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Retrofitting of shear damaged RC beams using CFRP strips

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Abstract The results of an experimental investigation are presented in this paper for retrofitting of shear damaged reinforced concrete beams by using U shaped CFRP strips. The experimental program is consisted of seven shear deficient T cross sectioned ½ scale simply supported beam specimens. One beam was used as reference specimen, and the remaining six specimens were tested in two stages. At the first stage, specimens were shear damaged severely, and then were retrofitted by using CFRP strips with or without fan type anchorages. Finally, retrofitted beams were tested up to failure. Three different CFRP strip spacing were used such as 125 mm, 150 mm, and 200 mm. The effect of anchorages on shear strength and behavior of the retrofitted specimens is investigated. CFRP strips without anchorages improved the shear strength, but no flexural failure mode was observed. Specimens showed brittle shear failure due to peeling of CFRP strip from RC beam surface. Shear damaged specimens retrofitted with anchoraged CFRP strips showed improved shear strength and ductile flexural failure. Maximum strains at anchoraged strips were approximately 68% larger than that of strips without anchorages.

Keywords: RC beam, shear retrofitting, CFRP strips, anchorages

1. Introduction

CFRP is being commonly used in more than 10 years, because it is light in weight, easy to apply, resistant to corrosion and environmental conditions, does not change the geometry of the elements and there are many different types and sizes in the market suitable for different kinds of strengthening details. Externally bonded FRP reinforcement has been proved to be applicable for the strengthening or retrofitting of many types of RC structures such as columns, beams, slabs, walls, tunnels, chimneys, and silos, and can be used to improve flexural and shear capacities, and also provide confinement and ductility to compression members (Ritchie *et al.* 1991, Sharif *et al.* 1994, Chajes *et al.* 1995, Sato *et al.* 1996, Ehsani *et al.* 1997, Norris *et al.* 1997, Khalifa *et al.* 1998, Triantafillou 1998, Khalifa *et al*. 1999).

In order to take full advantage of the potential ductility of the RC beam, it is desirable to ensure flexural behavior dominant rather than shear governed ultimate strength. Shear failure is catastrophic and occurs with no in advance warning of distress. Many of the existing RC beams are deficient in shear strength and they need strengthening or retrofitting. Deficiencies occur because of several reasons such as insufficient shear reinforcement or reduction in steel area due to corrosion, increased service

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load, construction defects. In these situations, externally bonded CFRP reinforcement can increase the shear capacity. The studies that investigate the effect of strengthening or retrofitting of shear deficient RC beams by using CFRP frequently encountered at literature. The main parameters that affect the behavior of retrofitted specimens are investigated, and the effects of CFRP strip width and arrangement on these behaviors are studied. Other parameters can be cited as shape and arrangement of the CFRP members, amount of CFRP, number of layers and strip inclination (Swamy *et al.* 1999, Taljsten and Elfgren 2000, Kacklakev and McCurry 2000, Li *et al.* 2001, Khalifa and Nanni 2002, Taljsten 2003, Diagana *et al.* 2003, Arduini and Nanni 1997, Jayaprakash *et al.* 2008, Barros *et all.* 2007, Barros and Dias 2006, Khalifa and Nanni 2000). In one of the study of the ACI (ACI Committee Report 440, 1996), strength and stiffness of shear deficient RC beam were improved significantly by using different CFRP arrangements and shapes.

The main factor that determines the retrofitted specimens' behaviors, strength, stiffness and ductility performance against shear is the failure mode of CFRP member. Experimental studies in the literature conclude three different modes of failure for concrete structures that are strengthened with CFRP. The observed failures are, debonding of CFRP from concrete, epoxy failure due to exceeding shear strength of adhesive-concrete interface and the rupture of CFRP. Since CFRP was very high axial tensile strength, CFRP rupture is seen very rarely. If this failure mode is encountered, the overall capacity of the CFRP is used, and the aim of the strengthening is reached. However, in most cases CFRP debonds from concrete surface or the adhesive concrete interface reaches its shear strength capacity and fails before the CFRP rupture. The most frequently seen mode of failure is the debonding of the CFRP from concrete just a couple of millimeters below the surface. This failure mode hinders retrofitted specimens to reach desired ductility values, and beams fail before reaching yield strength of tension reinforcement (Anil *et al.* 2010). Researchers are advising application of anchorages to CFRP strip ends for preventing this type of failures (Khalifa and Nanni 2000). However, limited numbers of studies are encountered in literature on this subject.

In this study, shear damaged T cross sectioned beams were retrofitted with wrapping U shaped CFRP strips, and were tested under monotonic four point loading. Three different CFRP spacing s_f= 125 mm, 150 mm and 200 mm were used. The ends of CFRP strips were anchoraged to concrete by using fan type CFRP anchorages. The effect of using fan type anchorages on retrofitted beam shear strength, behavior and increase in ductility were investigated (Toptaş 2009, Mertoğlu 2009).

