Residual Strength and Crack Propagation of Reinforced Concrete Columns under High Temperatures

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ABSTRACT

In the present study, reinforced concrete columns with dimensions of 200×200×1200 mm were tested under static loading and high temperatures. In the experimental work, square cross-section columns with compressive strength of 28 MPa were tested up to failure. Mechanical properties such as compressive strength, were examined under static load and then under temperatures such as 500 and 800 °C. Column specimens with the same geometry and with concrete covers of 10 and 17 mm were also put under test. Mode of failure, ductility, stiffness, and energy dissipation for all tested specimens are discussed. The test results showed that the strength capacity of reinforced concrete columns was affected by the column cover. The increment in temperature led to a reduction in the strength-carrying capacity of the columns and increased the axial and lateral displacements. The static compressive strength was reduced by 36.84 and 48.81% when the applied temperature was 500 and 800 °C, respectively. The stiffness of the specimen with 17 mm cover was 29.27 and 46.86% less than that of 10 mm cover for axial and lateral displacement, respectively. Also, the specimen with 10 mm cover exhibited decreased energy dissipation by 1.69 and 12.54% for axial and lateral displacement.

Keywords-residual column strength; column crack propagation; reinforced concrete column; high temperature; ductility; stiffness; energy dissipation; mode of failure

I. INTRODUCTION

During the recent years, many researchers have focused on the effect of high temperate on the behavior and strength of concrete columns. When structural elements, such as the columns, are subjected to high temperatures, the strength carrying capacity and the bond are reduced. When concrete is exposed to high temperatures, this leads its resistance is decreased to 25 and 75% at 300 and 600 °C, respectively [1]. The residual strength achieved after a fire is influenced by different factors that produce concrete mechanical properties [2]. After fire exposure, concrete can recover a large proportion of its compressive strength if the temperature did not exceed 500 °C [3]. Specimens under sustained load during heating show relatively higher compressive strength compared to those that are not loaded during heating [4], due to the development of cracks under compression load that consequently slow the entry of heat through the specimen [5]. It could also be due to the presence of compression inhibiting the development of tensile cracks generated by differential expansion.

In terms of tensile strength of concrete, very little work that has been done on this area. At 400 °C, the tensile strength of concrete decreases with temperature to about 55-70% of its original value [4]. The modulus of elasticity decreases rapidly with rising temperature, depending on the aggregate type. At 400 °C, only 40-50% of the original stiffness remains. Siliceous aggregate concrete loses more stiffness than lightweight aggregate concrete [4]. Above 400 °C, the stress-strain behavior of concrete changes considerably, and it experiences a much larger degree of ductility. It has been observed that with increased temperature the strength and initial stiffness reduce and ductility increases [6]. Authors in [7] applied high temperatures on normal and high strength concrete columns with length around 3000 mm. The experimental investigation showed that high strength concrete specimens' capacities are lower than normal weight concrete's. Authors in [8] investigated the effect of axial restraint on columns under fire loads in case of fixed end specimens. The test results indicated that for specimens under the same load ratio, the axial restraint ratio has less effect on the development of column axial load. Authors in [9] investigated the load carrying capacity of columns under fire temperature levels of 400, 600, and 900 °C for a period of exposure of 30 min at the age of 28 days. The results showed that the values of theoretical analysis are close to the ones obtained from the experimental tests. Authors in [10] declared that the strength resistance capacity of the columns decreases by 14.29, 28.57, and 42.86% at 400, 500, and 650 °C respectively. Increase in the applied temperature led to increase in the lateral and axial deflection of the tested columns. Increases in the main and tied reinforcement ratio enhance the strength capacity of the tapered column and improve ductility.

