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Structural Behavior of Eccentrically Loaded R.C. Columns under Fire Temperature Loading

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Abstract: The main goal of this research paper is to investigate the response of the RC rectangular columns under loading simultaneously exposed to fire by using experimental study. The number of test columns were seventeenth columns. The dimension for these columns was 1600mm for length and 150mmx150mm for the cross-section. The columns were tested under axial load with two different types of eccentricity 60 mm 100mm, while the third type of loading is tested as a beam. The eccentric compression load was applied by using top and bottom cap with a column bracket. The eccentric load was applied simultaneously with fire. The test was performed under a high temperature of (400°C, 600°C, and 900°C) on the side of a compression face. At each temperature burning, cooling by two techniques of cooling, and normal cooling (by open air) and fast cooling (by direct water). The experimental results show decreasing in ultimate load capacity with increasing of temperature burning, ultimate load, load-deflection curve, strain profile, neutral axis, moment-curvature, and ductility.

Keywords: fire, an eccentric load, load capacity, eccentricity, types of cooling, strain.

1. Introduction

Concrete column is considered to be an important structural element in reinforced concrete structure because it supports the structure and carry the loads to the foundation or supports, so each damage or failure occurs in the column might cause a partial or full failure of the structure by possibly chain action [1].

The modern buildings should be provided resistance to different types of loading especially when exposing to high temperature. Always, structural engineering does not take into account the effect of high-temperature loading in the design of the structural elements. The effect of fire on structural members depends on different factors such as the amount, kind and distribution of fire, loading, the duration of exposure to fire, the cooling method practice, ventilation, and compartment size. In order to keep the human life and avoid the serviceability damage and collapse in the structure, the hightemperature fire effects need to be considered in the strength of the various main elements, such as

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columns, beams, slabs, shear walls [2]. The effect of fire on structural members depends on different factors such as the amount, kind and distribution of fire, loading, the duration of exposure to fire, the cooling method practice, ventilation, and compartment size. The fire could bring a chemical reaction, essentially decomposition of $Ca(OH)_2$ will cause a decrease in concrete compressive strength, which follows the development of heat. Most huge fires start from small ones, and during their development, the rate at which heat is produced exceeds the rate at which it is dissipated. It is important the structure withstand for a given time under fire effect [3]. The primary on-site investigation technique is a visual inspection, which is used to classify the degree of damage for each structural concrete member. Visually apparent damage is induced by heating includes collapse, deflection, spalling, cracking, surface crazing, colour changes, and smoke damage. A visual survey of reinforced concrete structures is performed using a classification scheme from The Concrete Society, (1990) [4]. Concrete made with siliceous or limestone aggregate shows a change in color with temperature. As this change depends on the presence of certain compounds of iron, there is some difference in the response of different concretes, so that the maximum temperature the change in color is permanent. Hence, the maximum temperature during a fire can be estimated posterior. The color sequence is approximate as follows: pink or red between 300 and 600°C, then grey up to about 900°C, and buff above 900°C. Thus, the residual strength can be approximately judged: generally, concrete whose colour has changed beyond pink is suspect, and concrete past the grey stage is probably friable and porous [5]. The column is usually vertical member and used to support an axial load and it can also resist moment, her and torsion [6].

2. Research Significant

The main objective of this research paper is to investigate the structural response of the RC rectangular columns under load simultaneously exposed to fire by using experimental study. The current research proposes a prototype RC are subjected to during fire and eccentric loading. That it will give a good idea about the rehabilitation and repair of the damaged columns due to high-temperature fire.

3. Experimental investigation

The main idea of the present research paper is to conduct an experimental test of the RC columns under high temperature. Seventeen prototype RC column were loaded under uniaxial force and fire. The dimensions of the columns are given in Figure 1. These columns were cooled normal cooling by (open air) and quick cooling by (water). The experimental programme was divided into two groups depending on the eccentricity of the applied force Table 1.

