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STRENGTHENING OF MODIFIED REACTIVE POWDER CONCRETE COLUMNS WITH CFRP

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Abstract: An experimental investigation was conducted to investigate the behavior of modified reactive concrete (MRPC) columns before and after strengthening with carbon fiber reinforced polymer (CFRP) sheets jacketing under eccentric axial load. Twelve columns were tested up to failure, strengthened and retested to examine strengthening efficiency and to evaluate the effects of variation of the concrete type (normal or MRPC), presence of steel fibers and main steel reinforcement ratio. Experimental results showed that CFRP jacketing increases the ultimate failure load of strengthened columns up to 185%, highly stiffens them (reduces lateral displacements) and allow more ductile failure than the original columns. Also, inclusion of steel fibers in MRPC columns increases failure loads up to 83%, prevents spalling of the concrete cover and increase the ductility.

Keywords: *Modified Reactive Powder Concrete, Columns, Carbon Fiber Reinforced Polymer, Strengthening.*

تقوية اعمدة خرسانة المساحيق الفعالة المعدلة باستخدام البوليمر المسلح بالياف الكاربون

الخلاصة: يتناول هذا البحث دراسة عملية على سلوك اعمدة مصنوعة من خرسانة المساحيق الفعالة المعدلة (MRPC) قبل و بعد التقوية باستخدام الياف الكاربون (CFRP)والمعرضة الى احمال محورية لامركزية. تم فحص و تقوية و اعادة فحص اثنى عشر عمودا لاختبار كفاءة التقوية و معرفة تاثيرات تغيير نوع الخرسانة (عادية او MRPC) و وجود الياف الحديد ونسبة حديد التسليح الرئيسي. اظهرت النتائج العملية ان التقوية باستخدام CFRP زادت احمال الفشل القصوى للاعمدة المقواة حتى 185 % كما زادت كثيرا من صلادتها (قللت الازاحات الجانبية) و سمحت بفشل اكثر مطيلية من الاعمدة الاصلية. كما ان استخدام الياف الحديد في اعمدة MRPC زاد احمال الفشل حتى 83% و منع تشظي خرسانة الغطاء و زاد المطيلية.

1. Introduction

Reactive powder concrete (RPC) is an ultra high strength, low porosity cement-based composite with high ductility. Unlike conventional concrete, RPC containing a significant amount of steel fibers exhibits high ductility and toughness (energy absorption) characteristics [1,2]. In addition to its ultra-strength characteristic, RPC has other high performance properties, such as low permeability, limited shrinkage, increased corrosion and abrasion resistance and increased durability. RPC is composed of particles with similar elastic moduli and is graded for dense compaction, thereby, reducing the differential tensile strain and increasing enormously the ultimate load carrying capacity of the material [3,4,5].

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Since 1990s, researches on RPC were mostly conducted based on the principle of homogeneity enhancement by eliminating coarse aggregate, while little ones used coarse aggregate in producing RPC. *Collepardi et al. (1997)* [6] produced modified reactive powder concrete (MRPC) by replacing part of (or all) fine sand by 8 mm crushed aggregate. Results show that the replacement of the fine ground quartz sand (0.15-0.4mm) by an equal volume of well graded natural aggregate (maximum size is 8 mm) did not change the compressive strength of the RPC at the same water-cement ratio but flexural strength was lower when graded coarse aggregate replaced all the very fine sand. MRPC was easier during mixing to be fluidized and homogenized than RPC as stated by *Ma et al. (2004)*[7]. They also recorded higher modulus of elasticity and lower strains at peak stress for MRPC.

Fiber reinforced polymers (FRPs) are high performance materials that consist of high strength fibers embedded in a polymer matrix to combine the strength of the fibers with the stability of the polymer resins [8,9]. FRPs have unique properties making them extremely attractive for structural applications. They offer better strengthening alternative to traditional steel jacketing because they are durable, noncorrosive, have high strength-to-weight and stiffness-to-weight ratios, possess good fatigue behavior and allow easy handling and installation [8,10-12].

Strengthening concrete columns with FRP jackets has proved to be very effective in enhancing ductility and axial load capacity [8,10,13,14]. FRP confinement increases the lateral pressure on the column which prevents concrete expansion and cause the development of a triaxial stress field within the confined column. The axial strength and ductility of the confined concrete increases with the increased lateral pressure which result in an increase in the concrete's compressive strength and an increase in the strain at which the concrete crushes [10,12,13].

The confinement effectiveness of FRP jackets depends on different parameters, namely, the type of concrete, steel reinforcement, thickness of FRP jackets (number of layers) and stiffness and loading conditions [9,10,12]. FRP confinement is more effective for circular columns than for square or rectangular columns. This is because the lateral expansion of concrete under compression is uniformly confined in a circular column, unlike in rectangular one where confinement is concentrated at the corners rather than over the entire perimeter [10,11,13,15].

2. FRP Strengthening of Eccentrically Loaded Columns

Columns can be strengthened to increase the axial, shear and flexural capacities for a variety of reasons such as eccentric loading, lack of confinement, seismic loading, accidental impacts and corrosion [10]. In field applications, most columns are not under perfect concentric loading. This produces a non-uniform confining stress due to the strain gradient which in turn reduces the effectiveness of column [16].

Parvin and Wang (2001)[16] found that FRP wrap was effective in strengthening of eccentrically loaded square columns, and that the eccentricity diminished the axial load capacity and corresponding axial deflection. Similar observations were also noted by *Li and Hadi (2003)*[17] and *Hadi (2006)*[18] for eccentrically loaded circular concrete columns wrapped with CFRP sheets.

Research conducted by *El Maaddawy (2009)* [19] and *Song et al. (2013)*[20] indicated that as the magnitude of eccentricity increased, the gain in strength due to FRP wrap decreased and the mid height lateral displacement of the columns increased. This was also concluded by *Al-Musawi (2012)*[21] for CFRP wrapped for reinforced normal and self-compacting concrete rectangular columns under eccentric loading.

Malik and Foster (2010)[8] found that CFRP confinement effectiveness decreases in concentrically loaded FRP confined RPC columns because of the lower dilation of RPC under axial load. For the eccentrically loaded columns the CFRP was shown to be effective in controlling the failure of the columns with considerable straining occurring beyond the peak loading.

Sadeghian et al. (2010)[22] found that bending stiffness and moment capacity of large-scale rectangular concrete columns increased with the addition of longitudinal layers of FRP, but curvature capacity did not increase. For the wrap configuration with angle orientation, in addition to bending stiffness and moment capacity, the curvature capacity also improved.

Benzaid and Mesbah (2013)[13] stated that the effect of CFRP confinement on the bearing and deformation capacities of columns decreases with increasing concrete strength, thus FRP confined low strength concrete columns had higher gain in their load capacity than high strength concrete columns. Similar results were also recorded by *Li and Hadi (2003)*[17], *Hadi (2006)*[18] and *Song et al. (2013)*[20].

Most of the available literature dealt with "initial" strengthening of "conventional" concrete columns with FRP jackets. In contrast, the objective of the present work is to investigate the behavior of MRPC columns failed under eccentric compression loads then strengthened with CFRP sheets and retested under the same conditions to examine strengthening effectiveness of damaged or deteriorated columns in existing structures.

3. Experimental Program

In the experimental program twelve reinforced concrete square columns were cast, tested up to failure under eccentric compression loading, strengthened after failure with CFRP jacketing and retested. Three of these columns were fabricated with normal strength concrete (NC) and nine with modified reactive powder concrete (MRPC). Details of these main stages are given in the following.

