Effect of Shape and Size on Fiber Reinforced Polymer Composite Wrapped Concrete Columns

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Abstract:

Rehabilitation of structures with FRP composites has proved to be cost effective method of enhancing the service life of structures. FRP composites are used for retrofitting and Rehabilitation of Columns and Bridge Piers. The shapes of the columns have a significant effect on confining strength of FRP Wraps. A lot of research has been carried out around the globe varying different parameters and finding usable data. This paper presents results of axial compression test conducted on over two hundred and forty concrete specimens having circular, square and rectangular cross sections. The effect of shapes, sizes and shape modification of the cross sections on the load carrying capacity of FRP wrapped concrete prisms and cylinders, has been studied. The project also studies the effect of shape modifications on enhancement in load carrying capacity in case of non circular cross section. Investigation was done on rectangular columns to increase the confinement effectiveness by modifying it into elliptical cross-sections. All the experimental results were compared with analytical values calculated as per the ACI-440.2R-08 code. The results of experiments and comparison are presented.

Keywords: FRP, Fibre reinforced polymer, Shape, Size, Strengthening, Column

INTRODUCTION

In construction industry, over the last two decades, Fiber Reinforced Polymer (FRP) composites have become a primary choice for strengthening buildings and bridge components because of their high strength to weight ratio and stiffness-to-weight ratios, ease of application, cost effectiveness and such other salient traits. FRP composites are also considered as excellent substitutes for building components like concrete bridge decks, reinforcing bars and pre-stressing materials. These FRP composites are widely used for retrofitting and rehabilitation of building columns and bridge piers. Confinement of columns by means of FRP jackets is done by containing the dilation of concrete by wrapping the fibers in the hoop direction of concrete columns.

In past decade research has been carried out taking into account possible parameters in strengthening using FRP wrapping. *Mirmiran et al*, tested fifty four concrete filled FRP tubes in uniaxial compression under displacement control mode to study the dilation characteristics of confined concrete. They found that the dilation rate finally stabilizes at an ultimate value which is a function of the jacket's stiffness [1]. *Tan et al* tested to failure fifty two half scale rectangular columns with aspect ratio 3.65 under a concentric load to investigate the effect of fiber type configuration and fiber anchors on the strength enhancement of the columns[2]. *Pan et al* performed axial compression test on six FRP wrapped slender rectangular columns modified to elliptical shape having slenderness ratio L/b ranging from 4.5 to 17.5. The strengthening effect of FRP was observed to be decreasing with the increase in the slenderness ratio[3]. *Yousef et al* studied factors such as ultimate stress, rupture strain, jacket parameters, and cross-sectional geometry affecting the stress–strain behavior of FRP-confined concrete[4]. *Silva et al* studied the environmental effects such as humidity, UV rays, exposure to moisture, salt fogs, thermal cycles on mechanical properties of GFRP laminates and consequently on strengthened columns[5]. *Benzaid et al* experimentally scrutinized the effects of increasing the corner radius and the no of GFRP layers on the confined compressive strength of square columns[6].

Shape of cross section, corner radius, grade of concrete, FRP volumetric ratio are some of the important factors that affect the confinement effectiveness of FRP wraps. The experiments presented here were formulated to make a comprehensive study to determine the extent these parameters can be used to enhance the load carrying capacity in case of non-circular columns.

Confining pressure for cylinders

In case of cylinders the whole cross sectional area is effectively confined because the confining pressure is uniformly distributed along the perimeter as shown in fig 1. The behavior of confined cylinders is similar to a thin walled cylinder. The equation for confining pressure[7] is given as,

$$f_l = \frac{\rho_{frp} E_{frp} \varepsilon_{frp}}{2} \tag{1a}$$

Where, E_{frp} = Young's modulus of FRP wraps

ε_{frp} = strain in FRP wraps at failure

ρ_{frp} = FRP volumetric ratio

$$\rho_{frp} = \frac{\pi.d.n.t_f}{\pi.d^2/4} \tag{1b}$$

where, d = diameter of cross section

n = no of layers

t_f = thickness of FRP wrap

Confining pressure for non circular cross sections

In case of non circular cross sections the confining pressure is affected by the sharp edges. The dilation in non circular cross section is effectively contained by the FRP wraps only at the corners due to stress concentration as shown in fig 2. The effective confined area is reduced because stress concentration causes arching of concrete core along the sides. The equation for confining pressure for non circular cross section is given as[7],

$$f_l = \frac{k_a \rho_{frp} E_{frp} \varepsilon_{frp}}{2} \tag{2a}$$

In order to account for the reduced effective confined area, the confining pressure is reduced by a shape factor k_a[1] and is given by the following equation,

$$k_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2 \tag{2b}$$

where, $$A_e/A_c = \frac{1 - \dfrac{\frac{b}{h}(h-2r)^2 + \frac{h}{b}(b-2r)^2}{3A_g} - \rho_g}{1-\rho_g} \tag{2c}$$

in which, ϱ_g = ratio of area of steel to gross cross sectional area

The FRP volumetric ratio is given as,

$$\frac{2.n.t_f.(b+h)}{bh} \tag{2d}$$

Confining pressure for elliptical cross sections:

Shape modification of rectangular cross section to elliptical shapes is one of the effective method to increase the confining pressure provided by the FRP wraps. The confined compressive strength for elliptically modified non circular cross section is given as[8],

$$f'_{cc} = f'_{co} + 2\left(\frac{b}{a}\right)^2 f_l \tag{3a}$$

In the above equation for confining pressure is same as eq. (1a). The FRP volumetric ratio for elliptical cross section is given as following[8],

$$\rho_{frp} = \frac{[1.5(a+b) - \sqrt{ab}]\, t_f}{ab} \tag{3b}$$

EXPERIMENTAL WORK

The primary aim of this experiment was to study the effects of shapes, sizes and shape modification (corners) on the confinement effectiveness of the FRP wraps and to achieve maximum confinement. The grade of concrete and the height on specimen was kept as M30 and 300mm for all specimen. The specimen were casted in the following manner.

1. For all the three cases i.e. circular, square and rectangular specimens were casted in three sizes in increasing order of the cross sections as shown in Table 1.
2. In the case of rectangular and square columns the cross sections were carefully decided so that each square column has a corresponding rectangular column having the same cross-sectional area.
3. The size of the rectangular columns were chosen in such a way that the aspect ratio is equal to 1.5 or greater than 1.5. This is to take care of the effect of aspect ratio in rectangular columns.

All specimens were wrapped with one layer of glass fiber wraps. Glass fibers had an ultimate strength of 2400 MPa, elastic modulus of 80 kN/mm^2 and a density of 2.78 g/cc as per manufacturer's data sheet (R&M International Pvt. Ltd., Mumbai). Resin epoxy was used as matrix and had two component (base and hardener) mixed in the ratio of 100:35 as suggested by the manufacturer. All specimens were pretreated with resin primer in order to achieve a smooth surface and good bond between FRP and the specimen surface. FRP wraps were applied to both sharp edged and rounded edged prisms. The rounded edged non circular prisms had a corner radius of 37.5 mm. Rectangular prisms were also modified to elliptical shapes before FRP wrapping by placing them in elliptical moulds.

Compression test was carried out on all specimens on a 200T compression testing machine (CTM) under a load control mode with loading rate of 2.5 kN/sec. Electrical strain gauges were fixed in longitudinal and lateral direction at mid height to measure the ductility and dilation of concrete.

RESULTS AND DISCUSSIONS

Stress strain curves

It was observed from the axial stress vs. axial strain diagrams that the behavior of GFRP wrapped specimens was similar to control specimens till the lateral expansion of concrete started. As the concrete starts to dilate, GFRP wraps get activated and start containing the specimens from dilating laterally thereby providing passive confinement. The confining pressure provided by the jacket keeps increasing proportional to the applied axial load until failure. As the jacket gets completely activated the axial stress strain curve starts to flatten and is closer to a straight line in lateral direction until failure. Response of FRP wrapped cylinders and prisms to axial compression has been found to be bilinear. The elastic response of the specimens is represented by an initial straight portion of the axial stress vs. axial strain curve. This straight portion is followed by a transition stage in which the concrete starts to dilate and FRP wraps start providing confining pressure. This transition stage is then followed by a straight portion which continues till failure as the confining pressure keeps on increasing till failure. Axial stress vs. axial strain curve of FRP wrapped specimens does not have any descending branch as the confining pressure keeps increasing until failure. In case of circular cylinders, a significant increase in ductility has been observed as the values of axial strains and lateral strains of wrapped cylinders were much higher than the unwrapped cylinders as shown in Fig 3. Fig 4 shows that glass fibers effectively restrained the dilation in cylinders as the failure of wrapped cylinders occurred at a very high value of lateral strains. In case of GFRP wrapped non circular prisms with sharp edges, increase in ductility was negligible as compared to bare prisms which can be observed in Fig 5. It can be seen in Fig 6 that the dilation of prisms was contained at a lesser rate than GFRP wrapped non circular prisms with rounded edges. Rounding of edges greatly increased the ductility of wrapped square prisms which is evident from axial stress vs. axial strain diagrams. Also, in case of wrapped non circular prisms with rounded edges dilation of concrete was effectively contained as compared to sharp edged wrapped prisms as is seen in Fig 8. It can be read from Fig 7 that rectangular prisms modified to elliptical shapes exhibited excellent increase in strength and ductility as compared to bare and wrapped prisms with rounded edges

