

# Numerical Investigation on the Behavior of Eccentrically Loaded LWRC Columns at Elevated Temperature

Haitham Al-Thairy<sup>1</sup>, Faaiza Al-Naqeeb<sup>1</sup>

<sup>1</sup>Department of Civil Engineering, College of Engineering, University of Al-Qadisiyah, Iraq

**Abstract**— In this paper, a numerical model is presented to simulate the behavior and failure of LWRC columns subjected to eccentric compressive load at elevated temperature using the finite element code ABAQUS. Validation of the numerical model was ensured throughout comparison numerical results with the available published experimental tests results. The validated numerical model was implemented in conducting extensive parametric study to understand the effects of important parameters on the response of eccentrically compressed LWRC column at elevated temperature. These parameters include effect of increasing the concrete cover, effect of changing the exposure time, effect of increasing the exposed temperature, effect of temperature distribution around column section, effect of temperature distribution along column length, and effect of eccentricity ratio. The numerical results indicated that increasing the concrete cover of the column section results a considerable increasing of the ultimate load capacity. In addition, there is an increase in the ultimate load capacity when the temperature exposure time is reduced to the half, whereas, if the exposure period is increased to twice and three times the original exposure time, the ultimate load shows a slight decrease. Moreover, the ultimate load capacity of the LWRC column decreases when temperature is increased. Finally, the ultimate load capacity increased of the LWRC column when the temperature is distributed over larger distance of the column length.

**Keywords**— eccentric load, elevated temperature, failure mode, LWRC columns, Numerical modeling.

## I. INTRODUCTION

Columns are considered as the most important members and their failure has a catastrophic consequences and may cause a significant damage to the building [1]. Hence, it is necessary to pay attention in designing the columns to resist different types of loading and conditions. Fire events are commonly occurring inside the building resulting safety hazard of the occupants and a risk of structural collapse. Further, the high temperatures caused by the fire flame have a great impact on material and mechanical properties of structural members, such as columns, slabs, beams, shear walls, ...etc [2]. Therefore, design

approaches to reinforce such concrete members must be sought to withstand the stresses and meet the construction requirement for a desired design period.

Concrete is a material that has an excellent intrinsic behavior when exposed to fire [3,4]. In this context, using lightweight concrete (LWC) in the concrete construction is the most successful approach to increase the span of fire resistance [4, 5]. The most common way to produce LWC is using lightweight aggregate (LWA) by using the production of Lightweight Expanded Clay Aggregate (LECA). LECA consists of thin, lightweight, bloated fragments of burnt clay, which is also considered a low-cost, high-porosity, environmentally friendly commodity [6]. The occurrence of voids and pores in LECA are the main reason of the good fire resistance, good thermal properties, and acoustic insulating properties of this type of concrete [6].

However, the current standards and codes of practice have not explicitly addressed the effect of fire on the behavior of lightweight reinforced concrete (LWRC) columns [ 3-5 ]. According to the ACI 213R [5], LWC is more fire resistant than normal weight concrete due to lower coefficient of thermal expansion and lower thermal conductivity. However, the ACI 216.1 [4] suggests that the compressive and tensile strengths of semi-lightweight concrete decrease upon increasing the temperature. In addition, the ACI 216.1 [4], did not address the effect of high temperature on the analysis and design of lightweight concrete members (LWC) in its provisions and requirements. Further, the EC2 [2] discusses the decrease in compression and tensile strengths of normal concrete at elevated temperatures and does not discuss the effect of the temperature on lightweight concrete. Furthermore, the EC4 [4] evaluates the decrease in compressive strength of normal weight concert (NWC) and LWC at high temperature and shows the stress - strain response of concrete in compression under high temperature similar to that of EC2 [2]. According to Raut and Kodur [8], one of the most important parameters that should be considered in the fire design of RC columns is the minimum thickness of concrete cover. In addition, research studies have shown that most collapses in fire-damaged concrete structures are caused by failure of steel reinforcement [9, 10]. This is because the reinforcement is usually placed near the concrete surface. Hence, the reinforcement is subjected to a greater temperature increase, and its strength is first affected in comparison to the main body of concrete [10].

One the other hand, more attention in recent years has been paid to the accelerated demand on using LWAC in concrete industry due to its remarkable advantages over the conventional concrete, such as high thermal insulating, low dead load, and low earthquake forces. Because of the different thermal characteristics of LWAC ingredients, its performance is greatly affected at high temperatures [11]. El-Shaer [12] conducted experimental program to investigate the structural behavior of LWRC column subjected to elevated temperature. Four RC columns with same dimensions were considered in the tests. Two of the columns are composed from LWC using LECA as a partial replacement of the normal weight coarse and fine aggregates with a volumetric percentage of 50%. In addition, two of the tested columns were subjected to elevated temperature of 550°C from four sides. Tests results have shown that the unheated LWRC columns have undergoes a slight reduction in load-carrying capacity, stiffness, and toughness compared to normal-weight concrete columns. However, the heated LWRC columns showed higher ultimate load compared to normal weight concrete columns. Also, El-Shaer [12] presented a numerical study to investigate the behavior of LWRC columns exposed to elevated temperature using the finite element modeling package ANSYS 13. The experimental tests results conducted by El-Shaer [12] were used to verify a numerical model. The verified numerical model was used to cover a wider range of parameters affecting the behavior of LWRC columns exposed to elevated temperature. Numerical results have shown that the percentage of reduction in the ultimate capacity of unheated columns increases as the concrete type changed from normal to light weight concrete, while the percentage of reduction in the ultimate capacity of heated columns was decreased as the concrete type changed from NWC to LWC. In addition, the rate of loss in stiffness increased with increasing the duration of exposure to elevated temperature of NWC, while for LWC the rate of loss in stiffness decreased. Haddad and Ashour [13] have conducted experimental study to investigated thermal performance of fibrous lightweight aggregate concrete short columns. Seventy-two column specimens with different lateral steel confinements were prepared and cast with and without hooked steel fiber reinforcement and subjected to temperatures from 300oC to 700 oC. Then, the column specimens were tested under uniaxial compression load. Results have shown a marked reduction in rigidity and compressive load capacity of the column with increase in strain at peak stress when exposure temperatures up to 400 oC. Further, thermal cracking was found to be proportional to exposure temperature with its extent reduced upon the use of steel fibers or steel confinement. Results have also revealed that Failure modes of column specimens varied from brittle to semi-ductile fracture with longitudinal steel buckling noticed for columns heated at 700oC. Al-Naqeeb and Al-Thairy [14] have presented experimental investigation on the effect of elevated temperature on the behavior of LWRC columns. Six RC columns were considered in the experimental tests. LECA was used in three columns, while the three remaining columns used natural aggregate. The columns were exposed to elevated temperatures of 400oC and 500oC. After

exposure to elevated temperature, the columns were axially loaded by compression force using an eccentricity ratio ( $e/h$ ) equal to 0.5. The experimental test results demonstrated a remarkable decrease in the ultimate carrying capacity of the columns when subjected to elevated temperature. The experimental test results have also revealed that the LWRC columns have more fire resistance than the NWRC columns under same elevated temperature.

