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Anchorage Effect on Flexural Fiber Reinforced Polymer (FRP) Laminate Strengthening of Lightweight Concrete Beams

Tariq Aljaafreh[1], Eyosias Beneberu[2], Ph.D., P.E., & Nur Yazdani[3], Ph.D., P.E., F.ASCE

Abstract

Lightweight (LW) concrete is finding increasing use primarily to decrease the dead load, reinforcements needed and member sizes. The beneficial effect of flexural fiber reinforced polymer (FRP) laminates in enhancing the capacity of normal-weight concrete has been well-demonstrated. However, such application on LW has not been explored in depth, especially with confining anchorage systems that can prevent premature debonding of the flexural laminates. This study investigated the effect of utilizing mechanical anchorage and FRP U-wrap anchorage on the performance of LW concrete beams. The carbon FRP laminate enhanced the flexural capacity of all strengthened beams by up to 12%. The CFRP U-wrap was found to be more effective than the mechanical anchorage in delaying the debonding failure of the flexural laminate and increasing its tensile strain by as much as 81%. However, the mechanical anchorage was more effective in increasing the elastic stiffness of the beams. Strengthened beams are likely to have increased durability due to the decreased crack width, length and spacing. The demonstrated failure modes of cover delamination and U-wrap debonding contradicted the theoretical failure mode from the American Concrete Institute (ACI) guidelines. Such guidelines do not currently include the contribution of FRP anchorage systems for concrete structures.

Keywords: CFRP, lightweight concrete, U-wrap, mechanical anchorage, flexural strengthening, debonding failure mode

1. Introduction

Lightweight (LW) concrete is finding increasing use in structures, primarily because it is 20–40% lighter than normal weight (NW) concrete. LW concrete can decrease the dead load, number and size of foundations, reinforcements needed and member sizes (NRMCA, 2003). There are two types of LW concrete: all-lightweight concrete, which has fine and coarse lightweight aggregates, and sand-lightweight concrete, in which the fine aggregate is normal-weight sand (ACI 211.2, 1998). LW concrete has 28 days compressive strength in excess of 17 MPa and density in the range of 1680 to 1920 kg/m^3 (ACI 213, 2003).

Concrete structures deteriorate or get damaged over time due to various reasons, such as chemical attacks, adverse environment, rebar corrosion, design and construction errors, impact loading, and combinations of these factors. Like other types of concrete, LW concrete may also deteriorate with time which necessitates repair and rehabilitation. Externally bonded steel plates, external post-tensioning, and externally bonded fiber reinforced polymer (FRP)are some of the available methods for strengthening such deteriorated/damaged structures (Jumaat and Alam, 2008).External FRP laminates for concrete have high strength-to-weight ratio, excellent corrosion resistance, quick and easy installation, and ease of application in areas where there is limited access (Fig. 1).

[1]Doctoral Student, Department of Civil Engineering, University of Texas at Arlington, Box 19308, Arlington, TX 76019.
[2] Post-Doctoral Fellow, Department of Civil Engineering, University of Texas at Arlington, Box 19308, Arlington, TX 76019.
[3] Professor and Corresponding Author, Department of Civil Engineering, University of Texas at Arlington, Box 19308, Arlington

Fig. 1. CFRP strengthened concrete beams

Several prior studies showed the beneficial effect of FRP laminates in improving the flexural, shear and axial capacities, as well as durability of concrete structural members(ACI 440R, 2007). Numerous studies have been conducted on strengthening NW reinforced concrete (RC) beam members using FRP wrapping (Kim et al., 2008; Anil 2007; Al-Saidy et al., 2010).Reed et al. (2005) studied CFRP strip strengthening of several series of reinforced concrete beams. Their flexural capacity was enhanced by 10 to 20%, and the CFRP exhibited the debonding mode of failure. The ultimate load carrying capacity of FRP strengthened beams is affected by the controlling failure mode. In nearly most applications, the failure occurs by debonding of the FRP from the concrete substrate rather than FRP rupture (Grelle and Sneed, 2013). The debonding modes could be concrete cover delamination, intermediate flexural crack-induced interfacial debonding, plate-end interfacial debonding and intermediate flexural shear crack-induced interfacial debonding (Teng et al. 2002, 2003). In some cases, the failure occurs by crushing of the concrete in compression before yielding of the reinforcing steel or yielding of the steel in tension followed by concrete crushing (ACI 440.2R, 2008).

