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Behavior of Different Shape of Concrete Prism Strengthened with FRP Material under Compressive Axial Load

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Abstract: This paper presents experimental investigation undertaken to evaluate the effects of strengthening using glass and carbon fiber reinforced polymers(GFRP and CFRP) on the strength capacity of concrete. A total of 17 concrete prisms, of three different sizes (100×100×300mm, 100×150×300mm, 150 diameter ×300mm long concrete cylindersstrengthened with FRP wrapping materials were tested under compressive loading. Different shapes were studied to determine the changes in strength of concrete samples. The performance of different wrapping materials with different configurations was examined to find criterions governing modes of failures. The influence of key parameters including the size and corner shape of the prisms and type of the wrapping material are discussed.Test results indicates that the compressive strength of the samples increase significantly when strengthened by using FRP materials.Higher compressive strength was found for all CFRP samples compared to specimens wrapped with GFRP fabrics. Among of the different shapes, cylindrical specimens show the highest strength than all other types of specimens.

Key words: Concrete prism, glass fiber-reinforced polymer,carbon fiber-reinforced polymer, compressive strength, wrapping materials

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INTRODUCTION

Fiber Reinforced Polymer (FRP) Composites are defined as: “A matrix of polymeric material that is reinforced by fibers or other reinforcing material” (Grace *et al.*, 2004). Polymers, reinforcing fibers, fillers, and other additives are the main ingredients of the composite materials and each of them plays an important role in the performance of the final product (Neale and Labossiere, 1991). The application of FRP materials for repair and strengthening of civil engineering structures are being progressively studied in recent years. In general, FRP offerslow density, high stiffness and strength, excellent resistance to corrosion, and a very low coefficient of thermal expansion in the fiber orientation (Heffernan, 1997).

Garden and Hollaway(1998) have described FRP materials as having numerous advantages, including superior weather resistance, corrosion resistance, thermal insulation properties, and particularly tensile and fatigue strength.However, the high material cost of FRP composites, restricted deflections, and unknown long-term performance have for many years limited the use if FRP for civil engineering structures(Neale and Labossiere, 1991). Despite declining prices in composites as a result of improved manufacturing processes, FRP still remains relatively expensive when compared to traditional materials (Meier, 1992).

Several FRP systems are now commercially available for the external strengthening of concrete structures. Fiber materials commonly used in these systems include glass, aramid, and carbon. Of these, glass fiber represents the predominant reinforcement because of its relatively low cost and good balance of properties. The fibers are available in many forms such as pultruded plates, uniaxial fabrics, woven fabrics and sheets. Although, FRP are more effective for flexural strengthening rather than shear strengthening due to its anisotropic properties, shear strengthening can be achieved if the fiber orientation is changed.

In some cases, it is necessary to change the existing structural system due to the change of usage rather than rebuilt a new structure. A common example is the appearance cracks on the beams or columns in the structure or crack occurs at the beams with the increase of load due to stress concentration. The application of FRP reinforcement is able to overcome this problem. However, the choice on whether to use a sheet or laminate system is based on the application, cost and designers preference.

In this experimental study, the effects of GFRP and CFRP fabrics on the strength capacity of the concrete, changes in the concrete strength due to the different shapes of the concrete specimens were investigated.The objectives of this study are:

i) To investigate the behavior of concrete sample strengthened with CFRP and GFRP under compression

ii) To determine the mode of failure of the control concrete sample and the strengthened concrete sample (strengthening with CFRP and GFRP)

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Literature Review:

Bond Mechanism:

Chajes *et al.,* (1996) performed a single lap shear test to study bond and force transfer mechanism in strengthening concrete members through externally bonded plates. Different tests were carried out to study the possible effects of concrete strength, surface preparation, and type of adhesive on the average bond strength. Two failure modes were observed: direct concrete shearing beneath the concrete surface and cohesive-type failure, depending on the type of adhesive. Their findings showed that the concrete surface preparation was the most effective wayfor improving the average bond strength and no further increase in failure load can be achieved beyond the effective bond length. They also found that if the failure mode of the joint is governed by shearing of the concrete, the ultimate bond strength will be proportional to the square root of compressive strength of concrete.

