BEHAVIOR OF RC T-BEAMS STRENGTHENED IN THE NEGATIVE MOMENT REGION WITH CFRP LAMINATES

Sinaph M. Namboorimadathil, University of Missouri-Rolla, Rolla, MO

J. Gustavo Tumialan, University of Missouri-Rolla, Rolla, MO

Antonio Nanni, University of Missouri-Rolla, Rolla, MO

Abstract

The use of Carbon Fiber Reinforced Polymer (CFRP) laminates as an effective and versatile technique for strengthening reinforced concrete (RC) structures has developed into a sizable industry in recent years. Prior research has demonstrated the ability of CFRP laminates to enhance both the shear and flexural capacity of RC structural members. In this context, this research attempts to address an important practical issue that is encountered in strengthening the negative moment regions of RC continuous beams. This is a critical region due to the concurrence of maximum of moment and shear. In addition, there are installation restraints due to the presence of columns (inhibiting continuity for the flexural strengthening) and of the beam flange or slab (inhibit anchorage for the shear strengthening).

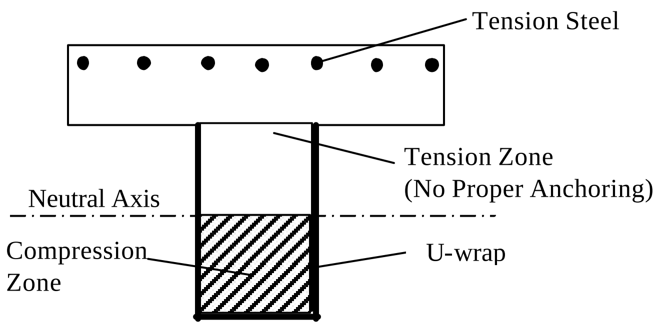
This paper describes the shear and flexural behavior of RC T-beams strengthened in the negative moment region with CFRP laminates. Three RC T-beams, 14 ft long and 20-in deep with a 4 by 32-in flange, were cast. For all specimens, column stumps were also cast and used as the point of application of the load. One beam served as a control specimen, while one was strengthened for flexure (CFRP laminates applied besides the column) and the other one for flexure and shear (CFRP laminates in the form of U-wraps terminated at the flange intrados). Test results indicated that FRP reinforcement was effective in strengthening for both shear and flexure the negative moment region under the installation constrains encountered in practice. This is comforting news for professionals who are working in the field of structural repair and strengthening.

Introduction

The negative moment region or the support region of continuous reinforced concrete (RC) beams is a critical one due to the simultaneous occurrence of maximum moment and shear. In addition to this, the presence of columns and other components such as electric and plumbing lines, and HVAC ducts, makes it difficult to strengthen this region using conventional techniques like steel plate bonding, section enlargement, external stirrups etc. For instance, the use of thick steel plates bonded to the floor surface will raise the floor level, which may be undesirable. In this context, due its low profile and ease of installation, composite materials such as carbon fiber reinforced polymer (CFRP) can be used to provide an economical and versatile solution for extending the service life of structures. CFRP laminates may provide strengthening solutions for all types of structural elements such as beams, columns, walls and slabs (Nanni, 1999).

Design guidelines for the shear and flexural strengthening of RC members using externally bonded FRP systems are being developed by American Concrete Institute – Committee 440 (ACI 440). Most of the experiments conducted to validate the design methodology for FRP flexural strengthening consisted of rectangular or T-beams on which the strengthening was applied to the positive moment region of the member (Sadathmansesh and Ehsani, 1991; Annaiah et al., 2001;). However, in the negative moment region, the strengthening is not as simple as in the case of the positive moment region because the columns prevent the application of FRP system over the web portion of the beam. It has been demonstrated that the addition of CFRP strip to beams in the negative moment region increases their stiffness and the strength (Grace, 2001). However, in that investigation, the restraint caused by the columns in the application of the strengthening system was not considered. In field situations, for flexural strengthening, the only alternative left is to apply the FRP reinforcement on the flanges on either side of the column, as shown in Figure 1a. The effectiveness of external shear reinforcement (i.e. U-wrap) is also uncertain in this region. In most of the field situations the portion of the beam section just below the flanges, were the U-wrap is terminated, is in tension in the negative moment region (Figure 1b). If proper anchorage is not provided, debonding can initiate at the free ends of the U-wrap, compromising the efficiency of the strengthened member.

