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CFRP Strengthening of plain and reinforced concrete members

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ABSTRACT: Reinforced concrete structures can deteriorate for different reasons, among them are cracking, carbonation and chloride attack. Reinforced concrete can be considered to have failed when significant cracks occur. Cracking of the concrete section can not be prevented; however, the size of the cracks can be limited and controlled by reinforcement. Cracking defects can allow moisture to penetrate and corrode the reinforcement. Increasing resources are deployed to maintain aging structures due to such deterioration and cracking. Furthermore, increasing demands on existing infrastructure require it to be improved. Strengthening and retrofitting are therefore a major area in civil engineering and it is important to develop inexpensive and efficient strengthening techniques. The governments and the private sector are spending heavily on retrofitting and upgrading aging infrastructure and buildings. The recent upgrade of concrete and steel bridges worldwide are contemporary examples for this. Also, a number of buildings have been retrofitted recently. In Australia for example, many buildings has been retrofitted including but not limited to: Mercedes Benz Building in South Melbourne, City Link-Burnley Street Viaduct in Melbourne, Northgate Westfield shopping town in NSW, Princess Alexandria Hospital in Brisbane, BHP-Billiton Pellet Plant in Whyalla in South Australia. In the UAE, a number of buildings have been retrofitted but no bridges as they are relatively new. The main aim of this paper is to summarise recent experimental research findings performed at Dubai Mens College for CFRP strengthened concrete members.

Three types of experiments were performed on strengthened plain and reinforced concrete beams, slabs and columns. It was found that the beams strengthened diagonally exhibited the best performance. Ultimate failure leading to collapse was found to be caused by either one or combination of the following factors: crushing of the concrete, delamination of CFRP laminates, tensile fracture of the matrix, tensile fracture of the fibers when stresses exceed its strength; yielding of the rebar; or by bond failure between the concrete and the rebar. Among the findings for the strengthened slabs, the increase in bending strength decreased with increasing the internal reinforcement of the slab before strengthening. The maximum increase in the strength of the unreinforced beams, slabs and columns was 490%, 114%, and 50%. These values decreased as the reinforcement ratio increased. It was also found that the optimum number of raps is two for confining circular columns if the CFRP sheets were to be applied in a single day.

1 INTRODUCTION

Reinforced concrete structures can deteriorate for different reasons, among them are cracking, carbonation and chloride attack. Reinforced concrete can be considered to have failed when significant cracks occur. Cracking of the concrete section can not be prevented; however, the size of the cracks can be limited and controlled by reinforcement. Cracking defects can allow moisture to penetrate and corrode the reinforcement. Carbonation, or neutralization, is a chemical reaction between carbon dioxide in the air with calcium hydroxide and hydrated calcium silicate in the concrete. The water in the pores of Portland cement concrete is normally alkaline with a pH in the range of 12.5 to 13.5. The rate of carbonation is dependent on the relative humidity of the concrete - a 50% relative humidity being optimal. Chlorides, including sodium chloride, can promote the corrosion of embedded steel rebar if present in sufficient concentration. For this reason, only fresh raw water or potable water for mixing concrete should be used. The coarse and fine aggregates should not contain chlorides and admixtures that contain chlorides should not be used. Strengthening due to the above problems can be done using different methods which traditionally were based on concrete section enlargement and inserting using epoxy-sets dowels (rebars) to connect the new to the existing concrete, thus transferring part of the load to the new section using bond action. CFRP strengthening system has proven excellent performance in recent years. In the following discussion the three main constituents of CFRP strengthening systems are reviewed, based on the information gathered from the available literature in the airspace industry and more recently the construction industry: namely the adhesive, the matrix, and the fibres (Teng etal, 2002; Bjorn 2006, Seracino, 2004).