Horiguchi *et al*. (1997) investigatedthe bond behavior of CFRP sheets under the influence of different concrete strengths and test methods (namely, direct tensile test, flexural, and shear test). The largest average bond strength resulted in tensile test, followed by lower bond strength in the flexural test. The lowest average bond strengths were observed in the shear test. Three failure mechanisms were identified: shearing of the concrete, delamination and FRP rupture. It was found that in concretes with low compressive strength (24.8MPa), the failure occurred in the concrete. By increasing the compressive strength of the concrete the failure mode changed to delamination of the fibers. The rapture of the FRP sheets was observed in the flexural tests with higher strength of concrete. In addition, the bonded length did not have any effect on the ultimate load of the sheet.

Brosens and Van Gemert (1997) employed two concrete prisms externally connected with 3 layers of CFRP on two opposite sides. The findings showed that an increase in bonded length increases the failure load. This is contrary to findings of other researchers. However, they did find a reduction in effectiveness of the bonded lengths at longer lengths. They concluded that for computational purposes a linear bond stress distribution in the FRP sheet may be assumed.

Maeda *et al*. (1997) studied the effects of number of FRP layers, type of FRP material, and bonded length on the bond strength. Test results showed that, as the stiffness of the fiber sheet increases, the ultimate load increases. Their finding showed the ultimate strength of FRP sheets for bonded lengths over 100mm did not change, implying the existence of an effective bond length.

Confinement:

Confinement of compression concrete is an effective approach to improve column deformability. Saadatmanesh *et al*. (1994) conducted a research on reinforced concrete columns externally wrapped with FRP composite straps. In the experimental studystress-strain model proposed by Mander *et al*. (1988) was used to assess the effect of FRP confinement on strength and ductility of concrete columns. Their findings showed that FRP composite straps significantly increased the axial strength and ductility of concrete members.

Tan (2002)studied the use of FRP systems in strengthening of rectangular columns with aspect ratio of 3.65. They investigatedthe effect of fiber type and configuration, and the presence of plaster finishes on the strength enhancement off the columns. It was concluded that transverse fiber sheets led to an increase in the axial load capacity of the column by confining the concrete.If adequately confined by outer transverse fiber sheets the delamination of the fiber sheets is more likely to occur in the case of glass fiber fabric than for carbon fiber sheets for the systems investigated in the study.

Saadatmanesh *et al*. (1996) conducted an experimental program to study the seismic behavior of circular columns strengthened with GFRP composite straps. Both active and passive retrofit methods were tested in this experiment and specimens were tested in a steel reaction frame. It was concluded that the strength and displacement ductility of circular column externally wrapped with GFRP composite straps improved significantly as a result of the confining action of the straps. The straps are highly effective in confining the core concrete and preventing the longitudinal reinforcement from buckling under cyclic loading. It was also reported that both active and passive retrofit schemes provided additional confinement.

Matrix Properties:

The matrix serves as a bonding agent of the composite. Its main function is to protect the fibers from environmental attack and damage due to handling. It also transfers applied loads between fibers through shearing stresses. The most common matrix material used is resin, which includes polymers and epoxies. Resin matrix generally has low strength, low modulus and poor mechanical characteristics. Its behavior is dependent on the duration, rate and frequency of loading, and the ambient temperature. When load is maintained over a long period of time, creep will appear. At high rate of loading, the stress-strain curve appears to be linear, whereas at low rate of loading the behavior is nonlinear (Meier, 1987).

Effects of Cross-Section:

Shape of cross-sections of columns can directly affect the confinement effectiveness of externally bonded FRP jackets. According to the previous study enhancement on axial compressive strength and ductility for square or rectangular columns with sharp corners and flat sides is less effective compared to circular ones. This reduction in effectiveness of confinement may be due to the stress concentrations at the corners or inefficient confinement at the flat sides. Therefore, a possible approach to increase the confinementlevel is to modify the cross section of the column to a circular section (Rochette and Labossiere, 2000).

