The Behavior of RC Beams Retrofitted with Carbon Fiber Reinforced Polymers (CFRP)

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Abstract- The need for the introduction of economical and quicker retrofitting techniques is increasing due to the ever-aging infrastructure and damages produced by major catastrophic events around the world. The application of Carbon Fiber Reinforced Polymers (CFRPs) for strengthening and retrofitting of reinforced concrete structures is gaining popularity due to its higher strength, lightweight, durability, corrosion resistance, and aesthetic value. This study presents the results of two strengthened and two retrofitted beams in comparison to control specimens. Two specimens were strengthened and two were retrofitted by attaching CFRP (Sika Carbo-Dur S812 or Sika-Wrap 230C) to the tension side of the beams using high strength epoxy. The results show that one CFRP strip/wrap simply attached at the tension side can help the damaged beam regain/pass the original strength. All specimens fail due to debonding of CFRP from the concrete surface emphasizing the need for efficient anchorage systems. Among the four patterns adopted, CFRP strips along with u-shaped anchorages at the ends provided the highest strength enhancement of 17.36%.

Keywords-*CFRP; strengthening; retrofitting; reinforced concrete beams; debonding*

I. INTRODUCTION

Collapse and cracking of structural elements of buildings, bridges, or other structures take place due to poor construction practices, use of low quality materials, inappropriate design of elements, and application of unexpected external loads that have not been considered during the design. Retrofitting is defined as the strengthening intervention that is able to restore an acceptable level of safety against such actions [1]. The terms retrofitting and strengthening are generally used interchangeably. However, more precisely, the term rehabilitation is used when a structure is strengthened before an earthquake or other damaging phenomena whereas strengthening of damaged structures is called retrofitting [2]. Carbon Fiber Reinforced Polymer (CFRP) is made of two components, carbon fiber and resin and is used extensively for the retrofitting of reinforced concrete structures. It has the desirable properties of higher strength, light weight, durability, electrical and corrosive resistance, and good aesthetic appearance. The base material (poly acrylonitrile-PAN) of CFRP has higher molecular orientation [3]. In 1977, because of its higher stiffness and high strength-to-weight ratio, CFRPs were used in the casing of aircrafts. In 1980, CFRPs were used as a reinforcement material in reinforced concrete beams.

Ever since their first use in the construction industry, CFRP retrofitted members have been extensively investigated, both experimentally and numerically. Authors in [4] compiled a database of 127 beam specimens from the literature which were externally bonded with CFRP and GFRP sheets to increase the flexure capacity and were tested under 4-point loading. About one third of the tested specimens with external reinforcement demonstrated strength increase of 50% or more in combination with considerable deflection capacity. Authors in [5] used three different reinforcement ratios of CFRP and concluded that with

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the increase in reinforcing ratios in beams, their load carrying capacity increased. Authors in [6] carried out an experimental study of RC beams to investigate the behavior of structurally damaged full-scale RC beams retrofitted with CFRP laminates. The increase in maximum load value of the specimens was between 7% and 33% for retrofitting in flexure. The main failure mode found was plate debonding which reduced the efficiency of retrofitting. Authors in [7] performed experimental and numerical studies of CFRP retrofitted beams and concluded that the strength of RC beams with single layers of CFRP was enhanced from 18 to 20% and for double layers from 40 to 45%. The deflection of RC retrofitted beams was also decreased by about 80% that of control beams. Authors in [8] studied the flexure behavior of corroded reinforced concrete beams strengthened with CFRP and found 30 to 50% increase in capacity along with improvement in stiffness. CFRP has also been used in other RC components and under different loading conditions. For example, T-beams [9], columns [10], shear walls [11], and joints [12]. Similarly, various RC components retrofitted with CFRP were investigated under various loading conditions, e.g. under torsion [13], impact loading [14], and under fire exposure [15].

In many practical situations, adopting a comprehensive retrofitting scheme is not feasible due to financial, time, or execution constraints. Therefore, the main objective of this study is to investigate the effect of simple retrofitting schemes on the flexural behavior of reinforced beams. Two specimens were strengthened and two were retrofitted by attaching CFRP (Sika Carbo-Dur S812 or Sika-Wrap 230C) to the tension side of the beams using high strength epoxy. In addition, one strengthened and one retorfitted beam had u-shaped anchorages of the same Sika-Wrap 230C. The results are discussed and recommendations are presented in the subsequent sections.