Only a very limited number of prior studies were located herein on the application of FRP laminates on LW concrete. Yazdani and Goucher (2015) investigated the effect of FRP wraps on increasing the durability of LW concrete. The study included 42 cylinders that were immersed in a saline solution for 50 days under electricity induced accelerated testing. The variables were the types of concrete, types of FRP and the number of FRP layers. FRP laminates significantly reduced steel corrosion in LW concrete, thereby increasing the long-term durability. Shannag et al. (2012) strengthened 40 LW concrete beams using carbon FRP (CFRP). The study considered different CFRP configurations, such as jacketing from the bottom and both sides, whole bottom width strips and half-bottom width strips. Jacketing was found to be the most effective CFRP application scheme to enhance the ultimate load capacity of the beams. Most of the strengthened beams experienced cover delamination as the failure mode. Shabeeb et al. (2011) investigated the behavior of LW concrete slabs under different preloading levels and various repair techniques, such as steel plates, CFRP sheets and ferrocement layering. Test results showed an increase in strength and stiffness, with a decrease in ductility for the CFRP strengthened slabs, which exhibited failure by CFRP debonding.

The efficiency of the external FRP strengthening can be increased by using anchoring systems (Fig. 2) that may increase the FRP-concrete bonding (Grelle and Sneed, 2013) and prevent or delay the debonding of FRP (Shbeeb et al., 2011; Zhang et al., 2012). Anil and Belgin (2010) investigated the effect of the number, arrangement and types of anchorage on stress distribution between the CFRP layer and the concrete substrate. The study considered mechanical anchor bolts and CFRP U-wrap anchors. It was found that mechanical anchorage increased the FRP-concrete bond by more than 45% compared to the CFRP fan type anchorage. Mechanical anchorage was useful in increasing the effective length of the CFRP strips for transferring stresses, thereby enhancing the strength and stiffness of the specimens.

(a) Mechanical anchors

(b) Fan Anchors ((FHWA, 2012)

(c) U wraps (ElSafty et. al, 2013)

Fig.2. Various CFRP Anchor Types

Kim et al. (2008) investigated the performance of doubly reinforced NW concrete beams with prestressed CFRP sheets and several types of anchoring, such as FRP U-wraps with and without mechanical anchors and CFRP sheet-anchored U-wraps. The beams with nonmetallic CFRP sheet anchoring exhibited the best stress redistributions and ductile failure due to the contribution of CFRP anchors. Several studies on NW concrete showed that CFRP fan anchors increased the contribution of the CFRP flexural laminates in shear/flexure and delayed debonding (Kim et al., 2014; Smith et al., 2013; Anil and Belgin, 2010).

It is apparent that extensive literature is available on external FRP fabric strengthening of NW concrete members; however, there have been only a few past investigations on such strengthening for LW concrete. The past studies with LW concrete showed FRP debonding or the concrete cover delamination as the primary failure modes of the flexural members. With increasing use of LW concrete, the need for external strengthening systems (such as FRP laminates) for such structures that are deteriorated or damaged will continue to rise.

The prevention or delay of debonding or delamination type of FRP failure in such strengthened structures could be achieved through appropriate anchoring of the external FRP system. Such anchoring may carry additional importance in light of the lower strengths of LW concrete as compared to NW concrete.

The extensive background review conducted as a part of this study failed to locate any prior investigation on the effect of anchorage systems for external FRP strengthening of LW concrete structures. The study reported herein was designed to fill this knowledge gap by exploring the effect of various anchoring systems on the failure modes and flexural capacities of LW concrete beams with CFRP flexural strengthening. Two types of anchors were investigated herein: mechanical anchor bolts and CFRP U-wraps.

