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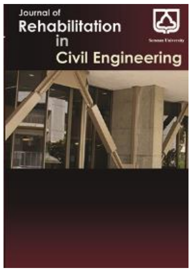

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Behavior of FRP-Confined Reactive Powder Concrete Columns under Eccentric Loading

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ABSTRACT

Fiber reinforced Polymers (FRP) have widely used for the purposes of enhances strength and ductility of concrete columns. Proper design of such hybrid columns, however, requires a better recognition of the behavior of concrete columns confined with FRP. In this paper, the influence of FRP thickness, concrete compressive strength, and column size on the performance of eccentrically loaded reactive powder concrete (RPC) columns confined with FRP is investigated. In this regard, five different FRP thicknesses, three types of column sizes, and concrete compressive strength values ranging from 140 MPa to 180 MPa are considered. For this purpose, two-dimensional nonlinear finite element analyses are carried out so as to predict the behavior of FRP-confined RPC columns. OpenSees software is employed to analyze the considered columns. To validate finite element model, the numerical predictions are compared with the experimental data. The study, from a numerical point of view, derived some important relevant conclusions regarding the behavior of RPC columns confined with FRP.

1. Introduction

Fiber reinforced polymer (FRP) composite structures are finding broader acceptance from end users through a wider range of applications in civil infrastructure as an alternate to conventional concrete, steel, and timber structures [1]. Extensive experimental researches have approved that external confinement by means of FRP wrapping increases highly the strength and ductility of concrete columns [2-9]. In this context, an area where the use of FRP has attracted considerable interest is in the confining of reactive powder concrete (RPC) columns. Reactive powder concrete has been used in many application fields of the construction industry, such as civil engineering, mining engineering, and military works for the last two decades [10-

12]. Compared to normal strength concrete (NSC), RPC has ultra-high compressive strength, limited shrinkage and high toughness. By taking advantage of the ultra-high compressive strength of RPC, the size of columns for newer high-rise buildings can usually be reduced, so one can get more space to use and to rent [13-15]. In this context, since reactive powder concrete is poor in tension and ductility, a column without any form of reinforcement will fail when subjected to cyclic loads or/and a relatively small tensile load. In this regard, the use of FRP to strengthen the concrete is an effective solution to increase the overall strength of the structure [16]. The response of FRP-confined concrete columns is affected by several parameters such as concrete compressive strength, wrap thickness, and size effects. One of the techniques used to identify the behavior of confined concrete columns is the utilization of finite element method. In the field of numerical approach, several studies have been conducted in order to study the behavior of FRP confined concrete columns using finite element analyses. Parvin and Jamwal [17] studied the performance of axially loaded, small-scale, and fiber-reinforced polymer (FRP) wrapped normal-strength concrete columns with various wrap angle configurations, wrap thicknesses, and concrete strengths through finite element analysis. The finite element analysis results showed substantial increase in the axial compressive strength and ductility of the FRP-confined concrete cylinders as compared to the unconfined cylinders. It was observed that the increase in wrap thickness also resulted in enhancement of axial strength and ductility of the concrete columns.

Jiang and Wu [18] proposed a nonlinear finite element model that was developed in the Drucker-Prager (DP) plasticity framework to evaluate axial compressive behavior of FRP-wrapped normal-strength concrete columns using ABAQUS software. Detailed finite element modeling was used in assessment of existing FRP-wrapped concrete columns. Plastic dilation, friction angle and cohesion for FRP confined concrete (normal-weight) are extensively investigated by analyzing test results, and models for each of them were developed, leading to a modified DP model for finite element analyses of FRP confined concrete columns.

Finite element analyses using ANSYS were utilized to conduct a parametric analysis [19].The effect of the thickness, stiffness, and fiber orientation of the FRP layers as well as the interfacial bonding between the FRP wraps and the concrete on the strength and stiffness of the repaired normal-strength concrete columns was evaluated using the finite element modeling. It was concluded that the thickness of the FRP wraps has a significant effect on the strength and stiffness of the repaired columns. Additionally, it was mentioned that increasing the thickness of the FRP layers can increase the strength and stiffness considerably of the repaired normal-strength concrete columns.

Elsanadedy et al. [20] carried out non-linear finite element analysis using LS-DYNA software to study the effect of specimen size and confinement stress ratio on FRP-confined normal/high strength concrete cylinders. It was concluded that the specimen size has an insignificant influence on the FRP-confined concrete cylinders. Additionally, it was evident that by increasing the confinement stress ratio the strength and ductility of FRP-wrapped specimens increases.

Issa et al. [21] conducted nonlinear finite element analyses to study the behavior of fiber-wrapped concrete columns under axial compressive loading. The ADINA software was used in the finite element analyses using a Drucker-Prager framework with an elastic-perfectly-plastic response, a non-associative flow rule, and a Von Mises yield criterion with dependence on hydrostatic stress. The results showed that increasing the thickness of FRP layers enhances the strength of the fully wrapped concrete cylinder. Furthermore, when the wider wrap of FRP was used the strength of the wrapped concrete cylinder was increased.

As it is shown by this brief literature review (see [22] for further detail) most of the previous studies based on the finite element modeling have been conducted to predict the response of normal strength concrete columns retrofitted by FRP wrapping. Additionally, previous studies have not adequately investigated the combined effects of unconfined concrete compressive strength, wrap thickness, and column size. Although several studies have been conducted to investigate the response of normal/high strength concrete columns confined with FRP wrapping, analyzing and evaluating the mechanical response of reactive powder concrete columns confined with fiber reinforced polymer is still a challenging issue. Moreover, most of the previous studies have been conducted to study the behavior of confined columns tested under concentric loads. However, columns in practical conditions due to unintentional load eccentricities and possible construction error is subjected to eccentrically load [23-25]. In view of these shortcomings, in this study, the finite element analyses are conducted to study the behavior of reactive powder concrete columns confined with FRP. The FRP-confined RPC columns considered in this study are subjected eccentrically compressive load. The two-dimensional finite element model used in this paper is based on discrete finite element methodology. OpenSees software is employed to carry out the finite element analyses of the considered columns. In order to validate the finite element model, experimental results from columns tested under axial compressive load with different eccentricity is compared to those obtained from finite element analysis. Sections of the emphasis of this paper will be on the study of the effects of unconfined concrete compressive strength, wrap thickness, and column size on the response of FRP-confined RPC columns. The finite element analysis study of this paper is expected to provide adequate knowledge into the behavior of FRP-confined RPC columns which will be useful for efficient applications in practical engineering projects especially for newer high-rise buildings.

