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Behavior of damaged and undamaged concrete strengthened by carbon fiber composite sheets

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Abstract. Many existing concrete structures suffer from low quality of concrete and inadequate confinement reinforcement. These deficiencies cause low strength and ductility. Wrapping concrete by carbon fiber reinforced polymer (CFRP) composite sheets enhances compressive strength and deformability. In this study, the effects of the thickness of the CFRP composite wraps on the behavior of concrete are investigated experimentally. Both monotonic and repeated compressive loads are considered during the tests, which are carried out on strengthened undamaged specimens, as well as the specimens, which were tested and damaged priorly and strengthened after repairing. The experimental data shows that, external confinement of concrete by CFRP composite sheets improves both compressive strength and deformability of concrete significantly as a function of the thickness of the CFRP composite wraps around concrete. Empirical equations are also proposed for compressive strength and ultimate axial deformation of FRP composite wrapped concrete. Test results available in the literature, as well as the experimental results presented in this paper, are compared with the analytical results predicted by the proposed equations.

Key words: columns (supports); confined concrete; ductility; strength; fibers; stress-strain curves.

1. Research significance

Many existing concrete structures need rehabilitation or strengthening because of improper design or construction, change or modification in the purpose of usage and damage caused by environmental effects or natural hazards. For rehabilitation and strengthening, advanced composite materials have several advantages, like low weight to strength ratio, being easily applicable and durability. For more common use of these materials during rehabilitation and strengthening, more experimental data and analytical investigations are needed. In this paper, experimental data, as well as, empirical expressions proposed for the behavior of damaged and undamaged concrete strengthened by external confinement of CFRP composite sheets are presented.

2. Introduction

There are many existing reinforced concrete structures that do not meet the requirements given by the current building design and construction codes by various aspects. Besides the structural deficiencies vary in a wide range, low quality of concrete and lack of adequate lateral reinforcement

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to provide sufficient ductility may be regarded as two of the major problems. This paper deals with the above mentioned deficiencies and excludes many other possible weaknesses that the existing structures may be suffering. These two deficiencies need to be rehabilitated in a convenient way. Most convenient way may change according to the case being dealt. Sometimes the cheapest technique is the optimum solution, whereas sometimes the method that can be applied in the minimum time can be a better solution. In many cases the sizes of the structural members should keep their original dimensions. For the cases like when a time limitation for strengthening is present and/or the structural members have to keep their original dimensions, wrapping CFRP composite sheets around the vertical structural members, that are suffering from the above mentioned deficiencies, may be the most convenient way of rehabilitation and/or strengthening. The low density, high tensile strength and modulus, durability and being easily applicable are other advantages of CFRP composites, which are very important during and after the repair and/or strengthening procedure.

Many researchers conducted experimental studies on the behavior of concrete confined by lateral reinforcement, (Ahmad and Shah 1985, Mander *et al.* 1988a, Hsu and Hsu 1994, Saatcioglu *et al.* 1995, Ilki *et al.* 1997). Many analytical studies are also carried out on modelling the stress-strain behavior of concrete confined by lateral reinforcement, (Kent and Park 1971, Sheikh and Uzumeri 1982, Mander *et al.* 1988b, Cusson and Paultre 1995, Saatcioglu *et al.* 1995, Hoshikuma *et al.* 1997, Braga and Laterza 1998). Several researchers carried out comparative compilation studies on the available stress-strain models proposed for confined concrete, (Sheikh 1982, Ilki 1999). These studies proved that significant improvement on the compressive strength and deformability of concrete is possible by adequate confinement of concrete by lateral reinforcement. Similar enhancement on the behavior can be provided by wrapping high strength FRP composites around the structural member. In this technique, the fitting of the high strength fiber composite (glass fiber, carbon fiber, aramid fiber, etc.) to the structural member is maintained by an epoxy matrix. Fyfe (1996) summarised the going on experimental studies on the behavior of high strength fiber wrapped concrete members. Saadatmanesh *et al.* (1996, 1997) carried out an experimental program to investigate the seismic behavior of reinforced concrete columns rehabilitated and strengthened by using high strength glass fiber wraps. The researchers pointed out the efficiency of the wraps in confining the core concrete and preventing the longitudinal reinforcement bars from buckling under cyclic loads. They also concluded that, the fiber reinforced polymer wraps were effective in restoring the flexural strength and ductility capacity of the earthquake damaged concrete columns. For monotonic compressive loading, Fardis and Khalili (1982), Mirmiran and Shahawy (1997), Karbhari and Gao (1997), Toutanji (1999) and Xiao and Wu (2000) carried out experimental studies on the behavior of undamaged concrete externally wrapped by high strength fiber composites and proposed analytical stress-strain relationships for externally confined concrete. Saadatmanesh *et al.* (1994) carried out a parametric study that examines the effects of concrete compressive strength, thickness and type of external confinement for concrete columns externally reinforced with fiber composite straps.

In this study, the contribution of the confinement provided by externally wrapped CFRP composite sheets on the behavior of damaged and undamaged concrete is investigated experimentally under the effects of both monotonic and repeated compressive loadings. Empirical equations are also proposed for the compressive strength and ultimate axial deformation of externally confined concrete. Analytical results obtained by the proposed equations are compared with the results of available experimental studies in the literature, as well as the experimental results presented in this paper.