From reviewing and discussing the previous relevant research studies, it can be found that the effect of high temperature on the behavior of LWRC concrete columns has only been studied in very limited researches. In addition, the commercial finite element method has been successfully used to simulate the behavior and failure of normal weight reinforcement concrete columns at elevated temperatures with very reasonable accuracy. The stress-strain model of NWC along with the reduction factors of the strength parameters of the concrete proposed by EC2 [3] and EC 4 [7] were used to predict the degradation of the concrete strength under high temperature. Therefore, the main objective of the present study is the numerical investigation of the behavior and failure modes of LWRC columns at different elevated temperatures under eccentric loads using the commercial finite element software ABAQUS [15].

## II. THE RC COLUMN MODEL

### A. Material modeling

#### 1. Concrete

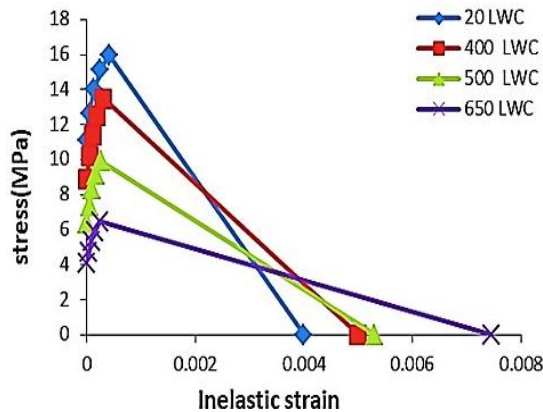
The concrete damage plasticity (CDP) model provided by ABAQUS was considered in the current study to simulate the performance of concrete material [14, 15]. In this mode, the damage initiation and the plasticity of concrete parts are taken into account in the finite element modeling whereas the compressive crushing and tensile cracking of concrete are assumed to be the main failure mechanisms. On the other hand, the deterioration of concrete in compression and tension due to elevated temperature was taken into consideration according to EC 4 [7]. In addition, the related plasticity parameters of LWRC column model are obtained from previously published numerical studies [16] as dilation angle ( $\Psi$ ) of 30; potential eccentricity ( $\epsilon$ ) of 0.1; viscosity parameter of 0.0015; initial equi-biaxial compressive yield stress to the initial uniaxial compressive yield stress ( $f_b/f_c$ ) of 1.16 and K value which is used to determine the multi-axial behavior of concrete of 0.67. Further, the mathematical model of compressive stress-strain relationship of LWC, suggested by EC 4 [7] was applied for ambient and elevated temperature. Furthermore, yielding and crushing strains of LWC under different temperatures were taken from the experimental study of Felicetti et al. [17]. One the other hand, the reduction factors of compressive strength acquired from the experimental tests of Al-Naqeeb and Al-Thairy [14] were used to estimate the degradation of mechanical properties of concrete under elevated temperature. Fig. 1 shows the stress- strain relationships of LWC at temperatures from 20 °C to 650°C used in the present numerical

model.

Fig. 1. Stress and inelastic strain relationships of LWC at high temperature used in current numerical model

The Poisson's ratio of LWC was used as 0.20 at 20°C and stays constant up to 150°C then it is linearly decreases to 0.1 at 400° C , then linearly reduced to zero at 1200° C.

On the other hand, the crack bandwidth model was employed in the current study for the tensile behavior of LWC at ambient and elevated temperature according to CEB mode [18] and



depending upon the aggregate size and concrete compressive strength [18]. Fig. (2), illustrates the stress-crack opening of LWC according to CEB mode. To calculate the degradation of tensile strength of LWC at elevated temperatures, the reduction factors of tensile strengths acquired from the experimental tests of Al-Naqeeb and Al-Thairy [14] were used in this research.

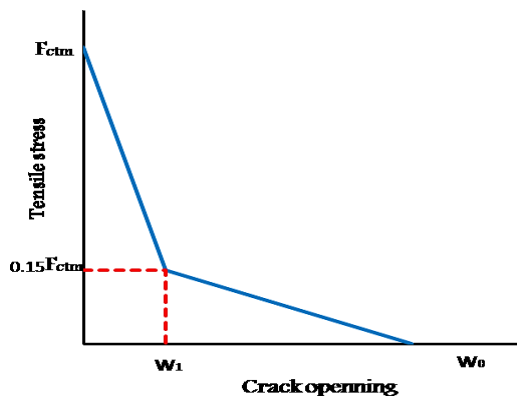


Fig. 2. Stress-crack opening relationship for LWC [18]

To simulate the crack initiation and propagation of concrete at ambient and elevated temperature, the damage parameter (dt) were used in current model. The damage parameter is estimated from the equation produced by ABAQUS [15].

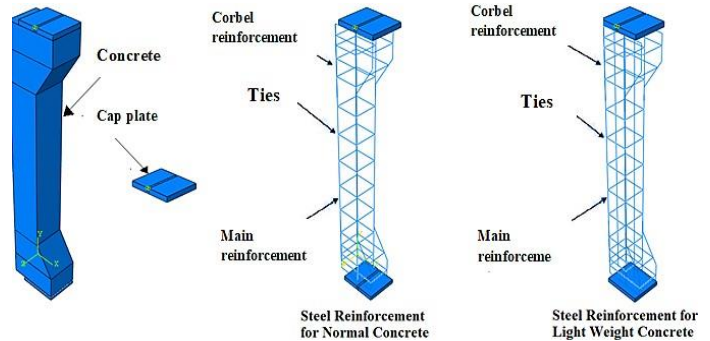
2. Reinforcing steel bars

The tensile stress-strain relationships of the steel proposed by EC4 [7] was used to simulate the behavior of reinforcing steel bars at ambient and elevated temperatures. The yielding stress; Poisson's ratio and modules of elasticity of reinforcing steel bars at ambient temperature were taken as 412 MPa, 0.2, and 2×105 MPa respectively. However, the effect of elevated temperature on the aforementioned material properties was

accounted for by using the thermal dependent reduction factors suggested by EC4 [7].

