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EFFECT OF FIRE EXPOSURE ON AXIALLY AND BIAXIALLY LOADED REINFORCED CONCRETE COLUMNS

A. A. Shaheen, H. A. Dahish , A.S.Farid and M. A. Abdul-Hady
Fayoum University, Faculty of Engineering, Civil Department, Egypt.

ABSTRACT
This paper presents the analytical investigation on the residual load capacity of reinforced concrete columns subjected to elevated temperature under axial and biaxial loads. The aims of the analytical program are verifying of the proposed numerical model and presenting a parametric study by using FEA program ANSYS V.13 for studying the effects of the concrete characteristic strength, rectangularity ratio, eccentricity ratio, and fire duration. Twenty-seven full-size columns models, which using ANSYS elements (Solid65, Solid70, Link8, and Link33), were constructed and subjected to axial and biaxial loads after fire exposure according to the ISO 834 standard fire curve. The firing time exposure are at room temperature, 1.5 hours and 3 hours. A comparison between the numerical predictions and the test results shows good agreements. The numerical results indicated that, the residual load capacity is directly proportional to the concrete characteristic strength. The column residual load capacity increased by increasing the concrete characteristic strength. The column residual load capacity decreased by increasing the rectangularity ratio and increasing firing duration.

Keywords: Reinforced Concrete, Columns, Elevated Temperature, Axial Load, Biaxial Bending, FEA, ANSYS

1. INTRODUCTION

Concrete structures generally behave well in fires. Most of the fire damaged of RC buildings can be repair and reused even after severe fires. When concrete exposed to heat, chemical and physical responses occur at elevated temperatures, such as loss of moisture, dehydration of cement paste and decomposition of aggregate. These changes will bring a breakdown in the structure of concrete, affecting its mechanical properties. Therefore, RC members without visible damage may have reduced strength and stiffness due to elevated temperatures. To repair the fire damaged RC members, it is essential to have a practical analytical approach to evaluate the residual strength and stiffness of RC members after fire events.

Many investigators had studied the R.C. columns under elevated temperature. **Mohammed Kadhum (2013) [1]** studied experimentally the effect of burning by fire flame on the behavior and load carrying capacity of reinforced concrete columns. **Nikhil Raut (2011) [2]** presented fire resistance experiments on RC columns, with and without fibers, under standard and design fire scenarios to evaluate the behavior under different parameters and develop a comprehensive macroscopic finite element based model for predicting the response of RC columns under realistic fire, loading and failure conditions. **Farid, A.S., (2011) [3]** studied experimentally and numerically using FEA program ANSYS the effect of fire exposure on the behaviour of reinforced concrete columns under axial and eccentric loads. **M. Mohamed Bikhiet (2004) [4]** presented an experimental work to study columns exposed to fire under axial load and to evaluate reduction in column compressive capacity after fire. **W. Mohamed (2004) [5]** studied experimentally the behaviour of biaxially and uniaxially loaded HSC square short columns strengthened with externally applied FRP laminates. **M.T.El-Mihilmy (1992) [6]** studied experimentally the behaviour and design of R.C.short columns Under biaxial bending. **Lin, C.H and Chen, S.T of NTUST (1990, 1988) [8, 9]** conducted a series of experimental studies in this area, such as the residual strength and stiffness of fire damaged columns under uniaxial and biaxial loading. **Lie, T.T.(1983)[10]** established the thermal conductivity model and experimentally studied the effect of axial loading, size of cross section, moisture content, and the types of aggregate on the residual strength of concrete columns. He also used the ultrasonic method and numerical calculations to determine the residual strength of the RC columns

2. VERIFICATION OF EXPERIMENTAL RESULTS BY USING THE FINITE ELEMENT MODEL (ANSYS)

The main objective of the verification is to verify the proposed numerical model.
A comparison of the results from the ANSYS finite element analysis with the experimental data for the reinforced concrete columns tested by Mohammed M.Kadhum (2013) **[1]**, Nikhil Raut (2011) **[2]**, Farid, A.S., (2011) **[3]**, M. Mohamed Bikhiet (2004) **[4]**, W.Mohamed (2004) **[5]**, and M.T.El-Mihilmy (1992) **[6]** is carried out. The dimensions and details of reinforcement for all specimens, load eccentricities and the material properties are shown in **table (1**).

