The behavior of reinforced concrete columns exposure to eccentric loads at high temperature

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Abstract. This paper aims to investigate the influence of high temperature on the reinforced concrete columns' behavior and load-carrying capacity when subjected to eccentric loads. Experimental tests were conducted on four RC column specimens reinforced by steel bars and subjected to four levels of temperatures: 20 ºC, 400 ºC, 500 ºC, and 650 ºC. One of these specimens was exposed to ambient temperature and considered as the control specimen. After exposure to elevated temperature, all columns were axially loaded by compression force using an eccentricity ratio (e/h) equal to 0.5. The experimental test findings demonstrated a remarkable decrease in the RC column's ultimate carrying capacity when subjected to elevated temperature. The columns' ultimate load capacity decreases by about 14.286 %, 28.571 %, and 42.857 % at elevated temperature magnitude of 400 ºC, 500 ºC, and 650 ºC respectively, compared with the control column at ambient temperature. Also, an increase in fire temperature resulted in a reduction in the load capacity with an increase in lateral and axial deflection of tested columns.

Keywords: Eccentricity, RC column, temperature, normal weight concrete, ultimate strength.

1. Introduction

One of the issues facing buildings is the exposure to elevated temperatures, hence, these buildings should be provided with adequate structural fire resistance to resist such circumstances, or at least give occupants time to escape prior strength and/or stability failure consequent. Being support the structure and transfer loads to the supports or foundation, concrete columns are important structural elements in reinforced concrete buildings. Therefore, any damage or failure occurs in the column may lead to a partial or complete failure of the structure by possibly chain action[1]. Axially loaded columns rarely exist in practice as some bending is almost always presents due to many reasons such as a slight initial crookedness of columns, the manner in which loading is applied by beams and slabs and the moments introduced by continuous construction [2]. Construction professionals are particularly concerned with the behavior of building structures in certain conditions, thus constructing buildings and structures that minimize the risks to people and property to the extent possible of the business and standing in the construction business[3,4].

Further, columns constructed from normal strength concrete (NSC) give the required fire resistance without any external fire proofing, Raut and Kodur [5]

A significant number of studies were conducted on the effect of fire on reinforced concrete columns and other studies focus mainly on the fire influences on the eccentrically loaded RC columns. For instance, an experimental study conducted by Jau and Huang [6] twenty two reinforced concrete corner columns with 2700 mm length and cross-sectional dimensions of (300×450mm) under high temperature. The parameters considered in the tests were the concrete cover thickness, concrete...
compressive strength, reinforcement ratio, eccentricity ratio, and fire duration. In the conclusion of the
works, it was observed that the eccentricity proportion, the compressive strength of concrete, steel
reinforcement ratio, the cover thickness of concrete, and fire period are the variables influencing the
occurrence of cracks in the essential series. The presence and features of surface fractures,
nevertheless, do not explicitly contribute to the reduction in strength.

Lie and Woolerton [7] have presented an experimental study to examine the effect of different
parameters such as the shape of cross section, thickness of concrete cover, reinforcement, aggregate
type, load, and load eccentricity on the fire resistance of RC columns. Forty one full-size RC columns
were cast, and tested under standard fire conditions. Test results have revealed that that using the
carbonaceous aggregate increased the fire resistance of RC columns. Also, heavy reinforcement
columns were noticed to give higher fire resistance and the end conditions influenced the slenderness
ratio of the column, which in turn decreased the fire resistance with increasing slenderness ratio.

The performance and failure mode of GFRP bars RC beams under high temperatures has been
investigated by Al-Thairy and Al-hasnawi [8] to explore the influence of high temperatures on load
resistance linked to concrete beams reinforced by glass fiber reinforced polymers (GFRPs). There have
been four GFRP reinforced concrete beams with cross-sectional measurements of width (250mm) and
height (160 mm), and (1250 mm) the total length depending on ACI 440.1R-15 [9], cast utilizing
standard concrete weight and considered in the experimental tests. One sample was not exposed to
elevated temperature (control), while the three samples have been subjected to elevated temperatures,
namely 350, 500 and 600 °C and then exposed to a monolithically raised one point load before failure.
The influence of elevated temperature on load displacement and the modes of failure of the tested
beams were explored and contrasted with the reference beam (20 °C) findings. The findings of the
experiments revealed that shear failure is the pre-dominant failure mode of all the GFRP beams
evaluated before and after higher temperatures exposure. Findings have also demonstrated that when
subjected to temperatures of 350 °C, 500 °C and 600 °C respectively, the drop in loading potential of
reinforced concrete beams subjected to heat was 4 %, 15 % and 19 % relative to the control beam (20
°C).