B. Geometrical modeling parameters

The three-dimensional eight-nodes solid element (C3D8R) with reduced integration and hourglass control and the eight-node solid linear element (DC3D8) with a temperature degree of freedom available in ABAQUS were considered in the



current model to model the RC column and supporting steel plates during structural and heat transfer analysis respectively. In addition, the three-dimensional two-node linear displacement truss element (T3D2) was used to model reinforcing steel bars at the structural analysis. Whereas, two nodes heat transfer link element (DC1D2) with a temperature degree of freedom was used to model the reinforcing steel bars during thermal analysis.

C. Assembly of the RC columns parts

Each numerical model of the RC column consists of three parts: LWRC column, bearing plate and reinforcing bar as shown in Fig (3).

Fig. 3. The assembled parts of RC column

The stress intensity at supports and loading points was prevented by using supporting and bearing steel plates with dimensions of (150×180×20) mm (length ×width× depth) as shown in Fig. (4). To simulate same experimental boundary condition of LWRC columns [14], displacement /rotation boundary option provided by ABAQUS was employed [15]. Further, the compression load was applied as a pressure load over the bottom bearing plate as conducted in the experimental tests [14] as shown in Fig. (4). Furthermore, the interaction between concrete columns and reinforcement cage was simulating using the embedded region interaction provided in ABAQUS [15]. While the relationship between concrete columns and supporting plates was simulated using tie interaction also available in ABAQUS [15].

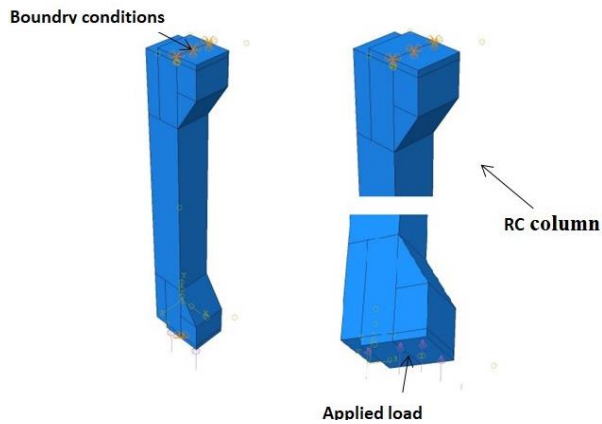


Fig. 4. Load application and boundary conditions used in the numerical model

#### D. The sequential thermal displacement analysis procedure

The sequential thermal displacement analysis procedure provided by ABAQUS was used in current model to conduct the analysis of eccentrically loaded LWRC columns at elevated temperature. This analysis consists of two steps;

I. The first step is heat transfer analysis which is used to determine the distribution of exposed temperature inside column cross-section including the reinforcement temperature. The corresponding time-temperature history obtained from experimental tests [14] was applied as a boundary condition on selected external surfaces of the column using amplitude option available in ABAQUS [15]. All thermal properties of concrete, reinforcement steel bars, stirrup such as specific heat, thermal expansion and conductivity were all defined as a function of temperature using values presented in EC 4 [14]. In addition, a contact interaction (tangential, normal, and thermal) was used to achieve the thermal interaction within reinforced concrete and reinforcing bars. A hard contact was used in the normal behavior, while a friction coefficient of 0.57 was used to define tangential behavior. The thermal behavior is carried out by using conductance parameters with maximum value of 0.00015.

II. The second step is the structural analysis which is used to evaluate the structural response of LWRC columns after exposure to heating. This step was initiated after completing the heat transfer analysis. The predefined fields option in ABAQUS was used to restore the distribution of temperature through the LWRC column during the heat transfer step as output data base file [15].

#### E. Mesh size optimization

The mesh size optimization analysis was achieved by decreasing the element mesh size in each direction of the column model and performs the numerical simulations until any further decrease in the mesh size has a negligible effect on the accuracy of the results. The following element sizes of the column elements was used: 10mm, 15mm, 20mm, 25mm, and 30mm as shown in Fig. (5). The load- displacements curves with different mesh size are shown in Fig. (6). Results in Fig. (6), show that the mesh size of 20 mm gives the most accurate results compared to the experimental test results of the column under eccentric load of  $(e/h)=0.5$  and at elevated temperature

650oC[14]. Therefore, 20 mm mesh size was adopted here for all the simulated columns.

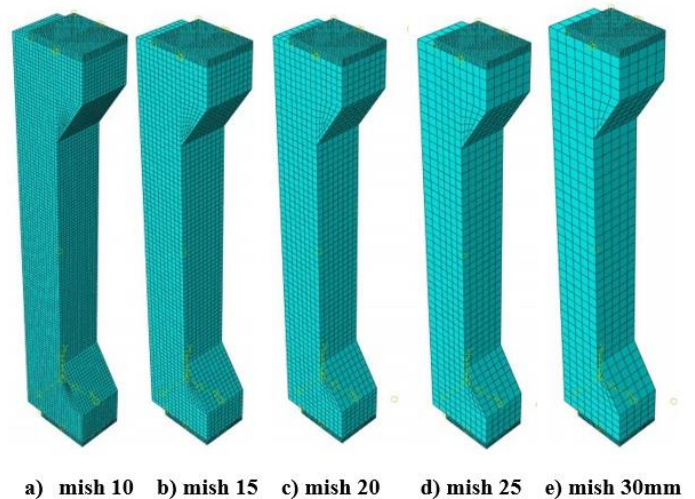


Fig. 5. The mesh sizes used for the mesh size optimization

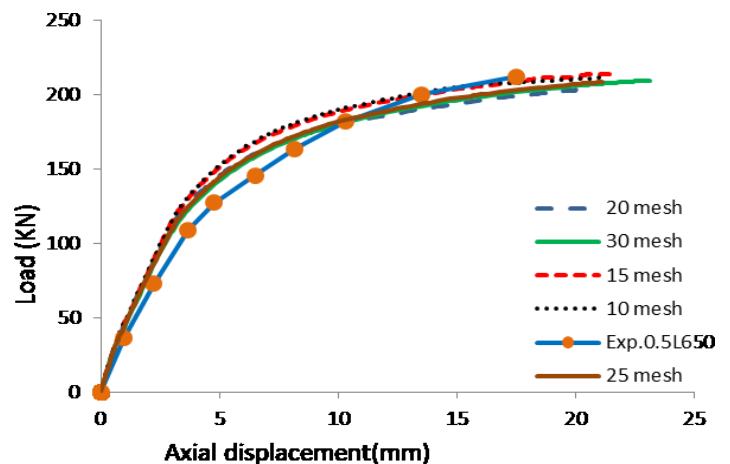


Fig. 6. Load-axial displacement curves of LWRC column (0.5L650) at different mesh sizes