The purpose of the adhesive is to provide a shear load path between the concrete surface and the composite material, so that full composite action may develop. The science of adhesion is a multidisciplinary one, demanding a consideration of concepts from such topics as surface chemistry, polymer chemistry, rheology, stress analysis and fracture mechanics. Only the most common type of structural adhesives will be discussed here, namely epoxy adhesive, which is the result of mixing an epoxy resin (polymer) with a hardener. Depending on the application demands, the adhesive may contain fillers, softening inclusions, toughening additives and others. The successful application of an epoxy adhesive system requires the preparation of an adequate specification, which must include such provisions as adherent materials, mixing/application temperatures and techniques, curing temperatures, surface preparation techniques, thermal expansion, creep properties, abrasion and chemical resistance. When using epoxy adhesives there are two different time concepts that need to be taken into consideration. The first is the pot life and the second is the open time. Most synthetic adhesives are based on polymeric materials, and as such they exhibit properties that are characteristic for polymers.

The matrix (resin) for a structural composite material can either be of thermosetting type or of thermoplastic type, with the first being the most common one. The function of the matrix is to protect the fibres against abrasion or environmental corrosion, to bind the fibres together and to distribute the load. The matrix has a strong influence on several mechanical properties of the composite, such as the transverse modulus and strength, the shear properties and the properties in compression. Physical and chemical characteristics of the matrix such as melting or curing temperature, viscosity and reactivity with fibres influence the choice of the fabrication process. Hence, proper selection of the matrix material for a composite system requires that all these factors be taken into account (Agarwal and Broutman 1990). Epoxy resins, polyester and vinylester are the most common polymeric matrix materials used with high-performance reinforcing fibres. They are thermosetting polymers with good processibility and good chemical resistance. Epoxies have, in general, better mechanical properties than polyesters and vinylesters, and outstanding durability, whereas polyesters and vinylesters are cheaper.

Fibres can be manufactured in continuous or discontinuous (chopped) form, but here only continuous fibres are considered. Such fibres have a diameter in the order of 5-20 μm, and can be manufactured as unidirectional or bi-directional reinforcement. The fibres used for strengthening all exhibit a linear elastic behaviour up to failure and do not have a pronounced yield plateau as for steel. There are mainly three types of fibres that are used for strengthening of civil engineering structures, namely glass, aramid and carbon fibres.Glass fibres for continuous fibre reinforcement are classified into three types: E-glass fibres, S-glass and alkali resistant AR-glass fibres. E-glass fibres, which contain high amounts of boric acid and aluminate, are disadvantageous in having low alkali resistance. S-glass fibres are stronger and stiffer than E-glass, but still not resistant to alkali. To prevent glass fibre from being eroded by cement-alkali, a considerable amount of zircon is added to produce alkali resistance glass fibres; such fibres have mechanical properties similar to E-glass. An important aspect of glass fibres is their low cost. Aramid fibres were first introduced in 1971, and today are produced by several manufacturers under various brand names.

2 EXPERIMENTAL PROGRAM

A total of 12 concrete beams 150mmx150mmx750mm, 16 slabs 600mmx600mm and 6 cylinderical columns 150 mm diamter and 300 mm long were prepared and tested to destruction at Dubai Mens College. The concrete mix had 370 kg OPC, 159 kg of DEWA water, 559 kg of 20mm crushed RAK Rock, 365 kg of 10mm crushed RAK Rock, 937 kg of 0-5mm crushed RAK Rock. The average measured strength of the concrete compressive strength for beams and slabs was 30 MPa. Tables 1, 2 and 3 show the key configurations of the beam, slab and column specimens, respcetivley. Series A slabs had no reinforcement. Series B, C, and D had 4 T8, 4T10, 4T12, respectively. For Series B slabs, B1 had no reinforcement, B2 had 2 CFRP strips, B3 had 3 CFRP strips and B4 had 2xCFRP strips in the x-x and 2xCFRP strips in the y-y to represent 2-way slab reinforcing. The CFRP sheets for beam shear strengthening were obtained from BASF type Mbrace C Sheet 640 400g/m^2 with 300 mm width and 0.176 mm thickness. The CFRP plates for beam strengthening were obtained from BASF type Mbrace laminate 150/2000 - 100 x 1.4mm. The CFRP plates for slab strengthening were obtained from BASF type Mbrace laminate 150/2000 - 50 x 1.2mm.

