Structural Engineering and Mechanics, Vol. 39, No. 2 (2011) 207-221

DOI: http://dx.doi.org/10.12989/sem.2011.39.2.207

Experimental behavior of eccentrically loaded R.C. short columns strengthened using GFRP wrapping

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(Received December 1, 2010, Accepted March 23, 2011)

Abstract. This paper aims to study the behavior of short reinforced concrete columns confined with external glass Fiber Reinforced Polymers (GFRP) sheets under eccentric loads. The experimental part of the study was achieved by testing 9 specimens under eccentric compression. Three eccentricity ratios corresponding to e/t = 0, 0.10, 0.50 in one direction of the column were used. Specimens were divided into three groups. The first group was the control one without confinement. The second group was fully wrapped with GFRP laminates before loading. The third group was wrapped under loading after reaching 75% of failure loads of the control specimens. The third group was investigated in order to represent the practical case of strengthening a loaded column with FRP laminates. All specimens were loaded until failure. The results show that GFRP laminates enhances both failure load and ductility response of eccentrically loaded column. Moreover, the study also illustrates the effect of confinement on the first crack load, lateral deformation, strain in reinforcement and failure pattern. Based on the analysis of the experimental results, a simple model has been proposed to predict the improvement of load carrying capacity under different eccentricity ratios. The predicted equation takes into consideration the eccentricity to cross section depth ratio, the ultimate strength of GFRP, the thickness of wrapping laminate, and the time of wrapping (before loading and under loading). A good correlation was obtained between experimental and analytical results.

Keywords: confinement; columns; eccentricity; glass fiber reinforced polymer (GFRP); wrap; strengthening

1. Introduction

The application of circumferential wrapping (FRP) as a new technique for external confinement and strengthening of reinforced concrete columns have been widely used in recent years. Such technique is relatively easy to apply in comparison to conventional methods. These composite wraps are thin, light, flexible, non-corrosive, and can be easily applied to structures with any shapes using suitable epoxies. Glass fibers are one of the most commonly used types of fibers. They are available and economically cheaper than carbon fibers. Glass fibers are electrically and magnetically neutral.

Several research studies (Lau 2001, Toutanji 2002, Chaallal 2003, El-Darwish 2005, El-Ghandour 2005), have been recently addressed to study the improvement of load carrying capacity of columns confined with external Fiber Reinforced Polymers (FRP) sheets. Ghith *et al.* (2002) tested a total of

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9 reinforced concrete columns. These columns were strengthened by adding an external confinement to the column sections by the use of continuous wrapping of GFRP. The wrapping was made as continuous stirrups around the perimeter of the column with different spacing. Two types of gluing epoxy were used for adhesion. All columns were tested under axial load. The study concluded that, strengthening reinforced concrete columns using continuous GFRP increases the ultimate capacity by 72% of the base column. Using wrapping for all columns with the same cross sectional area gave ultimate load 30% higher than concentration of the wrapping with spacing 5.0 cm. Using moderate types of adhesive epoxies increase the ultimate load than the use of strong adhesive epoxies.

Hodhod *et al.* (2005) study an experimental investigation into the behavior of high strength concrete square short columns subjected to biaxial eccentricity (e/t = 0.125) and strengthened by GFRP laminates. The study has experimentally proved the efficiency of FRP laminates, as a strengthening alternative, in enhancing the strength of biaxial loaded short square HSC columns. Partial wrapping with single layer of GFRP laminates is more efficient to enhance load and flexural capacities compared with double layer GFRP, as their strength enhancement ratios were 26% and 18%, respectively. In fully wrapped specimens with two FRP layers, the strength of column increases up to 28% over unwrapped specimen. Thus, strength enhancement is proportional to the number of FRP layers in fully wrapped specimens, while it is inversely proportional to the number of FRP layers in partially wrapped specimens. The study also concluded that, it is recommended to use partially applied single layered FRP laminates to obtain a significant strength gain of 26% rather than using double layered fully applied FRP laminates which achieved only 2% strength gain higher than the former arrangement. From the ductility point of view, increasing number of transverse layers reduces ductility enhancement ratio in partially wrapped specimens. On the other hand, it increases ductility enhancement ratio in fully wrapped specimens. Full wrapping with two layers is the most efficient method to enhance column ductility.

Kumutha *et al.* (2007) carried out an experimental work to evaluate the effectiveness of external wrapping of concrete columns with GFRP composite. Based on results, it was concluded that the external confinement can significantly increase the strength of the specimen under axial loading. The number of layers of FRP materials and the corner radius are the major parameters, having a significant influence on the behavior of specimens. A larger radius can expand the strong constraint zone and diminish the stress concentration. The results of experimental test showed that GFRP materials can produce a good lateral confinement pressure to column specimens. Then it can be used for strengthening or repairing structures.

