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Behaviour of reinforced concrete rectangular columns strengthened using GFRP

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Abstract

Rectangular columns are often used in bridge pier design, and they make up the majority of building columns. Columns in need of strengthening and retrofit are very common. This paper presents results of a comprehensive experimental investigation on the behavior of axially loaded rectangular columns that have been strengthened with glass fibre reinforced polymer (GFRP) wrap. This paper is intended to examine several aspects related to the use of glass FRP fabrics for strengthening rectangular columns subjected to axial compression. The objectives of the study are as follows: (1) to evaluate the effectiveness of external GFRP strengthening for rectangular Concrete Columns (2) to evaluate the effect of number of GFRP layers on the ultimate load and ductility of confined concrete and (3) to evaluate the effect of the aspect ratio of the column on the effectively confined cross-section. To cover a wide range of cross-sectional dimension ratios, three aspect ratios (a/b, where a and b are, respectively, the longer and shorter sides of the cross-section) were studied: $a/b = 1.0$, $a/b = 1.25$, and $a/b = 1.66$. Specimens with zero, one, and two layers of GFRP wrap were investigated. Totally nine specimens were subjected to axial compression which includes three control specimens. All the test specimens were loaded to failure in axial compression and the behavior of the specimens in the axial and transverse directions was investigated.

Keywords: Glass fibre reinforced polymer; Wrap; Ultimate load; Ductility; Aspect ratio; Confined

1. Introduction

In recent years, the use of externally bonded fibre-reinforced polymers (FRP) has become increasingly popular for civil infrastructure applications, including wrapping of concrete columns. Significant research has been devoted to circular columns retrofitted with FRP and numerous models were proposed. Shahawy et al. [1] verified a confinement model which was originally developed for concrete filled glass FRP tubes by conducting axial compression tests on a total of 45 carbon – wrapped concrete stubs of two batches of normal and high strength concrete and five different number of wraps. It was concluded that, the wrap significantly enhanced the strength and ductility of concrete by curtailing its lateral dilation and the adhesive bond between concrete and the wrap would not significantly affect the confinement behaviour [1]. The performance of concrete columns externally wrapped with aramid fibre reinforced polymer composite sheets has been studied by Toutanji and Deng [2]. Concrete cylinders confined with AFRP composite sheets were tested in axial compression and their stress–strain response was determined. It has been found that, the confinement with AFRP composite sheets constrains the lateral strain, producing a tri-axial stress field in concrete, which results in improving the compressive strength, maximum strain and ductility. Also the performance of the wrapped concrete specimens subjected to severe environmental conditions such as wet–dry and

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freeze–thaw cycles was investigated by them. Results show that specimens wrapped with aramid fibre experienced no reduction in strength due to wet–dry exposure, but some reduction was observed due to freeze–thaw exposure.

The behavior of FRP wrapped concrete cylinders with different wrapping materials and bonding dimensions has been studied by Lau and Zhou using finite element (FEM) and analytical methods [3]. It was found that, the load carrying capacity of the wrapped concrete structure is governed by the mechanical properties such as modulus and Poisson's ratio, of the wrapping sheet. An analytical equation was provided to estimate the shear stress distribution of an adhesive material for different wrapping geometries. A study on the compressive behaviour and strength of elliptical concrete specimens wrapped with CFRP has been described by Teng and Lam [4]. From the study it was found that, the axial compressive strength of FRP confined concrete in elliptical specimens is controlled by the amount of confining FRP and the major to minor axis length ratio a/b of the column section. The confining FRP becomes increasingly less effective as the section becomes more elliptical but substantial strength gains from FRP confinement can still be achieved even for strongly elliptical sections. The ultimate axial strain of the confined concrete was also shown to increase as the FRP confinement becomes larger. Based on the test results, a simple compressive strength model for FRP confined concrete in elliptical columns was proposed, in which the effect of the section shape is taken into account by a shape factor.

