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Flexure Behavior of Carbon Fiber Reinforced Polymers Retrofitted RC Beams

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ABSTRACT

Carbon fiber reinforced polymers (CFRP) have been widely used for retrofitting of reinforced concrete members over the past three decades. This study presents the experimental results of four reinforced concrete beams retrofitted with CFRP and tested under four point monotonic loading. CFRP strips (Sika Carbo-Dur S812) and wraps (Sika-Wrap 230C) were used in two different patterns to evaluate their effect on the flexural behavior of RC beams. Two beams were first tested until their ultimate capacity, retrofitted with the application of CFRP and re-tested again, and two beams were retrofitted before the application of any load. The CFRP strips provided in the middle one-third of the span with U-shaped anchorage at the ends enhanced the capacity of beams up to 15 percent. The stiffness of the beams were significantly increased as demonstrated by smaller displacement at the ultimate load. However, the CFRP wraps provided without the anchorage didn't enhance the strength due to pre-mature debonding.

Keywords: CFRP, retrofitting, strengthening, debonding, reinforced concrete structures.

INTRODUCTION

Retrofitting of old deteriorated buildings and damaged structures due to a major earthquake is becoming an increasingly adopted strategy because of the cost and time savings in comparison to construction of new structures. The application of Carbon fiber reinforced polymers on the external surface or near surface of RC structures is one such strengthening and retrofitting technique. More recently, CFRP rebars have also been developed which can be used as a replacement to conventional steel reinforcement. Investigation of the behavior of CFRP retrofitted reinforced concrete structures has been an active research field in the last three decades. Initially, the focus was more towards the experimental testing of CFRP retrofitted beams, column, joints, and other structural components. The focus is gradually shifting towards the development of numerical models and analysis methods to efficiently design and implement FRP retrofitting schemes. Esfahani et al. observed that if greater steel reinforcement is used i.e. in the range of code specified maximum reinforcement ratio, adequate ductility is ensured before failure [1]. Garden et al. concluded that CFRP plates bonded to the soffits of beams are effective in reducing crack widths and tensile concrete strains [2]. Ashour et al. studied flexural strengthened RC continuous beams using CFRP laminates and found that all strengthened beam specimens had higher ultimate load capacity than the corresponding RC control beams. However, the ductility decreased with the application of CFRP laminates [3].

Premature de-bonding is one of the biggest issues with CFRP retrofitting. Many researchers have tried to develop effective anchorage systems to avoid/delay de-bonding by enhancing the bond between CFRP and concrete surfaces.

One way to achieve a higher level of fiber utilization and avoid/delay premature failure due to de-bonding is to use some anchorage system while applying CFRP to concrete external surfaces [4]. For example, using shear straps as anchorages not only enhance shear strength of the beam but also reduce the chances of de-bonding of CFRP sheet used for flexural [5]. Deng and Lee considered eight cases with different configuration of spew fillet and different tappers. Results showed that the adhesive stress especially normal stresses on the CFRP interfaces and steel reinforcement are different due to the load transfer and the influence of singularity at the adhesive corner [6]. Pan et al. tested ten different concrete compositions by direct shear method and concluded that the actual concrete composition plays an important role in determining the bond capacity in the FRP to concrete joint [7]. Yao et al. concluded that surface preparation play an important role in CFRP-concrete bond [8]. Seo et al. compared Externally Bonded Retrofit (EBR) and Near Surface Mounted Retrofit (NSMR) and concluded that the member strengthened by NSMR had almost 1.5 times higher bond strength than that of EBR [9]. Various aspects of CFRP retrofitting of reinforce concrete structures have been extensively investigated recently. For example flexural behavior of CFRP strengthened beams [10, 11], shear behavior [12, 13], torsional behavior [14, 15], dynamic behavior [16], interfacial bond and debonding [17–20], and anchorage systems [4, 21, 22]. The need for repair and retrofitting after a major earthquake is well established as constructing huge infrastructure from the ground up is both economically challenging and time consuming. The purpose of this study is to determine the effect of simple CFRP strips/wraps applied on the tension side of reinforced concrete beams. This may be the quickest and simplest option in retrofitting beams of an existing damaged structure after an earthquake.

