ASIAN JOURNAL OF CIVIL ENGINEERING (BHRC) VOL. 16, NO. 5 (2015)
PAGES 607-620

COMPRESSION CAPACITY OF RC COLUMNS STRENGTHENED WITH LONGITUDINAL CFRP COMPOSITE

N. Moshiri* and D. Mostofinejad
Department of Civil Engineering, Isfahan University of Technology (IUT), Isfahan, Iran

Received: 5 January 2015; **Accepted:** 29 March 2015

ABSTRACT

In the present research, carbon fiber reinforce polymer (CFRP) composite with fibers aligned along the column axis was used to strengthen the RC columns. A newly introduced method named as grooving method (GM) was utilized to improve the compressive behavior of longitudinal FRP and postpone the buckling and delamination of longitudinal composite from concrete substrate. Two techniques of GM, i.e. externally bonded reinforcement on grooves (EBROG, to be pronounced as /*ebrʌg*/) and externally bonded reinforcement in grooves (EBRIG, to be pronounced as /*ebrIg*/) was used, as well as EBR method, to strengthen the column specimens. For this purpose, 11 RC column specimens with circular section of 150 mm diameter and height of 500 mm were tested under uniaxial compression. Experimental results showed that using the grooving method in strengthening the column specimen, significantly increased the load carrying capacity of specimens; while the conventional EBR method showed inconsiderable effects on the load capacity. The results demonstrated that utilizing EBROG and EBRIG techniques led to respectively 14.1% and 18.5% increase in the column maximum load. However, the column strengthened with EBR method indicated only 2.6% increase in the load carrying capacity.

Keywords: Compressive load carrying capacity; CFRP; grooving method (GM); buckling; EBROG; EBRIG.

1. INTRODUCTION

Confining RC columns by FRP hoop wraps has been widely used to increase the load carrying capacity and ductility of columns [1-8]. However, strengthening of columns with longitudinal composites, i.e. the composite with fibers aligned along the column axis, may also be used to enhance the column load capacity. In this method, the composite withstand compressive stresses and therefore, improve the maximum load of columns [9]. In 1990, Wu demonstrated that compressive strengths of composites made of glass, carbon and aramid

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*E-mail address of the corresponding author: n.moshiri@cv.iut.ac.ir (N. Moshiri)

fibers are 55, 78 and 20 percent of their tensile strengths, respectively [10]. While FRP composites may show considerable compressive strength, design guidelines do not consider their strength in practice [11-13]. One probable reason may be the buckling of composite under compression which leads to debonding of the composite from concrete substrate. Issa et al. demonstrated that restraining longitudinal composite by full-height FRP hoop wraps, improves the performance of longitudinal composite, and therefore, increase the ultimate load capacity of the strengthened column [14].

In order to prevent from or postpone debonding of FRP sheets, an alternative method to conventional externally bonded reinforcement (EBR), named as grooving method, was utilized to attach FRP sheets. Mostofinejad and Mahmoudabadi introduced externally bonded reinforcement on grooves (EBROG) as a technique of grooving method for flexural strengthening of RC beams [15]. They showed that externally bonding of FRP sheets on longitudinal grooves postpones or in some cases eliminates debonding of tensile FRP sheets from concrete substrate, and therefore, increases the load carrying capacity of the strengthened beams. Mostofinejad and Tabatabaei employed the EBROG technique in shear strengthening of RC beams and demonstrated that detachment of FRP strips did not occur in any of the beam specimens strengthened by this method; so that the dominant failure mode of the beams was flexural instead of shear failure [16]. In 2013, a new technique of GM was proposed by Mostofinejad and Shameli, known as externally bonded reinforcement in grooves (EBRIG) technique [17]. It was revealed that the EBRIG technique was more effective than EBROG in postponing debonding of FRP sheets from concrete substrate, and therefore, increasing the beam flexural capacity. Later, the grooving method was used to determine the effective bond length of FRP-to-concrete; and it was concluded that the GM significantly improves the bond behavior of CFRP-to-concrete [18].

Since the effectiveness of grooving method on improving the behavior of tensile FRP composite has been previously examined [15-20], therefore, in the present study, the influence of GM on the behavior of FRP composite under compression stresses is studied. For this purpose, an experimental program was conducted to examine the performance of grooving method (GM) in postponing the buckling and delamination of longitudinal CFRP used for strengthening of RC columns. Two techniques of GM, i.e. EBROG and EBRIG were used as well as the conventional method of EBR. The methods were employed to strengthen the columns with longitudinal CFRP through wet lay-up procedure; and their influences on improving the compressive behavior of FRP and enhancing the column load carrying capacity were compared.