3. Experimental procedure

3.1 Experimental program

Totally 27 cylindrical specimens with the dimensions of 150×300 mm were tested, which included 16 CFRP composite sheet wrapped concrete specimens and 11 plain concrete specimens. Eleven of the CFRP composite sheet wrapped specimens were the plain concrete specimens that were tested until failure in this program priorly and strengthened by CFRP composite sheet wraps afterwards. During the prior loading of these plain specimens, generally tests were stopped at the axial compressive strains between 0.004 and 0.008. The remaining 5 specimens were strengthened by CFRP composite sheet wraps without a prior damage. The properties of the test specimens, those were wrapped by CFRP composite sheets, are summarised in Table 1. The names of the specimens are given according to the concrete batch number they belong and the strengthening procedure that they were subjected before testing. R represents the repairing of the damaged specimens and S represents strengthening. For example, Specimen 2-12-R-S belongs to concrete batch 2 and it was repaired and strengthened, while Specimen 3-17-S belongs to concrete batch 3 and it was only strengthened since it was not damaged before. For three concrete batches, mix proportions, water/cement ratios and average unconfined compressive strengths at 28 days are given in Table 2. However, since all the tests were carried out after the age of 90 days, the compressive strengths of plain concrete specimens varied between 21.1 and 33.3 MPa. As admixture, plasticiser for batch 1 and 2 and superplasticiser for batch 3 are used.

Table 1 Properties of the strengthened test specimens

Specimen name	Procedure[1]	Unconfined compressive strength, f'_{co}, MPa	Fiber layers	Loading type[3]
1-15-R-S	D-R-S	26.9	1	M
1-16-R-S	D-R-S	23.8	1	M
3-13-R-S	D-R-S	33.3	1	M
2-12-R-S	D-R-S	23.6	1	C
2-13-R-S	D-R-S	21.6	1	C
3-14-S	S	32.0[2]	1	C
1-17-R-S	D-R-S	26.7	3	M
1-18-R-S	D-R-S	25.5	3	M
2-14-R-S	D-R-S	21.1	3	C
2-15-R-S	D-R-S	23.6	3	C
3-15-S	S	32.0[2]	3	C
3-16-S	S	32.0[2]	3	C
2-16-R-S	D-R-S	23.5	5	M
2-17-R-S	D-R-S	25.3	5	M
3-17-S	S	32.0[2]	5	C
3-18-S	S	32.0[2]	5	C

[1]D: damaged, R: repaired, S: strengthened
[2]Specimen itself was not tested, the strength value is the average of three specimens of the same batch.
[3]M: monotonic loading, C: cyclic loading

Table 2 Concrete mix proportions

Batch	C kg	FA kg	W kg	S kg	PS kg	AG1 kg	AG2 kg	A kg	W/(C+FA)	f'_{co} MPa
1	278	40	210	540	535	720	–	1.2	0.66	21.9
2	278	40	210	540	535	720	–	1.2	0.66	17.1
3	420	–	180	450	400	750	200	4.2	0.43	29.3

Note: C = cement; FA = fly ash; W = water; S = sand; PS = powdered stone;
AG1 = Aggregate Type 1 (4~8 mm), AG2 = Aggregate Type 2 (8~16 mm), A = Admixture

3.2 Repair and strengthening technique

For repairing procedure, the damaged specimens were placed in an epoxy resin filled steel tube and then the tube was capped and sealed in order to allow pressurised epoxy resin to fill the gaps and cracks in the specimens that were formed during the previous loading. After applying the pressurised epoxy resin in the steel tube, the tube was uncapped and the specimens were taken out. In order to prevent the epoxy resin to leak out of the gaps and cracks of the specimens, the specimens were covered immediately by paper coated with a thin layer of plastic that did not let epoxy resin leak out.

For strengthening, the repaired or undamaged specimens were wrapped by unidirectional CFRP composite sheets transversally. Before wrapping the specimens with CFRP composite sheets, surface preparation procedure of the specimens was carried out and then epoxy matrix was formed all around the specimens. For surface preparation, first, sanding and cleaning steps were carried out. Before applying epoxy adhesive, one layer of epoxypolyamine primer and one layer of epoxy adhesive putty were applied on the surfaces of the specimens. Other layers of epoxy adhesive were applied between the CFRP sheet layers and on the outer layer of CFRP sheets. The compressive and tensile strengths of the epoxy system were around 80 and 50 MPa, respectively. Tensile elasticity modulus of epoxy system was around 3000 MPa and its ultimate elongation was 0.025. The steps during strengthening needed to be carried out with great care to prevent stress concentrations and to obtain the tight fitting of the sheets on the specimens. The number of CFRP composite wrap layers varied as one, three and five, which corresponded to the maximum lateral confinement stresses of 7.55, 22.65 and 37.75 MPa respectively. For obtaining satisfactory bonding, 150 mm overlap length was considered during wrapping. In the cases of wrapped sheets to be more than one layer, the sheet was wrapped continuously and 150 mm overlap was formed at the end of the wrap. The characteristic tensile strength and tensile elasticity modulus of the fiber fraction of the CFRP composite sheets were 3430 and 230000 MPa, respectively. The average ultimate deformation of the CFRP sheets was 1.5 percent and their effective area per unit width was 1.65 mm^2/cm.

