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Shear strengthening of full-scale RC T-Beams using externally bonded CFRP sheets

S.-W. Bae[1], A. Belarbi[2], and A. Brancaccio[3]

[1] Texas Tech University, Texas, USA
[2] University of Houston, Texas, USA
[3] The First Brick Network Technology, Italy

ABSTRACT: Many research studies have investigated the behavior of reinforced concrete (RC) beams strengthened in shear with externally bonded fiber-reinforced polymer (FRP) composites; however, most were conducted on small-scale, rectangular cross-section specimens. This study, therefore, used full-scale RC T-beams to understand the behavior of large-scale concrete bridge girders strengthened in shear with externally bonded CFRP sheets. The work focused primarily on the transverse steel reinforcement ratio and the effect of mechanical anchorage systems. The results indicate that the use of CFRP increases shear strength and the use of a proper mechanical anchorage system further increases shear capacity. This work also revealed an interaction between transverse steel reinforcement and FRP strengthening.

1 INTRODUCTION

A significant portion of the infrastructure in the United States is in urgent need of strengthening and rehabilitation (ASCE, 2009). However, public funds for infrastructure rebuilding are extremely limited. Therefore, engineers have been looking for innovative solutions that reduce the costs associated with traditional methods. Fiber-reinforced polymer (FRP) materials offer one such solution. Using these materials has several advantages over traditional rehabilitation techniques. They are relatively easy to apply. They are flexible and can thus be molded to fit any geometry. They exhibit a high strength-to-weight ratio, and they are corrosion resistant. Externally bonded FRP composites are among the materials rapidly gaining popularity as a means to rehabilitate and retrofit existing concrete structures.

Over the last two decades, a number of research studies examined the behavior of reinforced concrete (RC) beams strengthened in shear with externally bonded FRP sheets. However, most were conducted on small-scale rectangular cross-section specimens while most RC bridge girders have a T-shaped section. The shape of the cross section is related also to the strengthening scheme. For example, a common way to strengthen rectangular beams is by fully wrapping the member. In the case of T-beams, however, this solution is impractical due to the presence of the flange. More focus should be placed, therefore, on T-beams with U-wrap and side-bonding configurations as well as on the use of mechanical anchorage systems to address the issue of debonding. In addition, few tests have been conducted on members with a span comparable to that of real bridge girders, and only one study has investigated the influence of scale effect on the shear behavior of members strengthened with FRPs. Though the primary use of FRP is to strengthen damaged structures, the effects of pre-existing cracks have not been widely investigated by previous researchers.

This study was conducted mainly to validate and expand on the findings of previous experiments with results from experiments on full-scale RC T-beams.

2 EXPERIMENTAL PROGRAM

The RC beams used in this study were designed to mimic the geometry of beams used in a bridge located in Troy, New York. Complete information on this bridge can be found in Hag-Elsafi et al. (2001). The purpose of this design was two-fold. (1) The bridge was built in 1932 and since then has suffered from severe corrosion damage and has been strengthened in flexure and shear with FRP sheets. The long-term behavior of the strengthening system will be monitored by New York Department of Transportation while this study could focus on the short-term behavior. (2) The RC T-beams of the Troy bridge was a typical case in which FRPs could be applied in terms of its size and age. To mimic this cross sectional layout as closely as possible and induce shear failure, the test beams should have been designed with the dimensions and reinforcement scheme shown in Figure 1.

