

Research Article

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Nonlinear-finite-element analysis of reactive powder concrete columns subjected to eccentric compressive load

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Abstract: Studies on the behavior of reactive powder concrete (RPC) columns under eccentric loading are limited. The effect of materials used in manufacturing these RPC columns has not yet been investigated. This research aimed to perform a nonlinear-finite-element analysis to determine the load-carrying capacity and displacement of RPC columns made of different RPC mixes and subjected to various loading eccentricities. This research investigates two types of parameters. The first parameter is the column's geometric parameters (the height L and the load eccentricity distance e). The second is the RPC material parameter (regarding the silica fume or fly ash used as pozzolanic material and the type of fibers used, whether steel or glass fiber). Results indicate that eccentric-loaded slender columns exhibit much less load-carrying capacity than the corresponding short columns. The 2 m-long columns with eccentricity ratio $e/t = 0.2$ resulted in a 65% average reduction in the ultimate load (P_u) compared to the corresponding 1 m-long columns. Using fly ash as a pozzolanic material instead of silica fume reduces the ultimate load (P_u) of an RPC column by an average of 60%. Using glass fibers instead of steel fibers also reduced P_u by 50%. The average percentage increase in the maximum vertical deflection ($\Delta y_{\max}$) of the short column ($L = 1$ m) is found in the range of 18–31% for eccentricity ratio $e/t = 0.1$ but 45–69% for $e/t = 0.2$. In contrast, for a slender column ($L = 2$ m), the percentage increase in $\Delta y_{\max}$ is in the range of 10–30% for both $e/t = 0.1$ and 0.2.

Keywords: reactive powder concrete, eccentric loading, nonlinear analysis, numerical analysis, RPC

1 Introduction

Investigating the mechanical properties and structural behaviors of different types of concrete, especially new types such as reactive powder concrete (RPC), is essential. The term RPC is used to describe the new ultra-high performance concrete (UHPC), which consists of fiber reinforcement, high cement content, pozzolanic admixtures like silica fume, water reduction admixture, and fine quartz sand instead of the ordinary aggregate.

Among the significant studies on the structural behavior of concrete is the study on the behavior of concrete columns subjected to eccentric compressive loading. Many researchers have studied different cases related to this topic. Wenjie *et al.* [1] conducted parametric studies to evaluate the effects of the mechanical properties of many parameters such as reinforcement, the reinforcement ratio, eccentric distance loading, the slenderness ratio, and the type of concrete on the compression behavior of RC columns. The results show that the compressive performance has significantly improved when using high-performance concrete, such as RPC, and the proposed cementitious composites. Research carried out by Falah *et al.* [2] presented a numerical investigation of the behavior of RPC hollow columns confined with a different number of layers of carbon-fiber-reinforced polymer (CFRP) attached at various places on the faces of the columns. The examined columns contained a different longitudinal reinforcement. All specimens were subjected to the axial load applied at the center and eccentric loading distances (25 and 50 mm from the center). The researchers concluded that CFRP slightly increased the strength of the confined columns.

Ahmad *et al.* [3] studied the behavior of RPC short circular columns with various types of steel fibers and lateral reinforcements (spiral and hoops) with different distances between them. The study concluded that using steel fibers in RPC prevents concrete cover spalling and increases ductility. Also, using longitudinal reinforcement

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in a high ratio leads to a delay in the buckling of columns and increases the strength.

Shi *et al.* [4] investigated the bearing capacity of RPC columns subjected to considerable eccentric loading. The columns made with or without steel fibers differed in section dimensions and reinforcement ratios. The ultimate load capacity of the RPC columns was calculated using a simple analytical approach under considerable eccentric loading. Test results indicated that the equivalent coefficients of RPC columns in the tensile region were 0.6 (with the steel fibers) and 0.4 (without the steel fibers).

Hussein *et al.* [5] developed a finite-element model to study the reinforced concrete column's behavior when subjected to eccentric loading. The study evaluated the technique of column strengthening by using steel jacketing, which consisted of external vertical angles and horizontal straps connected. The researcher studied the effects of the load eccentricity and the angle's dimension on the column's load capacity. The results showed that the column's load capacity increases as the size of the vertical angle increases. The researcher also concluded that double-sizing the external angles and the column had significantly reduced the effects of eccentric loading. Hao *et al.* [6] studied the load–displacement curve of RPC-filled steel tube-shaped columns subjected to eccentric loading. The researcher has concluded that increasing the column slenderness and load eccentricity decreases the load capacity.

Malik and Foster [7] conducted a numerical and experimental study on reinforced RPC columns. All columns have a typical 150 mm-squared cross-section. Both eccentric and concentric compression loads had been applied with various eccentricities. The study showed that adding high volumes of fibers is a valuable way to prevent the fragmentation of the concrete cover and the buckling of the longitudinal reinforcement. The authors also concluded that the conventional procedure of determining the interaction diagrams for normal force and bending moment produced good results for sections loaded with more than minimum loading eccentricities.

Hadi *et al.* [8] investigated the behavior of the empty core RPC columns restricted with a circular tube of CFRP. The dimensions of the specimens were 206 mm in diameter, a height of 800 mm, and a 90 mm circular hollow. The researchers used three different confining methods. The first method was external confining with a carbon fiber-polymer tube. The second one was internal confining with a PVC duct and external confining with a CFRP duct. The last one was restricted internally to a steel duct and externally to a CFRP duct without any steel

reinforcement. All columns were subjected to eccentric and concentric loadings. The results indicated that using the CFRP tube increased the column strength and enhanced the column's ductility. Ductility was also improved by using the PVC tube for internal confinement.

A nonlinear analysis using the finite-element method was conducted in this study to investigate the effects of different parameters on the behavior of RPC columns and the load capacity. These parameters were different pozzolanic materials and fibers used in manufacturing such columns. Also, other parameters, such as column length and the eccentric loading distance, were investigated.

