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Performance of reactive powder concrete slender columns exposed simultaneously to eccentric load and elevated temperatures

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Abstract. The objective of this study is to examine the impact of elevated temperatures on the structural response of slender columns made of reactive powder concrete (RPC) subjected to eccentric axial loads. Nine RPC column specimens were exposed to a temperature at three different levels: 450 °C, 600 °C, and 750 °C, and to three eccentricities: 50 mm, 100 mm, and 150 mm. The columns underwent fire exposure while being subjected to axial loading equal to 60 % of their ultimate capacity. The outcomes of the experimental tests indicate a noticeable lateral displacement of the RPC columns at high temperatures. The results show that at a constant temperature 750 °C, the mid-height lateral buckling for various eccentricities is significantly higher comparing 50 mm with 100 mm and 150 mm by 59 % and 81 %, respectively. While this rate becomes 36 % and 35 % for 600 °C. At 750 °C, the lateral mid-height buckling is found to be significantly greater when compared to 450 °C and 600 °C by 106 % and 69 %, respectively (for 50 mm eccentricity). While the ratio becomes 48 % and 46 % (for 100 mm eccentricity), one of the main findings in the research is that a low eccentricity value 50 mm, which has a high load, gives higher buckling for each elevated temperature. The mode of failure regarding the column depended on the eccentricity value where the high eccentric loaded columns showed prolonged ductile behavior, while the least eccentric loaded columns showed a brittle type of failure.

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1. Introduction

The fire resistance of a variety of structures, especially the capacity of concrete, is greatly diminished by spalling when exposed to high temperatures [1]. Many researchers nowadays developed new construction materials that can be used in residential buildings, which can be compared to bricks that work as fire insulators autoclaved aerated concrete blocks have excellent fire resistance, making them a popular choice for use in fire-prone areas. Pure axial loaded columns are usually uncommon in practice owing to the fact that bending is nearly always present for many reasons, including the minor initial deviation of columns, the method, in which beams and slabs transfer loads, and the moments provided by continuous construction of beams through columns [2]. A study was made by Santiago et al. [3] where it was observed that the bending moment for steel beams restricted by a couple of fire-protected steel columns increases with the increase in the temperature profile. However, columns made of normal-strength concrete (NSC) provide the necessary fire resistance without the need for additional suitable insulation [4]. Abdulhaleem et al. [5, 6] conducted a study to explore the impact of recycled aggregate concrete and the inclusion of steel fibers on the strength of self-compacting concrete (SCC). The research aimed to investigate how the use of recycled aggregates and the addition of steel fibers influenced the overall strength properties of SCC, the findings from the experimental study indicate that the inclusion of steel fibers has a beneficial impact on improving the mechanical properties of SCC, especially in terms of enhancing tensile strength. Additionally, the incorporation of 50 % recycled aggregates in the concrete mixture resulted in a notable increase of approximately 20 % in compressive strength. Concrete's fire behavior is fundamentally tied to temperature-dependent material characteristics. Because thermal diffusivity is lower in concrete than in steel, large temperature gradients are often formed inside fire-exposed concrete members. Due to the high thermal inertia, the core area may take a long time to heat up. Thus, although concrete's compressive strength is quickly lost at a critical temperature, which is not different to the corresponding temperature for steel strength loss, structural efficacy is not impaired until the mass of the material reaches the same temperature. This necessitates a thermal response study of the whole structural member [7]. Klak et al. [8] reviewed the behavior of different reinforced concrete elements when subjected to high temperatures. The study found that both the concrete and reinforcing bars are negatively impacted by fire. It was observed that the flexibility and stiffness of the structures decrease as the fire exposure increases or the stress levels rise. On the other hand, it was found that the flexibility and stiffness improve with a larger cross-section of the structural elements. However, the maximum deflection of the slab was found to decrease non-linearly during the fire test. As the temperature decreases, the bottom of the concrete slab begins to cool, leading to an increase in the yield strength of the bottom reinforcement. This causes the bottom reinforcing to contract along with the lower half of the slab. Al-Zuhairi et al. [9] conducted a study on the behavior of reinforced hybrid concrete columns consisting of two fully-bonded concretes under biaxial loading The findings indicated a noteworthy increase of 33.5 % in the ultimate load-bearing capacity of hybrid columns compared to conventional columns. Additionally, a 38 % increase in the ultimate load was observed when reducing the hybrid's ratio to 0.16. The study concluded that hybrid columns with smaller hybrid ratios can withstand higher loads and moments while exhibiting fewer axial strains.

Reactive powder concrete (RPC) was developed by Richard & Cheyrezy [10, 11], which claimed that it is a form of ultra-high-performance concrete (UHPC) with compressive strengths ranging from 200 MPa to 800 MPa, depending on the mix proportions and the curing temperature by eliminating coarse aggregates and optimizing the granular mixture, it becomes possible to achieve a homogeneous and dense cementitious matrix that demonstrates superior mechanical performance. Furthermore, the remarkable durability of RPC makes it a more practical and economical choice for tall buildings and structures with large spans, particularly those exposed to severe weather and deicing agents [12]. Achieving sustainable green development is required [13]. Typically, RPC necessitates a high concentration of cement and finely ground quartz sand, causing an increase in construction expenses and contributing significantly to the release of carbon dioxide (CO_2) into the atmosphere. By partially replacing cement with industrial by-products, such as fly ash, silica fume, slag powder, and other effective mineral additives, the peak hydration heat, construction cost, and carbon emissions of RPC can be reduced, while its microstructure, strength, impermeability, and resistance to corrosion can be improved [14, 15]. Sanjuán & Andrade. [16] conducted a study comparing the durability properties of RPC to other types of UHPC and found that RPC demonstrated exceptional durability. The research found that the air permeability coefficient of RPC was 50 times lower and the rate of steel corrosion was reduced by 25 times when compared to other types of UHPC.