3.3 Test setup

The specimens were tested under either monotonic or cyclic uniaxial compressive loads. An Amsler universal loading machine with the capacity of 5000 kN was used with appropriately adjusted measurement ranges. Axial displacements were measured by displacement transducers while axial and lateral strains were measured by post-yield type straingauges of 60 mm gauge length (TML, PL-60-11-3L) and 5 mm gauge length (TML, YFLA-5). The straingauges were

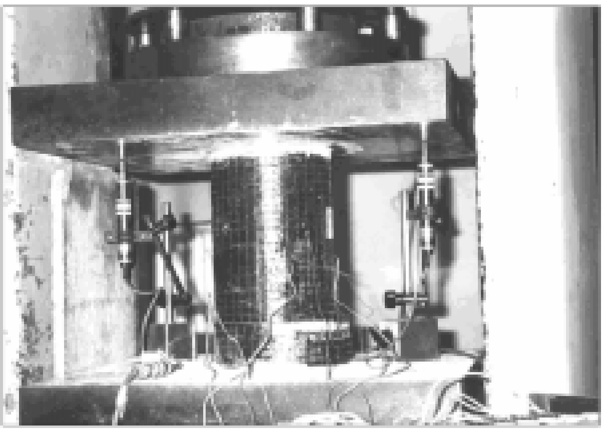

Fig. 1 Test setup

located at the midheight of the specimens. Data acquisition was carried out by a TML TDS-302 Data Logger and the recorded data was utilised by using a computer. The general appearance of the test setup can be seen in Fig. 1.

4. Results

4.1 Test results

Failures of all of the strengthened specimens were due to sudden failure of CFRP composite sheets at varying level of axial strains, ranging from 0.0093 to 0.0496 with an obvious tendency to increase by the increase in the thickness of the CFRP composite wrap. However, the lateral strains were around 0.006 and 0.012 for all specimens independent of the thickness of the CFRP composite wrap, with the exceptions of Specimens 1-17-R-S and 2-14-R-S, where the lateral strains were recorded until the strain level of 0.004. As also mentioned by Xiao and Wu (2000), the average rupture strain of the wrapped CFRP composite sheets was below the average rupture strain determined by the tensile tests of flat coupon samples. This difference is thought to be due to uneven distribution of lateral strains as a consequence of uneven distribution of damage. Since none of the specimens failed because of insufficient overlap length, 150 mm seems to be an adequate overlap length for these specimens. General outline of the test results is presented in Table 3. In Table 3, f'_{co} and ε_{co} are the unconfined concrete compressive strength and the corresponding axial strain, respectively.

In order to investigate the effect of gauge length during measuring axial deformation, measurements were carried out in 5, 60 and 300 mm gauge lengths during the test of Specimen 2-17-R-S. The average stress-strain relationships obtained by the utilisation of the data measured by displacement transducers in the gauge length of 300 mm and by the straingauges with the gauge lengths of 5 and 60 mm are presented in Fig. 2, together with the stress-strain relationship of this specimen before repair and strengthening (Specimen 2-17). As seen in this figure, since the distribution of the damage was not homogenous over the entire height of the specimens, slightly different stress-strain relationships were obtained for different gauge lengths. In this paper, the average deformations

Table 3 Outline of the experimental results

Specimen name	Compressive strength, f'_{cc} MPa	Maximum axial strain, ε_{cc}	Maximum lateral strain, ε_{ch}	f'_{cc}/f'_{co}	$\varepsilon_{cc}/\varepsilon_{co}$
1-15-R-S	51.8	0.0093	NA	1.93	4.65
1-16-R-S	46.4	0.0133	NA	1.95	6.65
3-13-R-S	48.5	0.0131	0.0078	1.46	6.55
2-12-R-S	48.3	0.0145	0.0066	2.05	7.25
2-13-R-S	46.9	0.0163	0.0087	2.17	8.15
3-14-S	47.2	0.0144	0.0079	1.48	7.20
1-17-R-S	78.5	0.0206	NA	2.94	10.30
1-18-R-S	82.4	0.0273	NA	3.23	13.65
2-14-R-S	71.6	0.0243	NA	3.39	12.15
2-15-R-S	83.8	0.0345	0.0116	3.55	17.25
3-15-S	83.8	0.0343	0.0103	2.62	17.15
3-16-S	91.0	0.0392	0.0108	2.84	19.60
2-16-R-S	107.4	0.0402	NA	4.57	20.10
2-17-R-S	98.8	0.0361	0.0063	3.91	18.05
3-17-S	107.1	0.0496	0.0064	3.35	24.8
3-18-S	107.7	0.0432	0.0100	3.37	21.6

obtained by the utilisation of the axial displacement measurements are taken into account during the comparison of the experimental data, because it is believed that they are better representatives of the average axial deformation along the entire height of the specimen. Mirmiran and Shahawy (1997) also concluded that the average strains measured by displacement transducers were as accurate as the measurements made with the embedded strain gauges, especially since the strain gauges reached their readability limits at around 2 percent strain levels, which proved too low for CFRP composite sheet wrapped concrete specimens.