2 RPC

The strength of concrete was determined by the properties of its mortar and the interface between aggregates and the mortar. Generally, aggregates occupy 70–80% of the volume of concrete. Hence, aggregate properties such as texture, shape, maximum size, mineralogy, and strength determine the concrete features and performance. The cracks usually start on the interfaces and grow through the concrete matrix. Coarse aggregates try to arrest crack growth, producing branching cracks, and some of the particles are fractured. These mechanisms depend on aggregate properties, especially the surface texture, shape, and strength differences between the aggregates and the matrix [9]. However, a coarse aggregate is a significant part of the normal-strength concrete, making up 40% of the total volume. Eliminating the coarse aggregate means a much higher content of cementitious dosage [10]. Removing coarse aggregates has developed as new promising RPC. It was first developed in the early 1990s by Bouygues laboratories in France. Then, in July 1997, they used it to build the Sherbrook Bridge in Canada. RPC is developing a composite material that allows the concrete industry to optimize its fabric use, generating economic benefits [11]. RPC has a broad application prospect in the bridge, nuclear power, ocean, oil, and military facilities and other industrial and civil construction projects with superior performance [12]. RPC's compressive strength is between 150 and 230 MPa, flexural strength is between 20 and 50 MPa, and Young's modulus of elasticity is between 45 and 65 GPa [13].

Zhang *et al.* [14] investigated the factors that affect RPC strength. They used four factors: water/binder ratio, silica fume volume content, sand/binder ratio, and ash volume content. Steel fibers with 1–5% volume percent and the specimens were subjected to basic curing tests for

7 and 28 days under natural, standard, and compound conditions. Al-Hassani and Ibraheem [15] proposed an equivalent-compressive-stress bi-linear block for an RPC section under a pure bending moment. Then, they used it to extract an equation to calculate the capacity for the nominal-ultimate flexural moment for singly reinforced rectangular RPC sections. The researcher verified the accuracy of the proposed equation by comparing it with other results adopted from the experimental tests.

3 Finite-element modeling

Software ANSYS version 15.0.7 is used to perform the nonlinear analysis. The concept of the finite-element process is to divide the body structure into a finite number of small elements connected by a finite number of nodes. The properties of materials and the relationships controlling these elements are considered and expressed in terms of nod displacement. The element's responses are expressed as finite numbers of degrees of freedom characterized as the value of functions at a set of models. Then, the finite-element model may then be approximately considered by the discrete model obtained by gathering the assemblage of all elements. The concept of disconnection assembly naturally occurred when examining different natural and artificial systems [16].

The SOLID65 element, Figure 1, is used in ANSYS models and represents the solid elements with or without rebar reinforcement. This element has eight nodes with three degrees of freedom for each node. This element is qualified for crushing in compression and cracking in tension. It provides the ability to define three various types of rebar. Dealing with the nonlinear properties is the most significant feature of this element. The concrete can crush, crack (in the three perpendicular directions),

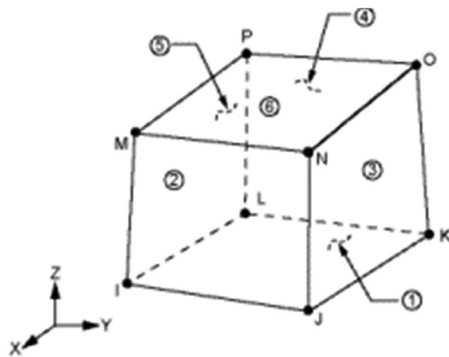


Figure 1: SOLID65-3D element.

creep, and has plastic deformation. A rebar is capable of compression and tension but not of shearing. It can creep and has a plastic deformation [17]. Solid 65 represents the different types of RPC adopted in this study.

The SOLID185 element has been used to represent the loading plates. This element includes the ability of plasticity, rotation, creep, large deflections, and strains. It represents the different types of steel bars adopted in this study. SOLID185 is a structural element having eight nodes with three degrees of freedom for each node and is suitable to model the general solid three-dimensional structures (Figure 2) [18]. LINK180 is a bar model that represents different engineering applications, like links, springs, sagging cables, trusses, *etc.* This three-dimension spar element is an axial tension-compression element with “three degrees of freedom” at each node, whereas the element bending is zero at pin joints (Figure 3).

A model was built for two types of RBC concrete columns, one with dimensions of 150 mm × 250 mm × 1,000 mm, and the other with dimensions of 150 mm × 250 mm × 2,000 mm. The cross-sectional area and the reinforcement ratio for both columns were fixed according to the minimum reinforcement requirements and for comparison between the two columns.

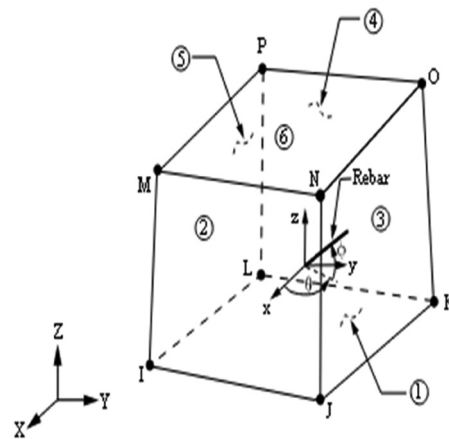


Figure 2: SOLID185-3D element.

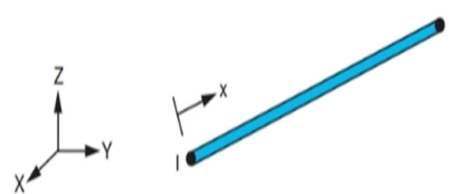


Figure 3: LINK180-Spar-3D element.

According to the reinforcement limits for the compression members in ACI-CODE 08, the area of the longitudinal steel reinforcement in the compression member should be between the minimum and maximum limits as follows:

Min. reinforcement area = $0.01 \cdot A_g \leq A_s \leq \text{Max. Reinforcement area} = 0.08 \cdot A_g$, as for our model will be:
 $375 \text{ mm}^2 \leq 452.16 \text{ mm}^2 \leq 3,000 \text{ mm}^2 \dots \text{ok};$
 where A_g is the gross area, and A_s is the reinforcement area of longitudinal bars.

The other limitation is the vertical spacing of ties should not exceed 16 longitudinal bar diameters, 48 tie bar, thus

Min. vertical spacing of ties $\leq \text{Min. } (16 \cdot 12, 48 \cdot 10);$
 $150 \text{ mm} \leq (192 \text{ mm}, 480) \dots \text{ok}$

The slenderness ratio for both types of columns can be calculated as follows:

$Kl/r = 1 \cdot 2,000 / (0.3 \cdot 200) = 33.4 > 22.$ for 2 m length column;

hence 2 m length column is a slender column.

$Kl/r = 16.7 < 22 \dots$ for 1 m length column;

hence 1 m length column is a short column.