2. Experimental program

2.1 Test specimens and materials

Seven, ½ scale T-shaped RC beam specimens were tested in the experimental program. Dimensions and reinforcement details are shown in Fig. 1. The distance between the supports is 3900 mm for all specimens. The cross-sectional geometries and longitudinal reinforcements are the same for all specimens. Longitudinal reinforcement consists of three 20 mm diameter steel deformed bars at the bottom, and two 8 mm diameter plain bars at the top of the beam. Shear reinforcement of all specimens consists of 6 mm diameter closed stirrups that are spaced at 300 mm along the beams. Specimens with deficient shear strength were retrofitted with 50 mm wide 930 mm long U shape CFRP strips. CFRP materials that were used in the experiments had unidirectional fibers. The main parameters that are investigated in this study can be cited as a) CFRP amount (three different spacing between CFRP strips

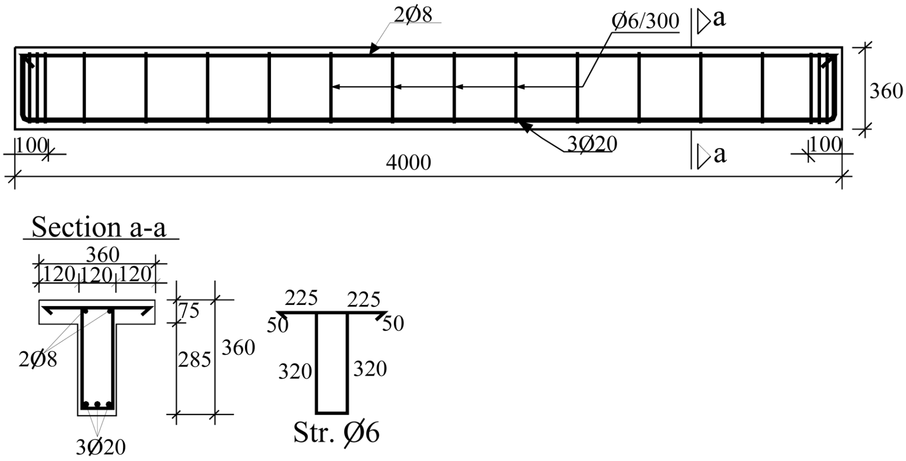


Fig. 1 Dimensions and reinforcement details of specimen

were used such as, s_f = 125 mm, 150 mm, 200 mm), b) anchorage application (CFRP ends were anchoraged or no anchorages were used). The properties of the specimens are summarized in Table 1. As can be seen from Table 1, the average compressive strength of the concrete is 25 MPa approximately. The mechanical properties of the reinforcing bars are shown in Table 2.

Specimen 1 with deficient shear reinforcement was tested without any retrofitting for reference purpose, and other six specimens were retrofitted in experimental program. Test of the retrofitted specimens was performed in two stages. Specimens were shear damaged at first stage, and then damaged specimens were retrofitted by using U shaped CFRP strips. Finally they were tested up to failure. The arrangements of CFRP strips that were used for retrofitting are given in Fig. 2. Three different CFRP strip spacing were used for retrofitting. 125 mm, 150 mm, and 200 mm CFRP strip spacing were considered for the Specimens 2, 5, Specimens 3, 6, and Specimens 4, 7, respectively. While fan type anchorage for CFRP strip ends were used for the Specimens 5, 6, and 7, no anchorages were applied to the Specimens 2, 3, and 4. CFRP strip ends were anchoraged to beam web and topping by using two anchorages. Anchorages at beam topping transferred tension load to beam topping along the CFRP strip fiber direction. Beam web anchorages prevented relative deformations across the shear cracks, and hence premature peelings of the strip ends were postponed. The details of the anchorages

Table 1 Properties of specimens

Specimen #	f_C (MPa)	Shear reinforcement ratio ρ_w and Dia./Spacing (mm)	CFRP strip used for retrofitting		
			Width w_f (mm)	Spacing s_f (mm)	Anchorage
1 (Control)	25.5	0.00056 and 6 / 300	No strengthening		
2 (Repair)	25.2		50	125	No
3 (Repair))	24.9		50	150	
4 (Repair)	24.8		50	200	
5 (Repair)	24.8		50	125	Yes
6 (Repair))	25.0		50	150	
7 (Repair)	24.9		50	200	

Table 2 Mechanical properties of reinforcements

Reinforcement diameter (mm)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Type
6	450	486	Plain
8	468	475	Plain
20	610	640	Deformed

