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Experimental behavior of eccentrically loaded RC slender columns strengthened using GFRP wrapping

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Abstract. This paper aims to examine the behavior of slender reinforced concrete columns confined with external glass fiber reinforced polymers (GFRP) sheets under eccentric loads. The experimental work conducted in this paper is an extension to previous work by the author concerning the behavior of eccentrically loaded short columns strengthened with GFRP wrapping. In this study, nine reinforced concrete columns divided into three groups were casted and tested. Three eccentricity ratios corresponding to e/t = 0, 0.10, and 0.50 in one direction of the column were tested in each group. The first group was the control one without confinement with slenderness ratio equal 20. The second group was the same as the first group but fully wrapped with one layer of GFRP laminates. The third group was also fully wrapped with one layer of GFRP laminates but having slenderness ratio equal 15. The experimental results of another two groups from the previous work were used in this study to investigate the difference between short and slender columns. The first was control one with slenderness ratio equal 10 and the second was fully wrapped and having the same slenderness ratio. All specimens were loaded until failure. The ultimate load, axial deformation, strain in steel bars, and failure mechanisms of each specimen were generated and analyzed. The results show that GFRP laminates confining system is less effective with slender columns compared with short one, but this solution is still applied and it can be efficiently utilized especially for slender columns with low eccentric ratio.

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

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 and Zhou 2001, Toutanji and Deng 2002, Chaallal *et al*. 2003,

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El-Darwish *et al*. 2005, El-Ghandour *et al*. 2005), have been recently addressed to study the improvement of load carrying capacity of columns confined with external Fiber Reinforced Polymers (FRP) sheets. Ghith and Anwar (2002) tested a total of 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.

Twenty three reinforced concrete columns were tested by Qiaoling and Hongtao (2004) under eccentric loads, the strength, ductility, and failure modes of the columns with and without CFRP bonding are compared and analyzed. Experimental results indicated that when bounded only with longitudinal CFRP, the strength of the columns increased but the ductility of the columns decreased slightly. When strengthened with transverse CFRP, the ductility of the columns improved significantly, and the ultimate strength increased as well. When strengthened by the combined action of the longitudinal and the transverse straps of CFRP, most significant improvement in the strength and the ductility of the columns resulted. On the basis of the experiment, the method of calculating the ultimate strength of eccentrically-loaded columns reinforced by longitudinal CFRP was presented, the calculated results fit well with the experimental data.

Hodhod *et al*. (2005) studied 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 was shown to be 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.

Zhong *et al*. (2005) carried out an experimental work to study the behavior of FRP confined square RC long columns under eccentric loading. A total of eight specimens with slenderness ratio of 20.4 were tested. These eight columns included four unstrengthened columns, and four columns strengthened by FRP jackets. The main parameter varied in the tests was the load eccentricity. The experimental results demonstrated that the strength cannot be enhanced effectively, but the ductility can be improved to some extent, especially for specimens with small eccentricities. If there is a need to enhance both strength and ductility of square RC long column, it was recommended that bi-directional FRP sheets be used, or some other effective measures be taken.

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.

Turgay *et al*. (2010) carried out an experimental program to investigate the behavior of concentrically loaded large-scale slender rectangular columns wrapped with CFRP. Twenty reinforced normal strength concrete columns were tested. Each column had a square cross- section with side length of 200 mm, and a length of 1000 mm. in length. All columns were unwrapped, partially wrapped or fully wrapped. Results shows that, all fully wrapped columns fractured at top or bottom while partially wrapped columns failed at the end of the confined regions. For slender columns, FRP increased the ductility but did not significantly increase the ultimate load.