II. EXPERIMENTAL STUDY

A. *Materials*

Concrete with a specified compressive strength of 4,000 psi was used for casting the beam specimens. The average compressive strength of the companion cylinders tested in accordance with ASTM C-39 as shown in Figure 1 was found to be 3,940 psi.

Fig. 1. Concrete cylinder test setup.

ASTM A615 Grade 60 steel (1/2in diameter bars) was used for tension reinforcement and Grade 40 steel (3/8in diameter bars) was used for transverse reinforcement as well as compression hangers. The average yield strength was found to be 59.94ksi and 52.28ksi for Grade 60 and Grade 40 steel respectively. Sika Carbodur S812 CFRP strips and SikaWrap 230C wraps/sheets were used for strengthening and retrofitting the beam specimens. These conform to ASTM D7205/D7205M-06 [16]. The properties of CFRP strips and wraps as provided by the manufacturer are given in Table I.

TABLE I. CFRP PROPERTIES

CFRP Type	Thickness (in.)	Width (in)	Tensile strength (ksi)	Modulus of elasticity (ksi)
Sika Carbodur S812	0.047	3.15	400	23.2×10^3
SikaWrap 230C	0.0052	6	460	31.9×10^3

High strength epoxy Sikadur 30 [17] was used for attaching CFRP strips with the concrete surface. Similarly, for bonding the CFRP wraps to the concrete surface, Sikadur 330 [18] adhesive was used. Both types of epoxy are two-component thixotropic [17] epoxy including resin and filler designed for use at normal temperature. They conform to ASTM C-881 [19] and AASHTO M-235 [20] specifications.

B. *Test Specimens*

Five beams of 7ft length were casted and tested under 4-point (pure bending) loading. The dimensions and reinforcement details of the specimens are shown in Table I. Two beams were strengthened with CFRP before the application of any load whereas two beams were first tested to cracking moment and then retrofitted before testing again to collapse load. Two patterns were used for CFRP application, the first pattern consisted of a 3.15in wide and 0.0394in thick strip with 5in wide U-shaped anchorages at the ends as shown in Figure 3. The second pattern consisted of a 6in wide and 0.0052in thick wrap without any anchorage as shown in Figure 4. In both cases the CFRP was applied on the tension side in the middle half of the span. Each pattern was applied to one strengthened and one retrofitted beam.

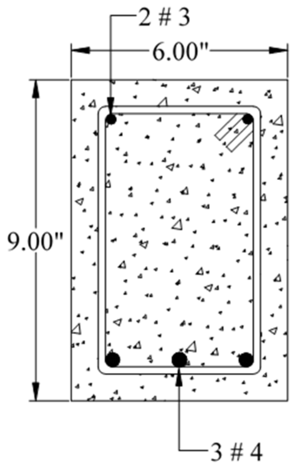

Fig. 2. Cross section details of the specimens.

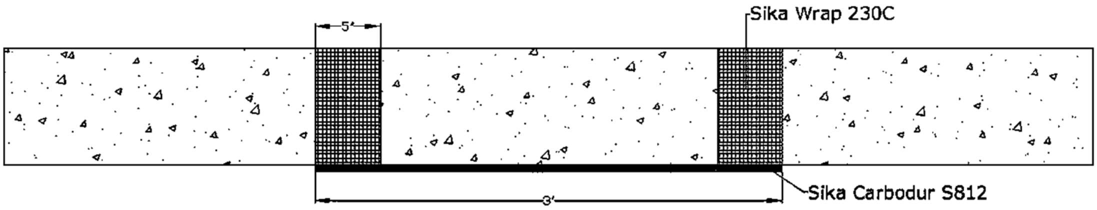

Fig. 3. First pattern of CFRP for beam specimens.

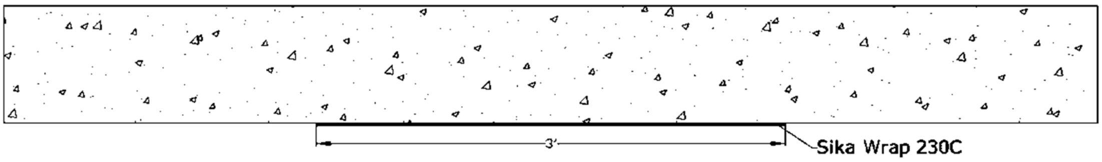

Fig. 4. Second pattern of CFRP for beam specimens.