3.1. Material Properties

Ordinary Portland Cement (ASTM Type I) was used for both NC and MRPC mixtures. Naturalsandof4.75mm maximum size and very fine sand with maximum size of 600µm were used as fine aggregate for NC and MRPC, respectively. Crushed gravel with maximum size of 10 and 8mm was used for NC and MRPC, respectively.

In addition, MRPC mixtures contained densified silica fume (SiO_2 > 98%), modified polycarboxylates based high range water reducing admixture (super plasticizer) (density = 1.09 kg/l at 20 °C) and hooked end short steel fibers with aspect ratio of 65 (length = 13mm and diameter = 0.2mm) and yield stress of 1130 MPa.

Deformed steel bars of nominal diameter of 6mm for closed ties and 10, 12, and 16 mm for main reinforcement were used in the tested columns. Table (1) gives the tensile test results conducted on samples of the used steel bars.

Table (1): Tensile test results of steel bars*

Nominal diameter (mm)	6	10	12	16
Yield stress (MPa)	435	482	532	528
Ultimate strength (MPa)	535	573	715	707

*Carried out at the College of Engineering, Al-Mustansiriaya University

3.2. Mixes and Mixing Procedure

Based on several trial mixes, one NC mix and three MRPC mixes that differ from each other only in volumetric steel fibers ratio (V_f) were adopted in this work as shown in Table (2).

Table (2): Mix Proportions of NC and MRPC.

Mix	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Silica fume* %	Silica fume kg/m^3	w/c	Super-plasticizer* %	Steel fiber** %	Steel fiber kg/m^3
MRPC0	900	495	495	25	225	0.18	5	0	0
MRPC0.75	900	495	495	25	225	0.18	5	0.75	58.5
MRPC1.5	900	495	495	25	225	0.18	5	1.5	117
NC	400	600	1200	0	0	0.45	0	0	0

*Percent of cement weight. **Percent of mix volume.

In the present work, mixing was performed by using 0.19 m^3 capacity horizontal rotary mixer. Firstly, the silica fume powder was mixed in dry state with the required quantity of sand for 5 minutes. Then, cement and crushed gravel were loaded into the mixer and mixed for another 5 minutes. The required amount of tap water was added to the rotary mixer within 1 minute. Then all the super plasticizers were added and mixed for an additional 5 minutes. Finally when used, steel fibers were dispersed uniformly and mixed for an additional 2 minutes.

A total of four batches of concrete (1 normal and 3 modified reactive powder) were used to cast the columns by using three wooden molds. Each batch was enough to cast three columns with three cubes of 100mm size to determine the compressive strength of concrete. Concrete compaction was performed through a table vibrator. After 24 hours, specimens were demolded and cured in water at room temperature for 28 days before testing.

3.3. Details of Tested Columns

All twelve columns (3 NC and 9 MRPC) were identical in nominal dimensions with square section 120mm x 120mm through the middle portion (500mm) of the column total height of 1000mm. Column ends were designed as corbels to easily apply eccentric loads. Eccentricity was kept constant at*e = 60mm=b/2* (Figure (1)).

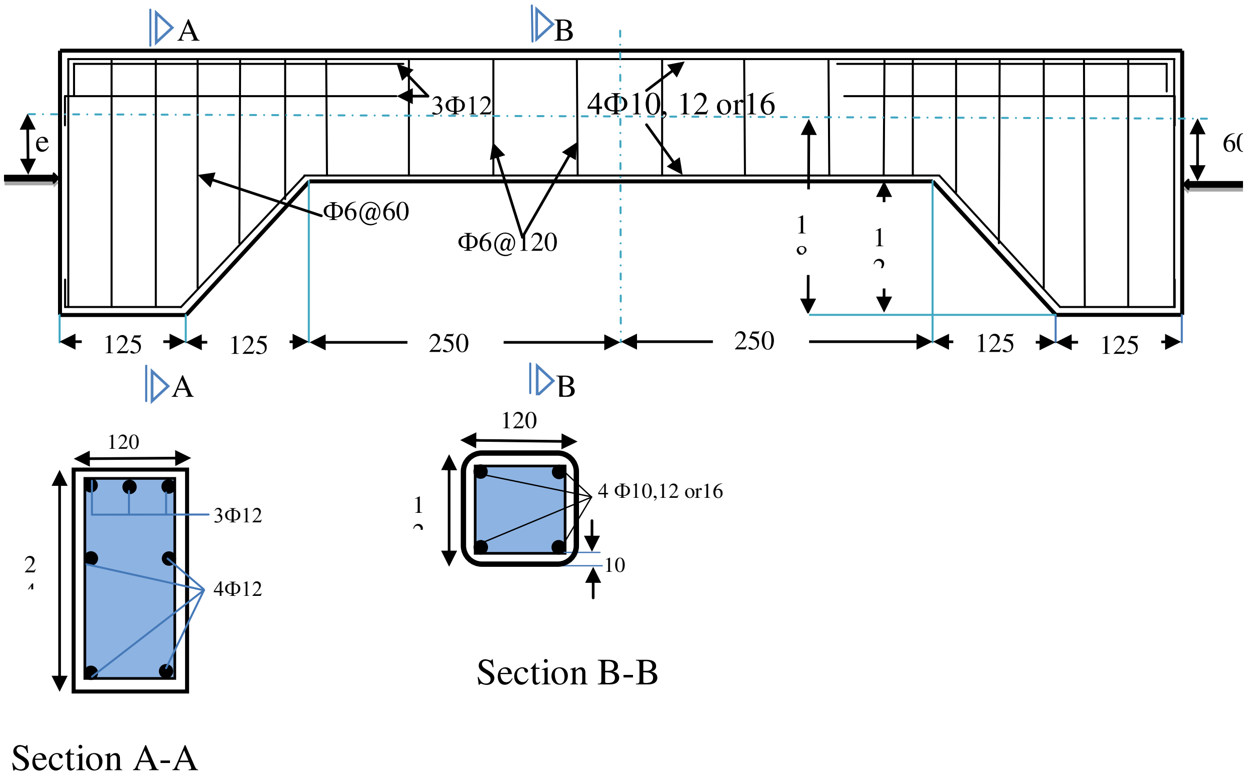


Figure (1): Details of tested specimen (All dimensions in mm).

All columns were reinforced longitudinally (vertically) with four steel bars (one at each corner) with nominal diameter 10, 12 or 16 mm (as variable). The columns contained the same transverse reinforcement of deformed bars with 6mm nominal diameter spaced at 120mm. The end corbels were reinforced with additional steel to prevent premature failure at ends during the test and to ensure failure in the middle portion. Figure (1) shows the geometry and reinforcement details of the specimens.

The test program and specimen details are summarized in Table (3), where (NC) refers to Normal Concrete , (MRPC) refers to Modified Reactive Powder Concrete, the numbers 10, 12 and 16 refer to longitudinal steel bar diameter and numbers 00, 0.75 and 1.5 refer to steel fibers content as a percentage of concrete volume.

Table (3): Details of tested columns

Column designation	Concrete type	Main longitudinal* reinforcement	Main longitudinal reinforcement ratio (ρ) %	Steel fiber (%)
NC-10-00	Normal	4Ø10	2.18	0
NC-12-00		4Ø12	3.14	
NC-16-00		4Ø16	5.58	
MRPC-10-00	Modified Reactive Powder	4Ø10	2.18	0
MRPC-12-00		4Ø12	3.14	

MRPC-16-00		4Ø16	5.58	
MRPC-10-0.75	Modified Reactive Powder	4Ø10	2.18	0.75
MRPC-12-0.75		4Ø12	3.14	
MRPC-16-0.75		4Ø16	5.58	
MRPC-10-1.5	Modified Reactive Powder	4Ø10	2.18	1.5
MRPC-12-1.5		4Ø12	3.14	
MRPC-16-1.5		4Ø16	5.58	

*All specimens have closed ties of Ø6@120 at the middle of specimens.