Masia*et al*. (2004)studied the ductilityand compressive strength of axially loaded square concrete prisms confined with CFRP wrapping. Test results showed that a significant increase in strength and ductility was achieved by CFRP wrapping.They also reported that the strength, strain and effectiveness of the confinement reduced with increase in cross sectional area.

Yang *et al*. (2001) studied the effect of corner radius on the performance of externally bonded FRP reinforcement. It was found that corner radius plays an important role on the performance of the CFRP laminates and as the corner radius decreases, the efficiency of the FRP wrapping also decreases. They also reported that multiple placements of FRP plies slightly improve the efficiency of the laminate except for the square or rectangular section.

Kim *et al*. (2003) conducted compression tests on concrete specimens confined with Carbon Fiber Sheet (CFS) to investigate the effect of various cross-sectional shapes (i.e. square, octagonal and circular) oncompressive strength of concrete members.Theyconcluded that circular section is most effective in load carrying capacity whereas square section is least effective.Test results also showed that octagonal and circular specimens have similar axial strengths for various lamination angles.

Rochette and Labossiere (2000) indicated experimentally that FRP confinement for square and rectangular specimens is much less effective in increasing the compressive strength and ductility compared to the circular ones. They also found that an increase in the radius of the column corner increases the axial compressive strength and ductility of the specimens.

Outline of the Test Program:

Materials:

In this study Ordinary Portland Cement (OPC) was used. The type of water used in this project was ordinary tap water. Water obtained for this experiment was of tap water from the material sand structure laboratory with the quality of the drinking water confirming to the general requirement of mixing water for concrete mix.

Aggregates for concrete mix are classified into two types, coarse and fine aggregates. Concrete containing coarse aggregate will generally have superior strength and inferior workability because of its high density, although the coarse aggregate has considerably less influence on the workability than the fine aggregate. Aggregates composed primarily of silica; quartz, granite and good limestone. In this project the maximum size of aggregate used was 10mm. Fine aggregates or sand used in this experiment has gone through a sieving process complying with BS 882: Part 2 1989. All of the fine aggregates used have to be air dried at least 24 hours before being used for mixing concrete. The grading limits for fine aggregates are shown in Table 1.

Table 1: Grading limits for fine aggregates as stated in BS 882: Part 2 1989.

Sieve Size	Percentage by mass passing BS sieve			
	Overall Limits	Additional limits for grading		
		C	M	F
10mm	100	-	-	-
5mm	89 to 100	-	-	-
2.36mm	60 to 100	60 to 100	65 to 100	80 to 100
1.18mm	30 to 100	30 to 90	45 to 100	70 to 100
600μm	15 to 100	15 to 54	25 to 80	55 to 100
300μm	5 to 70	5 to 40	5 to 48	5 to 70
150μm	0 to 15	-	-	-

Concrete Mix Properties:

In this project all specimens were made of the same concrete batch. Concrete with Grade was made according to British standard. The concrete mix proportion was designed based on the Department of the Environment (DOE) method.Referring to DOE method the water/cement ratio designed was 0.62 and the water value according to this method is 230 kg/m^3. The OPC was used with the cement content of 370 kg/m^3. The amounts of coarse and fine aggregates used in the concrete mix were 827 kg/m^3, and 971 kg/m^3, respectively.

FRP Materials:

The woven roving XD-600 FRP sheets were employed in the study as shown in Figure 1. FRP comprises of epoxy, glass fibers, and additives. One of a group of synthetic resins which undergo polymerization during curing of polyester has excellence adhesive properties, high strength, good chemical resistance, especially used in laminating and impregnating materials.

