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Performance of corner strips in CFRP confinement of rectilinear RC columns

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Abstract. Confining concrete columns by means of Fiber Reinforced Polymer (FRP) composites is the most common method used for enhancing the strength and ductility of concrete compression members. The shape of column section is taken from the significant parameters affecting efficiency of composite in confinement. In rectilinear columns, due to stress concentration on corners, the concrete is non-uniformly confined and the effectiveness of confinement is much reduced compared to circular columns. In this study, the compressive behavior of 9 rectilinear RC columns confined with CFRP strips is experimentally examined. To improve the confinement effectiveness in columns, some of the specimens are locally strengthened with CFRP strips at corners, before the application of horizontal CFRP wrapping. The number of confining layers and the shape of rectilinear section (square or rectangular) are the main parameters under investigation. Based on results of the current study, local reinforcement at the corners of rectilinear columns before horizontal wrapping eliminates stress concentration on the corners and avoids premature rupture of CFRP confining layers at these parts; thus increases the efficiency of composite in confinement. Furthermore, local reinforcement of the corners of column section is more effective in RC columns with square sections compared to rectangular sections.

1. Introduction

Jacketing RC columns with carbon Fiber Reinforced Polymer (FRP) composites can enhance both axial strength and ductility of the members, and may prevent buckling of the longitudinal reinforcement and also improve shear capacity. However, such effects are clearly apparent in circular sections, and not in rectilinear sections, especially those with sharp corners. Stress concentration on sharp corners of rectilinear columns provides a non-uniformly confinement around the concrete section [1]. The presence of sharp corners also results in premature rupturing of FRP composite at tensile stresses lower than the ultimate strength of fibers [1,2]. Consequently, the effectiveness of confinement is much reduced in rectilinear sections.

To increase the effectiveness of FRP confinement in rectilinear sections, researchers recommended smoothing the sharp corners with round fillets before the application of FRP confining layers, which reduces stress concentration on corners and increases the effective confinement area of the section (based on ACI 440.2R-08 [3]). Theoretical and experimental investigations reported in the literature [4-15] indicate that a significant improvement in the performance of composite in confinement was observed with an increase in corner radius; as the corner radius increases, the distribution of confining stresses around section becomes more uniform, leading to increase in the ultimate strength and strain of confined columns with

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round corners compared to those with sharp corners. Furthermore, the influence of shape modification on the performance of FRP confinement in rectilinear columns was recently studied by some research [16-19]. In their studies, the cross section of rectilinear column was changed to circular or elliptical shape by adding concrete or mortar elements before wrapping the FRP around the section. The results showed that the modified shape of cross section can significantly improve the behavior of rectilinear FRP confined column by reducing stress concentration on the corners and increasing the FRP efficacy.

Although rounding the corners or modification of the section of rectilinear columns are effective methods to increase the efficiency of composite in confinement, these methods involve additional costs and cannot be used in all cases. Campione et al. suggested the use of single vertical strips of FRP (with horizontal fibers) locally applied at the sharp corners beneath the horizontal FRP wraps in confinement of concrete columns with square sections [20,21]. They concluded that local reinforcement at the corners before the application of horizontal wrap avoids premature rupture of FRP at the sharp corners and improves the confinement effectiveness of horizontal layers and significantly increases the bearing capacity and ductility of column. Furthermore, Kiani, in 2010, modeled square concrete specimens strengthened with the aforementioned technique and examined the influence of different parameters, including the number of confining layers, the ratio of corner strip width to column dimension, and the effect of intermittent wrapping. His results showed that local reinforcement of the section corners eliminates stress concentration on these parts and makes distribution of the confining pressure almost uniform around the section. Furthermore, an increase in the width of corner strips induces more increase in ultimate strength and ductility of the confined column [22].

Despite the successful application of FRP corner strips to increase the efficacy of composite in FRP-confined square columns, sufficient attention has not been paid to the effect of its application in RC columns with rectilinear sections. Consequently, the current study is mainly aimed at experimental investigation of the performance of this method in confinement of rectilinear RC columns. Test parameters included the number of confining layers and the shape of rectilinear section (square or rectangular).

