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Experimental Investigation of External FRP Strengthening Column Against Secondary Moment of Slender Effect

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ABSTRACT

The essential design code guidelines for Fiber Reinforced Polymer (FRP) strengthened Reinforced concrete columns are limited to short columns strengthened with FRP wrapping. As a result, they are primarily non-applicable to slender RC columns where there is a significant second-order/slenderness impact. The purpose of the current study was to experimentally recognize how effectively longitudinal carbon panels (CFRP) and basalt fiber-reinforced polymer (BFRP) lateral wrapping can reduce lateral deflection and increase the strength of variable thin square reinforced concrete columns. A total of 8 square RC columns of 120 mm width were performed in three groups, according to the slenderness ratio 22, 29, and 35. The strengthened columns were developed using two distinct strengthening techniques. The first is a longitudinal CFRP laminate with lateral partial BFRP wrapping (EBWGL) plus grooved bonding, and the second is a lateral partial wrapping (EBW) of the BFRP film. The column was tested with 30 mm eccentric compression. In general, the EBWGL reinforcement technique significantly improves the flexural strength of columns. Moreover, it is noteworthy that the EBW method did not considerably reduce the secondary effect as the slenderness ratio increased. The EBGWL has a great reducing effect that gets better as the slenderness ratio gets higher.

1. Introduction

All over the world, the wide use of fiber-reinforced polymer (FRP) for the reinforcing and repair of reinforced concrete (RC) structures is becoming more popular due to its promising and proven performance [1–5].

Although the FRP reinforcement process improves the ductility and strength of short columns, designers are having difficulty using this material to reinforce slender RC columns subjected to eccentric loads.

The two main reasons are the lack of full instructions and design regulations for FRP reinforcement of slender RC columns, as well as the limited amount of research that has been conducted. The design provisions of a majority of design codes [6-12] neglect the slenderness second-order effect in columns and limited strengthening for short columns only.

The study of Tao and Hanf [13] found that the slenderness ratio has greater effects on the carrying capacity of FRP-reinforced RC columns compared to unconfined RC columns, as confinement enhances strength rather than bending stiffness demonstrates that the effectiveness of FRP reinforcement declines as the slenderness ratio increases. Additionally confirmed that the effect of CFRP confinement in improving the load-carrying capacity of the column is reduced by increasing the load eccentricity and slenderness ratio [14].

All columns examined had end hinges and were tested at the same eccentricity. The

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eccentricity to the diameter of the column was 1, and the length-to-diameter ratio was 20.4. They showed that longitudinal CFRP strengthens long RC columns while reducing lateral deflections [15].

In FRP, the use of concentric compression and traditional slender concrete columns is examined. They demonstrated that the load-carrying capacity of tangentially wrapped columns was limited to those with slenderness ratios of less than 40. The current investigation on slender RC columns that are enveloped in FRP indicates that the utilization of FRP to increase strength will result in the column becoming slenderer. As a result, the FRP-confined column's flexural stiffness is decreased. Because of this, the strength advantage resulting from FRP confinement cannot be utilized until the slenderness ratio of the confined column is less than an initial value. In other words, if the slenderness ratio of the FRP confined column exceeds limiting values, it will buckle and break even before reaching its ultimate strength. As a result, FRP confinement cannot be fully used to increase the column's axial load capacity. The purpose of this study is to evaluate the efficacy of longitudinal CFRP laminates and lateral BFRP wrapping in reducing the secondary slenderness effect and enhancing the flexural strength, initial flexural stiffness, and energy absorption of safe reinforced concrete columns.

2. Experimental work

There were eight tests on reinforced columns. Three groups were created from the columns according to the slenderness ratio, C1, C2, and C3, with three slenderness ratios K (Le/r) equals (22, 29 and 35) respectively where, k, Le, r are the effective length coefficient, the column's effective length, and the radius of gyration, respectively according to ACI 318-19 [16]. The overall heights of models were 1200, 1440, and 1640 mm for the column with both ends brackets (corbel) of 220 mm height at both ends. The clear test height (effective length) of columns is 760, 1000, and 1200 mm, respectively. All columns have 120 mm×120 mm square cross-section detentions.