The confinement model describing the behaviour of rectangular concrete columns retrofitted with externally bonded fiber-reinforced polymer material and subjected to axial stress was presented by Omar Chaallal et al. [5]. The derivation of the proposed model was based on the findings of an extensive experimental investigation involving the testing of 90 rectangular specimens representing three cross-sectional aspect ratios, two concrete strengths and five different numbers of FRP layers. It was found that the stiffness of the applied FRP jacket is the key parameter in the design of external jacket retrofits. In a study by Toutanji [6], tests were performed to evaluate the durability performance of concrete columns confined with fibre reinforced polymer composite sheets. The influence of wet/dry exposure using salt water on the strength and ductility of FRP wrapped concrete columns was evaluated. It was found that confinement of concrete cylinders with FRP sheets improves the compressive strength and ductility and the improvement in strength and ductility is dependent on the type of FRP composite sheets. The technique of wrapping thin, flexible high strength fiber composite straps around the columns for seismic strengthening, to improve the confinement and thereby its ductility and strength has been presented by Saadhatmanesh et al. [7]. Analytical models that quantify the strength and ductility of concrete columns externally confined by means of high strength fibre composite straps were presented. The results indicate that the strength and ductility of concrete columns can be significantly increased by wrapping high strength fibre composite wraps around the columns.

Thus, FRP wrapping of circular columns has proven to be an effective retrofitting technique. In contrast very limited data have been reported on rectangular columns retrofitted with FRP wrap, even though rectangular columns in need of retrofit are very common. The objective of the present paper is to study the behaviour of reinforced concrete rectangular columns with three different aspect ratios strengthened with externally applied GFRP jackets and subjected to axial compressive loading.

1.1. Research significance

The use of externally bonded FRP composite for strengthening and repair can be a cost-effective alternative for restoring or upgrading the performance of existing concrete columns. Even though a lot of research has been directed towards circular columns, relatively less work has been performed on square and rectangular columns, to examine the effects of external confinement on the structural performance. However, the vast majority of all columns in buildings are rectangular columns. Therefore their strength and rehabilitation need to be given attention to preserve the integrity of building infrastructure. This paper is directed towards this endeavor.

2. Experimental programme

2.1. Parameters of study

The following parameters were considered in this experimental investigation:

(a) The aspect ratio of the cross-section: To cover a wide range of cross-sectional dimension ratios, three aspect ratios (a/b where a and b are, respectively the longer and the shorter sides of the cross-section) were studied: $a/b = 1$, $a/b = 1.25$, and $a/b = 1.66$.
(b) The number of GFRP layers: Specimens with zero, one and two layers of GFRP wrap were investigated.

2.2. Materials

Ordinary locally available Portland cement having a specific gravity of 3.15 was made use of, in the casting of the specimens. Locally available river sand having a fineness modulus of 2.54, and a specific gravity of 2.62 was used. Crushed granite coarse aggregate of 20 mm maximum size having a fineness modulus of 7.94 and specific gravity of 2.94 was used. Water conforming to the requirements of water for concreting and curing as per IS: 456–2000 was used through out. The average standard 28-days compressive strength of concrete cubes was approximately 27.45 MPa with a mix ratio of cement: sand: gravel: water 1:1.3:3.29:0.47. Concrete cylinders were confined by wrapping them with glass fiber sheets namely chopped strand mat (CSM) having a density of 300 g/m^2. The resin system used in this work was general purpose polyester resin made of two-parts, resin and hardener. The manufacturer provided the following information on E-glass composite (resin + fibre) laminates that were used to wrap concrete columns: ultimate tensile strength = 250 N/mm^2, modulus of elasticity = 10500 N/mm^2 and ultimate strain = 3.5% maximum.

2.3. Details of test specimens

Totally nine reinforced concrete columns were tested under concentric compression in testing frame. The columns were cast horizontally in steel forms and compacted using a needle vibrator. The length (750 mm) and the cross-sectional area (15625 mm^2) were kept constant for all the specimens. Each specimen had middle test region 750 mm long and two enlarged capitals at their ends. The capital of height 160 mm was provided at both ends of the columns to distribute the load evenly. This configuration serves to stabilise the column during testing. All columns had longitudinal reinforcement consisting of 4 deformed bars, 10 mm in diameter with yield strength $f_y = 477.5$ N/mm^2 and ultimate strength $f_u = 603.5$ N/mm^2. In addition, 6 mm in diameter smooth bars with yield strength $f_y = 250$ N/mm^2@125 mm lateral spacing were used as stirrups. Column specimens were divided into three groups: 3 columns confined with 1 layer of GFRP, 3 confined with 2 layers of GFRP and 3 unconfined (control). The specimen names, as shown in the first column of Table 1, are composed of three terms. Each of these terms gives information about some aspect of the column which is described as follows: The first term refers to the number of sheets of GFRP making up the jacket. The second term describes the shape of the column cross-section. '*S*' refers to a square cross-section and '*R*' refers to a rectangular cross-section. The third term which is a number in subscript refers to the aspect ratio of the column cross-section.

