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Behavior of FRP Strengthened RC Elements with Carbon Fiber Anchors under Pure Shear

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ABSTRACT: Reinforced concrete structural members can be strengthened by Fiber Reinforced Polymer (FRP) sheets; however, premature debonding can lead to a great loss of the effectiveness in strengthening. The use of anchorage systems such as carbon fiber anchors can increase the amount of tension carried in the FRP sheets. Effective bond length (EBL) is a term which affects debonding, especially in strengthened structures without anchorage. In this research, panel specimens are strengthened with FRP and are tested under pure shear using the Universal Panel Tester. The effective bond length was calculated and compared based on different equations. By providing sufficient anchors at the ends of FRP sheets, debonding was prevented and rupture of some FRP sheets was observed. The presence of anchors increased the shear capacity of the specimens and higher strain values were reached at the ultimate stage.

1 INTRODUCTION

The use of Fiber Reinforced Polymer (FRP) in strengthening and rehabilitation of civil infrastructure has increased rapidly in the past two decades. FRPs are advanced composites consisting of high strength fibers such as aramid, carbon or glass embedded in a polymer resin. The fibers are the primary load-carrying components of the composite and, have a wide range of strength and stiffness with a linear stress-strain relationship up to failure. The polymer resin provides a medium for stresses to be transferred among the individual fibers, and helps maintain alignment of the fibers. During the late 1970s and early 1980s, the use of FRPs began to emerge in civil engineering infrastructure. While research related to the flexural behavior of FRP-strengthened elements has reached a mature phase, studies related to FRP shear strengthening is still in a less advanced stage. A recent innovation for the shear strengthening of reinforced concrete (RC) beams is to externally bond FRP composite plates or sheets. Several studies have indicated clearly that such strengthened beams may fail mainly in one of the two modes: tensile rupture of the FRP; and debonding of the FRP from the sides of the RC beam, depending on how the beam is strengthened (Chen & Teng, 2003). Due to the fact that debonding generally initiates from shear cracks in the concrete under FRP, the bond strength is limited by the tensile strength of the concrete. As it is also reported in literature, increasing the length of the FRP sheet bonded to the concrete surface does not enhance the bonding strength because there is an effective length beyond which the strength does not increase (Chen & Teng, 2001). Therefore, it is needed to provide a form of additional anchorage system in order to fully utilize the tensile capacity of the FRP sheet while shifting the failure mode from debonding to the rupture of FRP sheet. An example of such an anchorage system is shown in Figure 1.

2 PREVIOUS RESEARCH

Many researchers have noted the importance of providing some type of anchorage near the ends of the FRP strips or sheets to prevent debonding failure from occurring (Uji (1992), Khalifa et al. (1999), Khalifa & Nanni (2000), Triantafillou & Antonopoulos (2000), Chen & Teng (2003), Teng et al. (2004), Orton et al. (2008), and Ortega et al. (2009)). Uji (1992) stated that sufficient anchorage of the carbon fiber sheets are required similarly to steel stirrups in order to properly carry the shear force without debonding. Triantafillou & Antonopoulos (2000) recommended that if no access is available to the top side of T-beams, the FRP sheets should be attached to the compression zone of the concrete element with some type of simple mechanical anchorage device. When an anchorage device is utilized in practice, the failure mode of debonding is effectively prevented, changing the failure mode to a more desirable FRP rupture mode (Teng et al., 2004). When an anchorage device is installed, it does not entirely prevent debonding from occurring along the FRP sheets; a certain amount of debonding must be encountered in order to effectively engage the anchorage system. However, the ultimate goal should be the prevention of failure due to debonding, while allowing the FRP material to experience higher strains by utilizing its full tensile capacity. The use of anchorage allows the FRP sheets to carry load after debonding initiates. This leads to a more ductile response of the element (Ortega et al., 2009). Without an anchorage system in place, the strength of the entire strengthening system relies completely on the bond between the FRP material and the concrete substrate (Uji, 1992).

