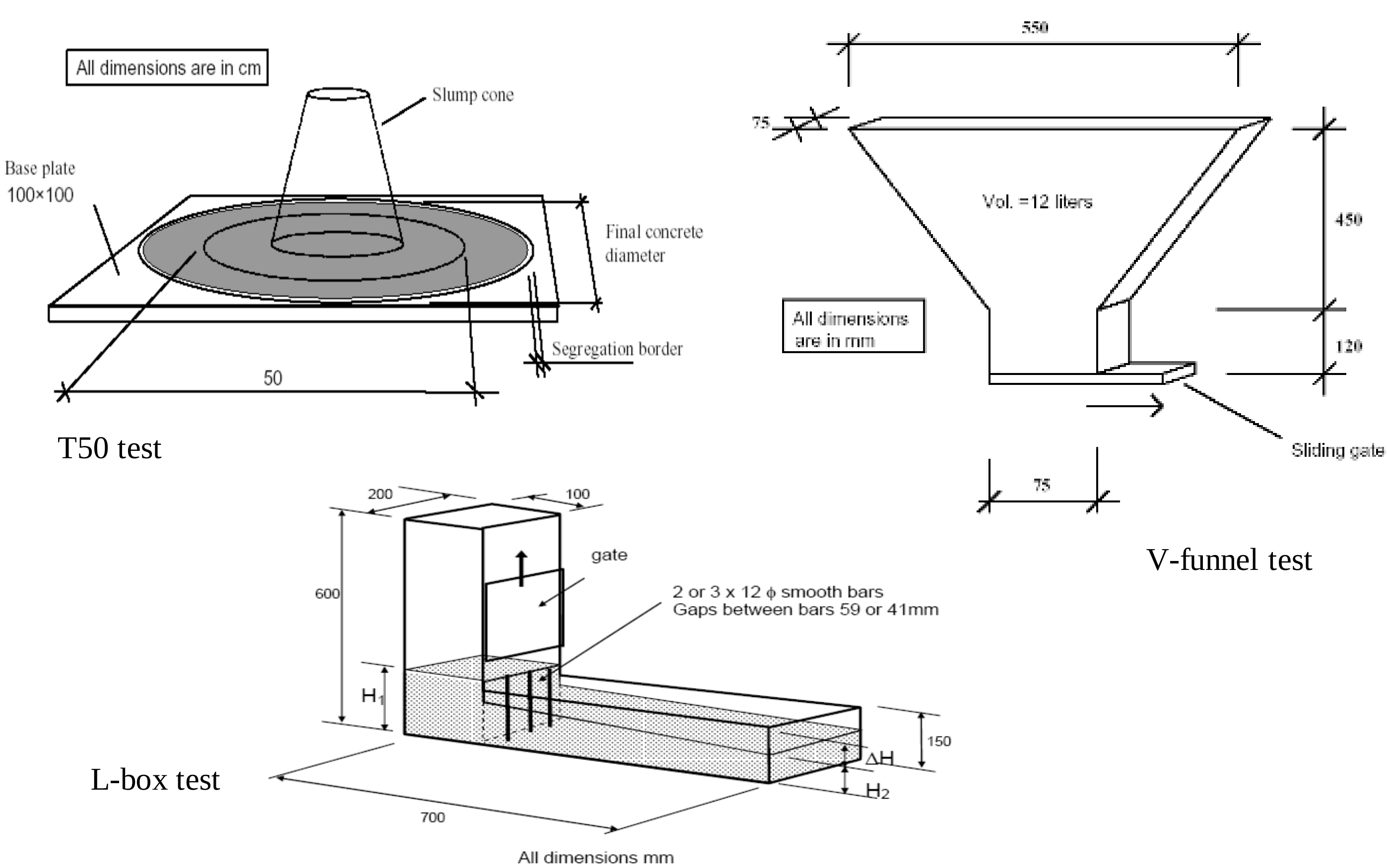

Fig. 2-Apparatus test. (Note: 1 mm = 0.0394 in.)