Authors in [12] utilized numerical analysis using the parametric fire model of Eurocode-1 to estimate the post-fire axial and lateral performance of reinforced concrete columns. Their study included two main steps. In the first step, the axial loadbearing capacity was evaluated from a parametric study for cantilever columns. In the second step, lateral load capacity, force-displacement behavior, stiffness, ductility, energy dissipation capacity, and residual displacements were estimated to determine the impact of fire on the behavior of the columns under lateral loads. The results showed that both the lateral load capacity and the ductility of the reinforced concrete columns decreased significantly due to fire exposure. Authors in [13] investigated the behavior and strength of Concrete Filled Steel Tube (CFST) columns under the effect of axial compression load considering parameters such as the diameter to thickness ratio and the height to diameter ratio. Strength carrying capacity and axial and lateral deformations with axial and lateral strains were explored. The test results showed that smaller heights within the same material gave higher strength capacity. The stiffness of the CFST is more than concrete and hollow steel section specimens' due to its high strength capacity with low displacement. The composite action of CFST gave more stiffness [13]. Authors in [14] simulated two columns using the finite element software SAFIR. The first was a steel profile column and the second was a Steel Profile Partially Encased in Concrete (SPPEC) column. Both columns were heated on four sides for 1 hr using the ISO 834 standard fire curve. Two boundary conditions were considered for both columns, simply and doubly supported and loaded with eccentric loading. A thermomechanical study was also carried out using the results of the thermal analysis to determine the influence of slenderness on the resistance of the steel and the partially encased profile in concrete columns under fire solicitation. The results proved that the slenderness negatively influences the fire resistance of the steel and composite columns and that the behavior of the composite columns is significantly better than that of the steel ones [14].

In this paper, the residual strength and crack propagation of prismatic reinforced concrete columns under high temperatures are investigated. The considered parameters included column cover of 10 and 17 mm and applied temperature of 500 and 800 °C, respectively.

II. EXPERIMENTAL WORK

A. Mechanical Properties of Concrete

The concrete specimens were tested for compressive strength and modulus of elasticity. The first examination was carried out under the influence of static load until failure. Then, temperatures of 500 and 800 °C were applied. The failure load of cylindrical concrete specimens was 500.3 kN and the compressive strength was 28.31 MPa at 28 days. The splitting tensile strength with failure load of 183.3 kN was 2.59 MPa. Three different moduli of elasticity, tangent, secant, and chord, were tested under static load. Figure 1 shows the stress-strain behavior of concrete cylinders under static load.

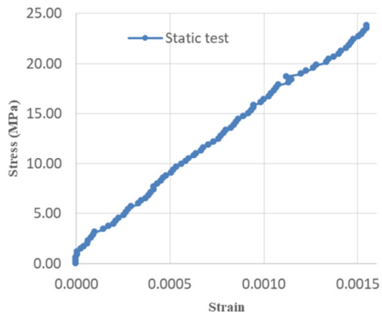


Fig. 1. Stress-strain behavior of tested concrete cylinders.

TABLE I. STATIC MODULUS OF ELASTICITY OF CONCRETE

Mark type	Tangent	Secant	Chord
Modulus of elasticity (MPa)	27595	25565	22247

The behavior started as linear up to the inflection point. Afterward the behavior became nonlinear and the stress was not proportional with strain. The magnitude of the modulus of elasticity is shown in Table I. Based on the ACI-318, the modulus of elasticity is 25007 MPa and the compressive strength is 28.31 MPa [15].

B. Mechanical Properties under Temperature Load Test

Two groups of concrete cylinders, each consisting of three specimens, were heated under 500 and 800 °C. The temperature-time behavior of the specimens is shown in Figures 2 and 3. Figure 4 presents the stress-strain behavior of tested concrete specimens. Table II lists the modulus of elasticity values. The temperature at the cover was higher than that recorded in the core. Figure 5 shows the behavior of concrete cylinder stress-strain under static and transit dynamic load. It is clear from the behavior of concrete that its resistance to static loads is higher than its resistance to temperature. Whenever the applied temperature increases, the increase begins to strain and the curve is towards the horizontal axis, meaning that the concrete has begun to lose its resistance and strength and stiffness decrease. Table III lists the residual strength and the reduction in compressive strength of concrete due to applied temperature loads based on static compressive strength.

TABLE II. COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY UNDER TEMPERATURE LOAD

Temperature (°C)	Compressive strength (MPa)	Secant modulus of elasticity (MPa)
500	14.49	17892
800	17.88	19874

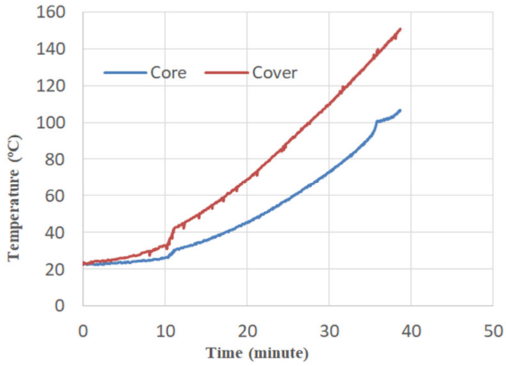


Fig. 2. Temperature-time behavior of tested concrete cylinders at 500 °C.