2. Finite element model

This section presents a brief description about the finite element modeling. Details on proposed model and modeling process can be found in Abbassi and Dabbagh [26]. A 2-D model of the FRP-confined RPC columns is built using the open system for earthquake engineering simulation software (OpenSees) [27]. The finite element modeling approach used in this paper is based on the discrete finite element methodology. In order to modeling by this methodology, cross-section of the FRP confined RPC columns is divided into two parts included: reactive powder concrete and fiber reinforced polymer. Each of the two parts is discretized into discrete several of smaller cross-section regions which are called fibers. The stress-strain model of FRP and RPC is required to describe the behavior each of the two parts (fibers). In this regard, on the basic of a number of studies on constitutive model of concrete in compression, modified Kent and Park model is used to define the compression behavior of RPC [26]. Modified Kent and Park model included three regions: parabolic ascending stress region, linear descending region and constant residual stress region that typical curve is shown in Fig. 1.

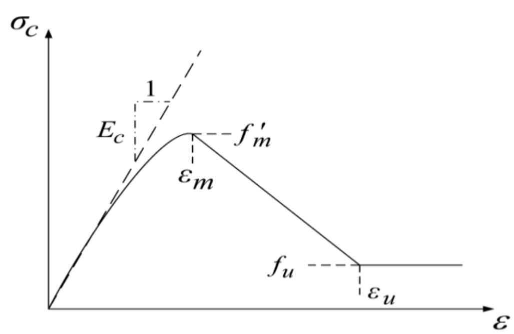

Fig. 1. Constitutive model of concrete in compression

Based on a number of tests and researches for concrete [28-31], it is assumed that a constitutive model for describing the stress-strain behavior of RPC in tension comprises an ascending linear elastic portion up to the tensile strength, and a descending linear portion that accounts for tension stiffening occurs after this point. The typical stress-strain behavior of reactive powder concrete in tension is shown in the Fig. 2.

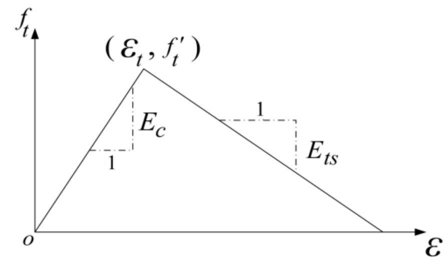

Fig. 2. Concrete constitutive model in tension

For FRP, it is assumed that the FRP constitutive model in tension and compression is linear elastic brittle. Additionally, FRP possesses the same elastic modulus in tension and compression [32]. The typical stress-strain behavior of FRP is plotted in Fig. 3.

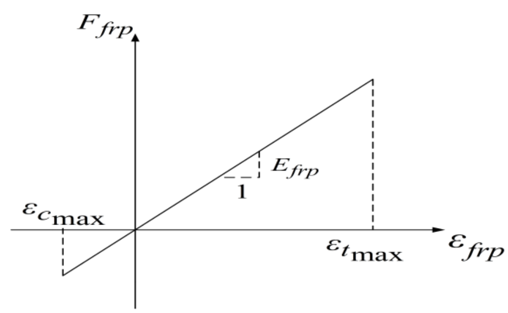

Fig. 3. CFRP constitutive model

The cross section response of the confined RPC columns is derived by integration of the constitutive stress-strain behavior of the fibers. A two-nodded nonlinear beam-column element is used to model the considered confined columns. The nonlinear behavior of the beam-column element at each cross section level derives entirely from the resultant nonlinear stress-strain response of the fibers.

3. Model validation examples

Usually, the finite element results should be presented to illustrate the applicability and accuracy of the proposed model. Therefore, to validate the described finite element model, the results of three structural FRP-confined RPC columns tested by Malik and Foster [33] are used to compare with the predictions from the finite element analyses. The considered columns tested by Malik and Foster [33] were cast with reactive powder concrete consisting of either steel fibers or without it. The concrete column specimens wrapped with either two types of carbon fiber reinforced polymer (CFRP) wrapping including: longitudinal and circumferential. Details for the CFRP type used for wrapping the columns and CFRP properties are presented in Tables 1 and 2, respectively.

Table 1. Details of CFRP type wrapping [33]

Laminate Structure	Wrap Type 1		Wrap Type 2	
	Carbon fiber Sheet	Wrap direction	Carbon fiber Sheet	Wrap direction
Layer1	CF120	Longitudinal	CF350	Longitudinal
Layer2	CF120	Longitudinal	CF350	Longitudinal
Layer3	CF120	Circumferential	CF120	Circumferential
Layer4	CF120	Circumferential	CF120	Circumferential

Table 2. Mechanical properties of CFRP [33]

CFRP Type	CF120	CF350
Tensile strength, $f'_{t\,frp}$	3800 MPA	2650 MPA
Modulus of Elasticity	240 GPA	640 GPA
Ultimate strain	1.55 %	0.4 %

The confined RPC columns were tested under axial compressive load with different eccentricities. Details of the column specimens are presented in Table 3.

Table 3. Material properties of RPC and column details [33]

Specimens	ρ (%)	f'_m (MPA)	f'_t (MPA)	E (mm)	D (mm)	H (mm)	Wrap type
FC20−2	2	165	7.7	20	152.3	1056	2
FC35−1	2	165	7.7	35	152.4	1058	1
PC35−1	0.0	143	3.3	35	152.4	1055	1

In Table 3, ρ is the volumetric percentage of steel fibers; f'_m is the compressive strength of RPC; E is the eccentricity of the load; D is the diameter of concrete column cross-section; H is the height of the column; and f'_t is the tensile strength of RPC. The comparison of nonlinear FE analysis results and experimental test results in terms of the axial load versus mid height lateral displacement are plotted in Figs. 4-6.