Providing sufficient anchorage system for FRP sheets is a complex task to accomplish. Improper anchorage of the material can create unwanted stress concentrations that will cause premature failures. Thus, several researchers have proposed anchorage systems which will develop the full strength of the FRP sheets. Systems such as, FRP U-anchors (Khalifa et al., 1999), threaded anchor rods (Deifalla & Ghobarah, 2006), FRP straps (Hoult & Lees, 2009), continuous and discontinuous FRP plates, and modified anchor bolt systems (Ortega et al., 2009) can be counted as the examples of anchorage systems.

2.1 Carbon fiber anchors

Carbon fiber anchors are started to be used as anchorage for FRP strengthening relatively recent. This technique was originally developed by the Shimizu Corporation in Japan. Lately a number of experimental studies have been conducted concerning CFRP anchors (Kobayashi et al., 2001; Özdemir, 2005; Orton et al., 2008; and Kim & Smith, 2009). The CFRP anchors are made from the same material as the sheet that is applied to strengthen the concrete member. They are saturated with epoxy and inserted into predrilled holes (Figure 2), and fanned out immediately after the sheet is placed. This process ensures that the anchors and sheet form a continuous composite unit to create a path for tensile load to transfer from the FRP sheet into the concrete element.

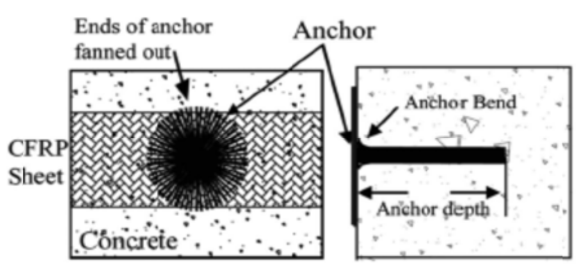

Figure 1. CFRP Anchor with a 360 degree fan, Orton (2008).

Figure 2. Strips of CFRP to form anchor, saturating and inserting anchor into predrilled hole.

CFRP anchors are classified as drilled in anchors (Kim & Smith, 2009). Research on the strength and behavior of the CFRP anchors is still limited to fully understand the mechanism. Therefore, current design procedures concerning CFRP anchors are often left to recommendations rather than experimentally produced equations. In this study, although limited, results of previous research efforts were used to determine the anchor depth, bend radius, amount of CFRP material in anchors, diameter of hole, fan length and opening angle. The required depth into the concrete for full development of the anchor has been studied by Özdemir (2005). Özdemir concluded that there is an effective embedment depth (at least 10 cm, in 10–20 MPa concrete with 14–20 mm diameter anchors) beyond which the capacity of the anchors no longer increases. However in some cases (especially for thin members like membranes), instead of using the effective depth, the CFRP anchors may be inserted through holes passing all the way from one side to the other side of the member and fanned on both sides as shown in Figure 3.

Another important parameter in CFRP anchors is the effect of the bend in the anchor as the fibers bend into the concrete hole. The sharp or rough edge at the corner of the drilled hole can cause stress concentrations in the anchor, leading to premature local rupture and reduction of the anchorage capacity. Therefore, proper rounding of the rough edge around the drilled anchor hole is needed when making a hole for CFRP anchors. Kobayashi et al. (2001) recommended an anchor hole chamfer radius of 1.9 cm in their study of CFRP anchors. ACI 440 (2008) recommends that all corners shall be rounded to a 1.3 cm radius. The total required length of a CFRP anchor is the sum of the embedment depth of the anchor and the fan length of the anchors. The fan length depends on the required bond strength between the fan and the main sheet and on the fan angle. The maximum load resisted by the anchorage system increases as the length of the anchorage fan increases (Kobayashi et al., 2001). The CFRP anchor must be long enough to allow the fan to cover the width of CFRP sheet. The fan should extend 1.3 cm. beyond the strip width as shown in Figure 3. Kobayashi et al. (2001) recommended that the angle of the CFRP anchor fan should be limited to less than 90 degrees.