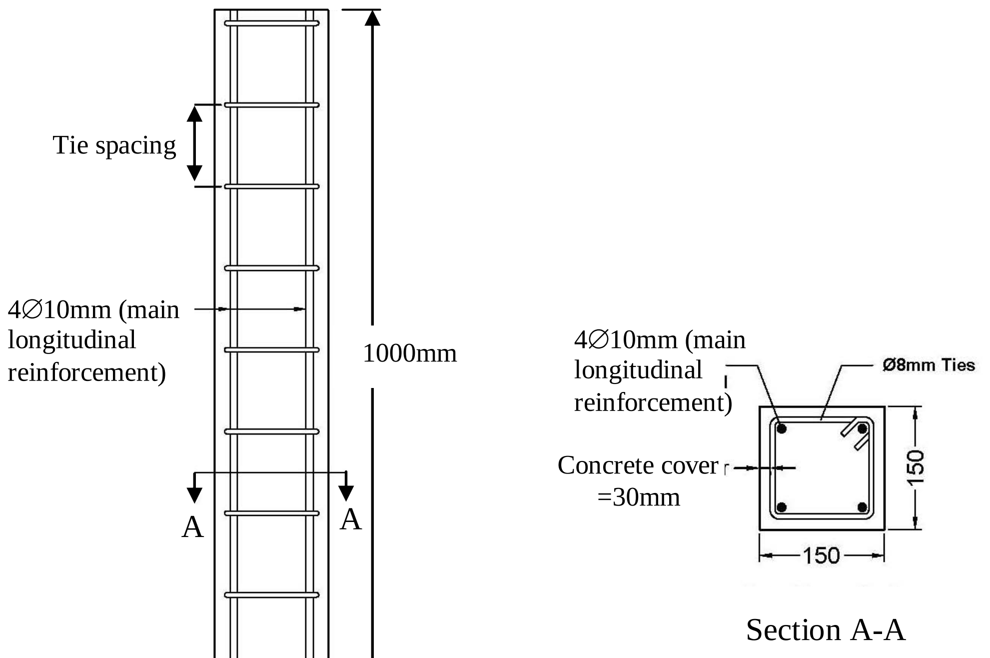

Fig. 3-Reinforcement details of reinforced SCC column specimens. (Note: 1 mm = 0.0394 in.)

Fig. 4-The network methane burners.

Fig. 5-Temperature measurement device.

Fig. 6-The testing measurement of axial deformation.

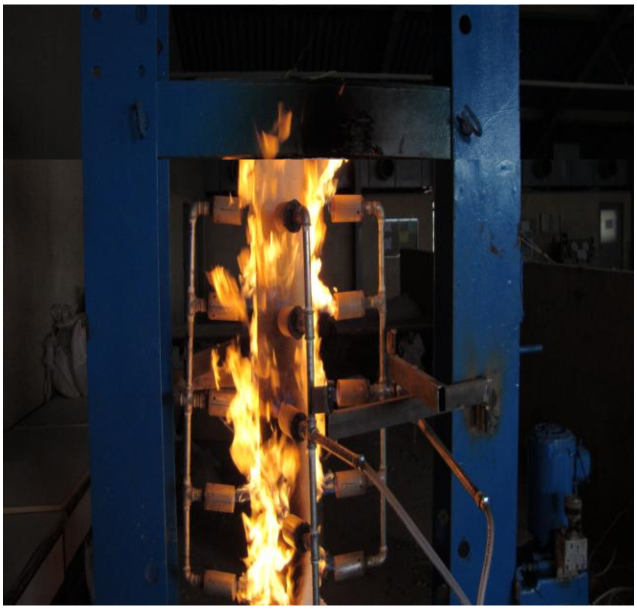

Fig. 7-Testing of SCC column specimens under 15% of ultimate load with exposure burning.

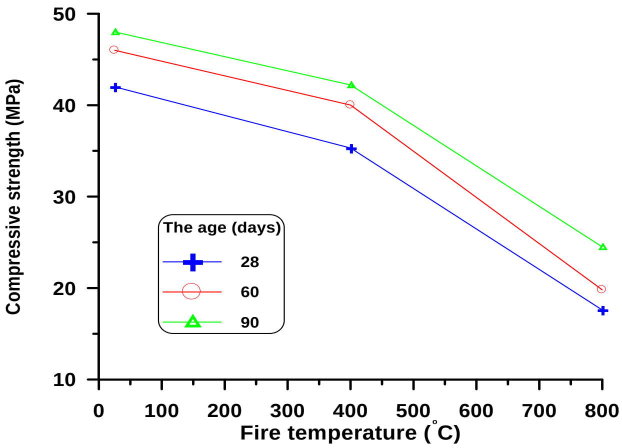

Fig. 8-Effect of fire temperature on the compressive strength.