2. Experimental procedure

2.1. Description of specimens

In this study, 9 rectilinear RC columns with corner radius of 8 mm and height of 500 mm were tested under uniaxial compression loading. The test program included 6 square RC columns with cross-sectional dimensions of 133 × 133 mm which were classified in groups S1 and S2, and 3 rectangular RC columns with cross-sectional dimensions of 110 × 160 mm which were placed in group R. Each group contained one reference column without external strengthening (Si - Ref or R - Ref) and two other columns confined using usual wrap and corner strip-wrap techniques. Classification of the tested specimens is given in Table 1. The first part of the name of specimen, Si or R, refers to the group of specimen, while the other parts include Ref for reference concrete columns without external strengthening, IVS (Intermittent Vertical Strip) utilized when the corner strip is used for strengthening of specimen, IW (intermittent wrap) referring to the horizontal CFRP wraps, and 1 or 2 as the number of CFRP wraps.

It is noteworthy that in different techniques used in the present research, column specimens were strengthened using intermittent CFRP strips spaced at clear 50 mm intervals along the height of column to save the CFRP. Furthermore, the ends of all columns were strengthened with additional 50 mm wide CFRP strips to prevent premature failure of specimens at the ends due to stress concentration.

Based on previous studies [21,22], a length of one-

Table 1. Classification of specimens and summary of test results.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Group	Specimen lable	No. of confining layers	Max. load (kN)	Ult. load (kN)	Ult. axial strain (%)	Ult. lateral strain (%)	Ductility; E_u(N.m≈J)	Increase in max load (%) compared to: Ref. column	Increase in max load (%) compared to: IW method	Increase in E_u (%) compared to IW method
S1	S1-R	-	453.80	381.61	0.00798	0.00871	-	-	-	-
	S1-IW.1	1	564.81	508.24	0.01486	0.01035	1780.10	24.5	-	-
	S1-IVS.1-IW.1	1	647.25	602.61	0.01797	0.01268	2496.46	42.6	14.6	40.2
S2	S2-R	-	449.19	380.11	0.00686	0.00869	-	-	-	-
	S2-IW.2	2	657.25	618.95	0.01483	0.01583	1901.75	46.3	-	-
	S2-IVS.1-IW.2	2	669.74	628.99	0.02354	-	3372.87	49.1	1.9	77.4
R	R-R	-	477.05	405.27	0.00704	0.00780	-	-	-	-
	R-IW.1	1	563.63	478.15	0.00907	-	1050.02	18.1	-	-
	R-IVS.1-IW.1	1	601.65	582.12	0.01326	0.01111	1680.74	26.1	6.7	60.1

third of the column section dimension for corner strips is an optimum length in corner strip-wrap technique. Accordingly, in this study, the length of corner strips along each side of the column was selected equal to one-third of column section dimension; i.e. 45 mm for square specimens and 35 mm for the smaller side and 55 mm for the larger side of rectangular specimen. The fibers in corner strips were aligned in horizontal direction.

A brief description of the specimens in different groups is given as follows:

a) Group S1: This group consists of three square RC columns; the first one is a reference specimen and the other two specimens are confined with one layer of CFRP sheets using intermittent wrap along the height of column (IW) and corner strip-wrap (IVS-IW) methods. The corner strips in this group included five CFRP strips with dimensions of 50×90 mm intermittently attached to each corner.

b) Group S2: The specimens of this group were designed to investigate the influence of number of confining layers on the performance of confining techniques used in the current research. For this purpose, three square RC columns were prepared for this group; one reference specimen and two specimens confined with two layers of CFRP wraps using IW and IVS-IW methods.

c) Group R: This group included three rectangular RC columns, one reference specimen and two specimens strengthened with one layer of CFRP composite using intermittent wrap along the height of column (IW) and corner strip-wrap (IVS-IW) methods (similar to group S1). Layout of this group was intended to examine influence of the shape of rectilinear cross section on the performance of utilized confining techniques.

Strengthening details of the specimens are presented in Figure 1.

