STRENGTHENING OF LIGHTWEIGHT REINFORCED CONCRETE BEAMS USING

CARBON FIBER REINFORCED POLYMERS (CFRP)

By

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Yes, you can see my name in front of these pages but this is not just my hard work this is a passion and a corporation of many great people who was with me from the first day I start working until this moment.

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My wife for all these night that she was awake for me , for every single step you were with me , thank you from my heart .

Sometime our life is for risking and everything for our dreams no one can see them except you.

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Abstract

STRENGTHENING OF LIGHT WEIGHT CONCRETE BEAMS BY USING

FIBER REINFORCED POLYMERS (FRP)

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This research aimed to investigate the effect of utilizing "Fiber Reinforced Polymer" (FRP) on the light weight concrete beams. The main hypothesis is that such utilization of the FRP will lead to strengthened lightweight beams. The research that has been done on this relationship is somewhat broad in the scope and have mostly focused on the normal-weight concrete. However, only few studies that have considered the light weight concrete. Eight Beams were tested in this research under four point bending test. Two beams were taken as a control beams without any external bonding of Carbon Fiber Reinforced polymer. Another two beams strengthened with external CFRP sheet bonded with epoxy only. Next two beams strengthened same as the previous two but anchored to the concrete by Mechanical Fixation which is anchor bolt. Two of the beams strengthened with CFRP sheet at tension face on the bottom and CFRP sheet as U-wrap at the ends to increase the anchorage to the concrete. The theoretical value for the strengthened beam was calculated according to ACI 440 and compared to the experimental value from the test. Four point flexural load test was considered in this research. Test result showed an increase in the strength of the strengthened beam compared to the control beam, while the deflections for strengthened beams were decreased. Strengthened with CFRP sheet using u-wrap anchor was the most effective

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system for strength enhancement which was 12% with respect to control beam. However the ductility of the beam was reduced significantly.

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Chapter 1: Introduction

1.1 Background

Bridges in the United States found to be at grade C+. In the last decade, huge effort and fund spent on the repairing of the infrastructure including bridges (ASCE'S Report 2013 Edition). Bridges can be deteriorated due to many factors: age, high loads, collision. More research is needed in order to find new techniques to repair the bridges. Searching for new technique to repair the old bridges is very important due to the high cost to create new bridges instead of old bridges.

There are many method to repair deteriorated concrete: steel plate, enlarge element, external post tensioning, and Fiber reinforced polymers (Zamin, Jumat and Alam 2007). In this research FRP is discussed due to many reason: weight to strength ratio, environmental impact, preventing corrosion, and less labor cost. FRP can be used to strengthen the structural element, Also Flexural, shear and durability can be improved by using FRP (ACI Committee 440R, 2007). Many researchers have studied the strengthening of normal concrete, however, a little research studies on the strengthening of lightweight concrete.

Lightweight concrete is made mainly using lightweight aggregate, the compressive strength after 28 days should be more than 17 MPa (2500 psi). Lightweight concrete is a useful construction building material, since it reduces the weight of the members by 20-40 % comparing to normal concrete. There are two types of lightweight: all-lightweight concrete which the fine and coarse aggregate used from lightweight, and sand-lightweight concrete which the normal weight sand used in the concrete and lightweight coarse aggregate (ACI Committee 211, 1998). Using of lightweight concrete in the building helps to decrease the weight of building which help to:

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1- Reduce the size of the element members.

2- Decrease the dimension of the foundation.

3- Decrease the required reinforcement.

4- Increase fire protection.

Recently, lightweight concrete has been used in hundreds of bridges especially decks, girder and piers. Using lightweight in girders allows the designer to use long span and small foundation due to decrease the dead load of the superstructure. In multi-story building, using lightweight concrete helps to reduce the dead load of the building (ACI Committee 213, 2003).

1.2 Research Objectives

The objective of this research is to study the strengthening of lightweight concrete beams using Fiber reinforced polymer. In this research, three types of anchorage were discussed: (1) without anchorage, (2) Anchor bolt, and (3) U-Wrap. In most cases, the failure of beams strengthened with FRP is due to debonding of the FRP sheet from the concrete. Anil and Belgin mentioned that the using of anchorage to the FRP could postponed the debonding of the FRP sheet from the concrete surface. A lightweight reinforced concrete beams will be tested with and without FRP strengthening. The samples was reinforced with low percent of steel in order to focus on the FRP strengthening.