2. EXPERIMENTAL WORK

2.1 Column specimens details

Eleven reinforced concrete columns with circular cross section of 150 mm diameter and 500 mm height were cast. The internal longitudinal reinforcement was consisted of 6#10 deformed bars restrained by 6#8@85 mm transverse ties. The yield and ultimate tensile strength of #10 were 406 and 538 MPa, respectively; while the corresponding values for #8 were 550 and 774 MPa, respectively. The steel cage shown in Fig. 1 was fixed in the mold with clear concrete cover equal to 20 mm. Concrete mix design was adopted to produce concrete with 28-day target strength equal to 28 MPa. Three concrete batches were produced to construct 11 RC columns in three different groups. Three standard cylinders (150×300 mm) were used to determine the concrete compressive strength of each group of column specimens, i.e. each concrete batch, simultaneous with test of the specimens.

Figure 1. Internal steel reinforcement

2.2 FRP composite characteristics

Carbon fibers with 0.131 mm net thickness, ultimate tensile strength of 4300 MPa, tensile modulus of 238 GPa and ultimate tensile strain of 1.8% were used for producing the wet lay-up composite. Furthermore, epoxy matrix with 30 MPa tensile strength, 4.5 GPa tensile modulus and 1.5% tensile strain was used for embedding the carbon fibers.

2.3 Test setup

Column specimens were tested under uniaxial compression with displacement control. A constant rate of 1.0 mm/min was adopted, controlled by the displacement rate of bottom support of the testing machine. Axial and transverse displacements were measured using three linear variable differential transducers (LVDTs) with an accuracy of 0.005 mm and total gauge length of 20 mm. Two vertical LVDTs were mounted 180° apart on column surface, along 240 mm mid-height of the column to measure the axial deformations. Axial strains were determined by dividing the average measurements of 2 vertical LVDTs to their gauge length which was equal to 240 mm. Transverse (or radial) displacements were measured by a horizontal LVDT, placed in mid-height of the column specimen. Similarly, radial strains were determined by dividing the radial displacements into the column diameter, i.e. 150 mm. Fig. 2 shows the instrumentations and test setup.