3.4. Support and Loading Conditions

The column specimens were tested in a 300 ton capacity universal testing machine. Columns were placed vertically and eccentrically with respect to the vertical axis of the testing machine as shown in Figure (2).

To apply a proper axial compression loading and transmit it to the column with accurate eccentricity, loading cap was manufactured having rectangular section (120×240mm) and thickness of 20mm,see Figure (3). The loading caps were made of high strength steel and each end of the columns was covered with loading cap. The lower end of the column was attached to the actuator of the machine, while the upper end was supported on the steel reaction cap of the machine. Both end supports were designed as hinged connections.

Figure (2): Test set-up and instrumentation.

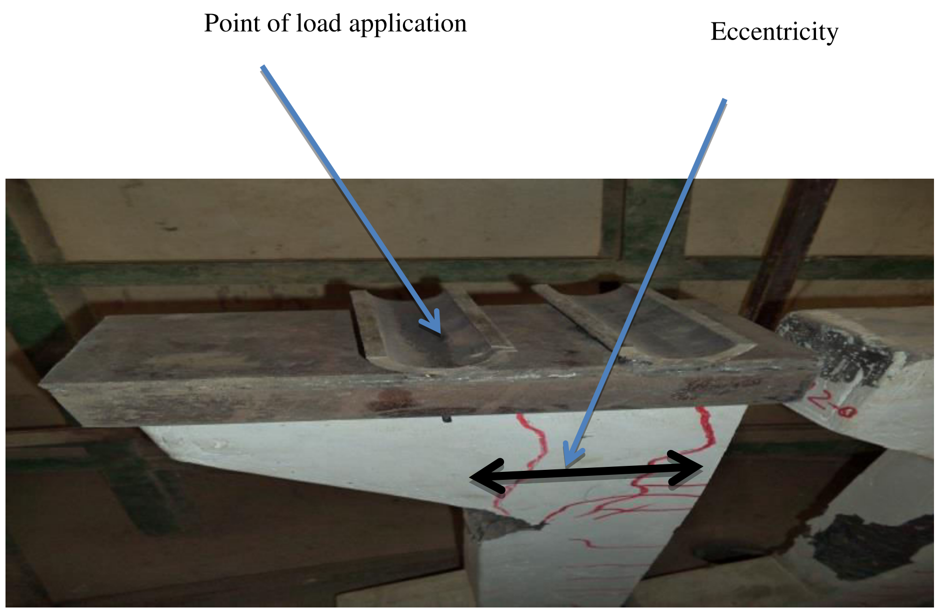


Figure (3): Loading cap

3.5. Measurements and Testing Procedure

During the test of each column, mid height lateral displacement has been measured by means of dial gauge placed at tension face of the tested column (Figure (2)). Dial gauge readings were recorded for each load increment to obtain complete axial load-mid height lateral displacement behaviour. The columns were tested under static loads, loaded gradually in successive increments of 5 – 10 kN, up to failure.

General behaviour of the tested column was monitored especially near failure where concrete crushing, spalling and/or buckling may take place. Also cracking developments of the column were observed during the test and crack patterns were mapped.

3.6. Strengthening Procedure

After failure, columns were prepared for strengthening. First, cracks were filled with a two component low viscosity epoxy resin using injection gun, and regions of crushed and/or spalled concrete were trowelled with epoxy modified cement mortar and left to cure. After a curing period of about 3 days, the column surfaces were smoothed (if rough or uneven) by grinding machine and cleaned by compressed air to obtain a sound, dry and contaminant free substrate.

A two part epoxy based resin (Sikadur – 330) was then brushed onto concrete surfaces within the middle portion between corbels, then, a CFRP sheet (Sika Wrap – 230C, Figure (4)) was carefully wrapped on the column (with 20 mm overlap) and rolled (without excessive force) parallel to the fiber direction until the resin was squeezed out between and through the fiber strands and distributed evenly over the entire sheet surface. After wrapping, the sheet was again coated with a layer of the epoxy resin to ensure that the sheet was fully soaked with resin. Figure (5) shows a strengthened column on the testing machine.

3.7. Retesting After Strengthening

After completion of strengthening process, the columns were ready for retesting under the same loading conditions and testing procedure as original columns (see sections 3.4 and 3.5) except that cracking behaviour did not observed directly because concrete surfaces were covered by CFRP (Figure (5)).

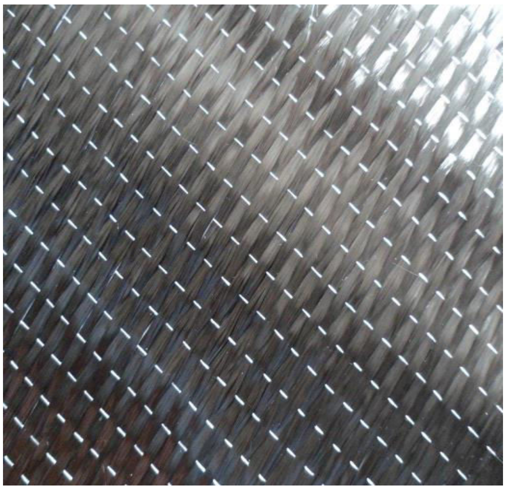


Figure (4): Sample of CFRP Sheet

Figure (5): strengthened column under Retesting

4. Results and Discussion

4.1. Original Columns

Experimental results of the tested columns in terms of effects of concrete type (compressive strength), main reinforcement and steel fibers on ultimate failure loads, general behaviour and axial load- lateral displacement behaviour, are presented and discussed in the following.

4.1.1. Ultimate Failure Loads

The experimentally obtained ultimate failure loads (P_u) of the tested columns are listed in Table (4).

Table (4): Ultimate failure loads of tested columns

Column designation	f_{cu} (MPa)	V_f (%)	ρ (%)	P_u (kN)
NC-10-00			2.18	83
NC-12-00	39	0	3.14	92.5
NC-16-00			5.58	102.5
MRPC-10-00			2.18	118
MRPC-12-00	84	0	3.14	133
MRPC-16-00			5.58	150
MRPC-10-0.75			2.18	155
MRPC-12-0.75	102	0.75	3.14	164
MRPC-16-0.75			5.58	185
MRPC-10-1.5			2.18	215
MRPC-12-1.5	116	1.5	3.14	244
MRPC-16-1.5			5.58	270

Results showed that the use of non-fibrous MRPC (f_{cu}=84 MPa) increases ultimate load of eccentrically loaded columns by about 42% - 46% as compared to NC columns (f_{cu}=39 MPa). Incorporating steel fibers in MRPC columns with a volumetric ratio of 0.75% and 1.5% increases ultimate loads by about 23% - 31% and 80% - 83% , respectively as compared to non-fibrous MRPC columns (Figure (6)).

It was also found that increasing main steel reinforcement from 2.18% to 3.14% and 5.58% increases ultimate loads by 11.4% and 23.5%, respectively for NC columns, 12.7% and 27.1% for non-fibrous MRPC columns, 5.8% and 19.3% for MRPC columns with 0.75% steel fibers, and 13.5% and 25.6% for MRPC columns with 1.5% steel fibers (Figure (7)).

The above results indicate that incorporating relatively high ratios of steel fibers (1.5% in particular) is more effective (regarding ultimate loads) than using higher ratio of main steel reinforcement (up to 5.58%) in eccentrically loaded MRPC columns. Also, increasing compressive strength by using MRPC instead of NC rises ultimate loads by higher rates than increasing main reinforcement (within the range used in this investigation). This agrees with the fact that compressive strength is the major factor affecting compression members. Steel fibers have increased ultimate loads by two ways: increasing compressive strength and bridging effect which arrests cracks widening thus delays failure.