Wattanapornprom et al. [17] investigated the fire resistance of RPC columns with various steel and polypropylene (PP) fiber ratios. Four columns with varying fiber ratios were tested in fires that burned for 30 min and 60 min. Following that, the behavior of RPC columns at increased temperatures was observed in terms of spalling depth, fiber failure mechanism, and residual strength. The results showed that increasing the volume percentage of steel fiber or the inclusion of PP fiber increases the column's fire resistance. Chadli et al. [18] found that the mechanical properties of RPC tend to improve when exposed to high temperatures, up to 200 °C. However, the compressive, flexural, and tensile strength decreases as the temperature rises above 200 °C. When exposed to 400 °C, a significant reduction in mechanical properties is observed compared to room temperature conditions. Additionally, the compressive strength of RPC deteriorates significantly within the temperature range of 600–800 °C. The addition of steel fibers in RPC helps to mitigate this degradation and reduces the risk of failure due to high temperatures. The results obtained by Abdulraheem & Kadhum [19] showed that it is more appropriate to evaluate the energy absorption capacity instead of using the displacement ductility index to assess the ductility of RPC columns after exposure to fire. Moreover, there was a noticeable decrease in the initial and secant stiffness of RPC columns after fire exposure, and the extent of reduction increased with the rising fire temperature from 400 °C to 600 °C. Jomaa'h et al. [20] studied the effect of the elevated temperature on RPC slender columns with various degrees in comparison with NSC slender columns, 18 total specimens were cast, 9 RPC columns and 9 NSC columns, the specimens were tested under fire exposure for 1 and 2 hours with temperatures of 450 °C, 600 °C, and 750 °C, respectively. It was found that the axial displacement and mid-height lateral displacement due to buckling were increased with respect to the temperature rise for the previous parameters mentioned the RPC showed greater strength than NSC and the percentage of strength loss in RPC was lower than NSC. Few studies have examined the uniaxial moment and fire impact on slender RPC columns together. This experiment examined how increased temperatures affected eccentricity-loaded RPC columns. The testing range regarding the temperature levels was selected depending upon the effect of the temperature level on the RPC, it was discovered that elevated temperatures from high fire flames can be categorized into two intervals with regard to the decline in strength in RPC: specifically, 23–200 °C and 300–500 °C. Within the 23–200 °C range, RPC either sustained or experienced a rise in its initial strength. Conversely, in the 300–500 °C range, RPC exhibited a significant decrease in its original strength. Exposure to temperatures around 500 °C resulted in the spalling of RPC specimens, leading to a loss of both mechanical and physical properties, with partial or complete spalling [21]. Izzat [22, 23] conducted an investigation to assess the impact of high-temperature fire exposure on SCC short columns. The findings revealed that the ultimate load capacity of columns exposed to fire decreases as the fire flame temperature increases. At burning temperatures of 300 °C, 500 °C, and 700 °C, the average residual ultimate load capacity for gradually cooled specimens was 91 %, 81 %, and 71 %, respectively.

2. Materials and Methods

To investigate the fire effect on RPC columns subjected to eccentric loading, a large-scale setup for laboratory experiment was made by Jomaa'h et al. [20] at the Civil Engineering Department / University of Kirkuk, and it was used in this study.

2.1. Testing Device Setup

The concrete column inspection device comprises a steel frame with dimensions of 20 mm in thickness, 2.8 m in length, and 1.44 m in breadth. A temperature measurement device is used to trace temperature, and, a thermal cable (Type K) is installed inside the oven to measure the ambient temperature around samples. The furnace is shown in Fig. 1.

Figure 1. Test setup.

This oven has three fundamental layers:

1. The outside is composed of standard clay bricks.
2. Ceramic fiber blanket that can endure temperatures of 1260 °C.
3. The inside layer is composed of firebrick that can resist temperatures of 1200 °C.

A flame of high-pressure gas is used to induce fire inside the furnace. The bonding substance used to construct fire bricks is heat resisting cement, which can resist temperatures of up to 1400 °C. Fig. 2 shows a schematic top view of the oven setup. The primary purpose of the oven chamber is to steadily raise the temperature for a specified time. The burning source is composed of single methane gas burners parallel to a single-sided column model throughout its length.

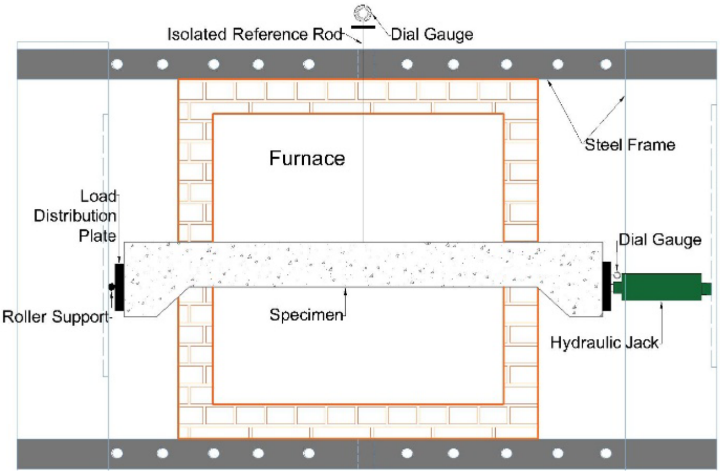


Figure 2. Top view drawing of the test device setup.