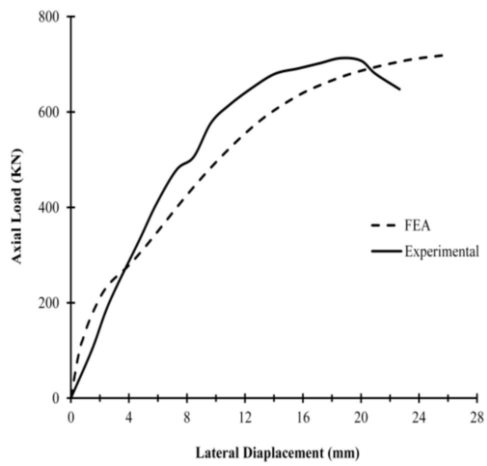

Fig. 4. Comparison of predicted results with test data for the column FC35-1

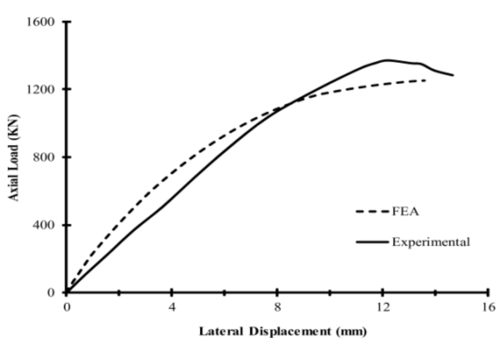

Fig. 5. Comparison of predicted results with test data for the column FC20-2

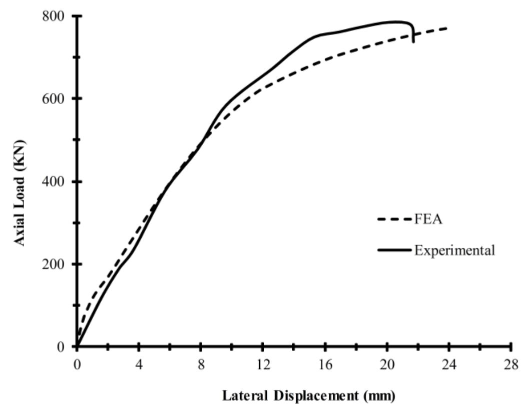

Fig. 6. Comparison of predicted results with test data for the column PC35-1

As shown in Figs. 4-6, the axial load-lateral displacement curve that was obtained from finite element analysis corresponds well with the test data.

Table 4 contrasts differences of experimental results and finite element analyses results in terms of peak axial load and corresponding moment.

Table 4. Comparison of test results with finite element analysis results

column	Peak axial Load, P_u (KN)			Moment at P_u (KN-m)		
	EXP	FEA	FEA/EXP	EXP	FEA	FEA/EXP
PC35-1	773	772	1	43400	42532	0.98
FC20-2	1367	1253	0.92	47000	46111	0.98
FC35-1	714	720	0.99	38900	45232	1.16
Mean			0.97			1.04
Standard Deviation			0.04			0.08

According to the comparisons (see Table 4), it can be seen that the results of finite element simulations with OpenSees have consistency with the experimental test ones. Additionally, note that the mean of the ratio of the predicted load to the experimental load and its standard deviation are in a proper range. This means that the finite element model can be used to analyze the behavior of FRP-confined RPC columns. Hence, given the demonstrated accuracy of this model, the finite element model will be used to perform a parametric study of the behavior of FRP-confined RPC columns in a subsequent section of this paper.

4. Parametric studies based on finite element analysis

The prediction of response of concrete columns confined with FRP is complex. The behavior of fully FRP-confined RPC columns is affected by a number of factors such as wrap thickness, column size, concrete compressive strength, fiber orientation, and stiffness of the FRP wraps. In this regard, the failure of reactive powder concrete columns confined with FRP should be appeared with adequate ductility and a change of its behavior from ductile to brittle with varying FRP thicknesses needs to be identified. Furthermore, the behavior of FRP-confined concrete columns that has actual size in practical engineering projects needs to be understood. Hence, in order to study the behavior of RPC columns confined with FRP, using the validated finite element model, three parameters are considered in this study: 1) wrap thickness, 2) concrete compressive strength, and 3) column size.

4.1. Effect of wrap thickness

The circular confined columns used for demonstrating the effect of wrap thickness have the same cross-section area and height, but different wrap thicknesses. To evaluate the effect of wrap thickness on the response of considered columns, five different FRP thicknesses are considered: 0.1225 mm, 0.245 mm, 0.3675 mm, 0.49 mm, and 0.735 mm. The dimensions and material properties of RPC columns that are used to study the effects wrap thickness are listed in Table 5.

To facilitate the comparison of specimens with similar parameters, the specimens are arranged in three groups. Group 1 keeps the value of concrete compressive strength at 130 MPa while the wrap thickness varies among five above-mentioned values. Groups 2 and 3 are similar to group 1, except concrete compressive strength has a value of 150 MPa and 170 MPa, respectively.

Table 5. Dimensions and material properties

Specimens	f'_m (MPA)	$f'_{t\,frp}$ (MPA)	E_{frp} (GPA)	Thickness of FRP (mm)	No. of FRP layers	Diameter (mm)	Height (mm)
GA1-1	130	3800	240	0.1225	1	152.4	1054
GA1-2	130	3800	240	0.245	2	152.4	1054
GA1-3	130	3800	240	0.3675	3	152.4	1054
GA1-4	130	3800	240	0.49	4	152.4	1054
GA1-5	130	3800	240	0.735	6	152.4	1054
GA2-1	150	3800	240	0.1225	1	152.4	1054
GA2-2	150	3800	240	0.245	2	152.4	1054
GA2-3	150	3800	240	0.3675	3	152.4	1054
GA2-4	150	3800	240	0.49	4	152.4	1054
GA2-5	150	3800	240	0.735	6	152.4	1054
GA3-1	170	3800	240	0.1225	1	152.4	1054
GA3-2	170	3800	240	0.245	2	152.4	1054
GA3-3	170	3800	240	0.3675	3	152.4	1054
GA3-4	170	3800	240	0.49	4	152.4	1054
GA3-5	170	3800	240	0.735	6	152.4	1054

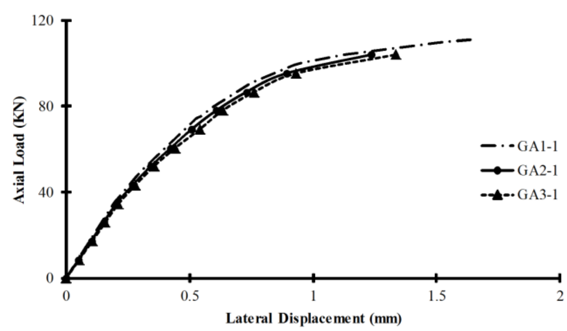

Fig. 7. Comparison of predicted results for columns GA1-1/GA2-1/GA3-1

Fig. 7. shows axial load versus mid-height lateral displacement response, measured at the mid-height, for the columns with FRP thickness=0.1225 mm. It is observed that the maximum lateral displacement predicted for GA1-1 is 1.64 mm.