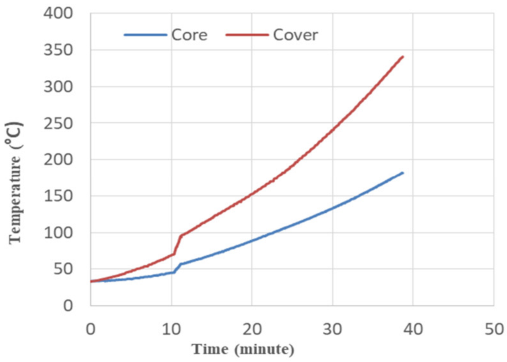


Fig. 3. Temperature-time behavior of tested concrete cylinders at 800 °C.

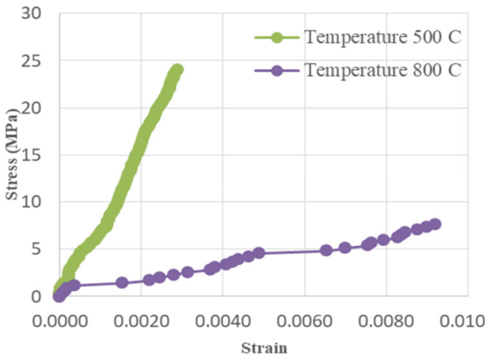


Fig. 4. Stress-strain behavior of concrete cylinders at 500 and 800 °C.

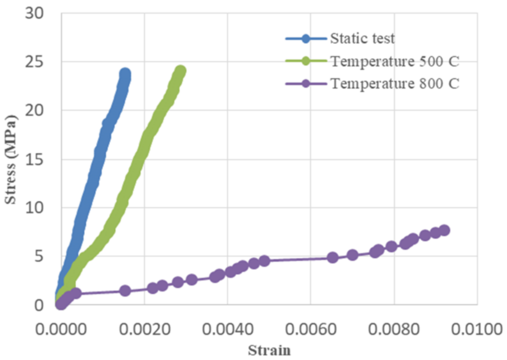


Fig. 5. Stress-strain behavior comparison of concrete cylinders under static temperature, 500, and 800 °C.

TABLE III. RESIDUAL STRENGTH AND REDUCTION IN COMPRESSIVE STRENGTH

Applied load	Compressive strength (MPa)	% Reduction in strength	% Residual strength
Static	28.31	---	---
500 °C	17.88	36.84	63.16
800 °C	14.49	48.81	51.12

C. Specimen Details

Six specimens were tested under static and temperature load. The dimensions and geometry of the tested column were 200×200×1200 mm reinforced by 4ϕ12 as longitudinal reinforcement and ϕ6@190 mm center to center tie reinforcements as shown in Figure 6. The specimen markings are listed in Table IV. The specimen mark was based on the classification of geometry, cover, and applied load. An example follows: PC-C10-H500 in which, PC (Prismatic Specimen) is the cross section type, C*XX* is the Concrete cover (*XX* = 10 or 17 mm), and H*YYY* is the maximum elevated temperature (*YYY* = 500 or 800 °C)

TABLE IV. SPECIMEN MARKS

Specimen mark	Concrete cover (mm)	Applied temperature (°C)
PC-C10-Control	10	Static
PC-C10-H500		500 and 800
PC-C10-H800		
PC-C17-Control	17	Static
PC-C17-H500		500 and 800
PC-C17-H800		

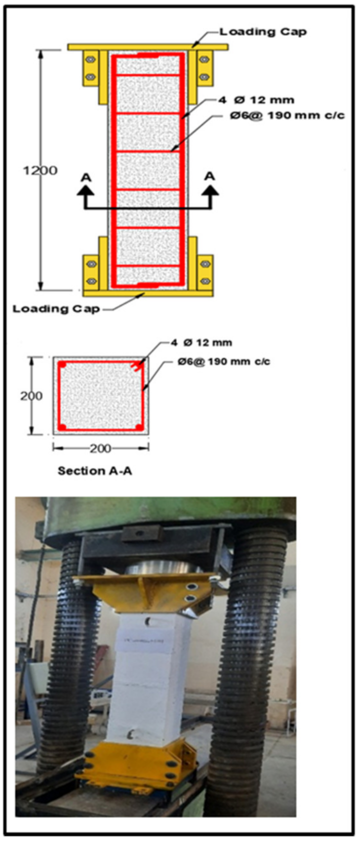


Fig. 6. Specimen details.