Benzaid *et al.* (2008) carried out a comprehensive experimental investigation on the behavior of axially loaded columns strengthened with GFRP. The objective of the study was to evaluate the effectiveness of external GFRP strengthening for rectangular columns. It also aimed to evaluate the effect of number of layers on the ultimate load and ductility of confined concrete and the effect of aspect ratio of the columns on the effectively confined cross section. For columns having aspect ratio of 1.00, the enhancement in axial load was about 4.05% and 16.22% for one and two layers of GFRP, respectively. For aspect ratio of 1.25, the enhancement in axial load was about 2.93% and 22.67% for one and two layers of GFRP, respectively. In case of columns with an aspect ratio of 1.66, ultimate load increased by about 2.57% and 22.67% for one and two layers of GFRP, respectively.

Even though a lot of research has been directed towards axially loaded columns, relatively less work has been performed on eccentrically loaded columns to examine the effect of external confinement on their structural performance. In reality, columns are almost strengthened under loading; however, the majority of studies examined the effect of strengthening before loading. Therefore, this paper is directed towards investigating the effect of these two major parameters on the behavior of strengthened columns.

2. Testing program

This section describes the experimental work performed through this study beginning with the used materials, specimen's details, measurement devices, test setup, and specimen's grouping.

2.1 Materials used

Ordinary locally available concrete constituent materials have been used to manufacture the test specimens. All specimens are made from one concrete mix with the proportion shown in Table 1. The target standard 28-days compressive cube strength f_{cu} = 25 MPa, and according to the EN the equivalent compressive cylinder strength, f_c' = 20 MPa. The results of testing cubes have satisfied the target strength.

The specimen's main reinforcement (longitudinal) is high grade deformed steel bars with 360 MPa nominal yield stress while the lateral reinforcement (stirrups) is mild smooth bars with 240 MPa nominal yield stress. Wrapping material is "SikaWrap®-430 G" which is a woven Glass fabric of 0.172 mm fiber thickness, 2300 MPa fiber tensile strength, and 76000 MPa fiber tensile modulus of elasticity. The ultimate tensile strength of the GFRP laminate is 270 MPa and the tensile E-modulus is 19000 MPa.

2.2 Specimens details

All tested columns have a square cross section of 150 × 150 mm, 1100 mm clear height and 1500 mm total height including two corbels head supporting the eccentric load. The column heads are designed to prevent premature failure. The details of typical specimen are shown in Fig. 1. The longitudinal reinforcement consisted of four steel bars of 10 mm nominal diameter. The stirrups of columns comprised 8 mm nominal diameter and were spaced 190 mm. To avoid premature failure, stirrups were concentrated in the columns head region (spaced at 80 mm). To attain most benefit from the strengthening layers, the column corners were cast round instead of sharp edged to reduce stress concentration to the minimum possible. The test specimens were cast and cured for 28 days before applying the GFRP layers.

GFRP laminates were wrapped in the transverse direction of the columns in continuous manner acting as a lateral confinement for the column. Wrapping was performed through the entire length of the column excluded the heads. A splice of 100 mm in the two directions and laminate thickness of 1mm were used. Fig. 2 shows test specimens during and after strengthening with GFRP layer.

Table 1 Mix design proportion (Average Strength = 25 MPa)