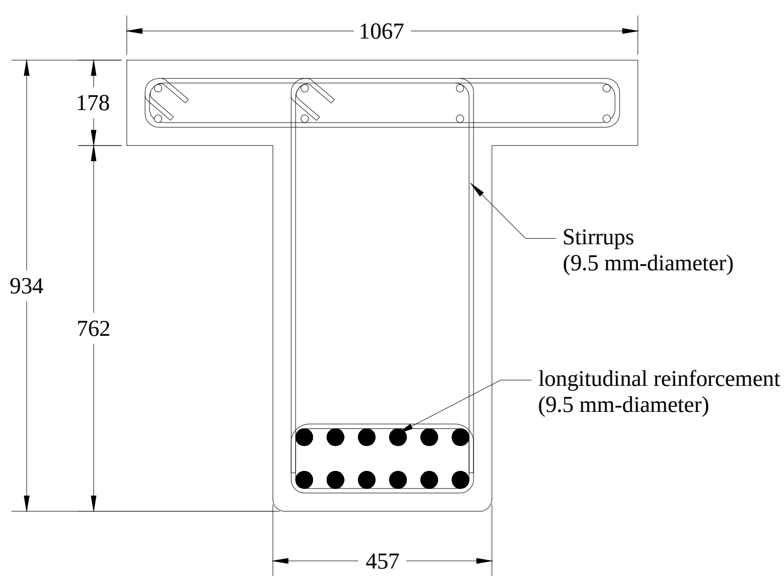


Figure 1. Cross section of the test beams used in this study (dimensions in mm).

Table 1 summarizes the test matrix used in this study. The denomination of the specimens indicates the stirrup spacing in inches (8 or 12), the strengthening configuration (S90 = strip at 90 degrees), and the presence of mechanical anchorage (NA = no anchorage, DMA = discontinuous mechanical anchorage, SDMA=sandwich discontinuous mechanical anchorage, and HA= horizontal additional FRP strips). Two different stirrup spacings were chosen to simulate moderate and low amounts of transverse reinforcement. The design using moderate transverse reinforcement, with 203 mm (8 in.) stirrup spacing, met the minimum requirement of AASHTO-LRFD (2008) for transverse reinforcement. This design also corresponds to the stirrup spacing of the Troy bridge. The design using low transverse reinforcement, with 305 mm (12 in.) stirrup spacing, did not meet the AASHTO-LRFD requirement and thus simulated a reduced amount of steel due to corrosion. Two beams denoted with PC were subjected to 60% of the anticipated ultimate load to introduce diagonal shear cracks before FRP strips were applied.

Table 1. Test matrix

Beam I.D.	Test I.D.	Test Parameters		
		Strengthening Scheme	Anchorage Type	Shear Reinforcement
1	RC-8-Control	None	Without Anchorage	#3@8 in. spacing
	RC-12-Control			#3@12 in. spacing
2	RC-8-S90-NA	Strip/90	Without Anchorage	#3@8 in. spacing
	RC-8-S90-DMA		Mechanical Anchorage	
3	RC-12-S90-NA	Strip/90	Without Anchorage	#3@12 in. spacing
	RC-12-S90-DMA		Mechanical Anchorage	
4	RC-12-S90-SDMA-PC	Strip/90	Sandwich Panel Mechanical Anchorage	#3@12 in. spacing
	RC-12-S90-HA-PC		Additional Horizontal FRP Strips	

The concrete used in this study was a ready-mix concrete with an expected 28-day target strength of 27.6 MPa (4000 psi) while the actual strength was measured at the time of testing. Transverse steel reinforcement (stirrups) consisted of reinforcing bars with a diameter of 9.5 mm and yield strength of 276 MPa (#3 Grade 40). Longitudinal reinforcement in the top flange was 16 mm in diameter and has yield strength of 414 MPa (#5 Grade 60) while bars with a diameter of 35 mm and yield strength of 414 MPa were used for flexural tension reinforcement.

The Carbon Fiber Reinforced Polymer (CFRP) sheets used for the shear strengthening in this study has tensile strength of 3792 MPa (550 ksi), elastic modulus of 228 GPa (33,000 ksi) and ultimate strain of 0.017. The FRP laminates used as plates for the mechanical anchorage systems was a glass and carbon hybrid pultruded strip embedded in a vinyl ester resin, originally developed to have a high bearing capacity (Rizzo et al., 2005). Its thickness and width were 3.2 mm (0.127 in.) and 102 mm (4 in.), respectively. The fastening system for the mechanical anchorages was commercial steel wedge anchors available in the market with a diameter of 12.7 mm (0.5 in.) and total length of 152 mm (6 in) (embedment length is 102 mm (4 in.)).