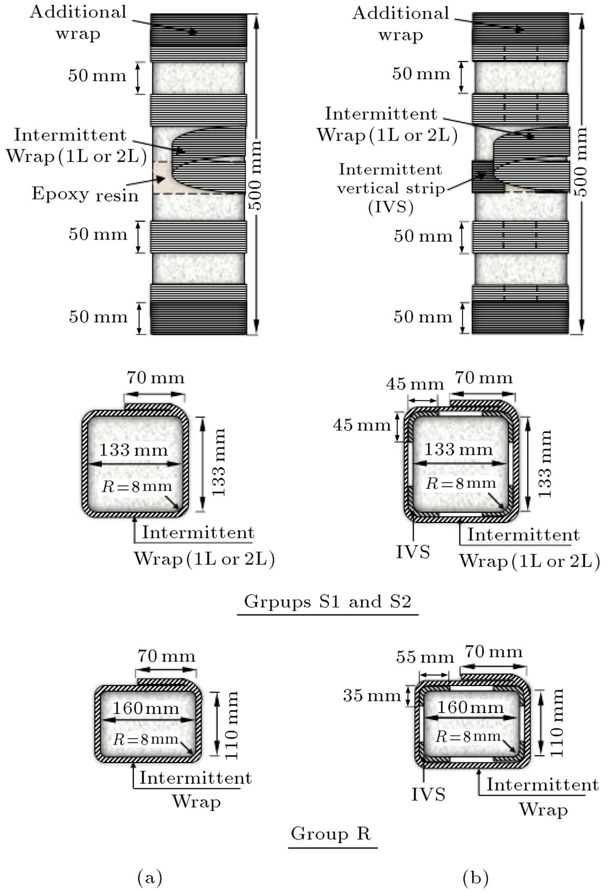

Figure 1. Strengthening details of the specimens: (a) Intermittent wrap (IW); and (b) intermittent corner strip-wrap (IVS-IW).

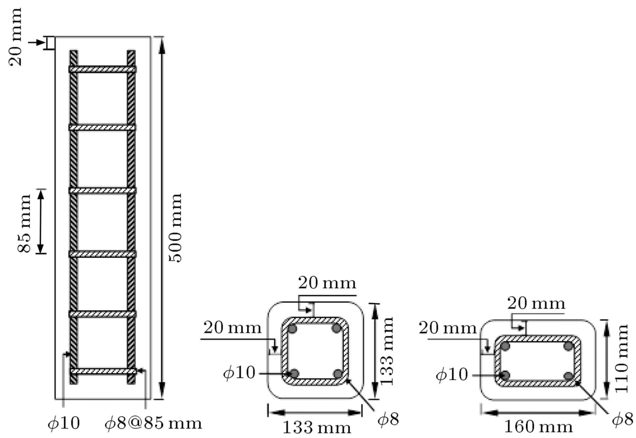

Figure 2. Details of specimens' reinforcement.

2.2. Material characteristics

The concrete used to construct specimens had an average 28-day compressive strength of 28 MPa which was determined by testing three 150×300 mm standard concrete cylinders for each group, loaded according to ASTM standard C39 [23]. To obtain the target compressive strength, 398 kg/m^3 of type I Portland cement, 888 kg/m^3 of sand, 783 kg/m^3 of coarse aggregate, and 240 kg/m^3 of water were used. Four 10-mm diameter deformed steel bars having a nominal tensile strength of 406 MPa were used as longitudinal reinforcement in all column specimens. As for the transverse reinforcement, 8-mm diameter ties with nominal tensile strength of 550 MPa spaced at 85 mm on the center were used. The clear concrete cover was 20 mm on each side, and also on top and bottom of the column specimens, to prevent direct loading of longitudinal bars. Furthermore, to prevent premature failure of specimens at the ends, both ends of all columns were strengthened using additional CFRP strips with 50 mm of width. Reinforcement details of columns are given in Figure 2.

RC columns were strengthened using unidirec-

Table 2. Mechanical properties of CFRP materials [24].

Fibers	Type	Thickness (mm)	Tensile strength (N/mm^2)	Tensile E-modulus (N/mm^2)	Elongation at break (%)
	SikaWrap-230C	0.131	4300	238000	1.80
Resin	**Type**	**Tensile strength (N/mm^2)**	**Tensile E-modulus (N/mm^2)**	**Flexural E-modulus (N/mm^2)**	**Elongation at break (%)**
	Sikadur® -330	30	4500	3800	1.50