Chapter 2: Literature Review

2.1 Fiber-Reinforced Polymers (FRP)

Fiber-Reinforced Polymer (FRP) is a composite material prepared from a resin matrix reinforced with fibers. The fibers are usually carbon, glass, or aramid. Matrix are usually epoxies, polystyrene, vinylesters, or phenolic. The fiber helps to provide strength and stiffness to the FRP system, whereas the matrix helps to bond the fiber and to transfer the load in the FRP system by shear stress between Fibers (ACI Committee 440R, 2007).

2.1.1 History of Fiber Reinforced Polymer

The first introduced of FRP product was a boat hull manufactured in the mid-1930s using a fiberglass fabric and polyester resin laid in a mold (ACI Committee 440R, 2007). Since then, FRP composite applications have been used in many areas: aerospace, marine, electrical, and transportation. Since 1940s, FRP composite materials have been used in the defense industry, especially for use in aerospace and naval applications. Due to the advantages of FRP composite especially the corrosion resistance, Public sector starts to use Fiber glass composite in oil industries.

Since the early 1950s, FRP composite has been used for equipment in the chemical, power, waste treatment, and metal refining. In the mid-1950s, FRP composite products were introduced to reinforced concrete structures. In the 1980s, a new developments of using FRP as a construction material were announced to use FRP reinforced bars in the concrete with special needed such as nonmagnetic properties or sever chemical attack. In 1986, the first highway bridge was built in Germany using composite reinforcing tendon. The fist FRP-reinforced concrete bridge deck was built in 1996 at Mckinleyville, West Virginia (ACI Committee 440R, 2007).

2.1.2 Fiber Reinforced Polymer Advantages.

FRP system can be defined as fiber and resin combined to form laminate where the resin used to bond the FRP to the concrete substrate. FRP material have many advantages: lightweight, noncorrosive, and have high tensile strength. These materials are existing in many form, it can be factory-made laminates or dry fiber sheet which can be wrapped to any irregular shape of structure before applying the Epoxy. Also the thin profile section of the FRP is desired in the structures applications for aesthetics concern. Strengthening with FRP system can be effective where limited access available and other traditional method would be hard to apply (ACI Committee 440R, 2007).

2.1.3 Fiber Reinforcement Polymers Projects.

One of the application of the FRP is to strengthening and retrofitting the old building by using external FRP composite. This process is simple, rapid, and effective to increase the flexural and shear capacity of the building. Many projects have been strengthened by externally FRP composite. Ibach Bridge was the first bridge strengthened with CFRP, the retrofitting process by using 2 mm (0.0787 inch) thick, and 150 mm (5.9 inch) wide CFRP laminate on the web of the box girders. Another bridge that strengthened with CFRP external layer is Boon County Bridges, this bridge was strengthened to increase the capacity of flexural and shear strength (Park, Roberston, and Rigges 2002).

2.2 Structural Lightweight-Aggregate Concrete

Lightweight concrete is made with lightweight aggregate conforming to ASTM C330, has an equilibrium weight up to 1842 Kg/m^3 (115 lb/ft^3), and has a compressive strength more than 17 MPa (2500 psi) at 28 days (ACI Committee 211, 1998). ACI 213R-

03 specify the equilibrium density between 1120-1920 kg/m^3 (70 -120 lb/ft^3), but most project using lightweight concrete with densities of 1681-1920 Kg/m^3 (105-120 lb/ft^3). Structural lightweight concrete is lighter than normal weight concrete by 25-35 percent (Thomas, Holm, and John 2001). The lightweight concrete consider as the best choice comparing to normal weight concrete. Shelby Creek Bridge in Kentucky assumes as an example of lightweight concrete success where 48 Mpa (7000 psi) compressive strength was achieved with a density of less than 2080 kg/m^3 (130 pcf) (Thomas et al. 2001).

2.2.1 History of Structural lightweight Concrete

The first use of lightweight concrete was before 200 years. Many of the old structure found in the Mediterranean region. The most famous buildings were built during the early Roman Empire include the Port of Cosa built in about 273 B.C from the natural volcanic materials, the pantheon Dome in 27 B.C , and the Coliseum which built in 75 to 80 A.D. by using crushed volcanic lava in the foundation. In 1928, the Commercial production of expanded slag began, and in 1948 the first production of lightweight aggregate for the structural purposes was produced using shale in eastern Pennsylvania (ACI Committee 211, 1998). In the early 1950s, Lightweight-aggregate concrete used in many structural building includes Building Frames, bridge decks, and precast products. Several multistory building were built using lightweight during 1950s. The 42-story Prudential life Building in Chicago and the 18-story Statler Hilton Hotel in Dallas were designed with a Lightweight concrete Floors. In 1980s, research started to produce high-strength lightweight concrete, with the result produced in 1992. This research allowed to use lightweight concrete in the areas where high strength and high durability required (ACI Committee 211, 2003).