The size of CFRP and GFRP layers were equal to the external perimeter of specimens plus 50mm for overlapping to prevent of any bonding failure under the pressure. After mixing the hardener and resin, the FRP materials were glued to the surface of specimens.

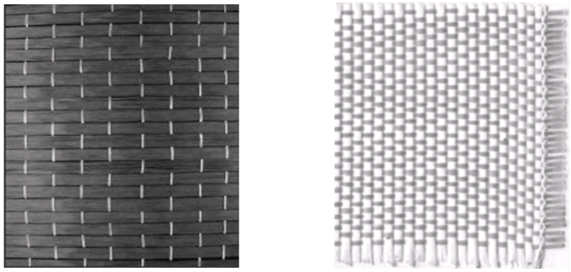

(a) Unidirectional CFRP (b) Woven Roving GFRP

Fig. 1: FRP Wrapping Materials.

Preparations of Samples:

A total number of 17 rectangular, square and cylindrical samples were made with the dimension of 100×100×300mm, 100×150×300mm, and 150×300mm, respectively, as presented in Figure 2 and Table 2.

Table 2: The type of content samples cast and tested.

Sample Shape	Square Sharp Corner	Square Circular Corner	Rectangular Sharp Corner	Rectangular Circular Corner	Cylinder
Area (mm^2)	10000	9800	15000	14800	17662
Control Specimen	1	1	1	1	1
7 day test	1	–	1	–	1
CFRP Continuous	1	1	1	1	1
CFRP Intermittent	–	–	–	–	1
GFRP Continuous	1	1	1	1	1
CFRP Intermittent	–	–	–	–	1
Total No. of Samples	4	3	4	3	6

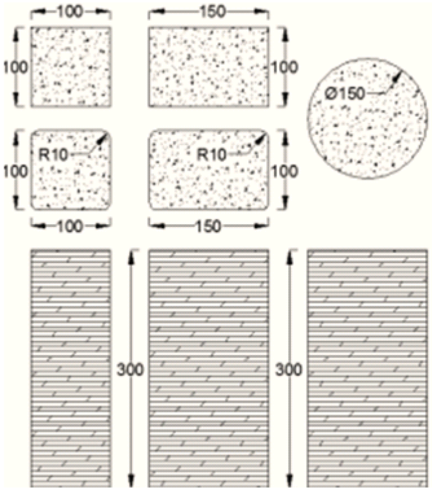


Fig. 2: Dimension of Variables.

Samples were demouldedafter 24 hours and cured in water tank. Then, control specimens were tested underaxialcompressive loadingafter 7 days of curing (see Table 3). After 14 days samples were taken out of the water and the surface of samples were smoothed and cleaned by hand grinder (see Figure3). The cleaning process has an important role because of preventing the creation of bubbles between the FRP wrapping materials and concrete and for sticking the FRP, the surface must be completely clean and smooth.The resin ingredient was mixed under room environment according to manufacturer specifications. To wrap FRP laminates, resin was mixed by addition of up to 60% of hardener Part B to the resin Part A. Blending ratio is 10 part of resin to 6 parts of hardener by weight. A paint roller was used to wet-out the concretesurface and fiber laminates. Finally, wet FRP laminates were wrapped around the concrete prism. The samples were then tested under axial compression.

Table 3: Compressive strength of Control Specimens.

Sample	Dimension (mm)	7 Day Compressive Strength (MPa)
Rectangular Sharp Corner	100×100×300	20.5
Square Sharp Corner	100×150×300	19.3
Cylinder	150×300	22.4


(a) Sharp Edge Sample (b) Round Edge Samples

Fig. 3: Sharp and Round Edged Samples.

Sample Notation:

17 specimens were used to address all selected variables, using the notation shown in Table 4.

Table 4: The notation of samples in this study.