Table 6. Finite element analysis results

Specimens	Max Axial Force, F max (KN)	Moment at F max (KN-m)	Δ_{mid} * at F max (mm)
GA1-1	111.1	6119.4	1.64
GA1-2	616.3	33943.1	28.36
GA1-3	686.5	37810.1	28.53
GA1-4	710.8	39151.1	22.25
GA1-5	748.6	41230	18.62
GA2-1	109.2	6015.2	1.68
GA2-2	672.6	37046.2	27.49
GA2-3	771.4	42488.6	30.33
GA2-4	810.8	44658.6	26.72
GA2-5	849.4	46785.2	20.89
GA3-1	104	5728.8	1.33
GA3-2	733.6	40405.4	27.15
GA3-3	840.7	46307.8	30.26
GA3-4	897.1	49410.9	28.67
GA3-5	945.6	52080	22.91

* Lateral displacement at mid-height of columns

As shown in Table 6, the value of maximum lateral displacement for GA2-1 and GA3-1 are 1.68 mm and 1.33 mm, respectively. Compared to other results of finite element analysis obtained from each examined groups (see Table 6), it can be concluded that cases with FRP thickness=0.1225 mm behave similar to those without FRP wraps because of brittle behavior and the little load capacity. In this context, it is concluded that the effect of the wrap thickness is minimal.

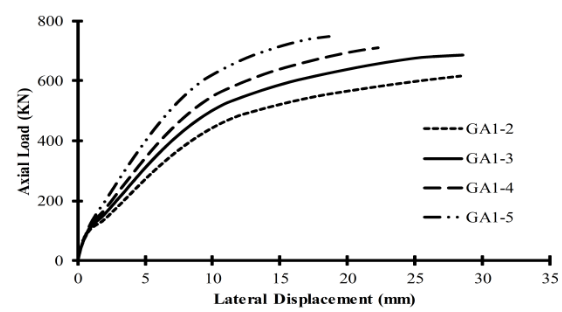

Fig. 8. Comparison of predicted results for columns GA1-2/GA1-3/GA1-4/GA1-5

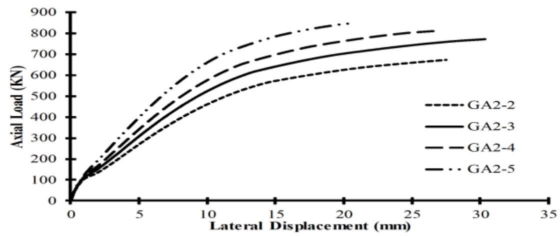

Fig. 9. Comparison of predicted results for columns GA2-2/GA2-3/GA2-4/GA2-5

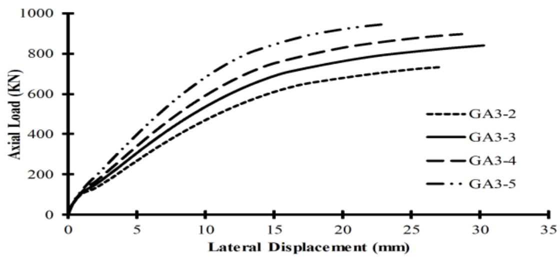

Fig. 10. Comparison of predicted results for columns GA3-2/GA3-3/GA3-4/GA3-5

Figs. 8-10 display how behavior of FRP-confined RPC columns changes while the FRP thickness is increased. Furthermore, details of the finite element analysis results are given in Table 6. From the Figs. 8-10, it can be seen that by changing the FRP thickness from 0.1225 to 0.245 mm (1 layer to 2 layers), the maximum axial load and corresponding maximum lateral displacement is increased. The value of maximum lateral displacement for GA1-2 is 28.36 mm. It is observed that the maximum lateral displacement of GA1-2 is about 17 times the maximum lateral displacement of GA1-1. Similarly, in this viewpoint, the maximum lateral displacement for GA2-2 and GA3-2 is about 16 and 20 times the maximum lateral displacement of GA2-1 and GA3-1, respectively. Furthermore, the moment corresponding to maximum axial load of confined RPC columns is increased. It can be mentioned that increasing wrap thickness from 0.1225 to 0.245 mm enhances the strength and ductility, with a transition from brittle to ductile behavior. Similarly, the load capacity (maximum axial load and corresponding moment) and maximum lateral displacement of FRP-confined RPC columns are increase when the thickness of FRP is enhanced from 0.245 mm to 0.3675 mm (2 layers to 3 layers). Even though this is in agreement with previous studies [19, 34-35], showing that the increase in wrap thickness also resulted in enhancement of axial strength and ductility of the concrete columns, it is noticed that increasing the ductility of FRP-confined concrete columns is not continued with increasing the FRP thickness in all conditions. In this regard, even though increasing the thickness of FRP from 0.3675 to 0.735 increases the load capacity, the ductility of confined RPC columns is decreased. In this context, the maximum lateral displacement is 23% decreased for GA1-4 in comparison with GA1-3. Compared to GA2-3, the maximum lateral displacement of GA2-4 is 12% decreased. Furthermore, the quantity of maximum lateral displacement for GA3-4 is 6% less than that for GA3-3. In like manner, decrease in maximum lateral displacement is observed when the thickness of FRP is varied from 0.49 mm to 0.735 mm. In this matter, the maximum lateral displacement is 17% decreased for GA1-5 in comparison with GA1-4. Additionally, the quantity of maximum lateral displacement for GA2-5 is 22% less than that for GA2-4. Similarly, maximum lateral displacement for GA3-5 is 20% less than that for GA3-4. According to the analyses carried out, it is observed that increasing the maximum lateral displacement of FRP-confined RPC columns do not always occur exactly at the mid-height of columns while the thickness of FRP is enhanced. In summary, it is concluded that the behavior of RPC columns has a balanced condition. One can conclude that if the column is confined with FRP thickness less than the balanced FRP thickness, increasing the thickness of FRP also resulted in enhancement of ductility of the confined RPC columns. On the contrary, if the column is confined with FRP thickness greater than the balanced FRP thickness, increasing the thickness of FRP resulted in decreasing the ductility of concrete columns. Besides the predicted response in terms of lateral displacement, it can be observed that increasing the thickness of the FRP layers can increase the load capacity (axial strength and moment) considerably.