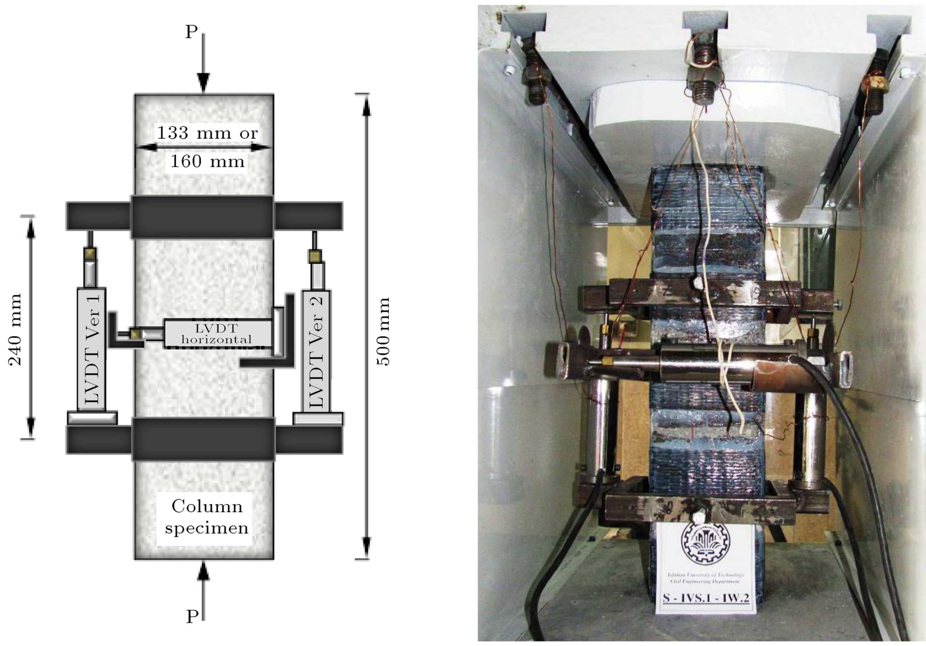

Figure 3. Test setup and instrumentation.

tional carbon composites and Sikadur-330 epoxy adhesive by means of wet lay-up procedure. The mechanical properties of a dry carbon fiber fabric and epoxy adhesive, as provided by the manufacturer [24], are summarized in Table 2.

2.3. Instrumentation and testing setup

All specimens were tested under monotonic uniaxial compression load by using a 2,000 kN capacity testing machine. The compressive load was applied in displacement control mode at a constant rate of 1 mm/min [23]. Axial and lateral deformations of the columns were measured by using three Linear Variable Differential Transducers (LVDTs) with the gauge length of 20 mm. Two vertical LVDTs were mounted on the two opposite sides of columns to monitor the average axial deformation. A very low scattering of results (less than 3%) between each pair of vertical LVDTs and in the average value was observed. Furthermore, one horizontal LVDT was mounted on a specific frame at the mid-height of each column to determine the lateral deformation. Axial and lateral strains used for plotting the load-strain curves were obtained from measurements of LVDTs divided by the length; the length was equal to 240 mm for axial strains and 133 mm for lateral strains in square specimens, and 160 mm for lateral strains in rectangular specimens. The testing setup of specimens is shown in Figure 3.

3. Results and discussion

The experimental specimens used in this study were subject to uniaxial compression loading test. The load-displacement and load-strain curves of the specimens at each group are illustrated in Figure 4. The test results, including the maximum and ultimate loads, ultimate strains, and ductility index, E_u, for each column specimen are presented in Table 1. It is worth mentioning that the failure of all reference columns in this study was completely ductile without any ultimate fracture point; therefore, the ultimate bearing capacity of reference specimens was determined using the equivalent point of 85% of maximum load on the descending branch of load-strain curve.

Furthermore, ductility index in Table 1 was quantified as the area under load-axial displacement curve