Percentage increase in strength

FRP wraps were very effective in confining circular cross sections compared to non circular cross sections as is evident from table 3. The sharp edges of a non circular prism adversely affect the confinement effectiveness of FRP wraps due to stress concentration at corners. It can be seen from table 4 and table 5 that the enhancement in strength was largest in case of non circular prism with the smallest cross sectional area (46.78% for 135 x 135 mm and 48% for 100 x 180 mm) and it was negligibly small in case of non circular prism with the largest cross sectional area (19.89% for 195 x 195 mm and 14.02% for 160 x 240 mm). The maximum corner radius that could be imparted to a non circular column depends upon the longitudinal reinforcement and the clear cover that is to be maintained. A constant corner radius of 37.5 mm was maintained for all the non circular prisms. The enhancement in strength due to rounding of edges was largest in case of columns with smallest cross sectional area (73.5% for 135 x 135 mm and 52% for 100 x 180 mm). The percentage increase in strength decreased with the increase in the cross sectional area of non circular prism and was lowest for largest cross sectional area (32.4% for 195 x 195 mm and 30.28% for 160 x 240 mm). The clear cover that is usually provided to columns is 40 mm (for severe exposure)[10]. Therefore the enhancement in strength that can be achieved by imparting corner radius is limited for large size columns as these columns will need a corner radius of higher value. In case of large no of columns, grinding of corners would prove to be a very cumbersome activity. In such cases, significant increase in strength can be achieved by modifying the non circular cross section into elliptical or circular shapes. The percentage increase in strength achieved by elliptical modification was higher than rounded edged prisms as can be seen in table 5 (78% for 100 x180 mm , 69% for 130 x 200 mm and 62% for 160 x 240 mm). The results in table 4 and 5 are displayed in graphical form in fig 9 and 10. Comparison as shown in fig 11 between enhancement in strength of specimens of three shapes circular, square and rectangular of same cross sectional areas showed that the increase was largest in case of cylinders and elliptically modified rectangular prisms. It was observed that the difference in enhancement in strength in case of non circular prisms with same cross sectional areas was not significant. It was observed that the enhancement in load carrying capacity depends upon the FRP volumetric ratio. FRP volumetric ratio depends upon the no of layers of FRP, thickness of each FRP layer and the ratio of circumference to c/s area. The load carrying capacity of FRP wrapped specimens decreased with the increase in size. This is because the FRP volumetric ratio decreases as the cross sectional size increases if the no of layers are not increased as shown in table 2. A straight line curve can be plotted showing +percentage increase in strength vs. cross sectional dimensions as shown in fig 14 and 15 representing the decrease in strength with increasing size.

It is worthy to note that as the area of a particular column type increases the load carrying capacity per unit cross-section area increases. This is called pedestal effect[11]. The three cross-section area of circular columns which were used had shown that the percentage strength enhancement due to FRP decreases with increase in column cross-section area.

The reason for this behavior is the percentage of FRP layer per unit cross-sectional area of column. This percentage decreases with increase in area i.e. 115% for 150 mm dia, 90% for 180mm dia and 75% for 220mm dia.

Comparison of experimental results with analytical values calculated as per ACI 440.2R-08 and J. G. Teng

The results obtained by experiments were compared with results calculated using analytical models suggested in ACI 440.2R-08(except elliptical columns) and J. G. Teng et al. (elliptical column). The experimental values were found to be more than the ones calculated by these models. For circular samples the experimental results were found to be more than 30% more than the analytical values calculated by models (Table 6). The difference was around 20% for square columns(Table7). For rectangular columns the results varied from 20% to 40%(Table 8).

Conclusions

Based on the results obtained from the experimental investigation following conclusions have been drawn:

1. The percentage increase in strength in the case of circular columns decreases due to decrease in the percentage FRP per unit area of column cross-section. If the percentage FRP per unit column cross-section is maintained by providing adequate layers the percentage increase in strength should become independent of the column cross section. This was observed in all types of columns.
2. Significant increase in strength was achieved due to rounding of edges of non circular prisms.

3. The enhancement in axial compressive strength achieved by modifying rectangular cross sections to elliptical shapes was remarkably high. It was significantly higher than the columns with cornered radius.
4. GFRP wraps effectively increased the ductility of cylinders, non circular prisms with rounded edges and elliptically modified rectangular prisms. Non circular prisms with sharp edges showed no significant improvement in ductility. Axial stress vs. axial strain diagrams obtained showed close confirmation with idealized curve suggested by Lam and Teng.
5. GFRP wraps were able to contain the dilation of concrete for a longer period which is evident from the axial stress vs. lateral strain diagrams.
6. The experimental results were compared with the calculated values predicted by analytical models. The results have shown the conservative nature of the codes and hence the values specified in the codes are safe to use.