2.2. Materials

The cement used in this experiment was Ordinary Portland Cement (CEM I-R42.5), which met Iraqi Standard Specifications 5/1984 [24]. A densified micro-silica fume with a minimum silicon dioxide content of 85 %, a specific gravity of 2.3, and a specific surface of 15 m^2/g was used in this work as a mineral additive. In this investigation, river sand with a maximum particle size of 4.75 mm was also used [25]. In addition, a high-performance water-reducing agent was used to enhance the workability at low water-cement ratios. The agent's chemical constituent, polycarboxylate polymer, conforms with ASTM C494 Type E. The admixture is light-brownish in color and has a specific gravity of 1.07 (±0.005) g/cm^3. PP monofilament fibers were used. The fiber length is 12 mm and the diameter is 0.032 mm, the aspect ratio (l/d) of the fibers is 375. The proportions and compressive strength of the mix are detailed in Table 1.

Table 1. RPC Mix. Proportions.

Cement (kg/m^3)	Micro silica (kg/m^3)	W/binder	Sand (kg/m^3)	Superplasticizer (kg/m^3)	PP fiber (kg/m^3)	Cube compressive strength, f_{cu} (MPa)	Cylinder compressive strength, $f_{c'}$ (MPa)
900	100	0.2	1350	20	3.2	118	94.4

2.3. RPC Column Specimens

In order to conduct this research, nine RPC columns were prepared according to standard concrete mechanics principles of strain compatibility and equilibrium of internal forces for the column. Fig. 3 shows the column interaction diagram. Table 1 displays the results of compressive strength testing used to determine the mix. of the RPC columns made.

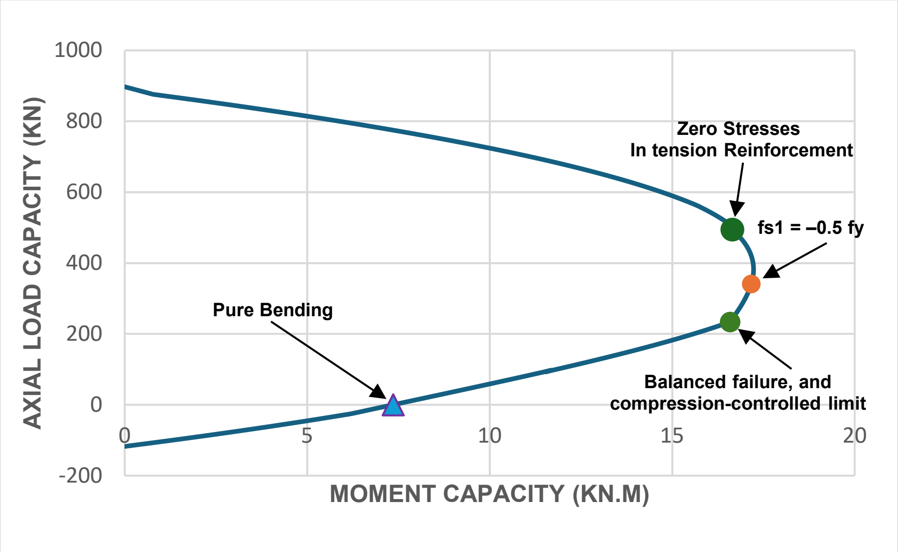


Figure 3. Column nominal strength interaction diagram.

The specimen is 1.6 m in height with 15 × 15 cm cross-sectional dimensions at the mid-height, at the brackets, the cross-section dimensions are 25 × 15 cm; the purpose of the brackets is to apply load at different eccentricities, and it was designed according to ACI318-19 [26]. Fig. 4 illustrates the column specimen drawings with reinforcement details and the arrangement of the thermocouple (K-type) embedded in the specimen. The capacities of the columns ($f_{c'}$ = 80 MPa) in relation to eccentricities are displayed in Table 2.

Table 2. Column capacities and test loads.

	Specimen designation	**Temperature**	**Eccentricity (mm)**	**Ultimate axial load capacity (kN)**	**Ultimate moment (kN.m)**	**Test load (kN)**	**Test moment (kN.m)**
1	RPC450-50	450	50	606	30	360	18
2	RPC450-100		100	181	18	110	11
3	RPC450-150		150	91	14	60	9
4	RPC600-50	600	50	606	30	360	18
5	RPC600-100		100	181	18	110	11
6	RPC600-150		150	91	14	60	9
7	RPC750-50	750	50	606	30	360	18
8	RPC750-100		100	181	18	110	11
9	RPC750-150		150	91	14	60	9