Sadeghian *et al*. (2010) studied the behavior of large-scale rectangular reinforced concrete columns wrapped with CFRP of different fibre layout under eccentric loading. Seven large-scale reinforced columns with 200 mm. in width, 300 mm. in height and an overall length of 2700 mm. were casted. The columns were wrapped with two, three, or five layers of CFRP with fiber orientations of 0 degree, 45 degrees, or 90 degrees. The eccentricities incorporated were 200 mm. or 300 mm. Results showed that, for large-scale columns strengthened with CFRP; there is a similar bilinear load-deflection curve as unstrengthened columns. Angle orientation showed little influences to the behavior of the columns. Notably, when the columns fail in tension-controlled failure, the transverse layer does not make significant improvement on the confinement of the compression section.

Elwan and Rashed (2011) conducted a research to examine the behavior of short reinforced concrete columns confined with external 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 while the second group was fully wrapped with GFRP laminates before loading, and the third group was wrapped under loading after reaching 75% of failure loads of the control specimens. 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. For axially loaded columns, the enhancement in ultimate load was about 16% and 30% in both under and before loading wrapped specimens. 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 analysis of the experimental results, a simple model has been proposed to predict the improvement of load carrying capacity under different eccentricity ratios. The proposed 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).

Most of the undertaken studies in the past were concentrated on studying FRP confined RC short columns subjected to uniaxial loading. However, in practice, columns usually undergo combined axial loading and bending moment. Also, additional moment due to column slenderness was considered to some extent. Even though a lot of research has been directed towards axially loaded short columns, relatively less work has been performed on eccentrically loaded slender columns to examine the effect of external confinement on their structural performance. Therefore, this paper is directed towards investigating the effect of GFRP wrapping on the behavior of slender columns subjected to eccentric compression.

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.

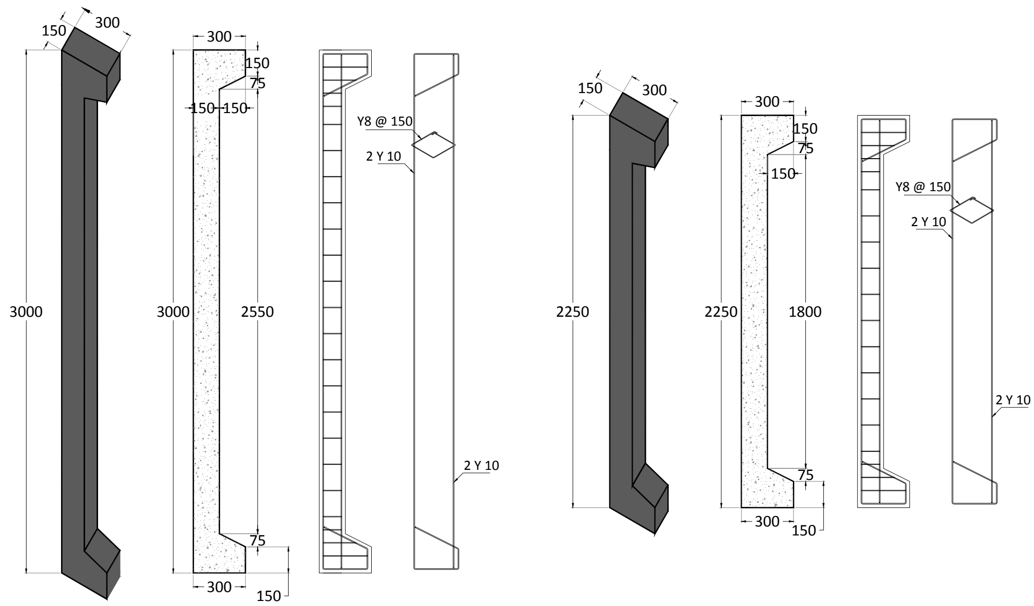
The specimen's main reinforcement (longitudinal) is high grade deformed steel bars with 360 MPa nominal yield stress while the lateral reinforcement (stirrups) is mild smooth bars with 240 MPa nominal yield stress. Wrapping material is "SikaWrap®-430 G" which is a woven Glass fabric of 0.172 mm fiber thickness, 2300 MPa fiber tensile strength, and 76000 MPa fiber tensile modulus of elasticity. Tests were done for 6-strips (40cm length, 4.0 cm width and 0.1cm laminate thickness) of the laminate, The load and its equivalent displacement between two remarkable points are recorded till failure. The ultimate tensile strength of the GFRP laminate is 270 MPa and the tensile E-modulus is 19000 MPa. Tests were done for 3-strips (40cm length and 4.00 cm width) with overlap splice lenght of 8, 10 and 12 cm respectively. The splice of 10 cm. overlap splice was perfect and no pull-out were recorded during test.