2. Test Procedure

2.1 Specimen Details

The study involved a total of eight LW reinforced concrete beams, each 152 mm wide, 203 mm deep, and 1.57 m long, as shown in Fig. 3. The flexural reinforcements consisted of two #3 bottom rebars, producing a reinforcement ratio of 0.0046 and an associated ultimate tensile strain of 0.0237, well below the tension controlled strain limit of 0.005 These values corresponded to the target concrete compressive strength of 27 MPa and the 420 MPa yield strength of the steel rebars.

The very lightly reinforced concrete beam had a low tension flexural capacity, allowing for the CFRP strengthening to be engaged in the beam failure process at a relatively low test load. The two #3 top rebars were used to hang the #3 shear reinforcement stirrups, consisting of #3 stirrups at different spacing, as shown in Fig.3. The beams were designed to allow the flexural mode to control the failure, and not the shear mode. Two control beams had no CFRP, and the remaining six had bottom flexural CFRP strengthening and various anchorage configurations, as shown in Table 1. The test matrix allowed for two sample replications for each CFRP/anchorage configuration. Because of the expected high normal stress concentration at the termination points of the longitudinal CFRP (ACI 440.2R, 2008), the proposed anchorage systems were applied near the termination points (Fig. 4) to redistribute the stresses and consequently prevent any debonding.

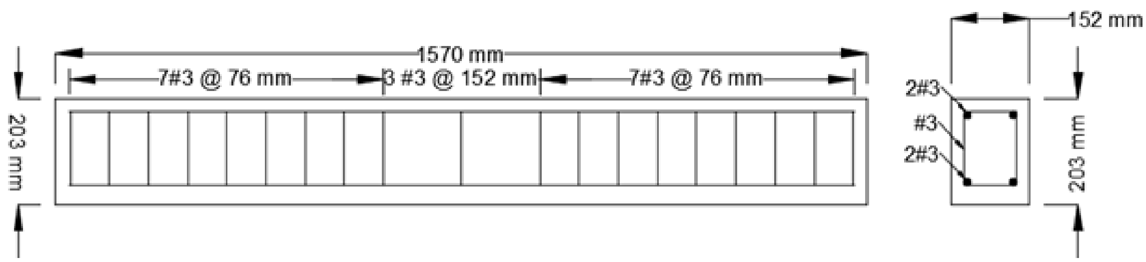


Fig. 3. Test beam details

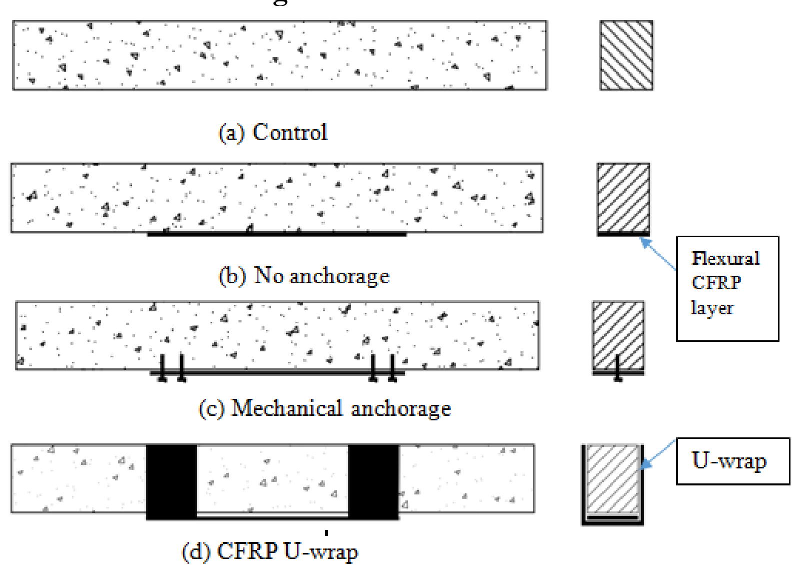


Fig.4. CFRP and anchorage schemes

Table 1.Designation of beams

Beam designation	Strengthening method	Anchorage Type
B1-C	Control (no CFRP)	None
B2-C	Control (no CFRP)	None
B3-N	CFRP flexural layer	None
B4-N	CFRP flexural layer	None
B5-M	CFRP flexural layer	Mechanical anchor bolts
B6-M	CFRP flexural layer	Mechanical anchor bolts
B7-U	CFRP flexural layer	CFRP U-wrap
B8-U	CFRP flexural layer	CFRP U-wrap

2.2 Concrete Sample Preparation

All specimens were made from LW concrete, with the mix design per the ACI guidelines (ACI 211.2, 1998), as shown in Table 2. The target slump, unit weight, and 28-day compressive strength were 76-102 mm, 1680 to 1920 kg/m^{3}and 27MPa, respectively.

