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Composites: Part B 38 (2007) 640–650
composites Part B: engineering
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Influence of edge sharpness on the strength of square concrete columns confined with FRP composite laminates

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Received 1 March 2006; accepted 29 June 2006
Available online 27 December 2006

Abstract

This paper presents the experimental and analytical results of the study carried out to investigate the influence of the radius of the cross-sectional corners (edges) on the strength of small scale square concrete column specimens confined with FRP composite laminates. The experimental part of the study was achieved by testing 20 specimens under uniaxial compression. Depending on the selected radius of the edges, the section varied from square to circular. Intermediate radii were about 1/6, 1/4, and 1/3 of the side dimension. The sharpest square specimens had a corner radius of 5 mm to make composite application easier and to avoid a premature rupture of the composite. The results show that smoothening the edges of square cross-section plays a significant role in delaying the rupture of the FRP composite at these edges, and the efficiency of FRP confinement is directly related to the radius of the cross-section edges. A modified analytical model is presented to predict the strength of FRP-confined square as well as circular sections. The predicted results are found to be in excellent agreement with the measured ones.

Keywords: A. Polymer fiber; B. Strength; C. Analytical modeling; D. Mechanical testing; Confinement

1. Introduction

Over the years, engineers have used different methods and techniques to retrofit existing structures by providing external confining stresses. For the past few years, the concept of jacketing has been investigated to provide such forces. Externally applied jackets, have been used as a reinforcement to contain concrete for different reasons. Engineers have used traditional materials such as wood, steel, and concrete to confine and improve the structural behavior of concrete members.

Section enlargement is one of the methods used in retrofitting concrete members. This method is as old as the concrete industry itself. Enlargement is the placement of reinforced concrete jacket around the existing structural member to achieve the desired section properties and performance. A reinforcing steel cage is placed on the outside of the existing deficient column, and then new concrete shell is poured to form the reinforced concrete jacket. The main disadvantages of such system are the increase in the column size obtained after the jacket is constructed and the need to construct a new formwork. This could be very critical, especially in commercial buildings, where the goal is usually to maximize the availability of leasable space.

Steel jacketing has been proven to be an effective technique to enhance the seismic performance of old bridge columns [1]. The steel jacket is manufactured in two shell pieces and welded in the field around the column. This type of jacket provides a passive type of confinement that is activated after the concrete starts to dilate and expands laterally in the compression zone as a function of high axial compression strains. However, this method requires difficult welding work and in the long term, the potential problem of corrosion remains unsolved.

Fiber reinforced polymers (FRP) has emerged over the last decade as a new material to be used in structural

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doi:10.1016/j.compositesb.2006.06.019

engineering, due to its attractive mechanical properties. FRP systems, however, have recently gained world-wide recognition as strengthening measures to increase the ductility and load carrying capacity of existing structural members. As a result, these materials have shown great potential in becoming an attractive alternative to concrete and even steel jackets.

Over the last few years, there has been a worldwide increase in the use of composite materials for the rehabilitation of deficient RC structures. One important application of this composite retrofitting technology is the use of FRP jackets to provide external confinement to RC columns when the existing internal transverse reinforcement is inadequate.

Several studies addressed seismic retrofitting methods to enhance the flexural strength, ductility, and shear strength of reinforced concrete columns confined with glass and carbon fibers [2–6].

Experimental testing was first performed on concrete cylinders wrapped with composites and subjected to uniaxial compressions [7,8]. Saadatmanesh et al. [9] used the stress–strain model proposed by Mander et al. [10] to analyze the behavior of concrete columns externally wrapped with FRP composite straps. The model was used to assess gain in strength and ductility of concrete column confined by FRP materials. Mirmiran et al. [11] discussed how FRP materials significantly enhance the strength, ductility and durability of concrete columns. The longitudinal fibers serve as flexural reinforcement, while hoop fibers provided confinement and shear strength. Samaan et al. [12] developed a confinement model for FRP-confined concrete applicable to circular sections only. The model predicts the entire stress–strain curve of FRP-confined concrete in both, the axial and lateral directions. Hosotani et al. [13] developed a FRP-confined concrete model applicable to circular and rectangular columns. This model is based on experimental results obtained from testing 200 mm diameter by 600 mm high circular specimens, and 200 mm × 200 mm × 600 mm square specimens, confined using carbon fiber laminates. Lam and Teng [14] proposed a new stress–strain model for FRP-confined concrete with explicit recognition of the different ultimate strain values for concrete confined by different types of FRP materials. The model also predicts the compressive strength of confined concrete by these materials. Lokuge et al. [15] proposed an analytical method to predict the behavior of laterally confined concrete columns subjected to eccentric static loading. The proposed method fully incorporates the effect of strain gradient on the lateral confining pressure exerted by transverse reinforcement. Tan [16] investigated the use of FRP systems in the strengthening of rectangular reinforced concrete columns with a section having an aspect ratio of about 3.65. He carried out an extensive test program to evaluate the axial load capacity of the FRP strengthened columns. He examined the effect of fiber type and configuration, and the presence of plaster finishes on the column response. A simple analytical method was also presented to evaluate the increase in the axial load capacity of the columns. Masia et al. [17] assessed the increase in strength and ductility under axial compressive loading for square-section plain concrete prisms achieved by wrapping with CFRP laminates.

Although a much better understanding of the structural behavior of RC columns retrofitted with FRP jackets existed more than 15 years ago, this technology remains in its developmental stages and much research is still needed. Thus far, the main thrust of research has been aimed at characterizing the behavior of columns with circular cross sections [18,19]. However the vast majority of all columns in buildings are square or rectangular columns. Therefore, their strengthening and rehabilitation need to be given attention to preserve the integrity of building infrastructure.