Notes: tC = (tF – 32)/1.8, 1 MPa = 145 psi

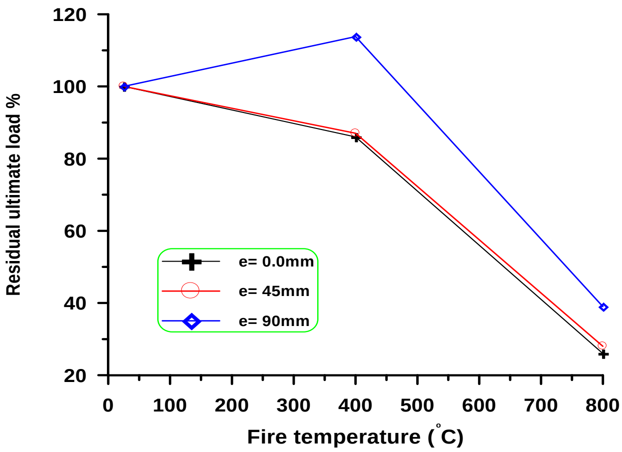

Fig. 9-Effect of fire temperature on the ultimate load of column specimens.

Notes: tC = (tF – 32)/1.8

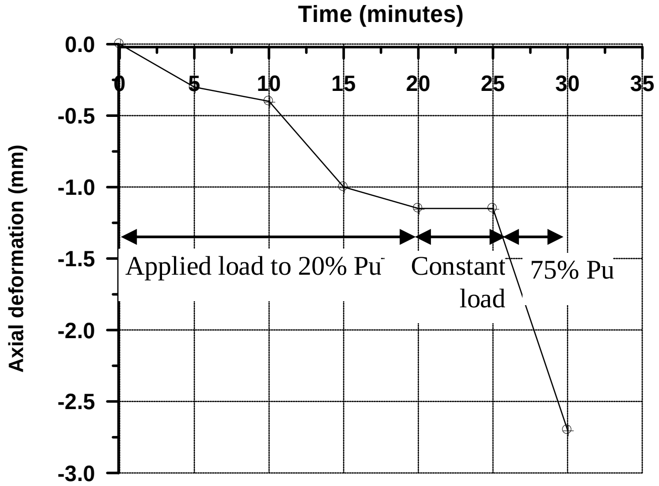

Fig. 10-Axial deformation versus time curve at centerline of column specimen before burning.

Note : 1 mm = 0.0394 in.

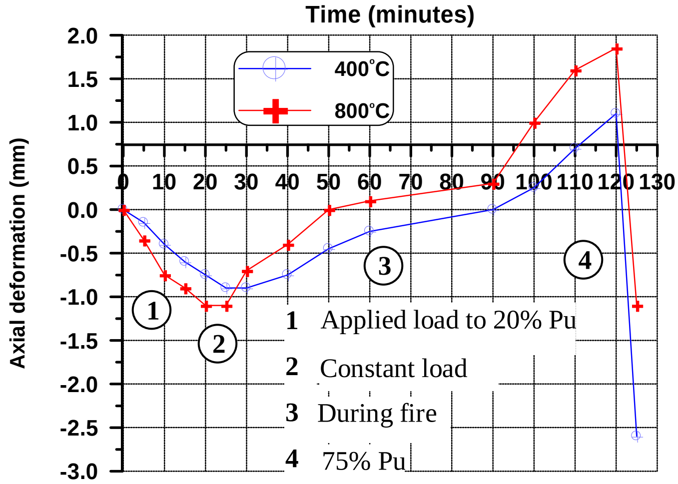

Fig. 11-Axial deformation versus time curve at 2.0 in. (50.8 mm) from the centerline of column specimen before, during and after burning.

Note : 1 mm = 0.0394 in.

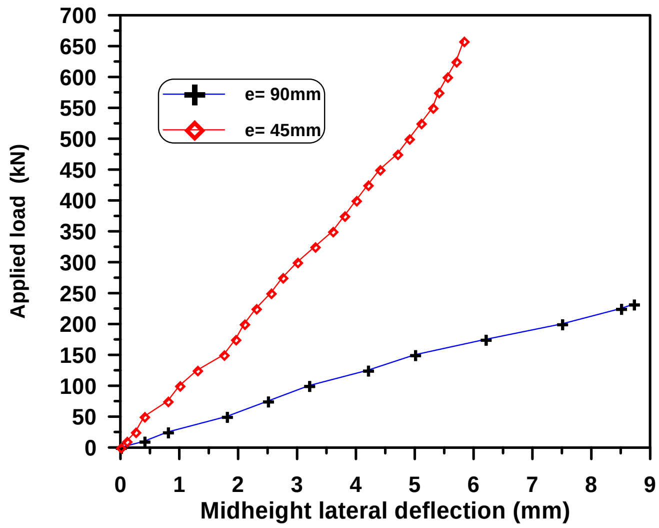

Fig. 12-Load versus midheight lateral deflection curve of SCC columns before burning.