Table (1): Description of finite element column model

Group No.	Reference Name	Col. No	Col. Dim mm	H mm	F_{cu} N/mm^2	R.F.T	Stirrups mm	e_x mm	e_y mm	Fire Time (min)
Group A Axial Loading	Bikhiet (2004)	AN1	150*150	1000	30	4Φ10	Φ6@100mm	0	0	___
		AE1	150*150	1000	30	4Φ10	Φ6@100mm	0	0	10
		AE2	150*150	1000	30	4Φ10	Φ10@100mm	0	0	20
	Nikhil Raut (2011)	AE3	305*305	3800	34.8	4Φ25	Φ10@100mm	0	0	218
		AE4	406*406	3800	75	8Φ25	Φ6@100mm	0	0	299
Group U Uniaxial Loading	Farid, A. S., (2011)	UN1	200*200	1000	25	6Φ12	Φ3@100mm	40	0	___
		UE1	200*200	1000	25	6Φ12	Φ3@100mm	40	0	25
		UE2	200*200	1000	25	6Φ12	Φ3@100mm	40	0	40
Group B Biaxial Loading	El-Mihilmy (1992)	BN1	250*250	1800	35.4	4Φ13	Φ8@175mm	125	125	___
		BN2	250*250	1800	35.5	8Φ13	Φ8@175mm	125	125	___
	Weal (2004)	BN3	200*200	1850	30	4Φ16	Φ8@190mm	25	25	___
	Kadhum (2013)	BE1	150*150	1500	30	4Φ10	Φ8@150mm	30	30	90
		BE2	150*150	1500	40	4Φ10	Φ8@150mm	30	30	90
	Nikhil Raut (2011)	BE3	305*305	3800	35.7	4Φ25	Φ10@100mm	24	24	181
		BE4	406*406	3800	127	8Φ25	Φ6@100mm	25	25	118

Note: A = Axial Load, U = Uniaxial Load, B = Biaxial Load, E = Exposed to Fire, N = Not Exposed to Fire.

2.1 Finite Element Model by ANSYS

2.1.1 Concrete Element

In this research, two solid elements are used to define the concrete in ANSYS code **[11]**. The concrete was modeled by solid65 and the element of solid65 was converted to solid70 to present the thermal element.

2.1.1.1 Solid65 Input Data

1-Temperature degree
2- Elastic modulus.
3- Ultimate uniaxial compressive strength
4- Ultimate uniaxial tensile strength
5- Poisson's ratio (U) for concrete
6- Shear transfer coefficient (βo) for open cracks and (βc) for closed cracks,

2.1.1.2 Solid70 Input Data

1- Thermal capacity
2- Thermal conductivity
3- Thermal diffusivity
4- Thermal expansion

2.1.2 Steel Element

2.1.2.1 Reinforcing Steel Bars

LINK8 is a spar that can be used in a variety of engineering applications. This element can be used to model trusses, sagging cables, links, springs, etc. This 3-D spar element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions.
The steel for the finite element models was assumed to be an elastic perfectly plastic material, and the strength was defined according to the data in the test.

2.2 Results and Discussions

Table (2) shows two results of the crushing load failure before exposed to elevated temperature and residual load capacity for firing columns model from experimental data obtained from literature.
Figure (1) shows the comparison between numerical and experimental results.
The present model successfully estimated the failure load of the columns. By analyzing, we found that the max % difference ratio from the comparative study between experimental test results and numerical results is 5.70%, which show good agreement with test results.
Therefore, the proposed model could be used for modeling as built columns in order to propose a suitable design.

Table (2): Comparison between experimental and numerical analysis

Column No.	Maximum Load (kN)		%Difference Ratio
	Test value	ANSYS value	
AN1	705	703	0.28%
AE1	600	626	-4.33%
AE2	530	550	-3.77%
AE3	800	834	-4.25%
AE4	3895	4034	-3.69%
UN1	545	557	-2.20%
UE1	450	444	1.33%
UE2	395	390	1.27%
BN1	350	365	-4.29%
BN2	425	421	1.03%
BN3	655	633	3.43%
BE1	241	249	-3.32%
BE2	261	259	0.77%
BE3	1000	1057	-5.70%
BE4	4981	5113	-2.65%