Material	Dolomite	Sand	Cement	Water
Mix Proportion (kg/m^3)	1305	615	350	175

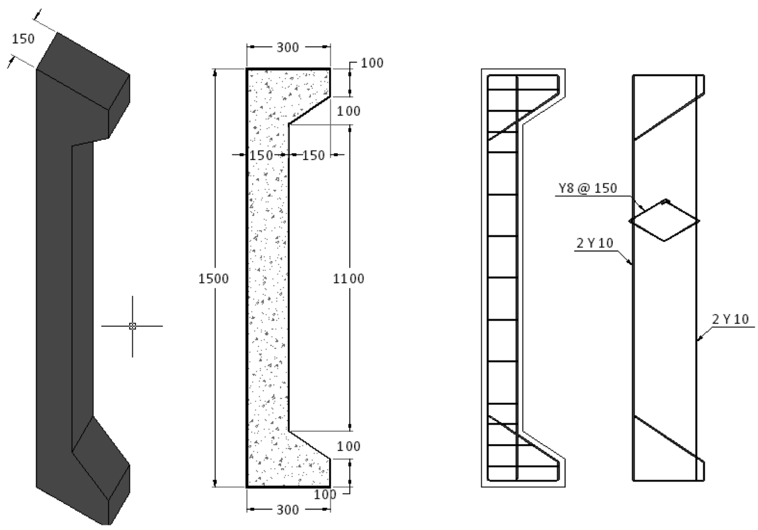


Fig. 1 Details of typical specimen

(a) During wrapping (b) After wrapping

Fig. 2 Test specimens during and after strengthening with GFRP

2.3 Specimens measuring devices

Two dial gauges with accuracy of 0.01 mm were used to measure the axial deformation and lateral deflection at mid height. The axial deformation was measured at the center line of specimen between two points with 1100 mm spacing. Electrical strain gauges with 10 mm length, 119.8 ± 0.2 ohms resistance, and gauge factor $2.11 \pm 1\%$ were used to measure the longitudinal strain of steel rebar at mid height of specimen. The measured strain was on the rebar at the side of column section that may subject to tensile strain during loading with eccentric load. The strain gauges were connected to a strain meter device with accuracy of 1×10^{-6}, and covered by a waterproof coating to protect them from water and damage during casting. At every stage of loading, cracks were observed and marked, if any. In addition, the strains are recorded automatically using a data acquisition system.

Fig. 3 Typical test setup for specimens

2.4 Test setup

The specimens were tested up to failure using the testing frame shown in Fig. 3. A load cell of 1000 kN capacity is used which is connected to a digital display unit. Applying the required eccentricity to the specimen was achieved by fixing a metallic strip of 150 mm long and 20 mm width on the loading frame on the same line of the vertical axis of load cell. The specimen was placed between two of these special bearing plates, and the specimen was moved freely to achieve the required eccentricity.

2.5 Specimen's grouping

Three groups of columns were tested. Group A consists of three specimens GA-S1, GA-S2, and GA-S3. The specimens were tested without strengthening under three different eccentricity ratios (*e/t*) of 0, 0.1, 0.5, respectively. Group B consists of three specimens GB-S1, GB-S2, and GB-S3 confined with continuous overlapped GFRP sheets. Each sheet of 600 mm width and 700 mm

Table 2 General description of test specimens grouping

Group	Specimen	Eccentricity ratio (*e/t*)	Wrapping condition	Remarks
Group (A)	GA-S1	0	without	Control specimen
	GA-S2	0.1	without	Control specimen
	GA-S3	0.5	without	Control specimen
Group (B)	GB-S1	0	(Full)	Wrapping before loading
	GB-S2	0.1	(Full)	Wrapping before loading
	GB-S3	0.5	(Full)	Wrapping before loading
Group (C)	GC-S1	0	(Full)	Wrapping under loading (at 75% of GA-S1 load)
	GC-S2	0.1	(Full)	Wrapping under loading (at 75% of GA-S2 load)
	GC-S3	0.5	(Full)	Wrapping under loading (at 75% of GA-S3 load)

length to provide over lap of 100 mm in each direction. The specimens were then tested under the three previously mentioned eccentricity ratios up to failure. Group C consists of three specimens GC-S1, GC-S2, and GC-S3. The specimens were loaded up to 75% of the failure load recorded by specimen with the same eccentricity ratio in group A, and kept constant for 36 hour to allow for confinement under loading. Then resuming loading up to failure. Table 2 summarizes the general description of the test specimens.

3. Experimental test results

This section describes the experimental test results and discussion concerning ultimate loads, axial deformation, lateral deformation at mid height, strain in steel rebar, and failure patterns.

3.1 Ultimate load

The maximum experimental values obtained from all the tests are summarized in Table 3. Comparing the ultimate load values, it is clearly shown that ultimate load of the wrapped specimens is higher than those of the control specimens. For axially loaded specimens, the increases in the ultimate load were about 16% and 30% in both under and before loading wrapped specimens respectively. For specimens with eccentricity ratio of 0.1, the increases in the ultimate load were about 15% and 26% in both under and before loading wrapped specimens respectively. For specimens with eccentricity ratio of 0.5, the increases in the ultimate load were about 10% and 20% in both under and before loading wrapped specimens respectively. Based on the above percentages, it could be seen that the enhancement in the ultimate loads of the wrapped specimens under loading were approximately about 50% of those of specimens wrapped before loading. It could be also observed that the percentage of increase in the ultimate load is inversely proportion to the eccentricity ratio. Fig. 4 shows the effect of the confinement on the ultimate load carrying capacity of the tested specimens.