(a) Flexural Strengthening



(b) Shear Strengthening

Figure 1. Strengthening of Negative Moment Region

The objective of this investigation was to evaluate the performance of externally bonded CFRP laminates in enhancing the flexural and shear capacities in the negative moment region of T-beams. This paper presents the experimental results of RC T-beams strengthened with CFRP laminates. The effect of longitudinal and transversal CFRP reinforcement in improving the flexural and shear capacities, respectively, was studied. The compliance of ACI 440 provisions with respect to the strengthening of negative moment region was also appraised.

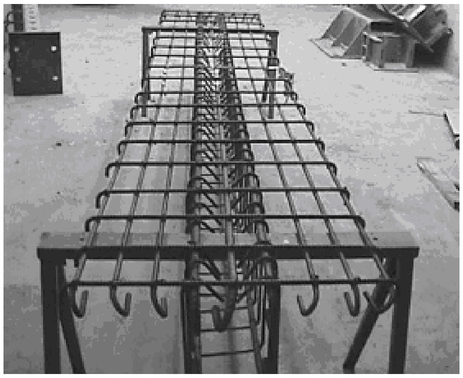
Experimental program

Test Specimens

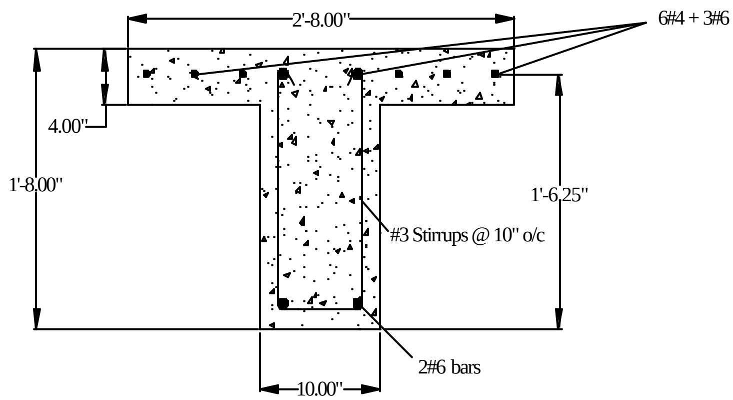
A total of three RC T-beams, 14 ft. long and 20 in. deep with 4 in. by 32 in. flanges, were fabricated for this experimental program. One of the specimens was tested without FRP reinforcement, and was identified as Beam B0. The stirrups in Beam B0 were placed at 10 in. on centers. The second beam was strengthened in flexure only and was denoted as Beam B1. In this specimen, the objective was to observe the flexural behavior; therefore, a potential shear failure needed to be avoided. So, the stirrups were provided at 5 in. on centers. Finally, the third specimen, identified as Beam B2, was strengthened in both flexure and shear. In this specimen, the stirrups were at 10 in. on centers. Beams

B1 and B2 were used to compare the behavior of internal and external shear reinforcement in the negative moment region.

An RC block of height 10 in. and cross section 10 in.×10 in., was cast on the middle of the flange at 6.5 ft. from one end of the beam to represent the intersection of the beam with a column. The objective of casting this block was to provide a restraint in the application of the strengthening system at the mid section of the flange. Figure 2 shows the cross section, Table 1 presents reinforcement details of the test specimens. Tests performed on the concrete showed that the average compressive strength was 5096 psi. for Beam B0, 5142 psi. for Beam B1, and 5380 psi. for Beam B2. Tensile tests on the steel rebars gave an average tensile strength of 63 ksi. Prior tests conducted at the University of Missouri Rolla (UMR) showed that the CFRP laminates had a tensile strength of 627 ksi and a tensile modulus of 38,289 ksi (Yang, 2001).