Shape of cross-sections of columns can directly affect the confinement effectiveness of externally bonded FRP jackets. Benefit of strength is higher for circular than for square or rectangular sections. Poor confinement may be due to low FRP jacket stiffness (type of FRP and numbers of layers) or due to sharp edges in cross-sections. Mitigation of this shape effect is achieved by rounding the corners of the square or rectangular sections. A study of the importance of this factor on the axial compressive strength of columns is performed experimentally by testing a series of concrete cylinders and square column prisms. Rochette and Labossiere [20] showed experimentally that for FRP wrapped concrete columns the strength and ductility gains increase with the radius of the column corner. Cole and Belarbi [21] investigated the effectiveness of FRP confinement on rectangular RC columns. They studied experimentally effects of (i) fibers type (AFRP, CFRP and GFRP); (ii) thickness of jacket; (iii) the aspect ratio of the rectangular cross section and (iv) the radii of the corners; on the axial strength and axial strain of rectangular RC column subjected to uniform compression. They observed that (i) GFRP jackets are more effective than CFRP or AFRP jackets at increasing the ultimate axial strength and ultimate axial strain of square RC columns; (ii) an increase in the sharpness of the corners of the cross section results in a lower ultimate strength; (iii) an increase in the aspect ratio of the cross section results in a lower ultimate strength. Yang et al. [22] studied effect of corner radius on the performance of externally bonded FRP reinforcement. They observed that as the corner radius decreases efficiency of FRP wrapping also decreases. Kim et al. [23] studied experimentally behavior and compressive strength of concrete members confined with Carbon Fiber Sheets (CFS) with four lamination schemes and three cross sectional shape viz. square, octagonal and circular. They observed that (i) circular section is most effective in load carrying capacity whereas square section is least effective; (ii) octagonal and circular specimens show similar axial strengths for various lamination angles. Maalej et al. [24] presented an analytical model to predict the load–displacement response of wall-like RC columns strengthened with

FRP wraps with and without sustained loading. They compared the analytical load–displacement response with experimental results and a close agreement was observed. Through a parametric study they also showed that the column's aspect ratio, the number of horizontal FRP layers, the corner radius, and the amount of vertical FRP reinforcement are all important parameters which influence the strengthening ratio of FRP-wrapped RC columns.

The purpose of this paper is to study the influence of the radius of the cross-sectional corners (edges) on the strength of small scale square concrete column specimens confined with FRP composite laminates. These specimens were tested in uniaxial compression. Depending on the selected radius of the edges, the section varied from square to circular. Intermediate radii were about 1/6, 1/4, and 1/3 of the side dimension. The square specimen with the sharpest edge had a corner radius of 5 mm to make composite application easier.

The experimental part of the study was achieved by testing a total of 20 column (models) specimens (10 unconfined and 10 confined) of plain concrete. Four of the 20 specimens were cylinders and the other 16 specimens were short square concrete columns with rounded edges and different in their corner radii.

Efficient analytical models – available in the literature – for strength prediction of FRP-confined circular sections are reviewed and discussed. A modified analytical model is proposed to predict the strength of FRP-confined square as well as circular sections. Cross-section shape and confining pressure effects as well as the influence of corner radius were duly incorporated in this model.

2. Experimental program

The experimental program in terms of specimen's details, test setup, instrumentation, and test procedure was conducted in two stages. The first stage included testing the standard 150 × 300 mm concrete cylinders. The second stage included the testing of the 500 mm height un-reinforced square (150 × 150 mm) columns. Table 1 shows the test program conducted for the specimens in this study. Carbon/epoxy jacket was used to confine the columns and cylinders.

Fig. 1 shows the cross-sections and dimensions of the jacketed specimens tested. The specimens include square columns and standard 150 × 300 mm cylinders wrapped with one layer of CFRP laminate.

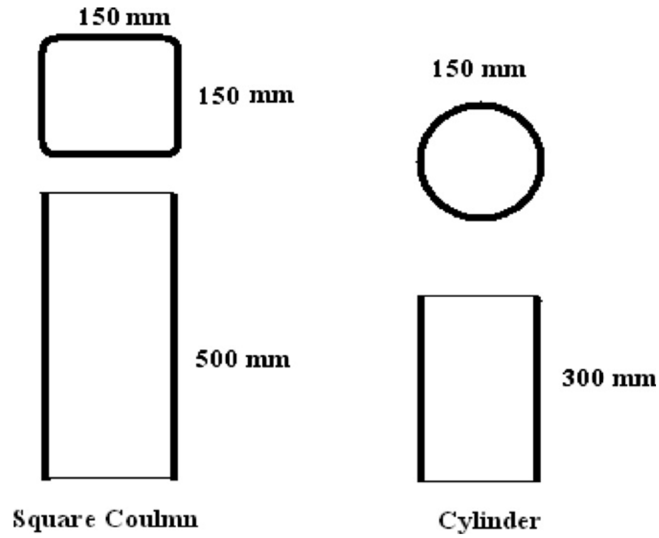

Fig. 1. Dimensions of control and jacketed specimens.

2.1. Material properties

2.1.1. Concrete

A ready-mix concrete was used. The nominal 28-day design strength of the concrete used ranged from 32 MPa to 35 MPa. The quantities of ingredients, used in the concrete mix are shown in Table 2.

2.1.2. CFRP laminate

The carbon fiber reinforcement polymer (CFRP) used in this study to strengthen the concrete specimens had a tensile strength of 935 MPa and a modulus of elasticity of 75,100 MPa. The thickness per layer was 1.2 mm. These mechanical properties of CFRP are summarized in Table 3.