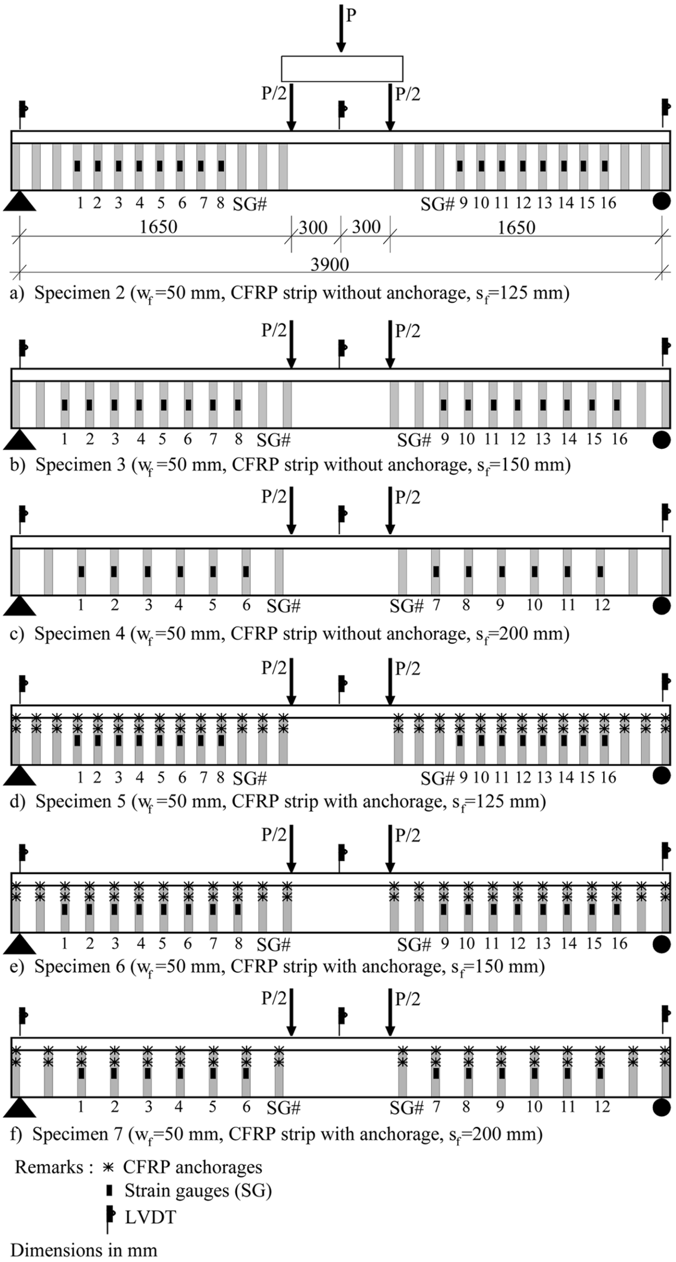


Fig. 2 Test setup and strengthening schemes of specimens

were given in Fig. 3. Fan anchorages are produced by wrapping 120 × 80 mm CFRP strip around 10 mm diameter 50 mm long reinforcing bars. After inserting 50 mm part of the anchorages in to drilled hole, the remaining 70 mm was cut into segments and bonded on to concrete surface like a fan shape. Holes with 14 mm diameter were drilled up to 50 mm depth. The picture of the CFRP fan anchorage is given in Fig. 4.

Before drilling of the anchorages holes, locations of them were marked, and after drilling, they were cleaned with compressed air. Before bonding CFRP members on to concrete surface, special consideration was given to the beam web surface preparation. Both sides of the beam web and bottom face of the topping were roughened mechanically by a grinding machine down to aggregate level, and then grinded surface was brushed. Surfaces were vacuum cleaned for removing loose particles and dust. Prepared mixture of epoxy was spread over both sides of the beam web up to 0.5 mm thickness approximately and anchorage holes were filled with epoxy. After inserting anchorages in their places CFRP strips were bonded on their predefined places at both sides of beam web. After bonding of CFRP strips, some pressure was applied on them by hand along the fiber directions to get rid of air bubbles

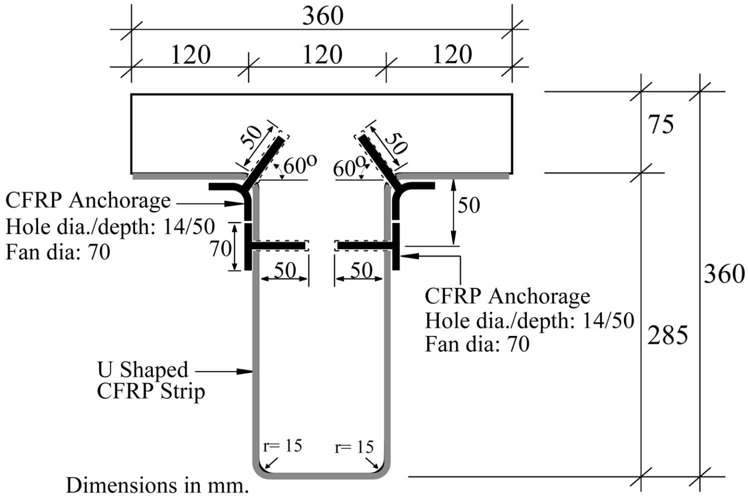


Fig. 3 Anchorage details of specimens

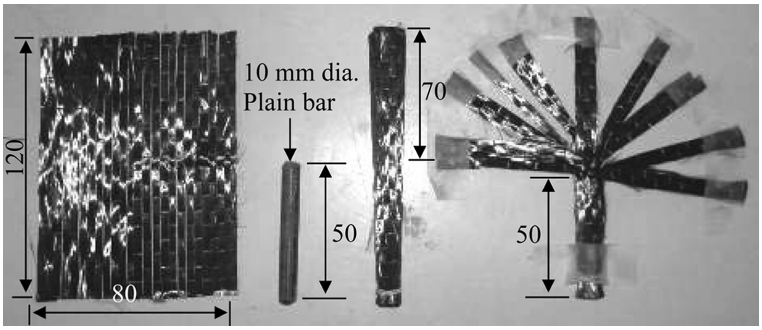


Fig. 4 Fan type CFRP anchorage

Table 3 Properties of CFRP sikawrap 160-C (unidirectional) and resin sikadur 330

Properties of CFRP	Remarks of CFRP*
Thickness (mm)	0.12
Tensile strength (MPa)	4100
Elastic modulus (MPa)	231000
Ultimate tensile strain (%)	1.7
Properties of resin	Remarks of resin*
Tensile strength (MPa)	30
Elastic modulus (MPa)	3800

*These values are supplied by the manufacturer.

entrapped between CFRP strips and concrete surface, and CFRP strips were soaked with applied epoxy on concrete. As the final step, the remaining 70 mm parts of the anchorages were opened like a fan and were bonded on to CFRP strips. The temperature during application was 20 ± 2ºC in all cases. After bonding operations was completed, specimens were cured for 15 days under laboratory conditions before testing. Sikawrap 160c CFRP sheets and Sikadur 330 epoxy was used for retrofitting. Properties of CFRP sheets and epoxy supplied by the manufacturer are given in Table 3.