The fiber anchors are fairly new and the manufacturers have limited design data for their anchors as few tests have been conducted on configurations using fiber anchors therefore, comprehensive design guidelines are yet not available.

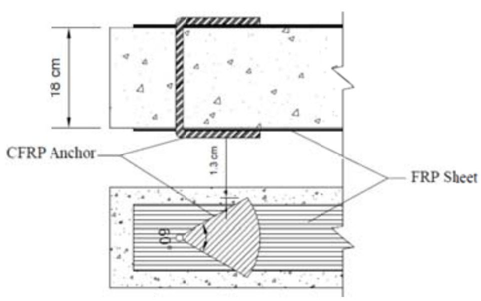

Figure 3. CFRP Anchor with a fan in one direction.

3 THE UNIVERSAL PANEL TESTER

The panel tester at the University of Houston was constructed in 1986 (Hsu et al. 1995) to perform biaxial or tri-axial tests on full-size reinforced concrete panels, shown in Figure 4. The maximum dimension of a panel specimen that can be tested is 1.4 by 1.4 m, with a thickness up to 406 mm. Each panel element represents an element cut out from large structures, such as bridge girders, shell roofs, nuclear containment structures, concrete offshore platforms or high-rise shear walls. The panel tester houses 40 in-plane hydraulic cylinders that are used to apply in-plane membrane forces on full-scale reinforced concrete panels.

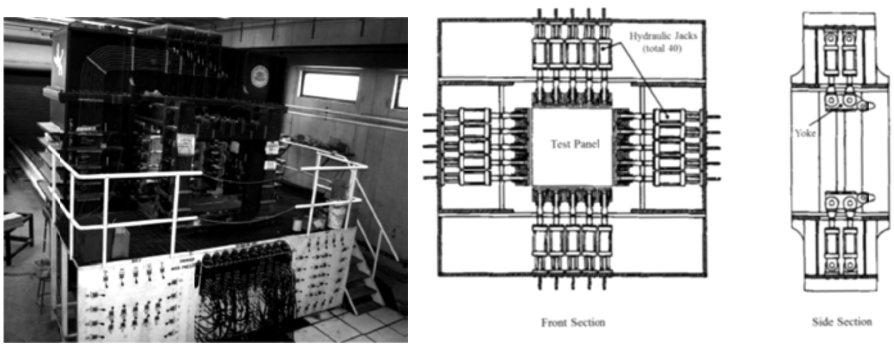

Figure 4. Illustration of load application by in plane hydraulic jacks (Hsu et. al., 1995)

Each jack is capable of producing 1110 kN in compression and 890 kN in tension and is equipped with spherical hinges at both ends to control the alignment of the applied forces. The loads are applied to the panel at five equally spaced locations along the four edges of the panel. The jacks are attached to the panel through connector yokes as shown in Figure 4. The load is applied through a sophisticated hydraulic system, consisting of a 35 Mpa pump unit and a complex series of valves and hoses. Originally, the automatic control used to allow for testing under load control only, but in 1995, a servo-control system was installed so that strain-controlled tests could be also performed.

4 TEST PROGRAM

The construction details of two reinforced concrete panel specimens (F2S1 and F2S2), tested under pure shear with Universal Panel Tester is presented in this section. The test panels are 1.4 m square elements with a thickness of 0.18m (Figure 5a), representing an element from the web of a T-Beam girder which is strengthened with U-wrapped FRP at the bottom of the girder (Figure 5b). Both specimens have a compressive concrete strength around 48 Mpa. The steel reinforcement spaces at 19 cm as a grid in diagonal directions. Properties of materials used in the panel testing are reported elsewhere in detail (Yang et al., 2013a; Yang et al., 2013b). Specimens are strengthened with one layer of FRP strip application with thicknesses of 1 mm, where the strips are oriented at 45 degrees to the principal stress directions. The strips have a width of 20 cm, and the center to center distance is 19 cm. The FRP sheets are continued around the bottom and the right side of the panel wrapping the specimen on these two sides only. The other side of the FRP sheet is cut right at the edge of the top and left side of the panel. On one of the two specimens, an anchorage system is applied on the top end of the FRP sheets to simulate the anchor in the beams. Tyfo® SEH Composite CFRP Anchors that were developed by Fyfe (2005) with a total length 51 cm and a fan angle of 60 degrees was used.