Fig. 7. LVDT locations.

Fig. 8. Furnace chamber.

The specimens were tested under static (normal) load (the load was applied at the center of cross section and there was no eccentricity). The applied temperature load was applied from the beginning up to the specified temperature using an electric furnace designed for conducting such high-temperature experiments with dimensions of 280 mm width, 460 mm length, and 750 mm height. The heat chamber has 8 heaters with power of 1300 Watt each, therefore three phase/ 220-volt AC power was needed. The heaters were extended along the circumference of the chamber with spacing of 100 mm along the height to ensure a uniform temperature distribution inside the chamber and around the specimen. The furnace chamber has three fixed sides and a moving one to slide the specimen inside the furnace. The furnace can take only one specimen each time. The furnace contains two type K thermocouples inside the chamber. The first thermocouple is connected to a data logger to record the real time temperature. The second one is connected to the controller of the furnace (PLC board) to control the rate of the temperature applied to the specimen. Figures 6 and 7 show the specimen geometry and dimension details. A steel cap was applied at the ends of each column to prevent stress concentration. Figure 7 presents the locations of LVDT at the center and at 200 mm above and below the center line of the specimen. Figure 8 shows the furnace chamber with the heat controller.

III. RESULTS AND DISCUSSION

A. Behavior and Strength under Static Temperature

Every structural element, such as reinforced concrete columns, is tested first under static loading (gravity load). The control specimen was tested to ensure the strength bearing capacity and then the temperature load was applied. Axial compression load was applied to the prismatic reinforced concrete columns at the center of cross section. Figure 9 shows the loading and unloading-axial displacement of control specimens PC-C10 and PC-C17. Specimen PC-C10 gave higher strength capacity and lower axial (longitudinal) displacement because the concrete core (concrete dimensions without cover) is bigger than that of the specimen with 17 mm cover and the column is a compression member (concrete resisted compression load).

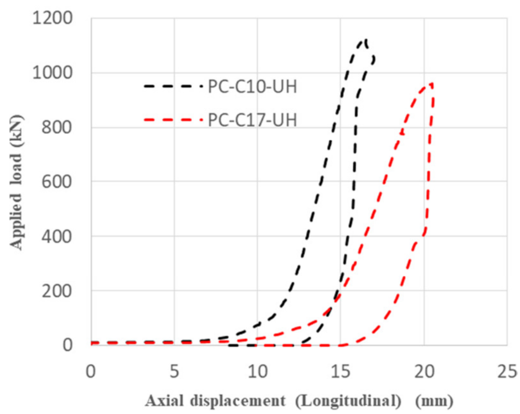


Fig. 9. Load-axial displacement of control specimens PC-C10 and PC-C17.

Figures 10 and 11 present the loading and unloading-lateral (buckling) displacement of control specimens PC-C10 and PC-C17, in which the lateral displacement was recorded 200 mm above the center line of the specimen (top), at the center of the specimen (middle), and 200 mm below the center line of the specimen (bottom). The middle displacement was the sum of the displacements from the bottom up to the center line, therefore the lateral displacement was more.

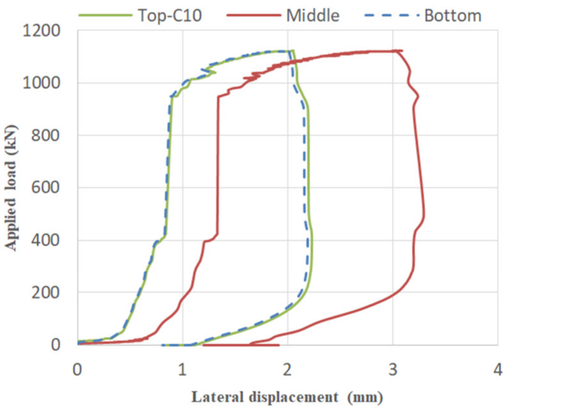


Fig. 10. Loading and unloading-lateral (buckling) displacement of PC-C10.