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Table 1 Test Matrix

Shapes		Circular (D)			Square (a x a)			Rectangular					
		C1	C2	C3	S1	S2	S3	R1		R2		R3	
								b	a	b	a	B	a
Dimensions (mm)		220	180	150	195	160	135	160	240	130	200	100	180
Area(cm2)		1521	1018	707	380	256	182	384		260		180	
No of specimens	Control	9	9	9	9	9	9	9		9		9	
	FRP wrapped with sharp corners	9	9	9	9	9	9	9		9		9	
	FRP wrapped with 3.75 cm (1.5") corner radius	-	-	-	9	9	9	9		9		9	
	FRP wrapped rectangular specimens modified to elliptical	-	-	-				9		9		9	
Total specimens for FRP wrapping		9	9	9	18	18	18	27		27		27	
Total specimens for concreting		18	18	18	27	27	27	36		36		36	

Table 2 FRP volumetric ratio for cross sections of different sizes

Shape	Size (mm)		no of layers (n)	Thickness of one layer in mm (t_f)	FRP volumtric ratio ρ_{frp}		No of layers required to maintain FRP volumetric ratio of the smallest c/s
Circular	150		1	0.353	$\frac{\pi.d.n.t_f}{\pi.d^2/4}$	0.009413	1.00
	180		1	0.353		0.007844	1.20
	220		1	0.353		0.006418	1.47
	b	h					
Square	135	135	1	0.353	$\frac{2.n.t_f.(b+h)}{bh}$	0.010459	1.00
	160	160	1	0.353		0.008825	1.19
	195	195	1	0.353		0.007241	1.44
Rectangular	100	180	1	0.353	$\frac{2.n.t_f.(b+h)}{bh}$	0.010982	1.00
	130	200	1	0.353		0.008961	1.23
	160	240	1	0.353		0.007354	1.49

Table 3 Results of axial compression test on control and GFRP wrapped cylinders

Diameter (D) (mm)	150		180		220	
	Control	GFRP wrapped (single layer)	Control	GFRP wrapped (single layer)	Control	GFRP wrapped (single layer)
Characteristic stress (N/mm^2)	24.78	53.29	26.18	46.43	28.44	49.59
Percentage increase in strength over control specimens	-	115.08	-	91.42	-	74.33

Table 4 Results of axial compression test on control and GFRP wrapped square prisms

Size (axa)(mm)	135 x 135			160 x 160			195 x 195		
	Control	Sharp edged GFRP wrapped (single layer)	Rounded edged GFRP wrapped (single layer)	Control	Sharp edged GFRP wrapped (single layer)	Rounded edged GFRP wrapped (single layer)	Control	Sharp edged GFRP wrapped (single layer)	Rounded edged GFRP wrapped (single layer)
Characteristic stress (N/mm2)	24.13	35.42	41.88	26.56	31.18	37.12	28.63	34.32	37.91
Percentage increase in strength over control specimens	-	46.78	73.55	-	29.28	53.14	-	19.89	32.42
Percentage increase in strength of rounded edged specimens over sharp edged specimens			18.24			19.05			16

Table 5 Results of axial compression test on control and GFRP wrapped rectangular prisms

Size (bxa) (mm)	100 x 180				130 x 200				160 x 240			
	Bare	sharp edged wrapped (single layer)	rounded edged wrapped (single layer)	Elliptical modified GFRP wrapped (single layer)	Bare	sharp edged wrapped (single layer)	rounded edged wrapped (single layer)	Elliptical modified GFRP wrapped (single layer)	Bare	sharp edged wrapped (single layer)	rounded edged wrapped (single layer)	Elliptical modified GFRP wrapped (single layer)
Characteristic stress (N/mm^2)	23.35	34.54	38.46	41.74	25.53	31.7	37.95	43.1	28.16	32.1	36.68	45.62
Percentage increase in strength over bare specimens		47.95	64.74	78.77		24.19	48.65	68.81		14.02	30.28	62
Percentage increase in strength of rounded specimens over sharp edged specimens			11.35				19.72				14.27	
Percentage increase in strength of elliptical specimens over rounded edged specimens				8.5				13.6				24.37

Table 6 Comparison of values of circular specimens

Diameter (mm)	Experimental Value (MPa)	Value calculated as per ACI 440.2R-08 (MPa)
150	54.13	40.21
180	48.51	37.77
220	51.10	35.55