2.1 Details of the tested columns

Each column specimen had a four-deformed longitudinal steel reinforcement bar with a diameter of $\Phi = 10$ mm. A2 18% steel reinforcement ratio was adopted within the range limits of ACI 318-19 [16] reinforcement requirement. Around the columns, 6 mm ties spaced at 90 mm c/c were used, with the exception of the area connected to the corbels end at one to six of the column's length, where the ties are spaced at 30 mm c/c. Additionally, a concrete cover measuring 20 mm was chosen. The mixing target for all columns was set at 30 MPa for the compressive strength of the concrete. Figure 1 shows the dimensions of the column sample along with all the information about the reinforcement.

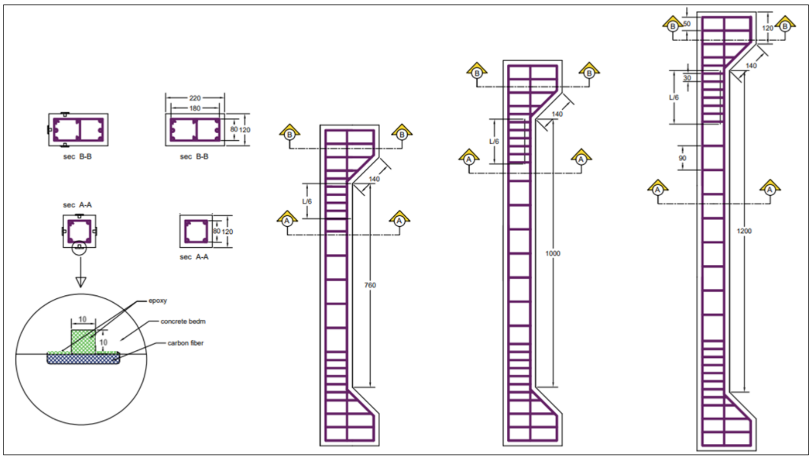


Figure 1. The column specimens with reinforcement details

2.2 *Strengthening details*

The strengthening configuration consisted of the following:

1. For external bonding wrapping technique (EBW) which is partial BFRP sheets confinement sheets in a transverse direction that consist of two layers plus overlap 100 mm, are sequentially distributed along the length of the columns with a 1:1 ratio wrapped with a width of 80 mm and a spacing of 160 mm c/c.
2. For a new technique of external bonding wrapping with longitudinal grooving bonding of CFRP laminates plus lateral wrapping (EBWGL).

Four CFRP laminates with 50 mm width on grooving with (10×10 mm) width×depth for four faces of columns in a longitudinal direction in addition to lateral partial BFRP wrapping sheets confinement as above. Furthermore. the edge of the columns has been rounded with a radius of 10 mm to prevent stress concentration.

As mentioned before, the specimen configuration has three groups (C1, C2, and C3). Group C1 consists of 2 columns with two sets (partial BFRP confinement (EBW-partial) and CFRP laminate with partial BFRP confinement (EBWGL-partial). Group C2 consists of 3 columns with five sets, (without any strengthening(reference), partial BFRP confinement (EBW-partial), CFRP laminate with grooving bonding plus partial BFRP confinement, and (EBWGL-partial). Finally, group C3 consists of 3 columns with three sets, without any strengthening(reference), partial BFRP confinement (EBW-partial), and CFRP laminate with grooving bonding plus partial BFRP confinement and (EBWGL-partial). The columns were tested by applying eccentric compressive loading with ratio (e/h) = 0.25, the target eccentricities were 30 mm from the center of the column respectively, according to the following description in Table 1.