The SOLID65 element (1,200 elements for a 1 m height column or 2,400 for a 2 m height column) with dimensions of $25 \text{ mm} \times 25 \text{ mm} \times 50 \text{ mm}$ is used to represent the RPC columns. The LINK180 element (168 elements for a 1 m height column and 336 for a 2 m height column) is used to represent the steel bars. Perfect bonds are considered

to exist between the concrete and reinforcing bars by linking the concrete with any adjacent bar at the same nodes. The SOLID185 element, which has 120 elements for both top and bottom plates, is used to transfer the applied load as in Figure 4. The tolerance value for the convergence criterion adopted in this non-linear analysis is 0.5%, with the implicit cracks and load control solution. Iteration numbers for all specimens ranged from 146 to 275.

The program is usually verified by analyzing previous experimental tests and matching the results. Hence to validate the designed finite-element model, the results of the structural RPC columns tested by Shi *et al.* [4] were analyzed for comparison with the analysis of the finite elements, and the analysis results were appropriate to the experimental results as shown in Figure 5.

4 Parameters studied in finite-element analysis

This research investigates two types of parameters. The first included the column's geometric parameters (the height L and the load eccentricity distance e). The second included the RPC material parameters (regarding the silica fume or fly ash used as pozzolanic material and the type of fibers used, whether steel or glass fiber).

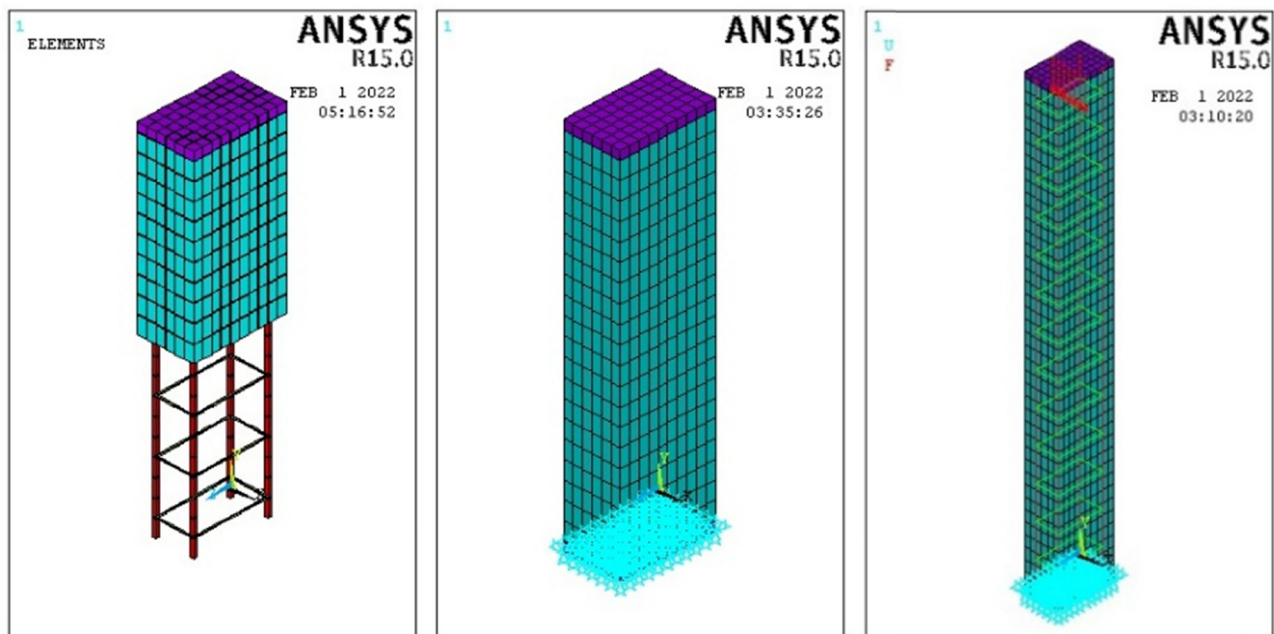


Figure 4: Ansys models-3D element (1 and 2 m height columns).

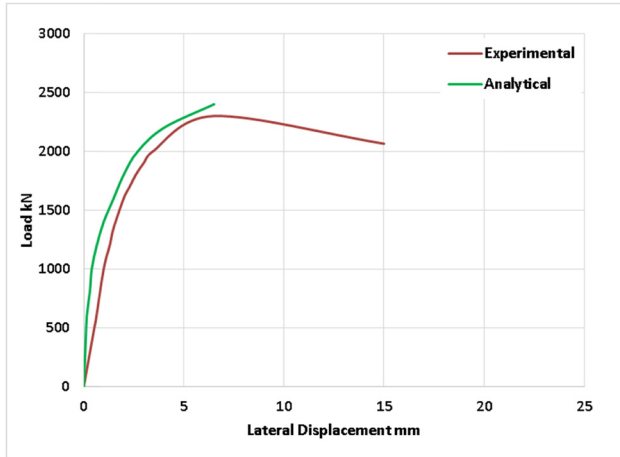


Figure 5: Load capacity–lateral displacement for the verification example columns.

4.1 Column's geometric

Figure 6 shows the actual dimensions of the tested columns. They have a typical reinforced concrete section (150 mm × 250 mm) for both 1 and 2 m height columns. The bottom edge of the column is restrained, while the top edge is free. The investigated percentages of eccentricity e/h are 0.1 and 0.2.

4.2 Materials

The RPC mixes adopted in this research were designed and tested by Gamal *et al.* [19]. Table 1 shows the properties of the different materials used in RPC mixes. The fineness – particle size distribution curve of silica fume, fly ash, and cement – is shown in Figure 7 [20]. Table 2 shows the RPC mix proportions.