Table 1
Summary of test results

Column designation	Failure load in KN	Maximum axial (microstrain)	Maximum transverse (microstrain)
$0S_1$	766.3	1575	1080
$1S_1$	786	1165	509
$2S_1$	940	1465	675
$0R_{1.25}$	750	1660	483
$1R_{1.25}$	772	1830	820
$2R_{1.25}$	920	3150	1950
$0R_{1.66}$	740	1190	750
$1R_{1.66}$	770	1355	785
$2R_{1.66}$	860	1875	1030

2.4. Fibre-reinforced polymer wrapping

The resin system used in this work was made of two-parts namely resin and hardener. The components were thoroughly hand mixed for at least 5 min. The concrete columns were cleaned and completely dried before the resin was applied. A first coat of thin layer of resin was applied and GFRP sheet was then wrapped directly on the surface. Special attention was taken to ensure that there was no void between the GFRP sheet and concrete surface. After the application of the first wrap of the GFRP sheet, a second layer of resin was applied on the surface of the first layer to allow the impregnation of the second layer of the GFRP sheet. Finally, a layer of resin was applied on the surface of wrapped columns. In all cases, the outside layer was extended by an overlap of 50 mm to ensure the development of full composite strength.[1]

2.5. Instrumentation and testing procedure

All specimens were loaded until failure under axial compression in a testing frame. All the nine columns were tested under similar conditions. Longitudinal and transverse strains were manually measured using DEMEC gauge with 100 mm gage lengths having a least count of 0.002 mm. Pellets were glued either on the concrete surface for control specimens or on the GFRP outer layer for strengthened specimens. Pellets were fixed at mid height of the column for strain measurements in both longitudinal and transverse direction. Strains were noted down for every 100 kN increment of load. Test set up for the columns is as shown in Fig. 1.

Fig. 1. Test set up.

3. Results and discussion

3.1. Overall behaviour

The maximum experimental values obtained from all the tests are summarized in Table 1. From the results, it can be seen that, the confinement of columns with GFRP wrap increases load carrying capacity of reinforced concrete columns. In addition, the greater the number of GFRP layers, the greater the gain in axial load carrying capacity with respect to unconfined columns. The maximum increases achieved in series $2S_1$, $2R_{1.25}$, and $2R_{1.66}$ with respect to control were 16.22%, 22.67% and 22.67%, respectively, whereas those achieved for series $1S_1$, $1R_{1.25}$, and $1R_{1.66}$, respectively, were only 4.05%, 2.93% and 2.57%.

3.2. Ductility response

Fig. 2 shows axial strain versus number of layers. From the figure it is evident that confinement with GFRP wrap improved the column's ductility. This increased ductility allows for a higher level of axial strain and a failure corresponding to rupture of the GFRP wrapping. In all the cases of strengthened columns, excepting that with $a/b = 1.0$, confinement with GFRP wrap improved the columns ductility. In most of the cases, failure initiated at or near a corner, because of the high stress concentrations at these locations. The ductility of the columns increased as the number of layers of wrapping increased. For $1R_{1.25}$ and $2R_{1.25}$ specimens, axial failure strain increased by as much as 10% and 90%, respectively as compared to that of control specimen $0R_{1.25}$. In the case of columns $1R_{1.66}$ and $2R_{1.66}$, the failure strain increased by as much as 14% and 58%, respectively as compared to that of $0R_{1.66}$. At the same stress level, the axial strains for the GFRP confined columns were always higher than the transverse strains.