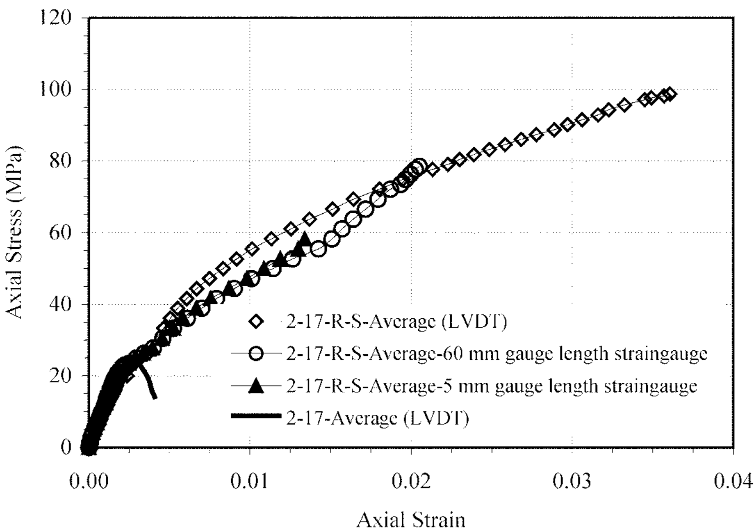

Fig. 2 Stress-strain relationships for specimens 2-17 and 2-17-R-S

The unconfined concrete compressive strength is determined to be slightly effective on strength enhancement, while it does not have a significant effect on axial deformability of CFRP composite sheet wrapped concrete, in the range of concrete compressive strengths investigated in this study, Figs. 3 and 4. Ultimate lateral strains seem not to be effected by the unconfined concrete compressive strength as well as thickness of the CFRP composite wraps, Table 3.

The compressive strength and axial deformability of the CFRP composite sheet wrapped concrete enhances significantly, with an increase in the thickness of the wrap. The experimental axial stress-axial strain and axial stress-lateral strain relationships are presented in Fig. 5. In this figure, the envelope curves are displayed for the specimens that were subjected to cyclic compressive loads. The variation of the initial stiffnesses of the specimens may be the consequence of level of prior damage and effectiveness of the repairing technique. The descending branches of these stress-strain curves could not be obtained due to sudden failure of the specimens.

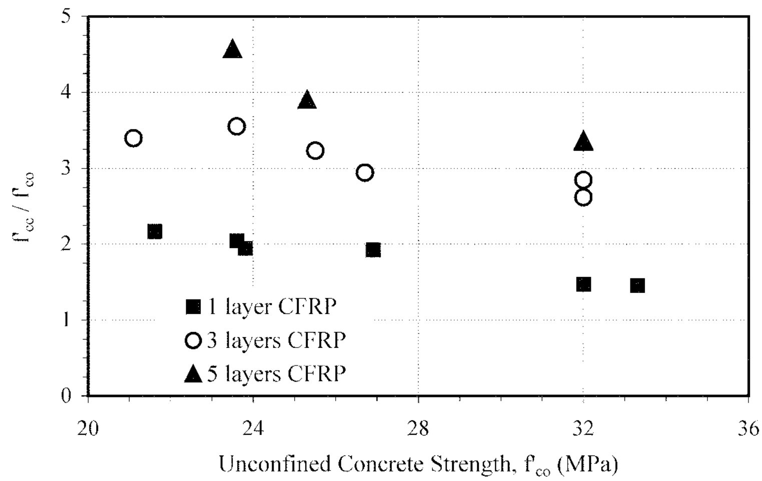

Fig. 3 Effect of unconfined concrete strength on the strength enhancement

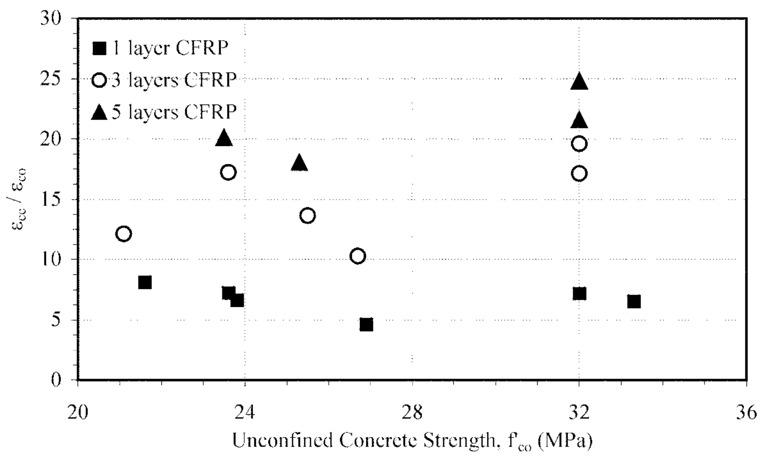

Fig. 4 Effect of unconfined concrete strength on the deformability enhancement

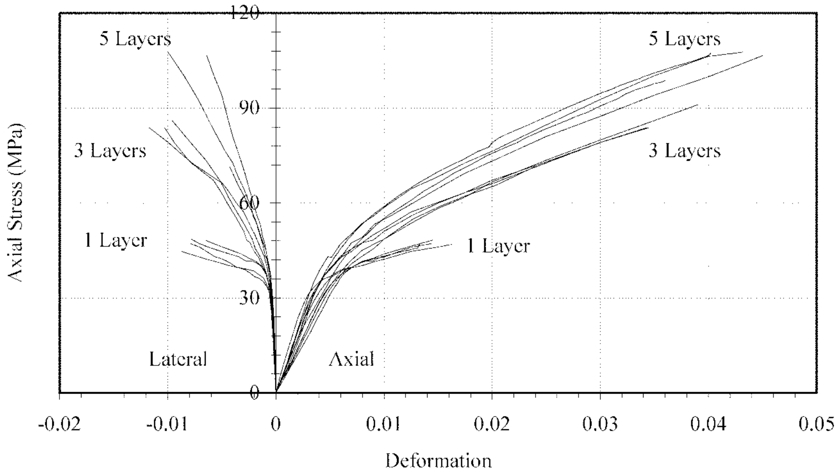

Fig. 5 Axial stress-axial and lateral deformation

Relative energy dissipation capacities of CFRP sheet wrapped specimens, $E_{exp.}$, are presented in Table 4 for three different thicknesses of CFRP composite wraps considered in this study. For this purpose, the area between stress-strain curve and the strain axis of the stress-strain relationship is calculated by a simple computer program. The average relative energy dissipation capacity for the tested original specimens before strengthening was approximately 0.2. Consequently, as seen in Table 4, energy dissipation capacity improves approximately 2, 6 and 13 times for one, three and five layers of CFRP composite wraps, respectively, when compared with unconfined concrete specimens.