2.2. Specimen preparation

A total of 16 unreinforced square columns with a 150 mm by 150 mm cross-section and 500 mm high with corner radii of 5 mm, 25 mm, 38 mm, and 50 mm were prepared. Two of each group were used as control specimens, and the remaining columns were wrapped with one layer of

Table 1
Properties and dimensions of specimens

Specimen	b (mm)	L (mm)	r approx. (mm)	r/b	No. of unconfined specimens	No. of confined specimens
S-r5	150	500	5	1/30	2	2
S-r25	150	500	25	1/6	2	2
S-r38	150	500	38	1/4	2	2
S-r50	150	500	50	1/3	2	2
CYL	150[a]	300	75	1/2	2	2
Total					10	10

r = the radius of the corner of the square specimen; b = dimension of the square specimen; D = diameter of the cylinder specimen.
[a] For this special case, width of the specimen is equal to diameter of the specimen.

Table 2
Proportions of ingredients used for concrete mix

Ingredients	Quantity
Cement	350 kg/m^3 Type I
Silica sand	504 kg/m^3
Washed sand	287 kg/m^3
10 mm aggregate	310 kg/m^3
20 mm aggregate	724 kg/m^3
Free water	163 kg/m^3
w/c	0.465
Admixture (Retarder + plasticizer)	0.6% by weight of cement

Table 3
Mechanical properties of CFRP

Thickness per layer, t_f (mm)	Modulus of elasticity, E_f (MPa)	Tensile strength, f_{FRP} (MPa)
1.2	75100	935

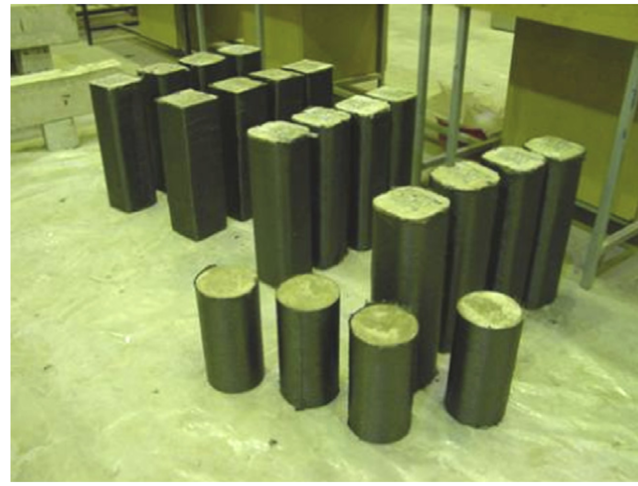

Fig. 2. Jacketed specimens.

carbon/epoxy jacket. Also a total of four concrete cylinders were prepared and tested. Two of the cylinders were wrapped with one layer of carbon/epoxy jacket.

Forms for the square column specimens were prepared using 18 mm plywood sheets cut and assembled to provide 90° corners with a plywood formed bottom. The forms were cut and assembled very carefully to ensure accurate vertical sides and 90° corners. In order to round off the corners of the square specimens, foam inserts with the desired radius were glued to the corners of the boxes. Metal clamps were used at mid height of the forms in order to ensure that the assembled boxes would be able to resist the fresh concrete pressure.

Casting of the test specimens took place in one day. The first specimens to be poured were the square ones followed by the standard 150 mm × 300 mm cylinders. Although the bottom of all specimens was formed, the top surface was finished very carefully using steel trowel to ensure a level surface.

The concrete mix was slowly poured into the forms to prevent segregation, and vibrator was used to vibrate the concrete carefully, to prevent voids from forming. Slump tests were taken on site to check the quality of the concrete used.

2.2.1. FRP jacketing

The concrete specimens, after 28 days of curing, were carefully sandblasted. Voids and deformities on the surface of the specimens were filled using gypsum paste.

The two-part epoxy system used, consisting of resin and hardener, was thoroughly hand-mixed for at least 5 min before use. The CFRP laminates were then applied directly onto the surface of the specimens providing unidirectional lateral confinement in the hoop direction.

Special attention was taken by the installers to eliminate any voids between the FRP laminates and the concrete surfaces. In the case of square columns a 150 mm overlap was used, while a 100 mm overlap was used in the case of circular specimens to insure the development of full composite tensile strength. Fig. 2 shows the columns and cylinders after jacketing with Carbon fibers.

All specimens were stored at room temperature for at least 7 days before testing. This was done to ensure that enough time had passed for the epoxy to cure. Prior to loading the specimens onto the test machine, the ends of the jacket were ground smooth to remove any uneven edges.

2.3. Instrumentation

2.3.1. Square columns

All columns were instrumented with four strain gauges bonded at mid-height of unconfined and confined specimens. Two of the four strain gauges (180° apart) were to measure the lateral strains, while the remaining two (180° apart) were to measure the vertical (longitudinal) strains. In addition to the strain gauges, two LVDTs (linear variable differential transducers) were mounted (180° apart) to capture the vertical displacements. Load cell under the specimen was used to capture the axial load readings. The wires for strain gauges, the load cell and the LVDTs were attached to data acquisition system and checked for readings. The instrumentation of the square column is shown in Fig. 3.

2.3.2. Cylinders

All cylinders were instrumented by two strain gauges mounted at the mid-height of each specimens, 180° apart on the concrete and the jacket surface to measure the lateral strains. To measure axial strain each specimen was fitted with two LVDTs that were mounted on two round sleeves at (180° apart) around the specimen. The sleeves were attached to the specimen with pin-type support that would not affect the dilation of the specimen. The wires for strain gauges, the load cell, and the LVDTs were attached to data acquisition system and checked for readings. Fig. 4 shows a sketch of the instrumentation of circular specimens.