No.	Samples	Notation
1	Control -Sharp Corner	Ctrl-SC
2	Control -Circular Corner	Ctrl-CC
3	CFRP -Sharp Corner	CFRP-SC
4	CFRP -Circular Corner	CFRP-CC
5	GFRP -Sharp Corner	GFRP-SC
6	GFRP -Circular Corner	GFRP-CC
7	Control –Cylindrical	Ctrl-CY
8	Cylindrical wrapped with Continuous CFRP	CY-CFRP-C
9	Cylindrical wrapped with Intermittent CFRP	CY-CFRP-I
10	Cylindrical wrapped with Continuous GFRP	CY-GFRP-C
11	Cylindrical wrapped with Intermittent GFRP	CY-GFRP-I

RESULT AND DISCUSSION

A total of 17 specimens including control specimens were tested until failure under incremental axial compressive load. The effects of the main parameters such as shape of the specimens, wrapping materials on the level of strengthening and confinement were investigated. This research indicates a significant improvement of the concrete strength in the presence of FRP wrapping layers.

Modes of Failure:

FRP-strengthened concrete prisms may be subjected to unfavorable failure modes in addition to crushing of concrete, such as rupture and debonding of FRP laminates. According to the test results, mode of failure is dependent on the shape of the specimens and type of the wrapping material. The general modes of the failure can be explained as follows:

i) Crushing of concrete
ii) Debonding of FRP
iii) Rupture of FRP

Since there is a stress concentration at the corners of sharp specimens, the cracks begin at those regions as shown in Figure 4(a). While, the stresses of the round corner samples decreaseat their cornersdue to the concentration of stress transfer from corner to the center of sample, thus the cracks were created in center of samples generally as shown in Figure 4(b).

In the perfect composite action between FRP laminates, debonding failure may invalidate the stress transfer from concrete substrate to FRP reinforcement and cause undesirable premature failure prior to the theoretically expected load. Debonding failure was initiated by crushing of the concrete.FRP laminate is expected to debond upon exhausting the cohesion resistance of the interface. The specimens reinforced with FRP laminates failed by concrete crushing followed by laminate debonding originating at the laminate ends. Debonding failure is significantly influenced by crack spacing due to the concrete crushing.

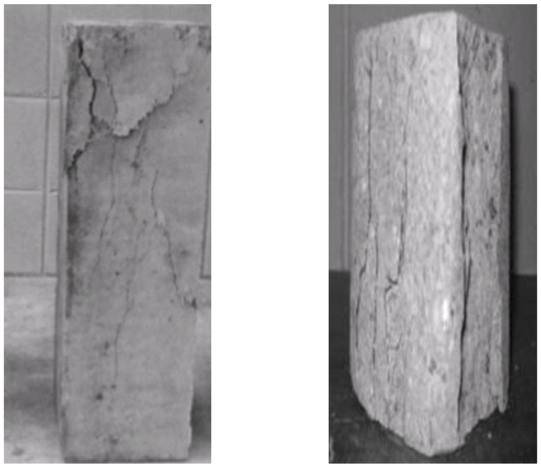

(a) (b)

Fig. 4: Modes of failure in sharp (a) and round corner (b) sample.

Rupture of the FRP layers initiates at a location of stress concentration or weakness following which FRP laminates expands toward the ends of the specimen along its length due to gradual FRP rupture. Such debonding follows two possible paths: along the interface between adhesive layer and concrete substrate or through the concrete substrate adjacent to the bond interface.

Failure of FRP-wrapped specimens was governed by rupture of the FRP in the hoop direction. Fully wrapped specimens usually fail due to this mode of failure, commonly preceded by gradual debonding of the FRP from the sample sides. As the axial concrete strain increases under load, the confining stress keeps increasing with the expansion of concrete until rupture of a FRP due to its linear elastic-brittle properties.Generally, a specimen is assumed to completely losethe load capacity when rupture of the FRP wrapping is observed.

The Effect of Cross-Section Shape on Load Capacity:

Control square and rectangular samples with sharp and round corners were tested under compressive loading. Crushing of the concrete happened due to the vertical compression.The maximum ultimatestrength observed was 12.30MPa for square sample with round corners. Test results are presented in Table 5. Compared to the samples with sharp corners, there is a difference in load carrying capacity attributed to the difference in effective cross section and distribution of the stressof the round corner samples. In sharp corner specimens the stress concentration isatedges of the samples, but in rounded corner specimens the concentration of the stress is in the central parts of the samples.