### III. VALIDATION OF NUMERICAL MODEL AGAINST EXPERIMENTAL RESULTS

The aforementioned analysis procedure was used in suggesting and validating of numerical model to study the performance of LWRC columns exposed to various elevated temperature. Validation of suggested model was done by comparing the numerical analysis results with the experimental tests results of Al-Naqeeb [20] which has presented an experimental study on the behavior and failure modes of LWRC columns under eccentric loads and subjected to elevated temperatures. LWRC columns with cross-sectional dimensions of 150mm  $\times$  150mm (width  $\times$  depth) and a total length of 1250 mm were exposed to temperatures ranging from 20 to 650  $^{\circ}$ C and then subjected to axial eccentric compressive load until failure. The columns ends were designed as corbels to prevent the premature local bearing failure at the concrete. The corbel's

dimensions equal 240mm ×150mm (width × depth) with a distance between them equal to 750mm. Fig. (7) shows the LWRC column considered in the validation examples.

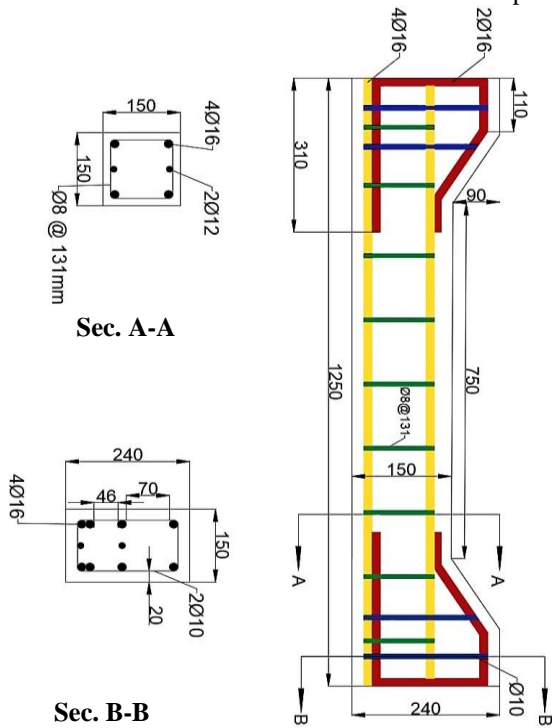


Fig. 7. Geometrical and reinforcement details of LWRC columns used in experimental tests of Al-Naqeeb [20]

A. Validation the heat transfer analysis

Figures 8 compares the temperature-time histories at the longitudinal reinforcement steel bars obtained from heat transfer analysis with that recorded from the experimental thermal tests [20].

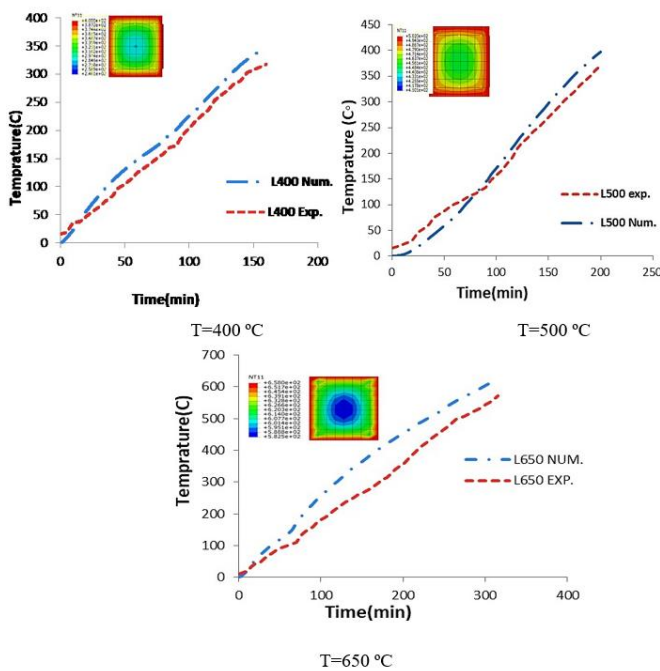


Fig. 8. Comparison of the temperature-time curves at reinforcing steel bars of the LWRC columns at eccentricity ratio (0.5) between experimental [16] and numerical results.

Good agreement can be seen between the two results. In addition, Figures 8 shows very good correlation of the maximum temperature at the reinforcement steel bars between predicted from the numerical model and that recorded experimentally with the maximum difference is about 4-7 %. This agreement indicates the accuracy of the suggested numerical model in capturing the temperature distribution inside column section.

B. Validation the structural analysis

Figures (9-11) demonstrate a comparison of the load-displacement relationships of LWRC columns considered in the current study after exposed to different elevated temperatures between experimental [20] and numerical results.

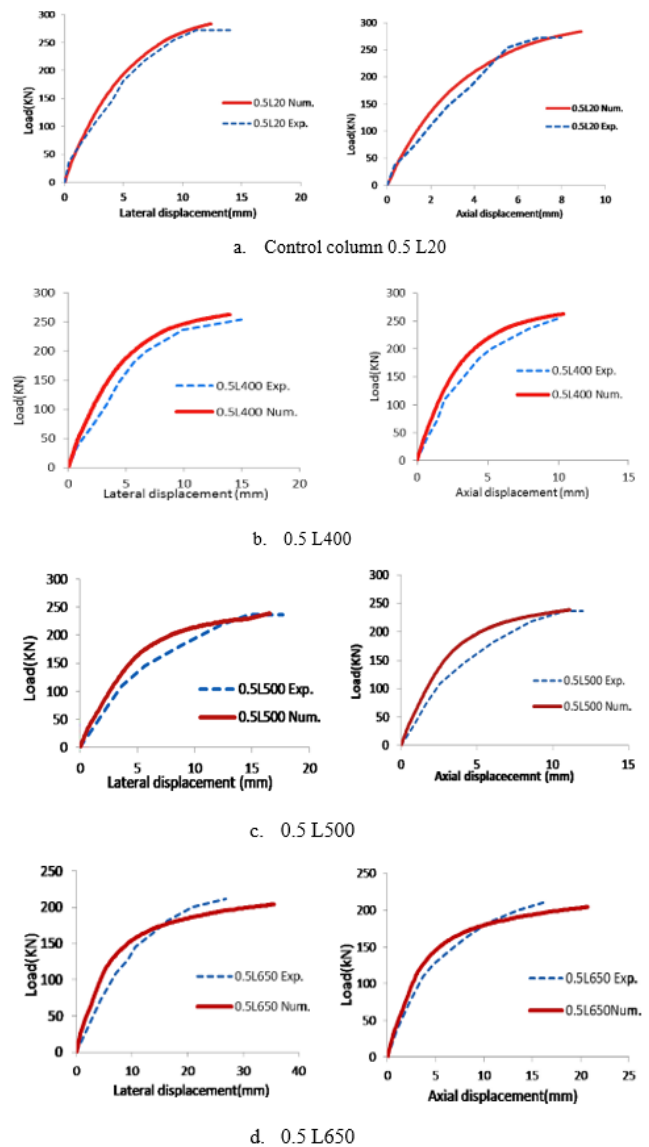


Fig. 9. Comparisons of the load-displacement curves between experimental and numerical results for LWRC columns at eccentricity ratio of (0.5)