Pure shear tests are performed in which equal tensile and compressive loads are applied up to failure in the horizontal and vertical directions respectively (pure shear condition at an angle of 45°). The applied load from the 40 in-plane jacks of the universal panel tester are monitored using load cells attached to each jack. Linear variable differential transducers (LVDTs) are used to measure the developed strain on both sides of the tested panels. Each side of the panel is instrumented symmetrically by 10 LVDTs. Four of the LVDTs are aligned horizontally, and another set of 4 LVDTs are aligned vertically, and each one of the remaining two is aligned along a diagonal direction as shown in Figure 6. The readings of the LVDTs and the load cells are stored by a data acquisition system.

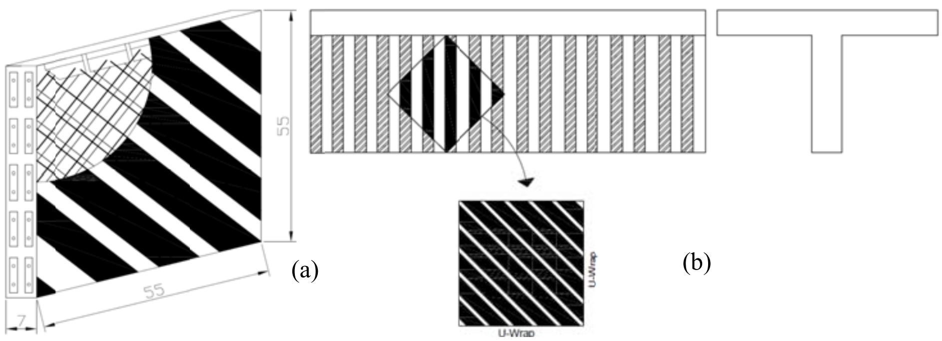

Figure 5. (a) Panel specimen, (b) The T-Beam idealized as an assemblage of membrane elements.

Concrete was mixed manually using a conventional mixer in the structural lab. Due to the size of the mixer, two patches of mixing were done for each panel. The specimens were cured for 7 days, covered with wet burlap and plastic sheets before being taken out of the formwork. The first step in applying the FRP is preparing the surface of the concrete. ACI (ACI 440.2R-08) recommends that the concrete surface should be free of all loose or unsound materials. In this research, the surface preparation was accomplished by first grinding the surface using a concrete grinding disk and then sandblasting the surface. Next, holes were drilled into the concrete where anchorage was needed. The edges of the holes were rounded over using a small grinder. Dust and debris was then removed from the holes by sandblasting and power washing. Once the specimen was prepared the FRP could then be applied. The application of FRP followed the manufactures recommendations (Fyfe, 2005). The FRP sheets were cut to length. Then the two parts of the Tyfo S epoxy were mixed according to manufacturer recommendations. Next, the sheets were applied and smoothed over the concrete to eliminate air bubbles and epoxy was applied to the sheets to get them fully saturated. Next, the anchors are inserted in position and fanned over the FRP sheet (Figure 7a); at last, another ply of FRP was applied onto the anchors. Figure 7b shows the details of the location of the FRP sheets and fiber anchors.