2.2 Test setup

A schematic view of the test setup and the arrangement of the measurement devices are shown in Figure 2. All specimens were tested as simple beam under the four-point loading with shear span to effective depth ratio (a/d) equal to 5. Load on the mid point of spreader beam was divided symmetrically into two concentrated load and applied to the specimens. Load was applied with a 600 kN capacity hydraulic jack and was controlled with a 400 kN capacity load cell. Mid point deflection and support settlement of the specimens were measured. CFRP strains were measured with strain gauges. Strain gauges were attached on to CFRP strips along the fiber direction. Strain gauges locations are given at Fig. 2. Strain gauges were attached left and right shear spans of beams symmetrically.

2.3 Testing procedure

First, reference specimen (Specimen 1) was tested under monotonic loading up to failure. Test result of the reference specimen was evaluated and loading limit for shear damage of specimens was determined. Reference specimen load level at which stiffness was suddenly changed before shear failure is chosen as a damaging loading level (56 kN). This load was applied to all of the specimens for shear damaging. This load level is the 90% of the ultimate shear force capacity of deficient shear reinforced reference specimen. Retrofitted Specimen 2, 3, 4, 5, 6, and 7 were tested in two stages. At first stage, they were loaded up to 56 kN shear force level to get severe shear damage. After this loading level, experiments were stopped and cracks and displacements were recorded. At this load level, measured residual maximum width of the shear cracks were between 1.4 mm to 2.0 mm, and residual mid point displacements were between 3.5 to 3.8 mm. Then at second stage, damaged specimens were retrofitted with U shaped CFRP strips. Finally, retrofitted specimens were tested up to failure.

3. Test results and discussions

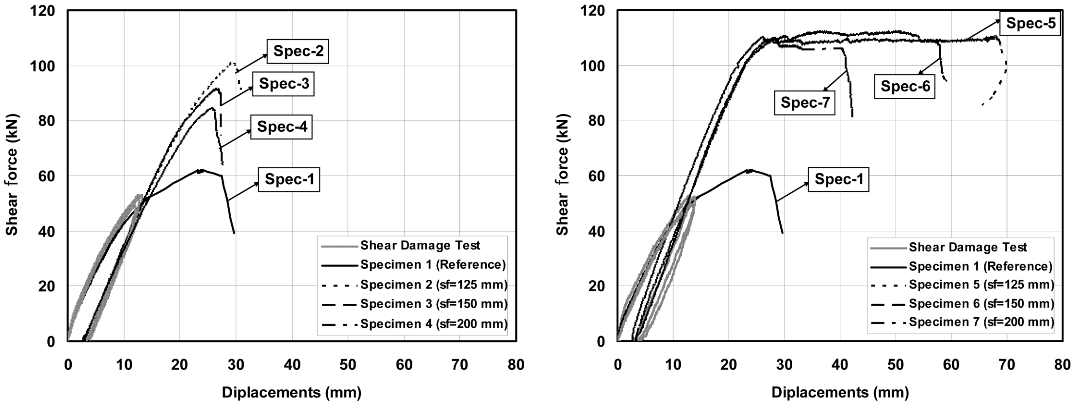
3.1 Behavior and failure modes of test beams

Shear force versus mid point deflection graphs of the specimens are given in Fig. 5. Due to the fact that, concrete compressive strength and shear reinforcement ratio of all specimens are very close, similar load-displacement graphs and general behavior were observed at the first stage of tests. In addition, shear damage distributions were also very similar. All of the specimens showed nearly the same displacement with same stiffness up to 40 kN shear load level. Shear cracks initiated at that level for all specimens. Wider shear cracks at left and right span were observed near the support regions than the regions at which loading was applied. Shear cracks propagated upwards the beam web and reached to beam topping and web intersection. A representative picture of shear damaging part of the experiment is given in Fig. 6 for the Specimen 4.

Ultimate shear strength of the retrofitted specimens changed according to spacing of the strips and to the presence of anchorages. As can be seen from Figure 5, no flexural behavior was observed at specimen retrofitted with CFRP strips without anchorages (Specimens 2, 3, and 4). Application of anchorages prevented shear failure, thus flexural behavior was observed, and specimens made larger displacements. Anchorages used at the CFRP strips ends significantly improved the ductility of the Specimens 5, 6, and 7 with deficient shear reinforcement. No rupture and damage was observed at CFRP strips during experiments. Test results are summarized in Table 4.

Fig. 7 shows crack patterns and failure modes of the specimens. Reference Specimen 1 failed at 62.07 kN shear load and 23.99 mm displacement. Specimen failed with brittle shear failure.

Specimens 2, 3, and 4 were failed with brittle shear failure due to peeling of U shaped CFRP strip ends. The ultimate shear load measured from the Specimens 2 and 3 were 101.34 kN and 91.69 kN, respectively. Average shear force capacities of the Specimens 2 and 3 were 55% larger than that of reference specimens. Specimen 4 with 200 mm CFRP strip spacing carried 36% more shear force than that of the reference specimen and failed at 84.65 kN due to shear. CFRP strips improved the shear force carrying capacity of the Specimens 2, 3, and 4 slightly, but they can not improve displacement capacity. Photograph taken after failure of the Specimen 4 is given in Fig. 8.



a) Specimen 2, 3, 4 (CFRP strip without anchorage) b) Specimen 5, 6, 7 (CFRP strip with anchorage)