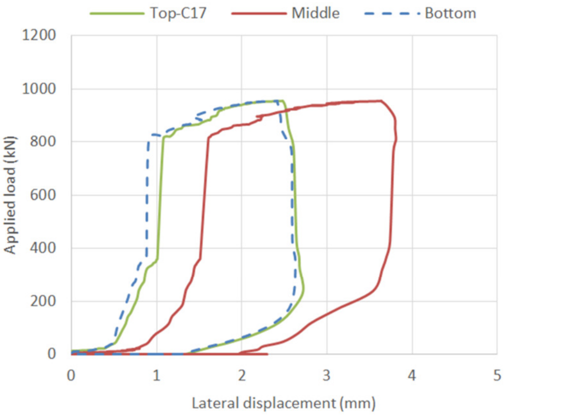


Fig. 11. Loading and unloading-lateral (buckling) displacement of PC-C17.

Specimen PC-C10 gave higher strength capacity and lower lateral displacement than PC-C17 due to the cover. The increase in the concrete cover reduces the load resistance of the column to lateral displacement (buckling) due to the reduction in concrete stiffness. Table V lists the maximum and failure loads with corresponding axial and lateral displacements for the control specimens PC-C10 and PC-C17 static temperature. Figure 12 shows the comparison between the control specimens with 10 and 17 mm cover. Increase in cover width lead to reduction in strength carrying capacity by 13% and increased lateral displacement by 23.05% and 63.72%.

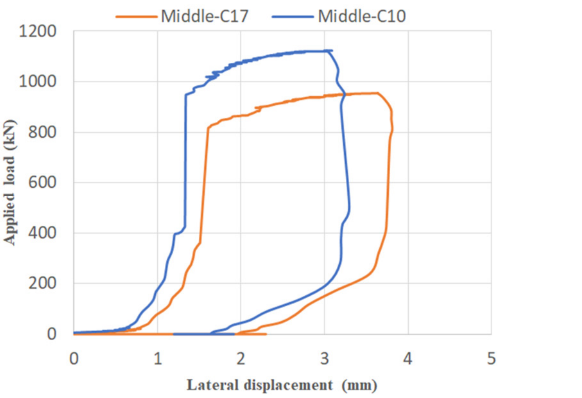


Fig. 12. Middle lateral displacement of PC-C10 and PC-C17.

TABLE V. MAXIMUM AND FAILURE LOADS WITH CORRESPONDING AXIAL AND LATERAL DISPLACEMENTS

Specimen	Maximum load P_m and failure load P_f (kN)		Axial displacement at P_m and P_f (mm)		Lateral displacement at P_m and P_f (mm)		
	P_m	P_f	Δ_m	Δ_f	δ_{Bm} (δ_{Bf})	δ_{Mm} (δ_{Mf})	δ_{Tm} (δ_{Tf})
PC-C10 Control	1100	1050	16.53	17.00	2.01 (2.15)	2.26 (3.24)	2.02 (2.19)
PC-C17 Control	958	897	20.34	21.25	2.43 (2.58)	3.70 (3.82)	2.48 (2.62)

B. Behavior and Strength under Elevated Temperatures

Two different temperatures, 500 and 800 °C, were applied. The tested specimens had the same geometry with the control specimens. The temperature was applied with a rate of 10 °C/min up to the designed final value. Figures 13 and 14 show the behavior of specimens PC-C10 and PC-C17. Table VI lists the strength capacity of each specimen with corresponding axial and lateral displacements.

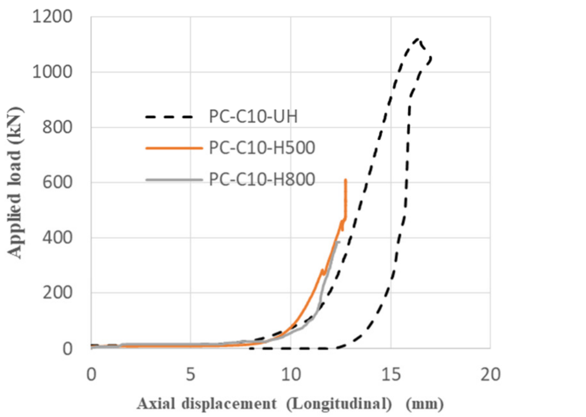


Fig. 13. Comparison between heated and unheated specimens with 10 mm cover.

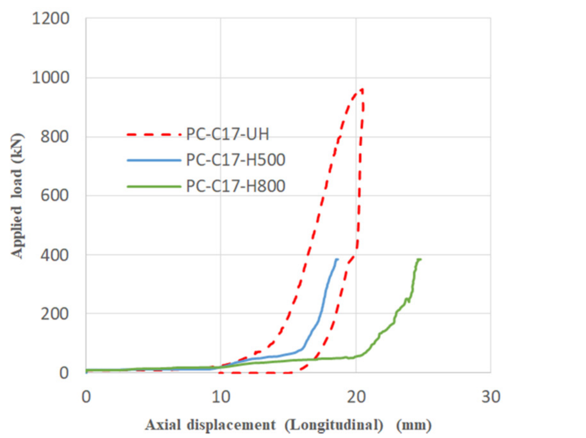


Fig. 14. Comparison between heated and unheated specimens with 17 mm cover.