The effect of fire flame burn on the performance and load-carrying capability of reinforcement
concrete columns was investigated by Kadhum [10]. One hundred and twenty columns were classified
to two series with target compressive strength of 30 and 40 MPa, and series labeled A and B
respectively. The first set samples were concentrically loaded, while the second and third set samples
were loaded with eccentricities of 30 and 80 mm. The optical thermometer and the infrared ray
thermometer constantly used to calculate the temperature. Column specimens have been designed to
sustain a full capacity load cell (150 tons) with a lifetime of (2 months) after being burnt at
temperature ranges of (400, 600, and 750 °C) with a fire flame over an exposure time of 1.5 hours. The
applied load was 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. Mostly on the faces of the test column
samples, cracks were found and drawn. The lateral deflections against loads were registered
instantaneously for each load increment. Test results have shown that the rise in fire temperature has a
major influence on the mid-height lateral deflection of column samples for series A and B series.

Buch and Sharma [11] experimentally studied the influence of eccentricity of axial loads on the fire
resistance of concrete columns and to examine the role of transverse tie confining reinforcement on
spalling of the concrete. Seven full-scale columns have a square cross section of 300 x 300 mm and
3150 mm height were used in the tests. Concrete grade, eccentricity of axial load, spacing of transverse
confining reinforcement, and arrangement of longitudinal reinforcement, and spacing of transverse
confining reinforcement were the variables of the study. Three columns had high strength concrete and
four other columns were cast using normal strength concrete. Two different eccentricities of 20 mm
and 40 mm of axial loads were chosen for creating uniaxial bending conditions. Two different
configurations of transverse reinforcement namely only perimeter tie and perimeter tie with a cross tie
were chosen. The observations and measurements for spalling were made only after the tests when the
columns had cooled down. From test results it has been noted that spalling is more serious and wide
spread in high strength concrete columns compared to normal strength concrete columns. As a result, fire resistance of high strength concrete columns gets reduced due to the premature spalling of concrete. The higher eccentricity ratio, the lower the fire resistance. Further, it has been found that the eccentricity of axial loads induced spalling of concrete on the compression face of the columns.

This research presents and discusses an experimental study of the behavior of reinforced concrete columns subjected to eccentric loads at high temperature. The geometric and material features of the reinforced concrete column specimens utilized in this experimental study were discussed in details. Also describes the technical details of the furnace, test machine, and measurement devices utilized to record the results of the experimental tests. Finally, this study will come up with useful and essential conclusions that may be used for more practical and safer design of eccentrically loaded RC columns exposed to elevated temperature.

2. Experimental program

2.1. RC column specimens

Four RC columns were considered in this study and designed according to ACI 318-14 [12]. Based on the tests of compressive strength, the RC columns also cast using normal weight concrete with equivalent compressive strength equal to 27.23 MPa. The section below gives the geometric material of the RC columns.

2.1.1. Material characteristics

1- Concrete mixture:

KARASTA Ordinary Portland Cement (O.P.C) (Type I) manufactured in Iraq was used for concrete mixes throughout the work. This cement complied with the Iraqi specification (IQS, No.5:1984) [13].

Aggregates: Fine aggregates were used from well-graded natural sand with a fineness modulus of 2.49 and SO3 =0.225% and was grading conformed to the Iraqi specification(IQS, No.45:1984)[1], Zone(2). Also, coarse aggregate with a maximum size of (14 mm) was used after it was accepted according to Iraqi specifications (IQS No. 45/1984) [14].

The normal weight concrete mixture with mix proportions of (1.0:1. 6:2.6) (cement: sand: aggregate) was designed based on ACI code 211.1-91 [15] and utilized to cast the RC columns. Three concrete cubes with dimensions of (150mm× 150mm×150 mm) and three concrete cylinders with 200mm height ×100mm diameter, have been cast, cured, and tested to determine the tensile and compressive strengths of the concrete at ambient temperature based on ASTM C 2012 specifications [16]. The findings demonstrated that the concrete's average tensile and compressive strengths are 1.98 MPa and 27.23MPa, respectively.

2- Steel bars: Four different sizes of deformed steel bars with diameters of 16mm, 12mm, 10mm, and 8 mm with the strength grade of G60 were utilized as longitudinal and transverse reinforcement. Uniaxial tensile tests were carried out to determine the yield stress, ultimate strength, and modulus of steel bars' elasticity, as summarized in Table 1.

