Available online at www.sciencedirect.com
SCIENCE DIRECT®
Cement & Concrete Composites 28 (2006) 638–649
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

Improving shear capacity of RC T-beams using CFRP composites subjected to cyclic load

Özgür Anil *

Civil Engineering Department, Gazi University, Maltepe, Ankara 06570, Turkey

Received 7 June 2005; accepted 11 April 2006
Available online 27 June 2006

Abstract

Various methods are developed for strengthening reinforced concrete beams against shear. Nowadays, external bonding of various composite members to RC beams was very popular and successfully technique internationally. This study present test results on strengthening of shear deficient RC beams by external bonding of carbon fiber reinforced polymer (CFRP) straps. Six RC beams with a T section were tested under cyclic loading in the experimental program. Width of the CFRP straps, arrangements of straps along the shear span, and anchorage technique that were applied at the ends of straps was the main parameters that were investigated during experimental study. Inclined CFRP straps were bonded along the shear spans of shear deficient beams for strengthening against shear by using epoxy. Arrangements and width of the inclined CFRP straps were the main parameters that were changed among the specimens. The test results confirmed that all CFRP arrangements improved the strength and stiffness of the specimens significantly. The failure mode, and ductility of specimens were proved to differ according to the CFRP strap width and arrangement along the beam. Experimental results were compared with the analytical approaches that were suggested by ACI-440 Committee report.

Keywords: Reinforced concrete beam; Strengthening; Shear; Epoxy; CFRP; Cyclic load

1. Introduction

Reinforced concrete (RC) beams in general fail in two types: flexural failure and shear failure. As it known well, the shear failure of RC beam is sudden and brittle in nature. It is less predictable and so it gives no advance warning prior to failure. Shear failure is more dangerous than the flexural failure. It is why the RC beam must be designed to develop its full flexural capacity to assure a ductile flexural failure mode under extreme loading. However, many of RC structures are encountered shear problems due to various reasons, such as mistake in design calculations and improper detailing of shear reinforcement, construction faults or poor construction practices, changing the function of a structure from a lower service load to a higher service load, and reduction in or total loss of shear reinforcement steel area causing corrosion in service environments.

The known strengthening techniques of shear deficient beams are as follows: CFRP applications, strengthening with externally applied clamps, jacketing with concrete layers, and external bonding of steel plates with epoxy. For strengthening shear deficient beams, numerous tests have been carried out, and shown that composite materials are an excellent option to be used as external reinforcing. Recently, innovative composite materials known as fiber-reinforced polymers (FRP) have shown great promise in rehabilitation of existing reinforced concrete (RC) structures. Rehabilitation of these structures can be in the form of strengthening of structural members, repair of damaged structures, or retrofitting for seismic deficiencies. In any case, composite materials are an excellent option to be used as external reinforcing because of their high tensile strength, light weight, resistance to corrosion, high durability, and ease of installation. Externally bonded FRP

* Tel.: +90 312 231 74 00/2215; fax: +90 312 230 84 34.
E-mail address: oanil@gazi.edu.tr

0958-9465/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2006.04.004

Nomenclature

Conversion factors

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

Symbols

a	shear span
d	effective height of the cross-section
f_c	compressive strength of concrete
L	length of the beam
M_{cal}	calculated moment capacities of specimens
M_{exp}	experimental moment capacities of specimens
V_{exp}	experimental shear forces of specimens
V_{cal}	calculated shear forces of specimens
ε_{CU}	maximum strain of concrete
ϕ	diameter of reinforcement
ρ_w	ratio of shear reinforcements

reinforcement has been shown to be applicable for the strengthening 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 [1–11].

Carbon reinforced knitted fibers were used for manufacturing CFRP plates that were frequently utilized for strengthening shear deficient beams. Strengthening with CFRP was became widely used technique recently. For this reason, the number of studies that were investigated effects of parameters on the behavior of shear deficient beams was increased significantly at literature. The ultimate load of the strengthened RC beam depends principally on the compressive strength of concrete, the yield strength of shear and longitudinal reinforcement, the tensile reinforcement ratio, shear span to depth ratio, the composite materials strength and ratio. Therefore researches were concentrated on performances and failure of CFRP strengthened shear deficient beams that were strengthened by using different arrangements and width of CFRP straps. Besides these, main parameters that were investigated in previous studies at literature were as follows: wrapping schemes and shape of the CFRP plates or straps, CFRP amount, ply combination and number, and inclination angle of fiber with respect to beam axis [11–20]. As a result of strengthening studies of shear deficient beams by using CFRP, arrangements and wrapping schemes were determined for improving strength and stiffness of existing beams. Then these results are collected and reported [21]. But monotonous loading was applied in all these studies and performance of the CFRP were not investigated under cyclic loading. Major failure mode under monotonic loading was called peeling of CFRP straps from the concrete surface at the strap ends. Peeling of CFRP straps ends caused early failure of beams without reaching their full ductility value. Beams were failed just before or after reaching tensile reinforcement's yield strength without showing any ductility. For preventing this type of failure, anchorage techniques should be developed and applied at the each ends of CFRP straps [22]. But very limited amount of study was found about the anchorage details of CFRP straps under cyclic load in literature.

This paper presents results of an experimental study conducted on the strengthening of shear deficient T cross-sectional beams by using external bonding of CFRP straps. Six specimens, one of which was a control specimen and the remaining five of which had deficient shear reinforcement were tested in an experimental program under cyclic load [23]. Four of the specimens with deficient shear reinforcement were strengthened with inclined CFRP straps, and remaining one tested without strengthening. Ends of CFRP straps of strengthened specimens were anchoraged to beam concrete according to wrapping schemes of CFRP straps. Ductile flexural failures of strengthened beams were aimed by this application. The results of test on these beams were compared with control beam. The effects of the type and arrangements of CFRP straps that were used for strengthening on behavior, strength, stiffness, failure mode and ductility of the specimens were investigated. Experimental results were compared with the analytical approaches that were suggested by ACI-440 committee report [21].

2. Experimental program

2.1. Test specimens and materials

A total of six T-section RC beams were tested under cyclic load in the experimental program. Dimensions and reinforcement details are shown in Fig. 1. The cross-sectional geometries and longitudinal reinforcements were the same for all specimens. Longitudinal reinforcement consists of three 20 mm diameter steel rebars in the bottom and top of the beam. Shear reinforcement consisted of 6 mm diameter closed stirrups, spaced at 75 mm spacing center to center throughout of the Beam-1. No stirrups were put in to Beam-2 and strengthened specimens Beam-3, 4, 5, and 6. Table 1 summarizes the specimen's properties. Average compressive strengths of concrete were determined from standard test of cylinders that were cast from the same concrete as was used for the beams. As can be seen from