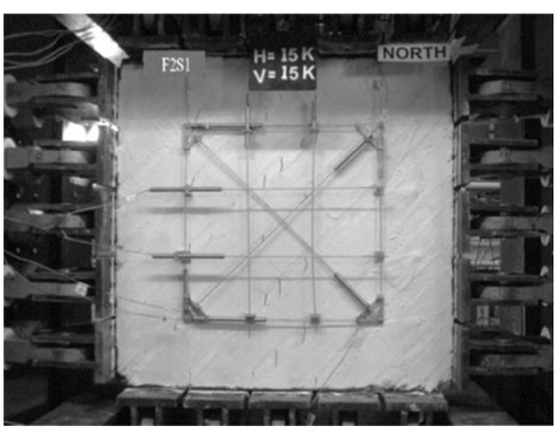

Figure 6. Instrumentation of Panel Element

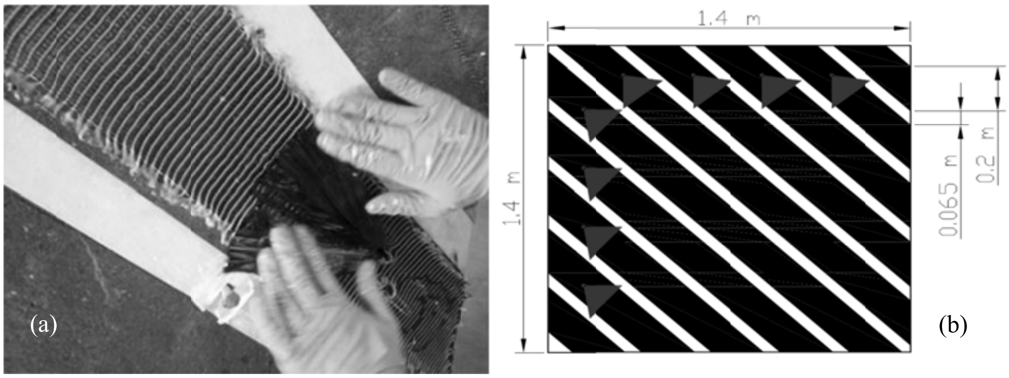

Figure 7. (a) Application and (b) design location of the of CFRP anchors on panel specimen

5 EFFECTIVE STRAIN IN FRP SHEETS

According to ACI 440.2R-08 the effective strain is the maximum strain that can be achieved in the FRP system at the nominal strength. It is typically expressed as a fraction of the ultimate tensile strain and is governed by the failure mode of the FRP system and of the strengthened reinforced concrete member which can be either rupture of FRP or debonding of FRP. In the case of FRP rupture, the effective strain is close but always slightly less than the ultimate tensile strain of FRP due to a non-uniform distribution of strains in the FRP. In the case of debonding, the effective strain in the FRP is much lower than the ultimate tensile strain of FRP. The equations used to calculate the effective strain in FRP, ε_{fe}, have been improved by several researchers as more experimental data becomes available. The factors generally considered in determining the effective strain are the stiffness of FRP, the strength of the concrete, the FRP strengthening scheme, and failure mode. In this paper, three different equations were used to evaluate the effective strain in the FRP. The equations and calculated strain values are presented in Table 1.

Table 1. Summary of effective strain based on different equations

Reference	Equation	Effective strain (ε_{fe})	
		Panel F2S1	Panel F2S2
ACI 440.2R-08	$\varepsilon_{fe} = K_v \varepsilon_{fu}$ $K_v = \dfrac{k_1 k_2 L_e}{468\varepsilon_{fu}} \leq 0.75 \quad L_e = \dfrac{2500}{\left(n_f t_f E_f\right)^{0.58}}$ $k_1 = \left(\dfrac{f_c'}{4000}\right)^{\frac{2}{3}} \quad k_2 = \dfrac{d_f - L_e}{d_f}$	0.00413	0.00415
Khalifa et. al. (1998)	$\varepsilon_{fe} = R\varepsilon_{fu}$ $R = \dfrac{0.0042(f_c')^{2/3} w_{fe}}{\left(E_f t_f\right)^{0.58} \varepsilon_{fu} d_f}$ $w_{fe} = d_f - L_e$ Sheets are in form of U − wrap	0.00456	0.00458
Khalifa et. al. (2000)	$R = \dfrac{(f_c')^{2/3} w_{fe}}{\varepsilon_{fu} d_f}\left[738.93 - 4.06\left(E_f t_f\right)\right] \times 10^{-6}$ $L_e = -0.432 t_f E_f + 94.3 \quad (metric)$	0.00563	0.00565