MATERIALS AND METHODS

Materials

Concrete in the ratio of 1:1.3:2 (cement: fine aggregate: coarse aggregate) with water-cement ratio of 0.65 was used to cast all specimens. Standard companion cylinders of 12 in. height and 6 in. diameter were casted with each beam and tested according to ASTM C39/C39M. The average compressive strength of concrete was found to be 3.67 ksi. ASTM A615 Grade 60 steel having ½ in. diameter were used as longitudinal reinforcement. The mean yield and ultimate strength for these rebars were found to be 60.10 ksi and 86.28 ksi respectively. Similarly, Grade 40 steel of 3/8 in. diameter were used as transvers reinforcement. The mean yield and ultimate strength for these rebars were found to be 52.30 ksi and 72.26 ksi respectively. The mechanical properties of the CFRP were obtained from the manufacturer. Tensile strength and tensile modulus of elasticity for CFRP laminates were 4.06×10^5 psi and 23.2×10^6 psi, respectively. The ultimate load and tensile modulus of elasticity for CFRP wraps were 350 kN/m width per layer and 28 kN/mm^2 respectively.

Test specimens

Four beam specimens were casted and six tests performed; two specimens were first tested without any retrofitting to act as control specimens, two specimens were pre-retrofitted (strengthened) i.e. CFRP strips/wraps were applied before testing, and two specimens were post retrofitted i.e. they were first tested to ultimate capacity, retrofitted and then tested again. The total length, effective span, breadth and depth of the beam were 7 ft, 6 ft, 6 in and 9 in respectively as shown in Figure 1. The beams were reinforced with 3, #4 bars on the tension side and 2, #3 bars on the compression side. Shear reinforcement consists of #3 stirrups at 4 in center to center throughout the length of the

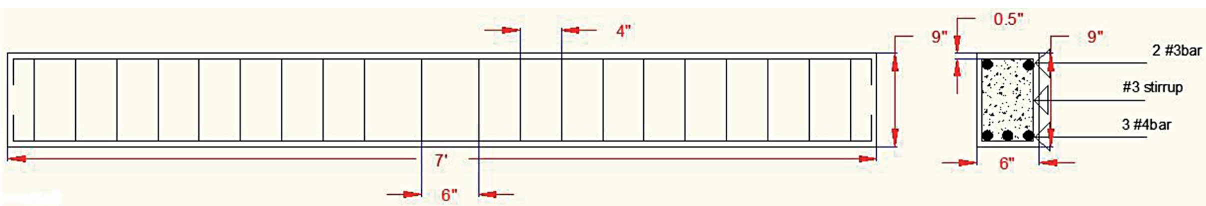

Figure 1. Longitudinal and cross sectional details of beam specimens

beams. A 0.5 in clear cover was provided to transverse reinforcement. Two specimens were retrofitted with CFRP strips (Sika Carbo-Dur S812) and two specimens were retrofitted with CFRP wraps (Sika-Wrap 230C). All the specimens were retrofitted only on the tension side in the middle 3ft span as shown in Figures 2 and 3. The width and thickness of the CFRP strips were 3 in and 0.047 in. (1.2 mm) respectively, whereas Sika wraps were 6 in wide and 0.039 in (1 mm) thick. To delay debonding of the wraps, U-shaped transverse wrapping were applied at the ends as shown in Figure 3. The bonding region (tension side of the beam) was made smooth using a grinder and the dust was cleaned before the application of the CFRP. A strong epoxy consisting of two components; Sikadur-30 and Sikadur-330 were mixed thoroughly in the ratio 1:0.5 and applied to bonding region. Then CFRP Strips/wraps were applied on the respective specimens. Air bubbles were removed and the retrofitted specimens were left undisturbed for one week curing.