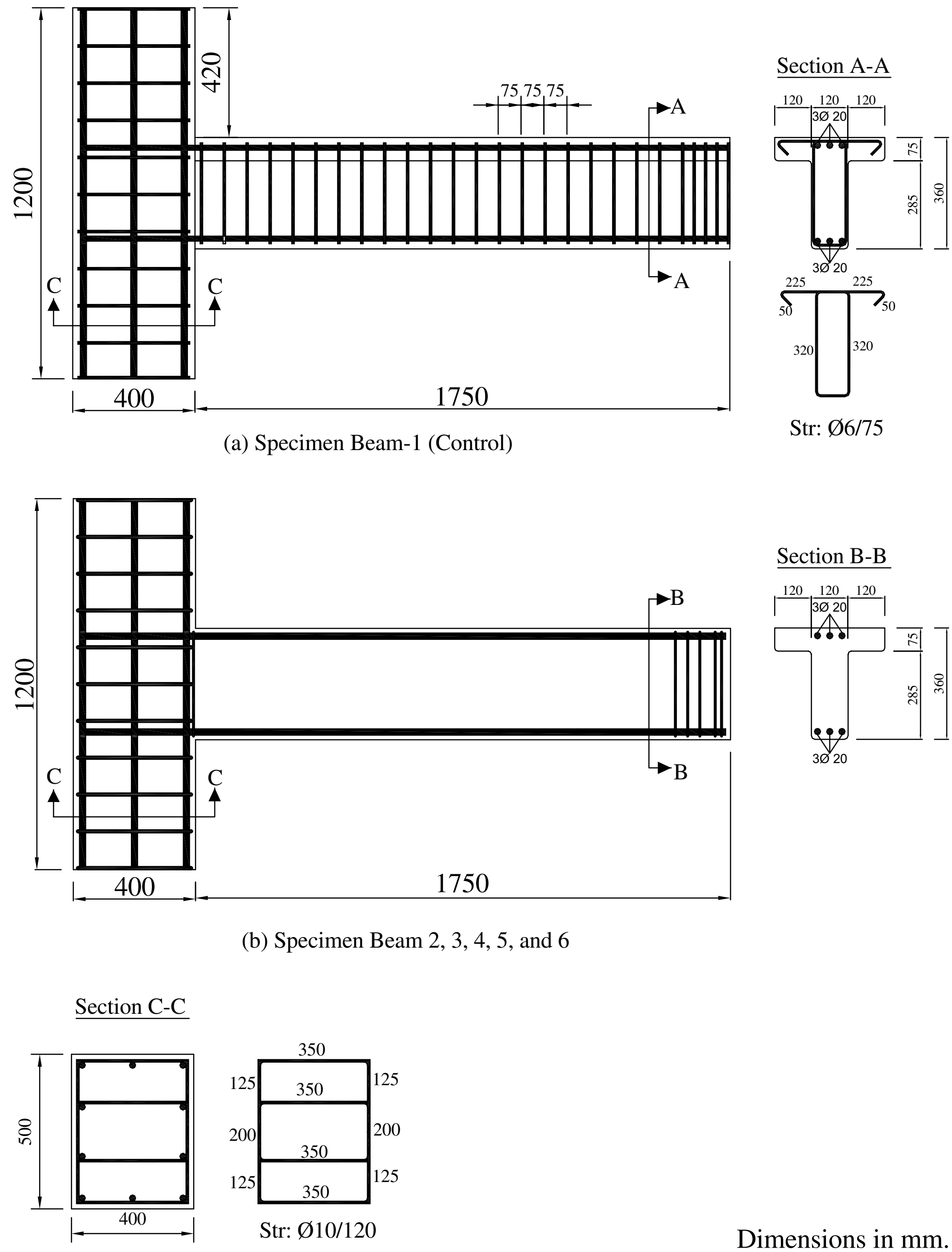

Fig. 1. Reinforcement details of specimens.

Table 1
Properties of specimens

Specimen #	L (mm)	a (mm)	d (mm)	a/d	f_c (MPa)	Stirrups ρ_w	CFRP strap properties for strengthening				
							Width	Angle	Spacing (mm)	Anchorage	Arrangements
Beam-1 (control)	1750	1675	335	5.0	33.0	0.00224	–	–	–	–	–
Beam-2 (control)	1750	1675	335	5.0	30.0	–	–	–	–	–	–
Beam-3 (strengthening)	1750	1675	335	5.0	35.6	–	50	45°–135°	285	Yes	Both side
Beam-4 (strengthening)	1750	1675	335	5.0	35.8	–	100	45°–135°	285	Yes	Both side
Beam-5 (strengthening)	1750	1675	335	5.0	35.2	–	50	45°–135°	143	Yes	Both side
Beam-6 (strengthening)	1750	1675	335	5.0	35.0	–	50/100[a]	45°–135°/90°[a]	285	Yes	Both side/U Wrap[a]

[a] 50 mm wide, 45°–135° inclined crossed CFRP straps at both side of the beam web, and perpendicular 100 mm wide "U" wrapped CFRP straps.

Table 1, the average compressive strengths of the concrete were greater than 30 MPa. Table 2 shows the mechanical properties of reinforcing bars used in the beams.

Beam-1 was the control specimen that was designed such that it had greater shear strength than flexural strength. Thus, ductile flexural failure was the dominant mode of failure. Other RC beams were designed to have a deficiency in shear capacity; thus, shear failure was the

Table 2
Material properties of reinforcements

Reinforcements	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus $\times 10^3$ (MPa)
6 mm bar	275.0	417.0	192
10 mm bar	304.2	443.1	198
20 mm deformed bar	414.0	687.9	205