Table 1 Beam Specimens

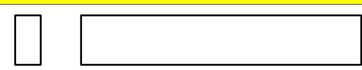
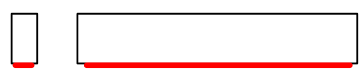
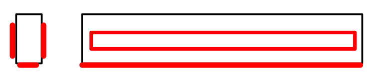
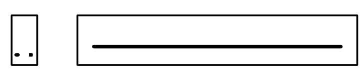
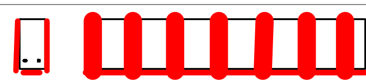
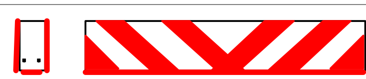
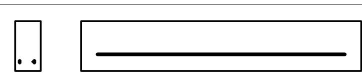
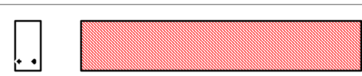
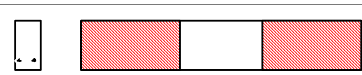
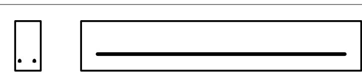
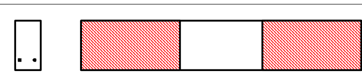
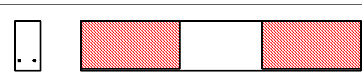
Beam umber	Description	FRP on Sides	FRP on Bottom	Sketch
B1	Unreinforced	No	No	
B2	Unreinforced	No	100 x 1.4	
B3	Unreinforced	100 x 1.4	100 x 1.4	
B4	2T8	No	No	
B5	2T8	7 x (100x1.4) each side	100 x 1.4	
B6	2T8	6 x (100x1.4) each side	100 x 1.4	
B7	2T10	No	No	
B8	2T10	2 x 300 sheet	No	
B9	2T10	Full 300 sheet	No	
B10	2T12	No	No	
B11	2T12	2 x 300 sheet	No	
B12	2T12	2 x 300 sheet	No	

Table 2 Slab Specimens

Specimen	Description	FRP	Exp. Load (KN)	Length (FRP) mm
A	A1 /plain	-	47.7	-
	A2 /plain	2	33	1120
	A3 /plain	3	48.6	1680
	A4 /plain	2+2	63.5	2240
B	B1 /T8	-	38.7	-
	B2 /T8	2	76.7	1120
	B3 /T8	3	90.4	1680
	B4 /T8	2+2	103.4	2240
C	C1 /T10	-	56.9	-
	C2 /T10	2	98.9	1120
	C3 /T10	3	111.5	1680
	C4 /T10	2+2	123.5	2240
D	D1 /T12	-	76.0	-
	D2 /T12	2	123.6	1120
	D3 /T12	3	135.0	1680
	D4 /T12	2+2	145.7	2240
TOTAL Length (mm)		**20160**		

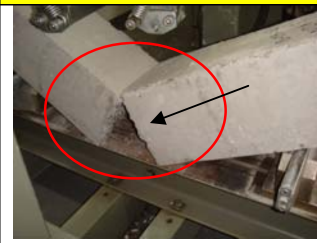
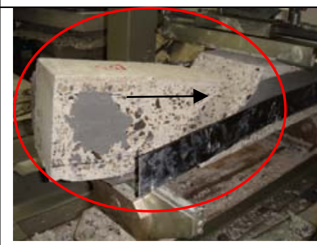
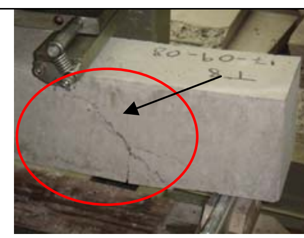
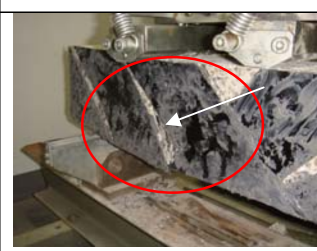
Table 3 Column Specimens