TEST SETUP

The specimens were tested in a straining frame having capacity of 200 kN as shown in Figure 4 and 5. All Specimens were tested under monotonically increasing quasi static loading. The load from the load cell was transferred to the specimens at two points using a steel girder

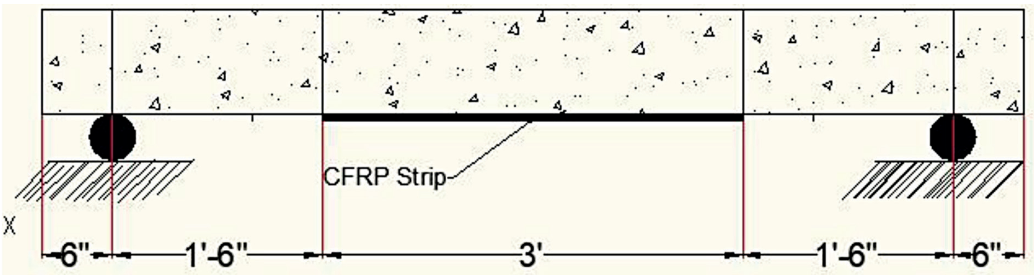

Figure 2. Side view of beams retrofitted by CFRP strips

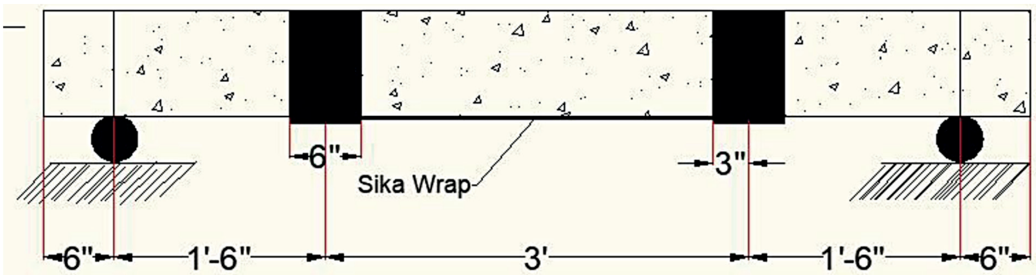

Figure 3. Side view of beams retrofitted by CFRP wraps

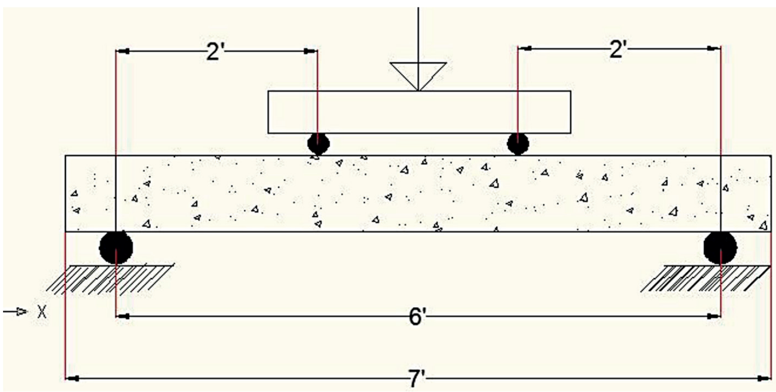

Figure 4. Schematic of test setup

Figure 5. Test setup

developing a four point loading arrangement. The test specimens had a constant moment span of 2 ft and shear span of 4ft (2ft from each side). Simply supported condition was established by resting the beam on rolled stiff steel girders from both side. Three gauges were installed below the beam to measure the vertical deflection. The loading and deflection data was recorded using UCAM-70A data logger.

RESULTS AND DISCUSSION

Failure pattern

The final cracking pattern of all specimens is shown in Figures 6 to 9. All specimens developed flexure cracks before failing through de-bonding of CFRP from concrete surface. The de-bonding was severe in CFRP strips as no anchorage was applied. The application of U-shaped anchorage at the two ends of CFRP wraps delayed the initial cracking and helped in reducing the de-bonding. The debonding of CFRP strips and wraps was initiated from the flexure cracks below the loading point.