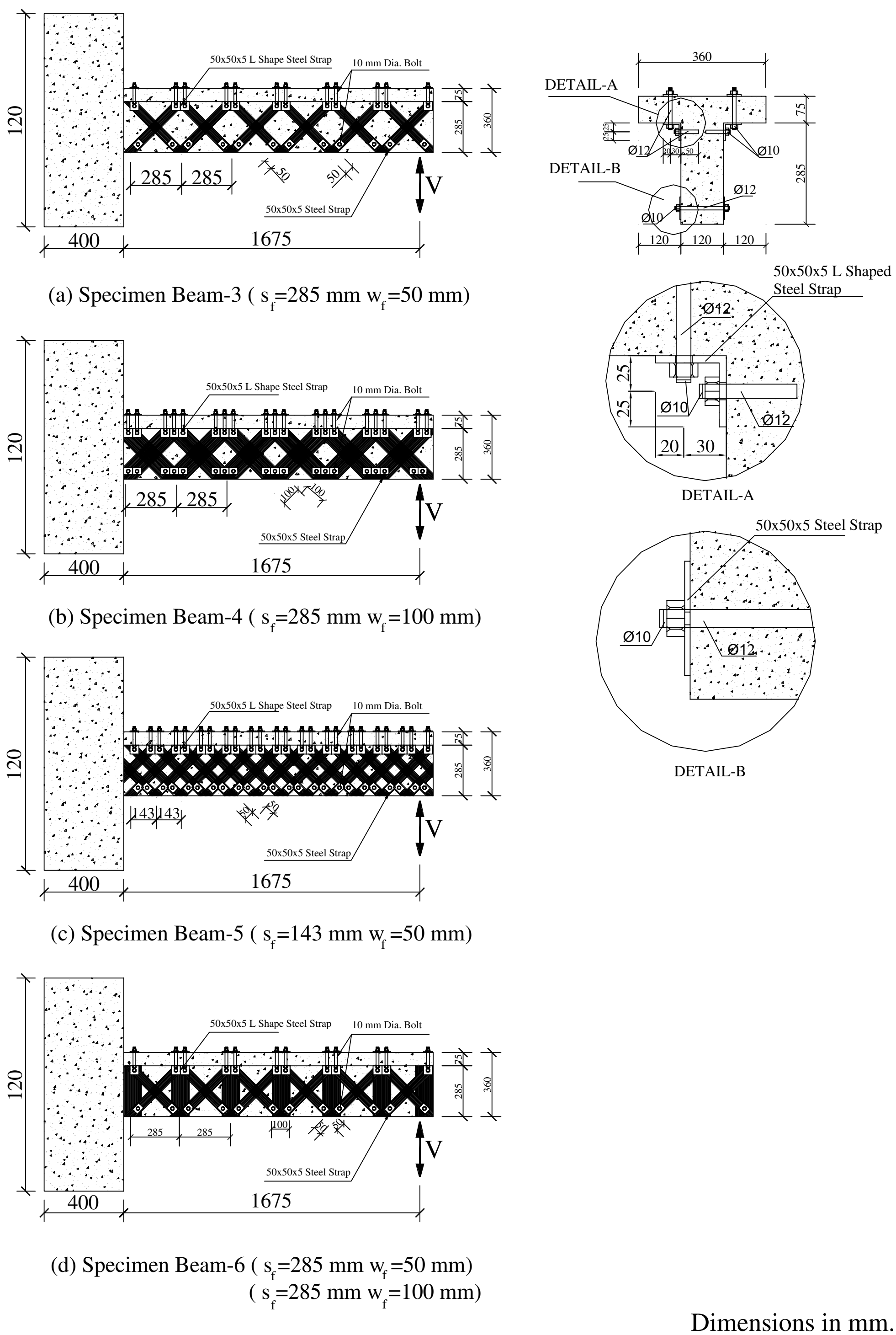

Fig. 2. CFRP strap arrangements of strengthening specimens.

dominant mode of failure. There were no shear reinforcements at shear deficient beams. Shear deficient beams were strengthening with bonded inclined CFRP straps. Strengthening with CFRP straps were not applied to Beam-2, thus it failed with brittle shear failure. The other specimens (Beam-3, 4, 5, and 6) were strengthened with different arrangements of inclined CFRP straps. The details of strengthening that were applied to specimens are shown in Fig. 2.

Beam-3 was strengthened with 50 mm wide inclined CFRP straps spaced at 285 mm. Inclination angles of CFRP straps that were bonded both sides of the beam were 45° and 135°. Each of the straps' ends was anchoraged to the beam. Anchorages of crossed CFRP straps at which overlapped region situated at the bottom and top of the beam web were positioned side by side. Beam-4 was strengthened with 100 mm wide inclined CFRP straps spaced at 285 mm. Inclination angles of the CFRP straps that were bonded both sides of the beam were 45° and 135°. Three anchorages were put at crossed CFRP straps when they are overlapped at bottom and top of the beam web, but if they are not overlapped, two anchorages were placed. Beam-5 was strengthened with 50 mm wide inclined CFRP straps spaced at 143 mm. Inclination angles of the CFRP straps that were bonded both sides of the beam were 45° and 135°. Each of the straps' ends was anchoraged to the beam with single anchorage. Anchorages of crossed CFRP straps were applied side by side. Beam-6 was strengthened with 100 mm wide CFRP straps at which fiber direction was made 90° with the beam axis as a second ply on the existing 50 mm wide inclined straps. Beam-6 had also 50 mm wide inclined straps with 45° and 135° like Beam-3. Vertical straps were wrapped like "U" around the beam web and spaced 285 mm. Vertical 100 mm wide straps were situated at the overlapping regions of 50 mm wide inclined straps and were confined overlapping regions. Two anchorages were put at the overlapping regions of 50 mm wide inclined straps and 100 mm wide vertical straps side by side. Single anchorages were put at the other ends of 50 mm wide inclined straps.

Anchorages had different details that are shown in Fig. 2 at the bottom and top of the beam web. Beams webs were drilled throughout with 12 mm diameter drill at the bottom and 10 mm diameter threaded rods are used for anchoraging CFRP straps. Small rectangular $50 \times 50 \times 5$ mm steel plates are used at both sides of the beam web for preventing peeling of CFRP straps from the concrete surface. L shaped $50 \times 50 \times 5$ mm steel plates were used at the top of the beam web. These "L" shaped plates were anchoraged to both beam web and topping. Top of the beam webs were drilled 12 mm diameter drill up to 50 mm depth and 10 mm diameter threaded rods were bonded with epoxy in to these holes. The other ends of "L" shaped plates were anchoraged to the beam toppings with 10 mm diameter threaded rods. Beam toppings were drilled throughout with 12 mm diameter drill. All strengthened specimens had the same anchorage details.

2.2. Bonding procedure

The same application steps were used for strengthening all specimens. Sikawrap 160c CFRP sheets and Sikadur 330 epoxy was used for strengthening. Properties of these products are given in Table 3. Before bonding CFRP members on the concrete surface, special consideration was given to the beam web surface preparation. Both sides of the beam web were roughened by a mechanical grinding machine until to expose the aggregate and then brushed. Surfaces were vacuum cleaned to remove loose particles and dust. Later on the epoxy resin had to be mixed in accordance with manufacturer's instruction. Mixing was carried out in a metal container and was continued until the mixture was a uniform color. Prepared mixture of Sikadur 330 epoxy was spread over both sides of the beam web up the 1.5 mm thickness. Then CFRP straps were bonded their predefined places at both sides of beam web. After bonding of CFRP straps, some pressure applied on them by hand along the fiber directions to get rid of air bubbles entrapped between CFRP straps and concrete surfaces and CFRP straps were soaked with applied epoxy on concrete. Finally, another 1.5 mm epoxy layer was applied on the CFRP straps along the fiber directions for protecting the CFRP fibers. The temperature during application was 20 ± 2 °C in all cases. After bonding operations was completed, specimens were cured for 15 days under laboratory conditions before testing.

2.3. Experimental set-up

A schematic view of experimental set-up and the arrangement of the measurement devices are shown in Fig. 3. Specimens are tested on a rigid platform and suspended to a rigid wall with two 45 mm diameter high strength steel mounting rods. Specimens can be assumed as cantilever with this mounting. Cyclic load was applied to free end of the beam by a loading system that was

Table 3
Properties of CFRP and resin

Properties	Remarks
Fiber orientation	0° (unidirectional)
Construction	Warp: carbon fibers (99% of total areal weight); Weft: thermoplastic heat-set fibers (1% of total areal weight)
Areal weight	$220 \text{ g/m}^2 \pm 10 \text{ g/m}^2$
Fiber density	1.78 g/cm^3
Fabric design thickness	0.12 mm (based on total carbon content)
Tensile strength of fibers	4100 N/mm^2 (nominal)
Tensile modulus of fibers	$231{,}000 \text{ N/mm}^2$ (nominal)
Strain at break of fibers	1.7% (nominal)
Resin (Sikadur 330)	Two component (A and B)
Resin mixture ratio	A/B = 4/1 (weight)
Resin tensile strength	30 N/mm^2
Tensile modulus of resin	3800 N/mm^2