Table 3 Summary of test results

Group	Specimen	First Crack load in kN	Ultimate load in kN	P_{cr}/P_u	Axial shortening (mm.)	Lateral deflection (mm.)	Strain in Rft. (microstrain)
Group (A)	GA-S1	300	440	0.682	1.85	-	-850
	GA-S2	200	348	0.575	1.45	1.05	-508
	GA-S3	150	200	0.75	1.6	2.70	+125
Group (B)	GB-S1	400	571	0.70	2.1	-	-1100
	GB-S2	320	440	0.723	1.7	1.3	-640
	GB-S3	200	240	0.833	1.65	3.00	+155
Group (C)	GC-S1	310	512	0.605	2.1	-	-1000
	GC-S2	220	400	0.55	1.6	1.2	-565
	GC-S3	160	220	0.727	1.6	3.00	+155

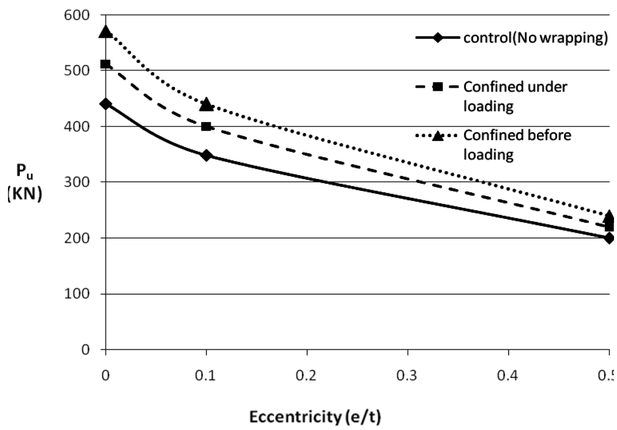


Fig. 4 Effect of confinement on ultimate load

3.2 Axial deformation

Fig. 5 shows the effect of confinement with GFRP on the axial shortening of the tested specimens. The figure shows that the axial shortening values of the wrapped specimens are always higher than those of the control specimens. This increase in axial shortening reflects the improvement of specimen's ductility before failure. For wrapped axially loaded specimens, the axial shortening increased by as much as 13.6% for both specimens wrapped before and under loading compared to that of the control specimen. For eccentrically loaded specimens with *e/t* equal 0.10, the axial shortening increases range from 10.3% to 17% for both specimens wrapped under and before loading respectively compared to that of the control specimens. For eccentrically loaded specimens with *e/t* equal 0.50, the axial shortening increased by as much as 3% for specimens wrapped before loading and no increase was observed for that wrapped under loading. These small ratio of increases for specimens with *e/t* equal 0.5 indicate the insignificant effect of wrapping on the ductility of specimens with high eccentricity ratios compared with those having small eccentricity and also show the independency on the time of wrapping compared with those having low eccentricity.

3.3 Lateral deflection

Comparing the lateral deflections values listed in Table 3, it is clearly shown that the confinement with GFRP wrapping increases the lateral deflection for eccentrically loaded specimens. For specimens with *e/t* equal 0.1, the recorded lateral deflections of the strengthened specimens under and before loading were higher than that of the control specimen by about 14.3% and 23.8%, respectively. This noticeable variation in percentages indicates that the time of wrapping is a significant factor for increasing the lateral deflection before failure and consequently ductility of specimens with low eccentricity before failure. For specimens with *e/t* equal 0.5 the recorded lateral deflections were higher than that of the control specimen by about 11% for both specimens. This indicates that the increase in lateral deflection for specimens with *e/t* = 0.5 is independent on the time of wrapping.

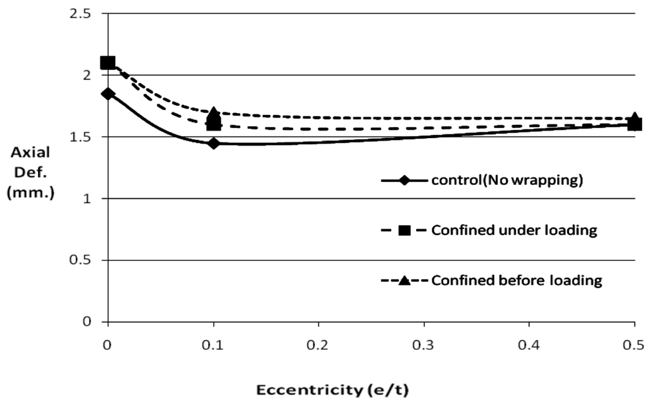


Fig. 5 Effect of confinement on ductility

3.4 Strain in steel bars

Fig. 6 shows the effect of the confinement with GFRP on the axial strain measured in steel bars of the tested specimens. From the figure it is evident that the confinement with GFRP improved the axial stain in steel rebar before failure especially for axially loaded specimens and specimens with low eccentric ratio (e/t = 0.1). For wrapped axially loaded specimens the increases in the axial compressive strain range were about 17.6% and 29% in both under and before loading wrapped specimens respectively. It was noticed that the percentage of increases are almost the same as those for ultimate load increases. For specimens with eccentricity ratio of 0.1, the increases in the axial compressive strain in steel rebar range from 11.2% to 26% in both under and before loading wrapped specimens respectively. The percentages of increases are also almost the same as those for ultimate load increases. For specimens with eccentricity ratio of 0.5, the increases in the axial tensile strain in steel bars are the same as 24% in both under and before loading wrapped specimens respectively.