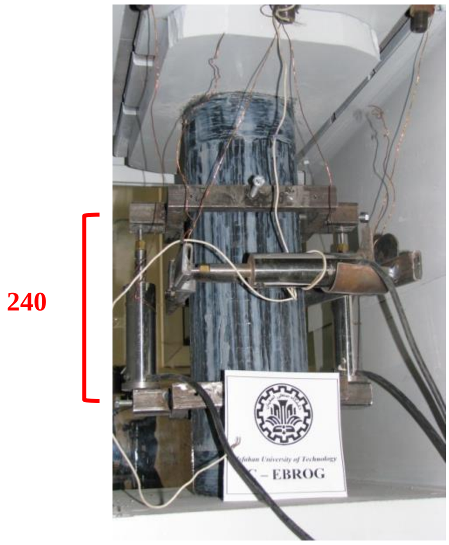


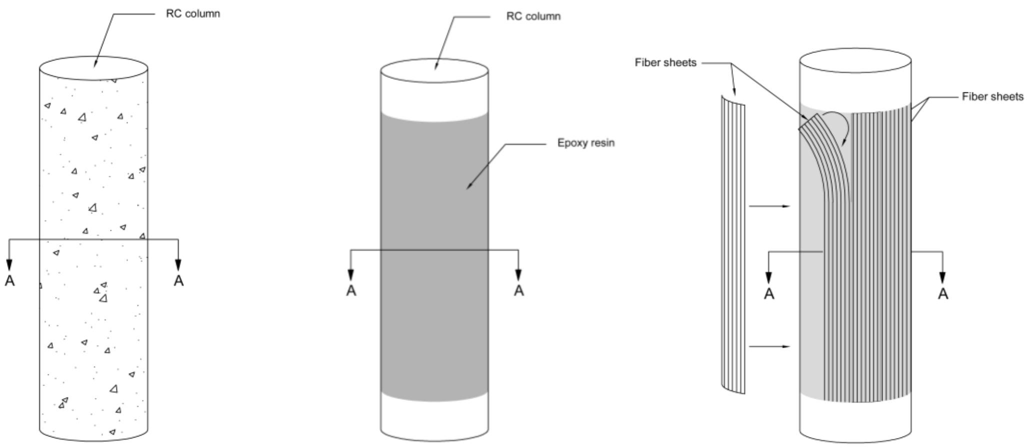
Figure 2. Instrumentation setup

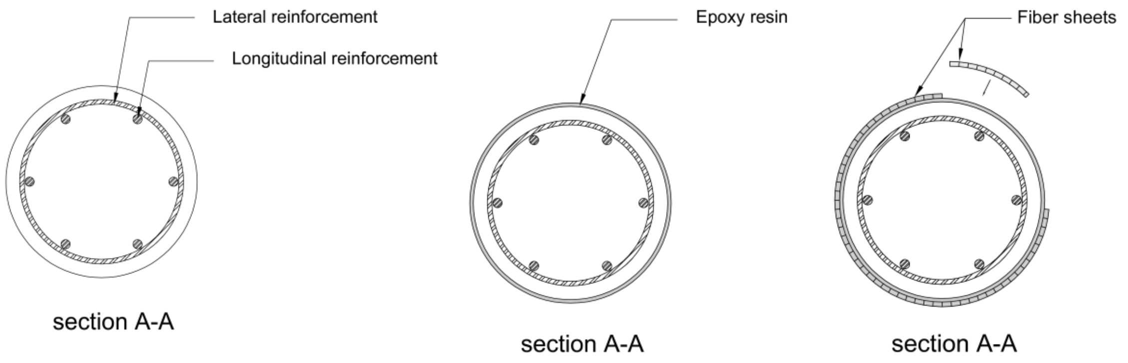
2.4 Strengthening of column specimens

Eight carbon fiber sheets with dimensions of 60×390 mm were used in all strengthening methods. The length of sheets (i.e. 390 mm) was adopted less than the column height to prevent stress concentration at the composite. Therefore, the column ends which had no longitudinal strengthening composite, were confined by FRP hoop wraps to prevent premature failure of columns at the ends and outside the test region [21, 22]. Three techniques were used for strengthening of the columns and are described briefly as follows. Detailed descriptions of the techniques could be found in [15, 17].

2.4.1 EBR method

As for surface preparation in EBR method, a thin layer of column surface was removed by a grinding machine and then coated by epoxy matrix. The longitudinal fiber sheets were then applied on the column surface and embedded by the matrix. The fiber sheets were attached adjacent to each other with no clear distance (**Error! Reference source not found.**Fig. 3).





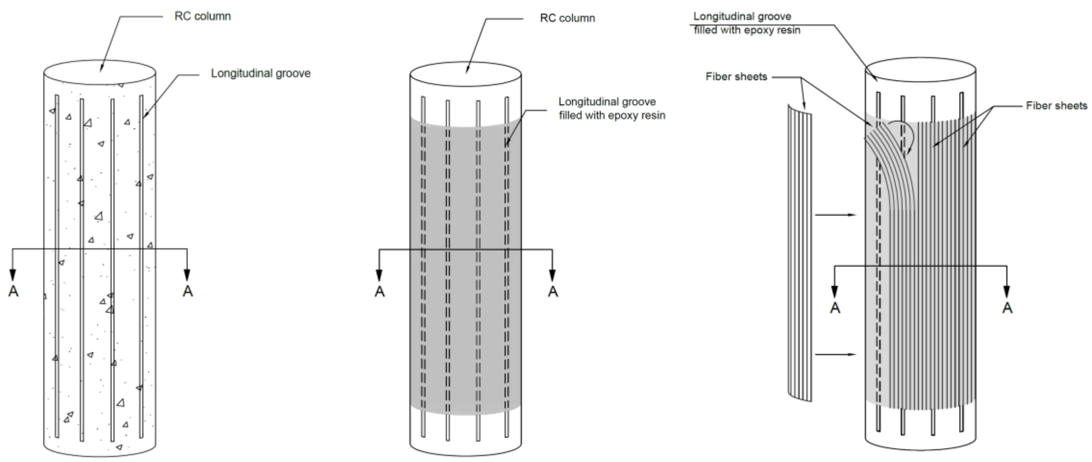
(a) (b) (c)