All test beams were subjected to a three-point bending as shown in Figure 2. Two actuators with a 489-kN (110-kip) tensile capacity pulled the beam upward while the reaction force generated the required shear force in the test region. The advantage of this configuration was that one test beam could be used for testing two specimens by moving the supports and relocating the cantilever portion. Thus, two distinct tests were performed on each beam as follows: (1) The left test region of the beam was tested first until shear failure occurred, (2) the supports, loading and reaction frames were moved such that the right test region was subjected to the same loading condition as the left test region, and (3) the right test region was tested.

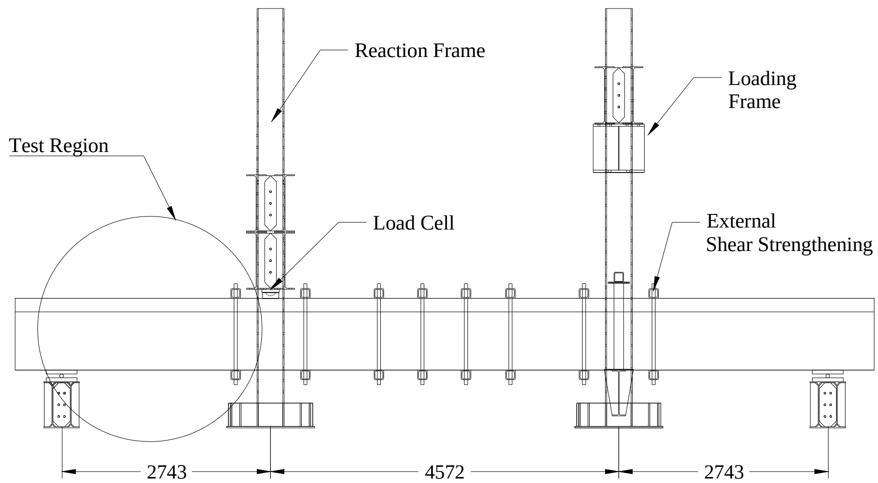


Figure 2. Details of test set-up (dimensions in mm).

All test beams except for the control beams were strengthened with one-ply CFRP strips in the form of a U-wrap with 90° fiber orientation to the horizontal axis. In order to enhance the shear contribution of FRP by preventing premature failure due to debonding, a discontinuous mechanical anchorage (DMA) system was installed on Beams RC-8-S90-DMA and RC-12-S90-DMA as shown in Figure 3. This system consisted of two CFRP pre-cured laminate plates bonded to each FRP strip with epoxy resin and anchored firmly in place with concrete wedge anchors and steel bolts. Other types of mechanical anchorage systems were used: sandwich discontinuous mechanical anchorage (SDMA) for Beams RC-12-S90-SDMA-PC and additional horizontal FRP Strips (HA) systems for RC-12-S90-HA-PC. The SDMA system is similar to the DMA system with the only difference being that the FRP strips are wrapped around the first FRP plate and secured tightly by overlapping it with the second FRP plate for better anchorage as depicted in Figure 4.