Notes : 1 mm = 0.0394 in., 1kN = 224.8 lbf

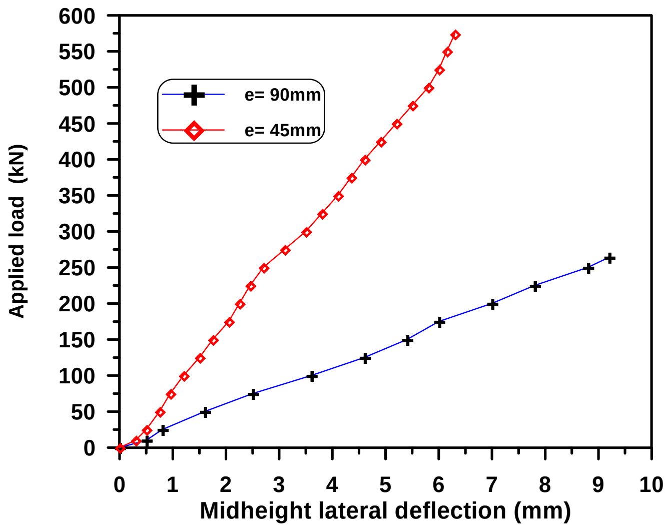

Fig. 13-Load versus midheight lateral deflection curve of SCC columns at exposure temperature 752°F (400°C).

Notes : 1 mm = 0.0394 in., 1kN = 224.8 lbf

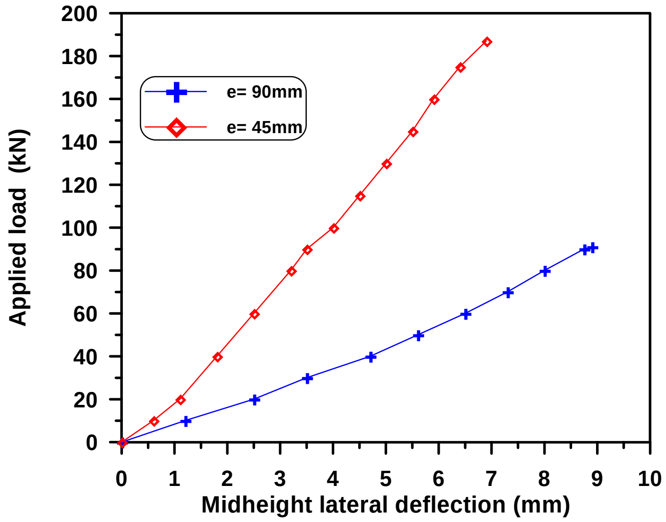

Fig. 14-Load versus midheight lateral deflection curve of SCC columns at exposure temperature 1472°F (800°C). Notes : 1 mm = 0.0394 in., 1kN = 224.8 lbf

Fig. 15-Formation of longitudinal cracks due to exposure to fire 752°F (400°C) and concentric loading. Note: tC = (tF – 32)/1.8

Fig. 16-Formation of transverse cracks due to exposure to fire 1472°F (800°C) and eccentric loading. Note: tC = (tF – 32)/1.8

Fig. 17-Formation of triangular-shaped cracks due to exposure to fire 1472ºF (800°C) and eccentric loading prior to failure. Note: tC = (tF – 32)/1.8

Fig. 18-Runoff water from SCC column specimen.

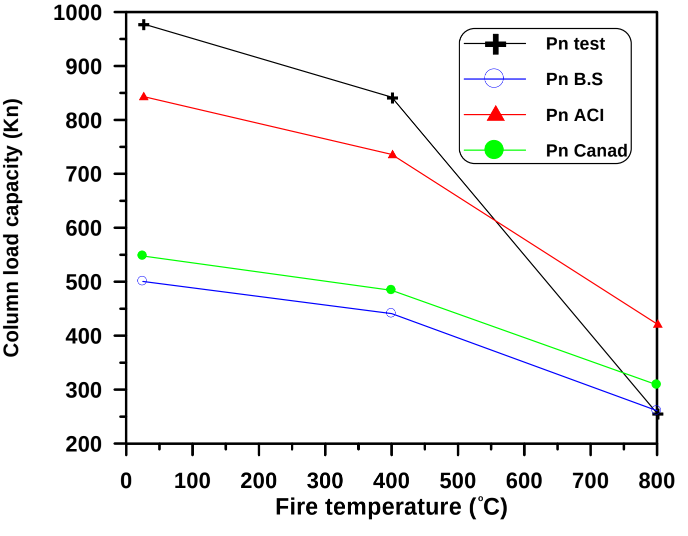

Fig. 19-Effect of fire temperature on the axial load capacity of SC column specimens.

Notes : tC = (tF – 32)/1.8, 1kN = 224.8 lbf