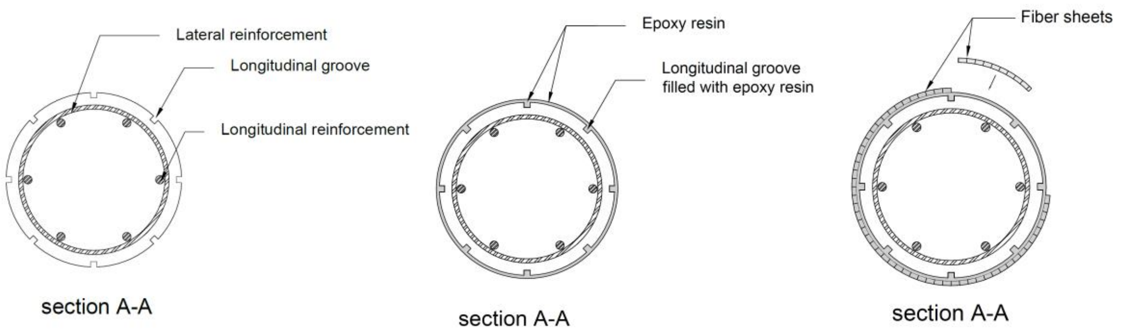
Figure 3. EBR technique: (a) removing a thin layer of concrete surface; (b) coating the column surface with a thin layer of epoxy; (c) attaching fiber sheets and adhering them with epoxy

2.4.2 EBROG method

In this method, 8 grooves with 10 mm depth, 10 mm width and 460 mm length were first cut in the concrete cover by a grinding machine and filled with epoxy matrix after cleaning the dusts. The clear distances of grooves were exactly the same and equal to 50 mm. The 8 fiber sheets were then attached on the grooves and a thin layer of epoxy was applied on the sheets (Fig. 4). Similar to EBR method, there was no clear distance between the fiber sheets in EBROG method and the sheets adjacently covered the whole column perimeter.

It is worth mentioning that the total length of grooves was chosen equal to 460 mm, i.e. less than the column height, in order to prevent stress concentration on the matrix and on the longitudinal composite during the loading. Furthermore, creating a groove by a grinding machine results in variable depth of the groove in its ends from zero to 10 mm (groove nominal depth). Therefore, the length of each fiber sheet in all strengthening methods was selected equal to 390 mm and less than the groove height, in order not to cover the groove ends along its variable depth.