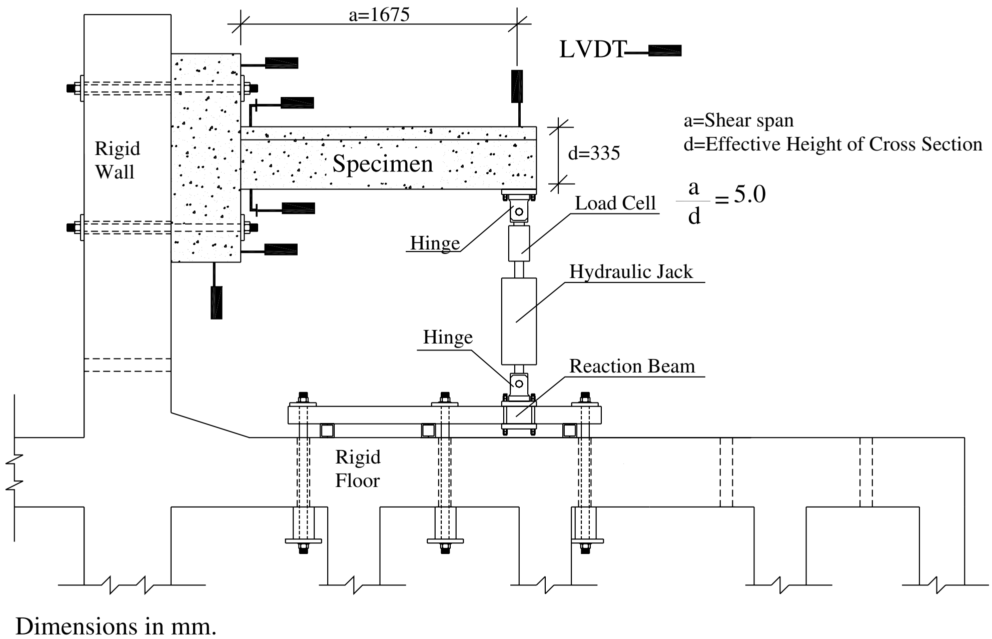

Fig. 3. Test set-up and instrumentation.

attached to both rigid platform and beam free end with a hinge joint. Load was applied a 1000 kN capacity hydraulic jack and was controlled with a 600 kN capacity load cell. After applying a couple of cycles in elastic region, load was increased up to calculated cracking loads at which first flexural and shear cracks were observed, and then load was increased up to yield load of flexural reinforcements gradually. Same loading cycles were applied to all specimens. But because of differences in shear load carrying capacities of specimens, load steps after first flexural and shear cracks loads were determined by the capacities and behaviors of the specimens. The ratio of the shear span length, 1675 mm, to the effective height of the beam, 335 mm, was 5.0 and was the same for all specimens. The beam free end deflection and moment curvature at the maximum moment region were measured with LVDT's and CFRP strain were measured with strain gauges. Strain gauges were attached to CFRP straps along the fiber direction and were attached to straps that were situated at a distance between 300 and 1000 mm apart from the rigid wall.

3. Experimental results and evaluations

3.1. Observed behavior and failure modes

Test results are summarized in Table 4. Fig. 4 shows cracking patterns and failure modes of specimens. In all specimens, the first crack always appeared as a flexural crack at the maximum bending moment region of the beam. In general first flexural cracks developed at 31% of the yield strength of specimens. Beam-1 control specimen showed ductile flexural behavior, due to longitudinal tension reinforcement yielding. After yielding, Beam-1 developed large displacements, and reached an ultimate load value that was 14% greater than the yield load. Beam-1 failed because of plastic hinge developed at maximum moment region.

Beam-2 at which no shear reinforcements were utilized collapsed with a brittle shear failure and without reaching its flexural capacity. Three main shear cracks developed in shear span and combined between beam web and

Table 4
Experimental results

Specimen #	Cracking load (kN)		Flexural yield load (kN)	Failure load (kN)	Yield disp. (mm)	Failure disp. (mm)	Stiffness at yield (kN/mm)	Ductility ratio	Failure mode at ultimate
	Flexure	Shear							
Beam-1 (control)	25	60	92.3	104.8	24.3	80.7	3.80	3.32	Flexure
Beam-2 (control)	25	45	–	41.4	–	12.0	–	–	Shear
Beam-3 (strengthening)	30	60	–	74.3	–	33.71	–	–	Shear
Beam-4 (strengthening)	30	60	91.1	89.9	26.8	39.1	3.40	1.46	Flexure
Beam-5 (strengthening)	30	80	90.0	90.0	31.5	31.5	2.86	1.00	Flexure–shear
Beam-6 (strengthening)	30	60	90.8	91.9	26.8	51.8	3.39	1.93	Flexure

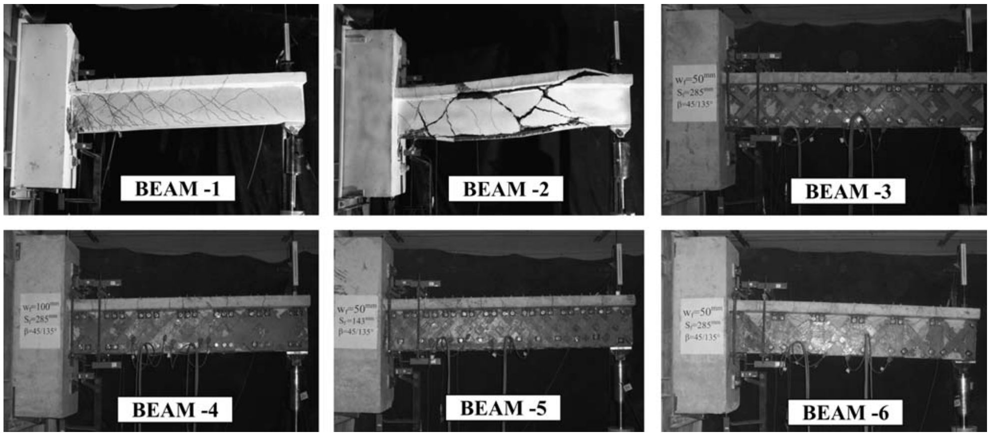

Fig. 4. Pictures of specimens after failure.

topping connection section. Beam-2 showed 2.23 times less strength than Beam-1.

First shear cracks were observed on Beam-3 at 60 kN load level. Shear cracks were propagated and confined all beam web along the third CFRP strap cross and with the same angle at which CFRP straps were bonded. The numbers of shear cracks that were parallel to second and first CFRP strap cross were increased with increasing load. Forty five degree inclined CFRP strap at first cross was ruptured from crossing region (Fig. 5a). Concrete cover was separated up to longitudinal tension reinforcement at the bottom of beam web where CFRP straps' anchorages were placed (Fig. 5b). As a result specimen lost its load carrying capability.

First shear cracks were observed on Beam-4 at 60 kN load level along the second CFRP strap cross and with the same angle at which CFRP straps were bonded. The number and width of shear cracks were increased with increasing load significantly. Longitudinal compressive and tension reinforcements of Beam-4 was reached their yield strength at 91 kN and 89 kN load respectively. After that point, specimen preserved its load carrying capacity for two full cycles. Forty five degree inclined CFRP strap at second cross at which first shear cracks were observed was ruptured, and specimen load carrying capacity dropped suddenly (Fig. 6a). Concrete cover was separated up to longitudinal tension reinforcement at the bottom of beam web where CFRP straps' anchorages were placed. As a result specimen lost its load carrying capability (Fig. 6b).