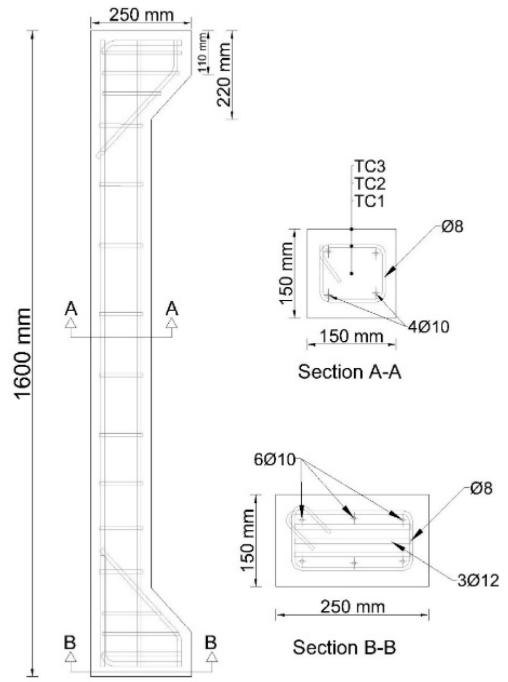


Figure 4. Dimensions and reinforcement details of RPC columns.

2.4. Experimental Procedure

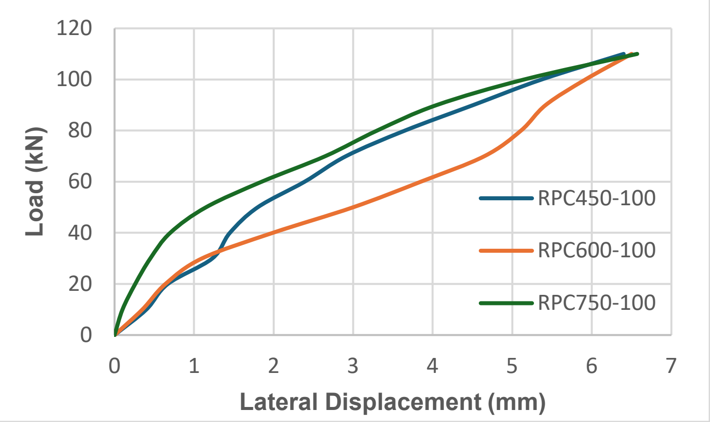
This research investigated the lateral deformation performance of RPC following high-temperature exposure on nine RPC column specimens. The combination mix components of specimens are listed in Table 1. After casting, the specimens were wrapped with a plastic film for initial curing to prevent moisture evaporation and then stored at 25 °C for up to 20 hours [27]. The specimens were then demolded and immersed in water for final curing at 25 °C for 14 days. To gain an advantage in producing RPC with exceptional mechanical properties (compressive strength about 100 MPa) using the conventional curing method without any additional provisions and also to simulate the practical site conditions, this study did not adopt the principle of heat treatment curing of RPC, which is one of the basics for developing RPC [28, 29].

In this work, three temperatures and eccentricities were employed to test the mechanical behavior of RPC specimens: 450 °C, 600 °C, and 750 °C, as shown in Table 2. Each set had three specimens that were initially compressed uniaxially. The axial load applied on the column was approximately 60 % of the ultimate load according to ASTM E119 (Section 7.4.2.2) [30]. To monitor the interior temperature of the specimen, a (K-type) thermocouple was put in each specimen during casting, one in the center (TC1) and the other linked to the reinforcement (TC2). After water curing, RPC has an extraordinarily high density and can store a considerable quantity of water to avoid specimen spalling during heating (i.e., high pore pressure generated by water vaporization), the specimens were dried in the sun for at least 50 days before being exposed to fire to reduce water content. A thermocouple (Type K) was used to monitor the temperature of the furnace (TC4) and ensure that it achieved the desired temperature another one was attached to the specimen cover (TC3), and lateral displacement was recorded every 5 minutes for 2 hours for all specimens.

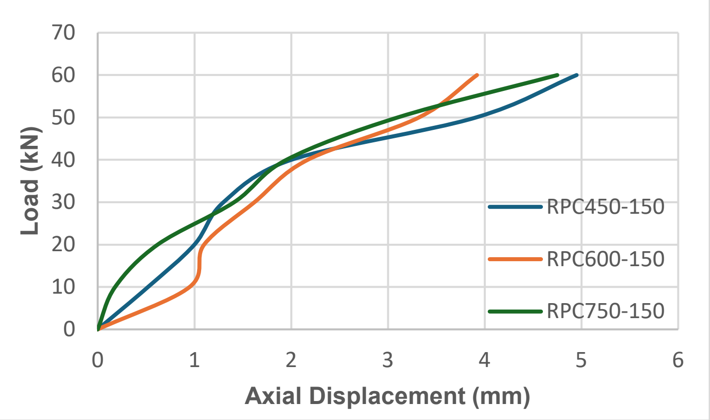
3. Results and Discussions

3.1. RPC Column Pre-Fire Behavior

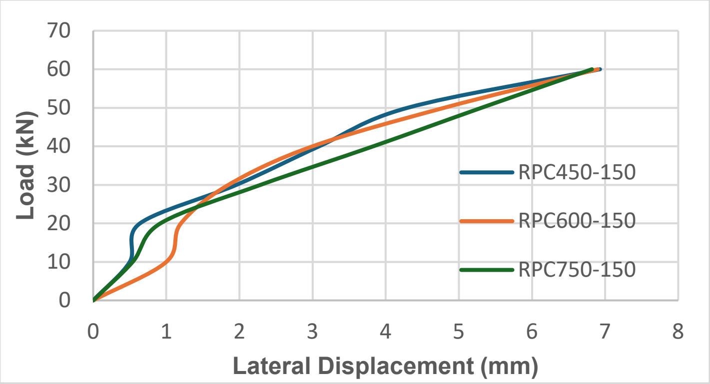
The mechanical behavior of the RPC columns before fire exposure is presented in Figs. 5 and 6, respectively.