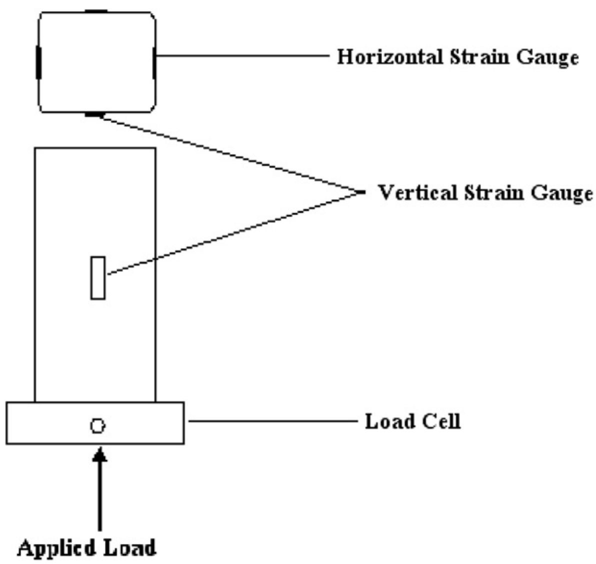

Fig. 3. Instrumentation of square specimens.

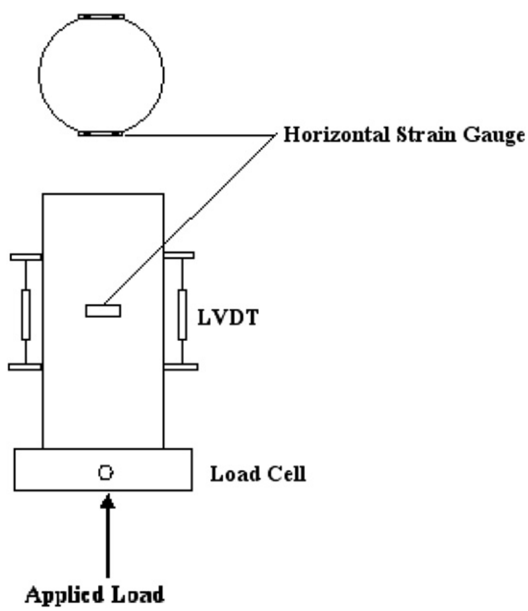

Fig. 4. Instrumentation of circular specimens.

2.4. Test procedure

All columns were capped with gypsum paste, while the circular specimens were capped with sulfur to ensure parallel surface and to distribute the load uniformly in order to reduce eccentricity. The test was conducted by first setting the specimen in test machine, centered under the machine spacer. The LVDTs were then zeroed out in preparation to start the test, and then the load was applied at a loading rate equal to 4 kN/s. The testing was performed using the Amsler hydraulic testing machine equipped with a moving piston that exerts an axial force. The capacity of this machine in compression is 10,000 kN and the specimens were tested under pure axial compression.

3. Discussion of results

3.1. Cylindrical specimens

The performance of the cylinders under axial load was consistent. Prior to the failure, cracking noises were heard, indicating the start of stress transfer from the dilated concrete to the CFRP jacket. The failure was gradual, ended with a sudden and explosive noise. It was characterized by crushing of concrete followed by cutting of the CFRP laminates at the middle portion of the specimen. The jacket rupture started at mid-height and progressed to up and down of the specimen. The sudden and explosive nature of the failure indicates the release of tremendous amount of energy as a result of the uniform confining stress provided by the jacket. Inspection of the broken samples showed good contact between the jacket and the concrete indicating that no debonding took place at any stage throughout the loading process.

3.2. Square specimens

There was a good enhancement in the performance of all confined columns. As expected, the degree of enhancement was directly related to the corner radius. Thus, columns with 50 mm corner radius had, among all square specimens, the highest improvement but less than that of the circular specimens. The ultimate strain was also highly improved.

The failure of all confined square columns took place at one of the corners within the mid height of the specimen. The failure was gradual and less explosive than that of the cylinders and was only preceded by the discoloration of the resin and some slippage sounds. This proves the fact that confining forces created by a square jacket tends to be concentrated at the corners. For this reason the rounding of the square column corners was used to provide a uniform confining stress.

Tables 4(a) and 4(b) show the summary of the experimental results obtained for all unconfined and confined square and cylindrical test specimens. These tables clearly show the gain in strength and stain achieved through confinement of columns. Further, these tables also illustrate that as corner radius increases, gain also increases and it becomes maximum for cylindrical column. Fig. 5 illustrates graphically how as the corner radius increases, gain in strength due to confinement increases. As shown in Table 4(b) the values of axial strains at ultimate loads are substantially small for unconfined specimens than confined specimens. This can be attributed to the fact that failure of specimens is primarily due to tensile lateral strains, developed under compressive axial strains (Poisson's effect). For unconfined specimens, at relatively lower axial strains, strains in the lateral direction reaches to tensile strength of the concrete. However, for confined specimens there is an FRP laminate to take this lateral tension which makes specimen to carry a much higher value of axial

Table 4(a)
Summary of experimental results for all specimens

Specimen designation	Specimen no.	Unconfined strength f'_{co} (MPa)	Confined strength f'_{cc} (MPa)	% Gain	% Gain average
S-r5	Specimen-1	28.68	41.18	44	40
	Specimen-2	30.94	42.49	37	
S-r25	Specimen-1	31.82	48.25	52	56
	Specimen-2	28.50	45.59	60	
S-r38	Specimen-1	27.70	56.96	106	94
	Specimen-2	30.29	54.96	81	
S-r50	Specimen-1	26.72	61.67	118	128
	Specimen-2	28.26	63.68	138	
CYL	Specimen-1	32.40	83.16	157	146
	Specimen-2	36.23	85.04	135	

Table 4(b)
Summary of experimental results for all specimens

Specimen designation	Axial strain at ultimate load (μm)		Increase (%)
	Unconfined	Confined	
S-r5	337	1167	247
S-r25	307	6949	1880
S-r38	207	7907	3720
S-r50	998	11,147	1017
CYL	616	9699	1475