Table 1. The uniaxial tensile tests results of the steel bars used in the present study

| Diameter (mm) | Yield stress Fy (MPa) | Elastic modulus(MPa) | εy= Fy /E/C | Ultimate strength Fu (MPa) |
|---------------|-----------------------|----------------------|-------------|---------------------------|
| 8             | 318                   | 200000               | 0.00159     | 447                       |
| 10            | 461                   | 200000               | 0.002305    | 545                       |
| 12            | 530                   | 200000               | 0.00265     | 628                       |
| 16            | 557                   | 200000               | 0.002786    | 666.50                    |

2.1.2. Geometrical characteristics and reinforcement details.

The geometrical and reinforcement details of the RC beams specimens used in the present study are illustrated in Table (2) and Figure (1) respectively. The columns were designed to resist the same axial
compressive load which is 600 KN with eccentricity ratio of 0.5 in order to compare the reduction in the strength of RC columns after the exposed to the elevated temperature 400˚C, 500˚C and 650˚C respectively except one column being tested without exposure to heating which is considered as the control specimens. Each column have the same square cross section with dimension of (150×150) mm and 1250 mm height and the upper and lower parts ends of the columns were designed as corbels according to (ACI 318-14)[12] specifications with dimensions of (240mm width, 150mm depth), to support the bearing plate used to achieve the required eccentricity and to prevent the local crushing and bearing of the concrete due to concentration of the stress at the upper and lower ends of the column. Dimensions of the column were chosen to fit the dimensions of the electrical furnace manufactured in this study along with the dimensions of universal testing machine. In addition, a minimum steel area (AS ≥ 1%) or 4Ø12mm was used for the main longitudinal reinforcement. Whereas, 9 stirrups were used as a transvers reinforcement using Ø 8mm@131 mm c/c .The corbels were designed with 2 Ø 16 as main reinforcement and Ø10mm at 80 c/c spacing as transverse reinforcement.

Figure 1. Dimensions and reinforcement details of RC column specimens.
Table 2. Details and designation of RC column specimens.

| Symbol | Main reinforcement | Stirrups           | Target Temperature °C (Concrete) |
|--------|--------------------|--------------------|---------------------------------|
| 0.5C20 | 4Ø12               | Ø8 @131mm c/c      | 20                              |
| 0.5C400| 4Ø12               | Ø8 @131mm c/c      | 400                             |
| 0.5C500| 4Ø12               | Ø8 @131mm c/c      | 500                             |
| 0.5C650| 4Ø12               | Ø8 @131mm c/c      | 650                             |

3. Thermal and structural tests

3.1. Thermal tests

Thermal tests were conducted on the concrete cubes, concrete cylinders, three normal weight columns, after 28 days of curing by using the electric furnace after being air-dried for 10 days. The column specimens tested thermally in the electric furnace by exposing them to different elevated temperatures (400°C, 500°C and 650°C). The concrete cubes and cylinders were thermally heated using an approximately identical heating rate exposed to the corresponding RC columns.

The electrical furnace was used to impose high temperatures to the RC column samples before the axial compressive load was applied. The dimensions of the electrical furnace are 1300 mm (length), 330mm (depth) and 290mm (height) with the highest applicable temperature of 900ºC.

The furnace is composed of eight electrical heaters. Every single heater with maximum temperature of about 100ºC. There are two heaters on each internal surface of the furnace to ensure a uniform to distribution of the temperature around the cross-section and along length of the column. Further, the furnace walls are comprised from three layers which are from inner layer to outer layer as follows: one layer of fireproof brick with 25 mm thickness, two layers of thermal wool with 2 mm thickness , one layer of thermal proof brick with depth 20mm (Italian origin), and steel plate with 4.2 mm thickness. The movement of the RC column specimens inside the furnace was supported by using three steel rods. Moreover, an electronically based system was used to control the rate of heating inside the furnace from an electric panel and heaters .In addition, a digital screen is attached to the system in order to monitor the target temperature of the electrical furnace. The details of the electrical furnace equipment are shown in Figure 2.

![Figure 2. Close-up details of the electric furnace.](image-url)

For each RC column specimen, a single Type-K thermocouple with a maximum temperature capacity of 600ºC, was connected at mid-height of main reinforcement steel bars to measure the steel
temperatures inside the concrete. Also, An external thermocouple shown in Figure (3.b) was also attached to the concrete surface with a maximum temperature capacity of 1200°C to measure and monitor the surface temperature of the concrete. The two Type-K thermocouples were connected to a digital monitor to record the temperature of the concrete and the reinforcement steel bars during the thermal tests. The locations of the steel bars thermocouples are shown in Figure 3.