Table 1: The column specimens' details

Group	**Model ID**	**Eccentricity e/h=**	**Longitudinal strength (CFRP) laminate**	**Strengthening technique**
CI Slenderness’ ratio =22	CI-e3o-Go-Bp	0.25	-	(EBW-partial)
	C1-e30-G1-Bp	0.25	4 laminates	(EBWGL-partial)
C2 Slenderness’ ratio = 29	C2-e3o-Go-Bo	0.25	-	reference
	C2-e3o-Go-Bp	0.25	-	(EBW-partial)
	C2-e3o-Gl-Bp	0.25	4 laminates	(EBWGL-partial)
C3Slenderness’ ratio = 35	C3-e3o-Go-Bo	0.25	-	reference
	C3-e3o-Go-Bp	0.25	-	(EBW-partial)
	C3-e3o-G1-Bp	0.25	4 laminates	(EBWGL-partial)

2.3 *Strengthening materials*

In the strengthening process, CFRP laminate and BFRP wrapping sheet were used for longitudinal and confinement respectively. All details of this material with their adhesive’s represented below. Table 2 illustrates the mechanical properties of CFRP laminate and BFRP sheet with their adhesive system provided by the manufacturer respectively.

Table 2: Mechanical properties of the strengthening material (manufacturer data sheet)

Material	Thickness (mm)	Elastic modulus (GPa)	Ultimate tensile strength (MPa)	Ultimate tensile strain (%)
CFRP laminate	1.2	171	2743	1.5
CFRP laminate epoxy	-	4	28	0.9
BFRP sheet	0.177	90	2000	2
BFRP sheet epoxy	-	4.5	30	0.9

2.4 Column strengthening procedure

For the externally strengthened columns, external bond strength techniques were used to confine the columns in the transverse direction using BFRP sheets for partially reinforced columns.

Initially, to provide adequate and strong adhesion between the BFRP wraps and the concrete column surface, a grinding machine was used to remove the outer, weak layer of the column's surface until the gravel surfaced, as seen in Figure 2 (a). Additionally, it is common practice to round the corners of square or rectangular columns before applying FRP wrap to improve the confinement of the wrap and prevent stress concentration on the wrap from sharp corners [17]. As such, column specimen corners were rounded with an electric machine to a diameter of 10 cm, as depicted in Figure 2 (b). Moreover, for columns that strengthened with a hybrid system that involved longitudinal CFRP laminate/BFRP wrapping, four longitudinal grooves at each face of columns were cut into the surfaces by a cutting machine to enhance laminate bonding. For groove preparation, longitudinal grooves with 1040-, 10-, and 10-mm length, width, and depth, respectively parallel with the columns' longitudinal axis as shown in Figure 2 (c). After cleaning the columns with air pressure and a water jet, these grooves were filled with laminate epoxy resin, and CFRP laminates were installed and fixed on the grooves as present in Figure 3 (a) and (b).

For horizontal wrapping, BFRP sheets were created and cut to the exact proportions required for full or partial wrapping using a spacing pattern (1:1). Therefore, it is recommended to use two layers plus an overlap of 100 mm length are recommended for wrapping. For fixing these sheets on a concrete surface, a layer of SIKADUR `330 epoxy was applied on both concrete surfaces as well as the BFRP sheet. Then, the BFRP sheet Fibers were wrapped around the specimens in a hoop-like pattern. Then, to get out any bubble probability, it is pressed with a roller as shown in Figure 3 (c).

2.5 Instrumentation and Test Procedures

Each column was tested under simply supported conditions with an axial load and an eccentricity of 30 mm using compression testing equipment. A displacement control system was used for the testing procedure.

To measure strains in the longitudinal directions at the mid-height of each column, strain gauges, and LVDTs were attached to their exterior surfaces.

Linear potentiometers were used to measure lateral deflections at one-quarter of the column height. The test setup utilized to test the columns is displayed in Figure 4. This image also shows some of the instruments employed in the current investigation.