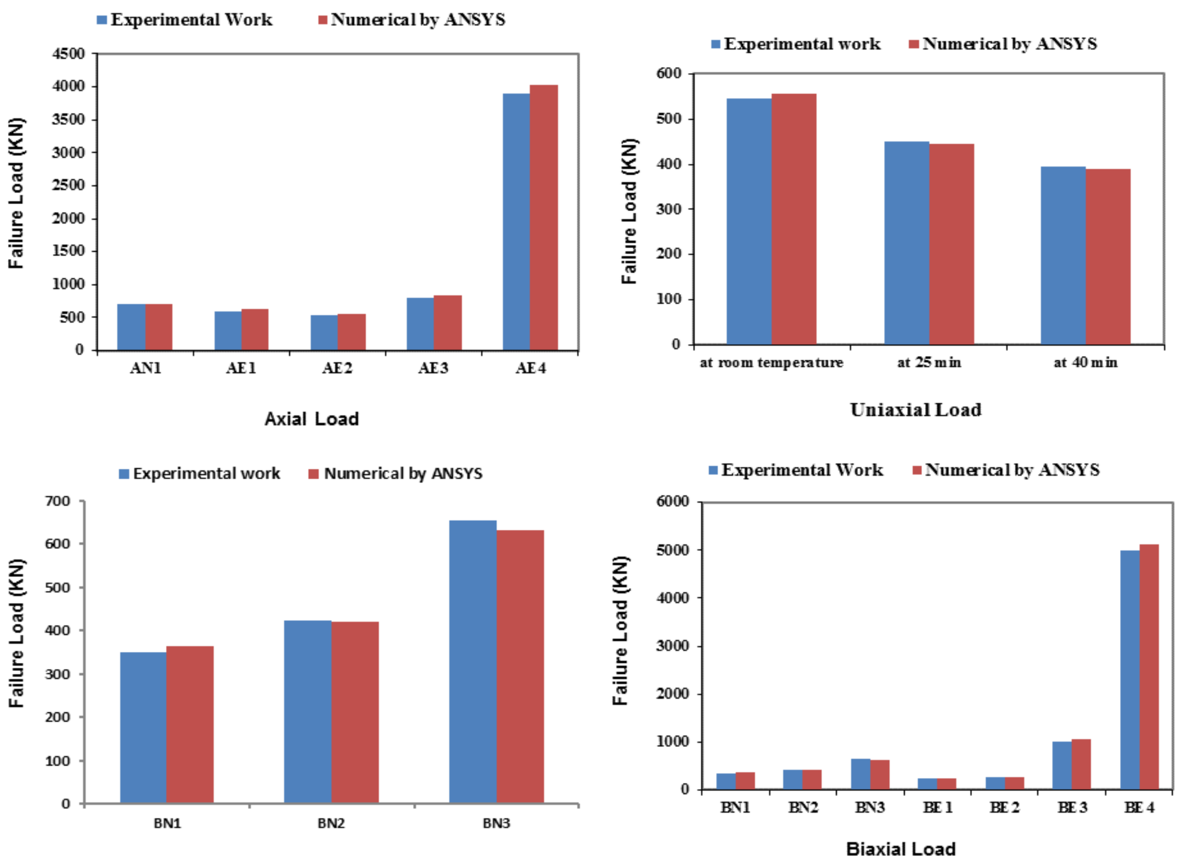


Figure (1): Comparisons between experimental work and ANSYS model results

3. Finite Element Analysis Program

3.1 Input Data finite element model by ANSYS

3.1.1 Solid65

1-Temperature degree (T=650^{o}C)
2- Elastic modulus (E_c = 4700√fc') MPa.
3- Ultimate uniaxial compressive strength
(fc' =25, 35, and 45) N/mm^2.
4- Ultimate uniaxial tensile strength (ft =0.1 fc').
5- Poisson's ratio (Ʋ) for concrete Ʋ =0.2.
6- Shear transfer coefficient (βo) for open cracks and (βc) for closed cracks, representing conditions of crack face for determining the amount of shear transfer across the crack were used. In present study, (βo) was assumed to be (0.2) while (βc) was (0.4).

3.1.2 Solid70

1- Thermal capacity (C= 860.3) J/Kg ^{o}K
2- Thermal conductivity (K= 1.873) W/m ^{o}K
3- Thermal diffusivity (D= 0.00356) m^2/hr
4- Thermal expansion (6.31x10^{-6})

3.1.3 Steel Element (LINK8)

The steel for the finite element models was assumed to be an elastic perfectly plastic material, and the strength was defined according to the data in the test. The used steel grade is 36/52. Material properties for the steel reinforcement for all models are as follows; Elastic modulus (Es = 200000 N/mm^2), Yield stress (Fy = 360 N/mm^2) and Poisson's ratio (Ʋ) for steel Ʋ =0.3

3.2 Parameters of the Numerical Analysis

A parametric study of twenty-seven columns of 3000mm long was conducted to investigate the effect of the following variables; concrete characteristic strength (F_{cu} = 25, 35, and 45 N/mm^2), the cross section 400mmx400mm, eccentricity ratio (e/t = 0%, 25%, and 40%) and fire duration (At room temperature, and exposure duration of 1.5, and 3hr to temperature at 650^{o}C). The details of each column were listed in **Table 3**. **Figure (2)** show the Column Cross Section, Reinforcement Details and Finite Element Mesh and Steel Mesh for Column Model. Column load and column residual load after exposed to elevated temperature were obtained at each load step; first crack loads, deformed shape and failure mode are obtained for each column at failure load.