2.2 Specimens details

All tested columns have a square cross section of 150 × 150 mm. The first two groups (A & B)

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

Material	Dolomite	Sand	Cement	Water
Mix proportion (Kg/m^3)	1280	640	350	175



(a) Typical specimens (A&B) (b) Typical specimen (C)

Fig. 1 Details of typical specimen

have 2250 mm clear height and 3000 mm total height including two corbels head supporting the eccentric load, while group C have 1800 mm clear height and 2250 mm total height. The column heads are designed to prevent premature failure. The details of typical specimens 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 1 mm were used. Fig. 2 shows test specimens during and after strengthening with GFRP layer.

2.3 Measuring devices

Two dial gauges with accuracy of 0.01 mm were used to measure the axial deformation and lateral deflection. The axial deformation was measured at the lower end of the specimen. The steel rod was fixed at the upper end of the specimen and the other end has leg on the dial gauge to obtain total axial deformation of columns. To record lateral deflection of column, another dial gauge was used at the mid height of the column.

Before casting the specimens, electrical strain gauges with 10 mm length, 119.8 ± 0.2 ohms resistance, and gauge factor 2.11 ± 1% were used to measure the longitudinal strain of steel rebar

(a) During preparation (b) Testing frame

Fig. 2 Test specimens during preparation and testing frame

Fig. 3 Typical test setup for specimens

at mid height of specimen. The measured strain was on the rebar at the column side that would be subject to tensile strain during eccentric loading. 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. In addition, the strains were recorded automatically using a data acquisition system. At every stage of loading, cracks were observed and marked, if any.

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 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 having slenderness ratio equal 20. The specimens were tested without strengthening for 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 having the same description of group (A) but fully wrapped with continuous overlapped GFRP sheets. Each sheet of 600 mm width and 700 mm length to provide over lap of 100 mm in each direction. Group C consists of three specimens GC-S1, GC-S2,

Table 2 General description of test specimens grouping

Group	Specimen	Slenderness ratio (l_u/h)	Eccentricity ratio (e/h)	Wrapping condition	Remarks
Group (A) -(Current study)	GA-S1	20	0	without	Control specimen
	GA-S2	20	0.1	without	Control specimen
	GA-S3	20	0.5	without	Control specimen
Group (B) -(Current study)	GB-S1	20	0	(Full)	
	GB-S2	20	0.1	(Full)	
	GB-S3	20	0.5	(Full)	
Group (C) -(Current study)	GC-S1	15	0	(Full)	
	GC-S2	15	0.1	(Full)	
	GC-S3	15	0.5	(Full)	
Group (D) -(Previous study)	GD-S1	10	0	without	Control specimen
	GD-S2	10	0.1	without	Control specimen
	GD-S3	10	0.5	without	Control specimen
Group (E) -(Previous study)	GE-S1	10	0	(Full)	
	GE-S2	10	0.1	(Full)	
	GE-S3	10	0.5	(Full)	

and GC-S3 having slenderness ratio equal 15. The three specimens were confined with continuous overlapped GFRP sheets using the same technique as group B. Table 2 summarizes the general description of the test specimens. The results of the previous work concerning the behavior of axially loaded short columns (Elwan and Rashed 2011) were added to the table as Groups D and E. Group D consists of three specimens GD-S1, GD-S2, and GD-S3 with the same cross section as the previous three groups but having slenderness ratio equal 10. The specimens were tested without strengthening under three different eccentricity ratios (e/t) of 0, 0.1, 0.5, respectively. Group E consists of three specimens GE-S1, GE-S2, and GE-S3 having the same description of Group D but fully wrapped with one layer of GFRP laminates.