Figures 9 (a-d) illustrate a reasonable agreement between the experimental and numerical results of the LWRC columns at eccentricity ratio of 0.5 (0.5L20, 0.5L400, 0.5L500, and 0.5L650). It can also be concluded from this figure that the difference in the experimental and numerical ultimate capacity

of LWRC columns is about 4%, 3.3% , 2.6%, and 3.4% at temperatures values of 20 °C ,400 °C, 500 °C, and 650 °C respectively.

Further, Figures 10 (a-d) shows that the difference between experimental and numerical values of the maximum load of LWRC columns at eccentricity ratio of 0.25 (0.25L20, 0.25L400, 0.25L500, and 0.25L650) is about 1.7 % , 1.6 % , 3.0 % , and 1 % corresponding to temperatures values of 20 °C , 400 °C ,500 °C and 650 °C respectively. While the results of concentrically loaded LWRC columns (0L20, 0L400, 0L500, and 0L650) shown in Figures 11(a-d) indicate that the difference between experimental and numerical values of the maximum load of LWRC columns is 0.95%, 0.3%, 0.97%, and 2.27% at temperature values of 20 °C, 400 °C, 500 °C, and 650 °C respectively.

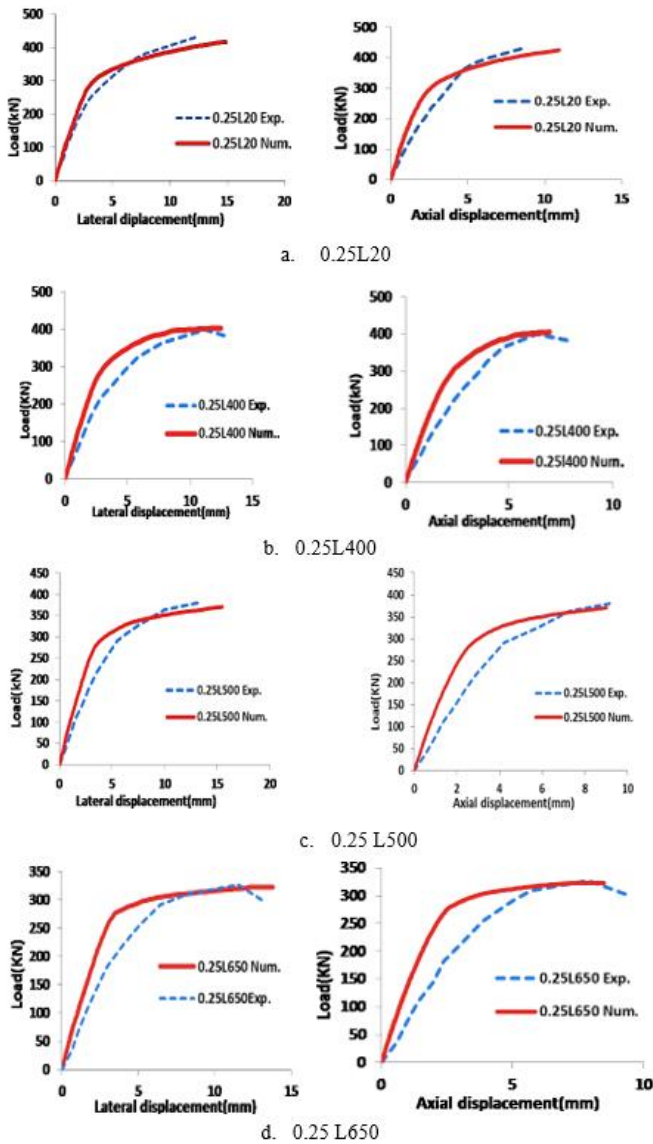


Fig. 10. Comparisons of the load –displacement curves between experimental and numerical results for LWRC columns of at eccentricity ratio of 0.25.

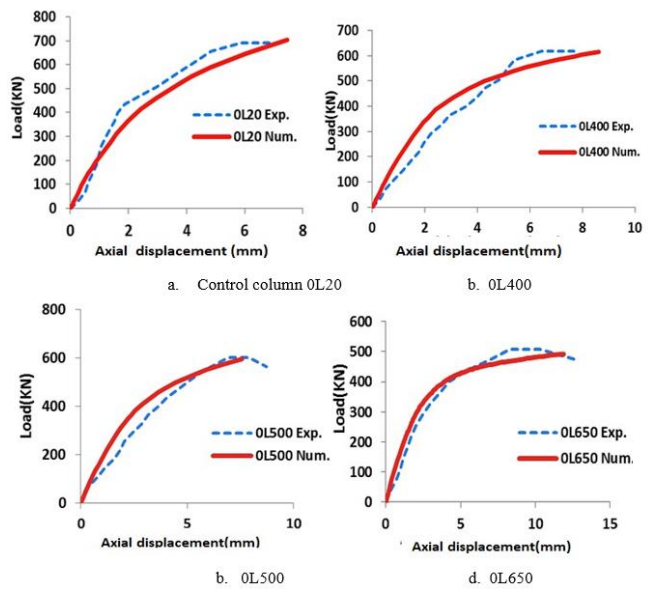


Fig. 11. Comparisons of the load –displacement curves between experimental and numerical results for LWRC columns under concentric load

This agreement reveals the ability of the proposed model to predict the response and failure load of LWRC columns with different eccentricity ratios and exposed to different elevated temperatures up to failure. Furthermore, Table (1) presents a comparison of ultimate load capacity of LWRC columns between numerical and experimental results. The number in the column symbol indicate the eccentric ratio used and the letter (L) refers to the LWC while the number that follow represents the degree of the exposed temperature.