(a) Lateral displacement of 50 mm eccentricity set.

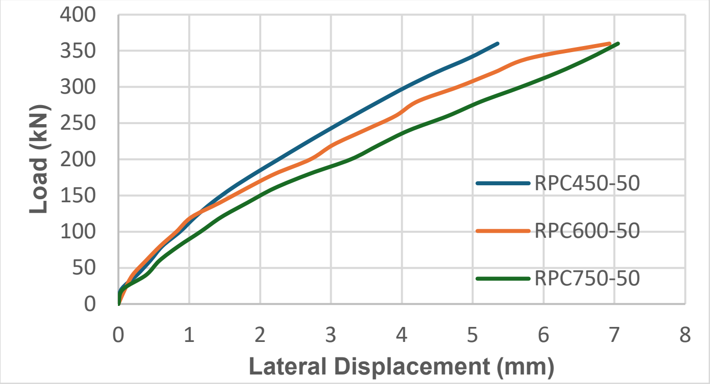


(b) Lateral displacement of 100 mm eccentricity set.

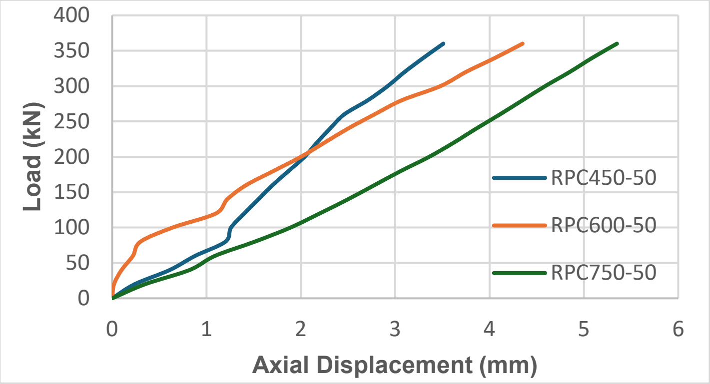


(c) Lateral displacement of 150 mm eccentricity set.

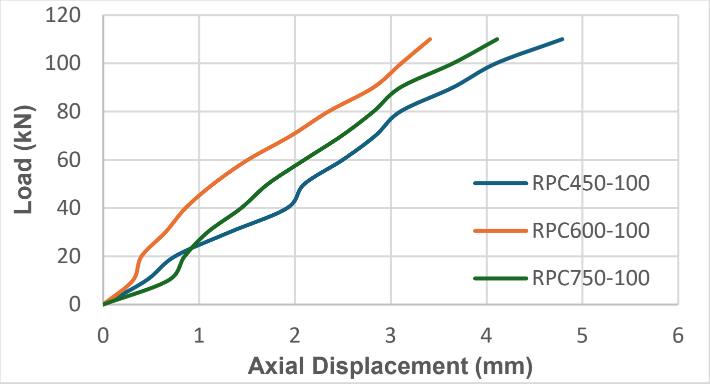
Figure 5. Lateral mid-height displacement.



(a) Axial displacement of 50 mm eccentricity set.



(b) Axial displacement of 100 mm eccentricity set.



(c) Axial displacement of 150 mm eccentricity set.

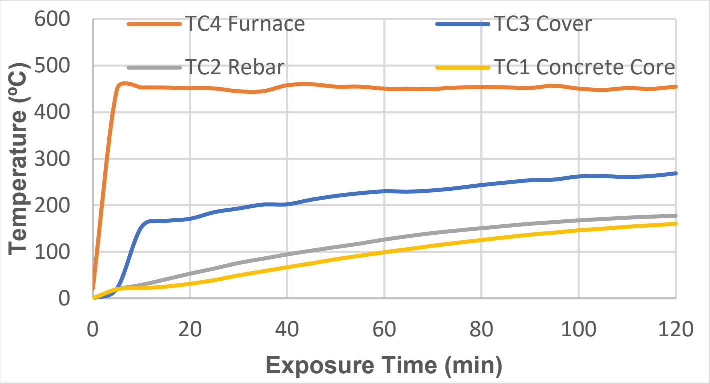
Figure 6. Measured axial deformation for all sets.

As depicted in the figures, nearly all the lateral deflection (lateral buckling) of the columns is consistent regardless of eccentricity, due to the fact that all the columns were subjected to approximately