3. Experimental rest 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 11% and 30 % in both slender (l_u/h = 20) and short (l_u/h = 10) columns respectively. For specimens with eccentricity ratio of 0.1, the increases in the ultimate load were about 20% and 26% in both slender (l_u/h = 20) and short (l_u/h = 10) columns

Table 3 Summary of test results

Group	Specimen	Ultimate load in kN	Axial shortening (mm.)	Lateral deflection (mm.)
Group (A) -(Current Study)	GA-S1	306	2.30	0.09
	GA-S2	250	1.90	1.98
	GA-S3	112	1.21	6.00
Group (B) -(Current Study)	GB-S1	340	3.00	0.11
	GB-S2	300	2.35	2.49
	GB-S3	120	1.20	7.2
Group (C) -(Current Study)	GC-S1	410	2.2	0.12
	GC-S2	340	2.07	1.82
	GC-S3	210	1.56	8.5
Group(D) -(Previous Study)	GD-S1	440	1.85	-
	GD-S2	348	1.45	1.05
	GD-S3	200	1.6	2.70
Group (E) -(Previous Study)	GE-S1	571	2.1	-
	GE-S2	440	1.7	1.3
	GE-S3	240	1.65	3.00

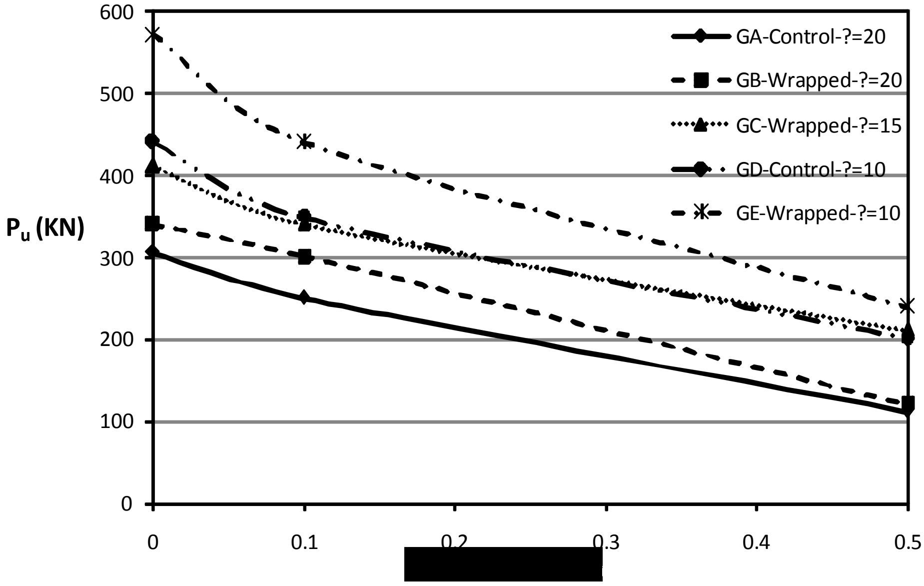


Fig. 4 Effect of confinement on ultimate load

respectively. For specimens with eccentricity ratio of 0.5, the increases in the ultimate load were about 7% and 20% in both slender (l_u/h = 20) and short (l_u/h = 10) columns respectively. Based on the above percentages, it could be seen that the enhancement in the ultimate loads of the slender wrapped specimens was approximately about 50% on average of those of short wrapped specimens. 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.