In Figs. 6(a), (b), stress-strain relationships of specimens tested under repeated and monotonic compressive loads are displayed. In Fig. 6(a), Specimens 1-16-R-S, 2-12-R-S and 3-13-R-S, those were wrapped by one layer, and in Fig. 6(b) Specimens 1-18-R-S and 2-15-R-S, those were wrapped by three layers of CFRP composite sheet, are presented. As seen in Fig. 6(a) Specimen 2-12-R-S was subjected to repeated compressive loads, whereas the other two were tested under monotonic increasing compressive loads, with an exception of one unloading and reloading cycle during the test of Specimen 3-13-R-S. The stress-strain envelopes for these three specimens are quite close to each other. The slopes of unloading and reloading branches of stress-strain relationship for Specimens 2-12-R-S and 3-13-R-S are almost same. These show that, for the number of the considered loading and unloading cycles, both the CFRP composite itself and CFRP

Table 4 Comparison of energy dissipation

Specimen	Wrap layers	Area under stress-strain curve, $E_{exp.}$
1-15-R-S	1	0.366
1-16-R-S	1	0.386
1-17-R-S	3	1.126
1-18-R-S	3	1.551
2-16-R-S	5	2.959
2-17-R-S	5	2.404

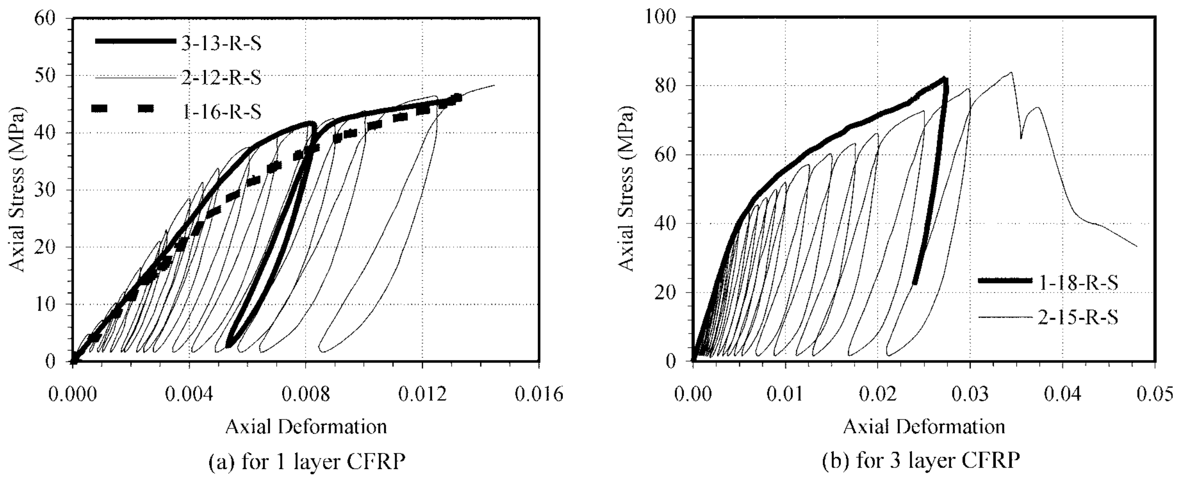

Fig. 6 Comparison of monotonic and repeated loadings

composite sheet wrapped concrete do not lose significant strength and stiffness by the increase in the number of loading cycles. Mirmiran and Shahawy (1997) tested one specimen that was subjected to three unloading and reloading cycles. After the comparison of the test data with other specimens that they tested under monotonic loading, they concluded that the initial stress-strain path might serve as an envelope for the case of quasi-static loading. They also pointed out that, while the loops became wider beyond the compressive strength of unconfined concrete, stiffness degradation was not as severe as steel-encased concrete.

The damaged specimens, after being repaired and strengthened, behaved quite similar as the strengthened undamaged specimens. In Fig. 7, stress-strain relationships of Specimens 2-16-R-S and 3-18-S are presented. As seen in this figure, the envelope curve of the stress-strain relationship of undamaged Specimen 3-18-S almost coincides with that of Specimen 2-16-R-S, that was repaired

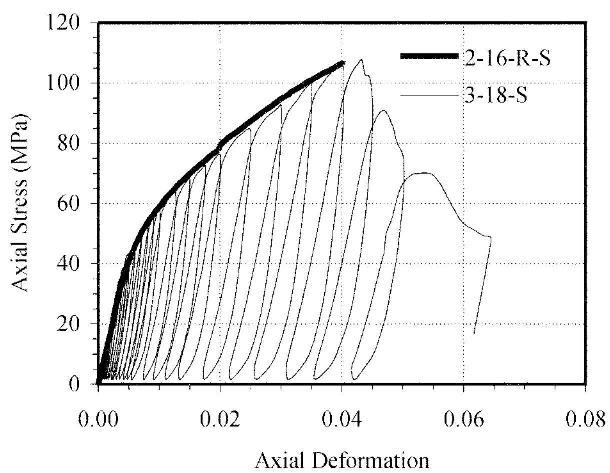

Fig. 7 Comparison of damaged and undamaged specimens-5 layers CFRP

and strengthened after it was damaged. This shows that, the application of the investigated strengthening technique to the damaged concrete members is as effective as the application to the undamaged concrete members. Note that, high quality workmanship should be provided during repair and strengthening.