3.3. Effect of aspect ratio

Fig. 3 shows the effect of cross-sectional aspect ratio on concrete columns wrapped with GFRP. As evident from the figure, increasing aspect ratio led to decreased ultimate strengths. Columns with aspect ratio 1.66 resulted in smaller ultimate axial and transverse strain values as compared with that of columns with aspect ratio 1.25. Fig. 4 compares the gain in axial load carrying capacity for different aspect ratios. The columns having aspect ratios 1.25 and 1.66, when wrapped with one layers showed a very slight increase in strength than that with aspect ratio 1.0.

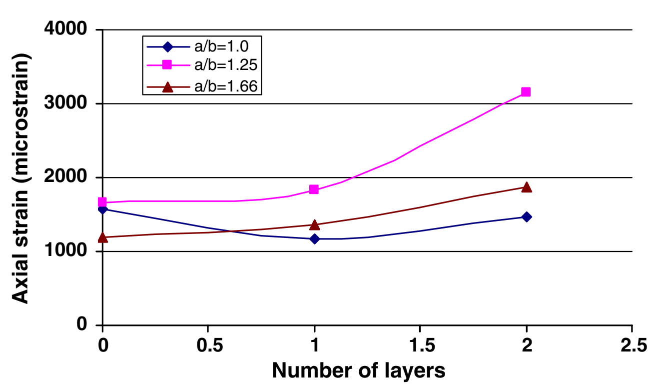

Fig. 2. Axial strain vs. number of layers.

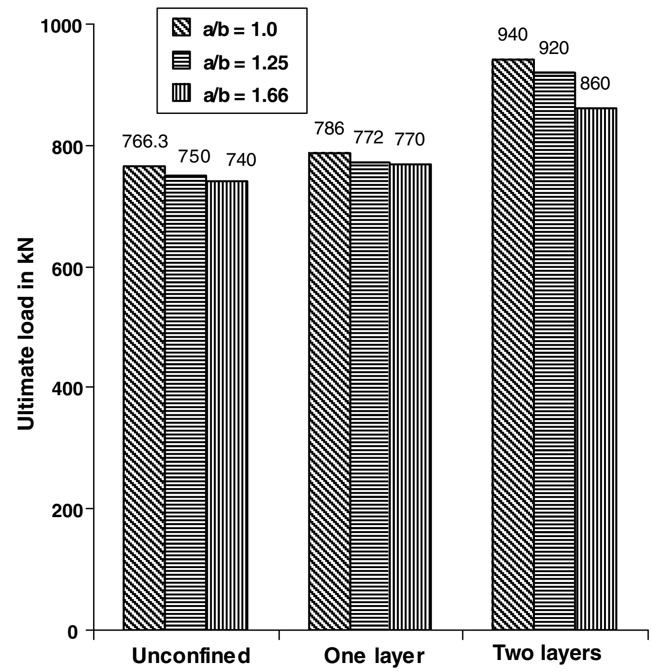

Fig. 3. Effect of aspect ratio on ultimate load.

3.4. Failure mode

In all cases, the failure of the columns was the result of the rupture of the FRP jacket except in that of the control specimens. Failure of the control columns was notably more violent than the columns with GFRP and even explo-

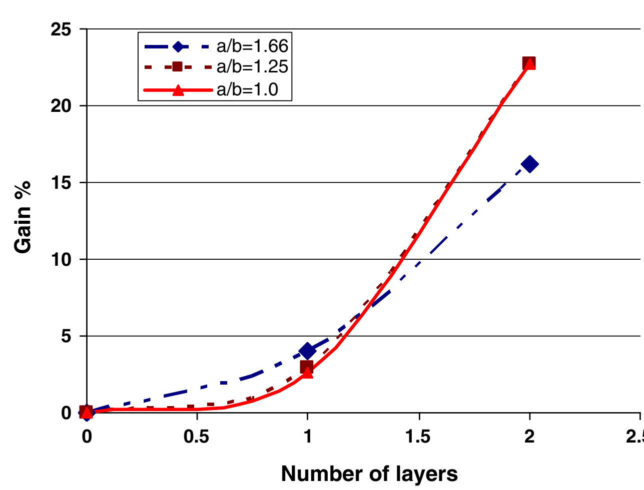

Fig. 4. Gain in ultimate load vs. number of layers.

