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Behavior of Reinforced Concrete Columns Exposed to Elevated Temperature

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Abstract

The present study includes the behavior of reinforced concrete columns under elevated temperature. Four specimens of columns were cast for this purpose, with a constant length of 540 mm and a constant sectional area of 100×100mm, with a curing time equal to 28 days. Then, the specimens are exposed to elevated temperatures (150, 300, and 600 °C) and to room temperature. After air-cooling, the specimens are examined as hinged-hinged supported columns with a point load applied at the top of the column. The ultimate load capacity, mid-lateral deflection, mid-axial displacement, failure mode, and crack formation are investigated. The results indicate an appreciable effect on the strength of columns caused by exposure to high temperatures, which is greater than 300 °C, where a decrease in the value of ultimate load is observed when subjected to a temperature level of 600 °C, where the ultimate load becomes 35.2% of the original value. Additionally, the specimens exhibit large deformation under extreme temperatures, resulting from a substantial drop in column stiffness; the stiffness of the column heated to 600 °C decreases by about 55.5% relative to that at ambient temperature.

Keywords: Columns, High Temperature, Elevated Temperature, Residual Mechanical Properties, Residual Properties of Reinforcement.

1. Introduction

One of the greatest threats to structures is fire. Presently, although civilization exists in various areas of existence, particularly in the context of building and construction, and despite the excessive technological advances in structural design and the complete management of the evolution, fire (generated by catastrophes or insecure circumstances or even mistakes that occur) threatens humans' lives and causes the structure to be risky. The building must have adequate structural fire protection to allow people to evacuate before structural strength or stability is compromised [1]-[4].

Both concrete and reinforcing steel can combust if they are subjected to fire; both will demonstrate undesirable behavior (adverse action, such as physical and geometrical characteristics), and the level of acceptance relies on the heat level under fire, fire endurance duration, and the temperature variation inside sections of both concrete and steel [5][6].

Elevated temperatures resulting from fire significantly affect the resistance and distortion characteristics of various structural components, including compression, flexural, and torsional members. Columns are essential components of compression members that transmit vertical and lateral loads to the structure's base, so failure of significantly located columns may result in the partial or complete failure of the structure. As a result, a better understanding of the structural behavior and response of reinforced concrete columns subjected to fire is necessary as the first step for the safety of human lives and to avoid costly structural damage [6].

The elevated-temperature endurance of concrete structures depends on the strength of their structural members. The response of reinforced concrete structures subjected to elevated temperatures is influenced by the capacities of steel and concrete under heating [7].

Several studies [8], [9] indicated that a decline in the structural properties of concrete occurs at elevated temperatures. The rate

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of degradation is affected by the types of coarse aggregate and concrete used.

In recent years, extensive research on concrete structural members, such as columns exposed to high temperatures, has been conducted, assuming a uniform thermal distribution across various concrete members, in accordance with ASTM E119 [7]. The objective of these investigations was to determine the strength and the deformation properties of concrete at elevated temperatures and to find out the causes of the changes that the material underwent in consequence of heat, some of those researches studied effect type of used aggregate in concrete mix, conventional (natural) or sustainable (recycled) [10], [11], effect of applied load, concentric or eccentric[11], [12], effect of shape of cross section area, square or rectangular [13], effect of using fibered or polymer concrete material [14]-[17], effect of type of reinforcement using carbon fiber reinforced polymer bars (CFRP) [18] or using glass fiber reinforced polymer bars (GFRP) [19],[20] instead of conventional steel bars and effect of scale model of column length used, prototype versus both of 1/2.23 and 1/3 length scale factor [7].

The purpose of the present study is to determine the influence of elevated temperatures on the behavior of reinforced concrete columns. Also, to investigate the effect of temperature on the mechanical properties of the material used in the construction of columns, such as compressive strength of concrete, yield strength, and tensile strength of steel reinforcement.

2. Material and Methods

2.1. Tested Column Specimens

The specimens' dimensions (100×100mm×540mm) are used; they are constrained by the internal dimensions of the furnace (500×600×750mm), which is used for the heating process, as shown in Fig. 1. Each column is reinforced by a main steel reinforcement of Φ6mm and steel ties of Φ4mm placed with a spacing of 100mm center to center. Fig. 2 shows the details of the tested column specimens. The specimens were exposed to three temperature levels (150, 300, 600 °C); they were heated gradually with a slow heating rate of 2 °C/min. in accordance with the ASTM E119 temperature-time curve [7] shown in Fig. 3. Once the required temperature level is attained, the specimens are thermally saturated for 1.5 hours at that level. Then, the furnace is switched off, and the air-cooling openings are opened. The specimens are left in the furnace for about three hours, after which they are removed and stored in the laboratory to cool in air for about 20 hours before testing. A column is examined at an ambient temperature of 30 °C and used as a reference specimen to compare with the results of the heated specimens. Table 1 illustrates the column specimens included in this study.