Table 5: Summary of the Test Results.

Sample	Material	Dimension (mm)	Area (mm^2)	Ultimate Load (kN)	Compressive Strength (N/mm^2)
Ctrl-SC	–	100×100×300	10000	205.00	20.50
GFRP-SC	GFRP	100×100×300	10000	284.80	28.48
CFRP-SC	CFRP	100×100×300	10000	308.80	30.88
Ctrl-CC	–	100×100×300	9657	205.69	21.30
GFRP-CC	GFRP	100×100×300	9657	298.21	30.88
CFRP-CC	CFRP	100×100×300	9657	325.54	33.71
Ctrl-SC	–	100×150×300	15000	289.50	19.30
GFRP-SC	GFRP	100×150×300	15000	397.05	26.47
CFRP-SC	CFRP	100×150×300	15000	426.45	28.43
Ctrl-CC	–	100×150×300	14657	303.40	20.70
GFRP-CC	GFRP	100×150×300	14657	425.20	29.01
CFRP-CC	CFRP	100×150×300	14657	461.55	31.49
Ctrl-CY	–	150×300	17671	395.83	22.40
CY-GFRP-C	GFRP	150×300	17671	603.46	34.15
CY-CFRP-C	CFRP	150×300	17671	654.71	37.05
CY-GFRP-I	GFRP	150×300	17671	547.98	31.01
CY-CFRP-I	CFRP	150×300	17671	610.18	34.53

For the square and rectangular specimens, the results of this experiment also indicate that as the cross section of samples decreases, the compressive strength increases.

In the strengthened samples two different kinds of behavior were recorded on CFRP and GFRPwrapping layers. The results show that CFRPsharp corner samples rupture occurs at onecorner,whileGFRP sharp corner sample was ruptured on four corners as shown in Figure5(a) and Figure 5(b), respectively.

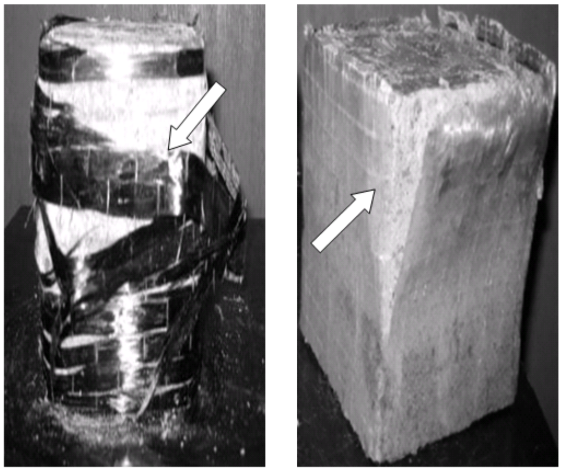

(a) CFRP Material (b) GFRP Material

Fig. 5: Mode of Failure of Sharp Corner Specimens Strengthened with CFRP and GFRP Material.

The failure in the round corner samples strengthened by FRP materials observed was in the center of the specimens due to reduction in concentration of stress at edges of prisms. After applying the load, external surface of sample starts to expand,caused by the vertical stress as shown in Figure 6(a) and Figure 6(b).Table 5 clearly shows that the confinement effectiveness increased gradually by rounding corners of concrete prisms.