Table (3): Description of finite element column model

Group No.	Col. No	R.F.T	Stirrups mm.	e/t%	Fire Time (hr)
Group (A) Fcu=25 N/mm^2	A1a1	8Φ16	Φ8@100mm	0	0
	A1a2	8Φ16	Φ8@100mm	0	1.5
	A1a3	8Φ16	Φ8@100mm	0	3
	A1b11	8Φ16	Φ8@100mm	25	0
	A1b12	8Φ16	Φ8@100mm	25	1.5
	A1b13	8Φ16	Φ8@100mm	25	3
	A1b21	8Φ16	Φ8@100mm	40	0
	A1b22	8Φ16	Φ8@100mm	40	1.5
	A1b23	8Φ16	Φ8@100mm	40	3
Group(B) Fcu= 35 N/mm^2	B1a1	8Φ16	Φ8@100mm	0	0
	B1a2	8Φ16	Φ8@100mm	0	1.5
	B1a3	8Φ16	Φ8@100mm	0	3
	B1b11	8Φ16	Φ8@100mm	25	0
	B1b12	8Φ16	Φ8@100mm	25	1.5
	B1b13	8Φ16	Φ8@100mm	25	3
	B1b21	8Φ16	Φ8@100mm	40	0
	B1b22	8Φ16	Φ8@100mm	40	1.5
	B1b23	8Φ16	Φ8@100mm	40	3
Group(C) Fcu= 45 N/mm^2	C1a1	8Φ16	Φ8@100mm	0	0
	C1a2	8Φ16	Φ8@100mm	0	1.5
	C1a3	8Φ16	Φ8@100mm	0	3
	C1b11	8Φ16	Φ8@100mm	25	0
	C1b12	8Φ16	Φ8@100mm	25	1.5
	C1b13	8Φ16	Φ8@100mm	25	3
	C1b21	8Φ16	Φ8@100mm	40	0
	C1b22	8Φ16	Φ8@100mm	40	1.5
	C1b23	8Φ16	Φ8@100mm	40	3

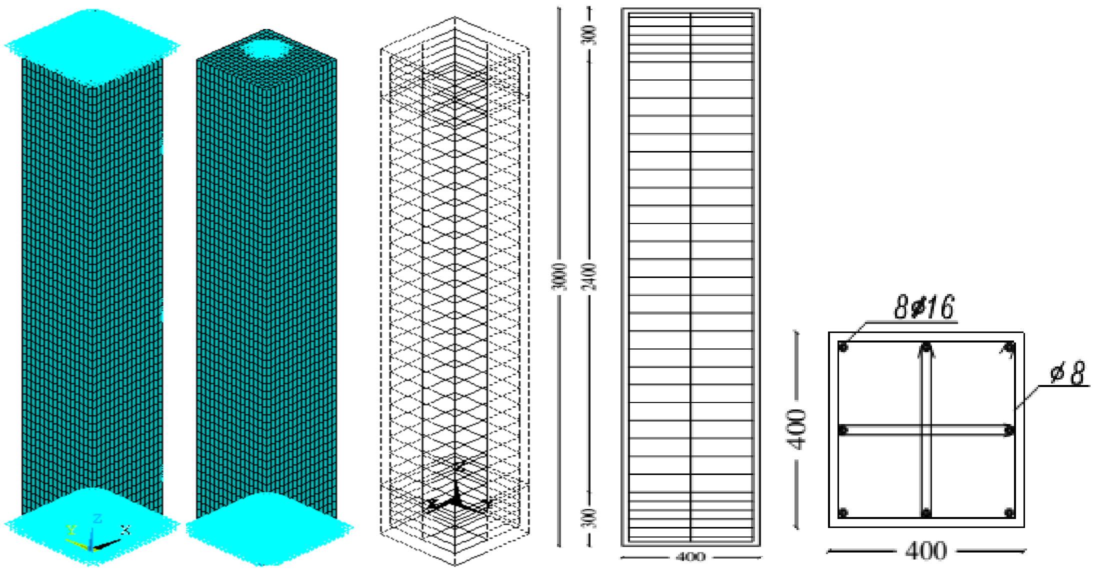


Figure (2): Column cross section, reinforcement details, finite element mesh and steel mesh for column model (400mmx400mm)

3.3 Temperature Effect and Equivalent Model Exposure Time

Figure (3) shows the **ISO-834 standard time-temperature curve [7]** used in the current study. The time-temperature relationship on the boundary member is defined in **equation (1)**.

$$T_b = 345 \mathrm{x} \log_{10}(8t + 1) + T_0 \qquad \textbf{(1)}$$

Where

t is time [min].