![Figure 3](image1.png)  
**Figure 3.** Positions of thermocouples.

### 3.2. Mechanical tests

The RC column specimens were tested using a hydraulic universal test machine with a maximum capacity of 2000 KN and minimum loading rate of 3 KN/min. A mechanical method was used in the recording and monitoring the load increment to the column. The heated RC column specimens along with the control specimens were subjected to one axial static point load up to failure using the mechanical test machine (see Figure 4).

![Figure 4](image2.png)  
**Figure 4.** Mechanical test machine

Two bearing plates were utilized at the bottom and top ends of the column to distribute the axial load over the loaded area and to achieve the required eccentricity. The bearing steel plate of columns is very important when testing the RC columns under eccentric loads to prevent concrete crushing and...
stress concentration at the column ends. The bearing steel plate is 20 mm in thickness to prevent the failure or deformation of the plate with a dimension of (150×180×20) mm (width x length x thickness). The required eccentricity was achieved by using the two bearing steel plates over the corbel at the locations length such that the resultant of the applied pressure on the plate is located at the intended value of the eccentricity from the center of the column section, as demonstrated in Figure 5.a. One the other hand, the boundary conditions of the column was arranged to represent the simply support condition by using a steel rods at top and bottom end with diameter of 10 mm which allow the ends to rotate freely about the perpendicular axis and prevent the end to move in vertical and horizontal directions. The load was applied in small increments and the measurements were recorded until failure occurs.

![Figure 5. a) Eccentricity loading Setup, b) Installing measurements devices of column specimen](image)

Cracks initiation and propagation were observed and marked on the surfaces of the RC columns specimens. In addition, two dial gauges of 0.01 mm accuracy were used to measure the horizontal and axial displacement: one of dial gauges was installed at the mid-height of the column to measure the horizontal displacement while other one was placed at the lower support of the column to measure axial displacement corresponding to each load increment as shown in Figure 5.b. The test was continued until a decrease in the loading capacity with a sudden increase in displacement was shown in the RC columns. Since the test is mechanical, load and displacement measurements were recorded manually at each load increment.

4. Tests results

4.1. Temperature–time histories
Three RC columns are exposed to three elevated temperatures which are 400 °C, 500 °C, and 650°C. The temperature time history inside the furnace, at concrete surface and at the steel bars were measured for all heated specimens using the type-K thermocouples and shown in Figure (7). It can be noted from this figure that the furnace heating rate were almost similar for all RC columns which is recognized by an abrupt increase in the temperatures up to (180-200)°C throughout the first ten minutes of heating time then the rate of heating was significantly decreased to about 4 °C/min up to 350°C /min. Finally, the heating rate decreased more to reach about (1-1.5) °C /min and remained constant up to the end of the test. All heated RC columns were cooled down naturally to air temperature. The recorded values of temperatures at the steel bars located at the concrete cover distance from the concrete surface are considerably lower than those of the concrete surface. However, the difference is not large compared to some types such as lightweight concrete, and this confirms the high temperature transferred from concrete to steel bars with respect to NWC and the reason is the high thermal conductivity of normal concrete. On the other hand, the difference in temperature between concrete and bar surfaces (ΔT (C-S)) is shown in Figure (8).

The concrete samples suffer from moisture losses caused by the evaporation of water within the concrete as after subjected to extreme temperatures. This approach contributes to a rise in internal tension and hence the emergence of cracks. Significant micro-cracks on samples occurred throughout the experiments due to exposed to elevated temperatures are 400, 500, and 650 °C, and one forms of concrete degradation at high temperatures may show local wear (cracks) in the material itself [17].

Some fine cracks also occur due to the difference in thermal expansion between concrete and steel. From thermal tests it was noted that column exposed to a heating temperature of 650°C witnessed a significant increase in the number and width of cracks. The cracks on the surface of the columns after being cooled with air were marked in red color as shown in the figure (6).