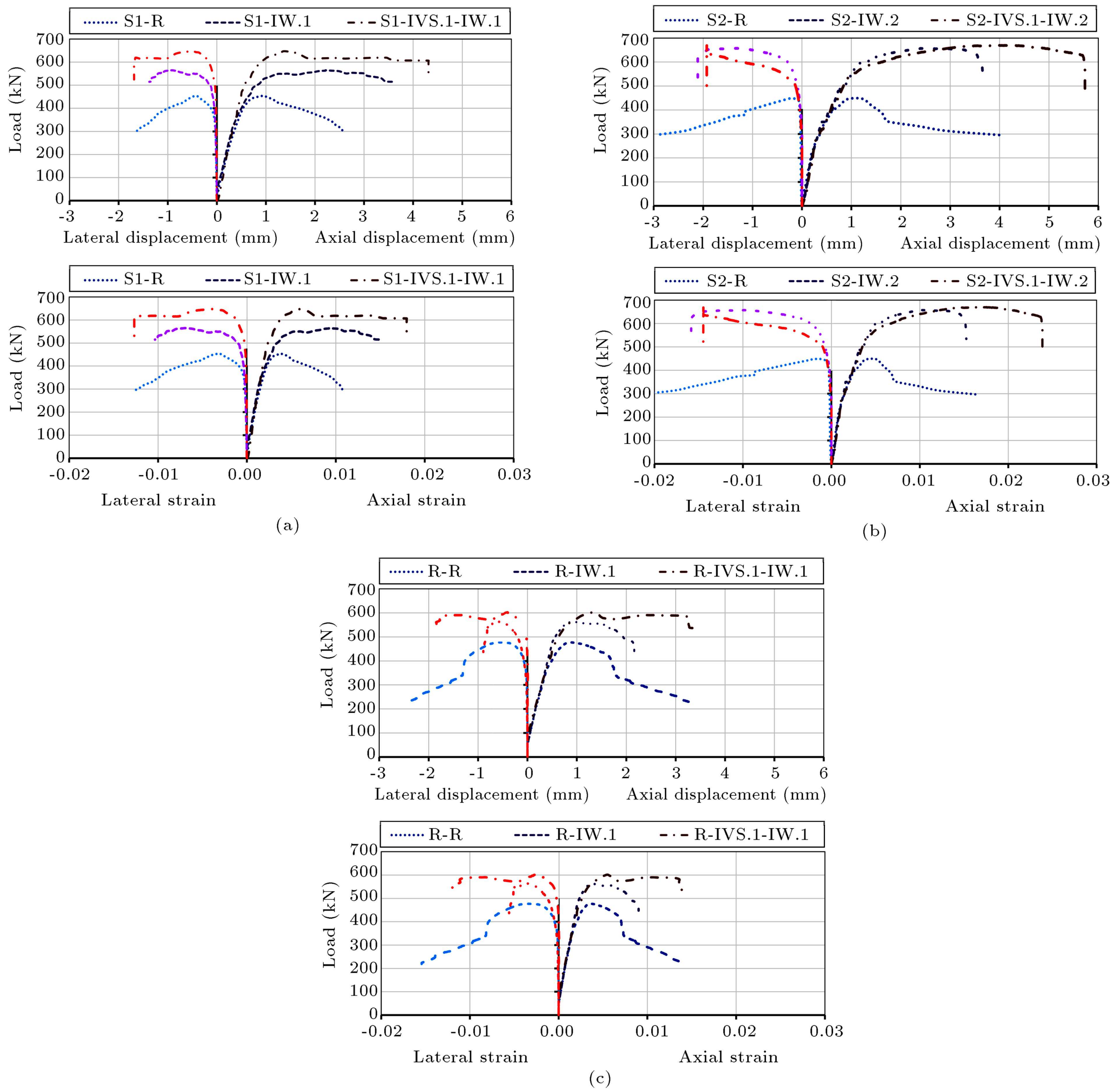

Figure 4. Load-displacement and load-strain curves of the tested specimens: (a) Group S1; (b) group S2; and (c) group R.

up to the failure point (Figure 4), which represents energy absorption of the specimen before failure. Note that ductility of a member is defined as its ability to sustain inelastic deformations prior to failure without substantial loss of strength; so, the area under load-displacement curve up to the point of failure may be used as an initial criteria and an indication for comparing the rates of energy absorption and ductility of the member [25,26].

3.1. Effect of confining technique

The increases in the maximum loads of CFRP confined columns compared to the reference specimens of each group are shown in column 9 of Table 1. It is observed in the table that the maximum loads of specimens S1-IW.1, S2-IW.2, and R-IW.1 confined using usual wraps have respectively increased by 24.5%, 46.3%, and 18.1% in comparison with the reference columns. When specimens are strengthened with CFRP corner strips before the application of horizontal wrapping, the increase in maximum loads compared to those of the reference columns are 42.6%, 49.1%, and 26.1% for specimens S1-IVS.1-IW.1, S2-IVS.1-IW.2, and R-IVS.1-IW.1, respectively. It is observed that the specimens strengthened with corner strip-wrap method have withstood much higher loads compared to the columns strengthened using conventional wraps.