T_0 is ambient temperature [°C].

T_b is boundary temperature [°C].

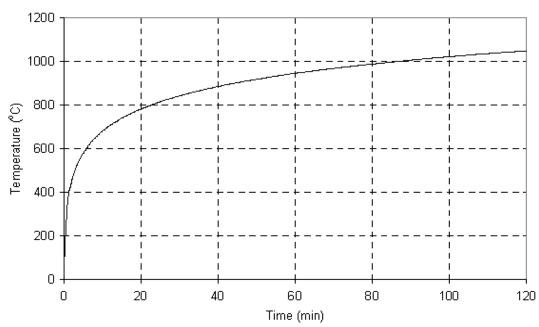


Figure (3): Standard ISO 384 firing curve

4. RESULTS AND ANALYSIS

4.1 Results

All of tested models were classified into three cases of a firing exposure, the reference column was A1a1 at room temperature condition while second and third case are at temperature 650°C after firing time of 1.5 hr, and 3 hr as mentioned before. The results of each column were listed in **Table 4**.

Table 5 show the Percentage of the residual load capacity for columns with different concrete characteristic strengths at different firing times under axial and biaxial loads

Figure (4) shows the effect of different concrete characteristic strength on columns residual load capacity at different firing cases.

Figure (5) shows first crack and deformed shape for sample of column models before and after exposure to fire.

Figure (6) shows the temperature distribution fire of column cross sections.

Table (4): Results of all columns

Group No.	Col.No.	Correct Load KN	Ansys %Residual Load	e/t %
Group(A) Fcu=25 N/mm^2	**A1a1**	4204	100	0
	A1a2	2825	67.20	0
	A1a3	2233	53.12	0
	A1b11	1368	32.54	25
	A1b12	835	19.86	25
	A1b13	642	15.27	25
	A1b21	855	20.34	40
	A1b22	468	11.13	40
	A1b23	351	8.35	40
Group(B) Fcu= 35 N/mm^2	**B1a1**	4851	115	0
	B1a2	3469	82.52	0
	B1a3	2732	64.99	0
	B1b11	1803	42.89	25
	B1b12	1155	27.47	25
	B1b13	887	21.10	25
	B1b21	1161	27.62	40
	B1b22	667	15.87	40
	B1b23	515	12.25	40
Group(C) Fcu= 45 N/mm^2	**C1a1**	6658	158	0
	C1a2	5113	122	0
	C1a3	4023	95.69	0
	C1b11	2406	57.23	25
	C1b12	1656	39.39	25
	C1b13	1308	31.11	25
	C1b21	1580	37.58	40
	C1b22	988	23.50	40
	C1b23	827	19.67	40