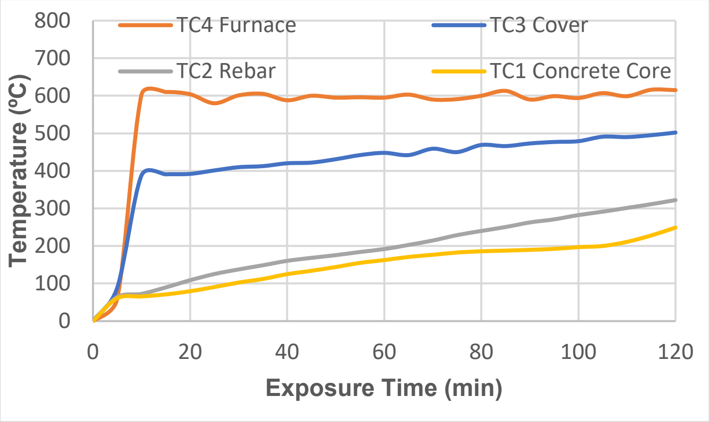
60 % of their ultimate load. Different eccentricities can have the same mid-height deflection due to the material's linear-elastic behavior and the fact that the load-carrying capacity of a column is affected by the accompanying moment as the moment increases, the applied load decreases as it is obvious in Table 2. This will give the same buckling behavior of the columns regardless of the eccentricity of the load. Fig. 6 shows that the axial displacement of the columns is approximately close to each other before the fire takes place, all columns with the same eccentricity exhibit similar structural behavior. Also decreasing axial load with increasing the applied moment can cause similar behavior of all columns and this matches with the behavior of the lateral buckling that was previously discussed. The bending moment creates tensile stress on the fiber opposite to the applied load face of the column and compressive stress on the face near the applied load, which leads to the formation of cracks on the tension face. The severity of the cracking is dependent on several factors, including the column's slenderness ratio, the magnitude of the eccentricity, and the compressive strength of the concrete. When the column is excessively slender and/or the eccentricity is large, the tensile stress on the tension face can become so high that it exceeds the tensile strength of the concrete, leading to the formation of cracks and potentially causing the column to fail.

3.2.1. Thermal profile

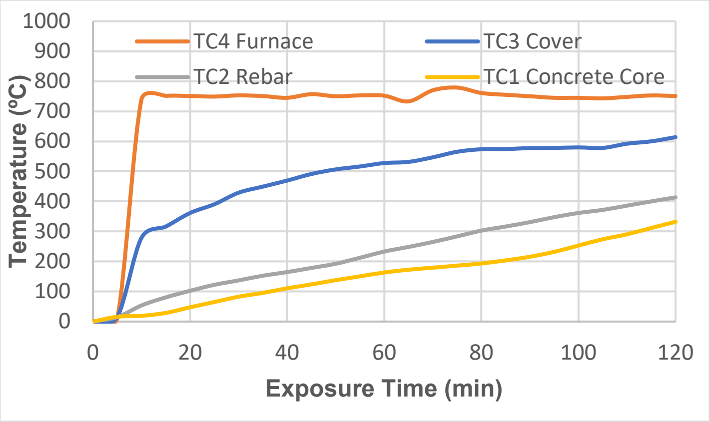
The thermal response for each set of specimens is presented in Fig. 7, in contrast to the first few minutes of each fire exposure, during which fire temperatures grew quickly, and the temperatures inside each column stayed constant. In addition, no plateau in temperature is seen, this plateau in temperature is a result of the latent heat spent by free capillary water in the column as it transforms from liquid to vapor also it can be since the PP fibers melt under high temperatures which creates paths for the water to escape [31]. As the bulk of this pore water evaporates, the rebar and concrete temperatures rise with the fire temperature [32]. In addition, the measures reveal that temperatures are lower inside the concrete core. This is due to the poor thermal conductivity and large thermal capacity of concrete, which impede the passage of heat energy into the interior layers of concrete [33, 34].



(a) Thermal profile for 450 °C fire exposure.



(b) Thermal profile for 600 °C fire exposure.

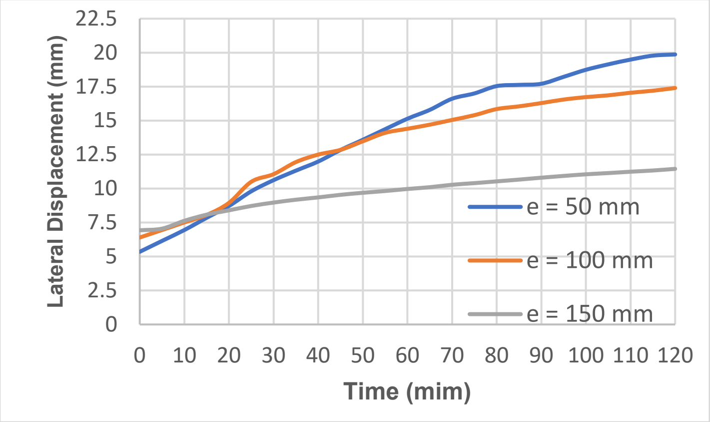


(c) Thermal profile for 750 °C fire exposure.

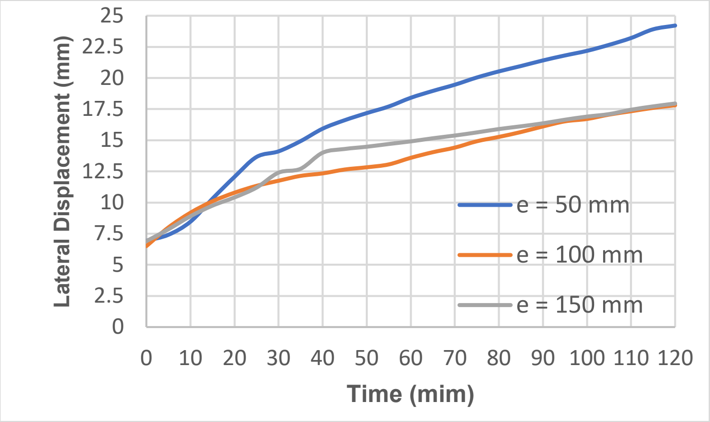
Figure 7. Thermal response of RPC during exposure phase.