Figure 5. Shear Force-Midpoint Displacement Curves of Specimens

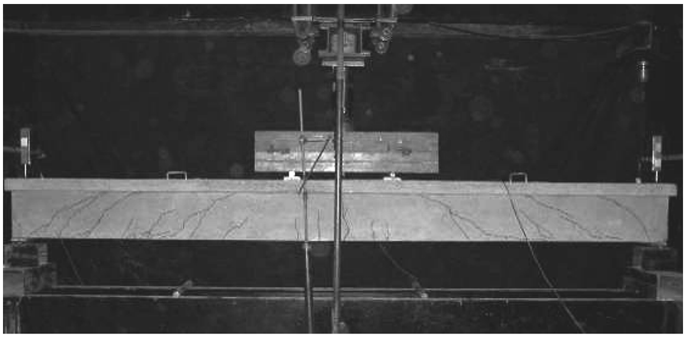


Fig. 6 Specimen 4 crack pattern after damaging test

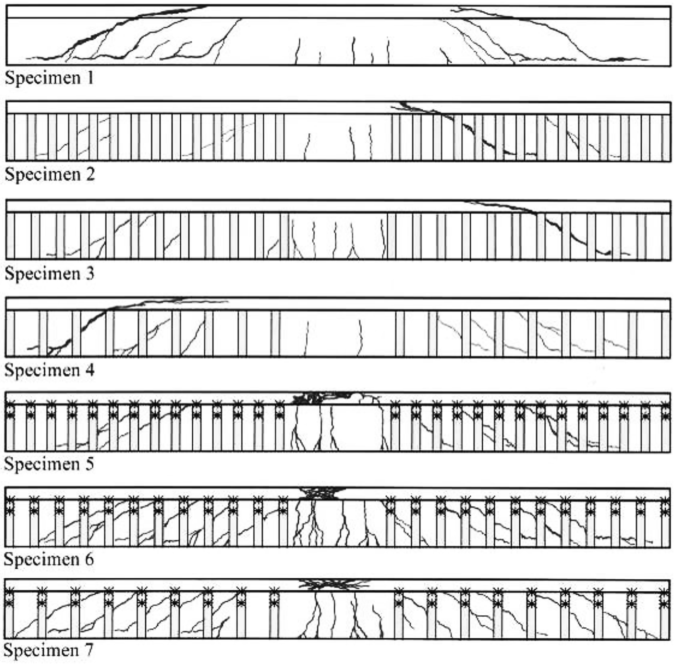


Fig. 7 Specimens crack patterns after failure

Specimens 5, 6, and 7 retrofitted with anchoraged CFRP strips reached their ultimate shear force capacities by making ductile displacements. All three of the specimens failed with crushing of topping concrete at maximum moment region under compressive forces. Reduced CFRP spacing prevented the growth of shear cracks. Measured shear crack widths at Specimens 5 and 6 that are strengthened with 125 mm and 150 mm spaced CFRP strips was smaller than that of the Specimen 7 with 200 mm spacing. Photograph that is taken after failure of the Specimen 6 is given in Fig. 9.

3.2 Strains at the CFRP strips

A typical strain vs. shear load graph is given in Fig. 10. The maximum strain values with strain gauge

Table 4 Test Results

Specimen #	Shear force (kN)		Displacement (mm)		Stiffness at yield (kN/mm)	Ductility ratio	Energy dissipation capacity (kN-mm)	Maximum strain at ultimate load ε (mm/mm)	Failure mode
	At yield	At ultimate	At yield	At ultimate					
1	-----	62.07	-----	23.99	-----	-----	1302.30	-----	Shear
2	-----	101.34	-----	29.54	-----	-----	1815.85	0.0047	Shear
3	-----	91.69	-----	26.86	-----	-----	1457.69	0.0049	Shear
4	-----	84.65	-----	25.87	-----	-----	1376.87	0.0051	Shear
5	110.30	112.66	27.86	68.48	3.96	2.46	6033.46	0.0080	Flexure
6	109.78	109.78	27.86	57.65	3.94	2.07	5094.77	0.0082	Flexure
7	109.72	109.72	28.65	40.46	3.83	1.41	3228.21	0.0085	Flexure

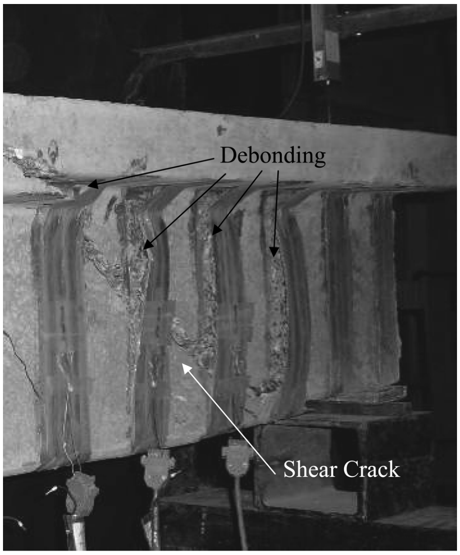


Fig. 8 CFRP Debonding at Specimen 4

Fig. 9 Flexural Failure of Specimen 6

number (sg#) are given in Fig. 11. While presenting the strain values, they are grouped according the CFRP strip spacing such as the Specimens 2 and 5 with spacing s_f = 125 mm, Specimens 3 and 6 with spacing s_f = 150 mm and Specimens 4 and 7 with spacing s_f = 200 mm. Due to localization of shear cracks at one shear span of the specimen without anchorages, one of strain value at which CFRP strips laid over the localized crack was measured larger than the other strains. Specimens 2, 3, and 4 without anchorages failed due to peeling of CFRP strips at the region where the widest shear crack occurred during damaging part of experiments. This main shear crack propagated and the specimens failed. Strains at the region of failure are significantly larger than the others. Localizations of shear cracks are prevented at the specimen with anchorages. Shear cracks are distributed along both of the shear spans and difference between the measured strains were smaller compared to the specimens without anchorages. But the strains at the regions where the widest cracks were observed during damaging part of the experiments were slightly larger than the others. As can be seen from Figure 11, the largest and smallest strain values are measured from the Specimens 5, 6, and 7 that is manufactured with fan type anchorages and from the Specimens 2, 3, and 4 without anchorages, respectively.