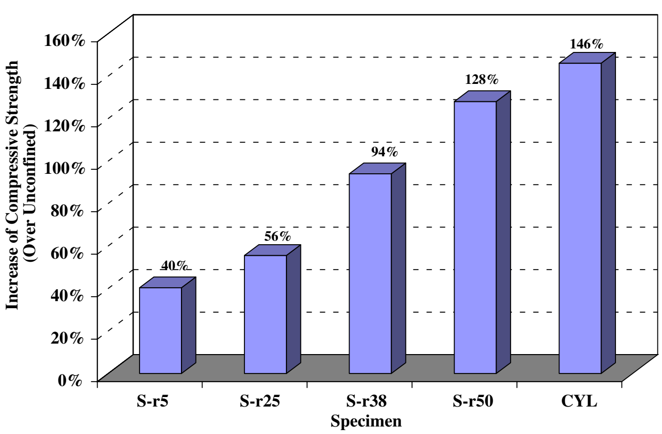

Fig. 5. Effect of corner radius on confined square columns.

strain. The confined specimen fails if lateral strains reach to such a high value that fiber fractures or concrete crushes.

Test results of the square confined columns show that confinement highly improves their ductility, but to a lesser degree than for cylinders. Fig. 6 clearly illustrates the effect of corner radii simply by comparing the stress–strain curves of square confined columns with corner radii (r) of 5, 25, 38, and 50 mm, with that of the confined cylinder. It can be seen that increasing the radius results in changing the behavior of the confined square column to become gradually similar to that of a confined cylinder. This behavior is illustrated in Fig. 7.

As can be observed in Fig. 6, all stress–strain curves of the confined specimens are bilinear with a transition zone. The second slope of these curves is function of the ratio r/b

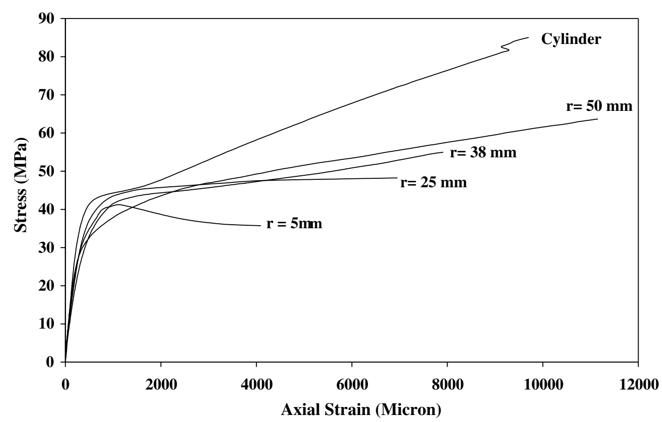

Fig. 6. Effect of corner radius on confined square columns.

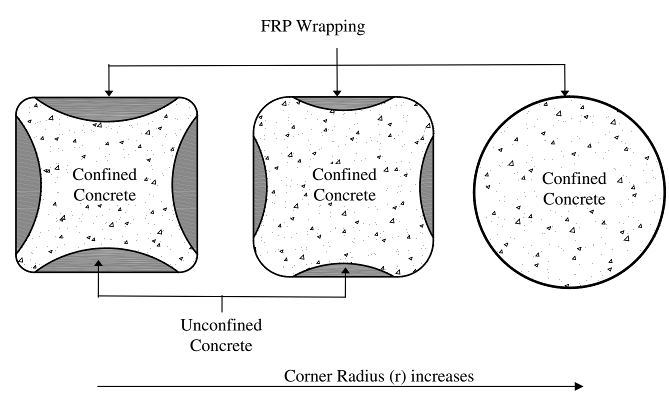

Fig. 7. Effect of corner radius on confined concrete in square and cylindrical columns.

(r – radius of the corner and b – is the width of the section = 150 mm). As this ratio increases, the slope increases, and hence the performance is improved.

3.3. Effect of confinement on ductility

It is expected that confinement will improve specimen ductility considerably. Figs. 8a–8e show that due to confinement ultimate axial and lateral strains have been

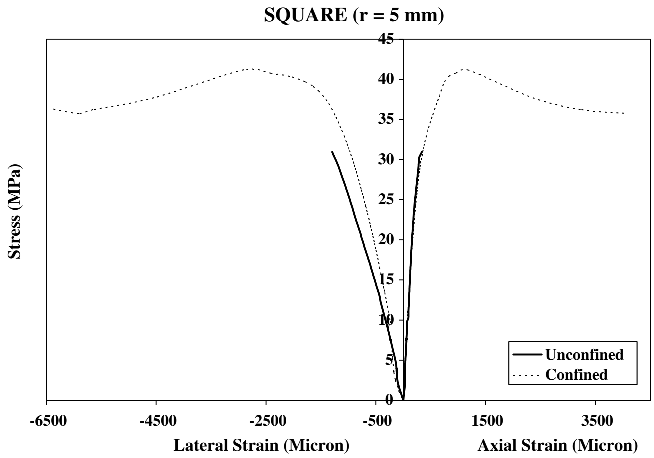

Fig. 8a. Improvement in ductility with CFRP confined concrete (S-r5 mm).

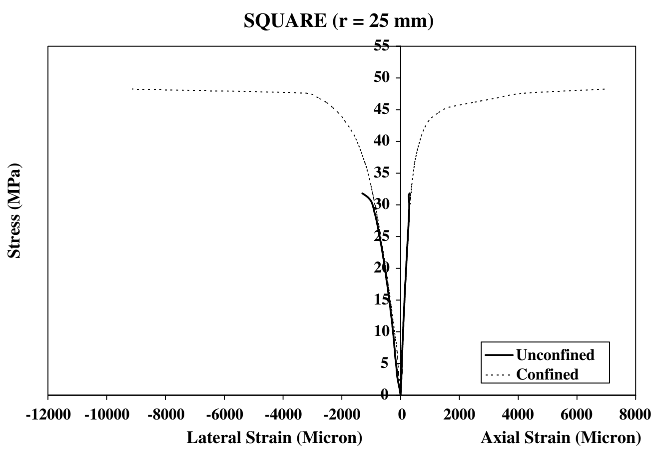

Fig. 8b. Improvement in ductility with CFRP confined concrete (S-r25 mm).