6 EXPERIMENTAL RESULTS

The smeared strain in the FRP was observed to be 0.008 in panel F2S1 and this value was 0.012 for panel F2S2. In the first panel which was U-wrapped without any anchorage system, the smeared strain in the FRP was higher than the effective strain calculated above. Therefore, the FRP debonded from the concrete substrate (Figure 8a). For the second panel that was U-wrapped and had an FRP anchorage system, the smeared strain in the FRP reached 0.012 which was very close to the FRPs ultimate strain. In this case some FRP rupture was observed in addition to some local debonding (Figure 8b). The shear stress and strain curve is plotted in Figure 9. A relatively ductile performance was observed for the specimen F2S2 and the descending portion of the stress-strain curve was also captured. The test was stopped when the shear capacity dropped to 75% of the peak value. Unlike the reinforced concrete elements without FRP (Hsu and Mo, 2010), the shear stress continued to increase at the post-yielding stage. This gain of the shear capacity is mainly attributed to FRP sheets. The F2S1 failed by premature FRP debonding. The comparison between the results indicates that the FRP anchor effectively prevented the debonding of the FRP.

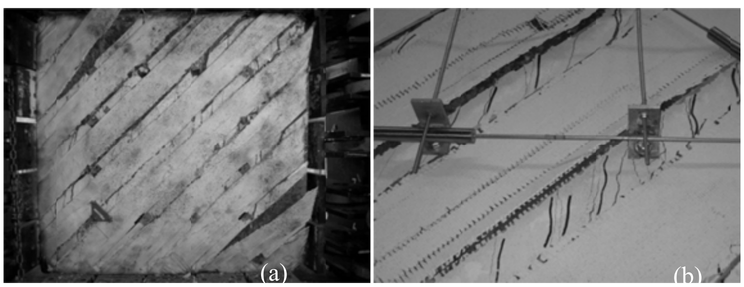

Figure 8. (a) Debonding of FRP sheets in panel F2S1, (b) Debonding and FRP rupture in panel F2S2

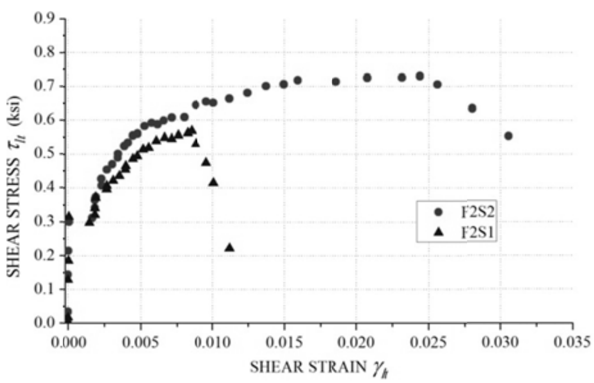

Figure 9. Shear stress and strain curve for specimen F2S1&F2S2.

7 CONCLUSIONS

In the light of gathered data from limited number of tests conducted, it can be stated that the carbon fiber anchors improve utilization of the tensile capacity of the FRP sheets in strengthened RC members while preventing the premature failure due to debonding until the crushing of concrete. The smeared strain in FRP is generally higher than the effective strain when no anchorage system is provided, which results in debonding of the FRP sheets from the concrete substrate. The ongoing research will focus on assessment of behavior of the CFRP anchorage systems under pure shear with more experimental data. The analytical prediction for effective strains for FRP systems with anchorage will also be tackled.

ACKNOWLEDGMENTS

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