Fig. 5. Failure modes.

sive. Local buckling of longitudinal reinforcement was observed in the unwrapped columns. For most wrapped columns, the failure was associated with concrete crushing at or near the column ends and marked by wraps rupturing in the circumferential direction. After failure the concrete was found disintegrated. Failure of GFRP wraps was observed at or near a corner in all the specimens mainly due to stress concentrations. This may be expected since column's sharp edges were not rounded off. In order to avoid stress concentration, attempt should be made to round off sharp corners. One should also ensure that the failure will not happen at end regions by increasing the number of wrapping layers in the end regions. Failure modes of specimens are shown through Fig. 5.

4. Analytical model

4.1. Confined concrete strength

A simple analytical confinement model is proposed to predict the ultimate load of GFRP strengthened reinforced concrete rectangular columns. For that, first it is necessary to evaluate the confined concrete strength f_{cc}. Unlike the case of FRP wrapped circular columns, the concrete in an FRP strengthened rectangular sections is not uniformly confined. Consequently, at the failure of the rectangular columns, the compressive strength in the concrete varies over the column section. For circular concrete columns confined with FRP composite wraps, the confined core concrete strength can be given as

$$f_{cc} = f_{co} + k_1 f_l \tag{1}$$

where f_{co} is the strength of unconfined concrete, k_1 is the confinement effectiveness co-efficient and f_l is the lateral confining pressure.

4.2. Evaluation of lateral pressure of confinement

For circular specimens, f_l is uniformly distributed and can be directly related to the amount and strength of FRP by

$$f_l = \frac{2t}{D} f_{frp} = \frac{\rho_{frp} f_{frp}}{2} \tag{2}$$

where t is the thickness of FRP jacket, D is the diameter of the concrete core f_{frp} is the tensile strength of FRP in hoop direction and ρ_{frp} = FRP volumetric ratio $= \frac{4t}{D}$.

It is proposed here that the compressive strength of FRP confined concrete f_{cc} in rectangular columns, defined as the average axial stress at the peak load as is commonly accepted, be given by an equation analogous to Eq. (1), with the replacement of the confining pressure by an effective confining pressure f_l'. That is

$$f_{cc} = f_{co} + k_1 f_l' \tag{3}$$

The effective confining pressure f_l' can be defined as

$$f_l' = k_s f_l \tag{4}$$

where k_s is the shape factor accounting for the effect of section shape and f_l is the confining pressure in an equivalent circular column.

For an FRP wrapped rectangular 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 f_l can be evaluated using Eq. (2) with the FRP volumetric ratio ρ_{frp} now given by

$$\rho_{frp} = \frac{2(B+H)t}{BH} \tag{5}$$

where B and H are breadth and depth of rectangular column section, respectively.

4.3. Parameters for confinement effect

The confinement ratio $\left(\frac{f_l}{f_{co}}\right)$ of FRP confined concrete is defined as ratio of the confining pressure to the unconfined concrete strength. Strengthening ratio or confinement effectiveness $\left(\frac{f_{cc}}{f_{co}}\right)$ is defined as the ratio between the strength of confined concrete to that of unconfined concrete, that measures how effectively the concrete is confined in a given cross-section. The main parameters that are likely to influence the confinement effect are the volumetric ratio of FRP, tensile strength of FRP in hoop direction, core concrete shape and the strength of unconfined concrete. The effect of confinement on these parameters was determined based on the test results. The peak strength f_{cc} of the confined concrete depends on the value of the lateral confinement pressure f_l. Fig. 6 shows the relation between confinement ratio and the strengthening ratio for the columns of the test series. For each series, the peak stress f_{cc} of the confined specimens was normalized by the strength of unconfined concrete f_{co}. It can be seen that, strengthening ratio is proportional to the volumetric ratio and the strength of FRP (in terms of lateral confining pressure f_l) and is inversely proportional to unconfined concrete strength. Therefore the relationship may be approximated by a linear function, with the slope depending on the cross-sectional shape. From the regression analysis, the relation between confinement ratio and strengthening ratio is written as