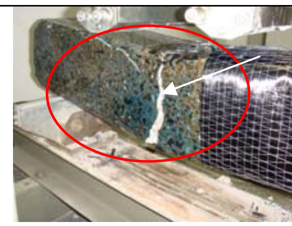
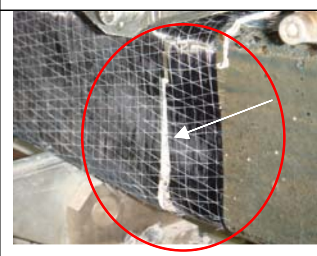
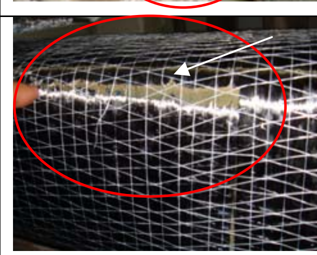
No of layer	Weight (Kg)	P(KN)	Rate (KN/Sec)	Stress σ (MPa)	% Δσ
Plain	12.98	752.6	6.8	42.6	0
One layer	12.46	969	6.8	54.83	29%
Two layers	12.46	1129	6.8	63.89	50%
Three layers	13.47	1134	6.8	64.17	51%
Four layers	12.46	1103	6.8	62.42	46%
Five layers	13.83	1059	6.8	59.93	41%

3 BEAM RESULTS

It is seen in Table 4 that there is a significant increase in bending strength due to strengthening particularly for plain beams. The increase is 490% for the plain concrete which failed in bending mode when comparing the results for B1 and B3. This increase is only 48% for reinforced beams failed by forming shear cracks when comparing B4 and B6. The highest load was obtained for B6 with diagonal plates at 45^0 which failed by forming shear cracks without CFRP rupture.