3.2 Axial deformation

Fig. 5 shows the effect of confinement with GFRP on the axial shortening at failure 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 for low eccentricity ratios (e/t = 0 & 0.10). However, the axial shortening values are almost the same for specimens with high eccentricity ratios (e/t = 0.5). It could be also noted that the increase in axial shortening values for slender specimens is higher than those of short specimens. For axially loaded specimens, the increases in the axial shortening were about 30% and 13% in both slender (l_u/h = 20) and short (l_u/h = 10) columns, respectively. For specimens with eccentricity ratio of 0.1, the increases in the axial shortening were about 23.7% and 17.2% in both slender (l_u/h = 20) and short (l_u/h = 10) columns, respectively. This increase in axial shortening reflects the improvement of specimen's ductility before failure especially for slender columns with low eccentricity ratios. For specimens with eccentricity ratio of 0.5, no significant increase was observed in slender specimens (l_u/h = 20) and slight increase by as much as 3% was observed in short specimens (l_u/h = 10). These small ratios 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.

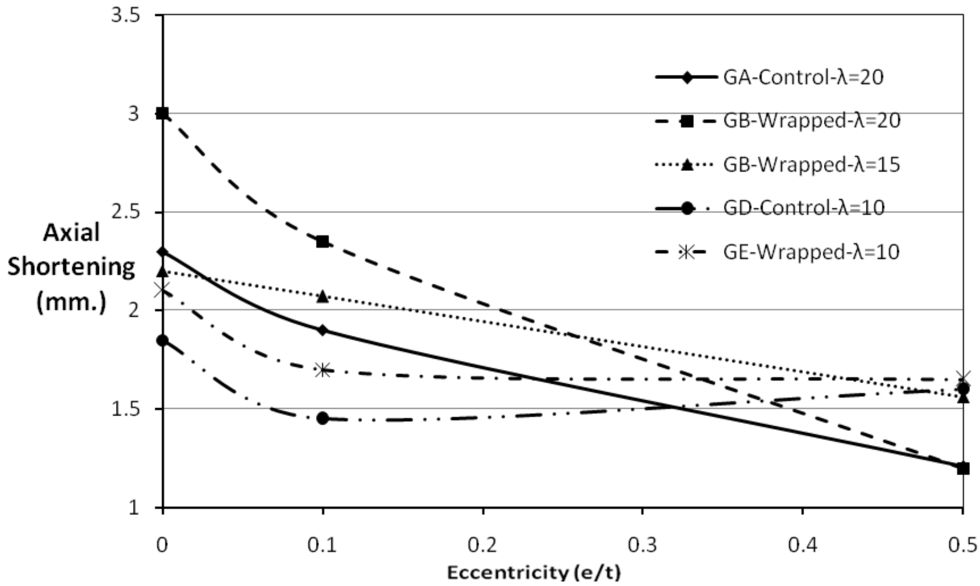


Fig. 5 Effect of confinement on axial shortening at failure

It was also observed that the axial shortening values of slender specimens with low eccentricity ratios were higher than those of short specimens, while the values of slender specimens with high eccentricity ratio were lower than that of short specimens. This may be attributed to the special case of instability for slender columns with high eccentricity ratio.