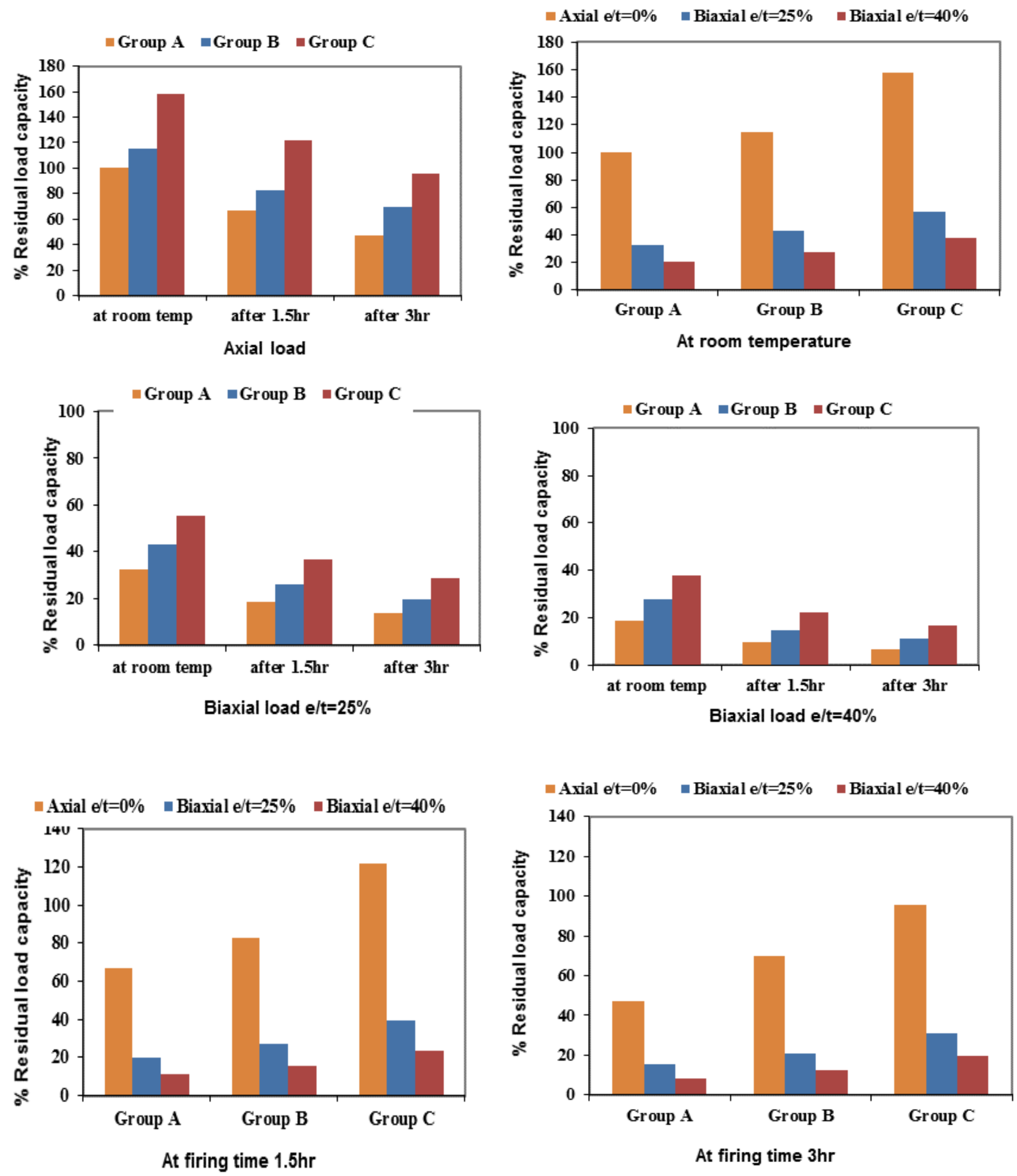
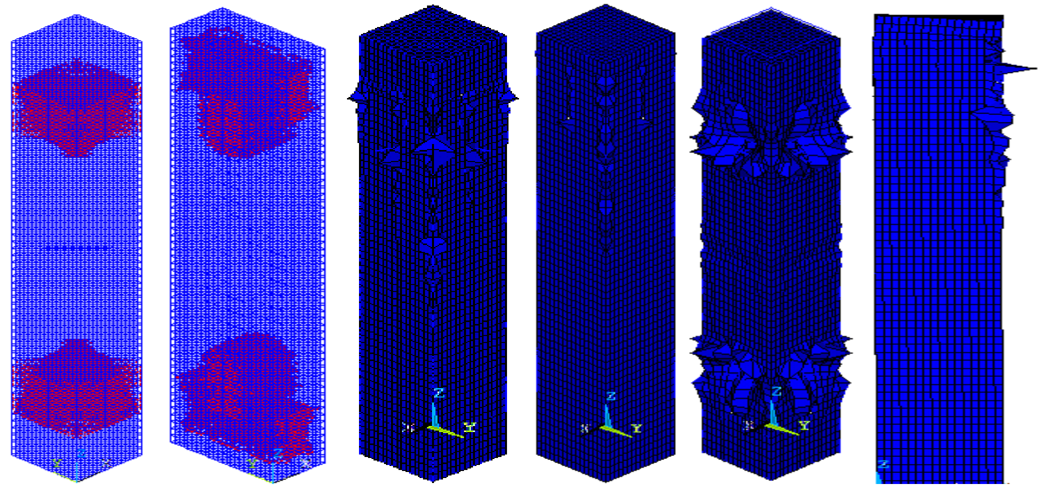
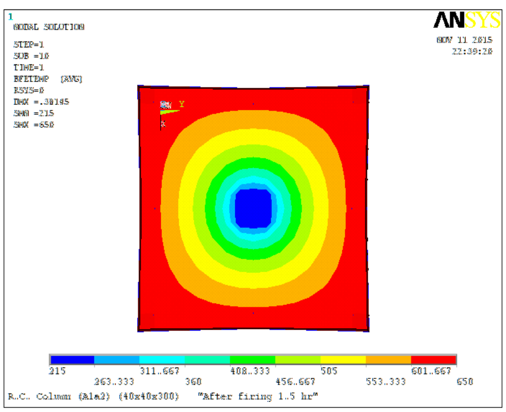