Table 3 presents the analyzed models of this study. Four main groups of samples are adopted. Each group consists of three samples that differ in the eccentric loading distance (zero at the centerline, 25 and 50 mm in the z -direction). The four main groups differed from each other in the concrete component materials. The first group, Group A121 (121 refers to the compressive strength of 121 MPa), consists of RPC, which contains 2% steel fibers as reinforcing fibers and 25% silica fume replacement of the cement content as a pozzolanic material. In the second group, Group B93, 2% steel fibers are used with 10% silica fume and 15% fly ash as pozzolanic materials. The third group, Group C93, has 2% steel fibers used as the reinforcement and 25% fly ash as the pozzolanic

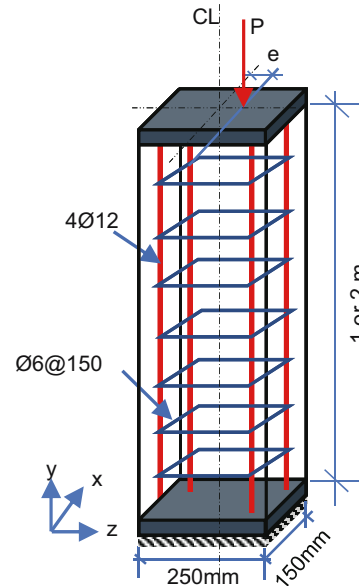


Figure 6: Typical dimension details of columns.

material. The last group, Group D59, has 2% glass fibers and 25% fly ash as pozzolanic material. The main longitudinal reinforcement (4Ø12) with a yield stress of 480 MPa, and the stirrups (Ø6@150) with a yield stress of 360 MPa, are the same for all groups.

The different mixes of the four groups (A121, B93, C66, and D59) adopted in this study have a compressive strength of 121, 93, 66, and 59, respectively.

To find the concrete modulus of elasticity related to each RPC mix, Eq. (1) is adopted to calculate them. This equation was found by Al-Hassani *et al.* [21]:

$$E_c = 113.43 (f'_c)' + 31126.7, \quad (1)$$

where E_c is the modulus of elasticity of RPC (in units of MPa) and $(f'_c)'$ is the ultimate compressive strength of RPC (in units of MPa).

The modulus of elasticity for the four RPC groups (A121, B93, C66, and D59) obtained from this equation is (44,850, 41,670, 38,610, and 37,820) MPa, respectively.

Figure 8 shows the typical stress–strain curve adopted in this study [15].

5 Results and discussion

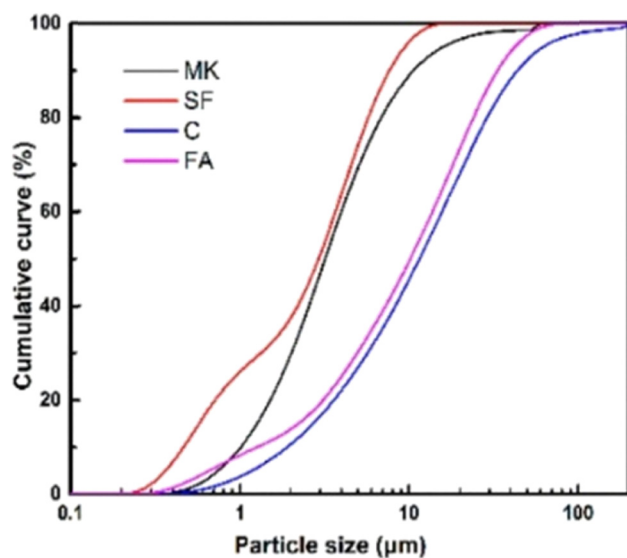
In general, the results obtained from the study, as listed in Tables 4 and 5, indicate that as the loading eccentricity increases, the ultimate load-carrying capacity will decrease. Also, the types of pozzolanic material and fibers used in

Table 1: Material properties [17]

Properties of cement					
Type	Specific gravity	Standard consistency	Initial setting time	Final setting time	
OP cement I - 42.5N	3.15	352%	75 min	380 min	
Properties of silica fume and fly ash					
Item	Composition	Color	Specific gravity	Bulk density	
Silica fume/Sika Comp. Egypt	A latently hydraulic blend of active ingredients	Grey Powder	2.13	300 (kg/m ³)	
Fly ash/Sika Comp. Egypt	Alumina silicate	Grey-fine powder	2.2	320 (kg/m ³)	
Properties of super plasticizer					
Type	Aspect	Relative density	pH	Chloride ion content	
Visco Crete –1,000 RM/Sika Comp. Egypt	Light brown liquid	1.12 [kg/l]	≥6	<0.2%	
Properties of fibers					
Item	Shape	Diameter (mm)	Length (mm)	Surface area (kg/m ²)	Tensile strength (MPa)
Steel fibers	Straight	0.8	25	—	1,000
Glass fibers	Extremely fine, single filaments, measuring 13 μm	—	18	105	—

manufacturing RPC columns have considerable effects on both ultimate load capacities and their vertical and lateral displacements.

The tables show that using fly ash instead of silica fume in manufacturing an RPC column reduces the ultimate load of that column by an average value of 39%.

**Figure 7:** Fineness-particle size distribution for silica fume, fly ash, and cement [20].

This percentage is the average value obtained from investigating different load eccentricities, whether the column length is 1 or 2 m. Using fly ash instead of silica fume also reduces the column vertical and lateral displacements (at the free end) by average percentages of 27 and 33%, respectively.

The obtained results also show that using glass fibers instead of steel fibers in manufacturing an RPC column reduces the ultimate load of that column by an average value of 47%. This average percentage covers different load eccentricities and lengths of the column. Using glass fiber instead of steel fiber also reduces the column vertical and lateral displacements (at the free end) by average percentages of 38 and 43%, respectively.

The results obtained also show that using glass fibers instead of steel fibers in manufacturing an RPC column reduces the ultimate load of that column by an average value of 47%. This average percentage covers different load eccentricities and lengths of the column. Using glass fiber instead of steel fiber also reduces the column vertical and lateral displacements (at the free end) by average percentages of 38 and 43%, respectively.

The effects of different load eccentricities on the ultimate load and its corresponding vertical deflection are as follows:

Short RPC columns with a length of 1 m and a load eccentricity of 25 mm (*i.e.*, eccentricity ratio $e/h = 0.1$) are

Table 2: Mix proportions [17]

Group	Cement (kg/m ³)	Silica fume	Fly ash	Silica fume + fly ash	Steel fibers (%)	Glass fibers (%)	W/C	SP (%)	Comp. strength (MPa)
A121	650	25%	—	—	2	—	0.25	2	121
B93	650	—	—	Silica fume 10% + flyash 15%	2	—	0.25	2	93
C66	650	—	25%	—	2	—	0.25	2	66
D59	650	—	25%	—	—	2	0.25	2	59

SP = super plasticizer.