Table2. Concrete mix design

Ingredient	Weight (kg/m^3)
Type II Portland cement	255
Water	142
Sand	794
9.5 mm Streetman lightweight aggregate	551

It is important to specify the water absorption in concrete, and LW aggregates vary in the amount of water they absorb. LW concrete manufacturers recommend aggregate sprinkling with water prior to mixing to prevent water loss in the mix (Harding, 1995). To reach a saturated-surface-dry condition, the aggregates were soaked in a tub for two days to make sure that all pores were filled with water. Then, the water was drained from the tub to allow the aggregates to dry for 30 minutes (Heffington, 2000). Since the aggregates were saturated-surface-dry, no adjustment in the amount of mix water was needed.

After concrete mixing, three concrete cylinders (150 mm by 300 mm) were prepared per ASTM C 192/C 192M (2002) standards for compressive strength determination, in accordance with ASTM C 39/C 39M (2011). The fresh concrete slump was measured according to ASTM C 143/143M (2011) and equilibrium density was calculated according to ASTM C 567/567M (2014). All beams were moist cured for 21 days in a curing room under controlled temperature and humidity.

2.3 CFRP and Anchorage Materials

A common unidirectional CFRP laminate was used for both flexural and U-wrap anchorage, the properties of which are presented in Table 3. The flexural strengthening of the beams involved applying 150 mm wide and 760 mm long CFRP on the tension face to cover the constant moment region between the two loading points in the four-point test set up. A compatible two-part epoxy was used to affix the CFRP to the concrete surface. The mechanical anchorage consisted of two steel anchor bolts (9.5 mm diameter, 63.5mm length, and with 4.45 kN shear strength), installed at each end of the beam.

Table 2. CFRP properties

Cured laminate properties	Design values
Tensile strength	724 MPa
Modulus of elasticity	56,500 MPa
Elongation at break	1.0%
Thickness	0.51 mm
Width	304 mm

2.4 Concrete Surface Preparation

Adequate surface preparation is essential for proper bonding of the CFRP to the concrete substrate. An air needle scaler [Fig. 5(a)] was used to remove any loose concrete and achieve a concrete surface profile 3 (CSP 3), as established by the International Concrete Repair Institute (ICRI, 2013). Finally, air pressure and brush were used to remove any remaining dust, resulting in a clean and sound concrete surface [Fig. 5(b)].

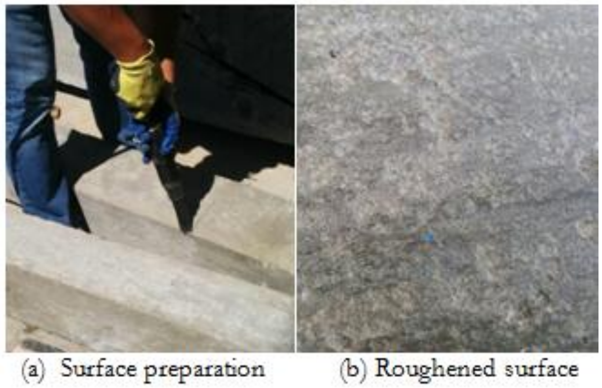


Fig.5. Surface preparation and roughened surface

2.5 Flexural CFRP and Anchorage Installation

A wet layup process was used to install the CFRP laminates. The ambient temperature during application was above 40 °F as specified by the CFRP manufacturer. The two-part epoxy was mixed thoroughly for five minutes as per specifications and applied on both the concrete and the CFRP using a special roller. The CFRP was then manually attached to the substrate and a roller was used to remove entrapped air at the CFRP-concrete interface. The CFRP was then allowed to cure for 10 days before conducting the flexural test.