Figure (4): The effect of different concrete characteristic strength on residual load capacity of all columns groups at different firing cases

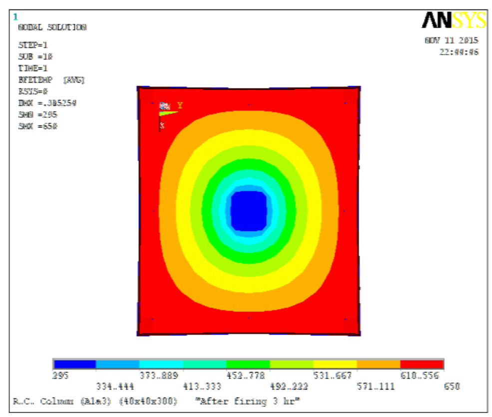


A1a1 A2a1 A1b12 B1b12 A1a3 C1b23

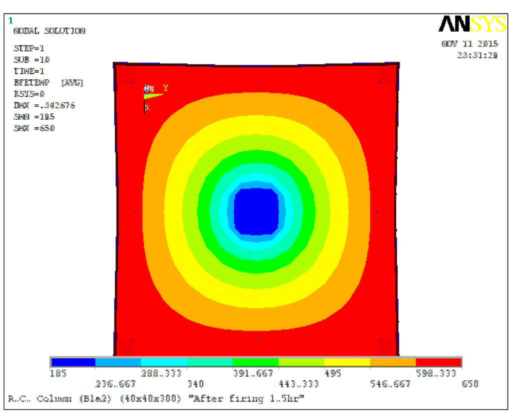
Figure (5): Sample for first crack and deformed shape for model column before and after exposure to fire



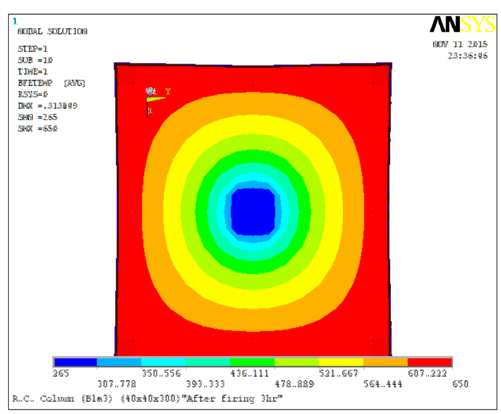
A1 at 1.5hr



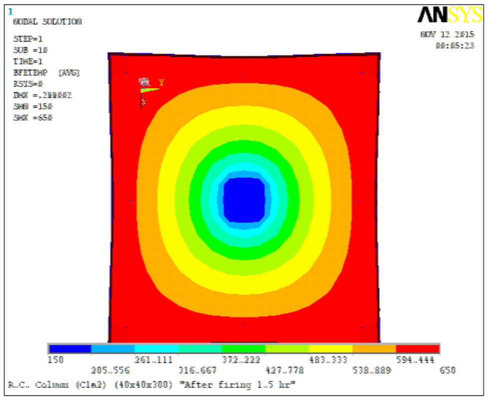
A1 at 3hr



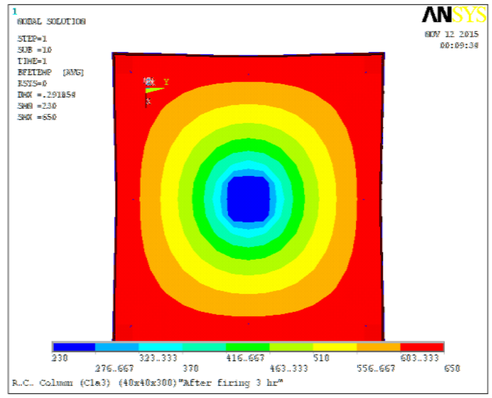
B1 at 1.5hr



B1 at 3hr



C1 at 1.5hr



C1 at 3hr

Figure (6): Temperature distribution for column (400x400mm) in all groups

Table (5): Percentage of the residual load capacity for columns with different concrete characteristic strengths at different firing times under axial and biaxial loads