Table 3: Columns designation

Group	Column designation	Pozzolanic material	Fiber type	Eccent. (mm)	Comp. strength (MPa)
A121	<i>i</i> SFSf 0	Silica fume 25%	Steel fiber 2%	0	121
	<i>i</i> SFSf 25	Silica fume 25%	Steel fiber 2%	25	121
	<i>i</i> SFSf 50	Silica fume 25%	Steel fiber 2%	50	121
B93	<i>i</i> SFFASf 0	Silica fume 10% + flyash 15%	Steel fiber 2%	0	93
	<i>i</i> SFFASf 25	Silica Fume 10% + flyash 15%	Steel fiber 2%	25	93
	<i>i</i> SFFASf 50	Silica fume 10% + flyash 15%	Steel fiber 2%	50	93
C66	<i>i</i> FASf 0	Flyash 25%	Steel fiber 2%	0	66
	<i>i</i> FASf 25	Flyash 25%	Steel fiber 2%	25	66
	<i>i</i> FASf 50	Flyash 25%	Steel fiber 2%	50	66
D59	<i>i</i> FAGf 0	Flyash 25%	Glass fiber 2%	0	59
	<i>i</i> FAGf 25	Flyash 25%	Glass fiber 2%	25	59
	<i>i</i> FAGf 50	Flyash 25%	Glass fiber 2%	50	59

i = column height (1 or 2 m), SF = silica fume, FA = fly ash, Sf = steel fibers, Gf = glass fibers.

found to show a reduction in the ultimate load but an increase in the vertical deflection compared to their corresponding concentrically loaded columns by average percentages of -25 and $+33\%$ respectively. When the loading eccentricity $e/h = 0.2$ (i.e., 50 mm), the average reduction in ultimate load is -45% . The increment in vertical deflections is $+57\%$.

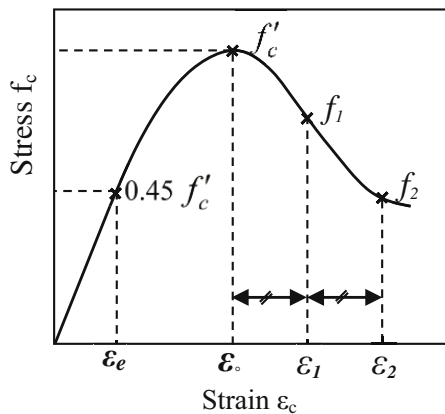


Figure 8: A typical stress–strain curve of RPC in compression [13].

The reduction in ultimate load capacity of the 2 m long slender RPC columns with 25 mm loading eccentricity is -15% compared to their corresponding concentrically loaded columns, whereas the increment in vertical deflection is $+18\%$. However, when the load eccentricity is 50 mm, the percentage differences become -53% (for ultimate load) and $+19\%$ (for vertical deflection).

When P_u load eccentricity in the 1 m high RPC column is doubled (from 25 to 50 mm), the lateral displacement at the free end increased by three times (as an average value), but in slender RPC columns of length 2 m, such average increase is only 1.5 times. The relationship between the applied load on a specific RPC column and the lateral displacement at the free end is plotted graphically in Figure 9 for short RPC columns with 1 m length and Figure 10 for slender RPC columns with 2 m length. These figures are plotted for each eccentricity ratio ($e/h = 0, 0.1$, and 0.2). From the figures, we can see RPC columns made of silica fume and steel fibers show greater ultimate loads than RPC columns made of fly ash and glass fibers for both column types ($L = 1$ m and $L = 2$ m). Also accompanied by larger lateral displacements

Table 4: Results for 1 m height column

Group	Column designation	Ultimate load (kN)	max Δ_y (mm)	Max displac. @ free end (mm)	Displacement @ mid-span (mm)	$\frac{(P_{ui} - P_{u0}) \times 100}{P_{u0}}$
A121	1SF.Sf.0	2,797	1.028	0.33	0.237	0
	1SF.Sf.25	1,950	1.301	1.117	0.313	-30.3%
	1SF.Sf.50	1,440	1.674	4.395	1.13	-48.5%
B93	1SF.FA.Sf.0	1,930	0.986	0.295	0.181	0
	1SF.FA.Sf.25	1,550	1.255	0.943	0.264	-19.7%
	1SF.FA.Sf.50	1,170	1.635	3.995	1.137	-39.4%
C66	1FA.Sf.0	1,580	0.823	0.221	0.138	0
	1FA.Sf.25	1,160	0.971	0.743	0.218	-26.6%
	1FA.Sf.50	877	1.184	2.887	0.803	-44.5%
D59	1FA.Gf.0	1,340	0.716	0.18	0.1	0
	1FA.Gf.25	1,020	0.843	0.641	0.368	-23.9%
	1FA.Gf.50	748	1.072	2.579	0.704	-44.2%

P_{u0} = Ultimate load corresponding to zero eccentricity.

P_{ui} = Ultimate Load corresponding to the indicated eccentricity.

Table 5: Results for 2 m height column

Group	Column designation	Ultimate load (kN)	max Δ_y (mm)	Max displac. @ free end (mm)	Displacement @ mid-span (mm)	$\frac{(P_{ui} - P_{u0}) \times 100}{P_{u0}}$
A121	2SF.Sf.0	1,510	3.367	0.091	0.039	0
	2SF.Sf.25	1,370	3.66	11.438	2.77	-9.3%
	2SF.Sf.50	785	3.682	16.454	4.001	-48.0%
B93	2SF.FA.Sf.0	1,300	2.6	0.06	0.03	0
	2SF.FA.Sf.25	1,170	3.358	11.129	2.757	-10%
	2SF.FA.Sf.50	621	3.401	15.762	3.728	-52.2%
C66	2FA.Sf.0	1,060	2.301	0.057	0.027	0
	2FA.Sf.25	834	2.623	8.494	2.051	-21.3
	2FA.Sf.50	457	2.679	12.089	2.934	-56.9%
D59	2FA.Gf.0	907	1.863	0.045	0.022	0
	2FA.Gf.25	754	2.216	6.82	0.163	-16.9%
	2FA.Gf.50	405	2.235	9.95	2.424	-55.3%

P_{u0} = Ultimate load corresponding to zero eccentricity.

P_{ui} = Ultimate load corresponding to the indicates.

at their free ends compared with their companion RPC columns made of fly ash and glass fibers for both types of columns ($L = 1$ m and $L = 2$ m).