Load-displacement relationships

The Load vs deflection relationships of the retrofitted beams in comparison with control beams are shown in Figures 10 to 13. It is evident that the ductility is significantly enhanced with the application of CFRP. In all cases, the retrofitted beams performed well in comparison to the control specimens in terms of strength and ductility. It must be pointed out that specimens B5 and B6 were tested to their ultimate capacity before the application of CFRP retrofitting. Therefore, it is remarkable to see that the application of a single CFRP strip enabled these specimens to regain/surpass their initial strengths as shown in Figures 12 and 13. The cracking load and ultimate load values and the corresponding deflection values are summarized in Table 1. The cracking load increased by more than 20% in case of specimens B3 and B6. However, a small increase in cracking load was observed for specimens B4 and B5. Similarly, the ultimate load is either reached or crossed for all the retrofitted specimens in comparison to the control beams.

Figure 6. Final crack pattern of specimen B3 (strengthened with CFRP strips)

Figure 7. Final crack pattern of specimen B4 (strengthened with CFRP wraps)

Figure 8. Final failure pattern of specimen B5 (retrofitted with CFRP strips)

Figure 9. Final failure pattern of specimen B6 (retrofitted with CFRP wraps)

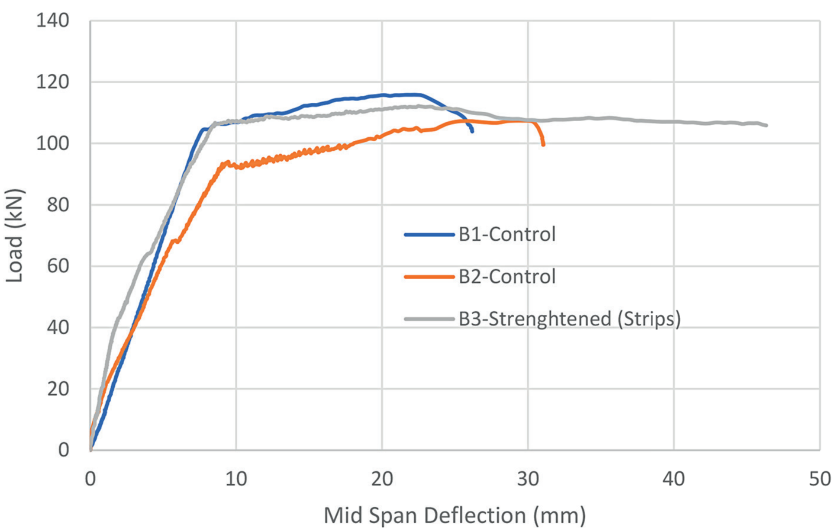

Figure 10. Load-displacement relationship of B3

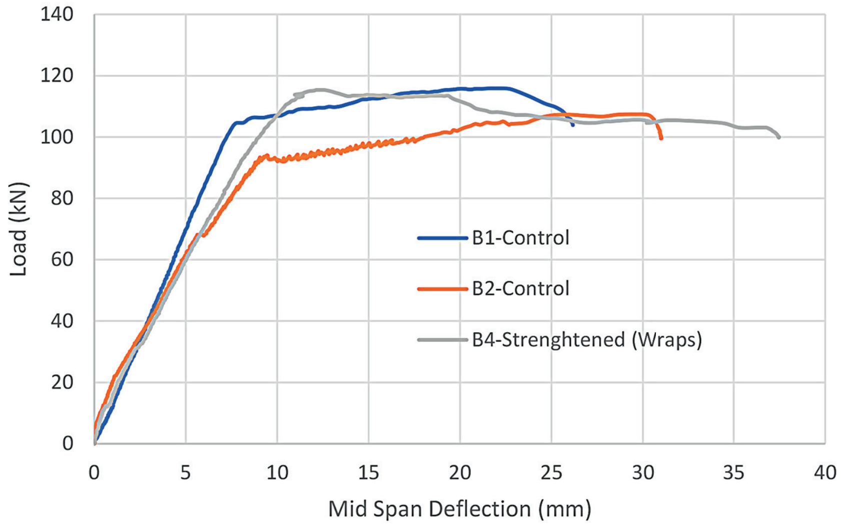

Figure 11. Load-displacement relationship of B4