Figure 1. The furnace used.

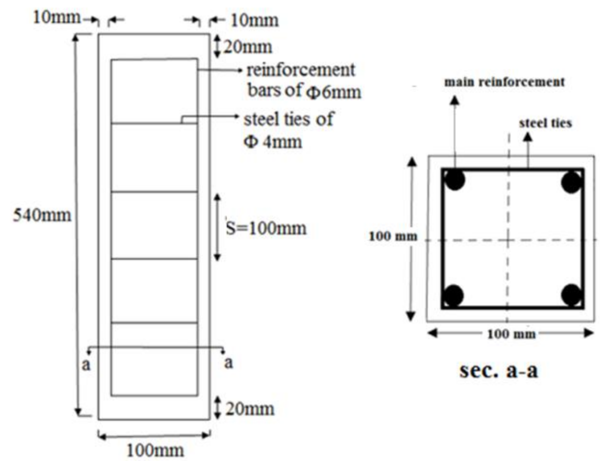

Figure 2. Details of specimens.

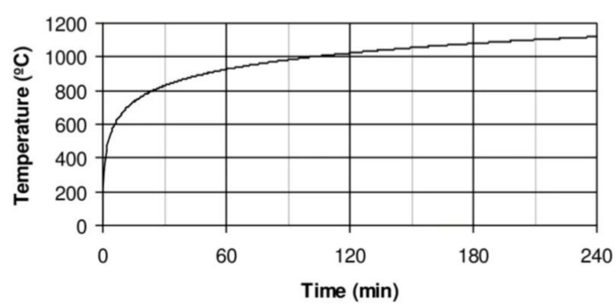

Figure 3. Standard time-temp. curve (ASTM E119).

2.2. Materials Properties

The concrete ingredients conform to BS882 Specifications [21], and were tested in compliance with B.S 1881 Specifications [22]. Ordinary Portland cement type (I); its chemical and physical properties are shown in Tables 2 and 3; they conform to the Iraqi Standard Specification IQS 5:1984 [23]. Natural aggregate and municipal water were used in the concrete mix. The fine aggregate passes through a 5mm sieve and has a fineness modulus of 3.71. At the same time, the coarse aggregate is crushed gravel with a maximum size of 14 mm and a bulk specific gravity of 2.65. The grading of the fine and coarse aggregates is shown in Tables 4 and 5, respectively. The reinforcement, Fig.4, was uncoated deformed steel bars of Φ6mm type B500DWR which has a nominal yield strength of grade 500MPa and tested yield strength of 667MPa used as main reinforcement and plain steel bars Φ4mm used as steel ties dimensioned according to the ACI-318 Code [24] and conformed with Iraqi Standard Specification IQS 209:1999 [25], and tested according to ASTM Specifications [26]. All tests were done in the Construction Materials Lab./ College of Engineering/ Mustansiriyah University.

Table 1. Columns' specimens' properties.

Column No.	Length (mm)	Sectional Area(mm²)	Temperature Stage (°C)	Type of cooling
C1			Room temp.	----------
C2	540	100×100	150	By air
C3			300	By air
C4			600	By air

Table 2. Chemical Composition of Cement.

Compound composition	Chemical composition	Percentage by weight	Limits of IQS 5:1984
Lime	CaO	62.22	-
Silica	SiO_2	22.01	-
Alumina	Al_2O_3	5.49	-
Iron oxide	Fe_2O_3	3.53	-
Magnesia	MgO	2.24	< 5
Sulfate	SO_3	1.92	< 2.8
Loss on ignition	L.O. I	1.10	< 4
Insoluble residue	I.R	0.50	< 1.5
Lime saturation factor	L.S. F	0.86	0.66 – 1.02
Main compounds (Bogue's equation) percentage by weight of cement			
Tricalcium silicate (C3S)		38.55	
Dicalcium silicate (C2S)		33.15	
Tricalcium Aluminate (C3A)		8.58	
Tetracalcium Aluminoferrite (C4AF)		10.73	

Table 3. Physical properties of cement.

Physical properties	Test result	Limit of IQS 5:1984
Fineness using Blaine air permeability apparatus (m^2/Kg)	3100	> 2300
Soundness using Autoclave method	0.19%	< 0.8%
Setting time using Vicat's instruments		
Initial (min.)	198	> 45 min
Final (hrs: min)	4:15	< 10 hrs
Compressive strength for cement paste cube (70.7 mm) at		
3 days (MPa)	19.4	> 15
7 days (MPa)	29.75	> 23
28 days (MPa)	48.33	-

Table 4. Grading of fine aggregate.