The results extracted here are generally compatible with other results from similar research. The authors concluded that increasing the eccentricity of the applied loads leads to a decrease in the load capacity of the columns with an increase in the mid-height displacement and concrete compressive strain. They concluded that increasing load eccentricity by $e/t = 0.1$ leads to a decrease in the load capacity by 25% and an increase in the mid-height displacement by 63%. Figure 11 shows the load mid-height displacement for the rectangular reference column [22].

Figure 12 shows the Ansys Nodal Solution for f_y displacements of Group121 (for 1 and 2 m height columns) with different eccentricities ($e = 0, 25$, and 50 mm).

Ductility is defined as a non-dimensional factor, *i.e.*, the ratio of ultimate deformation Δ_u to yield deformation Δ_y . The displacement ductility index can be calculated from the following formula [23]:

$$\text{Displacement - Ductility index} = \frac{\Delta_u}{\Delta_y}, \quad (2)$$

where Δ_u is the ultimate deformation and Δ_y is the yield deformation

Figure 13 shows how to determine Δ_u and Δ_y . The calculated values of the ductility index are represented

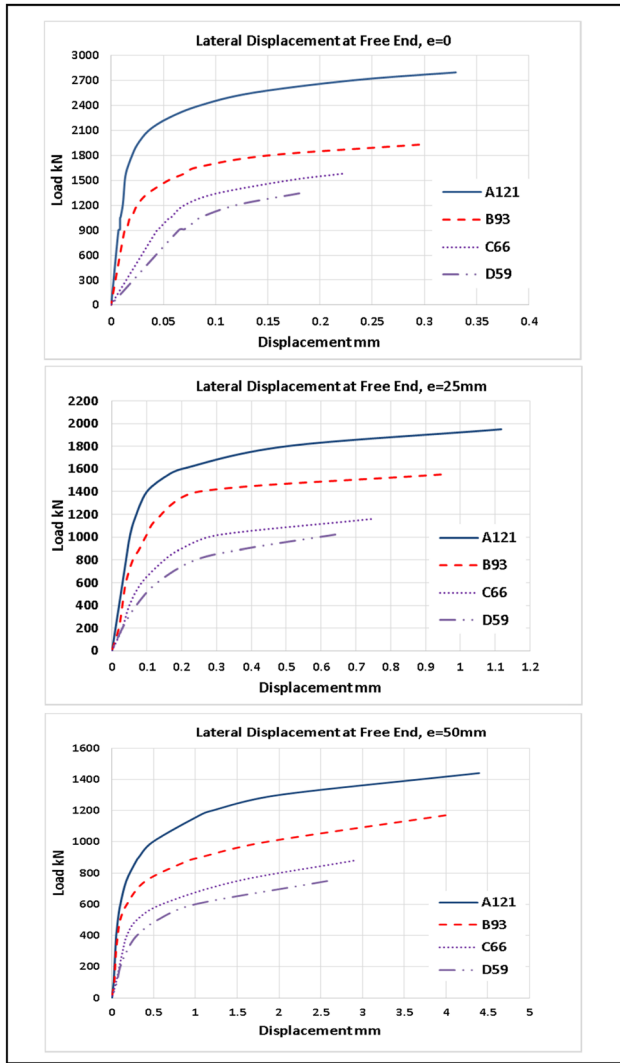


Figure 9: Effects of different eccentric loading (e) on the ultimate load capacity and displacements for 1 m height columns.

in Table 6. The results show that the ductility index decreases as the slenderness of columns increases. Also, the RPC mixes with steel fibers exhibit more ductility indexes than those with glass fibers.

6 Conclusions

In this study, free-standing reinforced columns (with a typical rectangular section of $150\text{ mm} \times 250\text{ mm}$) are manufactured using different mixes of RPC. The columns are loaded with an eccentric ratio $e/h = (0.1 \text{ or } 0.2)$ and numerically analyzed using nonlinear FE modeling. Two such columns are considered short columns ($L =$

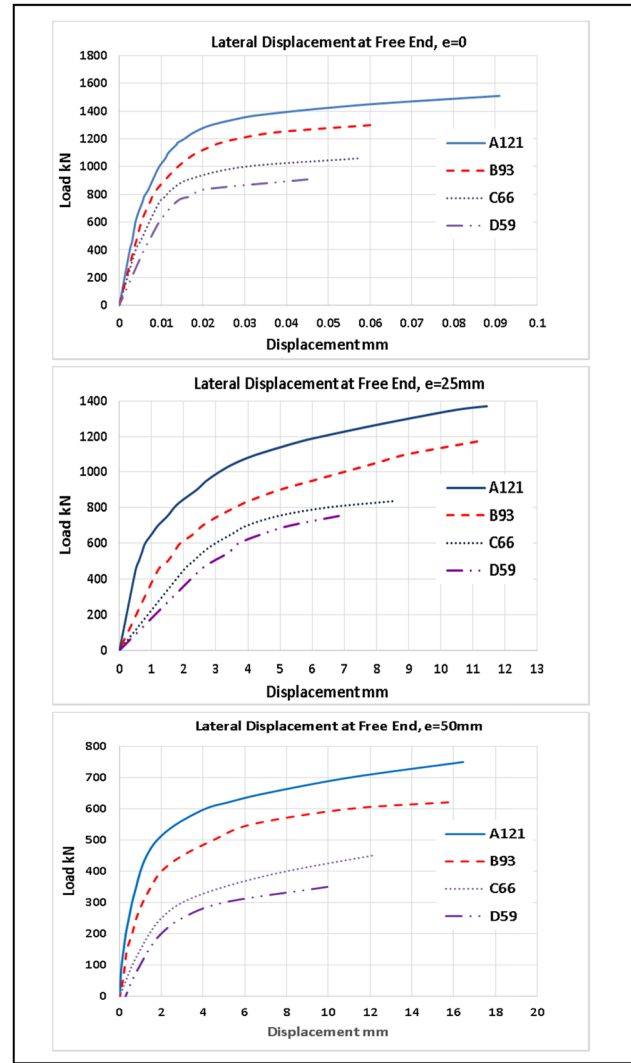


Figure 10: Effects of different eccentric loading (e) on the ultimate load capacity and displacements for 2 m height columns.

1 m) and slender columns ($L = 2\text{ m}$). A summary of the main study findings is listed as follows.