2.2.2 Structural Lightweight Concrete Advantages.

The lightweight concrete is lighter than Normal weight concrete by 20 – 40%, this may help to make save in the reinforcement and prestressed steel; transportation of precast element; reduced formwork for in site construction; and reduced the size of foundations as mentioned in the guide to use of lightweight aggregate concrete in the bridge. Many of other benefit can be drawn from lightweight concrete as reduced of inertial seismic load; manufacture large and long precast element without increases in insulation because of the porosity in the aggregate (ACI Committee 213, 2003). Another advantage of porosity in the lightweight is the internal curing which means that the soaked aggregate provide source of curing for hydration process. This advantage help to increase the strength and durability with the time (CIP 36 structure lightweight concrete, 2003).

2.2.3 Lightweight Concrete Projects.

Lightweight Concrete used in many structures all over the world since 1950s, because of its advantages. In North American precast and prestressed concrete producer have used high-strength lightweight for four decades. Lightweight concrete has been used in parking garage floor with double tees 15- 18m (50-60 ft.). Due to the reduction in the weight of the precast element, the transportation and handling of the precast members are easier (Harmon; NCBC 2010).

Some projects are shown in Figure 1, Figure 2, and Figure 3.

Figure 1: Strengthening of Piles using FRP

Figure 2: Strengthening of Steel Bridge

Figure 3: V-Wrap composite sheeting

2.3 Deterioration of Reinforced Concrete Building

The first used concrete is Roman who used a combination of lime , pozzolan, rubble and water , in 19th century The binder used in the combine derived from baking earth created from clay and sedimentary rock, at temperatures of up to 1500 ° C, to make clinker pellets. Once mixed with appropriate grinding additives and so ground up, it took the name of Portland cement, as a result of its likeness to Portland stone Concrete utilized in the trendy area and may be a mixture of water, cement, aggregates and, where required, admixtures (plasticizers, super-plasticizer) that modify its physics, properties, and performance characteristics (Technical Manual of MAPEI, 2011).

This material does not appear to own any weak points in terms of sturdiness, is formed with products that are promptly accessible, encompasses a comparatively low price, is straightforward to use, etc. However, this is partly true as an example, concrete has wonderful compressive strength, but poor tensile strength. This can be why it is strengthened with steel rods to beat this disadvantage, but which successively bring

about to alternative issues, as are going to be illustrated later (Technical Manual of MAPEI, 2011).

Another basic limitation of concrete is that it's terribly sensitive to the conditions within which it's mixed and applied. These conditions might vary staggeringly, therefore inflicting different kinds of issues. There are variety of variables that have a bearing on the standard of the merchandise, and therefore the lack of attention paid to those variables makes the concrete a lot of vulnerable. In recent years, the ever-increasing want for maintenance and repair interventions on structures has determined a decisive modification in what proportion is spent for repair operations, compared with what proportion is spent for building new construction (Technical Manual of MAPEI, 2011).

What is a lot of the continual increase of building prices nearly always makes repair operations economically a lot of viable, although deterioration of the structure is at a complicated stage. Even if concrete is well created, if it's put in an aggressive setting, sooner or later defects which outline the deterioration will seem.

Portland cement association (2002) describe the reason for deterioration could also be divided into four main sections: Chemical, Physical, Mechanical, Defects. All these four sections are related to each other in a way or another. In the following section, more details are illustrated.

2.3.1 Aggression from chemicals

This Aggression type can be divided into:

- Aggression by carbon dioxide
- Aggression by sulfate
- Aggression by chlorides
- Alkali-aggregates reaction

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Aggression by carbon dioxide

Figure 4: Aggression by chloride

Aggression as a result carbon dioxide is also manifested in two alternative ways in keeping with the encircling conditions. In constructions exposed to the atmosphere, carbonation of concrete takes place, while in hydraulic constructions, there's associate occurrence called leach that acts upon the cementitious paste. Carbonization is as a result of the penetration of carbon dioxide into the concrete.

2.3.2 Aggression by physical elements

- Freezing and thawing
- High temperatures
- Shrinkage and cracking

Freezing and thawing

Figure 5: Freezing and thawing

The result of ice is negative only within the case of the presence of water at its liquid state within the concrete. This doesn't essentially mean that the concrete should be absolutely dry, however the amount of humidity should not be more than a determined level, called "critical saturation".