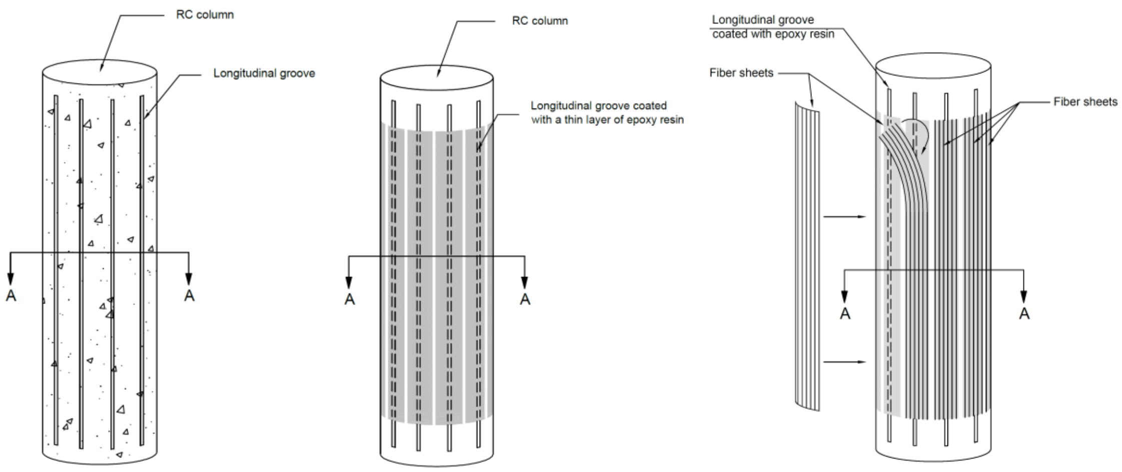


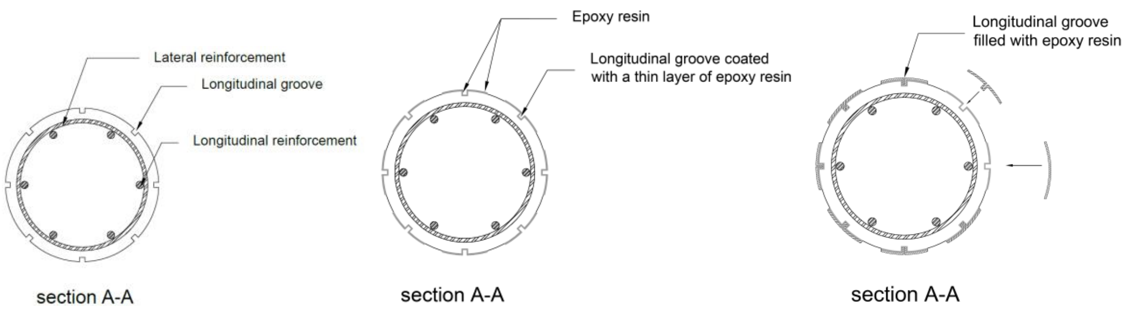
(a) (b) (c)

Figure 4. EBROG technique: (a) creating grooves; (b) filling the grooves with epoxy; (c) attaching fiber sheets and adhering them with epoxy

2.4.3 EBRIG method

Similar to EBROG method, 8 grooves with 10 mm depth, 10 mm width and 460 mm height were first cut into the concrete cover. The grooves were then coated with a thin layer of epoxy. Eight fiber sheets with 60×390 mm dimensions were attached to the column substrate, with direct contact to the internal surfaces of the grooves, as well as the column perimeter outside of grooves. In other words, each fiber sheet was applied inside each groove, and since the width of the sheet was larger than the sum of width of a groove and its side surfaces, the sheet partially covered the column substrate (Fig. 5). After bonding the fiber sheets, they were adhered with matrix and the grooves were completely filled with matrix. In contrast to EBR and EBROG methods in which the composite covered the whole perimeter of column, in EBRIG method, there were clear distances between adjacent fiber sheets almost equal to 20 mm.





(a) (b) (c)

Figure 5. EBRIG technique: (a) creating grooves; (b) coating the grooves with a thin layer of epoxy; (c) attaching fiber sheets and filling the grooves with epoxy

2.5 Specimens' layout

The column specimens were categorized in three groups. Table 1 demonstrates the specimens' details. The specimens' labels in most cases were consisted of the group number followed by the strengthening technique. For example, specimens *I-EBR*, *I-EBROG* and *I-EBRIG* were column specimens in group I strengthened by EBR, EBROG and EBRIG techniques, respectively. For better comparison of experimental results, a reference or control column was also tested in each group, labeled as *I-C*, *II-C* and *III-C* in groups I, II and III, respectively. Detailed descriptions of different specimens are as follows.

Table 1: Specimens Classification

Group No.	Specimen label	Control column	Longitudinal FRP	Strengthening technique
I	I-C	✓	-	-
	I-EBR	-	✓	EBR
	I-EBROG	-	✓	EBROG
	I-EBRIG	-	✓	EBRIG
II	II-C	✓	-	-
	II-EBROG-T	-	✓	EBROG
	II–EBROG-SE	-	✓	EBROG
	II–EBROG-T-SE	-	✓	EBROG
III	III-C	✓	-	-
	III-GFM(a)	-	-	-
	III-GFM(b)	-	-	-

a) Group I

Group I consisted of 4 column specimens, one control column and three columns each longitudinally strengthened with EBR, EBROG and EBRIG techniques, respectively. This group of specimens was designed and tested to study the effect of different techniques on the load carrying capacity of the strengthened columns.

b) Group II

Group II comprised of 4 column specimens including one control and three strengthened columns. Specimen *II-EBROG-T* was strengthened with EBROG technique. However, in this specimen, each strip of 60×390 mm dimensions was divided into two narrower strips with dimensions of 30×390 mm; and the two strips were attached on a groove subsequently. Therefore, the same amount of fiber sheets as the specimen *I-EBROG* was used and a 2-ply composite (i.e. a thicker composite) was created.

In specimen *II-EBROG-SE*, the strengthening technique was EBROG. However, in this specimen, the grooves were filled with a mixture of silica sand and epoxy with a weight proportion of 1:2. This specimen was planned to investigate the effect of replacement of a part of epoxy with a hardener in order to reduce the usage of epoxy. However, the mixture was approximately rough, and not as smooth as the pure epoxy resin. The size dimension of silica sand used in this study was in the range of 0.15-1.0 mm.