Table 7 Comparison of values of square specimens

Size (mm)		Experimental Value (MPa)	Value calculated as per ACI 440.2R-08 (MPa)
135 x 135	Sharp edge	39.6	29.40
	Rounded edge	42.94	35.55
160 x 160	Sharp edge	33.8	28.81
	Rounded edge	39.82	33.46
195 x 195	Sharp edge	36.02	28.22
	Rounded edge	39.34	31.52

Table 8 Comparison of values of rectangular specimens

Size (mm)		Experimental Value (MPa)	Value calculated as per ACI 440.2R-08 (MPa)
100 x 180	Sharp edge	36.54	26.67
	Rounded edge	38.36	28.45
	*Elliptical	65.39	31.82
130 x 200	Sharp edge	32.06	26.87
	Rounded edge	38.83	28.72
	*Elliptical	65.41	31.95
160 x 240	Sharp edge	33.60	26.50
	Rounded edge	38.57	28.10
	*Elliptical		30.96

* Values of elliptical specimens calculated as per analytical model suggested by J G Teng

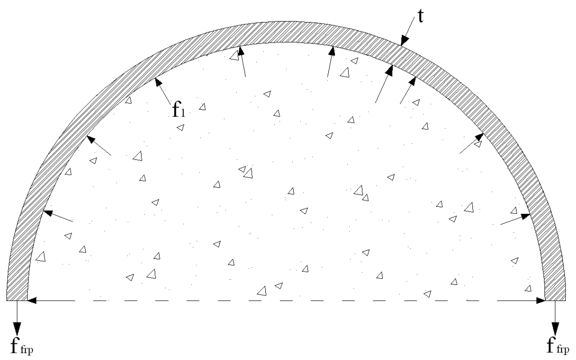

Fig 1 Lateral confining pressure in cylinders

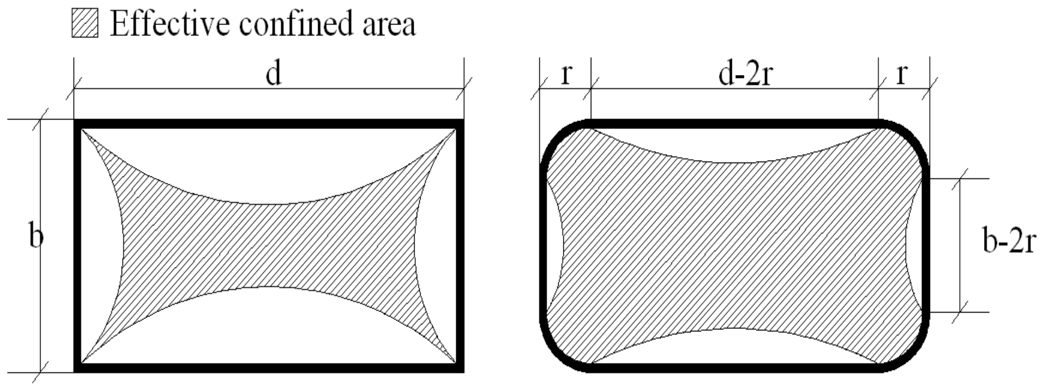

Fig 2 Effective confined areas of sharp edged and rounded edged wrapped non circular c/s