4.2 Expressions for compressive strength and ultimate axial deformation

It is known that, current design provisions and existing models for concrete confinement with steel are not applicable to concrete confined externally by fiber reinforced composite polymers, (Mirmiran and Shahawy 1997, Toutanji 1999). However, the available data in the literature is not sufficient enough for establishing a widely acceptable axial stress-axial strain model for FRP composite wrapped concrete. Although there are several models proposed, the results obtained by these models can be quite different from each other. In this paper, depending on the limited experimental data presented here, simple expressions are proposed for compressive strength and ultimate axial strain of FRP composite wrapped concrete. The results obtained by these expressions are compared with the experimental data presented by Mirmiran and Shahawy (1997), Toutanji (1999) and Xiao and Wu (2000), as well as the test data presented in this paper.

In Fig. 8, the free body diagram of a confined circular cross-section is given. In this figure, f_l is the lateral stress acting on concrete by the confinement, D is the diameter of the cross-section and s is thickness of the wrap. F_l, resultant lateral force applied on concrete, can be determined by Eq. (1) for unit height of the member.

$$F_l = f_l D \tag{1}$$

The tensile force of the wrapping material for unit height, F_j, can be determined by Eq. (2)

$$F_j = 2nsf_j \tag{2}$$

where n is the number of wrap layers and f_j is the tensile stress on the wrapping material. As observed during compression tests, all failures were due to rupture of CFRP composite wraps.

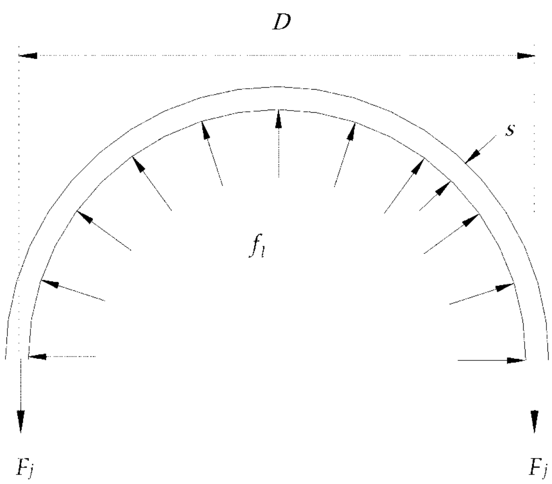

Fig. 8 Free body diagram of a confined circular cross section

Therefore, the maximum lateral confinement stress, $f_{l\max}$, that will be achieved just before the failure, can be obtained by considering the equilibrium condition for F_l and F_j and assuming that f_j is equal to the tensile strength of the wrapping material, Eq. (3)

$$f_{l\max} = \frac{2nsf_t}{D} \tag{3}$$

where f_t is the tensile strength of the wrapping material.

The experimental results indicated that, the compressive strength of the CFRP wrapped concrete was influenced by unconfined concrete strength and maximum lateral stress that can be applied by the wrapping material on concrete. Richart *et al.* (1929), depending on the experimental data, proposed the following equation for the compressive strength of confined concrete

$$f'_{cc} = f'_{co} + k_1 f_l \tag{4}$$

where f'_{cc} is the confined concrete strength and k_1 is the confinement effectiveness coefficient that Richart *et al.* (1929) assumed as 4.1. This equation became a basis for many studies and the equation is revised by several researchers. While k_1 is considered to be a constant number in the past, more recently, it is assumed to be a function of lateral stress and unconfined concrete compressive strength, (Mander *et al.* 1988b, Toutanji 1999, Saatcioglu and Razvi 1992). Mostly various functions of ratio of lateral stress to unconfined concrete strength were considered for k_1. Consequently, dimensionless expressions could be obtained for confined concrete strength. Likewise in this paper, two simple expressions are proposed for the compressive strength of concrete confined by FRP composite wraps as a function of the ratio of the lateral confinement pressure to the unconfined concrete strength, (f_l / f'_{co}). The statistical evaluation of the test data obtained in this study led to two expressions both resulting with the correlation coefficient of 0.98 for the compressive strength of CFRP composite wrapped concrete, $f'_{cc,1}$, $f'_{cc,2}$, Eqs. (5), (6).

$$f'_{cc,1} = f'_{co}\left[1 + 2.227\frac{f_l}{f'_{co}}\right] \tag{5}$$

$$f'_{cc,2} = f'_{co}\left[1 + 2.293\left(\frac{f_l}{f'_{co}}\right)^{0.867}\right] \tag{6}$$

In Table 5, the analytical results obtained by Eqs. (5) and (6) are compared with the experimental data.

For the axial strain corresponding to confined concrete compressive strength, Richart *et al.* (1929) proposed the following equation,

$$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 5k_1\frac{f_l}{f'_{co}}\right] \tag{7}$$

where ε_{cc} is the axial strain corresponding to compressive strength of confined concrete.