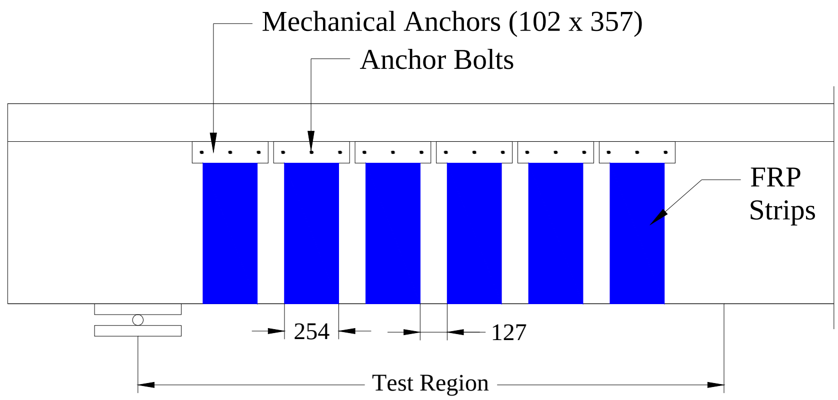
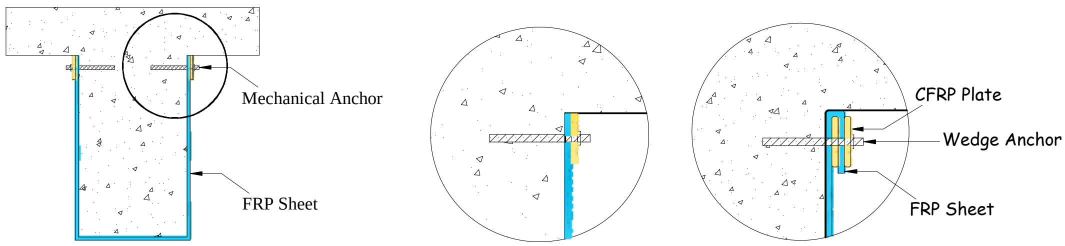


Figure 3. Configuration of externally bonded CFRP sheet strengthening with mechanical anchorage system (dimensions in mm).



(a) Cross-section (b) DMA systems (cz e)SDMA system

Figure 4. Details of mechanical anchorage system.