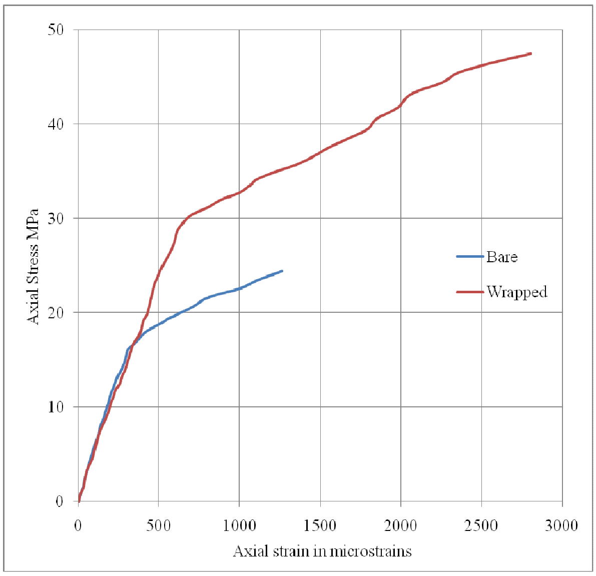

Fig 3: Axial stress vs. axial strain graph for 180 dia circular cylinder

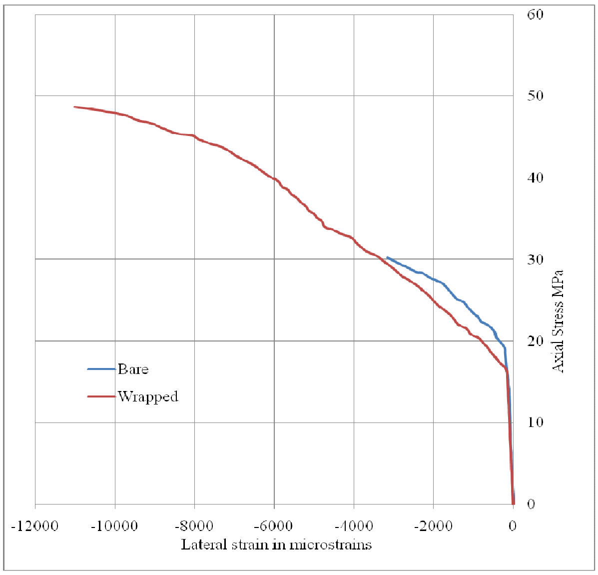

Fig 4: Axial stress vs. lateral strain graph for 220 dia circular cylinder

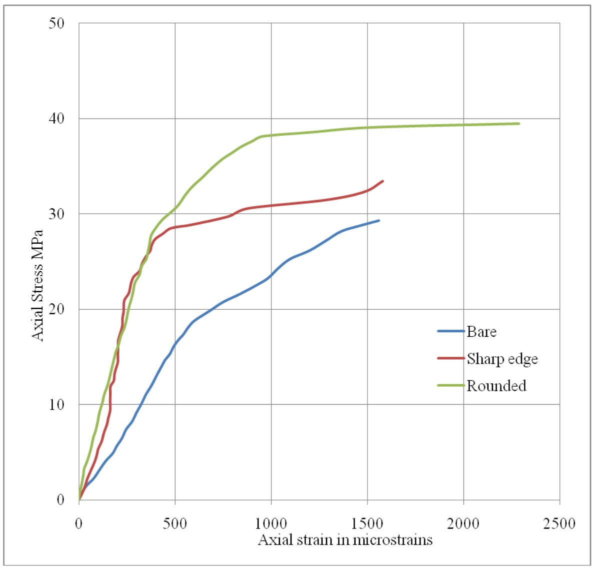

Fig 5: Axial stress vs. axial strain graph for 160 mm square prism

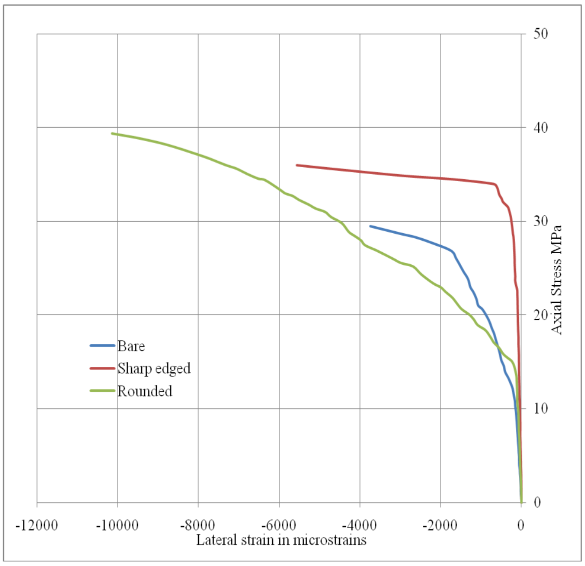

Fig 6: Axial stress vs. lateral strain graph for 195 mm square prism

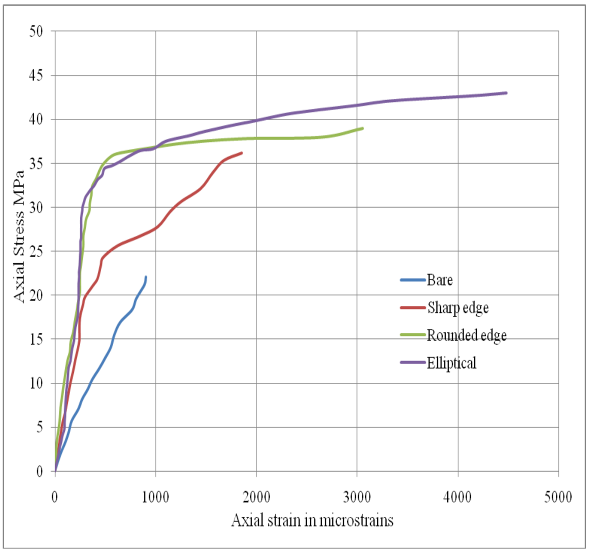

Fig 7: Axial stress vs. axial strain graph for 100 x 180 mm rectangular prism

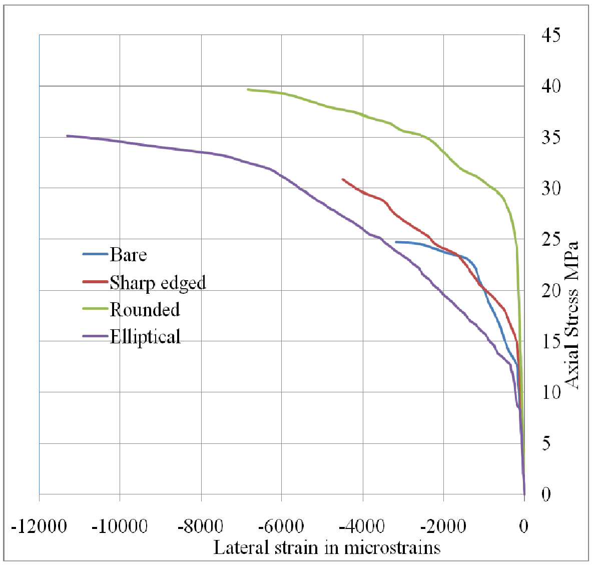