The average maximum strain that was measured from strips without anchorages is 0.0049 mm/mm for the Specimens 2, 3, and 4. This value is 22% larger than the value that is suggested by ACI Committee Report 440 and FIB (0.0040 mm/mm). Suggested value by the ACI Committee Report 440 and FIB is conservative for the specimens with anchoraged CFRP strips. The average maximum strain is 0.0082 mm/mm for the Specimens 5, 6, and 7. This value is 106% larger than the suggested value at ACI Committee Report 440 and FIB. Anchorages prevented peeling of the CFRP strips from concrete surface, and significantly improved the specimens' ultimate shear load capacities.

3.3 Shear strength and stiffness

Shear strength and secant stiffness of specimens are given at Table 4. CFRP strips significantly improved the shear strength and stiffness of shear deficient RC beams. 49% of shear strength of the specimens with deficient shear reinforcement was provided by the CFRP strips without anchorages in average. However CFRP strips without anchorages were not capable for improving the displacement capacity. Shear strength of the specimens without anchorages is closely related with CFRP strip spacing. Specimen 2, 3, and 4 carried 63%, 48% and 36% larger shear force than the reference

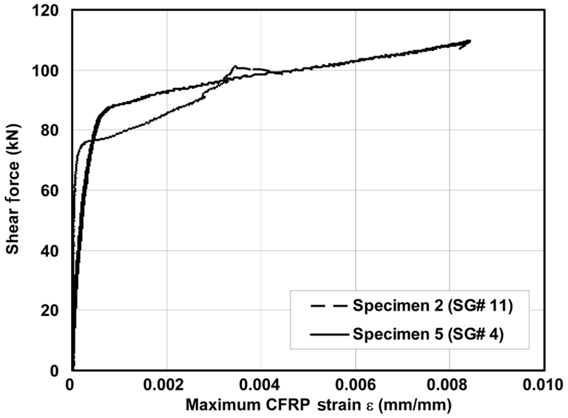


Fig. 10 Typical load- CFRP strain curves

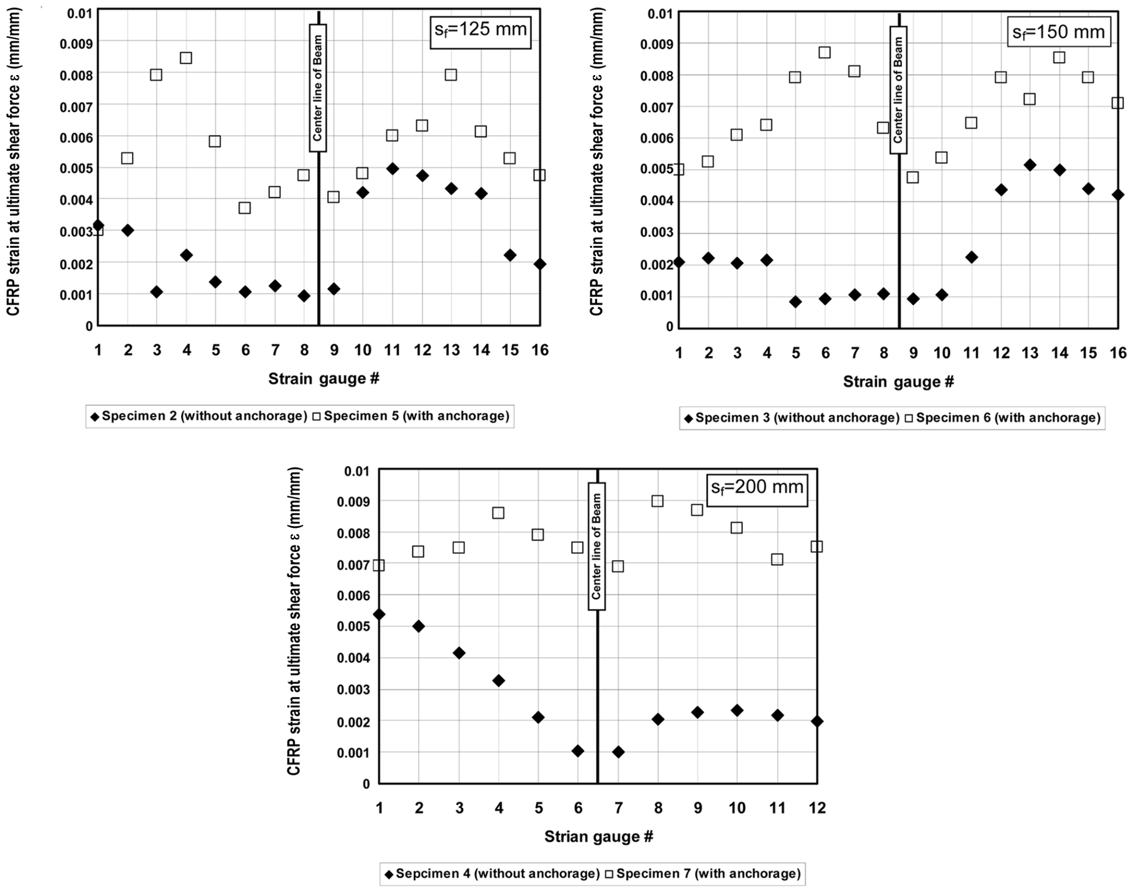


Fig. 11 CFRP strain at ultimate load

specimen, respectively. As the CFRP spacing increased, shear strength of the specimen decreased. Although shear capacity of the Specimens 2, 3, and 4 without anchorages increased, they can not reach flexural capacities, and they failed with brittle shear failure. Anchorages that were applied to strip ends are significantly effective on the shear strength and behavior of the specimens. Displacement capacities of the specimens with anchorages were significantly improved. Specimen 5, 6, and 7 retrofitted with anchoraged CFRP strips carried 77% larger average shear force than the reference specimen. Tension reinforcements of the Specimen 5, 6, and 7 that were retrofitted with anchoraged CFRP strips were yielded, and they were reached their flexural capacities.