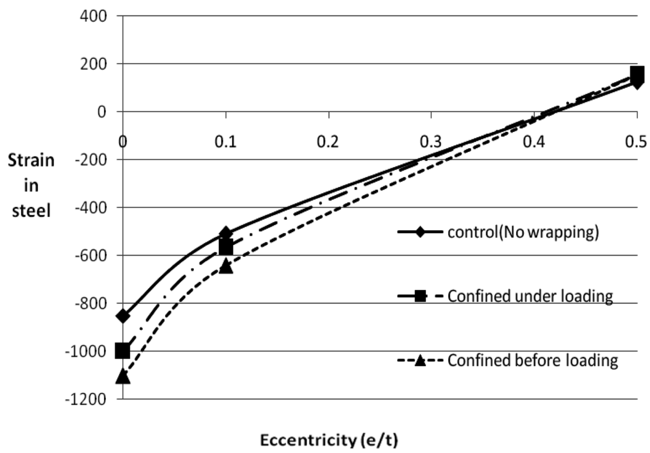
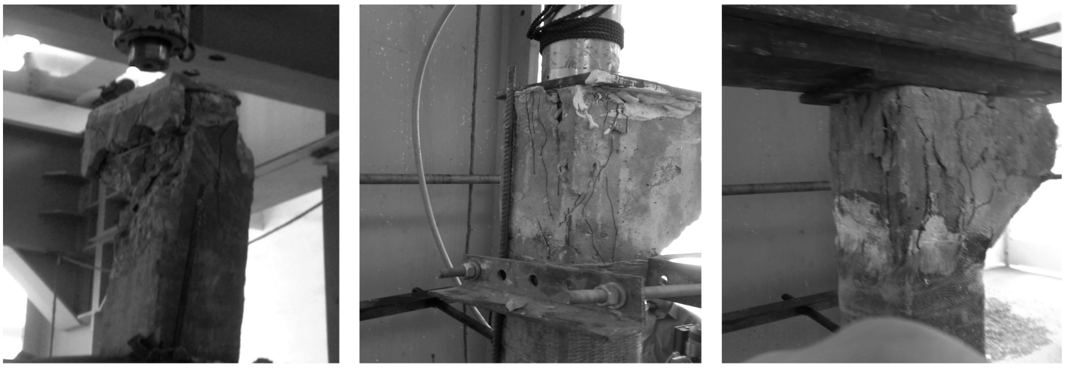


Fig. 6 Effect of confinement on strain in steel bars (microstrain)

3.5 Failure patterns

For axially loaded specimens, the failure was associated with concrete crushing near the column ends and outside wrapping for wrapped specimens as shown in Fig. 7. This may attributed to the



(a) Failure of GA-S1 (b) Failure of GB-S1 (c) Failure of GC-S1

Fig. 7 Failure patterns of axially loaded columns

(a) Failure of GA-S2 (b) Failure of GB-S2 (c) Failure of GC-S2

Fig. 8 Failure patterns of columns with e/t = 0.10

(a) Failure of GA-S3 (b) Failure of GB-S3 (c) Failure of GC-S3

Fig. 9 Failure patterns of columns with e/t = 0.50

high concentration of stresses near the column head. It may be also attributed to the rounded edges of the strengthened columns in the wrapped part which help to prevent stress concentration in this part and avoid rupture in GFRP laminate. For specimens with *e/t* equal 0.10, the failure patterns are crushing at lower head for control specimen, crushing at upper head outside wrapping for wrapped specimen before loading, and crushing at lower head outside wrapping for wrapped specimen under loading as shown in Fig. 8. For specimens with *e/t* equal 0.50, the failure patterns are tension cracks at upper and lower third associated with crushing in concrete for control specimen. Rupture in GFRP sheets followed by concrete crushing at mid height of column for wrapped specimen before loading, and rupture in GFRP sheets followed by concrete crushing under column head for wrapped specimen under loading as shown in Fig. 9.

4. Predicted analytical model

A simple analytical confinement model is proposed to predict the ultimate load of GFRP strengthened square reinforced concrete columns subjected to eccentric loads. To achieve that, it is necessary to evaluate the confined concrete strength. Most of the existing strength models for FRP-confined concrete adopted the concept of Richart *et al.* (1929), in which the strength at failure for concrete confined by hydrostatic fluid pressure takes the following form

$$f'_{cc} = f'_{co} + k_1 f'_1 \tag{1}$$

Where f'_{cc} and f'_{co} are the compressive strength of confined and the unconfined concrete respectively, f'_1 is the lateral confining pressure and k_1 is the confinement effectiveness coefficient. In applying their model to steel-confined concrete, Richart *et al.* (1929) assumed that k_1 is a constant equal 4.1.