Besides, a comparison has been made in Figure 5 for E_u of all confined specimens, showing the significant influence of IVS-IW technique in improving the ductility of columns. In fact, when corner strips are used as a part of confining CFRP, better performance

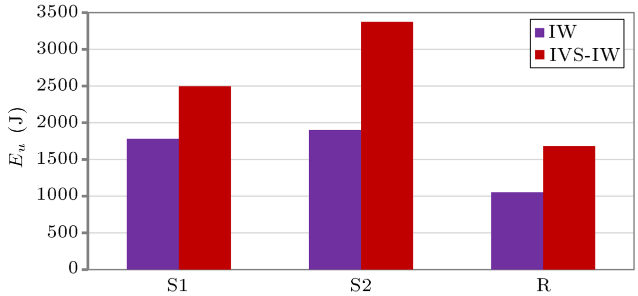

Figure 5. Comparison between the ductility of specimens with different methods of confining.

of the strengthening technique is observed due to the stress concentration eliminations on corners; this creates almost uniform distribution of confining pressure around column section and thus increases the effective confinement area of the section.

3.2. Effect of the number of confining layers (groups S1 and S2)

Comparison between the results depicted in Figure 4(a) and (b) shows that strengthening with two layers of CFRP confining strips increases both the strength and ductility of confined columns compared to the specimens strengthened with one layer of CFRP. It is also observed in column 9 of Table 1 that increases in the maximum loads of specimens S1-IW.1 and S1-IVS.1-IW.1 confined with one layer of composite, compared to those of the reference column, are, respectively, 24.5% and 42.6%. When column specimens were confined with two layers of CFRP strips, these increases reach to 46.3% and 49.1% for specimens S2-IW.2 and S2-IVS.1-IW.2, respectively.

The results also indicate that the corner strip-wrap method shows better performance in increasing the bearing capacity of column when thinner confining strips are used, i.e. when one layer of composite is used, the increase in maximum load for the column specimen strengthened by IVS-IW method is 14.6% compared to that of the specimen strengthened with conventional wrapping (IW); whereas this increase is almost 2% when two layers of CFRP strips are used (see column 10 of Table 1). This behavior can be justified as when the column specimen is confined with two layers of CFRP strips, confining stresses at corners reach to a higher level and, thus, stress concentration on corners becomes more critical compared to the case when one layer of confining strip is used. Consequently, the utilized corner strips cannot efficiently compensate these stresses at corners.

It is also observed from column 11 of Table 1 that the performance of corner strip-wrap technique is more significant in increasing the ductility of column when thicker layers of confining CFRP are used. For example, when one layer of CFRP is used for strengthening, increase in E_u for the specimen strengthened by IVS-IW method is 40.2% compared to that of the specimen strengthened with usual wrapping (IW); the corresponding increase improves to 77.4% in strengthening with two layers of composite.

3.3. Effect of the shape of rectilinear section (groups S1 and R)

Comparison of stress-strain behavior for column specimens in groups S1 and R (see Figure 4(a) and (c)) shows that the shape of rectilinear section considerably influences the strength and strain capacity of confined columns. As can be seen in the figures and also in column 9 of Table 1, the maximum load increment of square specimen confined using intermittent wrap is 24.5% compared with to reference column; while this increase is 18.1% for the rectangular specimen confined with IW method. Furthermore, the square specimen strengthened with corner strip-wrap technique has withstood the maximum load increment of 42.26% compared to the reference column, whereas this increase is 26.1% for the rectangular specimen confined using IVS-IW technique.

It is also observed from Figure 5 (and column 8 of Table 1) that the values of E_u for square columns are much greater than the corresponding values for the rectangular columns in both strengthening methods used in the current study. It can be concluded that although the corner strip-wrap technique is an effective method which improves the CFRP efficiency in confinement of rectilinear columns, the performance of this technique is highly dependent on the shape of rectilinear section; where the square sections provide a better performance. In rectangular sections, due to the higher non-uniformity of column geometry, higher stress concentration on corners occurred which reduced the CFRP efficiency in utilized confining methods.

3.4. Failure mechanism and CFRP rupture location

The failure mechanisms of tested specimens confined with IW and IVS-IW methods are shown in Figure 6. It is observed in this figure that the failure of all column specimens occurred around the mid-height of column. Besides, failure of all confined columns was controlled by tension rupture of CFRP. According to this figure, the location of CFRP rupture on column perimeter varies in different utilized confining techniques. In rectilinear sections, although the maximum tensile stresses and strains in confining composite occur in the middle of sides, the composite ruptures at section corners in lower strains due to stress concentration on these parts.