Secant stiffnesses of the specimens are calculated by using the slope of the line that is connecting the origin of the load displacement graphs and yield load value. Due to the fact that Specimen 2, 3, and 4 without anchorages can not reach the yield capacities, secant stiffnesses for these specimens are not calculated. Average secant stiffness for the anchoraged Specimens 5, 6, and 7 is 3.91 kN/mm. As CFRP strip spacing increased, secant stiffness dropped. Increase in the spacing of CFRP strips caused in increase of yield displacement, and drop in secant stiffness value. Average secant stiffness of the Specimen 5 and 6 retrofitted with 125 and 150 mm spaced CFRP strips is 3.95 kN/mm, and 3% larger than that of the Specimen 7 (3.83 kN/mm) that was retrofitted with 200 mm spaced CFRP strips.

When the load-displacement curves of the damaging part of the experiments are investigated, stiffnesses of the specimens are very close to each other at 56 kN load level. Average displacement of the Specimens 2, 3, 4, 5, 6, and 7 is 14 mm at 56 kN load. Average stiffness that is calculated for the damaging part of the experiment is 3.93 kN/mm. After retrofitting the Specimen 2, 3, and 4 with CFRP strips without anchorages, average stiffness of 3.67 kN/mm was observed at the same load level (56 kN). Average stiffness of the Specimens 5, 6, and 7 retrofitted with anchoraged CFRP strips is calculated as 4.58 kN/mm. Anchoraged CFRP strips improved the stiffnesses of damaged RC beams more than the ones without anchorages. 25% more stiffness increase was obtained from the Specimen 5, 6, and 7 with anchorages than the Specimen 2, 3, and 4 without anchorages.

3.4. Ductility ratios

Displacement ductility ratios of the specimens are summarized in Table 4. Displacement ductility ratio of the specimen is calculated by dividing displacement value at yield point to displacement at ultimate shear capacity. CFRP strips without anchorages can not provide required displacement capacity and no flexural ductility is observed. No ductility is obtained from the Specimen 2, 3, and 4 without CFRP anchorages. Anchorages are provided significant ductility to the Specimen 5, 6, and 7. Ductility ratios of these specimens are changing between 2.46 and 1.41. Displacement ductility ratios of the specimens decreased, when the CFRP strips' spacing increased, and as a result midpoint deflection increased also.

3.5 Energy dissipation capacity

The energy dissipation capacities are determined by calculating the areas under the load–displacement curves. Calculated energy dissipation capacities for the specimens are given in Table 4. According to calculated values, in average 19% more energy was dissipated by the specimens strengthened with CFRP strips without anchorages as compared to reference specimen. Specimens strengthened with anchoraged CFRP strips dissipated 267% more energy than the reference specimen in average. Specimens with anchoraged CFRP strips dissipated 2.05 times more energy than that of the specimens without anchorages. As the CFRP strip spacing increased, energy dissipation capacity decreased.

4. Comparison of analytical and experimental results

Comparisons of the experimental and analytical results are given at Table 5. Ultimate shear capacities of the specimens are calculated by using ACI 318 regulation (ACI Committee 318 1995), ACI Committee Report 440 (ACI Committee 440 1996), Eurocode 2 (Eurocode No. 2 2002), and FIB (FIB bulletin 2001) regulations. Shear strength of the specimens are calculated by using Eq. (1).

$$V_{CAL} = V_C + V_S + V_F \tag{1}$$

Concrete and shear reinforcement contributions are calculated by using ACI 318 regulations. On the other hand, CFRP capacities are calculated by using Eurocode 2 and FIB regulations. Equations that are used during calculations are given between Eq. (2) and Eq. (11).

Table 5 Comparison of analytical and experimental results

Spec #	Ultimate shear force (kN)			Ratio [a]	
	Experimental	Analytical			
		ACI 318 and ACI 440	Eurocode 2 and FIB	ACI 318 and ACI 440	Eurocode 2 and FIB
1	62.07	61.32	58.40	1.01	1.06
2	101.34	83.74	81.02	1.21	1.25
3	91.69	79.77	77.09	1.15	1.19
4	84.65	74.99	72.31	1.13	1.17
5	112.66	83.47	80.84	1.35	1.39
6	109.78	79.84	77.14	1.38	1.42
7	109.72	75.06	72.35	1.46	1.52