The lateral confining pressure of circular columns f_1 is uniformly distributed and can be directly related to the amount and strength of FRP according to the following equation

$$f_1 = \left(\frac{\rho_{frp}}{2}\right) f_{frp} = \left(\frac{2t_{frp}}{D}\right) f_{frp} \tag{2}$$

where ρ_{frp} is the volumetric ratio of FRP, f_{frp} is the tensile strength of FRP laminate, t_{frp} is the thickness of FRP laminate, and D is the diameter of the concrete core. Based on Eq. (2), the lateral confining pressure f'_1 can be defined as

$$f'_1 = k_s f_1 \tag{3}$$

Where k_s is the shape factor accounting for the effect of section shape and f_1 is the lateral confining pressure in an equivalent circular column. The equivalent circular column is defined here as one with the same FRP volumetric ratio as the rectangular column. Thus, the lateral confining pressure provided by FRP in the equivalent circular column can be evaluated using Eq. (2) with the FRP volumetric ratio in rectangular column as follows

$$\rho_{frp} = \frac{2(b+t)t_{frp}}{bt} \tag{4}$$

where b and t are breadth and thickness of the rectangular column section, respectively. Thus, Eq. (1) can be rewritten as follows for square columns with edge length b.

$$f'_{cc} = f'_{co} + k_1 k_s f_1, \text{ and } f_1 = \left(\frac{2t_{frp}}{b}\right) f_{frp} \tag{5}$$

Having determined the confined compressive strength of FRP confined concrete f'_{cc} and after setting the strength reduction factors to unity, the ultimate load carrying capacity of strengthened axially loaded column can be determined from

$$P_u = 0.85 f'_{cc} A_c + f_y A_s \tag{6}$$

Where A_c is the gross area of the concrete section and A_s is the total area of reinforcement. Using the test results of strengthened axially loaded column before loading (GB-S1), the value of $k_1 k_s$ was found to be 1.10

The effect of eccentricity and the time of wrapping should be also simulated in Eq. (5). The first coefficient k_e will represent the effect of the eccentricity ratio (e/t), while the coefficient k_t will represent the time of wrapping effect on the confined compressive strength. From the regression analysis of the test results, the value of k_e multiplied by k_t was found to be as follows

$$k_e k_t = 1.185(e/t)^2 - 1.2485(e/t) + 1 \quad \text{for wrapped columns before loading.} \tag{7}$$

$$k_e k_t = 0.044(e/t)^2 - 0.2112(e/t) + 0.242 \quad \text{for wrapped columns under loading.} \tag{8}$$

Thus, the final form of Eq. (5) becomes as follows

$$f'_{cc} = f'_{co} + k_1 k_s k_e k_t f_1 \tag{9}$$

In order to calculate the ultimate load carrying capacity of the confined columns under different eccentric loading ratios using the predicted equation, sectional stress and strain distributions specified in ACI 318-M05 and shown in Fig. 10 were used. Compressive concrete stress was modeled by a modified rectangular stress block. The confined compressive strength of concrete f'_{cc} calculated from Eq. (9) was used to model GFRP strengthened sections. An elastic perfectly plastic stress-strain relationship was used to model the tension steel using the test values (f_y = 360 MPa and, ε_y = 0.002). Considering strain compatibility, and force equilibrium, the ultimate load carrying capacity of the eccentric loaded columns were calculated in two cases in addition to the pure axial compression case as shown in Fig. 10. The first one is the compression failure state where the neutral axis of the section is just at the tension steel. The second is the balanced failure state. An "Excel" spreadsheet was adopted to calculate the ultimate load carrying capacity for the three cases as follows:

Case (1): Pure axial compression

a) Calculate the ultimate load carrying capacity using Eq. (6).

Case (2) : Compression Failure

a) Assume neutral axis at the C.G of tension steel

b) From strain distribution, calculate the strain of the compression steel ε_s'.

c) Using ε_s' Calculate the compressive stress in the tension steel f_s'.