3.2.2 Structural behavior of slender RPC column under fire

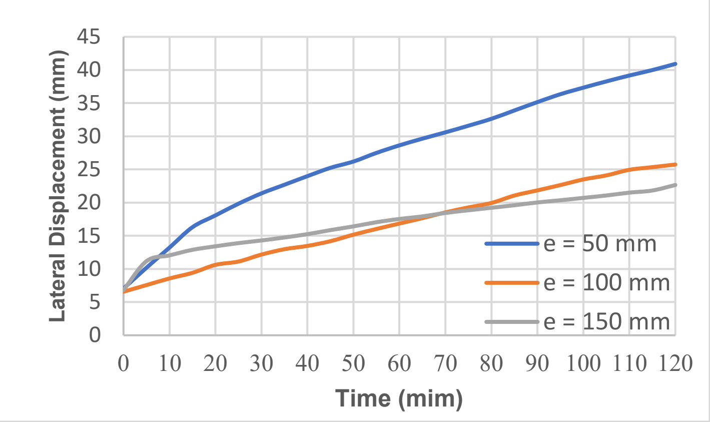
The structural behavior of RPC columns under fire is shown in Figs. 8 and 9, respectively. Lateral deformation was recorded for each set of temperature levels using a steel rod well isolated from heat using a 1200 °C ceramic blanket to prevent thermal expansion of the rod under fire and achieve accurate results. It can be noted that when comparing the same set of eccentricities with different temperatures, the deformation gets greater towards 750 °C, but when comparing different eccentricities for the same temperature, the set of e = 50 mm has higher deformation than others (Fig. 11), this is because the specimens with 50 mm eccentricity were subjected to a higher load, which makes the effect of temperature more noticeable on the specimen [35]. Also, the rate, at which the column deforms, gets lower over time.



(a) Lateral displacement for 450 °C fire exposure.



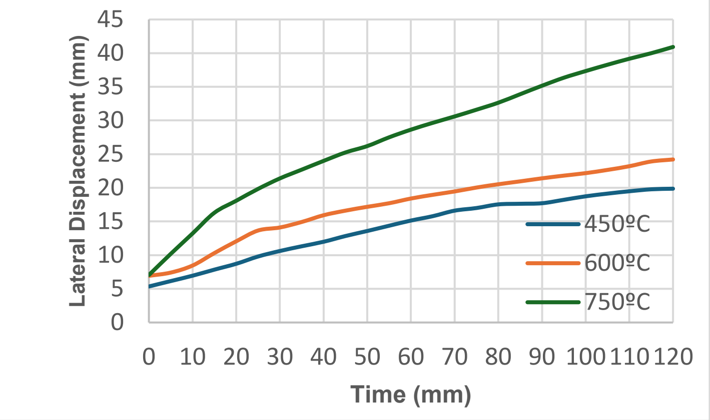
(b) Lateral displacement for 600 °C fire exposure.



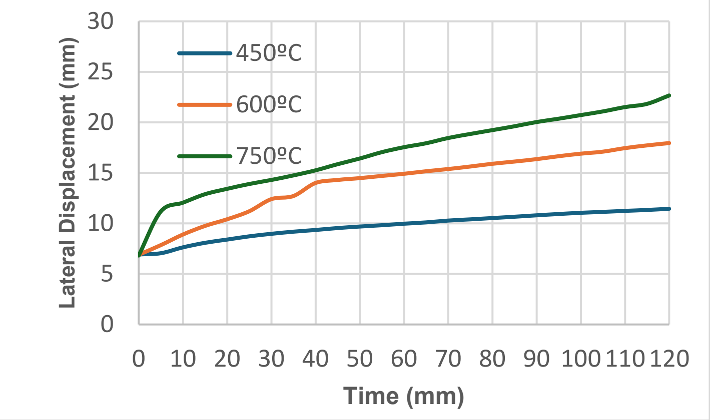
(c) Lateral displacement for 750 °C fire exposure.

Figure 8. Measured mid-height lateral displacement during fire exposure.

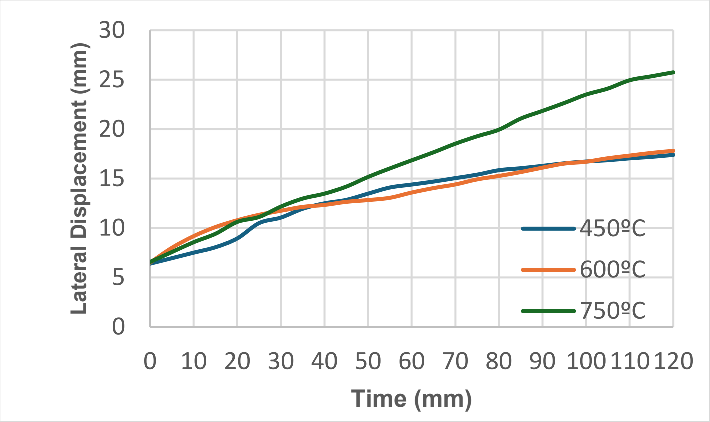
At the end of the test before unloading the column, the cracks that were previously formed in the tension face of the columns due to applied loads became very obvious and widened because of fire, this is due to the progressive loss in stiffness as the concrete loses its strength properties when exposed to fire, especially when the temperature reaches 200 °C and higher depending also on the amount of PP fiber in the mixture and fire duration [36, 37]. The crack patterns of the tested columns after exposure to 450°C, 600°C, and 750°C are shown in Figs 10a, 10b and 10c, respectively. In general, the cracks became more pronounced and widespread with increasing fire temperature.