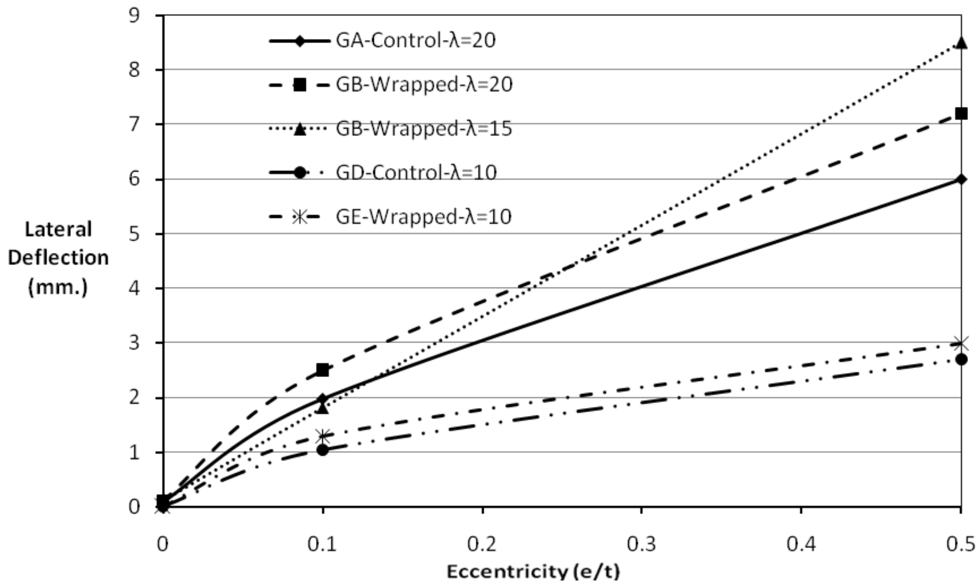
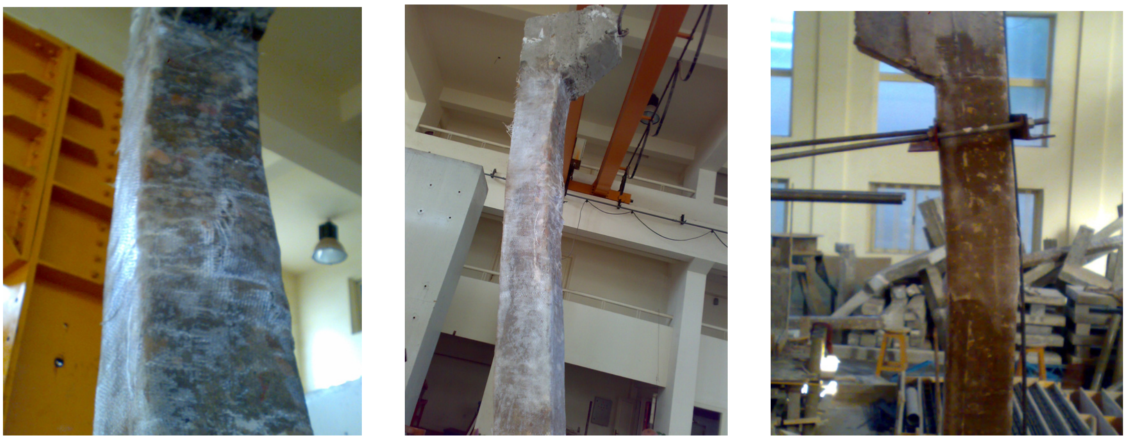


Fig. 6 Effect of confinement on lateral deflection at failure

(a) Failure of GA-S1 (b) Failure of GA-S2 (c) Failure of GA-S3

Fig. 7 Failure patterns of unwrapped slender columns



(a) Failure of GB-S1 (b) Failure of GB-S2 (c) Failure of GB-S3

Fig. 8 Failure patterns of wrapped slender columns

3.3 Lateral deflection

Comparing the lateral deflection values listed in Table 3, and shown in Fig. 6, 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 were higher than that of the control specimen by about 26% and 24%, in both slender (l_u/h = 20) and short (l_u/h = 10) columns respectively. For specimens with e/t equal 0.5 the recorded lateral deflections were higher than that of the control specimen by about 20% and 11%, in both slender (l_u/h = 20) and short (l_u/h = 10) columns respectively. This noticeable variation in percentages indicates that the wrapping is a significant factor for increasing the lateral deflection before failure and consequently ductility of eccentric loaded specimens before failure.