(a) Beam Reinforcement Cage



(b) Cross Sectional Details (Beams B0 and B2)

Figure 2. Reinforcement Details

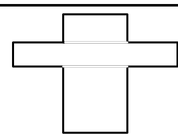
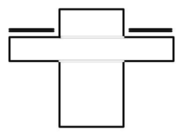
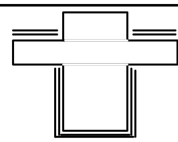
Table 1. Steel Reinforcement Details

Beam	Tension	Compression	Shear
B0	3 #6 + 6 #4	2 #6	#3 Stirrups @ 10”
B1	3 #6 + 6 #4	2 #6	#3 Stirrups @ 5”
B2	3 #6 + 6 #4	2 #6	#3 Stirrups @ 10”

For flexural strengthening of Beams B1 and B2, two plies of 10 in. wide CFRP laminates were applied on the flanges along both sides of the block. The laminates were terminated at 6 in. from the supports used for testing. For the shear strengthening of Beam B2, the entire web of the specimen, except the column region, was wrapped with two plies of CFRP laminates with fibers oriented along the transverse direction. The strengthening system was applied to the surface of the beams using standard procedures specified by the manufacturer. The surface treatment of concrete prior to the installation of strengthening system was done using water jetting, which proved to be very effective and environmentally friendly (Figure 3). A summary of the experimental program is provided in Table 2.

Figure 3. Water Jetting of Test Specimens

Table 2. Experimental Program

Beam	Strengthening Scheme		
BO	Flexural	None	
	Shear	None	
B1	Flexural	2 plies of 10 in. wide CFRP on both sides	
	Shear	None	
B2	Flexural	2 plies of 10 in. wide CFRP on both sides	
	Shear	2 Plies of CFRP U-wrap	

The beams were tested as simply supported inverted T-beams under three point bending with a free span of 13 feet. The purpose of the test setup was to obtain tension on the flanges, as in the case of the negative moment region of a continuous beam. The supports represented the points of inflection of a continuous beam, where the bending moment is zero. During testing, the load was applied on the column stump that was cast on the top of flange, which divided the beam into two unequal spans of 6 ft. and 7 ft., respectively. This helped to force the failure to occur in the longer span. Since the failure side was known prior to testing, instrumentation was limited to that region. Linear Variable Differential Transformers (LVDTs) were placed at mid span and quarter span to monitor the deflection of the beam and at the supports to measure settlement. Strain gages were attached to longitudinal bars, stirrups, FRP laminates, and concrete to measure the strains at different loading levels. The test setup is shown in Figure 4.