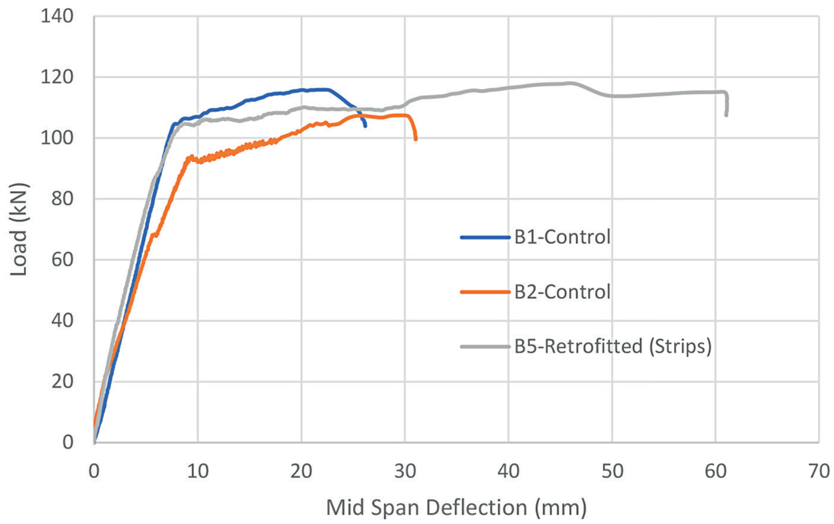

Figure 12. Load-displacement relationship of B5

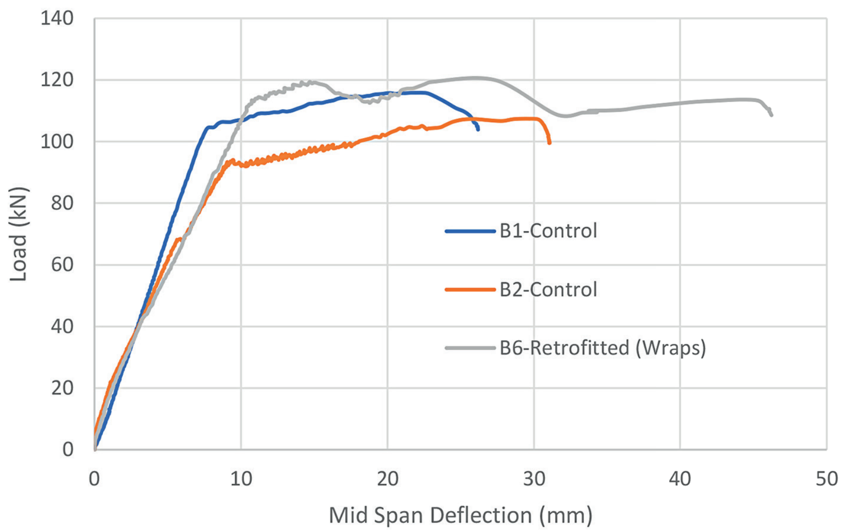

Figure 13. Load-displacement relationship of B5

Table 1. Summary of the test results of beam specimens

S. No.	Specimen	Retrofitting	Cracking Load (kN)	Deflection (mm)	Ultimate Load (kN)	Deflection (mm)
1	B1	None	40.21	3.00	111.50	24.38
2	B2	None	39.23	2.97	104.93	30.86
3	B3	Strengthened-strips	50.01	2.60	117.68	46.50
4	B4	Strengthened-wraps	42.17	3.50	113.46	20.00
5	B5	Retrofitted-strips	39.23	2.31	115.72	22.35
6	B6	Retrofitted-wraps	53.94	4.60	119.93	27.50

CONCLUSIONS

Following conclusions can be drawn from the experimental results obtained during this study. The results showed that the main failure mode was de-bonding of CFRP strips/wraps before they can reach their full capacity. Therefore, an effective anchorage scheme should be in place if maximum enhancement in strength and ductility is desired as a result of CFRP retrofitting. In spite the fact that one of the simplest and cheapest procedure was adopted in this study for retrofitting RC beams by applying CFRP strips/wraps only in the middle part on the tension side, the full strength was regained/enhanced and ductility significantly improved. The highest cracking moment and displacement was obtained for the specimen with U-shaped anchorages at the ends of CFRP wraps. This shows that even a simple anchorage scheme can increase the effectiveness of CFRP retrofitting by delaying the spread of micro-cracking and de-bonding.

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