1. The eccentrically loaded slender columns exhibited much less load-carrying capacity than the corresponding concentrically loaded short columns.
2. The reduction in the load-carrying capacity for a column with a specified length depends mainly on the pozzolanic material used (silica fume or fly ash) and the type of fibers used (steel fibers or glass fibers).
3. The average reduction in the load-carrying capacity of RPC columns is 60% when using fly ash instead of silica fume: 50% for using glass fibers instead of steel fibers, and 65% for a 2 m-long column compared to that of a 1 m-long column, 19% for short columns ($L = 1\text{ m}$) if the $e/h = 0.2$ instead of $e/h = 0.1$, and 49%

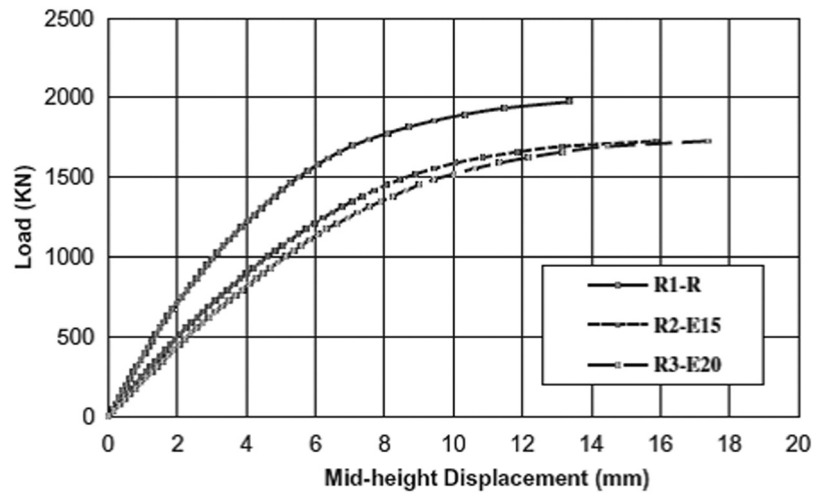


Figure 11: Load mid-height displacement for rectangular reference column [22].

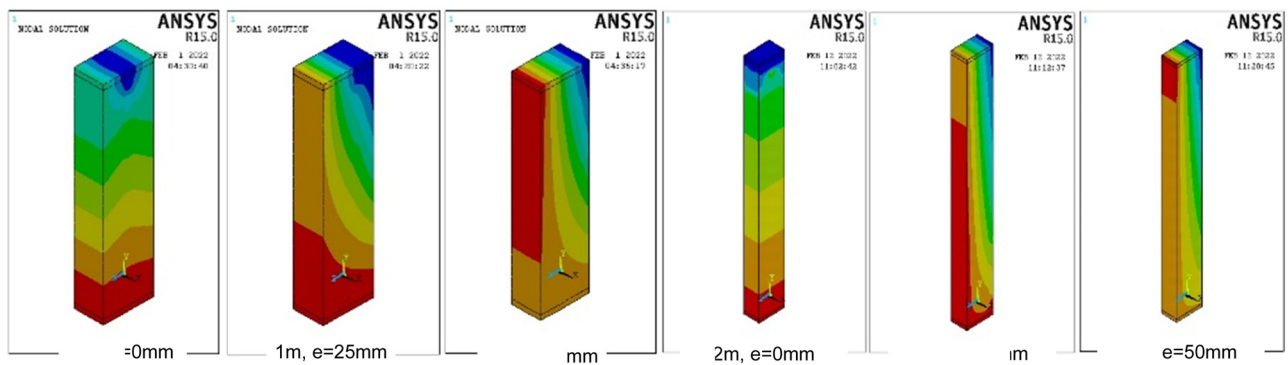


Figure 12: Ansys nodal solution for f_y displacements – Group121 (1 and 2 m height columns) with different eccentricities ($e = 0, 25$, and 50 mm).

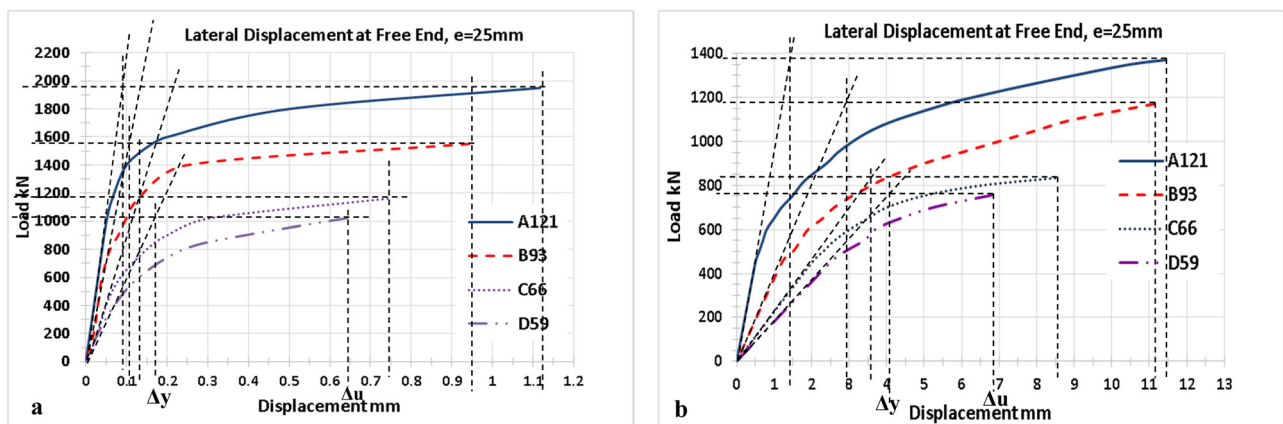


Figure 13: Determining Δ_y and Δ_u for: (a) 1 m height column and (b) 2 m height column.

Table 6: Ductility index

Group	1 m Height column	Ductility index (DI)	2 m Height column	Ductility index (DI)	$\frac{(DI_{2m} - DI_{1m}) \times 100}{DI_{1m}}$
A121	1SF.Sf.0	12.3	2SF.Sf.0	8.2	-33.3%
	1SF.Sf.25	12.5	2SF.Sf.25	8.1	-35.2%
	1SF.Sf.50	13.23	2SF.Sf.50	10.75	-18.8%
B93	1SF.FA.Sf.0	8.4	2SF.FA.Sf.0	3.1	-63.1%
	1SF.FA.Sf.25	8.98	2SF.FA.Sf.25	3.84	-57.2%
	1SF.FA.Sf.50	9.97	2SF.FA.Sf.50	4.25	-57.4%
C66	1FA.Sf.0	3.83	2FA.Sf.0	1.9	-50.3%
	1FA.Sf.25	5.5	2FA.Sf.25	2.4	-56.3%
	1FA.Sf.50	7.45	2FA.Sf.50	3.9	-47.7%
D59	1FA.Gf.0	1.86	2FA.Gf.0	0.93	-50.0%
	1FA.Gf.25	3.77	2FA.Gf.25	1.66	-55.9%
	1FA.Gf.50	5.23	2FA.Gf.50	2.9	-44.6%

for slender column ($L = 2$ m) if $e/h = 0.2$ instead of $e/h = 0.1$.