(a) Surface grinding

(b) Edge rounded

(c) Creating grooves

Figure 2. Process of strengthening modification

(a) Filling the grooves

(b) Longitudinal CFRP fixing

(c) BFRP sheet wrapping installation

Figure 3. Process of FRP applying

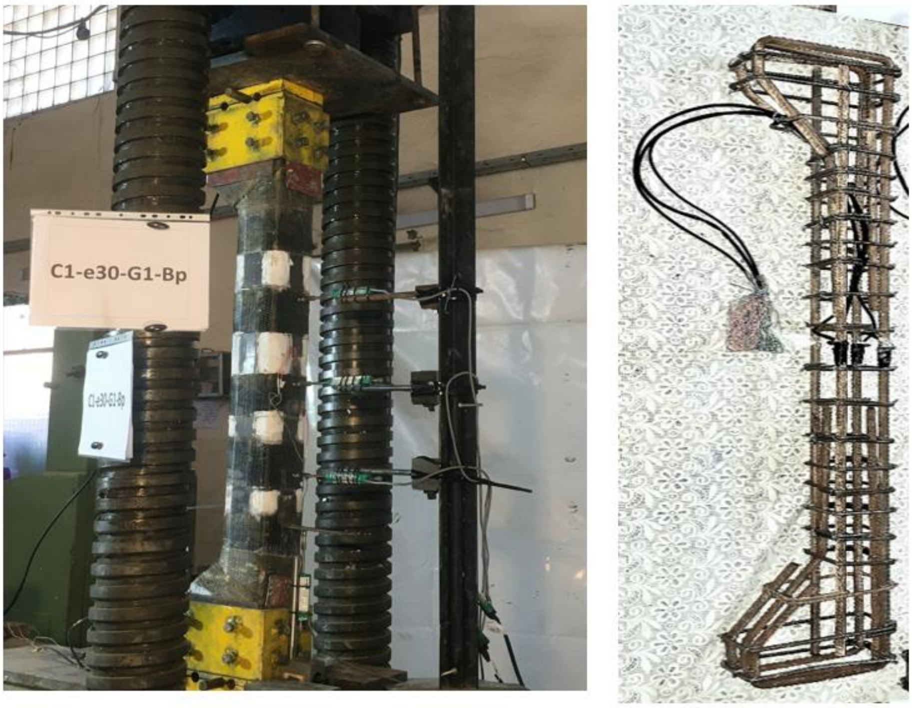
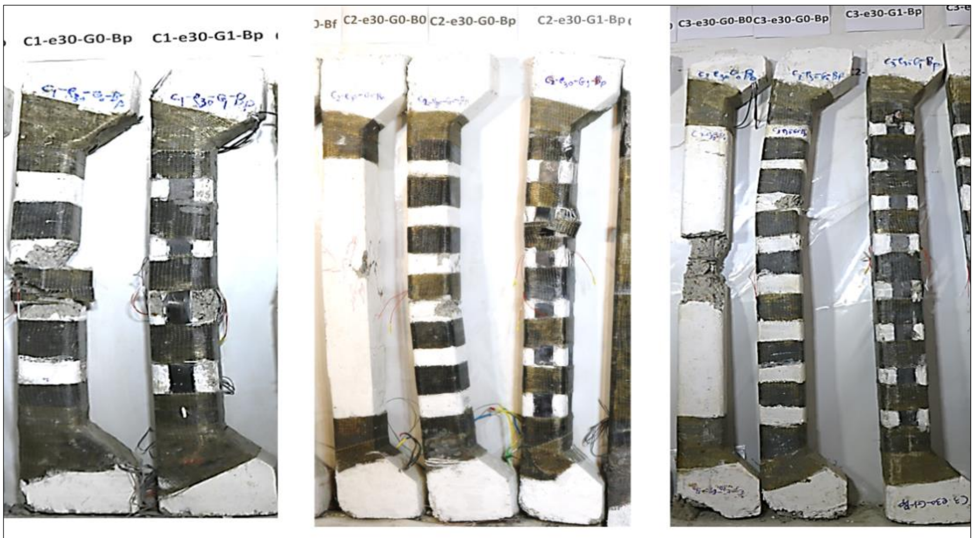