First shear cracks developed on Beam-5 at 80 kN load level. Note that this value was greater than the other specimens. At this load level, observed shear cracks was originated at 45° inclined CFRP strap of second cross that is situated close to supporting point of beam and propagated up to bottom of beam web (Fig. 7a). Then concrete cover was separated up to longitudinal tension reinforcement at the bottom of beam web where CFRP straps' anchorages were placed. Then specimen lost its load carrying capability (Fig. 7b).

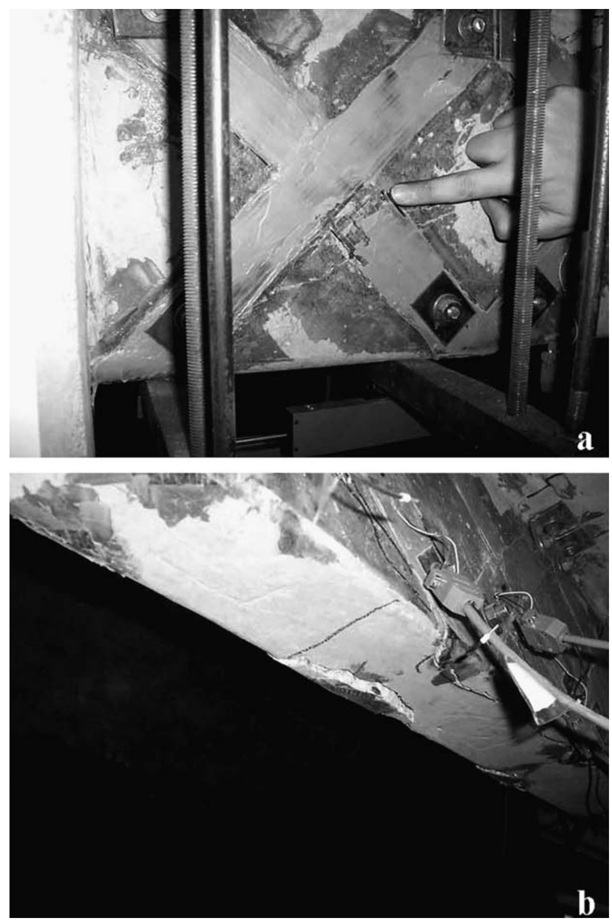

Fig. 5. Failure mode of specimen 3.

Beam-6 was strengthened with the same arrangement of CFRP straps that were used Beam-3. But additional CFRP straps were bonded as a second ply for preventing separation of concrete cover up to longitudinal tension reinforcement at the bottom of beam web. Additional 100 mm wide CFRP straps were bonded at the connection region of existing inclined CFRP straps, and these vertical straps were wrapped like "U" around the beam web and spaced

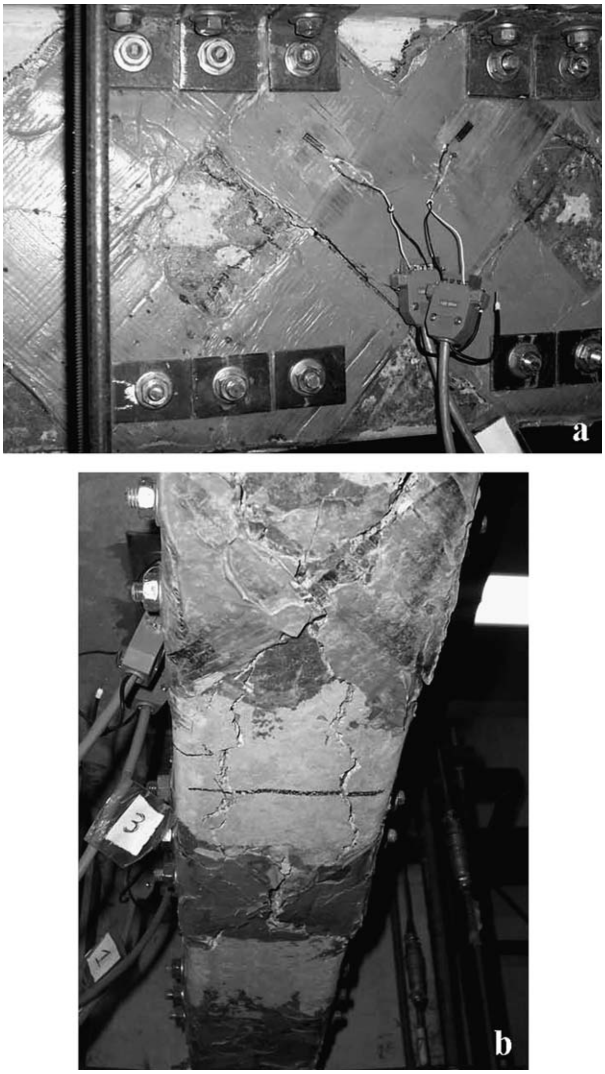

Fig. 6. Failure Mode of Specimen 4.

Fig. 7. Failure mode of specimen 5.

at 285 mm. First shear crack that was originated at 45° inclined CFRP strap of second cross developed on Beam-6 at 60 kN load level. This shear crack was started from bottom anchorages and propagated up to beam topping. Longitudinal compressive and tension reinforcements of Beam-6 were reached their yield strength at 90 and 91 kN load, respectively. There were no significant increase on the number and size of shear cracks up to these load level. A main crack was caused to separate all across the cross-section of the beam from supporting base. Beam-6 showed a ductile flexural behavior as a result of plastic hinge that was developed at this region. There were no newly developed shear cracks and changes at CFRP strain measurement along shear span, because all deformation was occurred at plastic hinge. After yield point, four more full cycles were applied to specimen.

3.2. Load–displacement behavior

Load–displacement relationships for the specimens are shown in Fig. 8. Beam-1 showed a ductile flexural behavior like expected. After yielding of longitudinal tension reinforcement at 92.3 kN, it underwent large displacement values. Beam-1 made 80.7 mm displacement up to failure, and reached a ductility ratio of 3.32. This ratio was the greatest among the specimens. In addition Beam-1 had the greatest yield stiffness value as 3.80 kN/mm among the specimens. Beam-2 at which no strengthening was applied was failed at 41.4 load level by making 12.0 mm displacement. The failure mode of Beam-2 was sudden and brittle shear failure. Beam-1 showed 2.23 and 6.27 times more strength and displacement than Beam-2, respectively.