TABLE VI. MAXIMUM AND FAILURE LOADS WITH CORRESPONDING AXIAL AND LATERAL DISPLACEMENTS

Specimen	***Maximum load P_{mh} (kN)***	**Axial displacement at P_{mh} and P_f (mm)**	**Lateral displacement at P_{mh} and P_f (mm)**		
	P_{mh}	Δ_{mh}	δ_{Bmh}	δ_{Mmh}	δ_{Tmh}
PC-C10-H500	590	12.75	0.5	1.32	1.6
PC-C10-H800	385	12.29	4.39	6.93	5.59
PC-C17-H500	385	18.50	1.63	1.85	2.66
PC-C17-H800	370	15.90	2.31	4.03	3.98

C. Stiffness of the Tested Specimens

The obtained load-displacement (axial and lateral) curves were acquired from the recorded measurements at mid, top, and bottom of the central mid height of each specimen (300 mm away from the mid height for each specimen). In the static tests, the applied axial normal load was applied at the bottom cross section center. Stiffness is the resistance of an elastic body to displacement or deformation by an applied force. The stiffness is defined as the ratio of the ultimate load to ultimate load displacement (axial and lateral). Table VII lists the calculated stiffness values of each specimen.

TABLE VII. AXIAL AND LATERAL STIFFNESS UNDER STATIC TEMPERATURE

Specimen	Stiffness-axial displacement k_a (kN/mm)	Stiffness-lateral-middle-displacement k_l (kN/mm)
PC-C10-Control	66.55	486.73
PC-C17-Control	47.10	258.65

D. Ductility of the Tested Specimens

Ductility is the ability of a concrete member, such as a reinforced concrete column, to bear or endure considerable displacements before failure. The ductility of concrete column is very important because it provides signs of collapse or failure. Concrete is a brittle material, i.e. it fails within the plastic zone (no elastic-plastic zone). The ductility for all tested specimens was calculated by dividing the displacement (axial and lateral) at ultimate load by the displacement at yield. Table VIII shows the results.

TABLE VIII. AXIAL AND LATERAL DUCTILITY OF TESTED SPECIMENS UNDER STATIC LOADINGS

Specimen	Ductility (axial)	Ductility (lateral)
PC-C10-Control	1.04	1.43
PC-C17-Control	1.04	1.03

E. Energy Absorption of the Tested Specimens

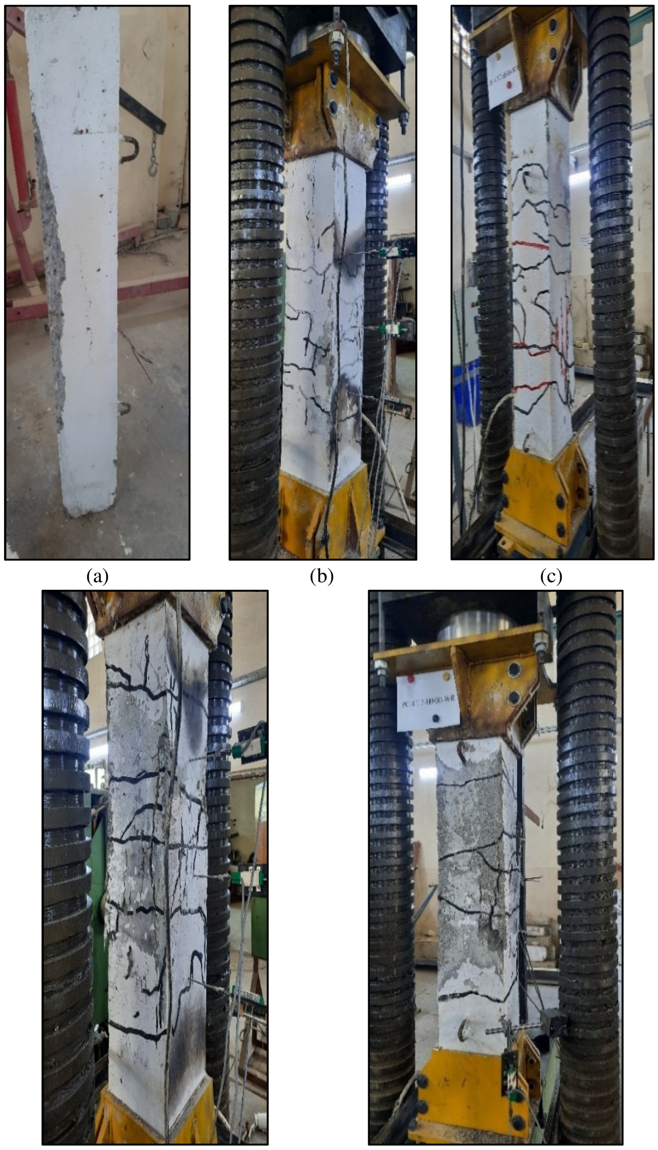
The energy absorption is the area under the load-(longitudinal and lateral) displacement curve. The resistance of plain concrete against applied load is less due to the low energy dissipation and low resistance in tensile strength. The energy absorption can be considered for the evaluation of the post-cracking behavior of reinforced concrete columns. Table IX lists the energy dissipation values of the tested specimens.