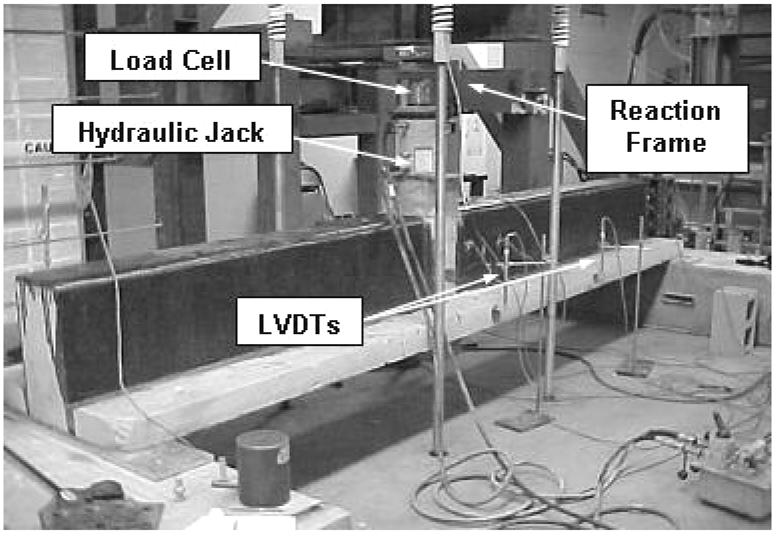


Figure 4. Test Setup

Results and Discussion

Beam B0 failed in the classical flexural failure mode, which is characterized by yielding of the tension steel followed by the crushing of concrete in the compression zone. The strengthened beams also exhibited flexural failures (Figure 5). Figure 6 shows the results in terms of total applied load versus mid span deflection. The moment-curvature diagrams were also plotted with curvatures obtained from the strain gage readings taken from longitudinal bars and concrete, respectively (Figure 7).

All beams cracked at practically the same level of load, at about 20 kips. After cracking, the decrease in stiffness in Beam B0 was larger than in Beams B1 and B2. The yielding strength of Beams B1 and B2 were increased by about 37% than that of the unstrengthened beam. The ultimate strength of Beams B1 and B2 were 41 and 39% higher than that of the control beam, respectively. There was a loss of ductility in both the strengthened beams, as expected. Due to safety reasons, the LVDTs were removed towards the end of the test and so the ultimate deflection of Beam B0 could not be recorded.

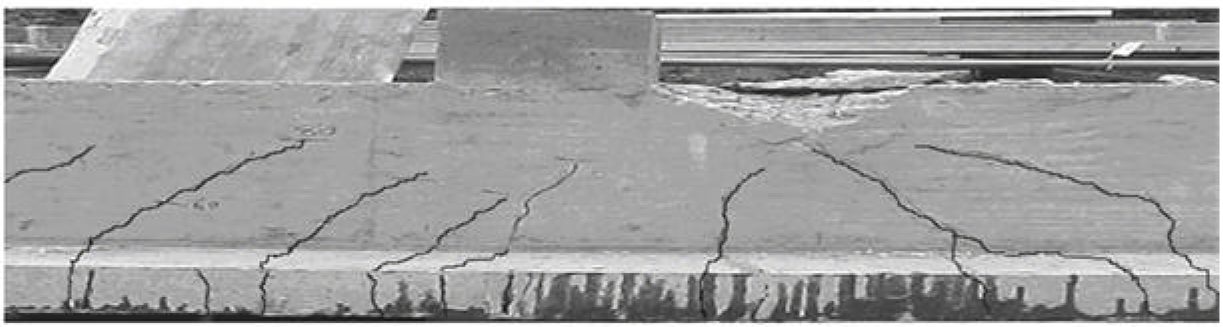


Figure 5. Final Failure in Beams by Crushing of Concrete (Beam B1)