TABLE I  
COMPARISON OF THE ULTIMATE LOAD AND THE ULTIMATE DISPLACEMENT BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

| Symbol   | Ultimate load capacity Pu(KN) |        | % difference | Ultimate axial deformation (mm) | % difference |
|----------|-------------------------------|--------|--------------|---------------------------------|--------------|
|          | Numer.                        | EXP.   |              |                                 |              |
| 0L20     | Numer.                        | 697.3  | 0.95         | 7.45                            | 8.7          |
|          | EXP.                          | 690.7  |              | 6.85                            |              |
| 0L400    | Numer.                        | 616    | 0.3          | 8.61                            | 9.8          |
|          | EXP.                          | 618    |              | 7.84                            |              |
| 0L500    | Numer.                        | 594    | 0.97         | 7.37                            | 4.5          |
|          | EXP.                          | 599.8  |              | 7.93                            |              |
| 0L650    | Numer.                        | 497.2  | 2.27         | 12.737                          | 23           |
|          | EXP.                          | 508.8  |              | 21.42                           |              |
| 0.25L20  | Numer.                        | 424.9  | 1.7          | 10.71                           | 23           |
|          | EXP.                          | 432.2  |              | 8.71                            |              |
| 0.25L400 | Numer.                        | 406.64 | 1.6          | 6.8                             | 22           |
|          | EXP.                          | 399.9  |              | 8.73                            |              |
| 0.25L500 | Numer.                        | 370.2  | 3            | 9.3                             | 6.8          |
|          | EXP.                          | 381.7  |              | 9.98                            |              |
| 0.25L650 | Numer.                        | 322.9  | 1.3          | 7.25                            | 7.8          |
|          | EXP.                          | 327.2  |              | 7.87                            |              |
| 0.5L20   | Numer.                        | 283.8  | 4            | 8.908                           | 11           |
|          | EXP.                          | 272.6  |              | 7.98                            |              |
| 0.5L400  | Numer.                        | 263    | 3.3          | 10.37                           | 5.5          |
|          | EXP.                          | 254.3  |              | 10.98                           |              |
| 0.5L500  | Numer.                        | 229.45 | 2.6          | 11.36                           | 4.5          |
|          | EXP.                          | 236.3  |              | 11.9                            |              |
| 0.5L650  | Numer.                        | 204.7  | 3.4          | 20.72                           | 16           |
|          | EXP.                          | 212.1  |              | 17.85                           |              |

IV. PARAMETRIC STUDY

A parametric study was carried out using the validated numerical model to investigate the effect of several parameters on the behavior and ultimate load of eccentrically loaded LWRC columns exposed to elevated temperature. These parameters are:

- (a) Effect of increasing the concrete cover.
- (b) Effect of changing the exposed time.
- (b) Effect of increasing the exposed temperature.
- (c) Effect of temperature distribution around the columns cross-section.
- (d) Effect of temperature distribution along the columns length
- (e) Effect of eccentricity ratio.

The following subsections discuss in details the above-mentioned parameters:

A. Effects of increasing the concrete cover

Figure 12 shows the load-displacement relationships of LWRC columns at eccentricity ratio of 0.5 exposed to temperature value of 650 °C with concrete covers of 20mm, 30mm, 40mm, and 50mm. Figure 12 clearly indicates that when increasing the cover from 20mm to 30 mm, 40mm, and 50mm, the ultimate load capacity increased by about 19.4 % 33.7 %, and 35.2 % respectively.

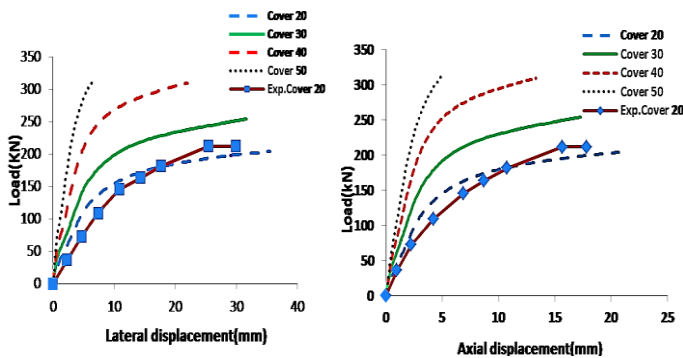


Fig. 12. Load-displacement relationship of 0.5L650 columns with different concrete covers

B. Effect of the exposed time

The exposed time was firstly decreased to the half of the experimental time exposure [16], and then increased to two-time and three -times of the experimental temperature exposure. The load- displacement relationships of the 0.5L650 column at different temperature exposure times are shown in Fig. 13. Results in Fig. 13 indicate that ultimate load capacity of the LWRC column increased by 8.9% and decreased by 7.2%, and 9.6% for the cases of half time, two times and three times of temperature exposure respectively.

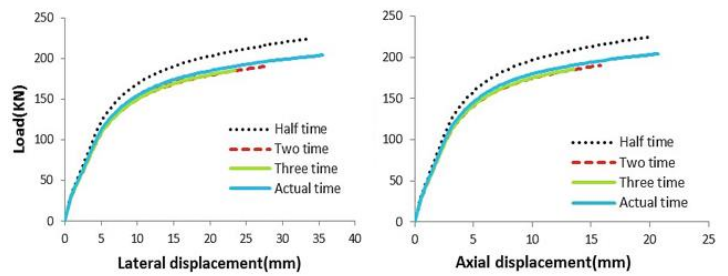


Fig. 13. Load-displacement relationship of 0.5L650 columns under different times of temperature exposed.

C. Effect of increasing the exposed temperature

The temperature was increased from 650°C to 750 °C and 850 °C for LWRC columns and the results are shown in Fig. 14. It can be seen from this figure that the ultimate load capacity of 0.5L650 columns decreased by 2.3 % and 5.7 % compared to the ultimate capacity of 0.5L650. This small reduction in ultimate load capacity may be due to the deterioration the mechanical properties of LWC and steel at elevated temperature [3, 7].