Sieve size (mm)	%Passing	
	Present work fine aggregate (%)	BS 882:1992 limits zone "M"
5.0	93.28	89 – 100
2.360	80.56	65 – 100
1.180	68.73	45 – 100
0.600	56.07	25 – 80
0.300	24.99	5 – 48
0.150	5.143	0 – 15

Table 5. Grading of coarse aggregate.

Sieve size (mm)	% passing	
	Present work coarse aggregate (%)	BS882:1992 limits
20.0	100	100
14.0	100	90 – 100
10.0	74.5	50 – 85
5.0	3.5	0 – 10
2.36	0	

Figure 4. Reinforcement steel details.

2.3. Mix Design

In producing the control and tested specimens, the dry concrete mix studied here is 1:1.5:3 (cement: fine aggregate: coarse aggregate) by weight, with a water/cement ratio of 0.45 by weight. According to B.S 1881 [22], three (150 x 150 x 150 mm) concrete cubes are cast with each mix to calculate the compressive strength (*fcu*) of the mix. This mix yields an average 28-day concrete cube compressive strength of about 31.5 MPa, measured at ambient temperature.

2.4. Loading, Setting Up, and Measuring Devices

After cooling the specimens in air, the test specimens are subjected to concentric axial load applied at the top of the column section with a simply supported height of 540mm. The columns are tested using a universal testing machine with a capacity of 3000kN, as shown in Fig. 5.

Two dial gauges of 0.01mm accuracy are attached to their locations by a magnetic clip, one to determine the lateral deflection at mid-height and the other to determine the axial displacement at mid-height of the column, as shown in Fig. 5.

At the start of loading (zero load), preliminary readings of the dial gauges are taken. After that, the load increases in 5 kN increments, and it is read at 5 kN intervals. In contrast, lateral deflection, central axial deformation, and crack pattern are measured continuously up to failure (i.e., the highest resistance point after which the load decreases).

Figure 5. Column specimen setup.

3. Results and Discussions

3.1. Control Specimen Results

Since the reinforced concrete columns consist of two main materials, which are concrete and steel, and to gain insight into the response of this type of construction after exposure to elevated temperature, both properties of concrete and steel after being subjected to elevated temperature are considered. According to B.S 1881[22], control specimens of three (150×150×150mm) cubes are cast with the mix to find out the compressive strength of the mix, and three other cubes are tested to find out the compressive strength after heating for each temperature level. Column specimens accompany concrete cubes; they are stored and cured in the same place and manner as column specimens. The average concrete compressive strength at room temperature is approximately 31.5 MPa, and the values for the other heated cubes are shown in Table 6. Also, the control specimens including three specimens of steel bars with length of 500 mm are tested according to ASTM Specifications [26] to find out the properties of steel at room temperature and other three specimens of steel bars are tested to find out the properties of steel after subject to extreme temperature for each temperature level, where the average yield strength and ultimate tensile strength of steel are about 667 and 950 MPa respectively at ambient temperature and the values of other heated steel reinforcement bars have be shown in Table 7.

3.1.1. Influence of high temperature on compressive strength of concrete

The test results are listed in Table 6. It is observed from this table that the compressive strength of concrete decreases when subjected to high temperature, except at a temperature of 150 °C, where an increase in compressive strength of about 3.5% from the original strength is observed. It might be this little increase in the compressive strength at 150 °C credited to the rapid evaporation of free water from both the pore structure and cement gel, which enhances interparticle surface attraction within the cement matrix. This, in turn, results in a denser microstructure and stiffer mechanical behavior under compressive stresses, contributing to the observed strength gain. Also, it is observed that a temperature of 300 °C has a slight effect on compressive strength, with a smooth increase of about 0.6% over the original strength. The same behavior is observed by researchers [27][8]. The compressive strength decreases rapidly beyond 300 °C, reaching 78.7% of the original strength after heating to 600 °C; the same behavior is observed by researchers [29], [30] for specimens of conventional aggregate mixes. This in strength occurs from the loss of bond between aggregate and cement paste because of different values of thermal expansion of cement paste and aggregate [31]. Additionally, exposure to high temperatures alters the natural position of aggregates and cement paste [32].

3.1.2. Influence of High Temperature on the Strength of Steel Reinforcement

Table 7 shows the yield strength and ultimate tensile strength of steel reinforcement after exposure to elevated temperatures.