In addition, in specimen *II-EBROG-T-SE*, the grooves were filled with the mixture of silica sand and epoxy (with 1:2 weight proportion) and the fiber sheets were attached in a way to produce a 2-ply (or thick) composite similar to specimen *II-EBROG-T*.

c) Group III

In order to investigate if the grooves which were filled with epoxy affected the column load carrying capacity, group III of the specimens were designed and tested. In this group, specimens *III-GFM(a)* and *III-GFM(b)* had 8 grooves with width, depth and length of 10, 10 and 460 mm, respectively; which were filled with epoxy matrix without applying any longitudinal fiber sheets, to examine the influence of matrix in the groove. These two specimens were exactly the same and tested as repeated specimens to get confident results. Specimen *III-C* was also a reference column in this group.

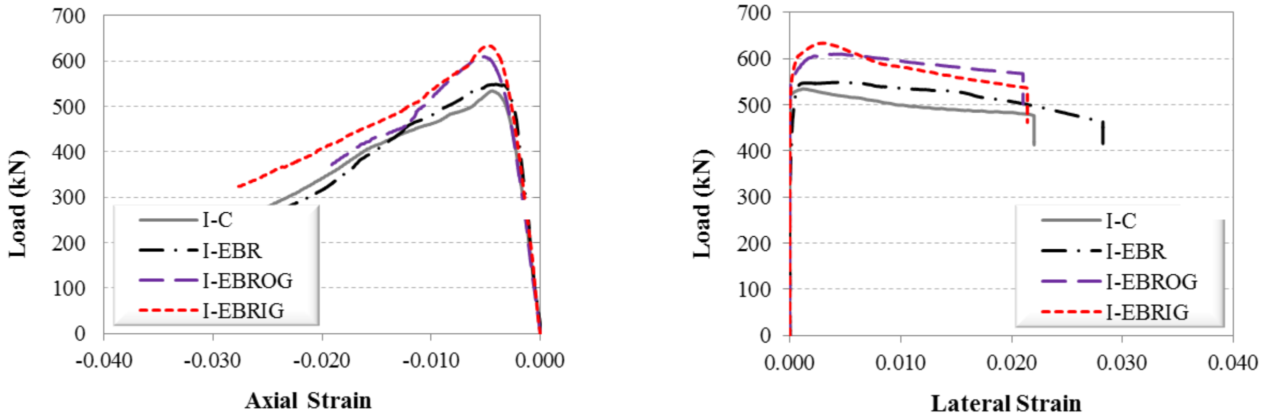
3. EXPERIMENTAL RESULTS

Column specimens were tested under monotonic axial compression. Experimental results are summarized in Table 2 and the load-strain curves of tested column specimens are plotted in Fig. 6, which will be discussed in the following section.