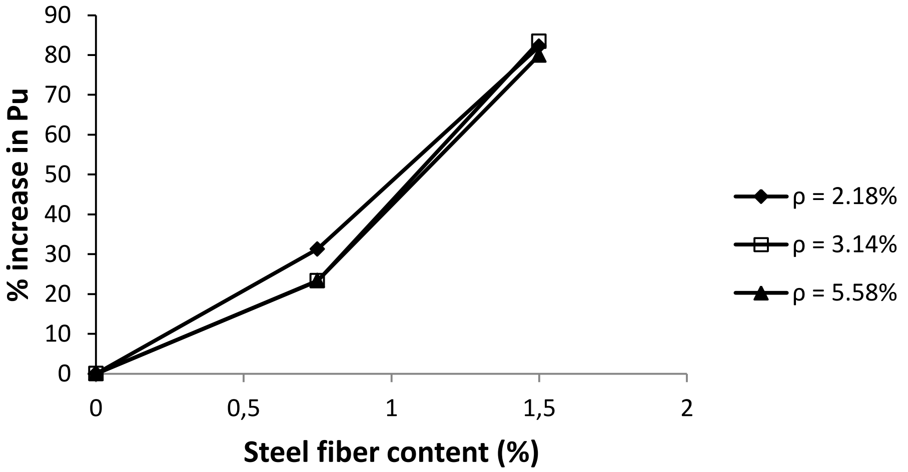


Figure (6) Variation of Ultimate Loads with Steel Fiber Ratio

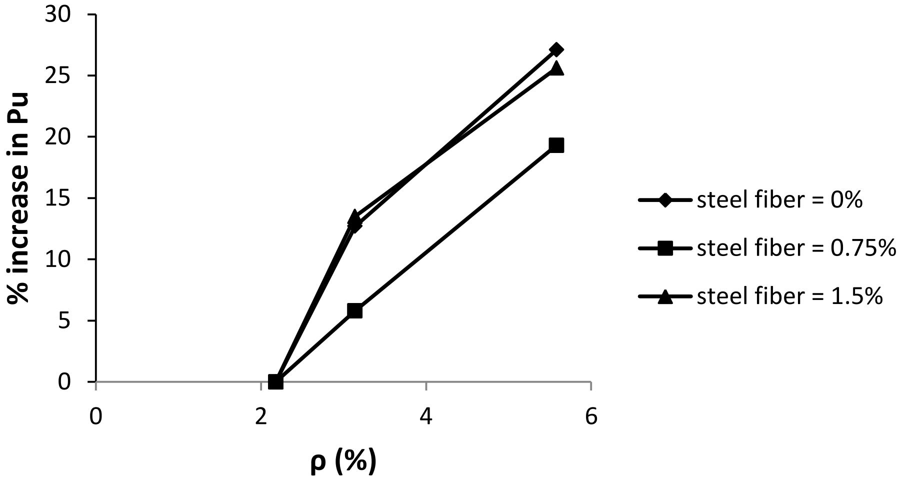


Figure (7) Variation of Ultimate Loads with Main Steel Ratio

4.1.2. Cracking Behavior and Failure Modes

Cracks patterns of the tested columns are shown in Figure (8). The general behaviour of the columns under test can be summarized as follows:

At early stages of loading, the column deformations were initially within the elastic range, then with load increasing, horizontal cracks were formed and propagated at and near mid height of the column tension face. As the load increases further, these cracks were extended toward the compression face crossing the neutral axis and other cracks appeared along the column height. At about 80% of ultimate failure load, the column began to buckle away of its axis. Buckling (which was more evident in lightly reinforced columns) continued and companied by cracks widening which followed by yielding of main reinforcement and then, the column failed.

ρ = 5.58% ρ = 3.14% ρ = 2.18%

(a) NC Columns

ρ = 5.58% ρ = 3.14% ρ = 2.18%

(b) MRPC Columns (V_f = 0%)

ρ = 5.58% ρ = 3.14% ρ = 2.18% ρ = 5.58% ρ = 3.14% ρ = 2.18%

(c) MRPC Columns (V_f = 0.75%) (d) MRPC Columns (V_f = 1.5%)

Figure (8) Original Columns After Testing

For non-fibrous NC and MRPC columns, concrete cover in compression face was suddenly exploded and/or spalled near failure, while the presence of steel fibers in MRPC columns prevented or delayed cover spalling until the crushing strength of concrete is reached. Furthermore, fibrous MRPC columns did not show any exploded spalling even at failure due to the arresting and confining effect of steel fibers which ensures more ductile behaviour.

Wider cracks (up to 5mm) with greater spacing (about 100mm) and less number were observed in NC columns than non-fibrous MRPC columns (Figure (8a and b)). Clear differences were observed in fibrous MRPC columns (Figure (8c and d)), where finer cracks with close spacing and high numbers were observed.

Finally, in addition to horizontal cracks, inclined cracks initiated at columns corners of tension face and propagated toward the compression face were observed near failure in highly reinforced columns (ρ = 5.58%) especially in non-fibrous columns (NC-16-00 and MRPC-16-00) as shown in Figure (8). This may be due to the stress concentration at these corners and absence of steel fibers.

4.1.3. Load-displacement Behavior

Load-mid height displacement behaviour of all tested columns are illustrated in Figures (9) through (15).

In general, initial linear-elastic response was observed in the load-displacement curves. After this stage, a nonlinear ascending portion was observed which characterized by a loss of initial stiffness, mainly because the formation and propagation of horizontal cracks in the column tension face. Displacements continued increasing under increasing loads until failure which took place after the cracks were widened and the column buckled.

In particular, Figures (9) and (10) show that increasing main reinforcement ratio from 2.18% to 3.14% and 5.58% clearly reduced mid height displacement under certain load for NC and non-fibrous MRPC columns. However, this effect is shown to be less in fibrous MRPC columns as shown in Figures (11) and (12). this may be attributed to the confining effect of steel fibers. Positive effect of steel fibers are also shown in Figures (13) – (15), where steel fibers obviously stiffened load – displacement curves as compared to curves of non-fibrous columns especially for lower ratios of main reinforcement (ρ = 2.18%, Figure (13)).