Loading Type	Group A (F_{cu}=25 N/mm^2)			Group B (F_{cu}=35 N/mm^2)			Group C (F_{cu}=45 N/mm^2)		
	At room temperature	At 1.5hr	At 3hr	At room temperature	At 1.5hr	At 3hr	At room temperature	At 1.5hr	At 3hr
Axial Load	100 % reference column	67.20 %	46.88 %	115 %	82.52 %	69.99 %	158 %	122 %	95.69 %
Biaxial Load e/t=25%	32.54 %	19.86 %	15.27 %	42.89 %	27.47 %	21.10 %	57.23 %	39.39 %	31.11 %
Biaxial Load e/t=40%	20.34 %	11.13 %	8.35 %	27.62 %	15.87 %	12.25 %	37.58 %	23.50 %	19.67 %

- In case of columns **at room temperature condition** under axial load; the increasing of F_{cu} = 25N/mm^2 with percentage of 40% to be F_{cu}=35N/mm^2, consequently the residual load capacity is increased with percentage of 15%. The increasing of F_{cu} = 25N/mm^2 with percentage of 80% to be F_{cu} = 45 N/mm^2, consequently the residual load capacity is increased with percentage of 58%.
- The residual load capacity of biaxially loaded column C2b23 (e/t=40%) with F_{cu}=45N/mm^2 **at firing time 3hr** which equal (19.67%) is nearly equal the residual load capacity of biaxially loaded column A1b12 (e/t=25%) with F_{cu}=25N/mm^2 **at firing time 1.5hr** which equal (19.86%).
- The residual load capacity of biaxially loaded column C1b12 (e/t=25%) with F_{cu}=45N/mm^2 **at firing time 3hr** which equal (31.11%) is **nearly** equal the residual load capacity of biaxially loaded column A1b11 (e/t=25%) with F_{cu}=25N/mm^2 **at room temperature** which equal (32.54%).
- The residual load capacity of biaxially loaded column C1b11 (e/t=25%) with F_{cu}=45N/mm^2 **at room temperature** which equal (57.23%) is nearly equal the residual load capacity of axially loaded column A1a3 with F_{cu}=25N/mm^2 **at firing time 3hr** which equal (53.12%).
- The residual load capacity of axially loaded column B1a3 with F_{cu}=35N/mm^2 **at firing time 3hr** which equal (64.99%) is twice the residual load capacity of biaxially loaded column A1b11 (e/t=25%) with F_{cu}=25N/mm^2 **at room temperature** which equal (32.54%).
- The residual load capacity of biaxially loaded column C1b33 (e/t=40%) with F_{cu}=45N/mm^2 **at firing time 1.5hr** which equal (23.50%) is nearly equal the residual load capacity of biaxially loaded column (e/t=40%) with F_{cu}=25N/mm^2 **at firing time 1.5hr** which equal (11.13%).
- The residual load capacity of biaxially loaded column B1b22 (e/t=40%) with F_{cu}=35N/mm^2 **at firing time 1.5hr** which equal (15.87%) is nearly equal the residual load capacity of biaxially loaded column A1b13 (e/t=25%) with F_{cu}=25N/mm^2 **at firing time 3hr** which equal (15.27%).

• The residual load capacity of biaxially loaded column B1b22 (e/t=40%) with F_{cu}=35N/mm^2 **at firing time 1.5hr** which equal (15.87%) is nearly twice the residual load capacity of biaxially loaded column A1a23 (e/t=40%) with F_{cu}=25N/mm^2 **at firing time 3hr** which equal (8.35%).
• The residual load capacity of biaxially loaded column B1b13 (e/t=25%) with F_{cu}=35N/mm^2 **at firing time 3hr** which equal (21.10%) is nearly equal the residual load capacity of biaxially loaded column A1b12 (e/t=25%) with F_{cu}=25N/mm^2 **at firing time 1.5hr** which equal (19.86%).

5. SUMMARY AND CONCLUSIONS

Results are presented, discussed and based on the analytical investigation; the following conclusions can be drawn:

1- Numerical analysis was found to be an effective method for analyzing the behaviour of fire exposed reinforced concrete columns under axial and biaxial loads.

2- For a high concrete characteristic strength, the column residual load capacity is increased as concrete characteristic strength increases.

3- Variation of the load capacity was low although the amount of F_{cu} increased from F_{cu} =25 N/mm^2 to be F_{cu} =35 N/mm^2, but the load capacity improved to 58% by increasing F_{cu} to be 45 N/mm^2, so that, the great variation was recorded when F_{cu} increased from 25 N/mm^2 to 45N/mm^2.

4- The residual load capacity is directly proportional to the concrete characteristic strength.

5- The residual load capacity of biaxially loaded column (e/t=25%) with F_{cu}=45N/mm^2 at firing time 3hr is nearly equal the residual load capacity of biaxially loaded column (e/t=25%) with F_{cu}=25N/mm^2 at room temperature.

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