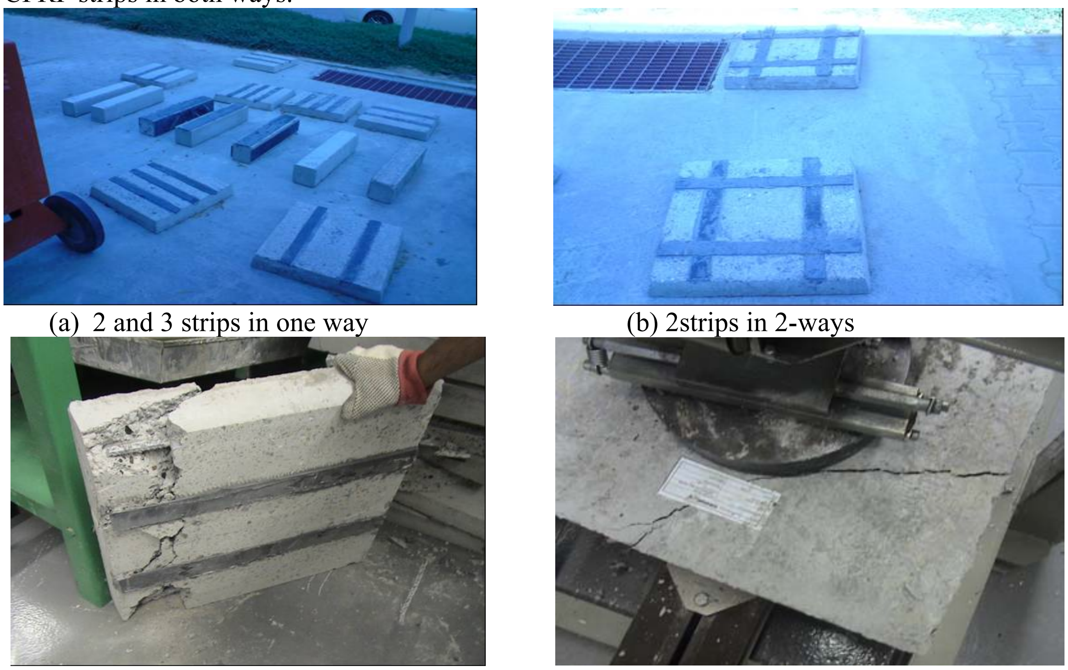
Table 4 Beam test results

Beam Number	Theoretical Results (KN)		Result (KN)	Observation	After Test
	Flexural	Shear			
B1	21	58.7	**14.5**	Flexural Failure	
B2	79.37	58.7	**76.5**	Shear Failure without FRP Rupture	
B3	79.37	58.7	**86**	Shear Failure due to FRP Debonding	
B4	46.35	58.7	**62.5**	Shear Failure	
B5	111.79	75.9	**66.5**	Shear Failure without FRP Rupture	
B6	111.79	93.02	**93**	Shear Failure without FRP Rupture	

B7	67.38	58.7	**55**	Shear Failure	
B8	67.38	92	**65**	Shear Failure with FRP Rupture	
B9	67.38	92	**40**	Flexural Failure	
B10	88	58.7	**70**	Shear Failure	
B11	88	92	**78**	Shear Failure with FRP Rupture	
B12	88	92	**85.5**	Shear Failure with FRP Rupture	

4 SLAB RESULTS

Figure 1 shows the tpyical failure mode for slabs. It is seen in Figure 2 that there is a significant increase in bending strength due to strengthening particularly for plain slabs. The increase is 87% and 114% for the plain concrete which failed in bending mode when comparing the results for the A series whith 2 and 3 strips, respectively. This increase is only 17% and 39% for reinforced slabs failed by forming shear cracks for series D, whith 2 and 3 strips, respectively. The results were inconsistent for CFRP strips in both ways.



(a) 2 and 3 strips in one way (b) 2strips in 2-ways

(c) typical slab failure (bottom view) (d) typical slab failure (top view)

Figure 1 slab specimens and failure

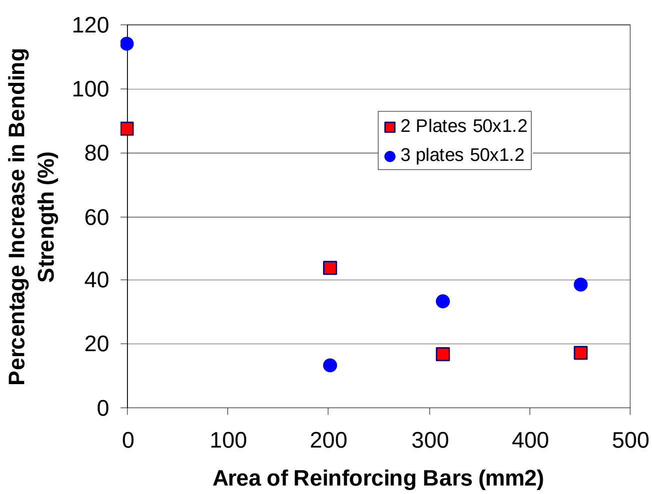


Figure 2 variation of bending strength of slabs with area of reinforcement

4 COLUMN RESULTS

Figure 3 shows the variation of column‘s strength with increasing the number of wraps. As all the wraps were applied in the same day to represent a particular constraint on site, thus there was insufficient time for the curing of the epoxy resin. Thus, it is clear that the optimum number of wraps is 2 with an increase in strength due to confinment of 50%. Figure 3 shows that increasing the number of wraps to more than 2, the additional CFRP sheets became less effective and reduce the strength. Figure 4 shows group photos for the specimens after testing. It can be concluded that the optimum number of wraps is 2, if the construction was to be done in a single day.