2.3.3 Aggression by mechanical elements

- Abrasion

- Impact

- Erosion

- Cavitation

Figure 6: Abrasion

If a material is hitting by particles from a tougher body, abrasion takes place. This is due to the friction that the tougher powder particles exercise on the surface of the material. It is therefore quite clear that abrasion depends directly on the characteristics of the materials that make up the concrete. As a result, we are able to improve resistance to abrasion by reducing the water/cement ratio or by sprinkling cement mixed with hard admixes and aggregates on the surface of the concrete.

2.3.4 Defects

Figure 7: Concrete Defect

Concrete it is mixture of variety of components. The method it's prepared depends on every project's single requirements; the higher the necessities, the more delicate the look of the mix are going to be. The main elements are cement, aggregates, water and admixtures. If any of these components are used incorrectly, one or a lot of weak points within the concrete may develop.

2.4 Method for strengthening Existing Structures.

One of the most widely used building material is concrete because of its low cost, ease in production and durability. Reinforced Concrete elements designed to hold a specific type of loads, but due to many factors the capacity of the elements are reduced. The main factor that affect the capacity of structural members and cause deterioration is the corrosion. When steel corrode in the structural members, the produced rust expanded to fill a greater volume which lead to increase the tensile forces in the concrete. This tensile forces cause cracking, delamination, and spalling as shown in Figure 8. Many reinforced concrete elements like beams and column need to be upgraded and strengthened in order to increase the load capacity (Zamin, Jumaat, and bin Alam 2007).

Figure 8: Corrosion

There are many cases where the building need to be strengthened such as: overloading, under-design of the existing structural members, manufacture error. Replacing the structure is not the best solution to increase the capacity of the building due to the high cost and environmental impact. In order to meet the new requirement for the building, existing structure can be repaired and strengthened. Many methods are available to strengthened or repair old structure. These methods include Ferrocement, Steel plates, and fiber reinforced polymer (Zamin et al. 2007; Shabeeb, Al-Akhrass, Shannag, and Alfendi 2011).

2.4.1 Ferrocement Laminates.

This method used to strengthen the old structure by reinforced the cement mortar with small diameter of wire mesh. The layer of ferrocement has higher tensile strength, toughness, ductility, durability, and cracking resistance. Ferrocement is used to repair the retaining structure which used below water table, such as sewer lines, tunnels, and pools. It is also used to strengthen the element to increase flexural and shear capacity by casting ferrocement on the tension face of the element (Zamin et al. 2007).

2.4.2 Strengthening using Steel Plate

Steel Plate is one of the most popular method to strengthen the concrete Beams. It is very efficient method to increase the flexural and shear strength for the concrete structures. Using steel plate to strengthen reinforced concrete element is widespread because of its availability, cheapness, easy to work, high ductility, and high fatigue strength. The most important part during execute this method is to prepare the concrete surface properly and the bonding agent between the concrete surface and the steel plate (Zamin et al. 2007).

2.4.3 Strengthening with External Post-Tensioning

Post-tensioning tendons provide an economical techniques for strengthening existing deteriorated structures (Krauser 2006). External tendons can be easily be used in the structures to apply vertical forces at the needed points as shown I figure 9;

Figure 9: External Post-tensioning

2.4.4 Strengthening using Fiber Reinforced Polymer (FRP)

Fiber Reinforced Polymer (FRP) method for strengthening concrete structures is a vital alternative to other traditional strengthening methods, such as steel plate, Ferrocement, and external post tensioning. This method use FRP composite sheet to strengthen the element externally. FRP systems have many advantages over traditional method for strengthening: it is lightweight, easy to install, noncorrosive. FRP method can be used to repair or restore the strength of an existing building.

FRP systems are applied in three forms: wet layup system where the saturation of the resin on the FRP will be cured on the site, and pre-preg system where the system prepared in factory by preimpregnated the Fiber sheet with a saturated resin and cured in place, and pre-cured system where the fiber saturated with resin and cured in factory then applied to the surface (ACI Committee 440R, 2008).

The efficiency of the external strengthening by FRP can be increased by using anchorage system. There are many anchorage system can be used to increase the bonding between the FRP and the concrete (Grelle and Sneed 2013). Using anchorage system helps to prevent or delay the debonding of the FRP layer so the maximum usage of the FRP is obtained (Anil and Belgin 2010).