(a) Failure of GD-S1 (b) Failure of GD-S2 (c) Failure of GD-S3

Fig. 9 Failure patterns of unwrapped short columns

(a) Failure of GE-S1 (b) Failure of GE-S2 (c) Failure of GE-S3

Fig. 10 Failure patterns of wrapped short columns

3.5 Failure patterns

For axially loaded slender control specimen GA-S1, the failure was crushing failure at upper third of column as shown in Fig. 7(a), while the failure of wrapped slender axially loaded specimen GB-S1 was started by rupture in the fiber coat in the tension side at mid height followed by rupture in the fiber coat in the compression side as shown in Fig. 8(a). For slender control specimen GA-S2 with (e/t = 0.1), the failure was crushing failure at upper third of column as shown in Fig. 7(b), while the failure of the wrapped specimen with the same eccentricity ratio GB-S2 was the same of GB-S1 as shown in Fig. 8(b). For slender control specimen GA-S3 with (e/t = 0.5), the failure was crushing failure at the middle height of column with wide cracks in the tension side as shown in Fig. 7(c), while the failure was rupture in the fiber coat in the tension side for wrapped specimen with the same eccentricity ratio GB-S3 as shown in Fig. 8(c).

For axially loaded short control specimen GD-S1, the failure was associated with concrete crushing near the column ends as shown in Fig. 9(a), and outside wrapping for wrapped specimen GE-S1 as shown in Fig. 10(a). This may attributed to the 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. Conclusions

The research conducted showed that the GFRP is less efficient in enhancing the ultimate load carrying capacity of slender columns compared to short ones especially with high eccentricities ratios. Confined slender columns with low eccentricity gain better enhancement in load carrying capacity compared with those with high eccentricity ratio. The observed results also indicate that the GFRP wrapping is more efficient in increasing the axial shortening values and consequently enhancing ductility for slender columns with low eccentricity ratios compared to short ones with the same eccentricity ratios. For columns with high eccentricity ratio, there is no significant effect of wrapping in enhancing the ductility for both slender and short columns. The wrapping also increases the lateral deflection values before failure in both slender and short specimens with low eccentricity ratios by almost the same percentage. However, the percentage of increase is almost twice for slender specimen with high eccentricity ratio compared to short one with the same eccentricity ratio. Specific conclusions are as follows:

(1) For axially loaded columns, the enhancement in ultimate load produced by GFRP wrapping was about 11% and 30% in both slender and short specimens, respectively. The axial shortening at failure increased by as much as 30% and 13% for both slender and short columns compared to those of the control specimens.

(2) For specimens with eccentricity ratio of 0.1, the increases in the ultimate load were about 20% and 26% in both slender and short specimens, respectively. The axial shortening increases by 24% and 17% for both slender and short specimens respectively compared to that of the control specimens. The recorded lateral deflections of both slender and short strengthened specimens were higher than that of the control specimen by about 26% and 24%, respectively.

(3) For specimens with eccentricity ratio of 0.5, the increases in the ultimate load were about 7% and 20% in both slender and short specimens respectively. The axial shortening increased by only 3% for both slender and short specimens. The recorded lateral deflections were higher than that of the control specimen by about 20% and 11% for both slender and short specimens respectively.

(4) For axially loaded slender control specimen GA-S1, the failure was crushing failure at upper third of column, while the failure of wrapped slender axially loaded specimen GB-S1 was started by rupture in the fiber coat in the tension side at mid height followed by rupture in the fiber coat in the compression side. For slender control specimen GA-S2 with (e/t = 0.1), the failure was crushing failure at upper third of column, while the failure of the wrapped specimen with the same eccentricity ratio GB-S2 was the same of GB-S1. For slender control specimen GA-S3 with (e/t = 0.5), the failure was crushing failure at the middle height of column with wide cracks in the tension side, while the failure was rupture in the fiber coat in the tension side for wrapped specimen with the same eccentricity ratio GB-S3.

It may be also concluded that, if there is a need to enhance ultimate load capacity of slender columns, it is recommended that bi-directional GFRP sheets be used.