Temperatures up to 300 °C have little effect on the mechanical properties of steel bars. Still, if the temperature is raised above this range, a decrease in yield strength and tensile strength will be observed; at 600 C, the yield strength and ultimate tensile strength are 93. 9% and 94.7% respectively, from the original values. The same behavior is observed by other studies [33].

3.2. Column Specimen Results

3.2.1 Ultimate Load Capacity

The failure loads obtained for each specimen in testing are presented in Table 8. It was observed that the ultimate load (the highest resistance point after which the load decreases) for all the specimens decreased with increasing temperature. In general, the first crack initiated at 23%-26.3 % of the ultimate load, as shown in Table 8. A decrease in the ultimate load of about 9.3% from original strength is observed when subjected to 150 °C for specimen (C2) and about 42.6% for specimen (C3) which is subjected to 300 °C but if the temperature is raised above this range, the decrease in the ultimate load will be more observed where at temperature of 600 °C the ultimate load of specimen (C4) becomes about 35.2% from that of ambient temperature load, the same behavior is observed by researcher [34] for unconfined square RC columns after heating (600 °C).

Table 6. Influence of temperature on compressive strength of concrete.

Column specimens	Temp. stage (°C)	Average compressive strength (MPa)	Standard deviation	Percentage residual compressive strength (%)
C1	Room temp.	31.5	0.5	100
C2	150	32.6	0.36	103.5
C3	300	31.7	0.26	100.6
C4	600	24.8	0.62	78.7

Table 7. Influence of temperature on reinforcing steel properties.

Temp. stage (°C)	Steel bar ϕ 6 mm						
	Yield strength (f_y)			Ultimate tensile strength (f_u)			
	Average MPa	Standard deviation	Residual strength (%)	Average MPa	Standard deviation	Residual strength (%)	* f_u/f_y
Room temp.	667	6.24	100	950	4.36	100	1.42
150	662	7.21	99.3	945	5	99.5	1.43
300	655	4.36	98.2	920	4.36	96.8	1.4
600	626	5.3	93.9	900	6.24	94.7	1.44

*The required Ratio of f_u/f_y is more than or equal to 1.25, which conforms to ACI code requirements [24].

Table 8. Test results of column specimens.

Column specimens	Temperature Stage(°C)	Cracking Load P_{cr} (kN)	Residual Ultimate Load P_u (kN)	P_{cr}/P_u (%)	percentage Residual $\frac{P_u}{P_u \text{ room temp.}}$ (%)	Max. Central Lateral Displacement (mm)	Max Mid-Height Axial Displacement (mm)
C1	Room temp.	31	135	23	100	1.28	0.43
C2	150	29	122.5	23.7	90.7	2.4	0.44
C3	300	19	77.5	24.5	57.4	3.02	0.42
C4	600	12.5	47.5	26.3	35.2	4.61	0.34

3.2.2. Load- central lateral displacement relationship

The lateral displacement is measured at the mid-height of the specimen. The values of lateral displacement for each specimen have been illustrated in Table 8 It is shown that as temperature increases, the lateral displacement increases for each specimen.

At the various temperature levels, the load–lateral displacement curves for the specimens have been shown in Fig. 6. The results of the test clarify that the lateral displacement increases slightly with the rise in temperature for the specimens heated to temperature levels of 150 °C and 300 °C, where the load– lateral displacement curves exhibit only slight differences with respect to room temperature curves. Beyond that level, the shape of the load–lateral displacement curves changes due to reduced strength in both concrete and steel at extreme temperatures, and the specimen becomes too brittle to withstand a small applied load. Thus, even a relatively small load will destroy the specimen, leading to a large lateral displacement; the same behavior is observed for unprotected columns with a gypsum layer in [35].

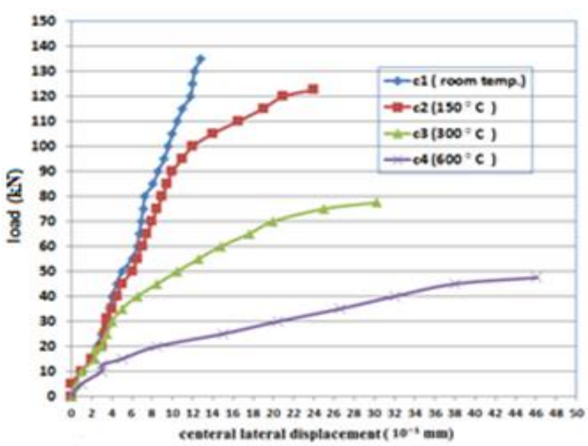

Figure 6. Load - central lateral displacement relationship for the specimens at different temperatures.