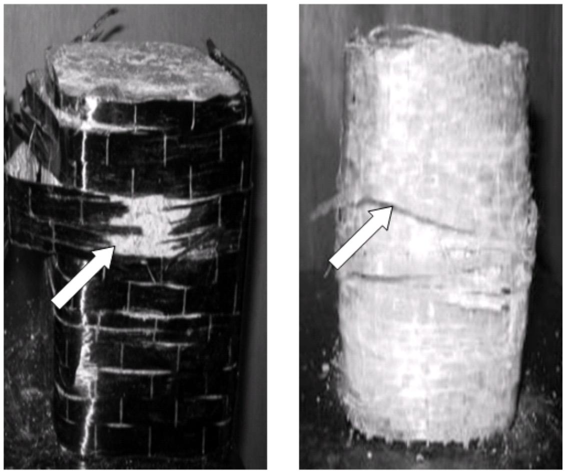

(a) (b)

Fig. 6: Mode of Failure of Round Corner Specimens Strengthened with CFRP and GFRP Material.

Comparison of Wrapped and Unwrapped Specimens:

The maximum compressive strength was observed inspecimens wrapped with CFRP laminates. The strength of sharp corner samples strengthened with CFRP increased up to 51% and the different shapes of the samples have significant effect on the strength of the specimens. Round corner CFRP specimens experienced an increase in compressive strength between 52% and 58% as shown in Table 5. All of the specimens failed when the fibers ruptured and the failure occurred suddenly due the brittle behavior of the composite materials.

Based on the results, compared to the GFRP samples, CFRP specimens have higher strengthcompare to GFRP samples. The result of this research demonstrated that the CFRP fabric has more impact to increase the strength of concrete than GFRP fabric.The outcome of this studyshowed that the compressive strength of the specimens wrapped with GFRP layers increased by 37% to 45%. Compared to samples strengthened with unidirectional CFRP, woven roving GFRP specimensshowedaround 13%lower valuesin strengthening of concrete prisms.Therefore, it can be concluded that the strength increase in the axial direction of the prism, before reaching the ultimate loadingwill be affected by the orientation of the woven glass fibers parallel to the applied load.

Ultimately both types of prisms failed by FRP ruptured but the rectangular prisms failed first in concrete crushing followed by FRP rupture. If debonding does not occur then the ultimate compressive strength of the section will be reached when failure occurs due to rupture of FRP or crushing of concrete.

Cylindrical Specimens:

Cylindrical specimens attained the highest compressive capacity among all specimens.Strengthening of cylindrical specimens implemented by two methods, continuous and intermittent wrapping. Test results indicated the effectiveness of continuous method in which the maximum compressive strength was observed.

Test results showed that as axial pressure increased, until it exceeded concrete compressive strength, lateral deformation of non-confined concrete increased and reached a stage from unconfined to confined concrete. Finally, lateral deformation kept increasing with the increase of load, until FRP was raptured and specimen was crushed.

Compressive strength of cylindrical specimens wrapped with GFRP laminates, increased about 38% and 52% for intermittent and continuous wrapping method, respectively (see Figure 7(a) and 7(b)). The main reason for changesin strength of concrete is expansion of cylinder in unwrapped regions due to thecompressive loading. Furthermore,unwrapped regions between FRP fabrics caused the stress concentration and concrete failure which cause lower strength than continuous wrapping method as shown in Table 5.


(a) Intermittent (b) Continuous

Fig. 7: Cylindrical Specimens Strengthened with GFRP Materials.

The improvement of compressive strength of the samples wrappedwith CFRP ishigher than GFRP due to the higher properties of carbon fibers (see Figure 8(a) and 8(b)). The concrete compressive strength wrapped with intermittent and continuous CFRP laminates increased around 54% and 65%, respectively, as shown in Table 5.