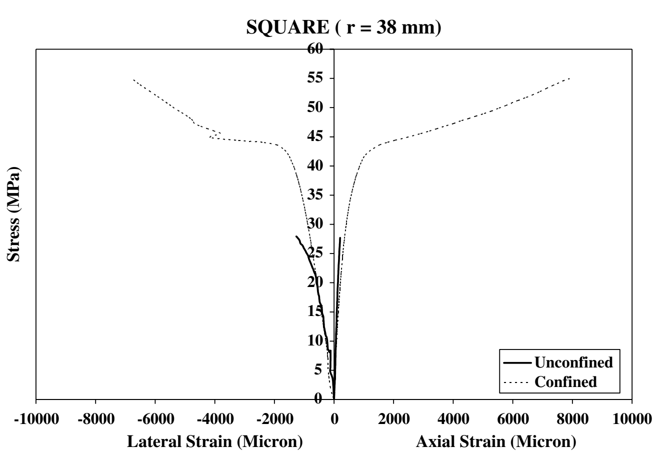

Fig. 8c. Improvement in ductility with CFRP confined concrete (S-r38 mm).

increased manifold. This is indirect representation of ductility enhancement. This enhancement in the ductility was observed with every group of specimens.

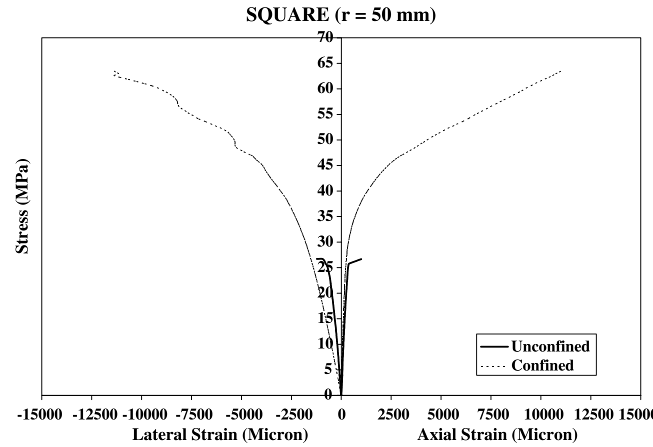

Fig. 8d. Improvement in ductility with CFRP confined concrete (S-r50 mm).

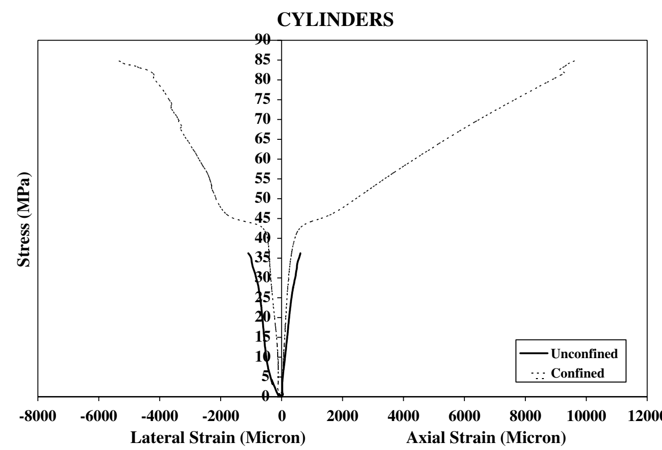

Fig. 8e. Improvement in ductility with CFRP confined concrete (cylinder).

3.4. Modes of failure

Figs. 9a–9e show the failed specimens after testing. The mode of failure can be characterized by shearing and splitting of the concrete in the control specimens. In these specimens, as the corner radius increases the splitting of concrete becomes uniform along the height, and it becomes almost vertical for the cylinder (Fig. 9e). For the jacketed specimen, as the corner radius increases, the mode of failure becomes sudden and more explosive, and it is most explosive for cylindrical specimen. Fig. 9 supports the fact that uniform confining pressure observed in cylinder specimens provides the most effective means of confinement.

4. Analytical model

A large number of tests have been reported in the literature on the axial compressive strength of circular concrete specimens confined with FRP. The majority of these tests were performed on concrete specimens without steel

Fig. 9a. Failed unconfined and confined square specimens ($r = 5$ mm).

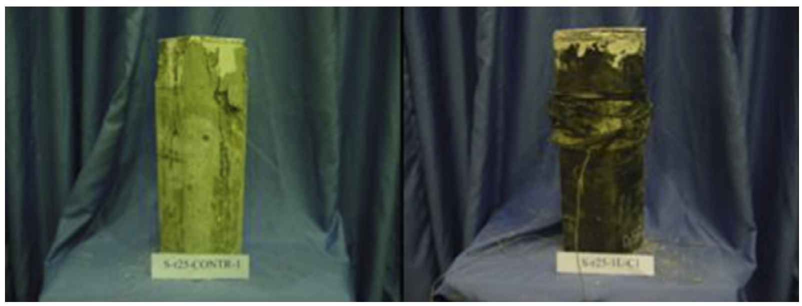

Fig. 9b. Failed unconfined and confined square specimens ($r = 25$ mm).