In this study, the experimentally determined axial strains corresponding to confined concrete compressive strengths were scattering, consequently statistical evaluation of the experimental data resulted with an expression with a lower correlation coefficient; 0.83. The expression proposed for the axial strain corresponding to compressive strength of concrete confined by FRP wraps is given

Table 5 Comparison of experimental and analytical results (compressive strengths)

Specimen	f_l MPa	f'_{co} MPa	$f'_{cc(exp)}/f'_{co}$	$f'_{cc(Eq.5)}$ MPa	$f'_{cc(Eq.6)}$ MPa	$f'_{cc(exp)}$ MPa	$f'_{cc(exp)}/f'_{cc(Eq.5)}$	$f'_{cc(exp)}/f'_{cc(Eq.6)}$
1-15-R-S	7.55	26.9	1.93	43.71	47.40	51.80	1.18	1.09
1-16-R-S	7.55	23.8	1.95	40.61	43.97	46.40	1.14	1.06
3-13-R-S	7.55	33.3	1.46	50.11	54.39	48.50	0.97	0.89
2-12-R-S	7.55	23.6	2.05	40.41	43.75	48.30	1.20	1.10
2-13-R-S	7.55	21.6	2.17	38.41	41.51	46.90	1.22	1.13
3-14-S	7.55	32.0	1.48	48.81	52.98	47.20	0.97	0.89
1-17-R-S	22.65	26.7	2.94	77.14	79.79	78.50	1.02	0.98
1-18-R-S	22.65	25.5	3.23	75.94	78.26	82.40	1.09	1.05
2-14-R-S	22.65	21.1	3.39	71.54	72.55	71.60	1.00	0.99
2-15-R-S	22.65	23.6	3.55	74.04	75.82	83.80	1.13	1.11
3-15-S	22.65	32.0	2.62	82.44	86.38	83.80	1.02	0.97
3-16-S	22.65	32.0	2.84	82.44	86.38	91.00	1.10	1.05
2-16-R-S	37.75	23.5	4.57	107.57	104.77	107.40	1.00	1.03
2-17-R-S	37.75	25.3	3.91	109.37	107.37	98.80	0.90	0.92
3-17-S	37.75	32.0	3.35	116.07	116.68	107.10	0.92	0.92
3-18-S	37.75	32.0	3.37	116.07	116.68	107.70	0.93	0.92
					Average:		1.05	1.01
					St. Dev. :		0.10	0.08

by Eq. (8).

$$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 15.156\left(\frac{f_l}{f'_{co}}\right)^{0.753}\right] \tag{8}$$

In Table 6, the comparison of experimental and analytical axial strains corresponding to the

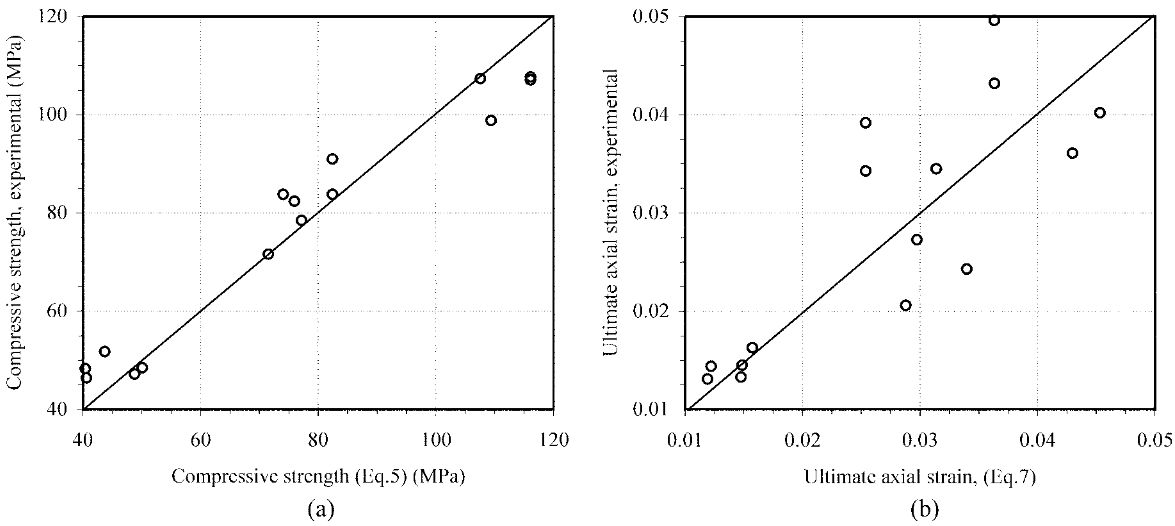

Fig. 9 Comparison of experimental and analytical results (a) for confined concrete compressive strength; (b) for strain corresponding to the confined concrete compressive strength

Table 6 Comparison of experimental and analytical results (maximum axial strains)