The strengths and stiffnesses of strengthened specimen Beam-3, 4, 5 and 6 were affected by the width of CFRP straps and arrangements that were used in strengthening. Beam-3 that was strengthened with 50 mm wide CFRP straps spaced at 285 mm was showed 20% less, and 80% more strength than Beam-1 control specimen and Beam-2 specimen without strengthening, respectively. Beam-3 was underwent 2.4 times less displacement than Beam-1, and failed with brittle shear failure without reaching yield

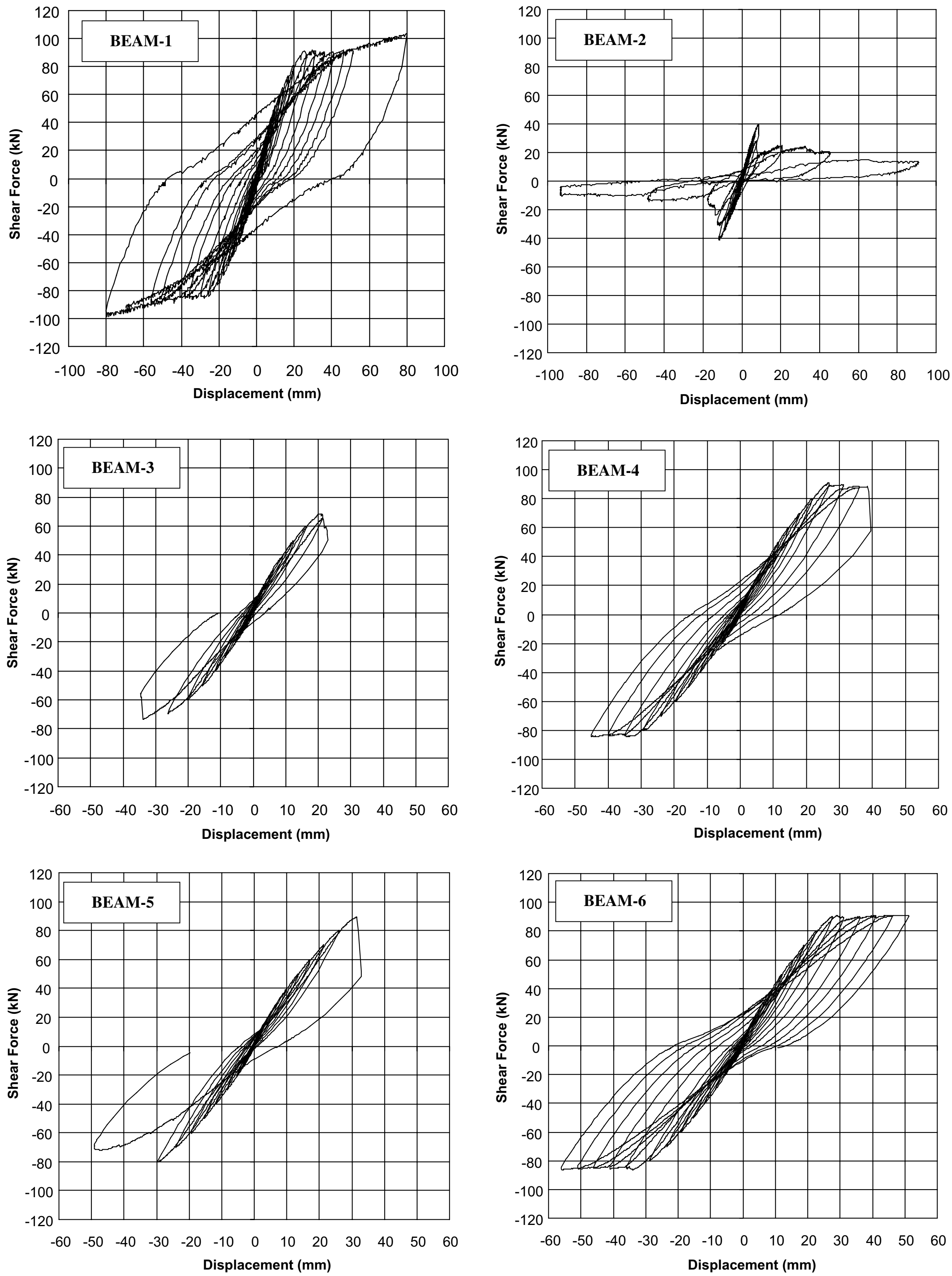

Fig. 8. Load–displacement hysteretic curves of test specimens.

strength of longitudinal tension reinforcement. Beam-3 measured largest strain, which was 4% larger than the ACI-440 committee report expected value, was 0.004167 mm/mm.

Beam-4 that was strengthened with 100 mm wide straps spaced at 285 mm was showed 1% less, and 2.2 times more strength than Beam-1 control specimen and Beam-2 specimen without strengthening, respectively. Beam-4 had close

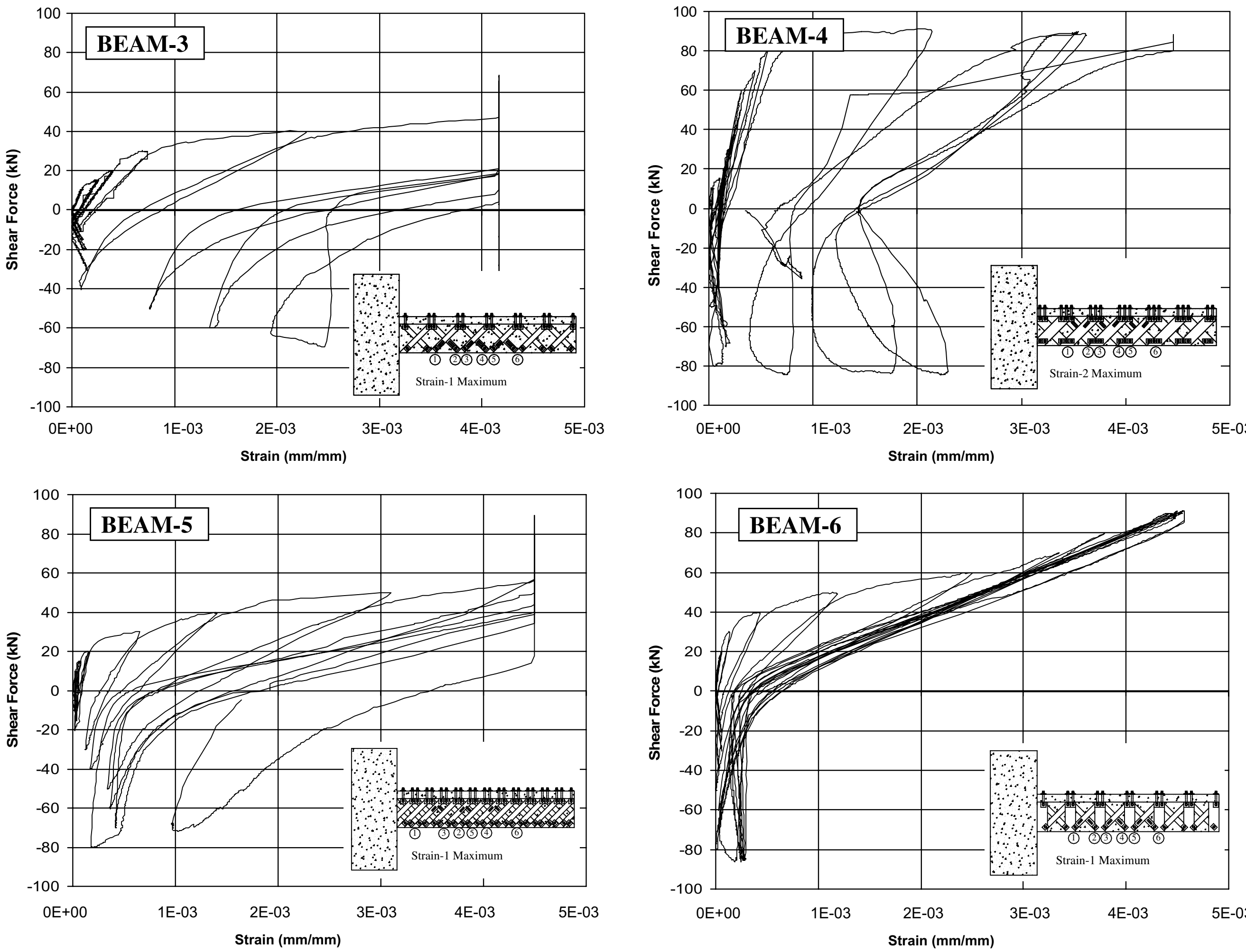

Fig. 9. Load–maximum CFRP strain curves of test specimens.