TABLE IX. ENERGY DISSIPATION UNDER STATIC TEMPERATURE

Specimen	Energy dissipation (axial) (kN.mm)	Energy dissipation (lateral)-middle (kN.mm)
PC-C10-Control	3613	3975
PC-C17-Control	3675	4545

F. Mode of Failure

Figure 15 shows the crack propagation under static and temperature loads as 500 and 800 °C. The final failure that occurred in the concrete columns under static load was flexural. When elevated temperature was applied, the intensity of the cracks increased.



(a) (b) (c) (d) (e)

Fig. 15. Crack propagation: (a) Control specimen-static test, (b) PC-C10-H500, (c) PC-C17-H500, (d) PC-C10-H800, and (e) PC-C17- H800.

G. Discussion

The experimental tests on reinforced concrete columns under static and temperature loads showed that the increased concrete cover leads to reduced strength capacity of concrete columns because the concrete core becomes smaller. When the reinforced concrete column specimens are exposed to elevated temperatures, the chemical composition and physical structure of concrete change considerably, so its compressive strength reduces. Table X lists the comparison between the two control specimens PC-C10 and PC-C17, with PC-C10 being used as the reference. The stiffness of specimen PC-C17 was less than that of PC-C10 because the strength capacity was more and the displacement less due to the moment of inertia of core concrete column in the case of 10 mm cover that lead increased elasticity. When the energy dissipation becomes less, the applied load will be absorbed by the column which works as full support and the other structural elements in the building become safer.

TABLE X. COMPARISON BETWEEN CONTROL SPECIMENS UNDER STATIC TEMPERATURE

Specimen	Decrease in stiffness (%)		Decrease in energy dissipation (%)	
	Axial	Lateral	Axial	Lateral
PC-C10-Control	---	---	1.69	12.54
PC-C17-Control	29.27	46.86	---	---

Regarding specimens under temperature load, the applied service gravity load was 35% of the ultimate strength capacity. The increase in the applied temperature lead to a decrease of elasticity, the column stiffness became less, and therefore the strength carrying capacity reduced with rising temperature. As mentioned in Table VI, the strength carrying capacity of PC-C10-H800 was less by 34.75% than the one of PC-C10-H500. A decrease 3.9% was recorded for the cover of 17 mm in comparison with 10 mm. Increase in applied temperature reduced the compressive strength and the resistance of the column was reduced, reflecting on the strength carrying capacity. The crack propagation and intensity increased for applied temperature load of 800 °C when compared with static and 500 °C temperature loads. The cracks had a wider distribution in the case of 10 mm cover as compare to specimens with 17 mm cover.

IV. CONCLUSIONS

The contribution of the current study lies in the knowledge of the structural behavior of the columns, the extent to which it is affected by high temperatures, and the damages resulting from thermal load on the mechanical properties and the bearing capacity. Based on the test results and observations about the reduction in concrete compressive strength due to applied temperature of 500 and 800°C, the following conclusions can be drawn:

- The strength carrying capacity of the tested columns decreased when they were subjected to high temperatures and the residual strength increased when the applied temperature increased.
- Axial and lateral displacements increased due to the applied temperature.
- Concrete cover plays an important role in reducing the effect of temperature. The cracks do not reach the reinforcement at specific temperatures.
- Greater number and size of the cracks that developed due to the applied temperature were observed when the cracks appeared in the early stages of applied heating. Crushing that occurred in the concrete and lateral displacements (buckling) were predominant failure modes under at the applied temperatures.
- The present study gave results for the residual resistance of reinforced concrete columns exposed to high temperatures through which a decision can be given whether it is suitable to keep this structural element or not in the building. Knowing the aging of cracks in relation to temperature helps making structural decisions. The decision to maintain the reinforced concrete columns can be based on knowing and comparing their mechanical properties and behavior under the influence of high temperature.