3.1. Materials Used

The normal strength concrete (NSC) are used in this experimental programme. All use mix materials (cement, gravel, and send) are confirmed with the existing used standards [7] and [8]. The mix design is given in Table 2, it was prepared in order to prepare cylinder compressive strength of about 40MPa. The mix design workability was satisfied with the requirement of [9].the main steel reinforcement (Ø12 mm) and secondary steel reinforcement (Ø8 mm) are confirmed with conforming to ASTM A615 [10]. The minimum steel reinforcement ratio of 1% and minimum ties spacing of 150mm is confirmed with the requirement of ACI-318M-14 [8]. All column specimens were cured for 28 days by using moist canvas sheets, shows Figure 2. The mechanical properties test result of the concrete at the age of 60 days before and after fire exposure are given in Table (3).



Figure 1. The tested column Dimensions.

Group	Fire Temperature (°C)	Column ID	Main Reinforcement	Eccentricity Of Applied Load (mm)	Cooling Technique
		А	4Ø12	60	Without burring
А	400	A4	4Ø12	60	Without
		A4F	4Ø12	60	Quick
		A4N	4Ø12	60	Normal
	600	A6	4Ø12	60	Without
		A6F	4Ø12	60	Quick
		A6N	4Ø12	60	Normal
	900	A9	4Ø12	60	Without
		A9F	4Ø12	60	Quick
		A9N	4Ø12	60	Normal
В	400	В	4Ø12	100	Without
		B4F	4Ø12	100	Quick
		B4N	4Ø12	100	Normal
	600	B6F	4Ø12	100	Quick
		B6N	4Ø12	100	Normal
	900	B9F	4Ø12	100	Quick
		B9N	4Ø12	100	Normal

 Table 1. Summary of columns test specimens.

Table 2. Mix design for 1	m3 concrete.
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Constituent Type	Mix Proportion
Cement (kg/m3)	450
Sand (kg/m3)	750
Gravel (kg/m3)	1050
Water (kg/m3)	189
W/c ratio	0.42
Slump(mm)	60

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			1 1				0	5		
Fire	25		400			600			900	
Temperature (°C)		W.O.C	N.C	F.C	W.O.C	N.C	F.C	W.O.C	N.C	F.C
Compressive	40	30	38.7	38.3	32	37	36	19.52	34	30
Strength (MPa)										
Splitting tensile	3	2.55	2.6	2.58	1.89	2.33	2.1	1	1.84	1.34
strength (MPa)										
Modulus of	3.31	2.58	2.62	2.57	2.2	2.33	2.23	1.2	1.84	1.25
rupture (MPa)										
Modulus of	40.9	10.31	14.6	11.26	6.15	7.4	6.68	1.9	2.6	2.14
elasticity (GPa)										

Table 3. Mechanical properties for used concrete at the age of 60 days.



Figure 2. Casting and curing process of column specimens.

3.2. Fire test

The reinforced concrete columns were burned by testing directly subjecting a fire flame from a network of methane burners. The fire flame hits only one side of these columns. The burner network is consisting of a steel box with dimensions (800×150) mm (length \times width) and contain three methane burners. While the control specimens were burned directly by fire flame from a net of methane burners in the same manner as shown in Figure 3. The fire attacked the compression side of the test RC columns as shown in Figure 4. The rate of $2C^{\circ}$ was used to increase the temperature for fire loading in order to reach the target temperature [11]. The time duration for fire applied was 30 minutes, after that the fire flume is off and the column was left to cool down to the ambient temperature. The vertical force was applied with a rate of 1kN/s. Three dial gauge was fixed at tension face and used in order to measure the lateral deflection at two ends and mid-height of test column. The concrete strain and steel strain of the test column was measured at the tension face by using strain gauges.

3.3. Test setup and procedure

The testing machine with maximum range capacity of 3000 kN was used to apply the eccentric load on the columns (Figure 3). The age of RC tested column was 60 days. The lateral deflection was recorded at each 10kN until failure. The axial deformation of RC columns was recorded by using vertical dial gauges having a maximum needle length of 30 mm mounted at the bottom face of the columns. The cracks formation were recorded and marked at column faces. The target temperature fire flame at tension face of columns was recorded by using a digital thermometer and infrared rays

thermometer. The vertical load was kept equal to 65% of the ultimate load before burning and applied fire flame. The loading was continued after burning until failure.