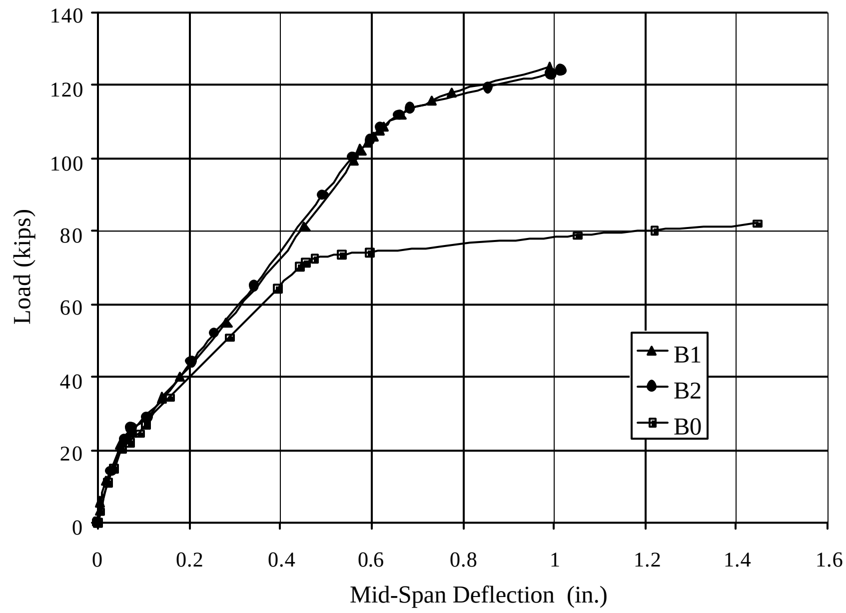


Figure 6. Load-Deflection Diagram

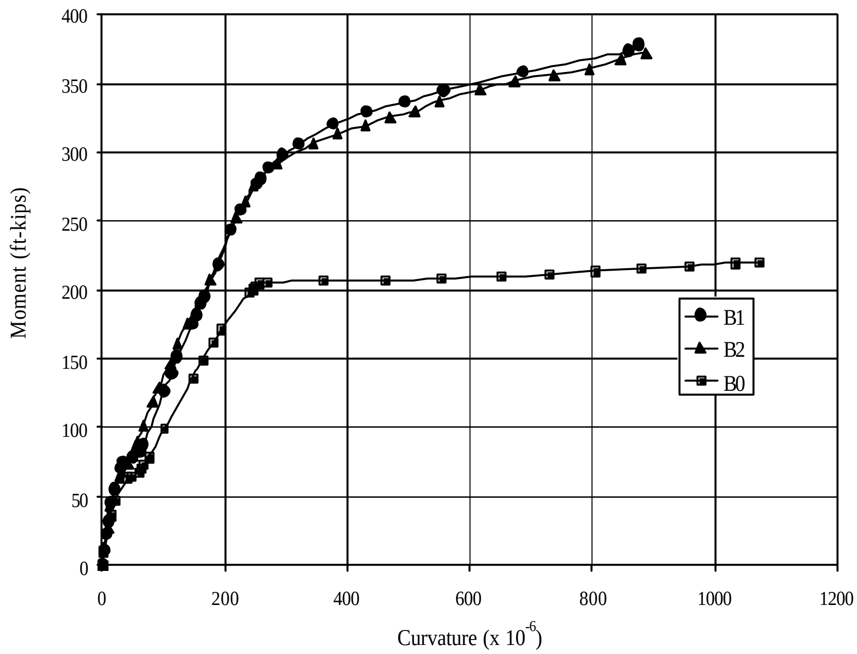


Figure 7. Moment- Curvature Diagram

Beams B1 and B2 followed the same load-deflection and moment-curvature patterns up to failure, even though their shear strengthening scheme was different as mentioned before. Peeling of the U-wrap was observed in Beam B2 when the load was nearing ultimate (Figure 8). However, this did not compromise the shear capacity of the beam and the final failure of this beam was due to flexure. The strain gauges located in the U-wrap indicated strains of about 2100 μ strains. This represents 12.6% of the ultimate strain specified for the laminate. The reason for recording low strain values might be the fact that the location of strain gages were close to that of peeling. Since Beam B1 (stirrups at 5 in.) and Beam B2 (stirrups at 10 in. and CFRP U-wrap) exhibited a similar behavior, it can be concluded that CFRP U-wrap was effective in enhancing the shear capacity in the negative moment region. The strain readings in the CFRP laminates used as flexural strengthening were similar in Beams B1 and B2 (Figure 9).