For beams B5-M and B6-M (Table 1), two steel anchor bolts were installed in a series at each end of the longitudinal CFRP as per the recommendation outlined in a previous investigation (Anil and Belgin, 2010). The anchor installation involved drilling 50 mm deep holes through the CFRP laminate and the concrete, followed by pressurized air cleaning and finally insertion of the anchors into the holes. A washer and nut arrangement was used to tightly affix the bolts, as shown in Fig. 6a. For beams B7-U and B8-U, a 305 mm wide CFRP U-wrap anchorage was applied at both ends of the flexural CFRP, with fiber direction transverse to the flexural CFRP, as shown in Fig. 6(b).

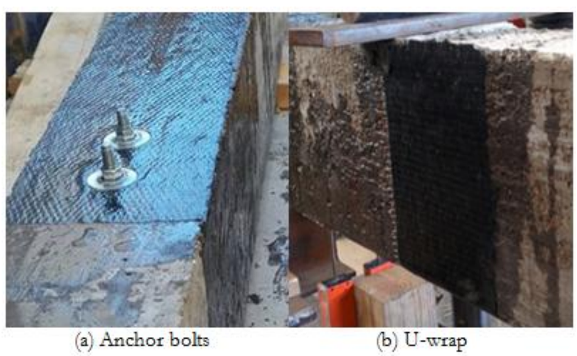


Fig.6. Mechanical and U-wrap anchor

2.6 Experimental setup

A four-point loading protocol was employed for the flexural testing of each beam (Fig. 7), ensuring a near constant bending moment region in the center part of the beams. The beams were loaded by a 1779 kN capacity hydraulic actuator that was mounted on a steel frame. A load cell with a capacity of 3000 kN was used to measure the load from the actuator. The mid-span deflection of each beam was measured by two linear variable displacement transducers (LVDT). One strain gage with 120 Ω electrical resistances was attached at the mid-point of the CFRP strips to monitor the strain. During the test, the load was applied at a rate of 22 to 35 N/sec, and the readings from the strain gages and the LVDTs were collected every second. Cracks were monitored and marked at different load levels. The test was stopped at the failure load level which was indicated by a sudden and significant drop of the applied load.

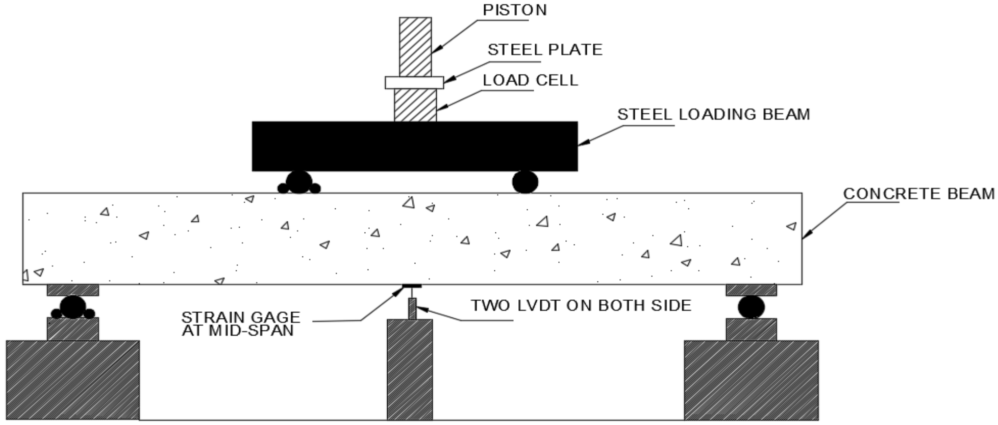


Fig.7. Test schematic

3. Results and Discussion

The average 28 day compressive strength, slump and equilibrium density for the concrete were found to be 28.9 MPa, 101mm and 1858 kg/m^3, respectively. This satisfies the specifications for LW concrete (ACI 213, 2014). The pair of two beams for each combination (Table 1) exhibited very close results. Hence, the test results discussed in the following sections represent the average of two beams from each category.