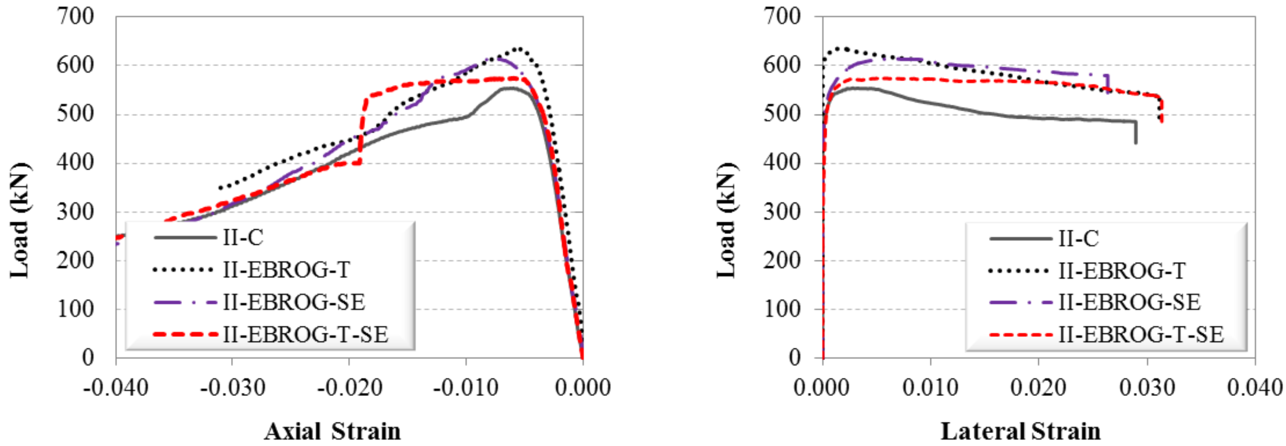
Table 2: Test Results

Group No.	Specimen label	ε_a (%)	Increase in ε_a (%)	P_{max} (kN)	Increase in P_{max} (%)
I	I-C	1.1039	-	534.7	-
	I-EBR	1.2268	11.1	548.7	2.6
	I-EBROG	1.2561	13.8	610.1	14.1
	I-EBRIG	1.5966	44.6	633.8	18.5
II	II-C	1.4714	-	554.5	-
	II-EBROG-T	1.7657	20.0	635.8	14.7
	II–EBROG-SE	1.7474	18.8	614.4	10.8
	II–EBROG-T-SE	1.8575	26.2	574.6	3.6
III	III-C	1.6900	-	555.9	-
	III-GFM(a)	1.2474	-26.2	563.0	1.3
	III-GFM(b)	1.4184	-16.1	578.0	4.0

P_{max}: Maximum load; ε_a: Ultimate axial strain.



(a)



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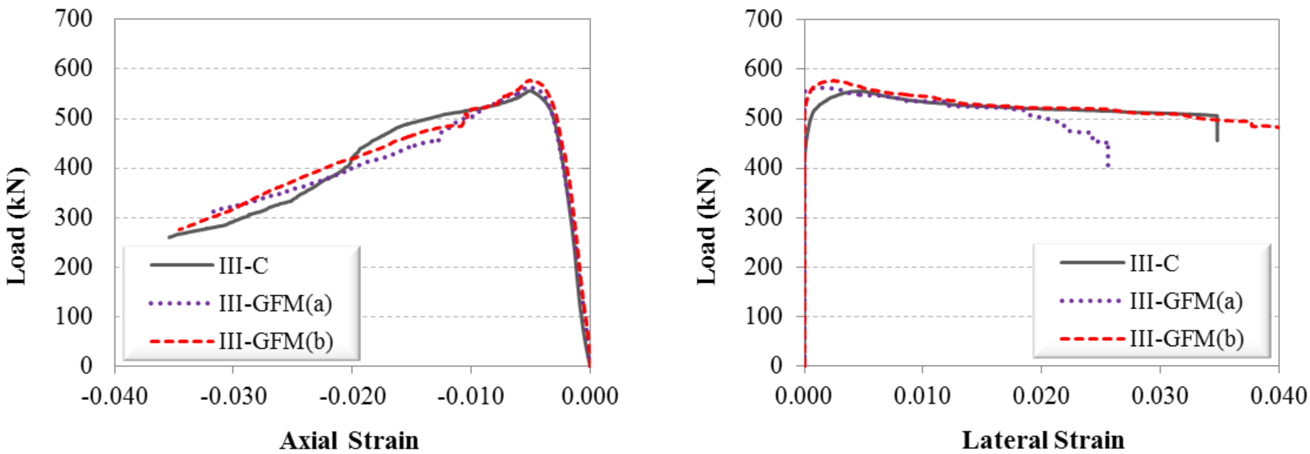

(c)

Figure 6. Load-strain curves of tested column specimens; (a) group I; (b) group II; (c) group III

3.1 Overall column behavior
Failure modes of different column specimens of groups I, II and III are shown in Figs. 7, 8 and 9, respectively. It can be seen in the figures that the dominant failure mode of the strengthened columns with longitudinal FRP, was debonding of composite from concrete substrate and its outward buckling. Debonding of FRP started before reaching the maximum load and the FRP protrusions developed and became larger as the loading was increased. As a result, the displacements measured by horizontal LVDT were not exactly the radial displacements of the specimen, but also included the composite protrusions.


(a) I-C (b) I-EBR (c) I-EBROG (d) I-EBRIG
Figure 7. Failure modes of column specimens of group I


(a) II-EBROG-T (b) II-EBROG-SE (c) II-EBROG-T-SE
Figure 8. Failure modes of column specimens of group II

(a) III-GFM(a) (b) III-GFM(b)

Figure 9. Failure modes of column specimens of group III

Load-strain curves of tested columns are shown in Fig. 6. It is revealed in this figure that the columns strengthened with longitudinal composite, failed in a gradual manner, similar to reference column (column with no external FRP strengthening). As a result, no distinct failure point could be observed for these columns. Therefore, the ultimate point was selected arbitrarily as the load level equal to 85% of maximum load of reference column in each group.