C. Test Setup

The beams were tested under 4-point loading (pure bending) as shown in Figure 5. The deflection was recorded using a UCAM-70A data logger.

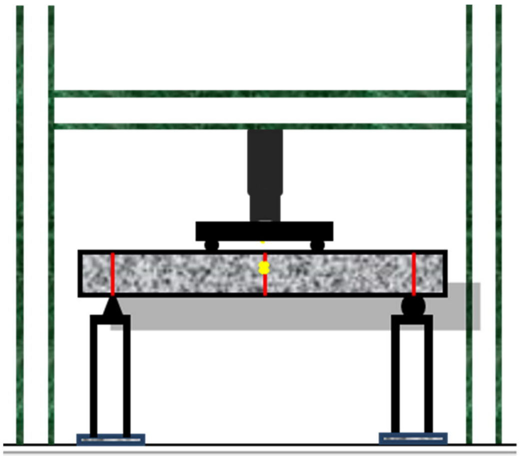

Fig. 5. Schematic of the test setup.

III. RESULTS AND DISCUSSION

A. Failure Pattern

The failure patters of the four strengthened/retrofitted specimens are shown in Figures 6-9. The predominant failure was due to the debonding of CFRP from the concrete surface. The higher flexural stresses in the middle half of the beams caused tensile cracks which were widened with the increase in the applied load. At the location of these cracks, concentrated stresses weaken the bond between CFRP and concrete and eventually lead to the complete debonding of CFRP from the surface. Failure immediately follows after the debonding. The specimens without any anchorages (specimens B4 and B6) experienced even more pronounced debonding as shown in Figures 7 and 9. The simple u-shaped anchorages (without any mechanical anchors) provided in the specimens B3 and B5 has a significant impact in reducing the crack widths and delaying debonding as shown in Figures 6 and 8.

(a)

(b)

Fig. 6. Final failure pattern of specimen B3.

B. Load vs Displacement Relationships

Figures 10 and 11 show the load vs mid-span deflection of control and strengthened beams with CFRP strips and wraps. The strengthened beams are in fact the control beams after they were tested to their ultimate capacity and were strengthened with CFRP before being tested again. It can be seen that the beams strengthened with CFRP strips regain/crossed their original strength but the beams strengthened with CFRP wraps fell slightly short of their original strength. In both cases, the strengthened specimens had larger ultimate displacement. However, reduced stiffness was observed in strengthened beams, especially the specimen with CFRP wraps. However, the final displacement recorded was much higher than that of both control specimens. It must be noted that the CFRP strip used in the specimen B3 was anchored by applying U-shaped wraps at both ends as shown in Figure 6. The effect of this anchorage can be noted by comparing Figures 10 and 11 as both ultimate load and displacement are higher for specimen B3 than for specimen B4.

(a)

(b)

Fig. 7. Final failure pattern of specimen B4.

(a)

(b)

Fig. 8. Final failure pattern of specimen B5.

Figures 12 and 13 show the load vs mid-span deflection of control and retrofitted beams with CFRP strips and wraps. The CFRP strip in beam B5 was anchored at the end using a U-shaped shear wrap as shown in Figure 8. This beam achieved the highest ultimate strength and the recorded displacement at failure was also the highest among all specimens. Retrofitted beam B6 reached the strength level of control specimen B2 but it was less than control specimen's B1.

(a)

(b)

Fig. 9. Final failure pattern of specimen B6.

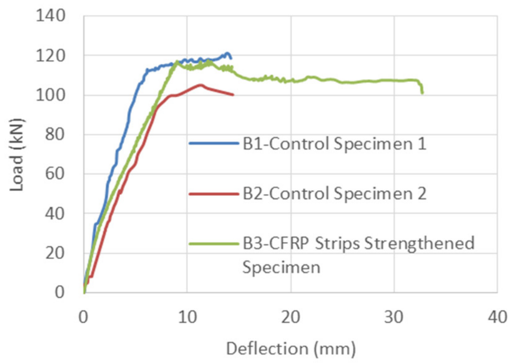

Fig. 10. Load vs displacement relationships of control specimens and a specimen strengthened with CFRP strips.