3.1 Load- Deflection Curves

Figure 8 shows the load-deflection curves for the strengthened and un-strengthened beams. The control beam showed ductile behavior before failure; it reached an ultimate load of 53.6 kN with the corresponding deflection of 29.7 mm. Except for the strengthened beam without anchorage, all other strengthened beams showed an increase in failure load as compared to the control beams, as shown in Table 4. This was due to the effectiveness of the proposed anchorage systems in delaying premature debonding. Previous investigations on NW reinforced concrete beams documented that an increase in flexural strength ranging from 10% to 160% can be obtained from FRP strengthening provided with various anchorage systems (Jumaat and Alam, 2008, Al-Saidy et al., 2010, Reed et al., 2005, Elsafty et. al., 2013).

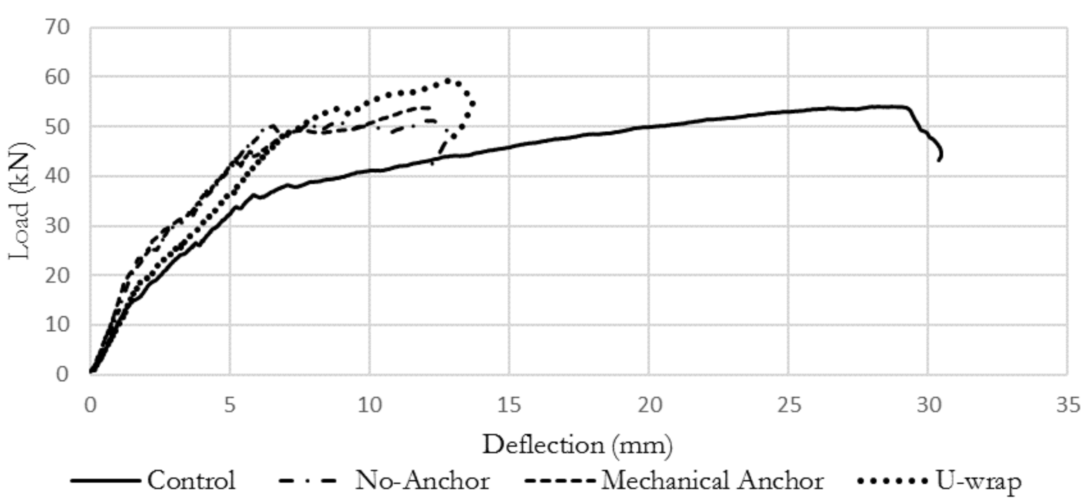


Fig.8. Load-deflection curves

Table 3. Summary of test results

Beams	Theoretical failure load, kN	Experimental failure load, kN	Maximum deflection, mm	Strength increase compared to control, %	Flexural CFRP strain at failure (micro strain)	Strain increase compared to un-anchored strengthened beams, %
B1-C, B2-C	51.9*	53.6	29.7	N/A	N/A	N/A
B3-N, B4-N	66.7**	51.4	12.7	-4.1	3000	N/A
B5-M, B6-M	66.7**	54.1	11.9	+1.0	3013	0.4
B7-U, B8-U	66.7**	60.1	12.2	+12.1	5455	81

* from ACI 318
** from ACI 440

The control beam's predicted failure load was 51.9 kN, as per the provisions of ACI 318 (2014), a 3% deviation from the experimental result. For all three strengthened beams, the identical theoretically predicted ultimate load carrying capacity was 66.7 kN, as per the provisions of ACI 440 (2008). This is due to the fact that ACI 440provisions do not currently recognize any anchorage effects on the contribution of flexural FRP wrapping on concrete member capacity. However, the experimental results showed different magnitudes of failure loads depending on the type of anchorage system utilized. The strengthened beams with no anchorage, mechanical anchorage, and U-wrap anchorage failed at loads of 51.4 kN, 54.1 kN and 60.1 kN, respectively. Table 5 presents the stiffness of each beam, defined herein as the slope of the linear elastic portion of the load–deflection curve (Shannag et al., 2012).All the strengthened beams experienced an increase in stiffness compared to the control beams.