4.2. Effect of concrete compressive strength

In order to study the effect of concrete compressive strength on the response of FRP-confined RPC columns, four other groups are also used. For group 1, the wrap thickness is kept constant at 0.245 mm while the concrete compressive strength varies among three values: 140 MPa, 160 MPa, and 180 MPa. Groups 2-4 are similar to group 1, except the FRP thickness have a value of 0.49 mm, 0.735 mm, and 0.98 mm, respectively. The detailed geometric and material properties of these columns are given in Table 7.

Table 7. Geometric and material properties

Specimens	f'_m (MPA)	$f'_{t\,frp}$ (MPA)	E_{frp} (GPA)	Thickness of FRP (mm)	No. of FRP layers	Diameter (mm)	Height (mm)
GB1-1	140	3800	240	0.245	2	152.4	1054
GB1-2	160	3800	240	0.245	2	152.4	1054
GB1-3	180	3800	240	0.245	2	152.4	1054
GB2-1	140	3800	240	0.49	4	152.4	1054
GB2-2	160	3800	240	0.49	4	152.4	1054
GB2-3	180	3800	240	0.49	4	152.4	1054
GB3-1	140	3800	240	0.735	6	152.4	1054
GB3-2	160	3800	240	0.735	6	152.4	1054
GB3-3	180	3800	240	0.735	6	152.4	1054
GB4-1	140	3800	240	0.98	8	152.4	1054
GB4-2	160	3800	240	0.98	8	152.4	1054
GB4-3	180	3800	240	0.98	8	152.4	1054

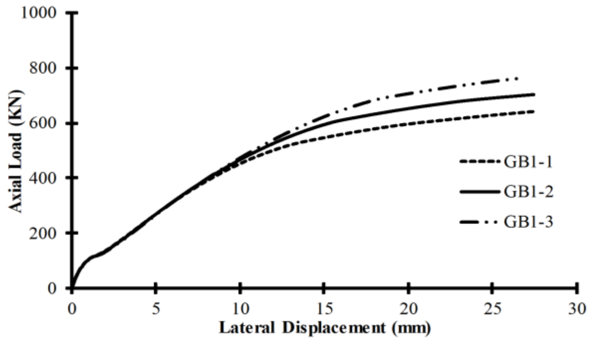

Fig. 11. Effect of the concrete compressive strength on the behavior of confined RPC columns-Group 1

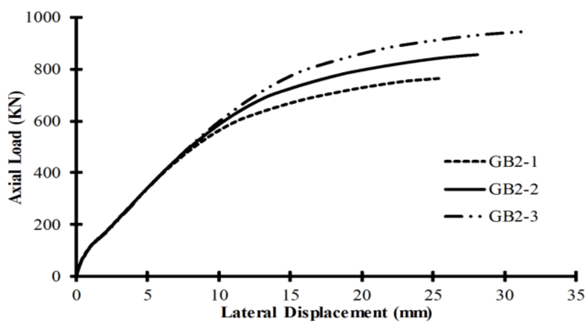

Fig. 12. Effect of the concrete compressive strength on the behavior of confined RPC columns-Group 2

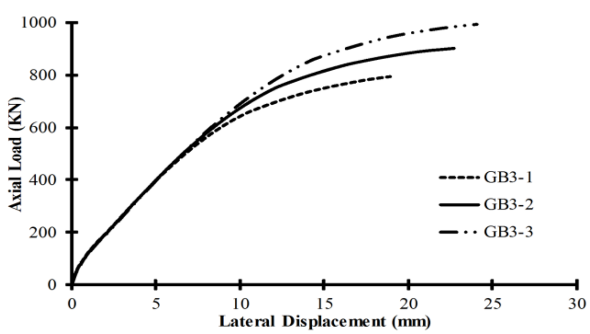

Fig. 13. Effect of the concrete compressive strength on the behavior of confined RPC columns-Group 3

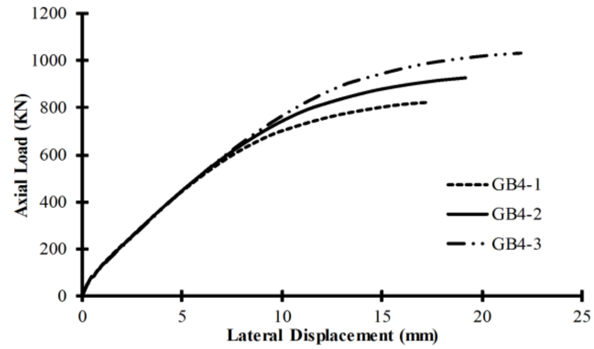

Fig. 14. Effect of the concrete compressive strength on the behavior of confined RPC columns-Group 4

Figs. 11-14 show axial load versus mid-height lateral displacement response, measured at the mid-height, for the five groups of specimens separately to show the effect of concrete compressive strength.

For columns with two layers of FRP (Fig. 11.), when the thickness of FRP is increased the mid-height lateral displacement is not changed significantly; however, slight increase in the load capacity is obtained. In this viewpoint, it can be concluded that more confinement levels might be required to capture the behavior of FRP confined RPC columns under the variation of concrete compressive strength. Therefore, the responses of FRP-confined RPC columns with different FRP thicknesses are then predicted. Summary of finite element analysis results is listed in Table 8.