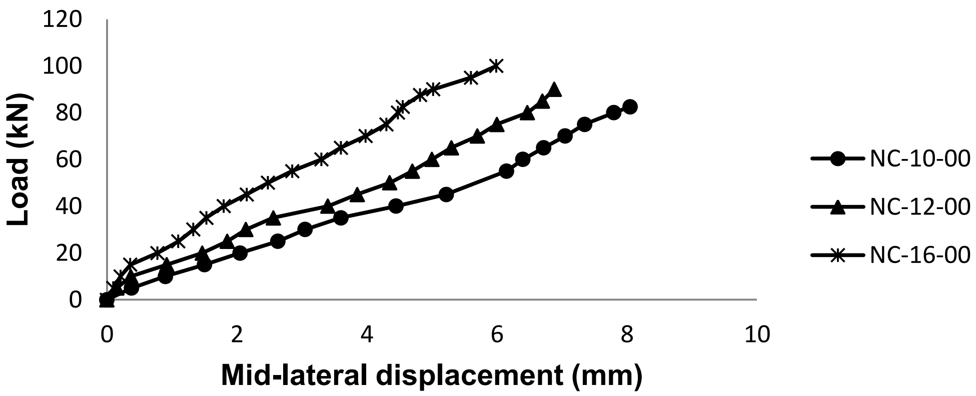


Figure (9) Load – Lateral Displacement Curves of NC Columns

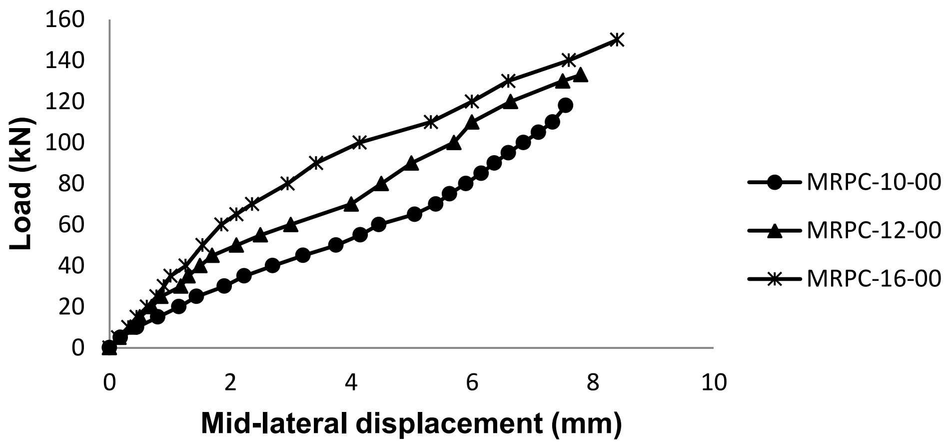


Figure (10) Load – Lateral Displacement Curves of MRPC Columns (V_f = 0%).

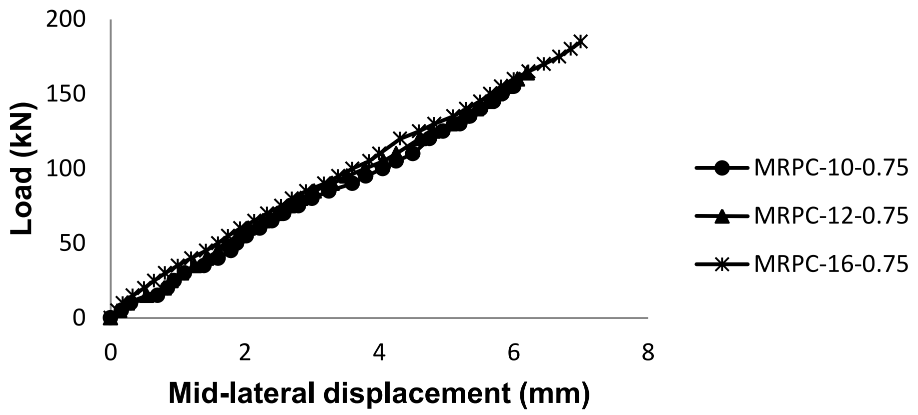
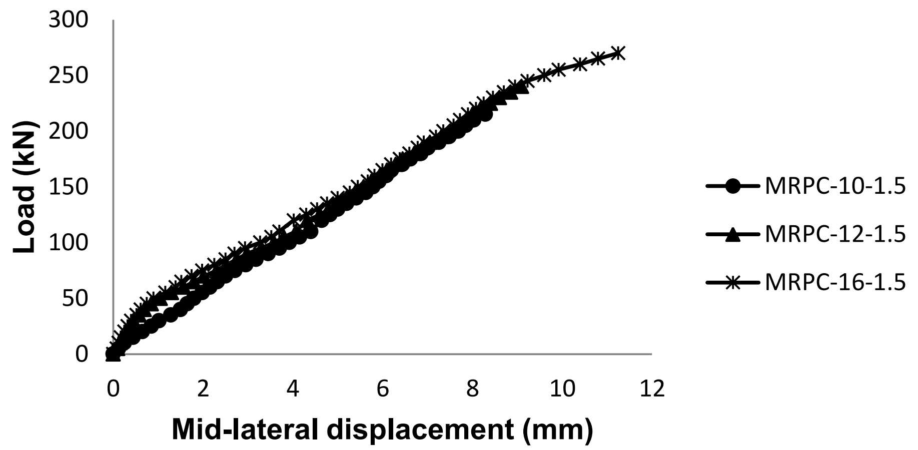


Figure (11) Load – Lateral Displacement Curves of MRPC Columns (V_f = 0.75%).



Figure(12) Load – Lateral Displacement Curves of MRPC Columns (V_f = 1.5%).

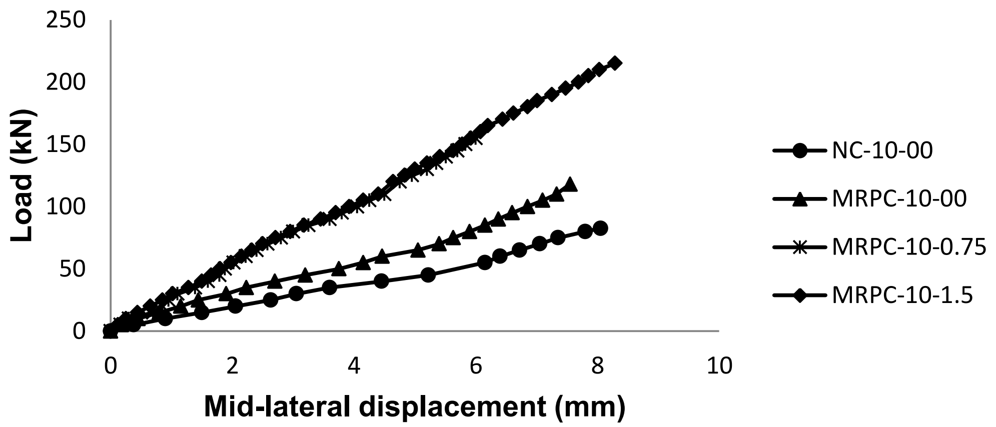


Figure (13) Load – Lateral Displacement Curves of MRPC Columns (ρ = 2.18%).

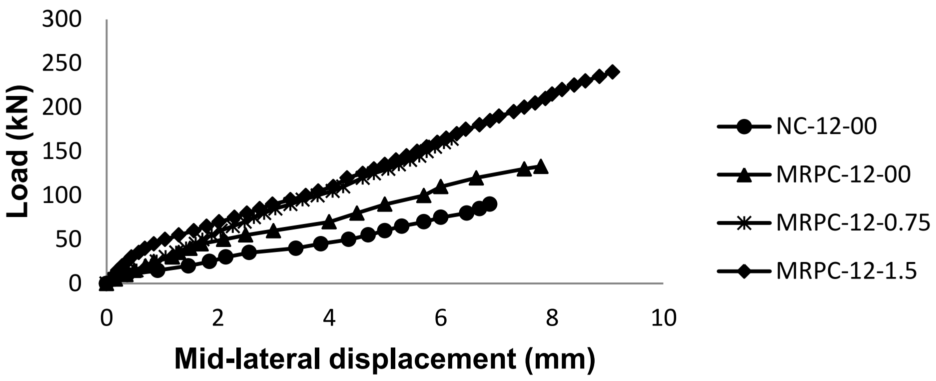


Figure (14) Load – Lateral Displacement Curves of MRPC Columns (ρ = 3.14%).