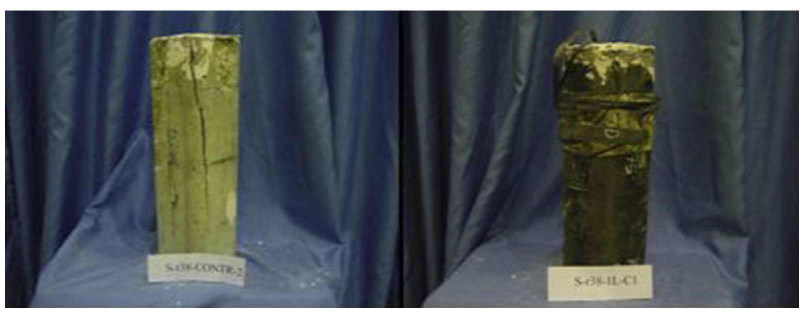

Fig. 9c. Failed unconfined and confined square specimens ($r = 38$ mm).

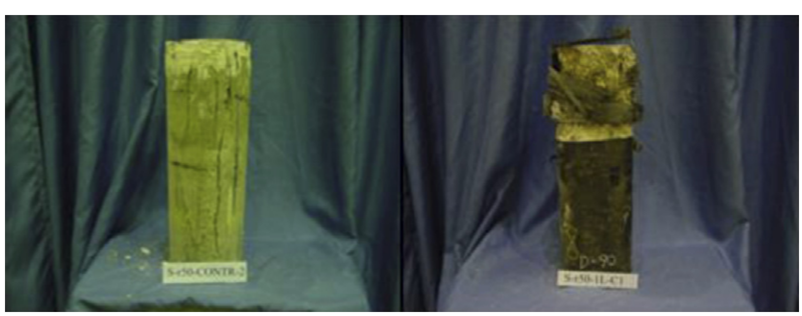

Fig. 9d. Failed unconfined and confined square specimens ($r = 50$ mm).

reinforcement. A limited number of tests have been reported in the literature on the axial compressive strength of square concrete specimens confined with FRP.

In general, majority of the existing strength models for FRP-confined concrete take the following form:

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 \frac{f_l}{f'_{co}} \quad (1)$$

where f'_{cc} and f'_{co} are the compressive strengths of the confined and the unconfined concrete, respectively, f_l is the lateral confining pressure, and k_1 is the confinement effectiveness coefficient.

A number of strength models have been proposed specifically for FRP-confined concrete, which employ Eq. (1) with modified expressions for k_1 [11,12,25–27]. Most of these models expressed k_1 in nonlinear form in terms of

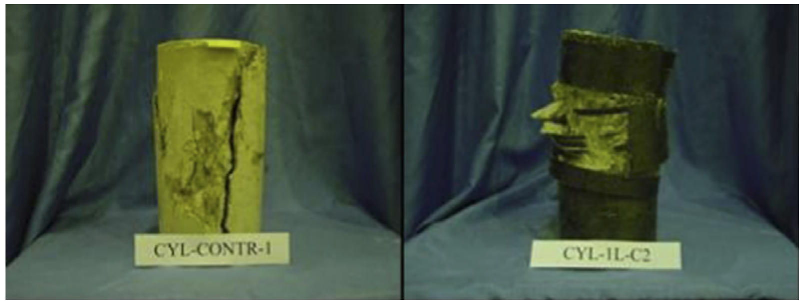

Fig. 9e. Failed unconfined and confined cylindrical specimens.

f_l/f'_{co} or f_l. Other researchers used a constant value for k_1 (between 2.0 and 3.3) indicating that the experimental data available in the literature show a linear relationship between the strength of confined concrete f'_{cc} and the lateral confining pressure f_l [14,28,29].

For application to FRP-confined concrete, the lateral confining pressure, f_l, can be related to the amount and strength of the FRP as follows:

For circular section,

$$f_l = \frac{2f_{\mathrm{FRP}}t}{D} \tag{2}$$

where, f_{FRP} is the tensile strength of FRP in the hoop direction t is the total thickness of the FRP jacket, and D is the diameter of the confined circular section.

For square section,

$$f_l = \frac{2f_{\mathrm{FRP}}t}{D}k_e \tag{3}$$

where D is the diagonal length of the square section (Fig. 10). With rounded corners, D can be written as

$$D = \sqrt{2}b - 2r(\sqrt{2} - 1) \tag{4}$$

and k_e, is a "shape factor", defined by Pessiki et al. [30] and Masia et al. [17] as the ratio of the confined area A_{confined} to the gross area of the cross-section A_{gross}, and can be written as

$$k_e = \frac{A_{\mathrm{confined}}}{A_{\mathrm{gross}}} \tag{5}$$

Limiting the expression of Pessiki et al. [30] to square sections and plain concrete allows k_e to be expressed as a function of the section dimension (b) and the corner radius (r) as

$$k_e = 1 - \frac{2}{3}\left[\frac{\left(1 - 2\frac{r}{b}\right)^2}{1 - (4 - \pi)\left(\frac{r}{b}\right)^2}\right] \tag{6}$$

The k_e values versus r/b for the specimens considered in this study are plotted in Fig. 11 which clearly shows the increase in the ratio of the confined area to the total area of the section as the r/b increases. The maximum value for k_e is 1.00 when $r/b = 1/2$ which is the case of circular section.

Furthermore, while the confining pressure is uniform around the circular sections, it is not uniform in the square sections where the confinement is more effective at the corners and less effective at the section sides (Fig. 7). The result is that: (i) not all the section is effectively confined; and (ii) the confinement pressure around the section is non-uniform which may cause a premature FRP failure. While the k_e shape factor was incorporated to consider the effect of confined area of the section, it is suggested here that the non-uniformity in confining pressure can be corrected using a modification factor of b/D where its maximum value is 1.00 for circular section in which the confining pressure is uniform (Fig. 10).