Chapter 3: Procedure

3.1 Introduction

This experiment purpose to examine the feasibility of using different type of anchorages systems to increase the bond of FRP layers applied to strengthen lightweight concrete beams in flexure. Details of the specimen design, experimental design, test setup, and test procedure are described in the following parts.

3.2 Test Program

In this experiment eight Lightweight Reinforced Concrete were tested. The experiment were designed to strengthen under reinforced Lightweight concrete beams by using CFRP sheet. The beams in this experiment were 152.4mm wide x 203.2 mm deep x 1575 mm long (6 inch wide x 8 inch deep by 62 inch long). The flexural reinforcement steel consisted of 2#3 bars on the bottom side. The top reinforcement steel consisted of 2#3 bars. The shear reinforcement consisted stirrups size #3 and spaced 6 inch center-center in the middle 304.8 mm (12 inch) portion of the beams and 76 mm (3 inch) center to center on the rest of the beams. The cover on the bottom side was 1.5 inch, but the cover on top and sides were 25.4 mm (1 inch). Beams details are shown in Figure 10. Two Beams were considered as control beams, whereas the other 6 beams were strengthened by carbon fiber reinforced polymer using three different anchorage systems as shown in Figure 11.
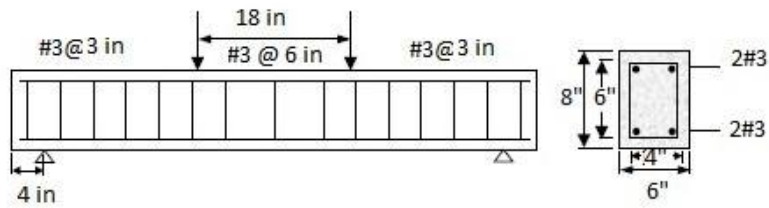
Figure 10: Reinforcement Details
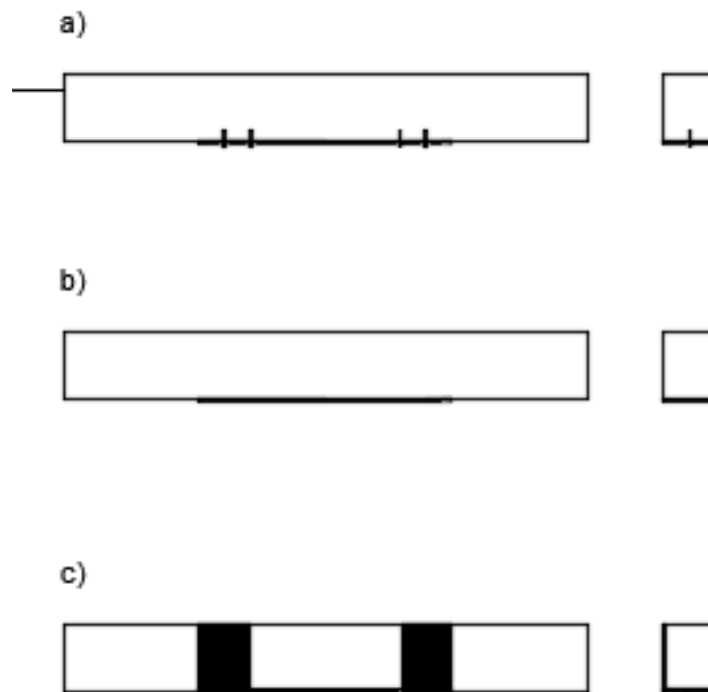
Figure 11: Types of Anchorage (a) Anchor Bolt, (b) Without Anchorage, (c) U-Wrap

All specimen were casted with lightweight concrete with maximum coarse aggregate size of 9.5 mm (3/8 inch) and the average compressive strength after 28 days was 28.9 MPa (4200 psi). The reinforcement used in this experiment had a yield strength of 413 MPa (60,000 psi)

The designation of beams is tabulated in the Table (3-1).