CFRP rupture in the specimens confined with IW method occurred at one of the section corners (Figure 6(a) and (c)). In this case, the cutting of fibers at sharp corners, due to stress concentration,

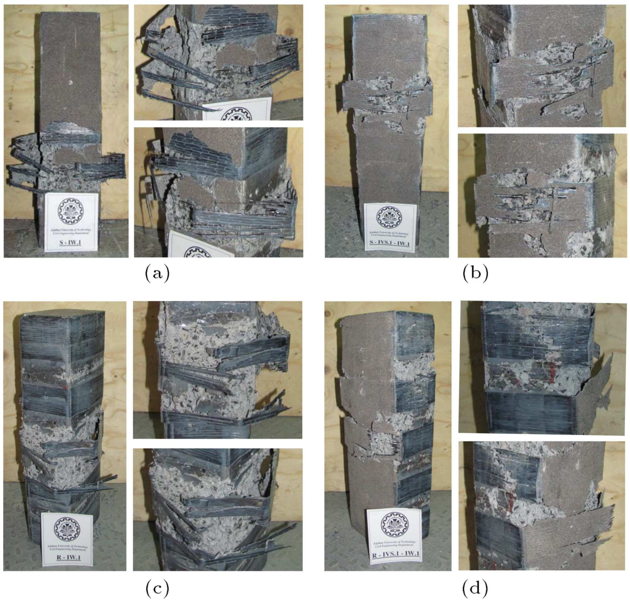

Figure 6. Failure mechanisms of specimens confined with different techniques: (a) IW in group S1; (b) IVS-IW in group S1; (c) IW in group R; and (d) IVS-IW in group R.

leads to premature rupture of composite, which reduces the efficiency of confining CFRP layers. However, the fracture of composite in the square specimens strengthened with IVS-IW technique occurred in the middle of one side (Figure 6(b)). Moreover, CFRP rupture in the rectangular specimen confined with IVS-IW technique occurred in the middle of side in one of the confining strips, and also occurred around the section corner in another one (Figure 6(d)). These observations demonstrate that local strengthening at section corners of rectilinear columns, before the application of horizontal wrapping, eliminates stress concentration on confining layers and transfers the composite rupture location from corners to the middle of one side. However, the application of CFRP corner strips in square sections is more effective than in rectangular sections because of the more uniform geometry of square columns.

4. Conclusions

The experiments undertaken for this research are based on 9 small size rectilinear RC columns, and are aimed at examining the performance of corner strip-wrap method in confinement of rectilinear RC column compared to conventional wrapping, as well the effect of number of confining layers and the shape of rectilinear section. Based on the experimental results of the current study, the following conclusions may be drawn:

1. Local strengthening at section corners of rectilinear columns, before the application of horizontal wrapping, considerably increased both strength and ductility of RC columns in this study; i.e. the maximum loads of square and rectangular specimens locally strengthened with intermittent corner strips and then confined with one layer of intermittent wraps increased by 14.6% and 6.7%, respectively, compared to those of specimens confined using conventional wrapping.
2. Using thicker layers of confining CFRP strips more increased the strength and strain capacities of RC columns tested in the current study. However, the performance of corner strip-wrap technique was more significant in increasing ductility of column when thicker layers of confining CFRP were used. For example, when one layer of strengthening CFRP was used, the increase in E_u for the specimen strengthened by IVS-IW method was 40.2% compared to that of the specimen strengthened with usual wrapping (IW); this increase improved to 77.4% in strengthening with two layers of composites.
3. The performance of confining techniques used in this research strongly depended on the shape of rectilinear section, where the square sections provided better performance by withstanding about 6.5% and 16.5% higher loads in IW and IVS-IW methods, respectively.
4. The corner strip-wrap technique investigated in the current study led to more uniform confining stresses around the section circumference and it led to increase in the effective confinement area of the section compared to conventional CFRP wrapping by eliminating stress concentration on corners; it also transferred the CFRP rupture location from corners to the middle of one side in both tested square and rectangular RC columns.

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Amirreza Moghaddas is a PhD candidate at Civil Engineering Department in Isfahan University of Technology (IUT), Isfahan, Iran. He received his MS degree in Structural Engineering from Isfahan University of Technology (IUT) in 2011. His research interests include application of fiber-reinforced polymer (FRP) composites in reinforced concrete structures for strengthening.