The above findings are specific for the three eccentricity ratios and the two cases of slenderness ratios. General findings could be established by conducting future experiments with different eccentricity ratios and wrapping at different stages of loading

References

Benzaid, R., Chickh, N. and Mesbah, H. (2008), "Behavior of square concrete column confined with GFRP composite wrap", *J. Civil Eng. Manag.*, **14**(2), 115-120.

Chaallal, O., Hassan, M. and Shahawy, M. (2003), "Confinement model for axially loaded short rectangular columns strengthened with fiber-reinforced polymer wrapping", *ACI Struct. J.*, **100**(2), 215-221.

El-Darwish, A., Khalifa, A., Khoury, S., El-Kurdi, A. and Morsy, A. (2005), "Analytical model for axially loaded rectangular reinforced concrete columns confined by fiber reinforced polymer jackets", *Proceedings of the 4th Middle East Symposium on Structural Composites for Infrastructural Application*, Alexandria, Egypt, May.

El-Ghandour, A., Abdelrahman, A., El-Afandy, T. and Mohamedien, M. (2005), "Analytical model for tested rectangular RC columns wrapped from three- sides by CFRP sheets", *Proceedings of the 4th Middle East Symposium on Structural Composites for Infrastructural Application*, Alexandria, Egypt, May.

Elwan, S.K. and Rashed, A.S. (2011) "Experimental behavior of eccentrically loaded R.C. short columns strengthened using GFRP wrapping", *Struct. Eng. Mech.*, *Int. J.*, **39**(2), 207-221.

Ghith, H. and Anwar, H. (2002), "Confinement effect of continuous GFRP wrapping on the behavior of R.C. columns", *Proceedings of the 3rd Middle East Symposium on Structural Composites for Infrastructural Application*, Aswan, Egypt, December.

Hodhod, O.A., Hassan, W., Hilal, M.S. and Bahnasawy, H. (2005), "Strength and ductility of biaxially loaded high strength RC short square columns wrapped with GFRP jackets", *Struct. Eng. Mech.*, *Int. J.*, **20**(6), 727-745.

Kumutha, R., Vaidyanathan, R. and Palanichamy, M.S. (2007), "Behaviour of reinforced concrete rectangular columns strengthened using GFRP", *Cement Concrete Comp.*, **29**(8), 609-615.

Lau, K.T. and Zhou, L.M. (2001), "The mechanical behavior of composite wrapped concrete cylinders subjected to uniaxial compression load", *Compos. Struct.*, **52**(2), 189-198.

Qiaoling, X. and Hongtao, Y.W.D. (2004), "Experiment and research of reinforced concrete column externally bonded with CFRP sheets under eccentric load", *Industrial Construction*, 2004-2011.

Richart, F.E., Brandtzaeg, A. and Brown, R.L. (1929), "The failure of plain and spirally reinforced concrete in compression", Bulletin No. 190, Engineering Experiment Station, University of Illinois, Urbana, IL, USA.

Sadeghian, P., Rahai, A. and Ehsani, M. (2010), "Experimental study of rectangular RC columns strengthened

with CFRP composites under eccentric loading", *J. Compos. Construct.*, **14**(4), 443-450.
Toutanji, H. and Deng, Y. (2002), "Strength and durability performance of concrete axially loaded members confined with AFRP composite sheets", *Compos. Part B*, **33**(4), 255-261.
Turgay, T., Polat, Z., Koksal, H.O., Doran, B. and Karakoc, C. (2010), "Compressive behavior of large-scale square reinforced concrete columns confined with carbon fiber reinforced polymer jackets", *Mater. Des.*, **31**(1), 357-364.
Zhong, T., Qing, Y. and Jinguang, T. (2005), "Experimental behavior of FRP-confined square RC long columns under eccentric loading", *Industrial Construction*, 2005-2009.

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