Table 8. Finite element analysis results

Specimens	Max Axial Force, F max (KN)	Moment at F max (KN-m)	Δ_{mid} * at F max (mm)
GB1-1	642	35362.3	27.47
GB1-2	703.2	38730.2	27.42
GB1-3	764.3	42098	26.93
GB2-1	764.3	42098	25.38
GB2-2	856	47149.8	28.08
GB2-3	945.6	52080	31.52
GB3-1	794.3	43747.2	18.9
GB3-2	901.9	49675.6	22.69
GB3-3	993.6	54727.4	24.06
GB4-1	823.4	45353	17.38
GB4-2	926.6	51038.4	19.17
GB4-3	1031.8	56832.3	21.93

* Lateral displacement at mid-height of columns

Based on the finite element analyses results (Table 8), it can be seen that the addition of concrete compressive strength improves the load capacity of the confined RPC columns in terms of the axial load and corresponding moment. The curves (Figs. 12-14) demonstrate that the mid-height lateral displacement of the columns enhanced by increasing the compressive strength of RPC. In cases GB2-2 and GB3-2, the prediction of the maximum axial load increased 12% and 14% as compared to GB2-1 and GB3-1, respectively. Additionally, the predicted peak axial load of GB4-2 is 13% higher than that of the GB4-1. Furthermore, it is observed that the rate increase in the maximum axial load is almost constant with the increase in the compressive strength of RPC. Based on the finite element analyses results, it can be concluded that the increase in the compressive strength of RPC which results in the increase in load capacity (axial load and moment), give rise to higher ductility of FRP-confined RPC columns while the number of FRP layers constant.

4.3. Effect of column size

For parametric study purposes in terms of column section, the finite element analysis is performed for five groups. Group 1 keeps the value of concrete compressive strength at 130 MPa while the diameter of cross-section varies among three values: 300 mm, 350 mm and 400 mm. Group 2-5 are similar to group 1, except concrete compressive strength have a value of 140 MPa, 150 MPa, 160 MPa, and 170 MPa, respectively. Additionally, it is noticed that these five groups is considered to have the same height=3 m and FRP thickness=0.3675 mm

(3 layers). The geometric and material properties of the analyzed FRP-confined RPC columns to investigate the size effect are summarized in Table 9.

Table 9. Geometric and material properties

Specimens	f'_m (MPA)	$f'_{t\,frp}$ (MPA)	E_{frp} (GPA)	Thickness of FRP (mm)	No. of FRP layers	Diameter (mm)	Height (mm)
GC1-1	130	3800	240	0.3675	3	300	3000
GC1-2	130	3800	240	0.3675	3	350	3000
GC1-3	130	3800	240	0.3675	3	400	3000
GC2-1	140	3800	240	0.3675	3	300	3000
GC2-2	140	3800	240	0.3675	3	350	3000
GC2-3	140	3800	240	0.3675	3	400	3000
GC3-1	150	3800	240	0.3675	3	300	3000
GC3-2	150	3800	240	0.3675	3	350	3000
GC3-3	150	3800	240	0.3675	3	400	3000
GC4-1	160	3800	240	0.3675	3	300	3000
GC4-2	160	3800	240	0.3675	3	350	3000
GC4-3	160	3800	240	0.3675	3	400	3000
GC5-1	170	3800	240	0.3675	3	300	3000
GC5-2	170	3800	240	0.3675	3	350	3000
GC5-3	170	3800	240	0.3675	3	400	3000

Figs. 15-19 illustrate axial load versus mid-height lateral displacement response, measured at the mid-height, for each considered groups.