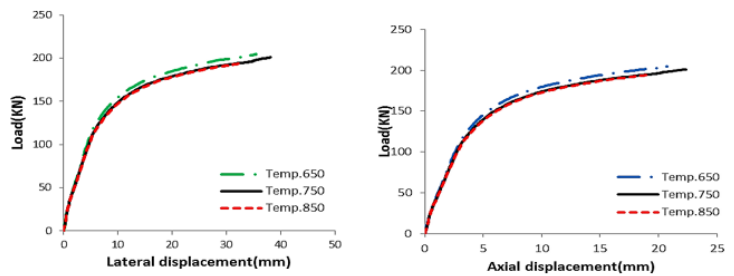
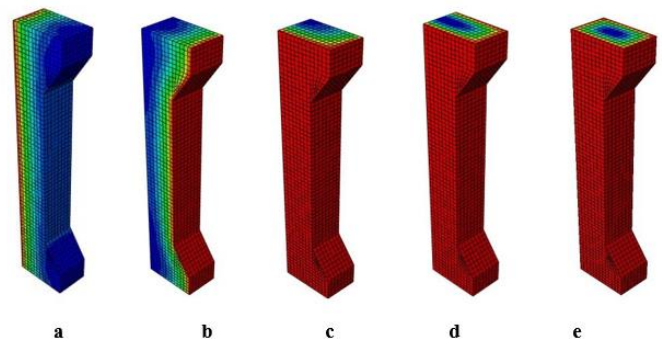


Fig. 14. Load-displacement relationship of 0.5L650 columns under different exposed temperature.

D. Effect of temperature distribution around the columns cross-section

In this parametric all sides, one side, two sides and three side of concrete column section were subjected to temperature as shown in Fig. 15.



a) One side exposure (Tension side) ; b) One side exposure (compression side); c) Two sides exposure d) Three sides exposure e) 4-sides exposure

Fig. 15. Temperature distribution around concrete columns used in the parametric study

The load- displacement curves of the aforementioned cases are shown in Fig. 16 of 0.5L500 columns. Figure 16 reveals that the ultimate load capacity of the LWRC column increased by 7.8%, 2.5%, 4 %, and 2% in case of one side of temperature exposure (tension side) , one side of temperature exposure (compression side), two-side of temperature exposure and three-side of temperature exposure respectively compared to that of all-sides of temperature exposure.

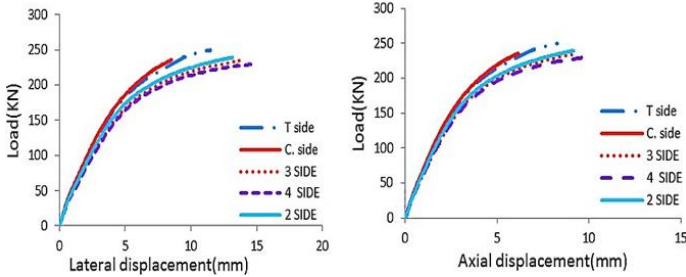


Fig. 16. Load-displacement relationships of 0.5L650 columns with different temperature distribution around concrete columns

#### E. Effect of temperature distribution along the columns cross-section

To investigate the effect of changing the temperature exposure length of the concrete column on the ultimate load capacity of 0.5L650 concrete column, half-length of, quarter length and three-quarter length of temperature exposure were considered in the numerical simulations as shown in Fig. 16 and the analysis results are shown in Fig.17 . Results shown in Fig.17 indicate that by decreasing the exposed length to half of column length, the ultimate capacity increases by about 15.7% compared to that with full length temperature exposure. Further, the ultimate capacity corresponding to of quarter - length temperature exposure and three-quarter length temperature exposure, are increased by 25.8% and 3.8 % respectively compared to that of the column corresponding to full temperature exposure length.

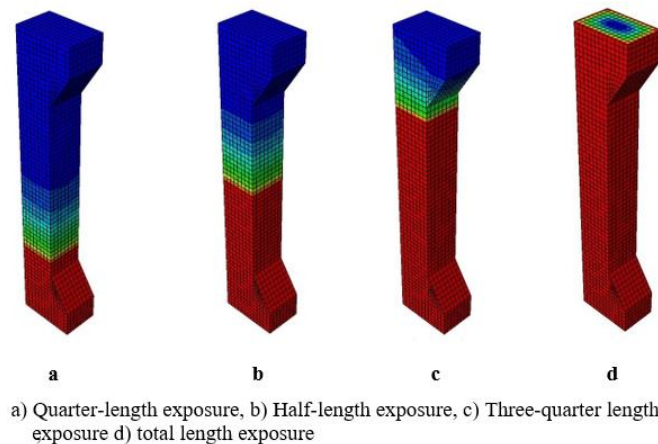


Fig. 17. Temperature distribution along the concrete columns considered in the study

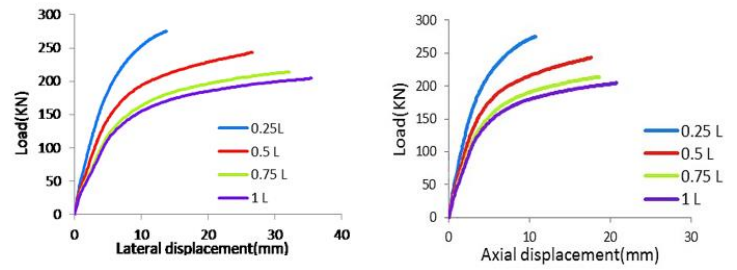


Fig. 18. Load-displacement relationship of 0.5L650 columns under different temperature distribution along the concrete column

#### F. Effect of eccentricity ratio

The effect of three eccentricity ratios ( $e/h$ ) which are 0.5, 0.75 and 1.0 on the ultimate load capacity of 0.5L650 concrete column are investigated in this section as shown in Fig.19. The corresponding load displacement curves are shown in Fig. 20.

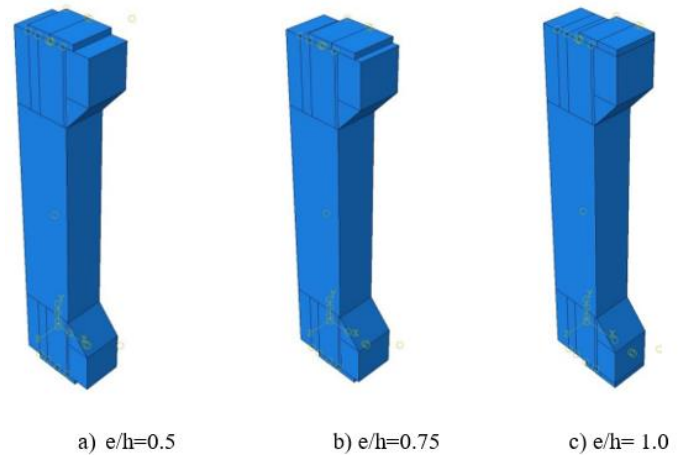


Fig. 19. Concrete columns under different eccentricity ratios

The results in Fig. 19 show that the ultimate load capacity of the LWRC column decreases by 33.3% and 63.3% when the eccentricity ratio increased from 0.5 to 0.75 and 1.0 respectively.