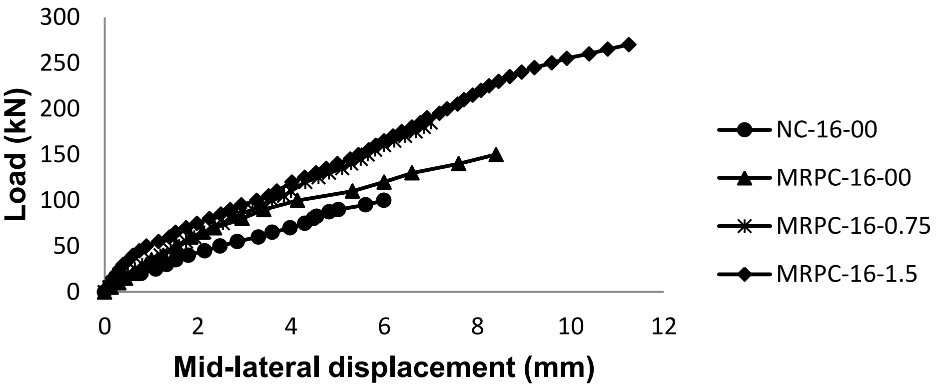


Figure (15) Load – Lateral Displacement Curves of MRPC Columns (ρ = 5.58%).

4.2. Strengthened Columns

Behavior of columns strengthened by CFRP jacketing will now be discussed regarding their ultimate failure loads, failure modes and load – displacement characteristics as compared to the original columns.

4.2.1. Strengthening Effectiveness

The main purpose of strengthening any structural member regardless the method used, is to restore or increase its load carrying capacity. The method of CFRP jacketing used in this investigation to strengthen failed NC and MRPC columns was proved successful in terms of increasing ultimate loads (carrying capacity) of the tested columns up to 185% of those of original columns as listed in Table (5).

Table (5) Ultimate failure loads of original and strengthened columns with their increasing ratios

Column designation	f_{cu} (MPa)	V_f (%)	ρ (%)	P_{uo}* (kN)	P_{us}** (kN)	Increasing ratio $(P_{us} - P_{uo}) / P_{uo}$ (%)
NC-10-00			2.18	83	237	185.5
NC-12-00	39	0	3.14	92.5	252	172.4
NC-16-00			5.58	102.5	277	170.2
MRPC-10-00	84	0	2.18	118	307	160.1

MRPC-12-00			3.14	133	292	119.5
MRPC-16-00			5.58	150	338	125.3
MRPC-10-0.75			2.18	155	347	123.8
MRPC-12-0.75	102	0.75	3.14	164	427	160.3
MRPC-16-0.75			5.58	185	467	152.4
MRPC-10-1.5			2.18	215	302	40.4
MRPC-12-1.5	116	1.5	3.14	244	400	102.2
MRPC-16-1.5			5.58	270	562	108.1

* P_{uo}= Ultimate load of original column, ** P_{us}= Ultimate load of strengthened column

Table (5) shows that load increasing ratios were ranged from about 40% (in MRPC-10-1.5) to 185% (in NC-10-00). Higher ratios were recorded for NC columns (170% - 185%) and lower ratios in MRPC columns with 1.5% steel fibers (40% - 108%). This again reflects the major role of steel fibers in taking the original columns to their full carrying capacities before failure. This also indicates the higher effectiveness of CFRP jacketing in strengthening non-fibrous lower strength columns especially those lightly reinforced (ρ = 2.18%). However, similar finding was reached by other researchers [13, 17, 18, 20] as mentioned before.

4.2.2. General Behavior of Strengthened Columns

Figure (16) shows the strengthened columns after retesting. The presence of CFRP jacketing in strengthened columns did not allow direct monitoring of the cracking behavior of these columns under test, but it can be expected that at first stage of loading, the response was somewhat similar to that of original columns. After that, when new cracks were initiated or old cracks reopened, the tested column began to buckle under increasing load. Buckling was continued and the curvature of the column increased more and more until failure which generally characterized by formation of a wide crack (up to 10mm or more) causing rupture in the CFRP sheet near mid height of column tension face (Figure (17)).

ρ = 5.58% ρ = 3.14% ρ = 2.18%

(a) NC Columns

ρ = 5.58% ρ = 3.14% ρ = 2.18%

(b) MRPC Columns (V_f = 0%)

ρ = 5.58% ρ = 3.14% ρ = 2.18% ρ = 5.58% ρ = 3.14% ρ = 2.18%

(c) MRPC Columns (V_f = 0.75%) (d) MRPC Columns (V_f = 1.5%)

Figure (16) Strengthened Columns After Retesting

It is clearly shown that CFRP jacketing provides an effective confinement to the columns ensuring ductile failure with high deformation capacity (excessive curvature and wide cracks) allowing withstand greater loads. However, columns NC-16-00 and MRPC-16-00 were failed by reopening of repaired cracks at columns heads as shown in Figure (16).

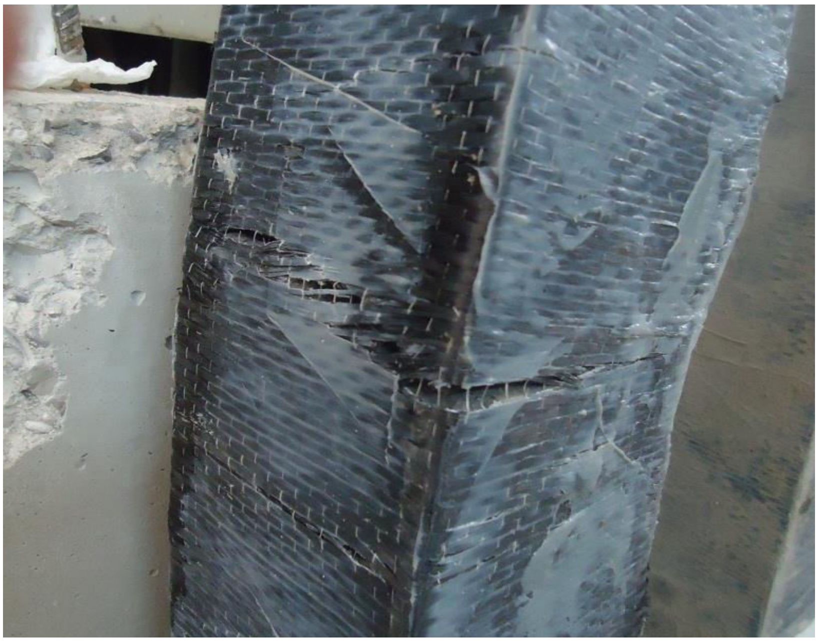


Figure (17) Rupture of CFRP Sheet at Failure

4.2.3. Load-displacement Behavior

Load – mid height displacement curves of both original and strengthened individual columns are illustrated in Figures (18) through (29).

It is clearly shown that CFRP strengthening highly stiffens the tested columns where steeper ascending parts (lower displacements) are observed. High ductility and toughness (in terms of area under load- displacement curve) was an important benefit obtained by using

CFRP jacketing which allow ductile and gradual failure (flat failure portion in load-displacement curve); a desirable characteristic in structural elements, especially columns. Higher stiffness and ductility were indicated when high main steel ratios and/or high steel fibers ratios were used (Figures (18) – (29)).