3.2.3. Load- mid-height axial displacement relationship

The mid-height axial displacement is measured at the mid-height of the specimen. The values of axial displacement for each specimen have been illustrated in Table 8. It is shown that the axial displacement decreases with increasing temperature for each specimen, but with a slight percentage increase (not considerable), especially at 150 °C.

Fig. 7 shows the load–mid-height axial displacement curves for specimens at various temperature levels. The experimental results indicate that as temperature increases, the axial displacement values decrease noticeably, especially at 300 °C and 600 °C, but not at 150 °C. The style of load – axial displacement curves exhibits only little difference from that of room temperature curves. Over that range, the load–axial displacement curves flatten due to the severe decrease in both concrete and steel strength at extreme temperatures; therefore, the specimen will have insufficient load resistance, and only a relatively low load can damage the column. The specimens exhibited a small axial displacement, which is more pronounced at 300 °C and 600 °C.

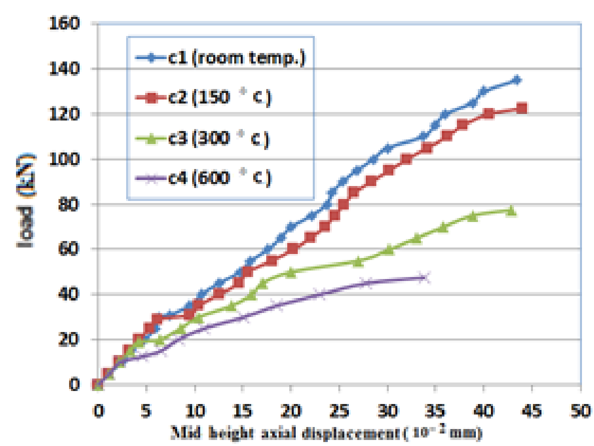

Figure 7. Load- mid-height axial displacement relationship for the specimens at different temperatures.

3.2.4. Load – temperature Curves

The residual load–temperature curves for all specimens are illustrated in Fig. 8. It is observed that at all temperature levels (150, 300, and 600 °C), the load behavior exhibits three stages under elevated temperature. Initially, at temperatures ranging from room temperature (30 °C) to 150 °C, a less considerable reduction in the ultimate load occurs. Then, between 150 °C and 300 °C, the ultimate load decreases significantly. Then, at the last stage, the behavior indicates a gradual, more noticeable reduction in the ultimate load as the temperature rises to 600 °C.

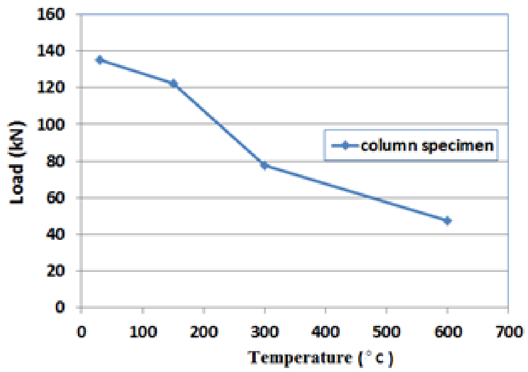

Figure 8. Variation of ultimate load with temperature for tested specimens.

3.2.5. Effective stiffness

A prediction of the deformation of tested columns under the effect of extreme temperatures can be obtained by evaluating their effective stiffness. Effective stiffness can be determined from the load-axial displacement curve as the percentage of the ultimate load to the observed axial displacement at this load. The values of the effective stiffness of each specimen are given in Table 9.

When the specimen is exposed to elevated temperatures, the retained water in the gaps evaporates, leaving capillary pores within the concrete mass and leading to a decrease in the mechanical properties of the concrete. Consequently, the stiffness of the specimens will reduce. The effective stiffness of specimens C2, C3, and C4 was decreased by about 11.5%, 41.2%, and 55.5%, respectively, when constructed with specimens C1, where specimens C1, C2, C3, and C4 were heated at room temperature, 150 °C, 300 °C, and 600 °C, respectively.

Table 9. Influence of elevated temperatures on the effective stiffness of tested specimens.

Column specimens	**Temp. stage (°C)**	**Residual ultimate load P_u (kN)**	**Max mid-height axial displacement Δ (mm)**	**Effective stiffness P_u/Δ (kN/mm)**	**Percentage residual (%)**
C1	Room temp.	135	0.43	314	100
C2	150	122.5	0.44	278	88.5
C3	300	77.5	0.42	184.5	58.8
C4	600	47.5	0.34	140	44.5

3.2.6. Failure mechanism and crack patterns

A common failure in most column specimens is crushing of the column end at the support, which becomes more apparent as temperature increases relative to ambient. The crushing at the end of the column may be attributed to a differential temperature distribution inside the furnace, where the column end is exposed to higher temperatures than other parts of the column, or to load intensity at the support. Figs. 9 to 12 describe the failure mechanism of the column specimens.