(a) Lateral displacement for 50 mm eccentricity.



(b) Lateral displacement for 100 mm eccentricity.



(c) Lateral displacement for 150 mm eccentricity.

Figure 9. Measured mid-height lateral displacement for different eccentricities.

(a) Crack pattern for 450 °C temp. Specimen.

(b) Crack pattern for 600 °C temp. Specimen.

(c) Crack pattern for 750 °C temp. Specimen.

Figure 10. Crack pattern for different fire level exposed specimens.

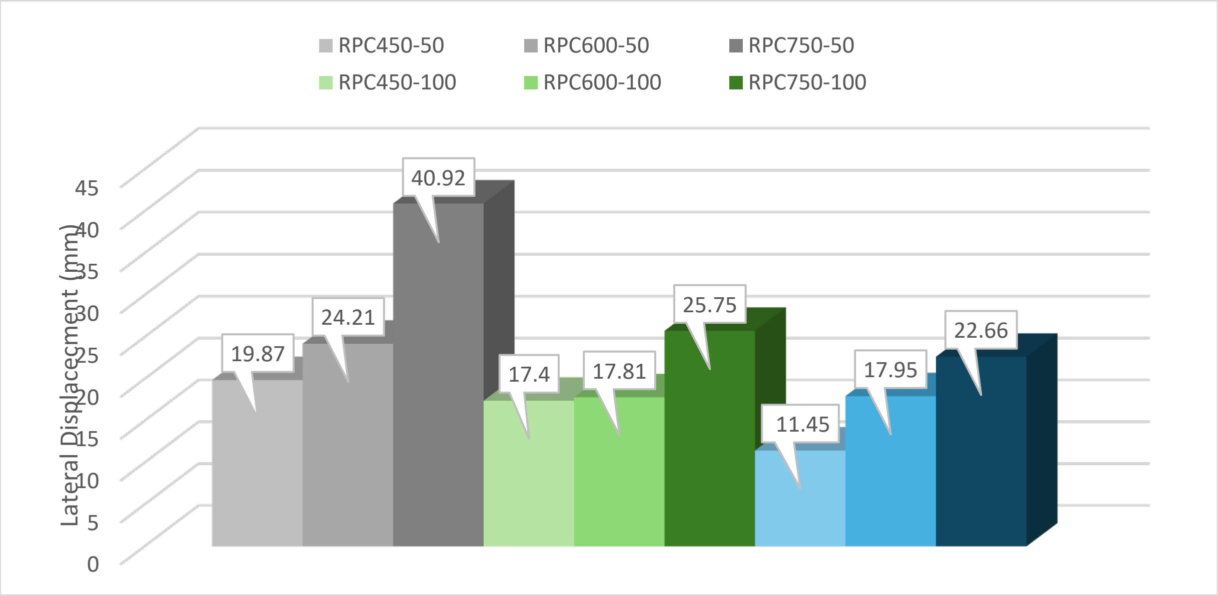


Figure 11. Max. Value of mid-height lateral displacement for RPC columns after 2 hours of fire.

4. Conclusions

In an attempt to investigate the structural behavior of RPC columns subjected to elevated temperatures, 9 specimens were made, specimens with different eccentricities of 50 mm, 100 mm, and 150 mm, each one subjected to fire flame of 450 °C, 600 °C, and 750 °C. Based on the results collected from the study, the following conclusions are summarized below:

1. The columns with the same cross-sectional area and reinforcement bars, applying 60 % of the ultimate load of each eccentricity, produce almost the same lateral deformation (±1 mm) before exposure to fire as the axial load decreases with increasing eccentricity.
2. The thermal profile (Fig. 7) shows simultaneous temperature rise in concrete core and steel reinforcement. For each exposure level of fire 450 °C, 600 °C, and 750 °C the temperature in the steel is 10 %, 18 %, and 20 % higher than the concrete core temperature at each time interval.
3. The difference in temperature between the cover of the specimens and the core of the specimens for 450 °C, 600 °C, and 750 °C is 40 %, 47 %, and 49 %, respectively, which indicates that the rate, at which the core temperature rises, is nearly identical for all levels of exposure.
4. The lateral deformation at 450 °C is higher by 14 % and 73 % when comparing 50 mm eccentricity with 100 mm and 150 mm, respectively, and all of the other groups show the same results, this is due to load intensity. It means that the effect of temperature is going to be more noticeable when the axial load is higher (Table 2).
5. When the eccentricity is constant, the temperature level will lead to more lateral deformation as it gets higher. The lateral buckling increased by 22 % and 106 % for columns subjected to 600 °C and 750 °C, respectively, compared to columns subjected to 450 °C.
6. The main conclusion is that in multistory buildings, the edge columns, which are subjected to axial load and uniaxial moment, are not considered to be more critical than internal columns, which subjected mainly to axial load.
7. The crack pattern depends on the eccentricity of loads and the temperature level around columns. More cracks with large penetrations to the concrete body are shown at higher eccentricities and higher temperatures.

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