Table 4. Stiffness comparison

Beams	Relative elastic stiffness (kN/mm)	Stiffness increase compared to control, %
B1-C, B2-C	10.6	NA
B3-N, B-4N	13.3	24.9
B5-M, B6-M	15.9	49.9
B7-U, B8-U	10.8	1.3

3.2 Effect of Anchor Type

As shown in Fig. 8 and Fig. 9, the load versus deflection and the load versus strain curves for each beam are unique. This is due to the variation in the relative efficiency of each anchorage system. Anchor bolts increased the load at failure by only 1% as compared to the control beams, and it increased the CFRP debonding strain by only 0.4%, as compared to the strengthened beams without anchorage. However, the U-wraps resulted in 12% increase in failure load as compared to the control beams and 81% increase in CFRP debonding strains compared to the strengthened beams with no anchorage. It is apparent that U-wrap anchorage was effective in confining concrete at the CFRP termination points and helped in delaying cracking and thereby increasing ductility. This finding agrees with previously conducted research on both lightweight and normal weight concrete where U-wraps were used as an anchorage for the flexural CFRP layer (Shannag et al., 2012, Elsafty et. al., 2013).

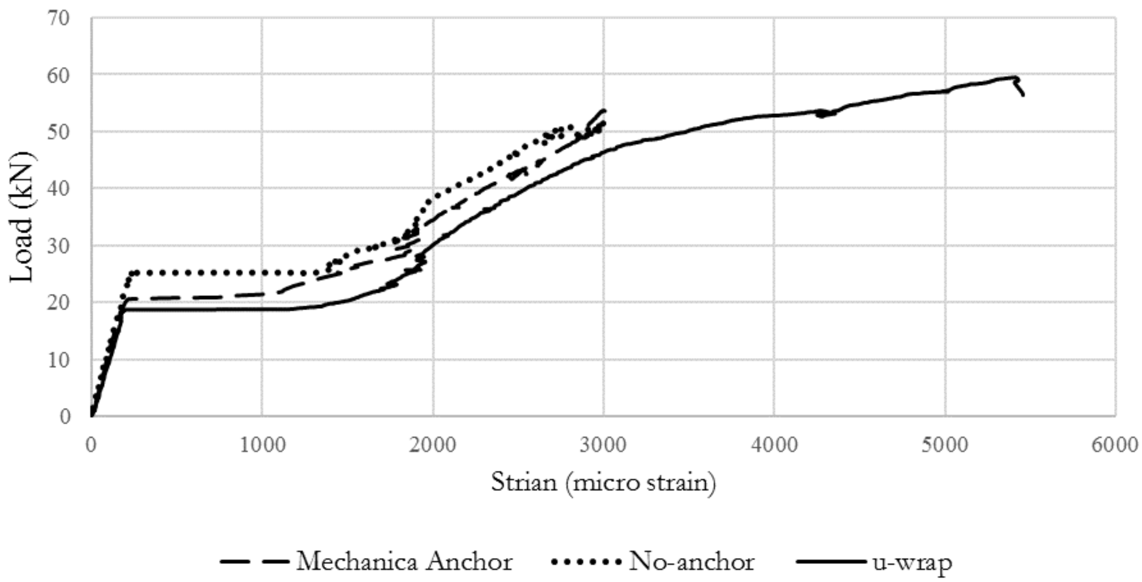
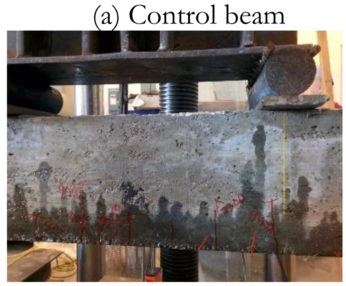


Fig.9. Applied load versus strain

3.3 Crack Patterns

The control beams experienced widely spaced cracks with approximate equal spacing within the central constant moment area, while the strengthened beams experienced small closely spaced cracks, as shown in Fig. 10. This improvement in crack width and crack distribution was the result of concrete confinement by the CFRP. It was also observed that there was no difference in crack width or crack spacing among the strengthened beams with anchorage systems. The enhanced crack patterns may increase the resistance to chloride ion and moisture intrusion, and resulting steel rebar corrosion, adding to the long-term durability. Previous similar study on CFRP strengthened lightweight concrete beams showed closely spaced and small cracks (Shannag et al., 2012), and no similar comparison to NW concrete was located during the background review.