- The deformations in the eccentrically loaded columns are greater than those in concentrically loaded columns. The percentage differences depend significantly on the length of the column and the eccentricity ratio e/h .
- The average percentage increase in vertical deflection at the free end of short columns ($L = 1$ m) is in the range of 18–31% for $e/h = 0.1$, and on the average 45–69% for $e/h = 0.2$. However, for slender columns ($L = 2$ m), the percentage increase in vertical deflection is in the range of 10–30% for both $e/h = 0.1$ and $e/h = 0.2$.
- The amounts of lateral displacement at the free end of columns are approximately four times larger than at mid-height, whether for short or slender columns and whether $e/h = 0.1$ or 0.2 .
- The ductility index decreases as the column's slenderness increases by approximately 50%. Also, the RPC mixes with steel fibers exhibit more ductility indexes than those with glass fibers.

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References

- Wenjie GE, Chen KA, Guan ZH, Ashour AS, Lu WE, Cao DA. Eccentric compression behavior of concrete columns reinforced with steel-FRP composite bars. *Eng Struct.* 2021 April;238(1):1–19.
- Falah MA, Ali YA, Al-Mulali MO, Al-Khafaji ZA. Finite element analysis of CFRP effects on hollow reactive powder concrete column failure under different loading eccentricities. *Solid State Technol.* 2020;63(2):1241–55.
- Ahmad AS, Alkhazraji FA, Omar SM. Experimental study of circular short columns made from reactive powder concrete. *Eng Tech J Univ Technol - Iraq.* 2016 September;34(A-9):1860–72.
- Shi CH, Long MI, Cao CH, Long GU, Lei MI. Mechanical property test and an analytical method for reactive powder concrete columns under eccentric compression. *KSCE J Civ Eng.* 2017;21(4):1307–18.
- Hussein AD, Elsamny MO, Nafie AM, Abd-Elhamed MO. Non-linear finite element analysis of eccentrically loaded RC columns strengthened using a steel jacketing technique. *Int J Emerg Eng Res Technol.* 2015;3(11):127–34.
- Hao WE, Xu XI, Niu ZH. Experimental study on the mechanical behavior of RPC-filled square steel tube columns subjected to eccentric compression. *Frat ed Integrita Strutt.* 2018;46:391–9.
- Malik AD, Foster ST. Behavior of reactive powder concrete columns without steel ties. *J Adv Concr Technol.* 2008 June;6(2):377–86.
- Hadi MU, Goiaz HU, Yu TA. Experimental investigation of CFRP confined hollow core reactive powder concrete columns. *Constr Build Mater.* 2018;174:3434–355.
- Aydin SE, Yazici HA, Yardimci ME, Yigiter HU. Effect of aggregate type on mechanical properties of reactive powder concrete. *ACI Mater J.* 2010 September; 107(5):441–9.
- Yujing LV, Wenhua ZH, Fan WU, Peipei WU, Weizhao ZE, Fenghao YA. Static mechanical properties and mechanism of C200 ultra-high performance concrete containing

- coarse aggregates. *Sci Eng Compos Mater*. 2020 June;27:186–95.
- [11] Arunkumar K, Muthukannan M, Kumar SU. Experimental behavior of fiber-reinforced reactive powder concrete. *Int J Eng Adv Technol IJEAT*. 2019;9(154):454–9.
- [12] Wang YU, Xin CU, Liu ZH. Key factors affecting the preparation and properties of reactive powder concrete. In *Conference of Energy and Environmental Protection*; 2017 Jun 29–30; Zhuhai, China. Atlantis Press, 2017. p. 6–10.
- [13] Al-Hassani HI, Al-Abasi JA, Al-Saraj WI. Proposed expressions for torsional capacity of RPC beams. *J Eng Dev*. 2015;19(3):25–33.
- [14] Zhang YU, Wu BI, Wang JI, Liu MO, Zhang XU. Reactive powder concrete mix ratio and steel fiber content optimization under different curing conditions. *Materials*. 2019 November;12(3615):1–19.
- [15] Al-Hassani HI, Ibraheem SU. A proposed equation for the evaluation of the nominal ultimate bending moment capacity of rectangular singly reinforced RPC sections. *Eng Tech J Univ Technol - Iraq*. 2011 May;29(5):925–34.
- [16] Pradeep K, Khan KH, Kumar N. Reliability analysis of composite steel column subjected to monotonic loading. *Indian J Appl Res*. 2014;4(9):213–9.
- [17] Pawar V, Pawar P. Non-linear analysis of reinforced concrete column with Ansys. *Int Res J Eng Technol*. 2016;3(6):2290–6.
- [18] Nath AR, Raj IN. Non-linear finite element analysis on confined concrete columns under concentric and eccentric compression. *Int J Sci Res*. 2015;4(10):1048–51.
- [19] Gamal K, Elsayed K, Makhlof M, Alaa M. Properties of reactive powder concrete using local materials and various curing conditions. *Eur J Eng Res Sci*. 2019;4(6):74–83.
- [20] Ling GA, Shui ZH, Sun TA, Gao XU, Wang YU, Sun YU, et al. Rheological behavior and microstructure characteristics of SCC incorporating metakaolin and silica fume. *Materials*. 2018;11(2576):1–16.
- [21] Al-Hassani HI, Khalil WA, Danha LU. Mechanical properties of reactive powder concrete (RPC) with various steel fiber and silica fume contents. *Eng Tech J Univ Technol - Iraq*. 2013;A-16:3090–108.
- [22] Kottb HA, El-Shafey NA, Torkey NK. The behavior of high-strength concrete columns under eccentric loads. *HBRC J Hous Build Natl Res Cent*. 2015;11(1):22–34.
- [23] Duan LI, Cooper TH. Displacement ductility capacity of reinforced concrete columns. *Concr Int*. 1995 November;17(11):61–5.