[a] Ratio of experimental ultimate capacity to analytical ultimate capacity values

$$V_f = \frac{A_{fv} f_{fe} (\sin\alpha + \cos\alpha) d_f}{s_f} \tag{2}$$

$$A_{fv} = 2 n t_f w_f \tag{3}$$

$$f_{fe} = \varepsilon_{fe} E_f \tag{4}$$

$$\varepsilon_{fe} = k_v \varepsilon_{fu} \le 0.004 \tag{5}$$

$$k_v = \frac{k_1 k_2 L_e}{11900 \varepsilon_{fu}} \le 0.75 \tag{6}$$

$$L_e = \frac{23,300}{(n t_f E_f)^{0.58}} \tag{7}$$

$$k_1 = \left(\frac{f_c}{27}\right)^{2/3} \tag{8}$$

$$k_2 = \frac{d - L_e}{d_f} \tag{9}$$

$$V_f = 0,9 \varepsilon_{fd,e} E_{fu} \rho_f b_w d (\mathrm{Cot}\Phi + \mathrm{Cot}\alpha) \mathrm{Sin}\alpha \tag{10}$$

$$\rho_f = \frac{2 t_f b_f}{b_w s_f} \tag{11}$$

While calculating shear force component (V_F) that is carried by CFRP strips, maximum effective strain value 0.004 mm/mm that is suggested by ACI 440 and FIB regulations are used. Calculated capacity values for the specimens retrofitted with anchoraged CFRP strips are lower than the ultimate shear capacities that are measured from experiments. Calculated and measured capacities of the specimens without anchorages are obtained very close, due to the fact that suggested and measured strains are close. Average calculated values of the specimens without anchorages are 16% and 20% lower than the measured ones, when ACI 440 and FIB regulations are used, respectively. Average calculated values of the specimens with anchorages are significantly lower than the experimental results. 40% and 44% lower values are calculated than experimental results, when ACI 440 and FIB regulations are used, respectively. Due to the fact that suggested value at regulations (0.004 mm/mm) is significantly lower than the measured maximum strains for the anchoraged specimens, conservative lower capacity values are calculated.

5. Conclusions

The following main conclusions can be drawn from this experimental study:

- Retrofitting of shear damaged RC beams by using CFRP strips can be easily applied and widely used.
- CFRP strips without anchorages improved the shear strength of shear damaged beam, but they can not prevent the shear failure. Both shear strength and behavior of the shear damaged beam were improved with anchoraged CFRP strips. Anchorages applied to CFRP strip ends prevented shear failure and showed ductile flexural behavior. No damage or rupture was observed at anchorages and CFRP strips.
- Specimen 2, 3, and 4 failed due to peeling of CFRP strip ends. CFRP strips without anchorages are not sufficient for improving the displacement capacity of the specimens. Specimens 2 and 3 carried 55% larger shear load than the reference specimen in average. Specimen 4 carried 36% larger shear force than the reference specimen.
- Anchorages that were used at the CFRP strip ends are significantly effective on improving the shear strength and behavior of the specimens. Displacement capacity of the specimens strengthened with anchoraged CFRP strips was significantly improved. Specimens 5, 6, and 7 with anchoraged CFRP strips carried 77% larger shear load than the reference specimen in average.
- Tension reinforcement of the Specimens 2, 3, and 4 without anchorages could not reach the yield capacity. Average stiffness for the anchoraged Specimens 5, 6, and 7 is calculated as 3.91 kN/mm. As the CFRP strips spacing increased, secant stiffness dropped. Fan type anchorages that were used at the ends of CFRP strips are significantly effective on improving stiffnesses. 25% more stiffness increase was observed at the anchoraged Specimens 5, 6, and 7 than the Specimens 2, 3, and 4 without anchorages at 56 kN load level.
- Anchorages improved the displacement capacity of the specimens, and displacement ductility ratios were improved. Displacement ductility ratios of the anchoraged specimens are varying between 2.46 and 1.41. Displacement ductility ratios of the specimens decreased, when the CFRP strips' spacing increased, and as a result midpoint deflection increased.
- Specimens with anchoraged CFRP strips dissipated 2.05 times more energy than that of the specimens without anchorages. As the CFRP strip spacing increased, energy dissipation capacity decreased.
- When the CFRP strains of the strips with anchorages and without anchorages are compared,

maximum strains at anchoraged strips are approximately 68% larger than that of strips without anchorages. Average strains of anchoraged Specimens 5, 6, and 7 are 106% larger than the suggested strain of ACI Committee Report 440 and FIB.

· Ultimate shear strength of the specimens is calculated by using ACI 318 regulation, ACI Committee Report 440, Eurocode 2 and FIB. Due to the fact that maximum strain value (0.004 mm/mm) suggested at regulations is significantly lower than the measured maximum strains for the anchoraged specimens, conservative lower capacity values are calculated. 40% and 44% lower values are calculated than experimental results, when ACI 440 and FIB regulations are used, respectively.

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Conversion factors

1 mm = 0.039 in
1 mm^2 = 0.00152 in^2
1 kN = 0.2248 kips
1 MPa = 145 psi

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Symbols

a : Shear span
A_{fv} : CFRP strip cross sectional area (mm)
b_f : CFRP strip width (mm)
b_w : Beam cross sectional width (mm)
d : Beam effective height (mm)
d_f : CFRP strip bonding length (mm)

E_f, E_{fu} : CFRP elastic modulus (MPa)
f_c : Concrete compression strength (MPa)
f_{fe} : CFRP strip rupture stress (MPa)
f_y : Shear reinforcement yield strength (MPa)
n_f : Number of the CFRP layer at one face
s_f : CFRP strip spacing (mm)
V : Shear force capacity of beam (N)
V_c : Shear force carried by concrete (N)
V_s : Shear force carried by shear reinforcement (N)
V_f : Shear force carried by CFRP strips (N)
w_f : CFRP strip width (mm)
α : CFRP strip angle with respect to horizontal plane
ε_f, $\varepsilon_{fd,e}$: CFRP strain
Φ : Angle of crack
ρ_f : Ratio of CFRP strip
ρ_w : Ratio of shear reinforcements