yield stiffness value to Beam-1 control specimen as 3.40 kN/mm. Beam-4 underwent 39.1 mm displacement which was half of the Beam-1 displacement up to failure. Beam-4 measured largest strain, which was 11% larger than the ACI-440 committee report expected value, was 0.004454 mm/mm.

Beam-5 that was strengthened with 50 mm wide straps spaced at 143 mm was showed 2% less, and 2.17 times more strength than Beam-1 control specimen and Beam-2 specimen without strengthening, respectively. Beam-5 had 2.86 kN/mm yield stiffness, which was 25% less than Beam-1 yield stiffness. Beam-5 was failed suddenly with brittle shear fracture without making any displacement after reaching yield strength of longitudinal reinforcement. Beam-5 measured largest strain, which was 12% larger than the ACI-440 committee report expected value, was 0.004493 mm/mm.

While planning the Beam-6 CFRP arrangements, the main effort was the prevention of separation crack that was developed parallel the beam axis of Beam 3, 4 and 5. For this purpose, "U" shaped CFRP straps that were bonded perpendicular to beam axis were used for wrapping beam web regions where inclined CFRP straps crossed each others. Beam-6 had quite good strength and stiffness with these CFRP arrangements, and it showed quite similar ductile flexural behavior like Beam-1 control specimen.

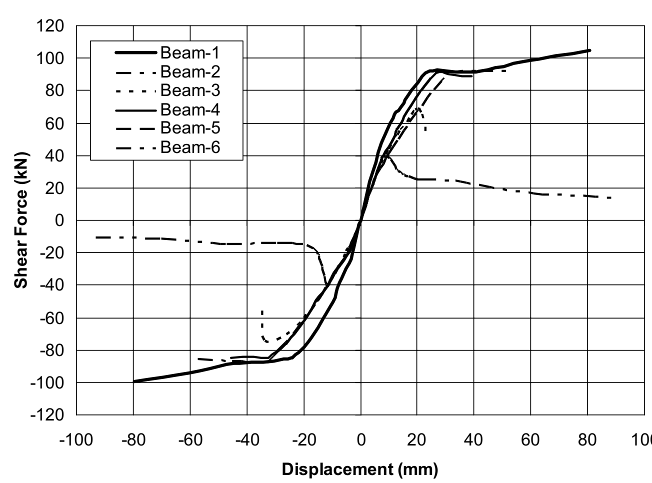

Fig. 10. Response envelope curves of test specimens.

Beam-6 was showed 2% less and 2.19 times more strength than Beam-1 control specimen and Beam-2 specimen without strengthening, respectively. Beam-6 had yield stiffness value of 3.39 kN/mm. Although Beam-6 was underwent 51.8 mm displacement which was 36% less than Beam-1, it showed ductile behavior. Beam-6 measured largest strain which was 14% larger than the ACI-440 committee report expected value was 0.004566 mm/mm.

Totally six strain measurements were taken from the specimens. The largest of these measurements was plotted in Fig. 9. Response envelope curves were drown by connecting peak points of loading cycles and were presented on Fig. 10. Comparisons of strength and stiffnesses of specimens were done by using these envelope curves.

4. Comparison of analytical and experimental results

Comparison of analytical and experimental moment and shear force capacities are presented in Table 5. The flexure moment capacities of specimens were calculated according to ACI 318-99 regulations [24]. The maximum concrete strain was taken as $\varepsilon_{CU} = 0.003$ mm/mm, and the flexural capacity of 0.12 mm thick CFRP straps was assumed to be negligible. The analytical shear force capacities of specimens were calculated according to method that was suggested at ACI committee report. The shear force carried by the concrete and shear reinforcements were calculated according to ACI 318-99 regulations. Only the concrete was contributed to shear force carrying capacities of specimens. Because there were no shear reinforcements at the specimens except Beam-1.

Analytical moment capacities of specimens were 17% less than the experimental moment capacities in average except Beam-2. Analytical shear load capacities of the all specimens and strengthened specimens were 12% and 20% less than the experimental shear load capacities in average, respectively. The closest match between analytical and experimental values was obtained at Beam-6 shear load capacity among the specimens. Author thought that the reason of obtaining smaller analytical results than experimental ones was the application of anchorages. The positive influence of anchorages to shear force capacity was not included in the analytical equations that were suggested by ACI-440 committee report. Author thought that the effect of anchorages to shear force capacity should be added to equations.

5. Results

External bonding of various CFRP members to shear deficient RC beam for strengthening purposes was very popular technique and widespread research area recently. But monotonic loading was applied in all studies that were encountered in literature for improving strengthening technique basis. Studies that were found in literature were not investigated performance of the CFRP members under cyclic loading. In addition dominant failure mode that was observed at past beam strengthening studies was peeling of the CFRP strap ends from the concrete surface. But there were limited amount of studies at literature about preventing this failure mode by applying anchorages to ends of CFRP straps. Furthermore no literature was found about application of anchorages under cyclic loads. For these reasons, an experimental study conducted on the strengthening of shear deficient beams by using external bonding of inclined CFRP straps under cyclic loads, and anchorages were applied for improving the performance of CFRP straps under same type of loading. As a result experimental data shortages about these subjects were ceased. Results and comments obtained from the experiments that were conducted on six specimens as follows:

- All longitudinal tension reinforcements of specimens reached yield strength in experimental program except Beam-3, and beams' shear capacities were increased significantly. Even Beam-3 shear capacity increased 1.79 times. Average of shear strength capacity increase observed at specimens Beam-4, 5 and 6 was 2.19 times. Expected increase of performance in shear capacity was obtained from specimens that were strengthened with inclined CFRP straps and subjected to cyclic loads.
- Stiffnesses of the specimens were very close to Beam-1 control specimen. Although Beam-5 had the smallest yield stiffness among the strengthened specimens, yield stiffness of Beam-5 only 25% less than the Beam-1 yield stiffness. Average of stiffnesses of Beam-4 and 6 that had quite good stiffness values were only 11% less than the Beam-1 control specimen stiffness.