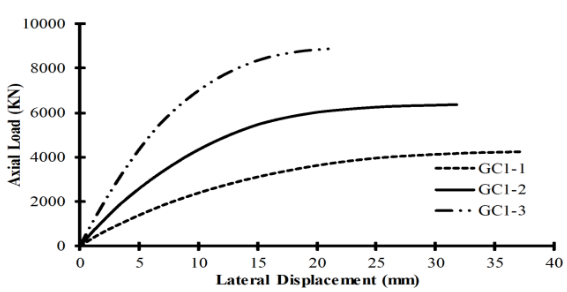

Fig. 15. Comparison of predicted results for columns GC1-1/GC1-2/GC1-3

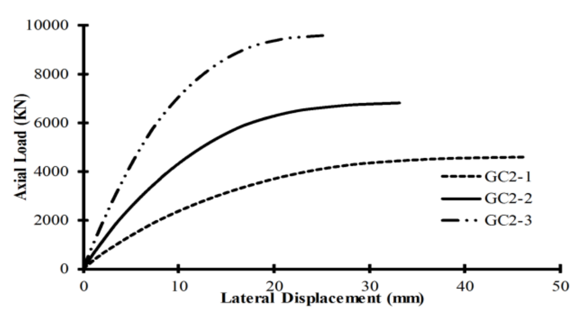

Fig. 16. Comparison of predicted results for columns GC2-1/GC2-2/GC2-3

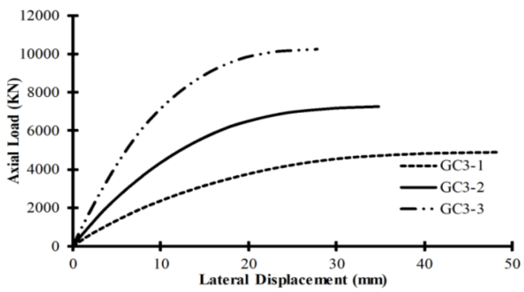

Fig. 17. Comparison of predicted resylts for columns GC3-1/GC3-2/GC3-3

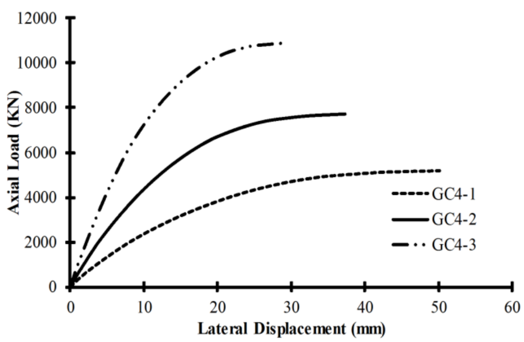

Fig. 18. Comparison of predicted results for columns GC4-1/GC4-2/GC4-3

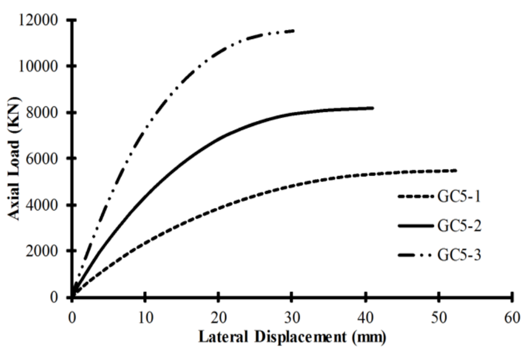

Fig. 19. Comparison of predicted results for columns GC5-1/GC5-2/GC5-3

It is evident from Figs. 15-19 that the response of a circular FRP-confined reactive powder concrete column is dependent on the cross-section size. In this regard, even though increasing of cross-section reduces the ductility of columns, the peak axial load of the confined columns due to the enhancement of cross-section is increased (see Table 10). As illustrated in Fig. 15-19, when the cross-section increases by 36% (increasing diameter of cross-section from 300mm to 350mm), the load capacity (axial load and corresponding moment) of the confined RPC columns is increased. Similarly, when the cross-section increases by 30% (increasing diameter of cross-section from 350 mm to 400 mm) the load capacity is also increased. Additionally, as the cross-section increases the ductility of columns is decreased. In this regard, As illustrated in Table 10, when the cross-section increases by 36% (increasing diameter of cross-section from 300mm to 350mm), the maximum mid-height lateral displacement of GC1-2 and GC2-2 is decreased by about 15% and 29%, as compared to GC1-1 and GC2-1, respectively. Furthermore, the predicted maximum mid-height lateral displacement of GC3-2 is 71.88% of the maximum mid-height lateral displacement of GC3-1. Similarly, the predicted maximum mid-height lateral displacement of GC4-2 and GC5-2 is 74.41% and 78% of the maximum mid-height lateral displacement of GC4-1 and GC5-1, respectively. Furthermore, when the value of the cross-section diameter is increased from 350 mm to 400 mm decreasing the maximum lateral displacement of the confined RPC columns is continued. It can be concluded that the response curves of the confined RPC columns is changed with a transition from ductile to brittle behavior. As it is expressed, results show that the effect of enhancement of cross-section size causes a reduction in the ductility of considered confined RPC columns in all five simulated groups. Hence, it can be mentioned if the same levels of ductility are desired, the columns with larger cross-section size shall require more confinement level than columns with smaller cross-section size.

Table 10. Finite element analysis results

Specimens	Max Axial Force, F_{max} (KN)	Moment at F_{max} (KN-m)	Δ_{mid} * at F_{max} (mm)
GC1-1	4247	233926	37.28
GC1-2	6363	350455	31.77
GC1-3	8880	489118	21.06
GC2-1	4586	252588	46.17
GC2-2	6808	374976	33.11
GC2-3	9575	527397	25.06
GC3-1	4888	269254	48.41
GC3-2	7261	399931	34.8
GC3-3	10242	564113	27.79
GC4-1	5187	285724	50.14
GC4-2	7722	425320	37.31
GC4-3	10888	599701	29.01
GC5-1	5484	302064	52.49
GC5-2	8185	450839	40.98
GC5-3	11528	634942	30.16

* Lateral displacement at mid-height of columns

5. Conclusions

In this paper the finite element analyses were conducted to study the effects of wrap thickness, concrete compressive strength, and column size on the behavior of reactive powder concrete columns confined with FRP wrap. The following conclusions are drawn from this study:

1. The load capacity (maximum axial load and corresponding moment) is increased while the concrete compressive strength is increased.

2. The ductility of confined RPC columns is increased with the increase in the concrete compressive strength.

3. The effect of enhancement of cross-section size causes a reduction in the ductility of considered confined RPC columns.

4. The strength of confined RPC columns is enhanced rapidly during the increasing the size of cross-section.

5. From the finite element analyses results due to the effect of variation of FRP thickness, it is concluded that the behavior of

RPC columns has a balanced condition. If the column is confined with FRP thickness less than the balanced FRP thickness, increasing the thickness of FRP also resulted in enhancement of ductility of the confined RPC columns. On the contrary, if the column is confined with FRP thickness greater than the balanced FRP thickness, increasing the thickness of FRP resulted in decreasing the ductility of concrete columns.

6. The load capacity included peak axial load and corresponding moment of FRP-confined RPC columns is increased when the thickness of FRP is enhanced.

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REFERENCES

[1] GangaRao, H.V.S., Taly, N., Vijay, P.V. (2007). “Reinforced Concrete Design with FRP Composites”. Englewood Cliffs, CRC Press, USA.

[2] Ma, R., Xiao, Y. (1999). “Seismic Retrofit and Repair of Circular Bridge Columns with Advanced Composite Materials”. Earthquake Spectra, Vol. 15, pp. 747-764.

[3] Pessiki, S., Harries, K.A., Kestner, J.T., Sause, R., Ricles, J.M. (2001). “Axial Behaviour of Reinforced Concrete Columns Confined with FRP Jackets”. Journal of Composites for Construction ASCE, Vol. 5, pp. 237-245.

[4] Karabinis, A.I., Rousakis, T.C. (2002). “Concrete Confined by FRP Material: A Plasticity Approach”. Engineering Structures, Vol. 24, pp. 923-932.

[5] Matthys, S., Toutanji, H., Audenaert, K., Taerwe, L. (2005). “Axial Load Behavior of Large-Scale Columns Confined with Fiber-Reinforced Polymer Composites”. ACI Structural Journal, Vol. 102, pp. 258-267.

[6] Wu, Y.F., Liu, T., Oehlers, D.J. (2006). “Fundamental Principles that Govern Retrofitting of Reinforced Concrete Columns by Steel and FRP Jacketing”. Advances in Structural Engineering, Vol. 9, 507-33.

[7] Wong, Y.L., Yu, T., Teng, J.G., Dong, S.L. (2008). “Behavior of FRP-Confined Concrete in Annular Section Columns”. Composites Part B: Engineering, Vol. 39, 451-466.