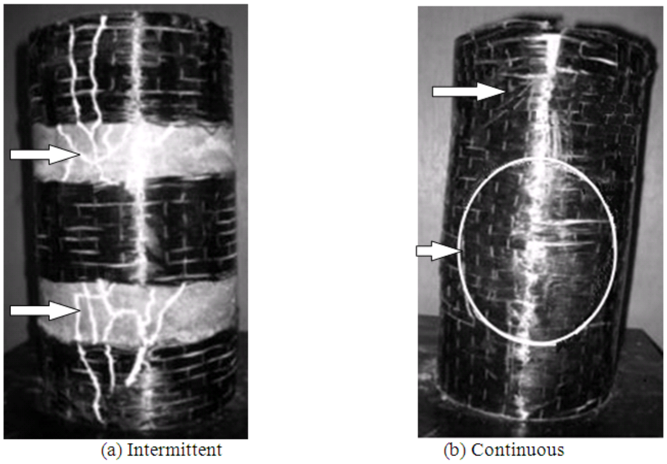
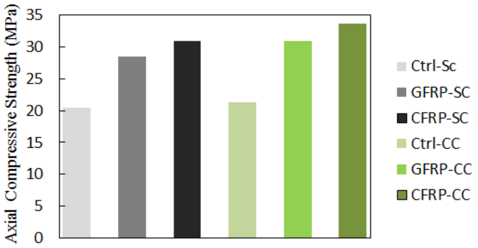
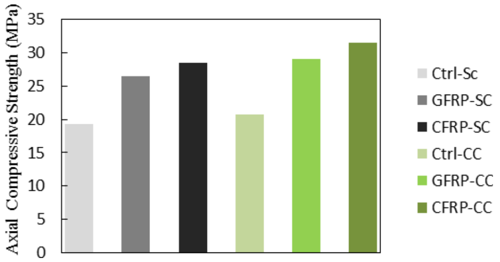

(a) Intermittent (b) Continuous

Fig. 8: Cylindrical Specimens Strengthened with CFRP Materials.

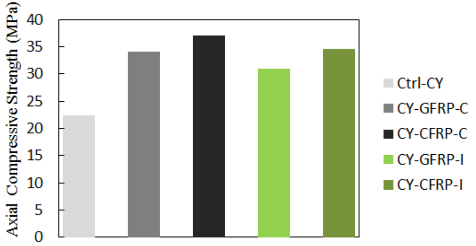
In cylindrical specimens, the cracks were observed near the mid-height of the cylinder and cracking followed by fiber rapture in regions of extensive cracks, while for the square and rectangular specimens, these cracks appeared only along the edges, where stress concentration was present.This may be due to the distribution of confining pressure in circular and square sections. For circular sections, the confining pressure is uniform, and is a function of hoop strength of the jacket. On the other hand, for square and rectangular sections, the confining pressure varies from a maximum at the corners to a minimum in between the edges. The confining pressure at the corners is due to the membrane action in the transverse sides of the tube, whereas at other points it depends on the flexural rigidity of the FRP composite. Therefore, both the corner radius and the dimensions of the tube affect the level of confinement exerted on the concrete core. The effects of size and wrapping materials are shown in Figures 9(a) to 9(c).



(a) 100×100×300mm



(b) 100×150×300mm



(c) R150×300mm

Fig. 9: The Effects of Size and Wrapping Materials on Peak Axial Compressive Strength.

Conclusion:

Based on the results of the study, the following conclusions can be made:

1. The strength of concrete specimens can be increased to some extent by using FRP wrapping materials. The percentage of the strengthincreaseof samples, strengthened with CFRP is about 52-58%. The percentage of strength increase forprisms strengthened with GFRP is about 37 - 45 %.
2. The strengthof samples with GFRP materials were 13% lower than CFRP prisms due to the higher properties of the carbon fibers. All of samples strengthened by CFRP ruptured just in one edge but the samples strengthened by GFRP ruptured more than one edge.
3. Square and rectangular samples with rounded cornersshowed an increase in the load carrying capacitybecause the failure of the fabrics was not at the corner of the samples. The reinforced circular corner sample had more strength than the reinforced sharp corner.
4. Cylindrical specimens attained the highest compressive strength capacity among all specimens.Mode of failure for cylindrical samples strengthened with intermittent wrapping occurred in between wrapping layers and as a result they reached 15% lowercompressive strength compared to the samples strengthened by continuous wrapping method.
5. The mode of failure in this study shows that the 50 mm over lapping is sufficient for the strengthening.

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