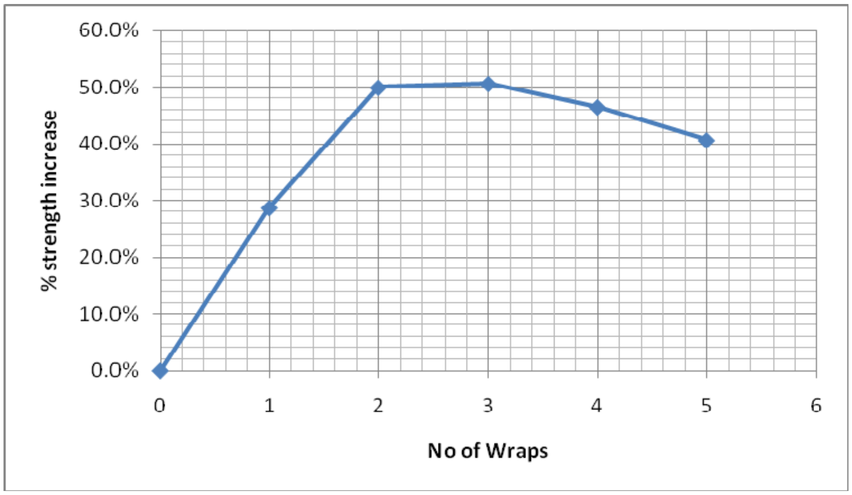


Figure 3 Variation of columns strength with increasing the number of wraps

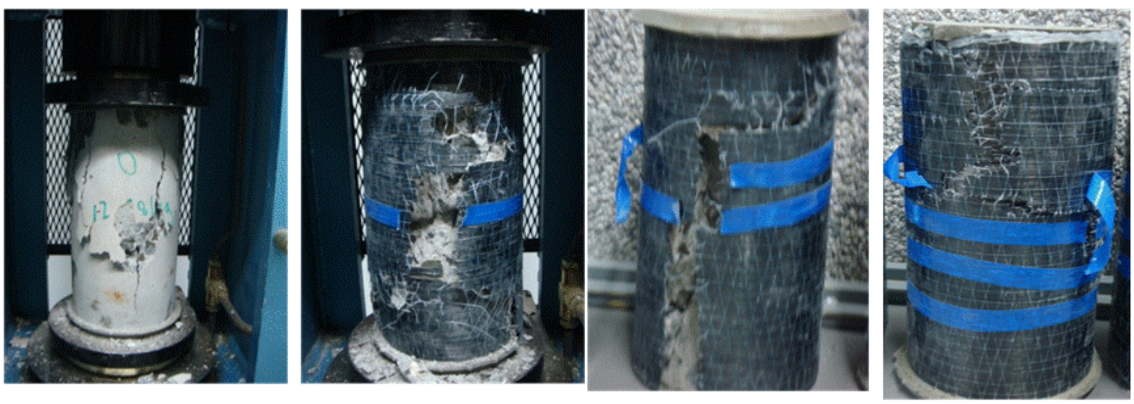


Figure 4 (a) plain column, (b) 1 wrap, (c) 2 wraps, and (d) 4 wraps

5 CONCLUSIONS

It was found that there was a significant increase in bending strength due to strengthening particularly for plain beams. The increase is 490% for the plain beams which failed by forming bending cracks. This increase is only 48% for reinforced beams failed by forming shear cracks. The highest load was obtained for B6 with diagonal plates at 45^0 which failed by forming shear cracks without CFRP rupture. It was also found that there was a significant increase in bending strength due to strengthening particularly for plain slabs. The increase was 87% and 114% for the plain concrete slabs which failed in bending mode when comparing the results for the A series with 2 and 3 strips, respectively. This increase was only 17% and 39% for reinforced slabs failed by forming shear cracks accompanied by concrete crushing for series D, with 2 and 3 strips, respectively. The optimum number of wraps was found to be 2, if the construction was to be done in a single day.

6 REFERENCES

Teng J. G. etal, 2002, *FRP strengthening of RC structures*, John Wiley.
Bjorn T., 2006, *FRP strengthening of existing concrete structures*, Lulia University.
Seracino, R., 2004, *FRP composites in Civil Engineering*, CICE, Adelaide, Australia.
ACI 440.2R-02, 2002, *Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures*.