3 RESULTS AND DISCUSSIONS

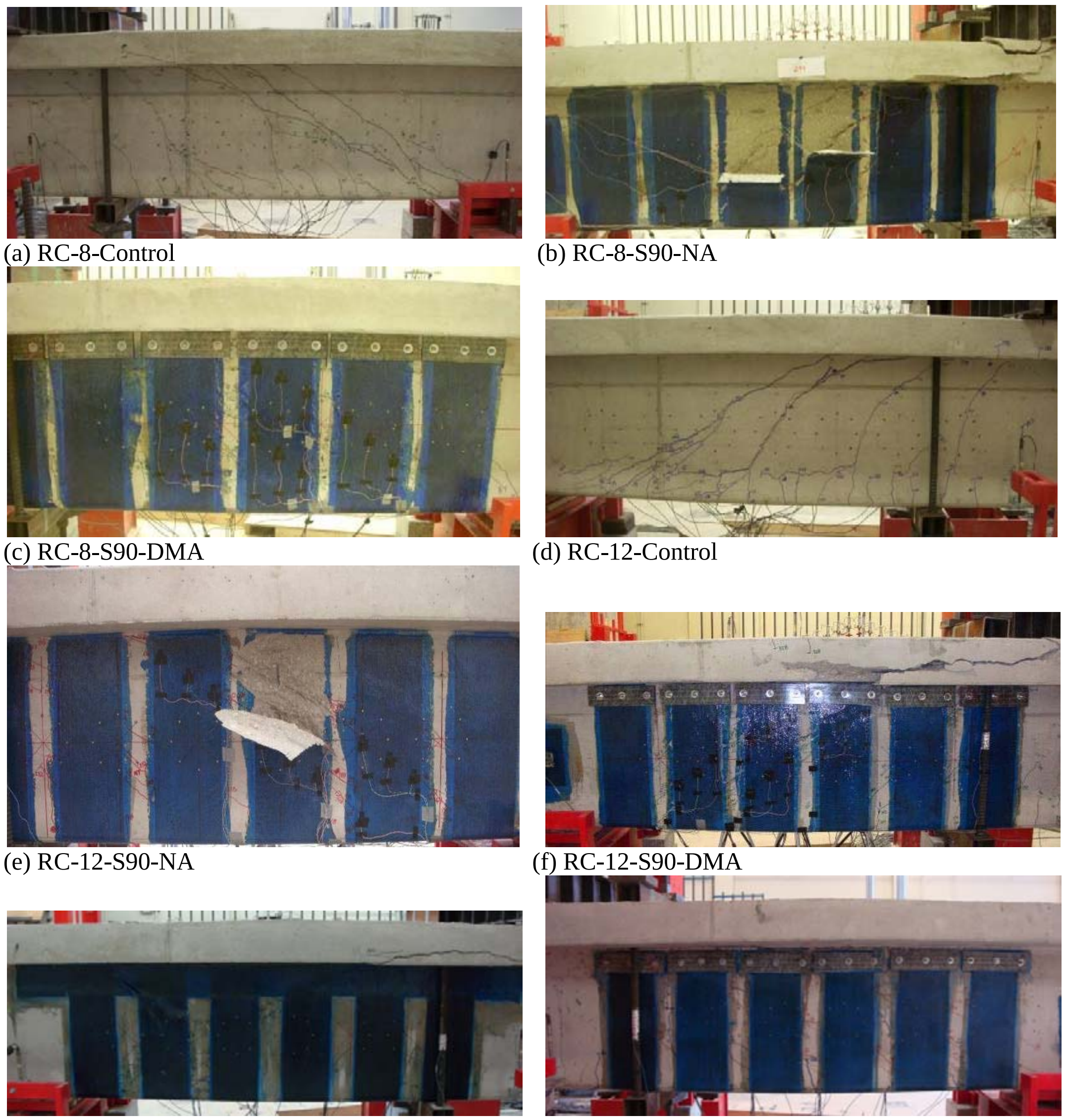
3.1 Failure Modes

The control beams RC-8-Control and RC-12-Control failed when the diagonal cracks in the web reached the flange, as shown in Figures 5(a) and 5(d), respectively. The FRP strengthened beams without mechanical anchorage systems RC-8-S90-NA and RC-12-S90-NA failed due to FRP debonding as shown in Figures 5(b) and 5(e), respectively. The FRP-strengthened beams with mechanical anchorages, RC-8-S90-DMA and RC-12-S90-DMA, failed primarily due to FRP debonding; however, the debonding of FRP was delayed due to the mechanical anchorage as shown in Figures 5(c) and 5(f). The additional horizontal FRP strips, used for RC-12-S90-HA-PC, could also delay FRP debonding as shown in Figure 5(g). The sandwich panel mechanical anchorage system, used for RC-12-S90-SDMA-PC, performed better than the ordinary mechanical anchorage systems, which completely prevented the debonding of FRP sheets almost until the failure; however, results showed a weak plane along the anchor bolts was formed, and the failure occurred along that weak plane as shown in Figure 5(h).

3.2 Shear Strength Gain

The actual shear strength gain of the test girders due to FRP strengthening can be defined as the difference between the shear strength of the FRP-strengthened beam and that of the corresponding control beam. The measured shear strengths, V_{test}, of all test beams were summarized in Table 2. However, the shear strengths of all test girders cannot be compared directly using the experimentally determined shear V_{test} because of the differences in concrete strength. Thus, the experimentally determined shear strengths V_{test} had to be normalized as:

$$V_{\text{test, norm}} = \frac{V_{c,\exp}}{\sqrt{\dfrac{f'_{c,spec}}{f'_{c,control}}}} + V_s + V_f \tag{1}$$



(a) RC-8-Control (b) RC-8-S90-NA

(c) RC-8-S90-DMA (d) RC-12-Control

(e) RC-12-S90-NA (f) RC-12-S90-DMA

(g) RC-12-S90-HS-PC (h) RC-12-S90-SDMA-PC

Figure 5. Failure Modes.

where $f`_{c,spec}$ is the concrete strength of test beams strengthened with FRP, $f`_{c,control}$ is the concrete compressive strength of the control beam, and $V_{c,\exp}$ is the contribution of the concrete, which calculated as:

$$V_{c,\exp} = V_{test} - V_s - V_f \tag{2}$$

where, V_s and V_f are the shear contribution due to the transverse steel reinforcement and FRP strips respectively, and they are calculated using the measured strains in the stirrups and FRP strips bridging over the critical crack that causes the failure of the test beams. This procedure is described in more detail in Brancaccio (2008). The normalized shear strengths, $V_{test,norm}$ of all test beams are presented in Table 2. The actual shear gain was then calculated using these normalized shear strength and also presented in Table 2.