For all specimens, the cracks initiated at the support and extended toward the mid-height of the specimens, and on all faces of the column, these cracks expanded continuously with increasing temperature.

Figure 9. Crack pattern of specimen C1 after testing and failure Mechanism.

Figure 10. Crack pattern of specimen C2 after testing and failure Mechanism.

Figure 11. Crack pattern of specimen C3 after testing and failure Mechanism.

Figure 12. Crack pattern of specimen C4 after testing and failure Mechanism.

3.3. Study Limitations

Due to practical and resource constraints, the current investigation used only a single specimen per temperature level, which led to study limitations. However, the outcomes of a single specimen recorded in this study showed valuable initial insights and correspond with known experimental outcomes. Some existing literature used a single specimen per temperature level and gave outcomes that closely align with established experimental findings. For example, the observed behavior at high temperatures is consistent with the findings reported by [4] and [13], and these studies confirm the trends observed in this study.

4. Conclusions

From the test results, the following conclusions can be drawn:

1. The concrete compressive strength reduces after exposure to high temperature (except at 150 °C and 300 °C), where a slight increase of about 3. 5% and 0.6% takes place after exposure to 150 °C and 300 °C, respectively. The Percentage residual compressive strength after exposure to 600 °C is about 78.7%.
2. The temperature up to 300 °C does not affect the mechanical properties of steel bars. Still, when the temperature exceeds this range, a reduction in both yield strength and ultimate tensile strength will be observed, with the values at 600 °C being about 93.9% and 94.7%, respectively, of the original values.
3. The ultimate load capacity of columns drops considerably when exposed to elevated temperatures, and the rate of decrease depends mostly on the temperature grade.
4. When the temperature increases, the load-lateral displacement curve will be affected, where at extreme temperature levels, the relation becomes softer than that at ambient temperature. This is more pronounced at temperatures up to 600 °C. In comparison, the load-lateral displacement curves at 300 °C and below show only a slight deviation from the room-temperature curve.
5. The load- axial displacement curve varies with the increment of temperature, where at elevated temperatures up to 600 °C, the relation has a flatter slope than that at ambient temperature. In contrast, there is only a simple difference in the relationship with ambient temperature at temperatures of 300 °C and lower.
6. The effective stiffness of columns affected by an increase in temperature, where the values decreased by about 88.5%, 58.8%, and 44.5%, respectively, at 150 °C, 300 °C, and 600 °C, compared with that at room temperature.
7. Three periods for the load-temperature curve for columns exposed to temperature levels of (150, 300, and 600 °C) are described below:

- First, a minor reduction in ultimate load happens between room temperature and 150 °C
- Then, a considerable decrease in the ultimate load is noticed at an interval from 150 to 300 °C.
- The last period exhibits a progressively more noticeable drop in the ultimate load with the increment in temperature grade, especially upon exposure to 600 °C.

8. During ordinary and extreme temperatures, the destruction of the end of the column at the support is an observed failure mechanism that happens in all column specimens, characterized by the formation of cracks starting from the support and expanding to the middle height of the specimens and along the surface sides of the column. This style of failure will become more evident as the temperature stage increases.

5. Recommendations

Based on the conclusions in Section 4, there is no expected danger of column collapse at normal temperature up to 300 °C, at which point the column retains about 50% of its capacity. However, when the temperature exceeds this level, the probability of collapse increases markedly, especially at 600 °C and above. Furthermore, the relationship between load and deformation (lateral displacement or mid- height axial displacement) indicates the nature of failure. Therefore, the shape of the deformation profile, plotted against column height, can help determine the column's structural integrity. In any case, the column's stiffness will decrease with temperature increase, making it easier to assess its suitability.

Also, increasing the resistance of column ends at supports, rather than allowing them to shatter under high heat, can alter the failure mode by using materials with desirable properties, such as high-strength concrete as a hybrid material, steel plates, carbon fibers, and others.

This study concerns short columns made of normal concrete and subjected to limited temperature levels. So, to obtain more results, other studies that consider parameters such as high-strength concrete, long columns, and elevated temperatures up to 800 °C may be investigated.

Conflict of interest

The authors declare there are no competing interests.

Author Contribution

Ahmed H. Daiyr Al-Ibadi: proposed the research problem.

All authors conducted the work equally.