Table 1 The designation of beams

Name	Beam designation	Number of Beams	Description	Anchorage Type
Control	B1	2	Control	None
Without Anchorage	B2	2	Only Epoxy to bond the FRP to Concrete surface.	
Anchor Bolt	B3	2	The far ends of FRP are fixed with Steel Bolt	Mechanical Fixation
U-wrap	B4	2	At the both ends, U-wrap was used.	U-wrap

The FRP system used is FRP sheet for flexural strengthening of the beams. The CFRP material was Sikawrap 117c. It installed onto the tension side of the beams with the orientation of fibers in the longitudinal direction of the beam. The dimensions of FRP sheets were 152.4 mm (6 inch) wide and 762 mm (30 inch) length along. Three different type of anchoring were used: Without anchorage where the epoxy (sikadure 300) was used to bond the FRP layer on the concrete surface. Other type of anchoring was u-wrap, in addition to epoxy bonding the CFRP sheet used on perpendicular direction to longitudinal direction of the beam. The last type of anchoring was Mechanical Fixation

system where the bonding of FRP to concrete increased by adding steel bolt on each end of the FRP layer.

3.3 Lightweight concrete

Lightweight concrete with maximum coarse aggregate size of 9.5 mm (3/8 inch), the lightweight aggregate used Streetman aggregate from Expanded Shale, Clay and Slate Institute (ESCSI) as shown in Figure 12.

Figure 12: Streetman lightweight aggregate 3/8 inch.

The others ingredients for lightweight concrete were: sand, cement type I/II, and water.

Standard Practice for Selecting Proportions for Structural Lightweight Concrete (ACI 211.2-98) was used to determine the first trial mix for the lightweight concrete. The slump needed in this experiment was 76.2-101.6 mm (3-4 inch). The target compressive strength was 27.6 MPa (4000 psi). The mix design is shown in the table (3-2).

Table 2 Concrete Mix quantities

Ingredient	Weight in (lb /yd^3)
Cement	600
Water	240
Sand	1340
3/8" Streetman Lightweight aggregate	930

3.3.1 Concrete mixing

It is important to specify the absorption percent of the ingredient in the concrete, but lightweight aggregate is vary in the amount of absorbed water. Lightweight manufacturer recommend to sprinkle lightweight before using in the mix to keep the amount of water using in the mix without any loss (Harding, M. 1995). To reach saturated-surface dry condition for the lightweight aggregate, it is recommended to soak the lightweight aggregate in the tub for 2 days minimum to make sure that all pores are filled with water as shown in Figure 12, after that remove water from the tub to allow the lightweight aggregate to dry in the open area for 30 minutes (Heffington, 2000).

Figure 13: Soaking of Lightweight Aggregate

Sand, water, cement, and lightweight aggregate are weighted out in the bucket. The aggregate was saturated-surface dry, so no adjustment in the amount of water needed. The concrete mix ingredient were added to the mixer starting with the lightweight followed by the sand, these two ingredient were mixed thoroughly together in the mixer. After these two the cement was added. Again the mixer was mixing the quant to get appropriate mix. After making the mix uniform, half quantity of water was added and turn the mixer until there is no free water in the mix. The rest amount of water was added gradually to get the desired mix.

After 3-5 minute of mixing, the concrete mix was discharged in the wheelbarrow. The slump test was done in accordance with ASTM standards as shown in Figure 14.

The mixer in UTA Lab as shown in Figure 15 was the one used in this experiment.

Figure 14: Slump Test

Figure 15: Concrete Mixer

3.3.2 Determination of concrete properties

After finishing mixing of the concrete, the properties of the fresh concrete were determined. The first property is slump which is done according to C143/143M and find to be 101-127 mm (4-5 inch). Another property need to be checked is the fresh density according to ASTM C138/138M. The last property which is important in case of lightweight is equilibrium density of the lightweight concrete is 1858 kg/m^3 (116 lb/ft^3) according to ASTM C567.

3.4 FRP Application

3.4.1 FRP properties

The FRP used in this experiment was CFRP from Sika. SikaWrap Hex 117c is a unidirectional carbon fiber fabric. This material is used to strengthen structural element by filled laminated using either Sikadur 300 or Sikadure 330 epoxy to form CFRP.

Figure 16: SikaWrap 117C

Table 3 SikaWrap 117C Typical Data Sheet

Cured laminate properties	Design Values
Tensile strength	1.05×10^5 psi (724 Mpa)
Modulus of Elasticity	8.2×10^6 psi (56,500 Mpa)
Elongation at Break	1.0%
Thickness	0.02 inch (0.51 mm)
Width	12 inch (304.5 mm)

3.4.2 Epoxy Properties

In this experiment, Sikadure 300 (high-modulus, high strength, impregnating resin) was used. Sikadure 300 is a two-component 100% solids, moisture-tolerant, high modulus epoxy. It can be used as an impregnating with SikaWrap structural strengthening system. Sikadure 300 is used as a seal coat and impregnating resin for horizontal and vertical application.