Figure 3. The burner network with a steel box.



Figure 4. The furnace and other equipment.

4. Results and discussion

The following mean results are discussed for this research paper;

4.1 Effect of Burning on Load versus Deflection Results

The load-mid-height lateral deflection curve of the tested columns with the flame temperatures of 400°C, 600°C, and 900°C at the eccentricity of (60 and 100mm) are shown Figure 5, 6, 7 and 8. These columns were subjected to the vertical loads simultaneously with the fire flame. The vertically applied load was

reached to 65% of the ultimate load before starting of burning. The normal cooling and fast cooling were used for burning tested columns. The load was continuously applied until failure. The significant effect was observed in the mid-height lateral deflection of columns of series A (e=60mm) and B (e=100mm) due to fire temperature. The load carrying capacity was decreased and lateral deflection was increased due to fire temperature. This can be attributed to the fact that heating causes a reduction in column stiffness, which is essentially due to the reduction in the modulus of elasticity of concrete and the reduction in the effective section due to cracking, which means that load-deflection curves for high temperatures compared with low temperatures. The load-deflection relation of the column specimens is almost linearly proportional for the two eccentricities (60 and 100mm) and for temperature exposure (400°C, 600°C and 900°). The maximum deflection occurred at mid-height and decreased towards the support of the column specimens.



Figure 5. Load versus mid-height displacement curve of column specimen at eccentricity (e=60mm), (a-fast cooling and b-normal cooling).



Figure 6. Load versus mid-height displacement curve of column specimen at eccentricity (e=100mm), (a-fast cooling and b-normal cooling).



Figure 7. Load versus mid-height displacement curve of column specimen A with 60mm eccentricity (a- 400°C, b-600°C and c-900°C).



Figure 8. Load versus mid-height displacement curve of column specimen B with 100mm eccentricity (a- 400°C, b-600°C and c-900°C).

4.2. Strain Profiles

The variation of concrete strain along the depth for tested columns during different stages of loading at the constant moment region is shown in Figures (9 through 12). The strains at mid-height section of the columns in compression zone for concrete and tension zone for steel reinforcement are measured using the data logger. At the early stages of the testing process, when the column is free from cracks, the concrete resists the tensile stresses. However, by increasing the applied load, cracks appear and the concrete layer at the mid-height of the columns becomes out of concrete tensile stresses resistance and the reinforcing steel begins to resist these stresses alone. At the last stage of the test when the crack height propagates and becomes wider, the yield in the reinforcing steel becomes more eventual in the tension zone of the interaction diagram, as well as, the compression zone of the columns suffers from decreasing in its depth and high compressive stresses. That means, at the last stage of the test, the behavior of columns is inelastic and high strain values exceed the yield strain value in the reinforcing steel and concrete at the mid of the columns crushes. All the tested columns in the present study exhibit similar behavior in the property of the concrete strains, but with variations in the value of strains from one column to the other during the different stages of the applied load and at failure stage.

From figures (9 through 11) below, noted from strain profile for columns when the column is exposed to 400oC compressive and tensile strain of concrete is same than columns without exposed to fire in comparison at the same load, this behavior may be attributed to the compressive of concrete is not impact by this fire temperature.

From figures (9 through 11) below, noted from strain profile for columns when the column is exposed to 600oC compressive and tensile strain of concrete is large than columns without exposed to fire in comparison at the same load, this behavior may be attributed to the compressive strength of concrete is decrease when increased of fire temperature with fast cooling. Nevertheless, when the cooling is normal to change the failure from tension failure to compression failure.



Figure 9. Strain Profile along Depth of Columns without cooling at (e=60mm).

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Figure 10. Strain Profile along Depth of Columns with normal and fast cooling at (e=60mm).



Figure 11. Strain Profile along Depth of Columns with normal and fast cooling at (e=100mm).



Figure 12. Strain Profile along Depth of Column without burning at (e=100mm).