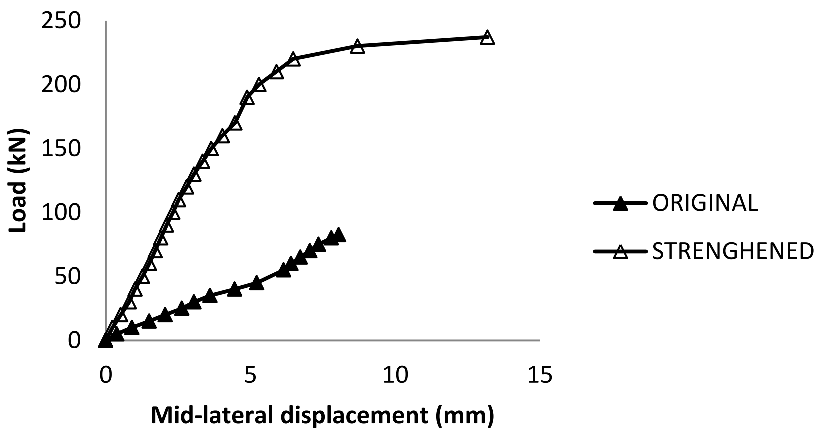


Figure (18) Load – Lateral Displacement Curves of Original and Strengthened Column NC-10-00

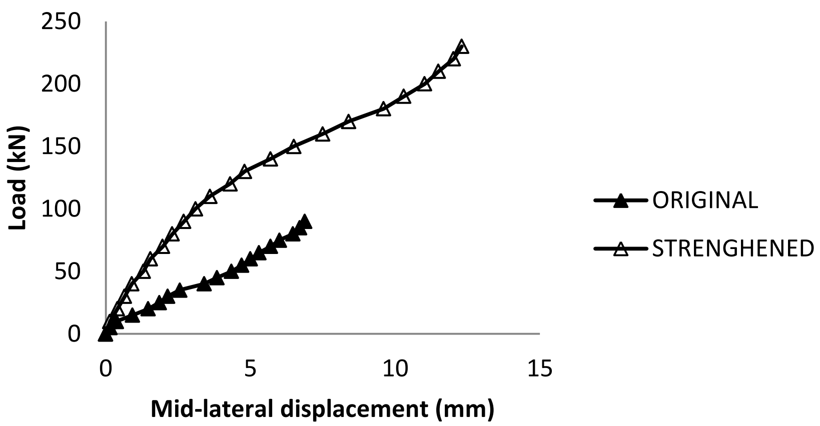


Figure (19) Load – Lateral Displacement Curves of Original and Strengthened ColumnNC-12-00

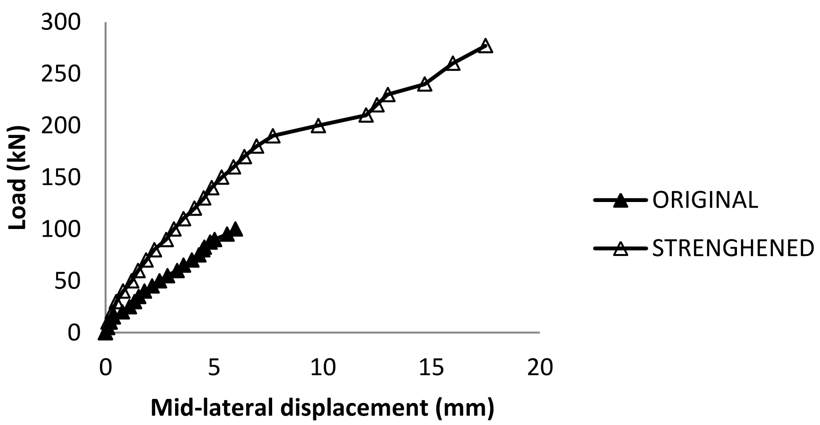


Figure (20) Load – Lateral Displacement Curves of Original and Strengthened Column NC-16-00

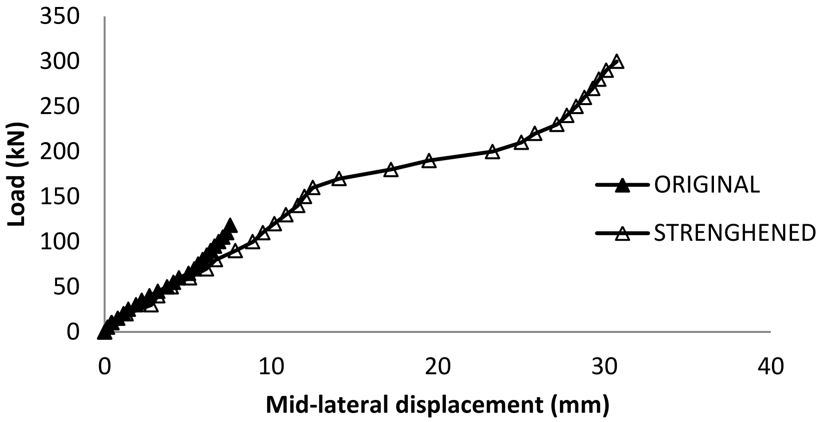


Figure (21) Load – Lateral Displacement Curves of Original and Strengthened Column MRPC-10-00

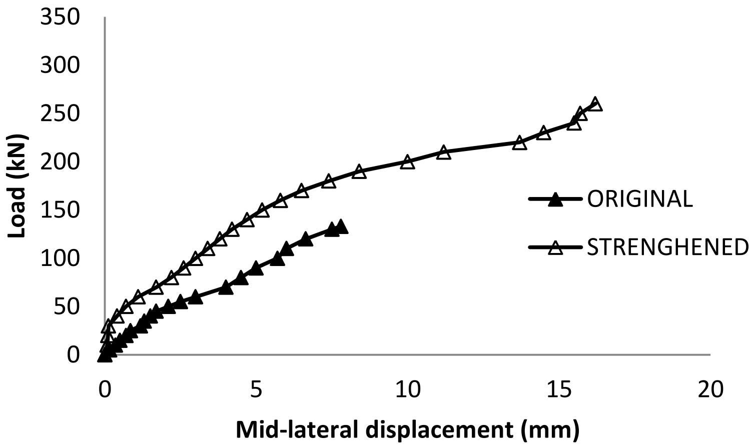


Figure (22) Load – Lateral Displacement Curves of Original and Strengthened Column MRPC-12-00

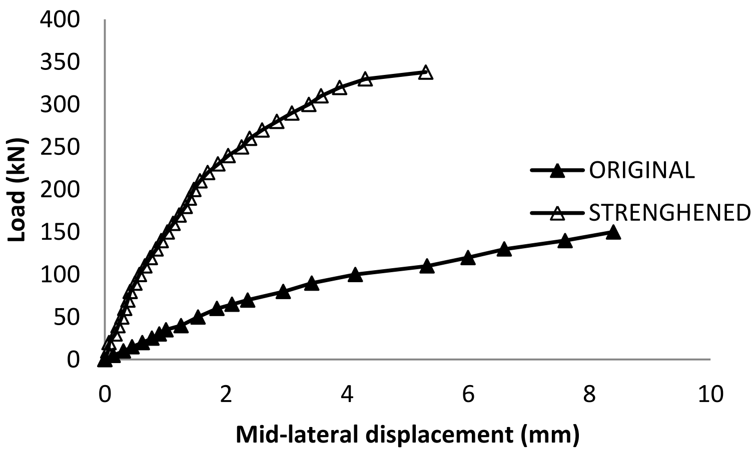


Figure (23) Load – Lateral Displacement Curves of Original and Strengthened Column MRPC-16-00

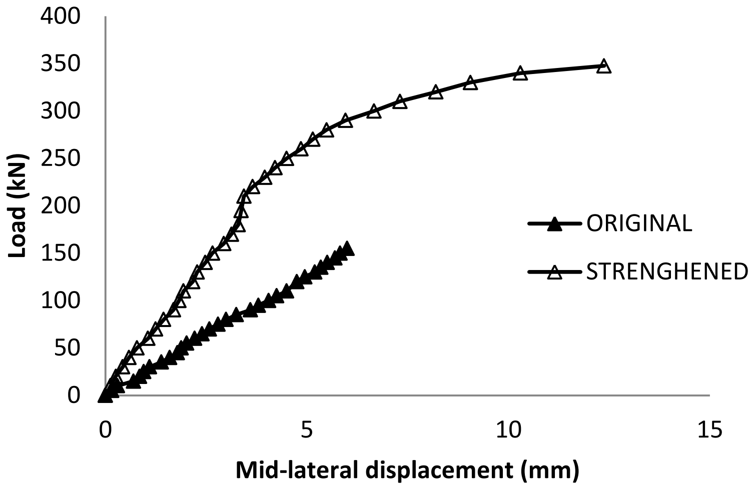


Figure (24) Load – Lateral Displacement Curves of Original and Strengthened Column MRPC-10-0.75