Figure 17: Sikadure 300

Table 4 Sikadure 300 Typical Data

Properties	Design Values
Tensile strength	8,000 psi (55 Mpa)
Tensile modulus	2.5×10^5 psi (1,724 Mpa)
Elongation at Break	3%
Flexural Strength	11,500 psi (79 Mpa)
Flexural Modulus	5×10^5 psi (3,450 Mpa)

3.4.3 Surface preparation

The most important thing during the FRP application process is the surface preparation. To prepare the concrete surface according to Sika recommendation many steps should be followed. Surface should be clean and sound. Remove dust, laitance,

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curing compound, and any foreign particle. Small chipping machine was used to remove any loose layer of concrete to open the texture as shown in Figure 18. After roughening the surface, Air pressure and brush were used to remove any dust remaining on the surface as shown in the Figure 19.

Figure 18: Surface preparation

Figure 19: Profile roughness

3.4.4 FRP installation

After preparing the surface to be ready for FRP installation. Specify the desired dimension for the FRP and make the lines on the concrete surface. Cut the FRP sheet to the specific length which is 762 mm (30 inch) length and152.4 mm (6 inch) width as shown in Figure 20. Then prepare Epoxy by adding Sikadure 300 part B to Sikadure 300 part A and mix it thoroughly for 5 minutes as recommended in the manufacturer instructions.

Wet lay-up method is applied in this experiment. Special epoxy roller is used to apply the epoxy on the area where the FRP is needed. Apply the epoxy on the FRP on both sides as shown in Figure 21. Then FRP is installed on the bottom sides of the beams, and roller used to remove all voids underneath the FRP layer as shown in Figure 22. Another layer of epoxy was painted on the top of FRP.

Figure 20: Prepare of FRP

Figure 21: Saturate the FRP sheet

Figure 22: FRP application

3.4.5 Fix the Anchorages.

Three type of anchorage investigated in this experiment. The first on is the anchor bolt, Two steel anchor bolt were used on each side to increase the bonding between FRP and concrete. This anchorage prevent the debonding of the FRP. Holes were drilled in the concrete with 2 inch depth, the hole was cleaned by air pressure in the

hole to remove all dust. Steel anchor was inserted in the hole to cross the FRP and then washer and bolt fixed tightly to prevent FRP from deboning as shown if Figure 23.
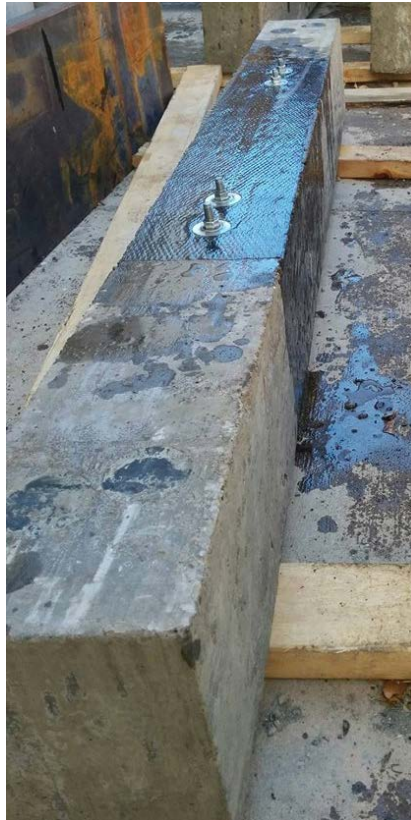
Figure 23 Anchor bolt

Another type of anchorage was u-wrap. This type of anchorage was installed to increase the bonding between FRP and concrete. U-wrap were applied on both ends of the FRP on the tension side which act as bonding force to the FRP and concrete beneath it (Grelle and Sneed 2013). The fiber direction in the u-wrap should be perpendicular to the longitudinal direction of the beams as shown in Figure 24.

Figure 24 U-Wrap Anchorage

3.5 Strain Gages

In this experiment, only one strain gauge was used for each beam. Strain gauges is a sensor whose resistance differs with applied force, it is used to measure strain in any element. The strain gauge used in this experiment was PFL-30-11 from Tokyo Company. Figure 25 shows the strain gauge.