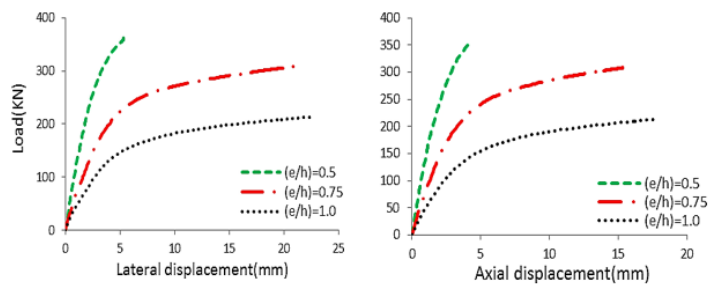


Fig. 20. Load-displacement relationship of 0.5L650 columns under different eccentricity ratios

## V. CONCLUSION

This study has proposed and validated a numerical model to simulate the behavior of eccentrically compressed LWRC columns under different elevated temperatures by using the finite element program ABAQUS. The validated numerical

model was implemented to carry out an extensive parametric study to investigate the effects of significant parameters on the response of LWRC columns under different elevated temperatures. The following are main conclusions drawn from this study:

1. The finite element software ABAQUS can reasonably predict the performance and ultimate load of LWRC columns at different elevated temperatures under eccentric loads if suitable geometrical, mechanical, thermal and material properties of the numerical model are selected and implemented correctly with the associated reduction factors suggested by [3,7].

2. Increasing the concrete cover to from 20mm to 30mm, 40mm, and 50mm has an influence on ultimate load capacity of LWRC column under elevated temperature. At temperature value of 650 °C, the maximum decrease in the ultimate load capacity of LWRC column is about 35% compared with that of the column with 20 mm concrete cover.

3. For LWRC columns exposed to elevated temperature of 650°C, results has shown when the temperature exposed period is decreased to half of the exposure time, the ultimate load capacity increases accordingly. While, when increasing exposed period to twice and three times of exposure period, the ultimate load capacity shows a slight reduction of the ultimate load capacity.

4. Increasing the exposed temperature results decreasing of the ultimate load capacity of LWRC columns under eccentric loading with

5. The distribution of the exposed temperature around the LWRC columns section and along the column length has considerable effect on the ultimate load capacity. When the temperature was distributed over larger surface of the column, the ultimate load capacity is decreased accordingly.

6. Increasing eccentricity ratio has an influence on decreasing the ultimate load capacity of LWRC.

#### REFERENCES

- Alhassnawi, M. K. M. and Alfatlawi, A. alridah S. (2018) \_Experimental Investigation on the Influence of Elevated Temperature on Reinforced Concrete Columns Strengthened with Carbon Fiber Reinforced Polymer products\_, International Journal of Civil Engineering and Technology (IJCIET), pp. 905–915.
- Buch, S. H. and Sharma, U. K. (2017) \_Fire resistance of reinforced concrete columns: A systematic review\_, Applications of Fire Engineering, pp. 141–150.
- Eurocode 2, Design of concrete structures, Part 1-2: General rules Structural fire design Euro code SS-EN-1992-1-2:2008, 3(July), Eurocode SS-EN-1992-1-12005, vol. 3, no. July, 2004.
- ACI 216-1-07, Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies; Reported by ACI Committee 216, 2007.
- ACI 213R-03, Guide for Structural Lightweight-Aggregate Concrete Reported by ACI Committee 213, pp. 1–38, 2013.
- Arioz O., Kilinc K., Karasu B., Kaya G., Arslan G., Tuncan M., Tuncan A., Korkut M. And Kivrak S. (2008) \_A Preliminary Research On The Properties of Lightweight Expanded Clay Aggregate\_, J. Aust. Ceram. Soc. 44 [1] (2008) 23-30.
- Eurocode 4, Design of composite steel and concrete structures, EN 1994, Part 1-2: General rules - Structural fire design, (August), pp. 1-109, Des. Compos. Steel Concr. Struct. – Part 1-2 Gen. Rules - Struct. Fire Des. no. August, 2005.
- Raut, N. and Kodur, V. (2011) \_Response of reinforced concrete columns under fire-induced biaxial bending\_, ACI structural journal, 108(5), pp. 610–619.
- Shi, X. Tan T., Tan K. and Guo Z.. (2004) \_Influence of concrete cover on fire resistance of reinforced concrete flexural members\_, Journal of Structural Engineering, 130(8), pp. 1225– 1232.
- Kigha, F., Sadeeq, J. A. and Abejide, O. S. (2015) \_Effects of temperature levels and concrete cover thickness on residual strength characteristics of fire exposed reinforced concrete beams\_, Nigerian Journal of Technology, 34(3), pp. 429–437.
- Barbhuiya, S., Tommy Y, Memon S., Nikraz H. (2014) \_Strength recovery of lightweight concrete under elevated temperature\_, in Advanced Materials Research. Trans Tech Publ, pp. 300– 305.
- El-Shaer, M. (2014) \_Structural Analysis For Concrete columns Subjected To Temperature\_, Acta Technica Corviniensis- Bulletin of Engineering, 7(2).
- Haddad, R. H. and Ashour, D. M. (2013) \_Thermal performance of steel fibrous lightweight aggregate concrete short columns\_, Journal of Composite Materials, 47(16), pp. 2013–2025.
- Al-Naqeeb F. and Al-Thairy, H. (2021) Structural behavior of lightweight reinforced concrete columns subjected to eccentric loads at high temperature, Al-Qadisiyah Journal for Engineering Sciences 14(2021), pp.083–091.
- Simulia, Analysis user's manual, 6.19 ed. Providence, Rhode Island, USA: Simulia, Dassault Systèmes, 2019.
- Albu-Hassan N. and Al-Thairy, H. (2020) Experimental and numerical investigation on the behavior of hybrid concrete beams reinforced with GFRP bars after exposure to elevated, Structures 28 (2020) 537–551.
- Felicetti R., Gambarov P.G., and Bamont P. (2012) Thermal and mechanical properties of light-weight concrete exposed to high temperature, Fire and Materials, 38, pp. 63–76.
- CEB Bulletin No. 213/214. CEB-FIP Model Code 90. London: Thomas Telford Ltd.; 1993.
- Hillerborg A. (1985) The theoretical basis of a Method to determine the fracture energy  $G_f$  of concrete. Mater Struct ,18(4):291–6.
- Al-Naqeeb F (2021) Behavior and Failure Modes of Lightweight Reinforced Concrete Columns at Elevated Temperatures under Concentric and Eccentric Loads. MSc thesis submitted to the council of college of engineering – University Of Al-Qadisiyah in partial fulfillment of the requirements for the degree of master of science in civil engineering (Structural Engineering)