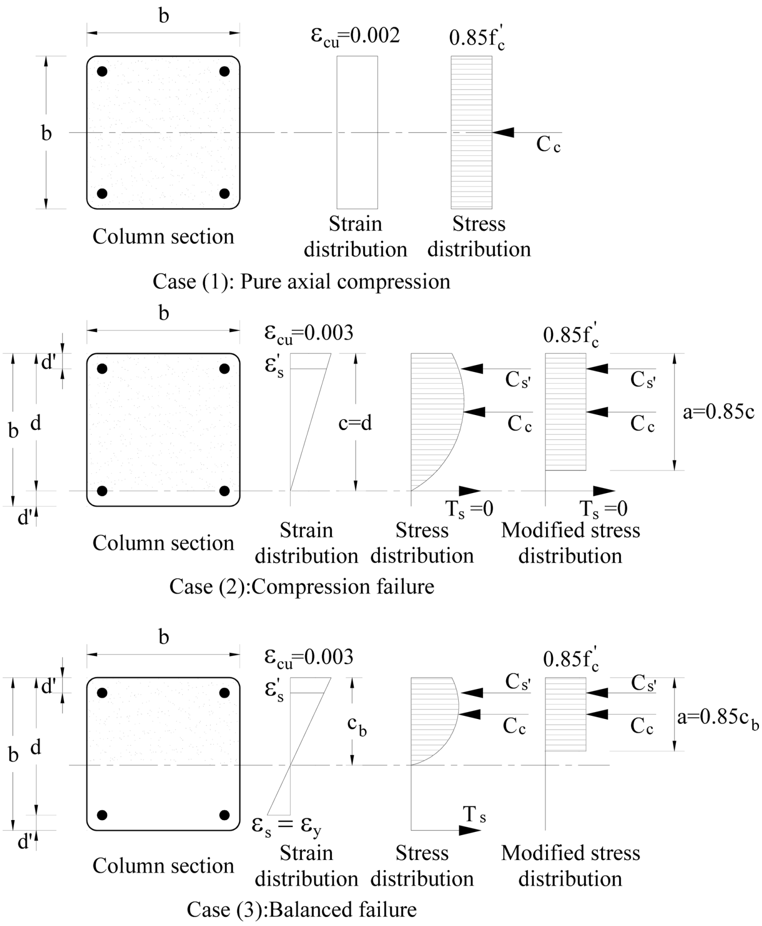


Fig. 10 Stress and strain distributions of strengthened square column section using GFRP at different cases of eccentric loading

d) Determine the internal compression forces of both concrete and compression steel respectively (C_C and C'_S)

e) Using section equilibrium, calculate the ultimate load carrying capacity of the section as follows

$$P_u = C_C + C'_S \tag{10}$$

f) Using section equilibrium, determine the ultimate moment of the section (M_u) from

$$M_u = C_C(b/2 - 0.5a) + C_S(b/2 - d') \tag{11}$$

where a is the height of the equivalent rectangular stress block and d' is the cover of compression steel.

g) Calculate the eccentricity ratio, and then calculate the *e/b* ratio for the square column.

$$e = \frac{M_U}{P_U} \tag{12}$$

Case (3) : Balanced Failure

a) From strain distribution, calculate the balanced neutral axis depth c_b.

b) From strain distribution, calculate the strain of the compression steel ε_s'.

c) Using ε_s' Calculate the compressive stress in the tension steel f_s'.

d) Determine the internal compression forces of both concrete and compression steel respectively (C_C and C_S')

e) Determine the internal tension force of the compression steel (T_S).

f) Using section equilibrium, calculate the ultimate load carrying capacity of the section by

$$P_u = C_C + C_S' - T_S \tag{13}$$

g) Using section equilibrium, calculate the ultimate moment of the section (M_u) from

$$M_u = C_C(b/2 - 0.5a) + C_S(b/2 - d') + T_S(b/2 - d') \tag{14}$$

h) Calculate the eccentricity ratio using Eq. (12), and then calculate the *e/t* ratio.

Exponential regression analysis has been made using the predicted results from the three cases specified above for the two confinement cases (before and under loading). This was in order to predict the two equations whose are valid to obtain the ultimate load carrying capacity of eccentrically loaded confined columns in both before and under loading cases. Fig. 11 shows the predicted relationship for the two confinement cases together with the experimental results. Table 4 shows comparisons between the predicted, $P_{u(pred.)}$, and experimental $P_{u(\exp.)}$, capacities.

As can be seen from Table 4, a good correlation was obtained between the experimental results and those got from the theoretical model. The maximum error was found to be 3% for strengthened columns with *e/t* equal 0 and 0.1 respectively. The underestimated prediction for the strengthened columns with *e/t* = 0.5 reflects ACI 318-M05 underestimation of the load carrying capacity of the control specimen with *e/t* = 0.50. The predicted value of the control specimen with *e/t* = 0.5 using ACI 318-M05 was underestimated by 8.8%.

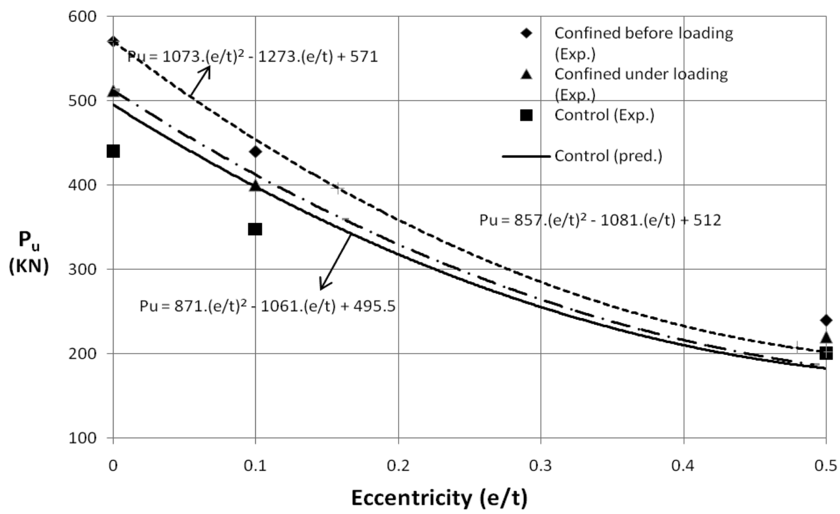


Fig. 11 Experimental and predicted analytical capacities of eccentrically loaded specimens