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References

[1] B. Kanagaraj, N. Anand, and E. Lubloy, “Fire performance of concrete: A comparative study between cement concrete and geopolymer concrete & its application—A state-of-the-art review,” *Case Stud. Chem. Environ. Eng.,* vol. 11, Art. no. 101212, 2025. https://doi.org/10.1016/j.cscee.2025.101212

[2] A. Hassan, F. Khairallah, H. Elsayed, A. Salman, and H. Mamdouh, “Behavior of concrete beams reinforced using basalt and steel bars under fire exposure,” *Eng. Struct.*, vol. 238, Art. no. 112251, 2021.

[3] N. Hisbani, M. A. Shams, M. A. Stanikzai, H. Almujibah, and O. Benjeddou, “Flexural performance of reinforced concrete beams exposed to uncontrolled fire with and without plaster protection,” *Sci. Rep.*, vol. 15, no. 1, Art. no. 31361, 2025. https://doi.org/10.1038/s41598-025-00146-8

[4] G. Z. Nikolai, "Thermal properties of concrete under sustained elevated temperature," *ACI Special Publication SP-25, Temperature and Concrete*, Detroit, MI, USA, pp. 1-31, 1971. https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/17330

[5] E. Garcia-Castillo, I. Paya-Zaforteza, and A. Hospitaler, “Fire in heritage and historic buildings, a major challenge for the 21st century,” *Dev. Built Environ.*, vol. 13, Art. no. 100102, 2023. https://doi.org/10.1016/j.dibe.2022.100102

[6] M. S. Mirza and T. T. Lie, "Response of direct models of reinforced concrete columns subjected to fire," *ACI Structural Journal*, vol. 87, no. 3, pp. 313-325, May-Jun. 1990. https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&ID=2638

[7] ASTM E-119, "Standard test methods for fire tests of building construction and materials," 2022. [Online]. Available: https://standards.iteh.ai/catalog/standards/astm/e9492688-caec-429c-a756-267071a5227d/astm-e119-22

[8] A. Venkateswara Rao and M. Achyutha Kumar Reddy, "Performance of concrete at elevated temperature," *IOP Conference Series: Earth and Environment Science*, vol. 796, 2021, doi: https://doi.org/10.1088/1755-1315/796/1/012038.

[9] P. Li, J. Liu, S. Duan, and R. Huang, "Variation pattern of the compressive strength of concrete under combined heat and moisture conditions," *Materials*, vol. 16, no. 4, p. 1548, 2023, doi: https://doi.org/10.3390/ma16041548.

[10] Z. Chen, Y. Liang, L. Mo, and M. Ban, "Residual properties and axial bearing capacity of steel-reinforced recycled aggregate concrete column exposed to elevated temperatures," *Frontiers in Materials*, vol. 7, p. 187, 2020, doi: https://doi.org/10.3389/fmats.2020.00187.

[11] Z. Chen, H. Liao, J. Zhou, and P. Ye, "Eccentric compression behavior of reinforced recycled aggregate concrete column after exposure to elevated temperature: Experimental and numerical study," *Structures*, vol. 43, pp. 959-976, 2022, doi: https://doi.org/10.1016/j.istruc.2022.07.018.

[12] F. Al-Naqeeb and H. Al-Thairy, "The behavior of reinforced concrete columns exposed to eccentric loads at high temperature," *ICCES, Journal of Physics: Conference Series*, vol. 1895, 2021, doi: https://doi.org/10.1088/1742-6596/1895/1/012055.

[13] T. T. Lie and R. J. Irwin, "Method to calculate the fire resistance of reinforced concrete columns with rectangular cross section," *ACI Structural Journal*, vol. 90, no. 1, pp. 52-60, Jan.-Feb. 1993. [Online]. Available: https://www.scribd.com/document/156300361/Paper-Method-to-Calculate-the-Fire-Resistance-of-Reinforced-Concrete-Columns-With-Rectangular-Cross-Section-NRCC-33114

[14] M. Elsayed, F. Althoey, B. A. Tayeh, N. Ahmed, and A. Abd El-Azim, "Behavior of eccentrically loaded hybrid fiber-reinforced high strength concrete columns exposed to elevated temperature," *Journal of*

Materials Research and Technology, vol. 20, pp. 1003-1020, 2022. [Online]. https://doi.org/10.1016/j.jmrt.2022.05.079

[15] S. Khalaf, F. Abed, A. El Refai, Y. Alhoubi, S. Ramzi, and H. Hajiloo, "PBO-FRCM and CFRP strengthened reinforced concrete columns: In fire and post-fire behavior," *Construction and Building Materials*, vol. 468, 2025. [Online]. https://doi.org/10.1016/j.conbuildmat.2025.142306

[16] S. Chandra and U. K. Sharma, "Mitigating fire resistance losses in corroded reinforced concrete columns using a hybrid fibers approach," *Engineering Structures*, vol. 340, 2025, doi: https://doi.org/10.1016/j.engstruct.2025.120755.