Therefore, the model of Eq. (1) can be employed as a general model for both circular and square sections

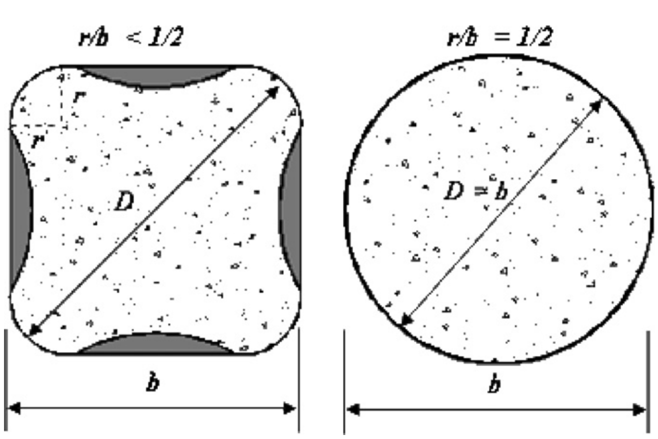

Fig. 10. Dimensions of confined sections.

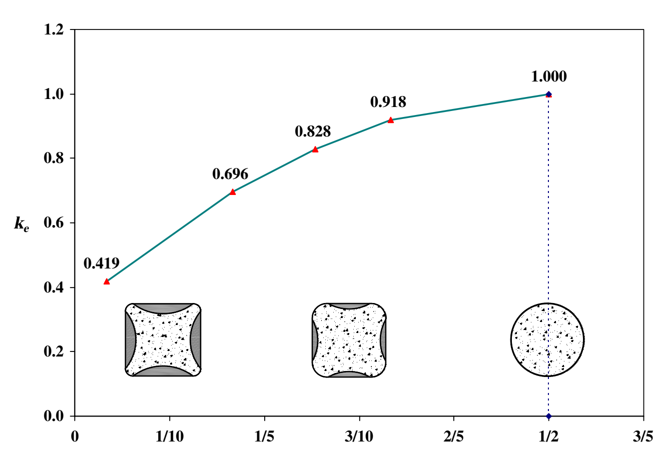

Fig. 11. k_e versus r/b for the specimens considered in this study.

Table 5
Summary of experimental and predicted results for all specimens

Specimen designation	Specimen dimensions				Experimental results			Theoretical results					
	b (mm)	r (mm)	r/b	D (mm)	f'_{co} (MPa)	f'_{cc} (MPa)	f'_{cc}/f'_{co}	k_e	f_l (MPa)	f_l/f'_{co}	f'_{cc}/f'_{co}	f'_{cc} (MPa)	$f'_{cc(Theor)}/f'_{cc(Exp)}$
S-r5	150	5	1/30	208.0	29.81	41.84	1.40	0.419	4.52	0.152	1.34	40.24	0.96
S-r25	150	25	1/6	191.4	30.16	46.92	1.56	0.696	8.16	0.271	1.67	50.25	1.07
S-r38	150	38	1/4	180.7	29.00	55.96	1.93	0.828	10.29	0.355	1.93	55.82	1.00
S-r50	150	50	1/3	170.7	27.49	62.68	2.28	0.9181	12.07	0.439	2.21	60.79	0.97
CYL	150[a]	75	1/2	150	34.32	84.10	2.45	1.000	14.96	0.436	2.37	81.29	0.97

[a] For cylinder, b = diameter of the specimen.

confined with FRP, in which the value of k_1 can be used as proposed by past investigators for circular sections; Lam and Teng [29] proposed k_1 as 3.3; Miyauchi et al. [28] proposed k_1 as 2.98, based on their experimental results on CFRP-confined concrete cylinders. Considering k_1 as the average value 3.14 to be used in the present study, the model can be written as

$$\frac{f'_{cc}}{f'_{co}} = 1 + 3.14 \frac{b}{D} \frac{f_l}{f'_{co}} \tag{7}$$

Using above model, the compressive strength of FRP-confined specimens of present study were predicted as shown in Table 5 which clearly exhibits excellent agreement between the experimental and predicted results for both the square and circular specimens. The maximum deviation is seen for S-r25 specimen and that is about 7%.

5. Conclusions

This work was conducted to study the compressive strength of FRP confined concrete. The experimental program included testing under pure axial load, 16 square concrete columns with 50 mm, 38 mm, 25 mm, and 5 mm corner radii. Two specimens of each group were confined with one layer CFRP, while the other two were unconfined used as control specimens. In addition, four 150 mm × 300 mm concrete cylinders were prepared. Two of these cylinders were confined with one layer of CFRP laminates, while the other two were unconfined used as control specimens. From the experimental program the following conclusions can be drawn:

- The best performance was that of the circular specimens followed by the columns having corner radius of 50 mm, 38 mm, 25 mm, then the 5 mm corner radius, respectively. This is attributed to the fact that a jacket delivers a uniform confining stress around the circular concrete core. As the shape changes away from circular i.e. from the large corner radius to the small one, the applied stress start to decrease with the lowest. This led to lower ultimate strength and concrete strain values of the square columns having lower corner radius, compared to that having large corner radius and of the cylinders.
- The failure of the carbon/epoxy jacketed specimens was explosive in nature releasing tremendous amount of energy.
- The FRP jacket increased both the axial load capacity as well as the ultimate concrete compressive strain.
- The failure of the specimens took place within the middle half of the specimen, regardless of its shape. Strain and LVDT readings were taken within the same area where the failure took place.
- The mode of failure was jacket rupture near the jacket's ultimate tensile strain. Good contact between the jacket and the specimen was always noticeable after close inspection of the damaged specimens.

- The failure of the square columns always starts at one of the corners proving that the stress concentration occurs at the corners.
- A modified analytical model is presented to predict the strength of FRP-confined square as well as circular concrete sections. The predicted results are in excellent agreement with the experimental results.

Acknowledgment

The author gratefully acknowledges the financial support received from the Saudi Arabian Basic Industries Corporation (SABIC) to conduct this research study. Thanks are also extended to the Director and employees of the Research Center at the College of Engineering, King Saud University for their great administrative efforts.

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