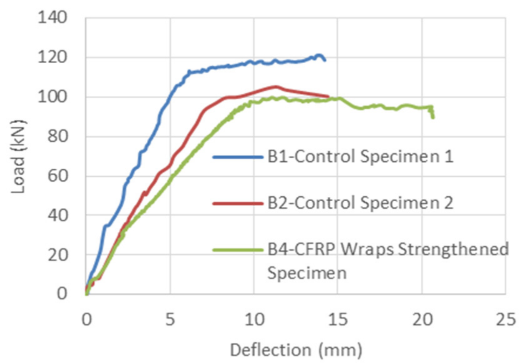

Fig. 11. Load vs displacement relationships of control specimens and a specimen strengthened with CFRP strips.

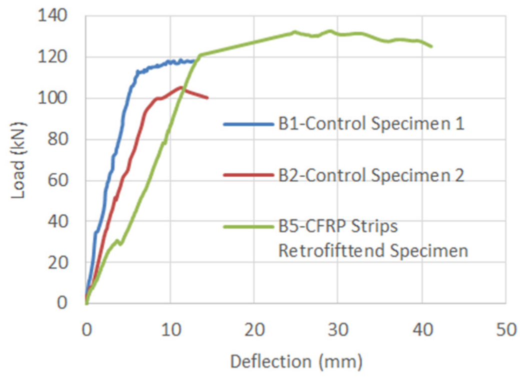

Fig. 12. Load vs displacement relationships of control specimens and a specimen retrofitted with CFRP strips.

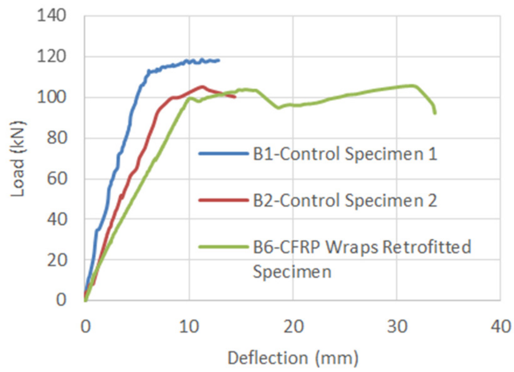

Fig. 13. Load vs displacement relationships of control specimens and a specimen retrofitted with CFRP wraps.

Table II shows the maximum load, the corresponding displacement, and the final load and displacement values for all specimens. The highest load and displacement capacity were observed for specimen B5 which was retrofitted with CFRP strips along with u-shaped anchorages. One of the most important characteristics observed for the strengthened and retrofitted beams was their ability to withstand inelastic deformations. This manifests an increased ductility of the beams which is highly desirable in earthquake resistant structures.

TABLE II. SUMMARY OF THE TEST RESULTS OF BEAM SPECIMENS

Specimen	Maximum load and corresponding displacement		Final load displacement		Debonding load (kN)
	P_{max} (kN)	Δ_{max} (mm)	P_f (kN)	Δ_f (mm)	
B1	121.11	13.76	118.65	14.21	--
B2	105.07	11.19	100.26	14.40	--
B3	117.61	12.03	101.09	32.71	113.74
B4	99.33	14.65	89.60	20.68	96.08
B5	132.71	29.10	125.21	41.09	131.36
B6	105.54	30.86	92.18	33.69	100.97

IV. CONCLUSIONS

This study investigated the effect of CFRP retrofitted on the flexural behavior of reinforced concrete beams. Six specimens were tested, two control beams, two beams strengthened with CFRP after testing to ultimate capacity, and two beams were retrofitted with CFRP before they were exposed to any loading. The following conclusions can be drawn from the results obtained in the study:

- A simple strip/wrap of CFRP applied at the critical locations can help damaged structural components regain their original (pre-loading) strength. All four specimens in this study regained/crossed the strength of control specimens with the application of a single CFRP strip/wrap in the middle half span on the tension side.
- The study demonstrates the common failure pattern in CFRP retrofitted beams is the debonding of CFRP from the concrete surface. Effective anchorage systems can greatly enhance the capacity of retrofitted RC structures by delaying the debonding process and stressing the CFRP to higher levels.
- The highest strength achieved in this study for a retrofitted beam is 17.36% higher the average strength of control specimens. This is an encouraging sign for the use of CFRP in retrofitting and strengthening of existing old or damaged RC structures. The application is quick, simple and doesn't involve high skilled labor.

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