(a) Control beam



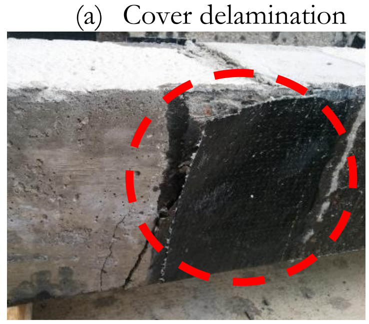
(b) Strengthened beam

Fig.10. Crack patterns

Failure Modes

The strengthened beams with no anchorage and mechanical anchorage failed by concrete cover delimitation as shown in Fig 11(a), while the one with U-wraps failed by debonding of the anchorage [Fig. 11 (b)] followed by debonding of the longitudinal CFRP. However, ACI 440 does not recognize debonding of U-wrap anchorage as a possible failure mode. The predicted failure mode for all strengthened beams as per ACI 440 was yielding of the steel reinforcement followed by rupture of the flexural CFRP layer. However, the normal stresses developed at the ends of the CFRP and the shear/flexural cracks caused cover delimitation and debonding of the CFRP before the longitudinal CFRP rupture strain was achieved. A majority of previously conducted research on CFRP strengthened beam also showed intermediate flexural crack-induced interfacial debonding of CFRP as a prevalent failure mode for both NW and LW concrete (Reed et al., 2005, Teng et. al., 2003, Shannag et al., 2012).

(a) Cover delamination



(b) U-wrap debonding

Fig.11. Failure modes for strengthened beams

4. Conclusions

The following conclusions and recommendations may be made based on the results of this study: Lightweight RC beams strengthened with a flexural CFRP layer and provided with anchorage systems exhibited an enhancement in flexural capacity, as compared to control beams without any flexural CFRP application. The capacity enhancement can vary based on the type of anchorage system used to confine the flexural CFRP laminate. U-wrap anchorage was found to be significantly more efficient in the strength enhancement with up to 12% additional contribution, as compared to un-strengthened beams. Providing anchorage at the termination point of the flexural CFRP improves the FRP-concrete bond by delaying premature failure of the CFRP for LW concrete beams. This is demonstrated by the fact that U-wrap anchorage enhanced the failure tensile strain in the flexural CFRP by 81%, again demonstrating the superior effectiveness of this type of anchorage. The relative elastic stiffness can be increased by up to 50% due to the addition of flexural CFRP in LW concrete beams with mechanical anchorages.

Without any anchorage, the stiffness can increase up to 25% due to the stiffening effect of the flexural CFRP. CFRP flexural strengthening results in shorter, narrower and more closely spaced flexural cracks in LW concrete beams, as compared to un-strengthened beams. The anchorage system does not affect the crack characteristics in such beams. The enhanced crack patterns may increase the resistance to chloride ion and moisture intrusion, and resulting steel rebar corrosion, adding to the long-term durability.

The CFRP strengthened beams failed either by cover delamination or debonding of the U-wrap, with no tensile rupture in the flexural CFRP laminate. This is due to the formation of shear/flexural cracks that prevented the CFRP from utilizing its full tensile capacity.

This contradicts the theoretical predicted failure mode of yielding of the tension steel reinforcement from ACI guidelines, followed by the tensile rupture of the CFRP laminate. This observation is in line with the findings from a majority of the previous studies. Debonding of U-wraps is also not among the failure modes specified in ACI guidelines. Currently available FRP design guidelines, including ACI 440, do not consider the effect of various anchorage systems in the flexural design of CFRP strengthened beams. However, the results from this study and other relevant studies on LW and NW concrete beams show the beneficial effect of anchorage confinement and would enhance the flexural design provisions. The current study involved small specimens and wet layup CFRP application procedure. Additional investigation with full-scale members, other patterns of anchorage configuration and FRP types is needed to refine the results from this study.

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