It is also demonstrated in Fig. 6 that the load-strain curves of strengthened columns have the same slope in first ascending branch as the reference column. It means that strengthening a column with longitudinal composite does not affect the stiffness of column up to maximum load, and in the descending branch as well.

3.2 Results of group I

Considering results summarized in Table 1, it is understood that the column strengthened with EBR method (*I-EBR*), carried a maximum load of 548.7 kN which showed 2.6% increase compared to reference column. However, specimens *I-EBROG* and *I-EBRIG* carried a maximum load of 610.1 and 633.8 kN, respectively; indicating 14.1% and 18.5% increase in maximum load compared to reference column. Therefore, strengthening a column with EBROG or EBRIG techniques resulted in significant increase in load carrying capacities.

By loading a strengthened column under compression, the compression stresses would be created in longitudinal composite due to stress transmission to the composite by means of interfacial bond stresses. Grooving method increases the contact area between FRP and concrete substrate. Furthermore, shear stresses between composite and transmits through groove depth to stronger concrete layers [15, 17]. Therefore, debonding of composite from concrete substrate is postponed and the composite withstand higher compressive stresses; leading to higher increase in load carrying capacity of strengthened column.

Furthermore, the direct contact area of FRP and concrete substrate in EBRIG technique is more than the contact area in EBROG, and therefore, EBRIG is more effective in enhancing the column maximum load.

3.3 Results of group II

According to Table 2, specimen *II-EBROG-T* carried a maximum load equal to 635.8 kN showing 14.7% increase respect to reference column; which is almost equal to the increase value observed for EBROG technique in specimen *I-EBROG*. It means that a 2-ply composite with the same amount of fibers as that of 1-ply composite, did not considerably affect the maximum load of column.

In addition, specimen *II-EBROG-SE* carried a maximum load of 614.4 kN indicating 10.8% increase in load capacity compared to control column (*II-C*). In this specimen, the fibers may have been scratched during applying the sheet on the groove, since the resin in the groove was mixed by sand and therefore was rough and not smooth. Improper grading of silica sand used in this study, not fully embedding the fiber sheets with matrix or scratching them during embedding the sheet may be contributed to weaker performance of composite in specimen *II-EBROG-SE* compared to specimen *I-EBROG*. It is also demonstrated in Table 1 that specimen *II-EBROG-T-SE* had a maximum load bearing capacity of 574.6 kN showing 3.6% increase compared to reference column of group II.

3.4 Results of group III

It can be seen in Table 1 that the load carrying capacities of specimens *III-GFM(a)* and *III-GFM(b)* were increased 2.6% on average, respect to reference column. It means that cutting grooves in the column cover and filling them with matrix, without applying any fiber sheet, has insignificant effect on load capacity of column and cannot considerably increase the column capacity. In other words, the increase in load carrying capacities of columns strengthened with EBROG and EBRIG techniques occurred due to the compression strength capacity of FRP composite, and not due to the matrix capacity in groove. Clearly, the grooves filled with matrix only provided lateral supports to postpone the FRP buckling.

4. CONCLUSIONS

In the present study, the influence of 2 techniques of grooving method, i.e. EBROG and EBRIG, in improving the performance of compressive CFRP sheets used to strengthen the concrete columns was investigated and compared with EBR method. The experimental results can be summarized as follows.

1. Strengthening a column with longitudinal FRP using EBR method did not considerably enhance the column load carrying capacity. However, using the grooving method significantly increased the column load capacity. The maximum load carrying of columns strengthened with EBROG and EBRIG techniques were increased 14.7% and 18.5%, respectively, compared to reference column; while the corresponding increase value for the column strengthened with EBR method was only 2.6%. The better performance of CFRP sheets in compressive strengthening of concrete columns in EBROG and EBRIG techniques may be attributed to the role of grooves in providing lateral support for longitudinal composite, and therefore, postponing the buckling of FRP.

2. The failure mode of longitudinally strengthened columns was a gradual and not abrupt failure, accompanied by FRP buckling and debonding from concrete substrate. In EBR method, a very thin layer of concrete surface was removed by FRP buckling; however, in GM, a thicker layer of concrete substrate was removed toward buckling. It can be concluded, therefore, that the interfacial bond stresses was transferred to the depth of concrete when GM was used.

3. Substituting a part of the epoxy matrix which was used for filling the grooves with silica sand, slightly decreased the performance of EBROG technique. However, the technique was still efficient enough to improve the column maximum load.

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