Table 5
Comparison of experimental and analytical results

Specimen #	Experimental strengths				Calculated strengths		Experimental/calculated	
	M_{exp} (kN m)	V_{exp} (kN)	$\frac{V_{exp}}{V_{exp\,(Beam\text{-}1)}}$	$\frac{V_{exp}}{V_{exp\,(Beam\text{-}2)}}$	M_{cal} (kN m)	V_{cal} (kN)	M_{exp}/M_{cal}	V_{exp}/V_{cal}
Beam-1 (control)	154.6	92.3	1.00	2.23	125.9	94.4	1.23	0.98
Beam-2 (control)	69.3	41.4	0.45	1.00	125.8	45.3	0.55	0.91
Beam-3 (strengthening)	124.5	74.3	0.80	1.79	126.0	61.1	0.99	1.22
Beam-4 (strengthening)	152.6	91.1	0.99	2.20	126.0	73.2	1.21	1.24
Beam-5 (strengthening)	150.8	90.0	0.98	2.17	126.0	72.4	1.20	1.24
Beam-6 (strengthening)	152.1	90.8	0.98	2.19	126.0	82.4	1.21	1.10

- Developed anchorages details were performed well under cyclic loads. Although there were no shear reinforcements in the specimens that tied the beam web and topping together, top anchorages that were applied for CFRP straps prevented separation of beam topping and web. In addition they were prevented peeling of the CFRP straps from concrete. Bottom anchorages were also prevented peeling successfully. The observed failure modes from experiments of Beam-3, 4, and 5 that were strengthened with CFRP straps bonded to both sides of beam web were quite crucial. Anchorages details that were applied to bottom of beam web were different from conventional stirrups. They did not pass under the longitudinal tension reinforcements and confined that region. As a result, tension forces that were transformed from CFRP straps to bottom beam web concrete caused to separate concrete parallel to beam axis up to longitudinal tension reinforcement. This large separation caused the failure of beams. But additional CFRP straps that were used at connection regions of crossed CFRP straps prevented this failure mode by confining Beam-6 beam web.
- Analytical shear load capacities of the strengthened specimens that were suggested by ACI-440 committee report were 20% less than the experimental shear load capacity in average. Author thought that the reason of obtaining larger experimental shear load capacities than expected was the successful performance of anchorages.

The study was an initial step to cease experimental data shortage and adding valuable experimental test data to literature about strengthening T cross-sectioned shear deficient beam by bonding inclined CFRP straps subjected to cyclic loads. But the number of specimens should be increased and different arrangements of CFRP straps should be tested under cyclic load like inclined CFRP straps. In addition different beams that had different ratios of shear span length to effective height should be tested under cyclic load. After increasing the amount of test data, analytical approaches should be developed for calculating the contribution of anchorage details to shear force capacity of beam.

References

[1] Ritchie P, Thomas D, Lu L, Connelley G. External reinforcement of concrete beams using fiber reinforced plastics. ACI Struct J 1991;88(4):490–500.

[2] Sharif A, Al-Sulaimani G, Basunbul I, Baluch M, Ghaleb B. Strengthening of initially loaded reinforced concrete beams using FRP plates. ACI Struct J 1994;91(2):160–8.

[3] Chajes MJ, Januska TF, Mertz DR, Thomson TA, Finch WW. Shear strengthening of reinforced concrete beams using externally applied composite fabrics. ACI Struct J 1995;92(3):295–303.

[4] Sato Y, Ueda T, Kakuta Y, Tanaka T. Shear reinforcing effect of carbon fiber sheet attached to side of reinforced concrete beams. In: El-Badry MM, editor. Advanced composite materials in bridges and structures, 1996. p. 621–7.

[5] Arduini M, Nanni A, DiTommaso A, Focacci F. Shear response of continuous RC beams strengthened with carbon FRP sheets. In: Non-metallic (FRP) reinforcement for concrete structures. Proceedings of the third symposium, Japan, vol. 1, 1997. p. 459–66.

[6] Sato Y, Ueda T, Kakuta Y, Tanaka T. Ultimate shear capacity of reinforced concrete beams with carbon fiber sheets. In: Nonmetallic (FRP) reinforcement for concrete structures. Proceedings of the third symposium, Japan, vol. 1, 1997. p. 499–506.

[7] Sato Y, Katsumata H, Kobatake Y. Shear strengthening of existing reinforced concrete beams by CFRP sheet. In: Nonmetallic (FRP) reinforcement for concrete structures. Proceedings of the third symposium, Japan, vol. 1, 1997. p. 507–14.

[8] Ehsani M, Saadatmanesh H, Al-Saidy A. Shear behavior of URM retrofitted with FRP overlays. J Compos Construct 1997;1(1): 17–25.

[9] Norris T, Saadatmanesh H, Ehsani M. Shear and flexural strengthening of R/C beams with carbon fiber sheets. J Struct Eng 1997;123(7):903–11.

[10] Khalifa A, Gold W, Nanni A, Abel-Aziz M. Contribution of externally bonded FRP to the shear capacity of RC flexural members. J Compos Construct 1998;2(4):195–203.

[11] Triantafillou TC. Shear strengthening of reinforced concrete beams using epoxy-bonded FRP composites. ACI Struct J 1998;95(2): 107–15.

[12] Khalifa A, Alkhrdaji T, Nanni A, Lansburg A. Anchorage of surface mounted FRP reinforcement. Concr Int ACI 1999;21(10):49–54.

[13] Swamy RN, Mukhopadhyaya P, Lynsdale CJ. Strengthening for shear of RC beams by external plate bonding. Struct Eng 1999;77(12):19–30.

[14] Khalifa A, Tumialan G, Nanni A, Belarbi A. 1999. Shear strengthening of continuous RC beams using externally bonded CFRP sheets, SP-188, American Concrete Institute. In: Proceedings of the 4th international symposium on FRP for reinforcement of concrete structures (FRPRCS4), Baltimore, MD, 1999. p. 995–1008.

[15] Taljsten B, Elfgren L. Strengthening concrete beams for shear using CFRP materials: evaluation of different application methods. Composites: Part B 2000;33:87–96.

[16] Kachlakev D, McCurry CC. Behavior of full scale reinforced concrete beams retrofitted for shear and flexural with FRP laminates. Composites: Part B 2000;31:445–52.

[17] Li A, Diagana C, Delmas Y. CFRP contribution to shear capacity of strengthened RC beams. Eng Struct 2001;23:1212–20.

[18] Khalifa A, Nanni A. Rehabilitation of rectangular simply supported RC beams with shear deficiencies using CFRP composites. Constr Build Mater 2002;16:135–46.

[19] Taljsten B. Strengthening concrete beams for shear with CFRP sheets. Constr Build Mater 2003;17:15–26.

[20] Diagana C, Li A, Gedalia B, Dlemas Y. Shear strengthening effectiveness with CFF strips. Eng Struct 2003;25:507–16.

[21] ACI Committee 440, State-of-the-art report on fiber reinforced plastic (FRP) reinforcement for concrete structures, American Concrete Institute, Detroit, Michigan, 1996. 68 pp.

[22] Khalifa A, Nanni A. Improving shear capacity of existing RC T-section beams using CFRP composites. Cement Concr Compos 2000;22:165–74.

[23] Keleş M. Improving shear capacity of existing RC T-section beams using angular CFRP strips under cyclic load, MSc. Thesis, Gazi University, Civil Engineering Department, Ankara, Turkey, pp. 120 [in Turkish].

[24] ACI Committee 318, Building code requirements for structural concrete (ACI 318-99), American Concrete Institute, Detroit, 1995. 369 pp.