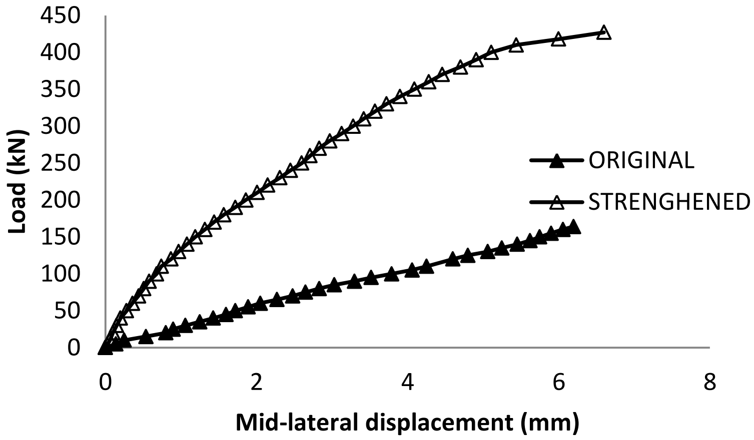


Figure (25) Load – Lateral Displacement Curves of Original and Strengthened Column MRPC-12-0.75

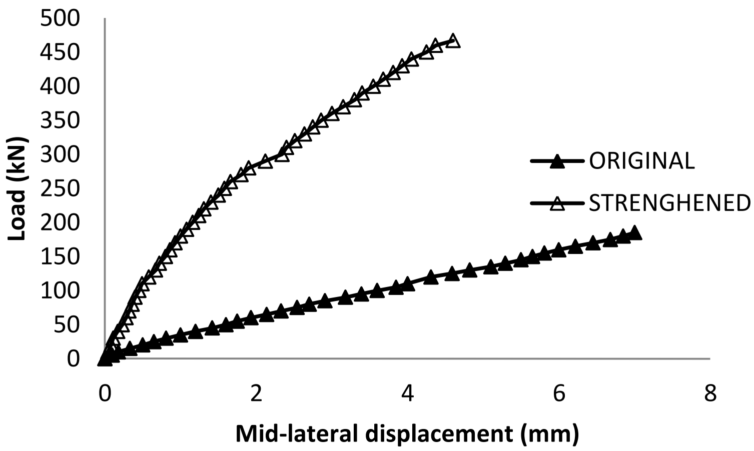


Figure (26) Load – Lateral Displacement Curves of Original and Strengthened Column MRPC-16-0.75

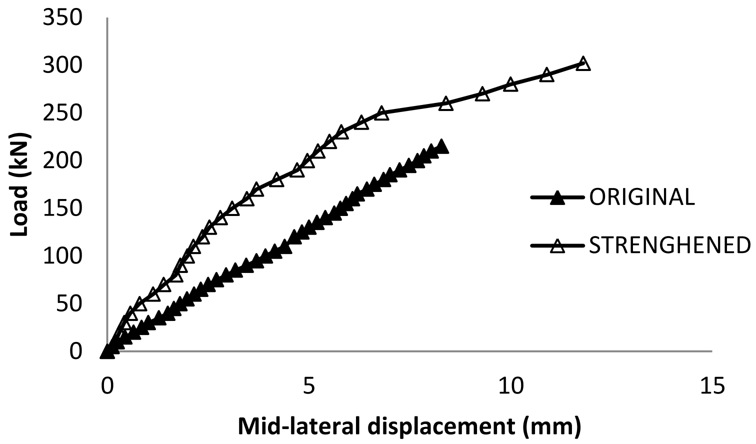


Figure (27) Load – Lateral Displacement Curves of Original and Strengthened Column MRPC-10-1.5

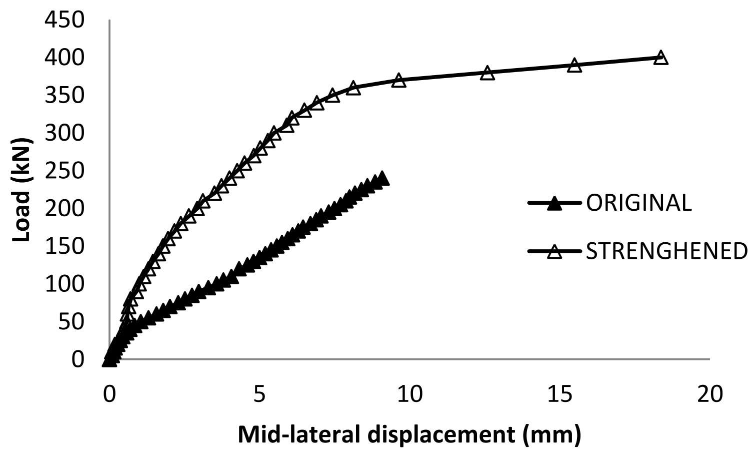


Figure (28) Load – Lateral Displacement Curves of Original and Strengthened Column MRPC-12-1.5

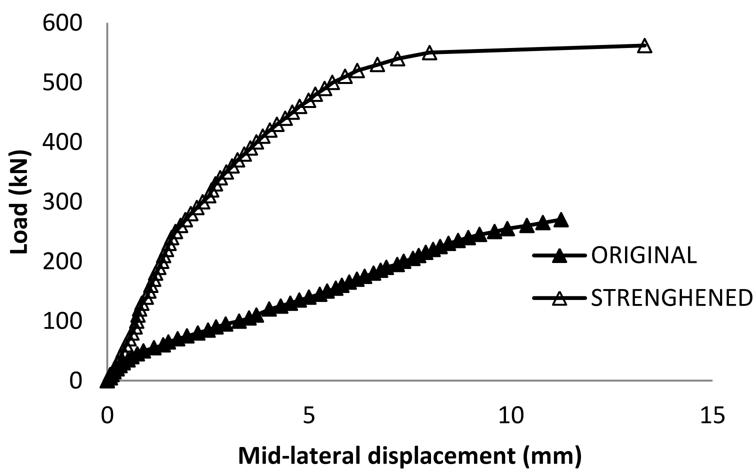


Figure (29) Load – Lateral Displacement Curves of Original and Strengthened Column MRPC-16-1.5

5. Conclusions

Based on experimental results of the tests conducted on eccentrically loaded NC and MRPC columns, the following main conclusions can be drawn:

1. Incorporating steel fibers in MRPC columns substantially increases their ultimate failure loads up to 83% (at 1.5% steel fibers) and stiffens load-lateral displacement curves (reduces displacements).
2. Lower effects than described in (1) above were observed when main reinforcement ratio increases from 2.18% to 5.58% (about 27% maximum increase in ultimate load).
3. Presence of steel fibers in columns ensures ductile failure which characterized by closely distributed higher number of finer cracks in column tension face than non-fibrous columns without spalling of concrete cover in compression face.
4. Strengthening failed columns by CFRP jacketing increases their ultimate failure loads in the range of 40% to 185% of the original failure loads and highly stiffens load – lateral displacement curves.
5. CFRP jacketing was more effective in increasing ultimate loads of lower strength concrete columns than higher strength columns.
6. CFRP jacketing provides an effective confinement to the columns ensuring more ductile failure with higher deformation capacity (larger displacements and greater buckling curvature before failure) than original columns.

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