REFERENCES

[1] *TR 33 Assessment and repair of fire-damaged concrete structures. UK: Concrete Society, 1990.*

[2] B. Chen, C. Li, and L. Chen, "Experimental study of mechanical properties of normal-strength concrete exposed to high temperatures at an early age," *Fire Safety Journal*, vol. 44, no. 7, pp. 997–1002, Oct. 2009, https://doi.org/10.1016/j.firesaf.2009.06.007.

[3] B. L. Williams, "Fire performance of FRP-strengthened reinforced concrete flexural members.," Ph.D. dissertation, Queen's University, Kingston, Canada, 2004.

[4] U. Schneider, "Concrete at high temperatures — A general review," *Fire Safety Journal*, vol. 13, no. 1, pp. 55–68, Apr. 1988, https://doi.org/10.1016/0379-7112(88)90033-1.

[5] G. A. Khoury, "Effect of fire on concrete and concrete structures," *Progress in Structural Engineering and Materials*, vol. 2, no. 4, pp. 429–447, 2000, https://doi.org/10.1002/pse.51.

[6] U. Schneider, "Modelling of concrete behaviour at high temperatures," in *Design of structures against fire*, 1986, pp. 53–69.

[7] V. K. R. Kodur, F.-P. Cheng, T.-C. Wang, and M. A. Sultan, "Effect of Strength and Fiber Reinforcement on Fire Resistance of High-Strength Concrete Columns," *Journal of Structural Engineering*, vol. 129, no. 2, pp. 253–259, Feb. 2003, https://doi.org/10.1061/(ASCE)0733-9445(2003)129:2(253).

[8] B. O. Wu and Y. H. Li, "Experimental research on fire performance of axially restrained RC columns with L-shaped cross section," in *Proceedings of the Fifth International Conference on Structures in Fire*, 2008, pp. 451–462.

[9] H. K. Alaa, "Structural Behavior of Eccentrically Loaded Reinforced Concrete Columns Exposed to Fire Flame," Ph.D. dissertation, Mustansiriayah University, Baghdad, Iraq, 2019.

[10] F. Al-Naqeeb and H. Al-Thairy, "The behavior of reinforced concrete columns exposure to eccentric loads at high temperature," *Journal of Physics: Conference Series*, vol. 1895, no. 1, Feb. 2021, Art. no. 012055, https://doi.org/10.1088/1742-6596/1895/1/012055.

[11] H. N. G. Al-Maliki, A. J. H. Alshimmeri, A. M. Ali, Y. M. Madhloom, and Y. Gamli, "Nonlinear Simulation Analysis of Tapered Reinforced Concrete Column (solid and Hollow) Behavior Under Axial Load," *International Journal of GEOMATE*, vol. 21, no. 86, pp. 131–146, 2019.

[12] M. Baghdadi, M. S. Dimia, and D. Baghdadi, "A Parametric Study of Fire-Damaged Reinforced Concrete Columns under Lateral Loads," *Engineering, Technology & Applied Science Research*, vol. 12, no. 5, pp. 9113–9119, Oct. 2022, https://doi.org/10.48084/etasr.5172.

[13] A. N. Hassooni and S. R. A. Zaidee, "Behavior and Strength of Composite Columns under the Impact of Uniaxial Compression

Loading," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 8843–8849, Aug. 2022, https://doi.org/10.48084/etasr.4753.

[14] F. Boursas, R. Boufarh, and B. Maghaghi, "The Influence of Slenderness in Steel and Composite Columns under Fire Conditions," *Engineering, Technology & Applied Science Research*, vol. 13, no. 1, pp. 10145–10150, Feb. 2023, https://doi.org/10.48084/etasr.5560.

[15] *ACI Committee 318, ACI CODE-318-19(22): Building Code Requirements for Structural Concrete and Commentary (Reapproved 2022). ACI, 2020.*