Figure 8. Peeling of U-wrap in Beam B2

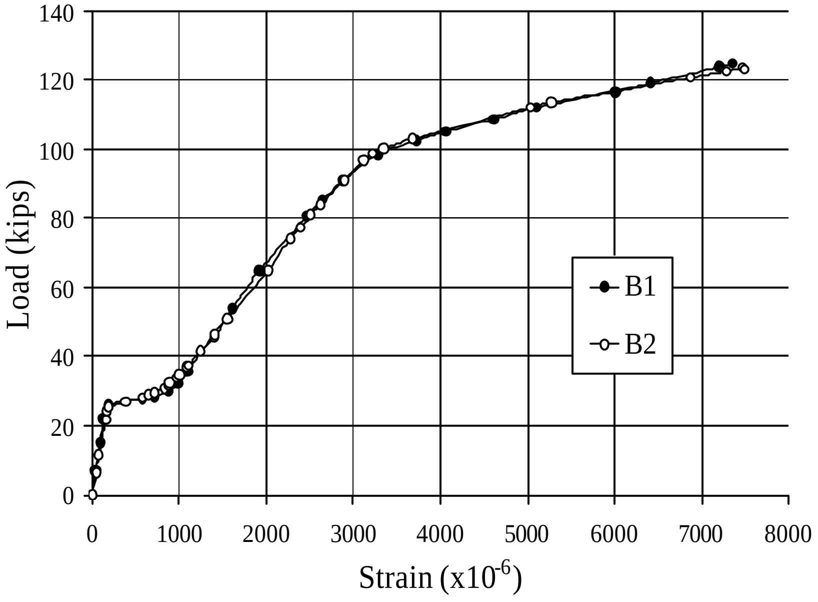


Figure 9. Load vs. Strain Diagram for CFRP Laminates in Flexure

Comparison with ACI-440 Guidelines

A summary of the data obtained from the shear and flexural analysis of the specimens are provided in Table 3, where r_f is the CFRP reinforcement ratio, c is the depth of neutral axis at ufailure, M_n is the nominal moment carrying capacity, and V_c, V_s, V_f and V_n are the shear carrying capacities of concrete, stirrups, CFRP U-wrap and the member, respectively.

Table 3. Analytical Data

Beam	Flexure			Shear			
	r_f	c (in.)	M_n (kips-ft)	V_c (kips)	V_s (kips)	V_f (kips)	V_n (kips)
B0	0	3.13	214	26.05	24.09	0	50.14
B1	0.00143	4.87	326	26.17	48.18	0	74.35
B2	0.00143	4.87	326	26.77	24.09	38.97	89.83

The nominal flexural capacities of Beams B1and B2 were computed according to ACI 440, without considering any reduction factors, as:

$$M_n = A_s f_s \left(d - \frac{b_1 c}{2} \right) + A_f f_{fe} \left(h - \frac{b_1 c}{2} \right)$$

The experimental moment carrying capacities of Beams B1 and B2 were 14 and 12% more than the predicted capacities, respectively. From these results it is clear that the strengthening methodology adopted in this investigation did not have any adverse effect on the flexural strength of the specimens.

For calculating the nominal shear capacity of Beam B2, the following relation was used (ACI 440), where the term V_f is the shear contribution of CFRP U-wrap. In this case also none of the reduction factors were considered for the calculations.

$$V_n = V_c + V_s + V_f$$

During the test this beam withstood a shear force of more than 68 kips, without developing any major shear cracks. Also, the behavior of this beam was very similar to that of Beam B1, in which additional stirrups were used instead of CFRP U-wrap. Thus, it can be concluded that the provisions of ACI 440 for flexural and shear strengthening is effective for negative moment region also.

Conclusions

Based on the results obtained from the experimental study, it can be concluded that:

- Externally bonded CFRP laminates are very effective in enhancing the strength, both flexural and shear, and stiffness of the negative moment region of T-beams. The increase in strength for Beams B1 and B2 were observed to be 41 and 39%, respectively

- The restraint offered to the application of strengthening system due to the presence of column did not affect the strength of the beams
- The equations provided by ACI 440 for flexural and shear strengthening of RC beams may be used for negative moment regions with strengthening provided as explained in this investigation

Acknowledgements

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