$$\frac{f_{cc}}{f_{co}} = 1 + 0.93\frac{f_l}{f_{co}} \tag{6}$$

For columns having rectangular cross-sections, the strength of the confined concrete can be satisfactorily evaluated using Eq. (6). Having determined the confined concrete strength f_{cc}, the ultimate load carrying capacity P_u of FRP strengthened columns can be determined from

$$P_u = (f_{co} + k_1 k_s f_l)A_c + f_y A_s \tag{7}$$

where A_c and A_s are area of concrete section and longitudinal steel, respectively. The value of $k_1 k_s$ was found to be 0.93 from Eq. (6).

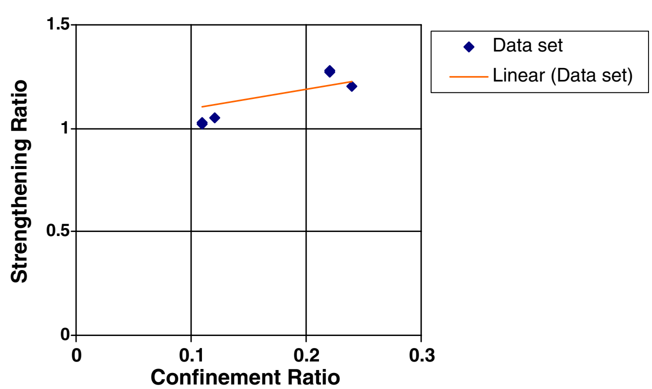

Fig. 6. Strengthening ratio vs. confinement ratio.

4.4. Validation of the proposed model

The ultimate load predicted from the proposed analytical model was compared with the experimental results as shown in Table 2. It was found that a good correlation was obtained between the experimental results and those got from the theoretical model. The maximum error was found to be only less than 7%. Eq. (6) can be satisfactorily applied to the reinforced concrete columns having square and rectangular cross-sections strengthened with FRP wraps, to predict the confined concrete strength and the corresponding ultimate load can be found out using Eq. (7).

5. Conclusions

Effective confinement with GFRP composite sheets resulted in improving the compressive strength. Better confinement was achieved when the number of layers of GFRP wrap was increased, resulting in enhanced load carrying capacity of the column, in addition to the improvement of the ductility. For columns having an aspect ratio of

Table 2
Comparison of experimental and analytical results

S.no	Aspect ratio (a/b)	f_{co} (N/mm^2)	Fiber type	t (mm)	f_l (N/mm^2)	f_l/f_{co}	f_{cc} (N/mm^2)	f_{cc}/f_{co}	Ultimate load P_u (KN)		% of error
									Experimental value	From analytical model	
1	1.0	40.26	E glass	1.1	4.4	0.11	41.54	1.03	786.0	829.0	−5.47
2	1.0	40.26	E glass	2.2	8.8	0.22	51.60	1.28	940.0	891.6	5.15
3	1.25	39.55	E glass	1.1	4.42	0.11	40.48	1.02	772.0	820.8	−6.32
4	1.25	39.55	E glass	2.2	8.84	0.22	50.11	1.27	920.0	883.9	3.92
5	1.66	38.56	E glass	1.1	4.54	0.12	40.52	1.05	770.0	804.6	−4.49
6	1.66	38.56	E glass	2.2	9.08	0.24	46.40	1.20	860.0	869.2	−1.07

t: thickness of FRP Jacket; f_{co}: strength of unconfined concrete; f_l: lateral confining pressure; f_{cc}: strength of confined concrete.

1.0, the enhancement in axial load was about 4.05% and 16.22%, for one and two layers of GFRP, respectively. For an 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. Use of GFRP in concrete compression members, produces an increase in strength, but this phenomenon is strongly influenced by the aspect ratio of the cross-section. The load carrying capacity of the column decreased, with increase in aspect ratio of the cross-section. The test results show a clear overall linear relationship between the strength of confined concrete and lateral confining pressure provided by FRP. Based on the analysis of the experimental results, a simple model has been proposed for the prediction of the ultimate load of FRP confined columns, and a good correlation was obtained between experimental and analytical results.

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