Specimen	f_l MPa	$\varepsilon_{cc(\text{Eq.7})}$	$\varepsilon_{cc(\exp)}$	$\varepsilon_{cc(\exp)}/\varepsilon_{cc(\text{Eq.7})}$
1-15-R-S	7.55	0.014	0.0093	0.68
1-16-R-S	7.55	0.015	0.0133	0.90
3-13-R-S	7.55	0.012	0.0131	1.10
2-12-R-S	7.55	0.015	0.0145	0.98
2-13-R-S	7.55	0.016	0.0163	1.04
3-14-S	7.55	0.012	0.0144	1.18
1-17-R-S	22.65	0.029	0.0206	0.72
1-18-R-S	22.65	0.030	0.0273	0.92
2-14-R-S	22.65	0.034	0.0243	0.72
2-15-R-S	22.65	0.031	0.0345	1.10
3-15-S	22.65	0.025	0.0343	1.35
3-16-S	22.65	0.025	0.0392	1.55
2-16-R-S	37.75	0.045	0.0402	0.89
2-17-R-S	37.75	0.043	0.0361	0.84
3-17-S	37.75	0.036	0.0496	1.37
3-18-S	37.75	0.036	0.0432	1.19
			Average :	1.03
			St. Dev. :	0.25

Table 7 Comparison of analytical results and experimental data in literature

Ref.	Wrap type	f'_{co} MPa	f_l MPa	$f'_{cc(\text{Eq.5})}$ MPa	$f'_{cc(\text{Eq.6})}$ MPa	$f'_{cc(\exp)}$ MPa	$f'_{cc(\exp)}/f'_{cc(\text{Eq.5})}$	$f'_{cc(\exp)}/f'_{cc(\text{Eq.6})}$	$\varepsilon_{cc(\text{Eq.7})}$	$\varepsilon_{cc(\exp)}$	$\varepsilon_{cc(\exp)}/\varepsilon_{cc(\text{Eq.7})}$
Toutanji	GE	30.93	7.33	47.25	51.28	60.82	1.29	1.19	0.012	0.015	1.25
Toutanji	C1	30.93	16.64	67.99	72.36	95.02	1.40	1.31	0.021	0.025	1.17
Toutanji	C5	30.93	17.76	70.48	74.77	94.01	1.33	1.26	0.022	0.016	0.71
Mirmiran	Gfiber	32.00	24.20	85.89	89.59	60.00	0.70	0.67	0.027	0.034	1.28
Mirmiran	Gfiber	32.00	39.10	119.08	119.30	76.00	0.64	0.64	0.037	0.038	1.02
Mirmiran	Gfiber	32.00	55.90	156.49	151.01	86.00	0.55	0.57	0.048	0.042	0.87
Xiao	CFRP	33.68	7.91	51.30	55.67	47.50	0.93	0.85	0.012	0.013	1.07
Xiao	CFRP	33.68	15.81	68.89	73.77	70.00	1.02	0.95	0.019	0.020	1.02
Xiao	CFRP	33.68	23.72	86.50	90.67	88.00	1.02	0.97	0.025	0.026	1.03
						Average :	0.98	0.93			1.05
						St. Dev. :	0.31	0.28			0.18

compressive strengths of the specimens tested in this study is displayed. In Fig. 9, the predicted values of compressive strength and ultimate axial strains are plotted versus experimental data. It should be noted that both Eqs. (6), (7) and (8) are valid for the range of lateral stresses and unconfined concrete strengths considered in this experimental study.

The results obtained by the proposed analytical expressions are also compared with the experimental data available in literature, Table 7. During the comparison, experimental data is selected, such that the unconfined concrete strengths and maximum lateral confinement stresses of the specimens are in or around the range considered in this study. It can be seen in Table 7 that, the proposed model can predict the compressive strengths and corresponding axial strains quite close to experimental results, particularly the experimental results obtained by Xiao and Wu (2000). It should be noted, the type of the material used for external confinement of the specimens tested by Xiao and Wu (2000) were same as the type of the material used in this study.

5. Conclusions

The following conclusions are drawn at the end of the experimental study conducted on CFRP composite sheet wrapped strengthened undamaged and damaged concrete specimens. It should be noted that, these conclusions are valid for the concrete members having circular cross-section.

The investigated strengthening technique is effective on strength and deformability enhancement. Consequently significant increase in energy dissipation capacity is possible. Therefore, this technique seems to be appropriate for strengthening the concrete members that suffer from low quality of concrete and lack of adequate lateral reinforcement. The repaired and strengthened specimens that were damaged priorly behaved similar to the strengthened undamaged specimens by means of strength, stiffness, deformability and energy dissipation characteristics. This indicates that, the investigated technique can also be used for strengthening of damaged concrete members after repair. Repeated compressive loading did not cause remarkable strength decay or stiffness degradation until high levels of axial strain. Consequently, the investigated technique will help the strengthened member to sustain repeated compressive loads that may occur during earthquakes.

Empirical expressions are proposed for the compressive strength and ultimate axial deformation of CFRP composite wrapped concrete based on experimental data. The predictions of the proposed expressions are in good agreement with the available experimental data in literature. It should be noted that, these expressions, that are derived depending on limited number of experimental data, should be carefully used by considering a significant safety margin.

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Notations

D = diameter
E_{exp} = dissipated energy
f'_{co} = unconfined concrete compressive strength
f'_{cc} = compressive strength of concrete confined by CFRP composite sheet
F_j = tensile force of the wrapping material
f_j = tensile stress of the wrapping material
F_1 = lateral force acting on concrete
f_l = lateral stress acting on concrete

$f_{l\max}$ = maximum lateral confinement stress
f_t = tensile strength of wrapping material
k_1 = confinement effectiveness coefficient
n = number of wrap layers
s = effective thickness of the wrapping material
ε_{co} = unconfined concrete strain corresponding to compressive strength
ε_{cc} = ultimate axial strain for CFRP composite sheet wrapped concrete
ε_{ch} = ultimate lateral strain for CFRP composite sheet wrapped concrete