Figure 4. Columns instrumentation

3. Results

3.1 Failure mode

All of the columns were tested until failure. Figures 5 demonstrate a typical column failure mode. the sudden disappearance of the concrete cover in the compression zone was responsible for the failure of control columns followed by slight outward buckling of the longitudinal reinforcement. For C1 (with slenderness 22) and C2 (with slenderness 29) columns, the failure was observed near mid-length whereas for C3 (slenderness 35) columns, it was at the mid-height. The failure of the columns of EBW strengthening was initiated by fine crack propagation near the mid-length combined with a lateral crack at the tension face with large buckling curvature due to the elongation of the longitudinal region caused by flexural stress. The final failure was caused by a concrete fracture in the compression zone; no Fiber breaking was seen. The failure of EBWGL reinforcement columns began with the formation of ripples in the outer circumferential BFRP sheet and CFRP laminate local buckling in the compression zone near mid-length. The causes of these events include fractures in the concrete, and longitudinal Fiber buckling without any debonding to the surface. The increase in load is further increased by crushing of the concrete and consequently, greater instability of the Fibers in the compression zone and eventual rupture of the outer circumferential sheets of the BFRP.



(a) C1 group (b) C2 group (c) C3 group

Figure 5. The failure mode of tested columns

3.2 Load–deflection (P–D) and axial load–moment (P–M) response

Table 3 shows the results of columns such as load capacity, lateral displacement, and moment for all columns.

Load–total moment which is (Pu-Mt) curves and primary moment are shown in Figure 6. The occurrence of nonlinearity in P–lateral displacement curve causes higher order nonlinearity in P–M plots as the P-M plot is quadratic for linear P– lateral displacement curve variation [18].

According to Figure 6, under low eccentric as well as axial compression loading levels, EBW strengthening significantly improved axial strength. In the case when the bending began to control the section's behavior or tension-dominant regime of the interaction diagram, the effectiveness of EBW strengthening decreased. In comparison, the specimens that had been strengthened with EBWGL showed a significant increase in peak strength.

ACI 440-2R 17 Code limited the confinement ratio due to excessive lateral displacement which is not desirable in stability issues. So, the EBWGL effective method to decrease the secondary effect which is represented by lateral displacement [19].

Figure 6 shows how the strengthening method influences the P-M relation and expands it compared to the reference column. moreover, columns that strengthen with the hybrid technique show high moment capacity gain over both references and only BFRP wrapping columns.

Table 3: The ultimate load capacity and mode failure of column specimens'

Group	Model ID	Ultimate load kN	Lateral displacement at Pu (ΔL) mm	Moment at Ult. Load = $Pu * (e + \Delta L)$ $(kN.mm) * 10^3$
Slenderness’ ratio = 22	C١-e3o-Go-Bp	557	10.21	22.40
	C1-e30-Gl-Bp	780	6.50	28.47
Slenderness’ ratio = 29	C2-e3o-Go-Bo	450.2	10.13	18.06
	C2-e3o-Go-Bp	524.05	18.02	25.16
	C2-e3o-Gl-Bp	612.3	13.30	26.50
Slenderness’ ratio = 35	C3-e3o-Go-Bo	287.15	13.20	12.40
	C3-e3o-Go-Bp	325	23.02	17.23
	C3-e3o-Gl-Bp	590	15.50	26.85

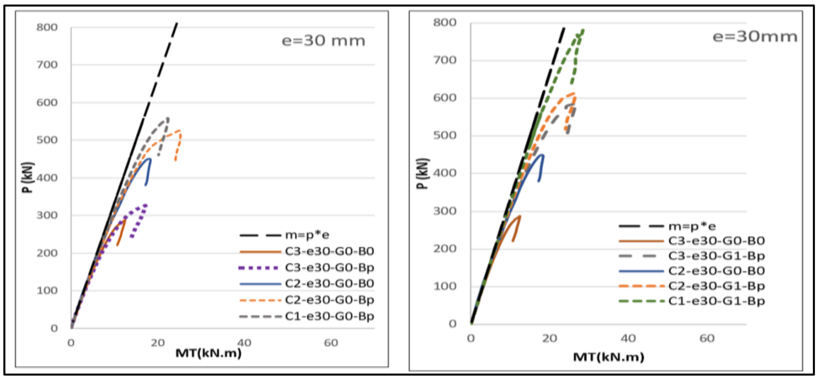


Figure 6. The load–total flexure moment which is (P-Mt) curves and primary moment for strengthening columns at eccentric 30 and 90 mm

However, using longitudinal CFRP laminate with a grooving technique (EBWGL) has interesting results with high enhancement in flexural capacity and shows development in its performance from the initial stage as well as at ultimate load until the failure stage as shown in Figure 6 due to the fact of CFRP laminate have high tensile strengthening modulus.