![Figure 6. The thermal crack pattern for heated columns](image_url)
Figure 7. Time-temperature histories of RC columns under different elevated temperature

Figure 8. The difference between the temperature of concrete surface and steel bars surface with time for RC columns under different elevated temperatures.
4.2. Failure modes and load-displacement relationships

The present study consisted of four normal concrete columns that were exposed to an eccentricity loading (e/h), which is equal to 0.5, and the first column was kept without exposure to temperature as a control specimen and the other three columns were exposed to high temperatures (400, 500, and 650) °C. Exposure of specimens to heat caused moisture loss because of the water evaporation inside the concrete as mentioned previously. This process was considered the main reason for increases in the internal pressures and cracks appear which in turn led to concrete weakening and deterioration. The columns that were heated to (400, 500, and 650) °C experienced a significant increase in the number and width of cracks when loaded compared to the unheated column. The development of cracks with increased load for all specimens was also recorded until failure in columns took place due to crushing in their compression region. The first cracks of the columns 0.5C20, 0.5C400, 0.5C500, and 0.5C650 were appeared at loads 20 kN, 20 kN, 10 kN, and 10 kN respectively as mentioned in Table 3. The crack pattern and failure mode of the RC columns are shown in figure (9). The fracture of the concrete cover in the columns occurred in different regions of the compression side, for the two columns (0.5C20) and (0.5C650) the crushing of concrete cover occurred at mid-height of the columns, while in the column (0.5C400) the crushing occurred at the upper part of the mid-height of the column. Lastly, the fracture of the concrete cover in the column (0.5C500) was at the lower end of the mid-height of the column. Due to the eccentric loading, the investigation revealed that the general failure mode in all test specimens was the buckling of the columns, the crushing of the concrete cover on the compression side, the appearance of cracks on the tension side, and its development towards the compression side.

It was also observed that the (0.5C500) and (0.5C650) columns were more fractured and deformed than the other columns due to their greater exposure to heat as shown in Figures 9(c,d). In addition to that, the data showed that the ultimate load capacity of the columns (0.5C400), (0.5C500), (0.5C650) were decreased by about 14.28 %, 28.57 %, and 42.85 % respectively, compared to the control unheated column 0.5C20 as shown in Figure (11). The decrease in the loading resistance of the columns could be due to degradations in concrete’s strength and reinforcing steel bars when they are exposed to high temperatures. Also, it is shown (see figure 10) that the lateral displacement of the columns increases with an increase in the temperature. The reason behind that can be related to the heating, which causes a reduction in column stiffness due to the reduction in the concrete elastic modulus and the reduction in the effective section because of the thermal and cracking expansions of concrete exposed to high temperature.
Figure 9. Column specimen failure for a) 0.5C20, b) 0.5C400, c) 0.5C500, d) 0.5C650

Figure 10. Load-lateral and axial deflection of heated and control RC columns under eccentric loading (e/h=0.5).

Figure 11. Effect of temperature on the ultimate loads of RC columns under different temperatures.
Table 3. Experimental result for all column specimens.

| Column symbol | Maximum Load carrying capacity (KN) | Percentage decreasing in load carrying capacity (%) | Ultimate axial deflection (mm) | Ultimate lateral deflection (mid-height) (mm) | P initial cracks kN |
|---------------|-----------------------------------|-----------------------------------------------|-------------------------------|------------------------------------------------|-------------------|
| 0.5C20        | 254.469                           | 0                                             | 10.3                         | 13.12                                          | 20                |
| 0.5C400       | 218.116                           | -14.286                                       | 12.6                         | 14.76                                          | 20                |
| 0.5C500       | 181.763                           | -28.571                                       | 13.69                        | 16.88                                          | 10                |
| 0.5C650       | 145.41                            | -42.857                                       | 15.9                         | 26.06                                          | 10                |

5. Conclusions

This paper presented an experimental study to investigate the behavior and failure modes of RC columns exposed to elevated temperature under an eccentric load. Four samples of RC columns were tested under an eccentric load with a eccentricity ratio (e/h) equal to (0.5) after heating three of these with an electric oven and other column without heating as a control. The behavior of the columns was recorded and evaluated in terms of temperature history and time, load-displacement relationships and failure modes have been recorded and evaluated in the study. The following conclusions can be drawn from the present study:

1. The experimental test results refer to decreasing in the ultimate load capacity with high temperatures where the residual ultimate strength is equal to 85.7 %, 71.4 % and 57.1 % for 0.5C400, 0.5C500 and 0.5C650, respectively compared to the control column 0.5C20 due to the decrease of the modulus of elasticity of steel and concrete with temperature increase.

2. It is noticed that the lateral mid height deflection and axial displacement were increased with the increase of the degree of heating when compared to the control un-heated specimen due to reduction in stiffness of these columns that produced from heating with high temperatures.

3. Thermal cracks of greater number and size were observed in the heat-exposed column specimens, and cracks were observed in the early stages of loading in the more heat-exposed columns.

4. Crushing in concrete and buckling of the columns has been the predominant failure mode for RC columns under high and ambient temperatures.

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