Fig 8: Axial stress vs. lateral strain graph for 130 x200 mm rectangular prism

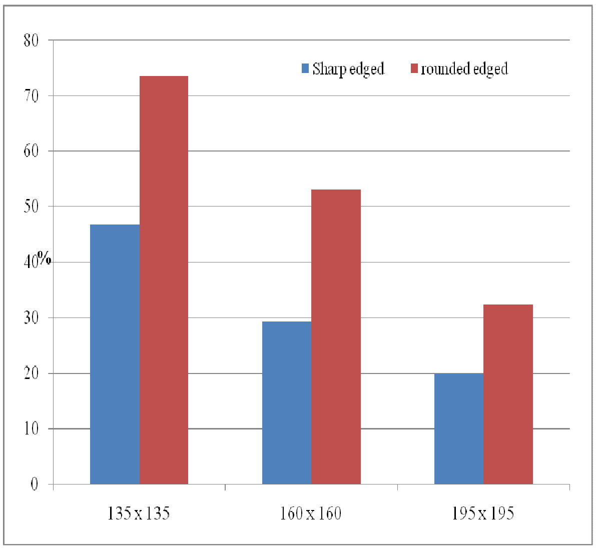

Fig 9: Comparison of percentage increase in strength of square prisms

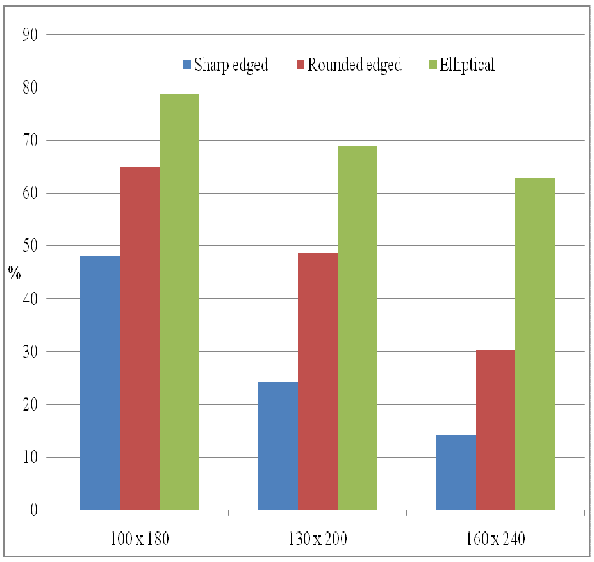

Fig 10: Comparison of percentage increase in strength of rectangular prisms

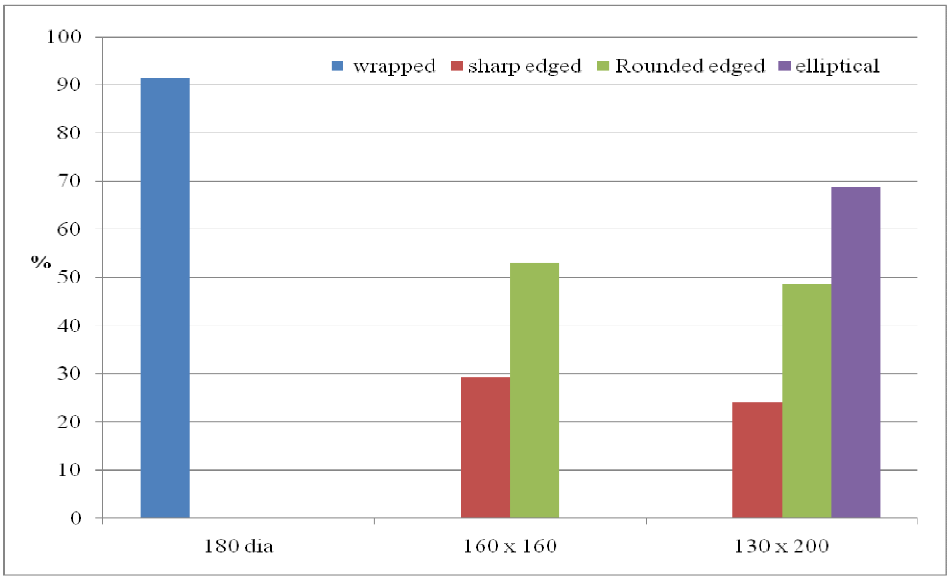

Fig 11: Comparison of percentage increase in strength of specimens of same areas

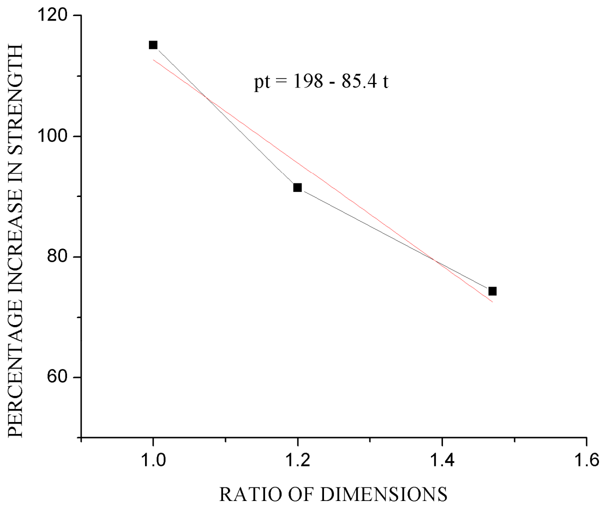

Fig 12: Percentage increase in strength vs. ratio of dimensions of cylinders

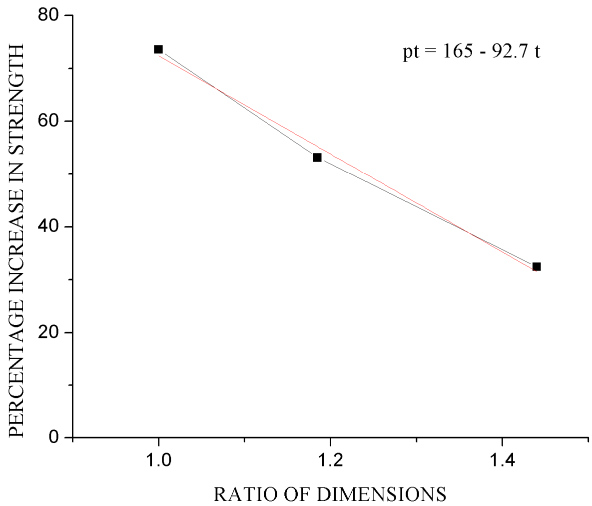