Table 4 Comparison of experimental and predicted results

Group	Specimen	Experimental Results		Predicted results				$\frac{P_{u(theo)}}{P_{u(\exp.)}}$
		Ultimate load in kN	$\frac{P_{confined}}{P_{control}}$	f'_{cc}	f'_{cc}/f'_c	Ultimate load in kN	$\frac{P_{confined}}{P_{control}}$	
Group (B)	GB-S1	571	1.298	239.24	1.196	571	1.152	1.00
	GB-S2	440	1.264	232.45	1.162	454.4	1.142	1.03
	GB-S3	240	1.20	226.37	1.132	202.63	1.11	0.844
Group (C)	GC-S1	512	1.164	208.72	1.044	512	1.033	1.00
	GC-S2	400	1.149	207.52	1.0376	412.45	1.036	1.03
	GC-S3	220	1.10	205.26	1.026	185.66	1.018	0.844

5. Conclusions

The research conducted showed that the GFRP is efficient in enhancing the ultimate load carrying capacity in addition to the improvement of the ductility of short columns subjected to eccentric loads. The confinement technique improves the concrete compressive strength and consequently the ultimate load carrying capacity. Better confinement was achieved when the columns are confined before loading rather than under loading. Confined columns with low eccentricity gain better enhancement in load carrying capacity and ductility compared with those with high eccentricity ratio. Specific conclusions are as follows:

1. For axially loaded columns, the enhancement in ultimate load was about 16% and 30% in both under and before loading wrapped specimens. The axial shortening increased by as much as 13.6% for both specimens wrapped under and before loading compared to that of the control specimen. The enhancement in the axial compressive strains measured in steel bars were 17.6% and 29% in both under and before loading wrapped columns respectively.
2. For specimens with eccentricity ratio of 0.1, the increases in the ultimate load were about 15% and 26% in both under and before loading wrapped specimens respectively. The axial shortening increases by 10.3% and 17% for both specimens wrapped under and before loading respectively compared to that of the control specimens. The recorded lateral deflections of the strengthened specimens under and before loading were higher than that of the control specimen by about 14.3% and 23.8%, respectively. The increases in the axial compressive strain in steel rebar were about 11.2% and 26% in both under and before loading wrapped specimens respectively.
3. For specimens with eccentricity ratio of 0.5, the increases in the ultimate load were about 10% and 20% in both under and before loading wrapped specimens respectively. The axial shortening increased by as much as 3% for specimens wrapped before loading and no increase was observed for that wrapped under loading. The recorded lateral deflections were higher than that of the control specimen by about 11% for both specimens. The increases in the axial tensile strain in steel rebar are the same as 24% in both under and before loading wrapped specimens respectively. This indicates that the increase in axial shortening, lateral deflection, and strain in steel for specimens with e/t = 0.5 is independent on the time of wrapping.
4. For axially loaded columns, the failure was associated with concrete crushing near the column ends outside of wrapping for wrapped columns. This may be attributed to the high stress concentration near column ends, and the rounded edges of the wrapped part of columns which

help to reduce stress concentration in the corners of the wrapped part and consequently help to prevent premature rupture in the wrapping laminate. For specimens with e/t = 0.10, the failure patterns are crushing at lower head for control specimen and crushing at upper head outside wrapping for wrapped specimen before loading, and crushing at lower head outside wrapping for wrapped specimen under loading. For specimens with e/t = 0.50, the failure patterns are tension cracks at upper and lower third associated with crushing in concrete for control specimen. Rupture in GFRP sheets followed by concrete crushing at mid height of column for wrapped specimen before loading, and rupture in GFRP sheets followed by concrete crushing under column head for wrapped specimen under loading.

5. Based on the analysis of the experimental results, a simple analytical model has been proposed for the prediction of the ultimate load carrying capacity of GFRP confined columns. A good correlation was obtained between experimental and analytical results.

The above findings are specific for the three eccentricity ratios and the two cases of confinement before loading and after reaching 75% of the ultimate load of the control specimens. General findings could be established by conducting future experiments with different eccentricity ratios and wrapping at different stages of loading.

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