[17] L. Yin, Y. Li, P. Chen, H. Cheng, and L. Gao, "Axial compression mechanical properties of steel-fiber-reinforced alkali slag concrete columns strengthened using carbon fiber-reinforced polymers at high temperature," *Construction and Building Materials*, vol. 474, 2025, doi: https://doi.org/10.1016/j.conbuildmat.2025.141164.

[18] S.-W. Yoo and J. F. Choo, "Behavior of CFRP-reinforced concrete columns at elevated temperatures," *Construction and Building Materials*, vol. 358, 2022, doi: https://doi.org/10.1016/j.conbuildmat.2022.129425.

[19] M. M. Abed Elslam, M. H. Agamy, M. Genidi, and M. Salem, "Fire resistance of square concrete columns reinforced with GFRP bars: Experimental and numerical investigation," *Engineering Structures*, vol. 305, 2024, doi: https://doi.org/10.1016/j.engstruct.2024.117732.

[20] A. Abushanab, U. Ebead, M. Genedy, and G. J. Ghattas, "Behavior of reinforced concrete columns made with seawater and glass FRP bars and subjected to high temperatures," *Results in Engineering*, vol. 24, 2024. https://doi.org/10.1016/j.rineng.2024.102339

[21] BS 882, "Specification for aggregates from natural sources for concrete," British Standard, pp. 1-5, 1992.

[22] BS 1881: Part 116, "Method for determination of compressive strength of concrete cubes," British Standard, 1983.

[23] Iraqi Specification No. 5 (IQS 5), "Portland cement," Baghdad, Iraq, 1984, p. 8.

[24] ACI Committee 318, "Building code requirements for structural concrete (ACI 318-2007, ACI 318R-2007)," American Concrete Institute, 2007.

[25] Central Organization Standardization & Quality, "Iraqi Specification No. 209: Carbon steel bars for the reinforcement of concrete," Baghdad, Iraq, 1999.

[26] ASTM A615/A615M-15a, "Standard specification for deformed and plain carbon-steel bars for concrete reinforcement," West Conshohocken, PA, USA, 2015.

[27] H. Weigler and R. Fischer, "Influence of high temperatures on strength and deformations of concrete," *ACI Special Publication SP-34*, vol. 1, pp. 481-493, 1972.

[28] G. Pachide, M. Gholhaki, A. Aljenab, and O. Rezaifar, "Compressive strength ratios of concretes containing pozzolans under elevated temperatures," *Heliyon*, vol. 10, no. 5, 2024, doi: https://doi.org/10.1016/j.heliyon.2024.e26932.

[29] B. Ouzturk, A. I. Turan, A. Kumbasaroglu, H. Yalciner, and Y. Ayaz, "The effect of elevated temperature on the mechanical properties of concrete produced with raw perlite aggregate," *Journal of Building Engineering*, vol. 118, 2026, doi: https://doi.org/10.1016/j.jobe.2025.115093.

[30] K. Sahani, S. Ghosh, R. Chatterjee, and A. K. Samanta, "Investigation on compressive strength and microstructural characteristics of slag-fly ash-based sustainable concrete under elevated temperature," *Journal of Structural Fire Engineering*, vol. 16, pp. 345-363, 2025, doi: https://doi.org/10.1108/JSFE-08-2024-0033.

[31] D. N. Nasser, "The effect of heat on some properties of concrete," M.S. thesis, Dept. Building and Construction Eng., Univ. of Technology, Baghdad, Iraq, 1983, p. 116.

[32] G. T. G. Mohamedbhai, "Effect of exposure time and rate of heating and cooling on residual strength of heated concrete," *Magazine of Concrete Research*, vol. 38, no. 136, pp. 151-158, Sep. 1986. https://doi.org/10.1680/macr.1986.38.136.151

[33] J. Zhao, Y. Jiang, and X. Li, "Flexural behavior of concrete beams reinforced with high-strength steel bars after exposure to elevated temperatures," *Construction and Building Materials*, vol. 382, 2023, doi: https://doi.org/10.1016/j.conbuildmat.2023.131317.

[34] A. Abadei and R. Masmoudi, "Experimental investigation of heat-damaged reinforced concrete columns strengthened with different schemes," *Structures*, vol. 69, 2024, doi: https://doi.org/10.1016/j.istruc.2024.107282.

[35] M. S. Farhan and A. M. I. Said, "Fire resistance of square reinforced concrete columns with one-face gypsum layer insulation under axial loading," *Results in Engineering*, vol. 20, 2023. https://doi.org/10.1016/j.rineng.2023.101294