4.3 Crack Patterns

The crack patterns at the failure stage of all specimen's column were shown in Figure 13. The numbers shown beside the cracks indicate the load when the crack reaches that position. The test results of load characteristics and deflection were given in Table 4.

Specimen Identification	Temperature Level (°C)	First Crack Load (kN)	Ultimate Load (kN)	Percentage Residual Ultimate Load (%)	Maximum Deflection at Mid-height (mm)
Axial	20	50	625	100	
А	20	40	547.5	100	21
A4	400	48	400	73	25.48
A4F	400	50	392.5	71.7	22.58
A4N	400	53	395	72.15	23.22
A6	600	60	387.5	70.8	30.29
A6F	600	66	435		14.66
A6N	600	51.5	415		12.36
A9	900	100	457.5		
A9F	900	110	360	65.7	9.52
A9N	900				7.41
В	20	52.5	342.5		25.36
B4F	400	60	302.5	88.3	35.8
B4N	400	50	290	85	25.43
B6F	600	47.5	317.5		32.98
B6N	600	55	327.5		15.78
B9F	900	55	340		22.66
B9N	900	50	292.5		29.95

Table 4. Test results of reference columns and columns exposed to fire flame for the two series A and B.

All columns are designed to fail in axial and uniaxial failure, which is recognized by the formation of cracks in the tensile stress zone, then yielding of steel bars and shifting the neutral axis toward the compression zone. The behavior of the tested columns under loading can be described as follows; At early stages of loading, the tested columns are free of visible cracks and then the first crack appears at the mid-height in the tension zone. The load at which the first crack appears refers to the cracking load (Pcr). Gradually, several cracks initiate in the tension zone, with the increase in the loads, these cracks become wider. In the final stages of loading, the cracks develop and extend faster, some of which reach the compression zone until failure occurs at ultimate load capacity (Pu), crushing occurs in columns that cured with a high temperature between 600oC to 900oC, as shown in Figure 14. All cracks appeared before exposed to fire flame, but with higher temperatures and longer exposure time, the width and length of the cracks increased and extension along the columns. The uniaxial loading had effect by increasing the eccentricity so increase cracks in mid-height were observed. From this table, it can be seen that the values of ultimate load decrease when the column specimen is exposed to fire flame.



Figure 13. Crack Patterns at Failure Stage (a-400°C, b-600°C, c-600°C and d-900°C).



Figure 14. Columns crushing

5. Conclusions

The following conclusions can be drawn based on the aforementioned experimental investigation of the Fire Behavior of Eccentrically Loaded RC Columns:

- The compressive strength of concrete decreases with fire exposure by an amount depending on the exposure temperature when burning for a limited period (30 min.).
- The splitting tensile strength is more sensitive to fire flame exposure than the compressive strength.
- The modulus of elasticity of concrete is the most affected factor by fire flame rather than compressive strength.
- The residual ultimate load was decreased significantly due to burning by fire flame for group A and B.
- The modulus of rupture is more sensitive to fire flame exposure than the compressive strength.
- Mid-height displacement index is effective to assess the effect of fire exposure on the buckling of NSC columns in which the values of the displacement indices are highly affected after fire exposure.
- The neutral axis depth for columns after exposure to fire is lower than control columns specimens (neutral axis moves down towards the compressed face when exposed to fire).
- The compression zone and neutral axis were decreased by increase eccentricity. These results occur when columns before and after exposure to fire. The strain in the concrete increase at exposure to fire flame compared with specimens before exposure to fire flame. Where the rate of increase of strain when increasing the temperature of fire flame and when increasing the exposure time (compression, tensile).
- An increase in concrete strain with an increase in eccentricity, these results occur when columns are before and after exposure to fire.
- At a temperature equal to 400oC or less, the type of cooling does not differ in terms of its effect on concrete, the strain of concrete with normal cooling similar to strain in concrete with fast cooling.
- The experimental results show that curvature through exposure to fire flame and after cooling by two methods are more than curvature before exposure to fire flame because of the increase of strain in compression concrete zone.

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