As it has been previously mentioned, it has been also noted that lateral deflection rises as load increases. Thus, it is possible to propose that columns strengthened using the EBWGL approach can bear a greater maximum load compared to columns strengthened using the EBW approach. Under maximum load, EBWGL ones provide a larger lateral deflection compared to EBR ones. Table 4 provides the lateral deflection values for reference columns as well as columns that are strengthened with EBWGL and EBW approaches under similar loading (reference column’s maximum loading capacity) for every ratio of slenderness to facilitate better comparisons. We can deduce that the columns strengthened using the EBWGL approach show less lateral deflection at a certain ratio of slenderness and under the same values of load. Accordingly, when put to comparison with reference and EBW columns, the EBWGL approach reduces secondary moments by increasing the column's flexural stiffness in each designated slenderness ratio (Table 4). The secondary moment regarding the EBW method-partially wrapping dropped by 34.6%, with a slenderness ratio of 29. Comparing the EBWGL approach to the reference column (C2-e3o-Go-Bo), partial wrapping fell by 63.4%. The secondary moment reduction for a 35-slenderness ratio for the columns that have been strengthened by EBWGL and EBW approach-partially wrapping has been 78.1% and 7.3%, respectively. In comparison to the reference column (C3-e3o-Go-Bo). It is noteworthy that the EBW method did not considerably reduce the secondary effect as the slenderness ratio increased. Although EBGWL has a great reducing effect that gets better as the slenderness ratio gets higher, this is consistent with the findings of [20].

Table 4: Lateral deflection and secondary moment effects under comparable loading at variables slenderness ratio

Columns	**Maximum load of non-strengthening column** **kN**	**e** **mm**	**KL_E/r**	**Lat-dis. Δ** **mm**	**Primary moment at same load) MP** **kN. m**	**Secondary Moment at Same Load Ms** **kN. m**	**Secondary moment/ Primary Moment (MS/MP)**	**Decrease in the secondary moment**
C2-e3o-Go-Bo	450	30	29	10.13	13.500	4.559	0.338	ref
C2-e3o-Go-Bp				6.62		2.981	0.221	34.6%
C2-e3o-Gl-Bp				3.71		1.667	0.124	63.4%
C3-e3o-Go-Bo	287.15	30	35	13.20	8.615	3.790	0.440	ref
C3-e3o-Go-Bp				12.24		3.514	0.408	7.3%
C3-e3o-Gl-Bp				2.89		0.831	0.096	78.1%

4. Conclusions

A total of 8 square RC columns of 120 mm width were performed in three groups (C1, C2, and C3), according to the slenderness ratio 22, 29, and 35. The strengthened columns were developed using two distinct strengthening techniques. The first is a longitudinal CFRP laminate with lateral partial BFRP wrapping (EBWGL) plus grooved bonding, and the second is a lateral partial wrapping (EBW) of the BFRP film. The column was tested with 30 mm eccentric compression.

In general, the EBWGL reinforcement technique significantly improves the. In slender columns, the effect of longitudinal CFRP laminate in carrying the load is more significant than lateral BFRP Fibers. The secondary moment regarding the EBW method -partially wrapping dropped by 34.6%, with a slenderness ratio of 29. Comparing the EBWGL approach to the reference column for the C2 group, partial wrapping fell by 63.4%. The secondary moment reduction for a 35-slenderness ratio for the columns that have been strengthened by EBWGL and EBW approach-partially wrapping has been 78.1% and 7.3%, respectively. In comparison to the reference column for group C3. It is noteworthy that the EBW method did not considerably reduce the secondary effect as the slenderness ratio increased. Although EBGWL has a great reducing effect that gets better as the slenderness ratio gets higher.

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