Fig 13: Percentage increase in strength vs. ratio of dimensions of square prisms

pt = percentage increase in strength of GFRP wrapped specimens over their respective control specimens

t = ratio of the specimen dimension to the smallest dimension of the shape

Fig 14 GFRP wrapped cylinder 150 mm in diameter failure due to tearing of fibers

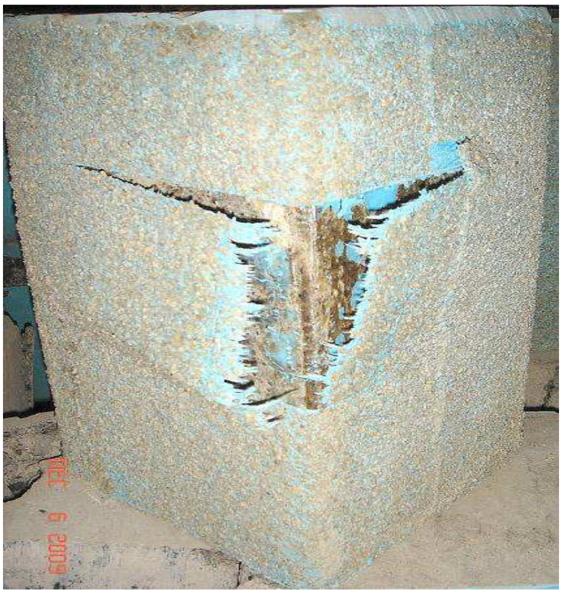

Fig 15 GFRP wrapped square prism with sharp edges 130 x 200 mm in size failure of fibers at corners due to stress concentration

Fig 16 GFRP wrapped square prism with rounded edges 100 x 180 mm in size

Fig 17 GFRP wrapped square prism with rounded edges 195 x 195 mm in size