Table 2. Nominal Shear Strength and Shear Gain Calculations Based on Normalized Concrete Strength

	RC-8 -Control	RC-12 -Control	RC-8-S90 -NA	RC-8-S90 -DMA	RC-12-S90 -NA	RC-12-S90 -DMA	RC-12-S90 -SDMA-PC	RC-12-S90 -HA-PC
f'_c (MPa)	19.3	19.9	20.7	23.8	28.9	30.5	19.2	18.3
V_{test} (kN)	**681**	**551**	**851**	**943**	**765**	**912**	**952**	**834**
V_c (kN)	322	289	385	790	91.5	407	524	391
V_s (kN)	359	262	284	248	182	170	165	170
V_f (kN)	-	-	182	38.6	172	243	262	273
$V_{test,norm}$ (kN)	**681**	**551**	**838**	**891**	**696**	**816**	**961**	**851**
Shear Gain (kN)	-	-	157	210	145	265	410	300
Shear Gain (%)	**-**	**-**	**23.1**	**30.8**	**26.3**	**48.1**	**74.4**	**54.4**

f'_c : Concrete strength, V_{test} : Measured Shear Strength, V_c : Shear Contribution of Concrete, V_s : Shear Contribution of Stirrups, V_f : Shear Contribution of FRP, $V_{test,norm}$: Normalized Shear Strength

Table 2 indicates that FRP strengthening increased the shear capacity, and its effectiveness depends on the variables considered. Specifically, the strengthened specimens of RC-12 series exhibited greater increase in shear strength than those of RC-8 series; the shear gains of RC-8-S90-NA and RC-8-S90-DMA are 23.1% and 30.8%, respectively while those of RC-12-S90-NA and RC-12-S90-DMA are 26.3% and 48.1%, respectively. This result confirms the findings of previous studies that the effectiveness of FRP decreases as the number of stirrups is increased (Pellegrino et al., 2002; Bousselham and Chaallal, 2004). This interaction between the number of stirrups and FRP strengthening should be considered in the design of FRP shear strengthened specimens. Table 2 further shows that the use of mechanical anchorage significantly increases the effectiveness of FRP shear strengthening, and the sandwich panel mechanical anchorage (SDMA) system performed best; the shear gains of RC-12-S90-DMA and RC-12-S90-HA-PC are 48.1% and 54.4%, respectively while that of RC-12-S90-SDMA-PC is 74.4%. In addition, it can be observed from the test results shown in Table 2 that the existing diagonal shear cracks before the application of FRP would not adversely affect the effectiveness of FRP shear strengthening.

4 CONCLUSIONS

From the experimental program conducted in this study, the following conclusions were drawn:

a. The beams strengthened with FRP tested in this study showed an increase in shear strength of about 23% to 26% as compared to the corresponding control beam when mechanical anchorages were not used.

b. The use of a mechanical anchorage system provided additional shear strength. The FRP strengthened beams with mechanical anchorage showed 7% to 48% higher shear strength than the beams without mechanical anchorage, depending on the types of mechanical anchorages used.

c. FRP shear strengthening was more efficient for beams with 12-in. stirrup spacing than for those with 8-in. stirrup spacing, implying there is an interaction between the shear contribution of FRP and stirrups. However, it needs further analytical and experimental studies to understand the interaction mechanism.

d. Overall, the results of this study obtained from the large-scale beam tests confirms the previous test results obtained from the small-scale tests. Therefore, the small-scale test results and the current design equations derived from such test results could be still valid to predict the behavior of full-scale RC beams.

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