[8] Bouchelaghem, H., Bezazi, A., Scarpa F. (2011). “Compressive Behaviour of Concrete Cylindrical FRP-Confined Columns Subjected to a New Sequential Loading Technique”. Composites Part B: Engineering, Vol. 42, pp. 1987-1993.

[9] El-Hacha, R., Abdelrahman, K. (2013). “Slenderness Effect of Circular Concrete Specimens Confined with SFRP Sheets”. Composites Part B: Engineering, Vol. 44, pp. 152-166.

[10] Morin, V., Cohen-Tenoudji, F., Feylessoufi, A. (2002). “Evolution of the Capillary Network in a Reactive Powder Concrete during Hydration Process”. Cement and Concrete Research, Vol. 32, pp. 1907-1914.

[11] Dowd, W.M., Dauriac C.E., Adeline R. (1999). “Reactive Powder Concrete for Bridge Construction”. Proceedings of the 5th ASCE Materials Engineering Congress, Cincinnati, USA.

[12] Chan, Y.W., Chu, S.H. (2004). “Effect of Silica Fume on Steel Fiber Bond Characteristics in Reactive Powder Concrete”. Cement and Concrete Research, Vol. 34, pp. 1167-1172.

[13] Aïtcin, P.C. (2000). “Cements of Yesterday and Today Concrete of Tomorrow”.

Cement and Concrete Research, Vol. 30, pp. 1349-1359.

[14] Lee, I. (2002). “Complete Stress-Strain Characteristics of High Performance Concrete”. PhD thesis, New Jersey Institute of Technology, New Jersey, USA.

[15] Ho, J.C.M., Lam, J.Y.K., Kwan, A.K.H. (2010). “Effectiveness of Adding Confinement for Ductility Improvement of High-Strength Concrete Columns”. Engineering Structures, Vol. 32, pp. 714-725.

[16] Abdelouahed, T. (2006). “Improved Theoretical Solution for Interfacial Stresses in Concrete Beams Strengthened with FRP Plate”. International Journal of Solids and Structures, Vol. 43, pp. 4154-4174.

[17] Parvin, A., Jamwal, A.S. (2006). “Performance of Externally FRP Reinforced Columns for Changes in Angle and Thickness of the Wrap and Concrete Strength”. Composite Structures, Vol. 73, pp. 451-457.

[18] Jiang, J.F., Wu, Y.F. (2012). “Identification of Material Parameters for Drucker-Prager Plasticity Model for FRP Confined Circular Concrete Columns”. International Journal of Solids and Structures, Vol. 49, pp. 445-456.

[19] Li, G., Kidane, S., Pang, S.S., Helms, J.E., Stubblefield, M.A. (2003). “Investigation into FRP Repaired RC Columns”. Composite Structures, Vol. 62, pp. 83-89.

[20] Elsanadedy, H.M., Al-Salloum, Y.A., Alsayed, S.H., Iqbal R.A. (2012). “Experimental and Numerical Investigation of Size Effects in FRP-Wrapped Concrete Columns”. Construction and Building Materials, Vol. 29, pp. 56-72.

[21] Issa, C.A., Chami, P., Saad, G. (2009). “Compressive Strength of Concrete Cylinders with Variable Widths CFRP Wraps: Experimental Study and Numerical Modeling”. Construction and Building Materials, Vol. 23, pp. 2306-2318.

[22] Yu, T., Teng, J.G., Wong, Y.L., Dong, S.L. (2010). “Finite Element Modeling of Confined Concrete-I: Drucker-Prager Type Plasticity Model”. Engineering Structures, Vol. 32, pp. 665-679.

[23] Hadi, M.N.S. (2003). “Behaviour of Wrapped HSC Columns under Eccentric Loads”. Asian Journal of Civil Engineering, Vol. 4, pp. 91-100.

[24] Hadi, M.N.S. (2006). “Behaviour of FRP Wrapped Normal Strength Concrete Columns under Eccentric Loading”. Composite Structures, Vol. 72, pp. 503-511.

[25] Hadi, M.N.S. (2009). “Behaviour of Eccentric Loading of FRP Confined Fibre Steel Reinforced Concrete Columns”. Construction and Building Materials, Vol. 23, pp. 1102-1108.

[26] Abbassi, M., Dabbagh, H. (2014). “Finite Element Analysis of Reactive Powder Concrete Columns Confined with CFRP”. International Journal of Civil Engineerng. (submitted)

[27] Mazzoni, S., McKenna, F., Scott, M.H., Fenves, G.L. (2007). “OpenSees Command Language Manual”. Pacific Earthquake Engineering Research Center, University of California, Berkeley, USA.

[28] Yalcin, C., Saatcioglu, M. (2000). “Inelastic Analysis of Reinforced Concrete Columns”. Computers and Structures, Vol. 77, pp. 539-555.

[29] Kwak, H.G., Kim, S.P. (2002). “Nonlinear Analysis of RC Beams Based on Moment-Curvature Relation”. Composite Structures, Vol. 80, pp. 615-628.

[30] Assan, A.E. (2002). “Nonlinear Analysis of Reinforced Concrete Cylindrical Shells”. Composite Structures, Vol. 80, pp. 2177-2184.

[31] Coronado, C.A., Lopez, M.M. (2006). “Sensitivity Analysis of Reinforced Concrete Beams Strengthened with FRP Laminates”. Cement and Concrete Composites, Vol. 28, pp. 102-114.

[32] Al-Amery, R., Al-Mahaidi, R. (2006). “Numerical Analysis of Multilayered CFRP Retrofitted RC Beams with Partial Interaction”. Composite Structures, Vol. 75, pp. 479-488.

[33] Malik, A.R., Foster, S.J. (2010). "Carbon Fiber-Reinforced Polymer Confined Reactive Powder Concrete Columns-Experimental Investigation". ACI Structural Journal, Vol. 7, pp. 263-271.

[34] Almusallam, T.H. (2007). "Behavior of Normal and High-Strength Concrete Cylinders Confined with E-Glass/Epoxy Composite Laminates". Composites Part B: Engineering, Vol. 38, pp. 629-39.

[35] Parvin, A., Jamwal, A.S. (2005). "Effects of Wrap Thickness and Ply Configuration on Composite-Confined Concrete Cylinders". Composite Structures, Vol. 67, pp. 437-42.