Figure 25 Strain gauge

3.6 Linear varying differential transformer (LVDY's)

LVDT is a type of electrical transformer used for measuring linear displacement and deflection. In this experiment, two LVDT's were used for each beam to measure the deflection at mid-point of the beam as shown in Figure 26 and Figure 27.
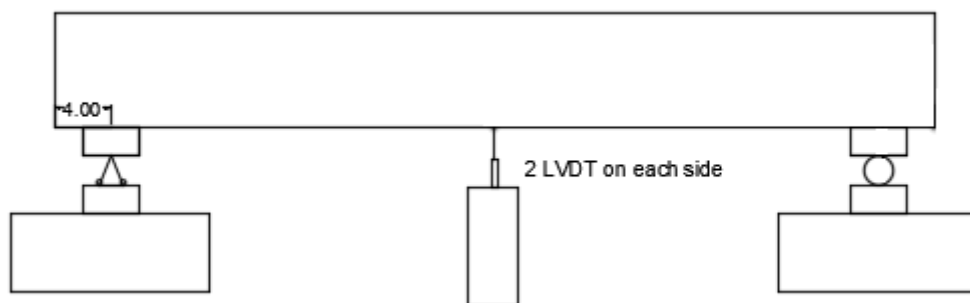

Figure 26 LVDT

Figure 27 LVDT Layout

3.7 Experimental setup

Four point loading was considered to test the beams and to determine the load-deflection relationship. Two support were used in each side of the beams. One end is hinged support and the other is roller. All supports were used from thick steel to prevent any deflection at the support. The same procedure done on the top of the beams to act as two point load.

On top of the loading beam load cell was setting and adjusted to be at the center of the loading beam. Load cell used to collect the actual load that the hydraulic testing machine provides, as shown in Figure 28. In this experiment 400 kips machine was used for the first 7 beams, but the last beam was tested using 60 kips machine. A pure bending moment was existed within a middle part of the beam. All beam were tested under constant rate of loading. The data was collected one data per second from the strain gages and LVDT's.

Figure 28 Test setup
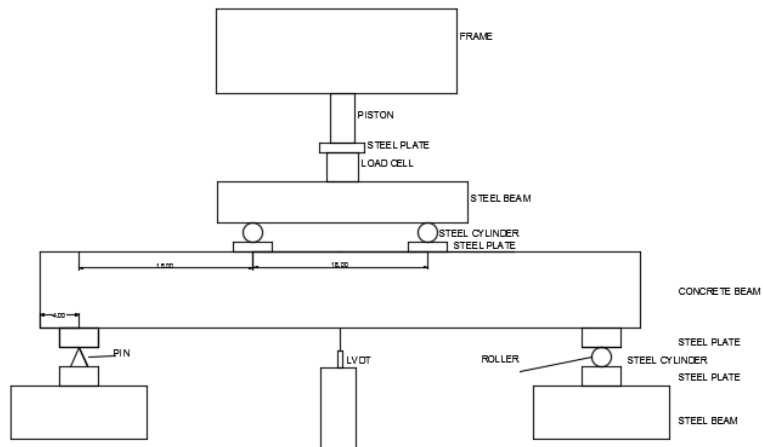
Figure 29 Test setup

Figure 30 Test Setup Drawing

Chapter 4: Preliminary analysis

Design calculations were performed in order to find the design values for the

unstrengthen beams and for the strengthen beams.

4.1 Un-strengthened beams design

Flexural design was performed using ACI 318-14 to calculate the design moment

for the un-strengthened beams. The compressive strength used was 4200 psi () and the

yield strength for the steel was 414 MPa (60,000 psi).

All beams were reinforced with 2#3 bar for flexural reinforcement and #3 @ 3

inch c/c for the shear reinforcement. The moment capacity for the un-strengthened beam

is found to be 9.23 kN-m (81.7 kips-in) and the maximum load was 51.9 KN (11.67

kips).the detailed design is in the appendix (A).

4.2 Strengthen beams design

Flexural design was performed using ACI 440 to calculate the design moment for

the strengthened beams. The reinforcement used in the strengthened beams is the same

reinforcement used in the control beams. The CFRP's used in this experiment were from

Sika Corporation. Sikawrap 117C and Sikadure 300 were used to strengthen the

lightweight concrete beams in flexure. The nominal moment capacity for the strengthened

beam is 15.25 kN-m (134.970 kips.in) and the maximum load was 66.7 kN (15 kips). See

appendix B for more details.

Chapter 5: Crack pattern and failure modes

5.1 Crack Pattern

The control beam experienced widely spaced cracks with equal spacing within

the constant moment area, whereas, the strengthened beams experienced closed

spacing cracks with small size. This improvement in the cracks width comes from the

confining of concrete by CFRP as shown in Figures 31-34.

Figure 31 Crack pattern for control

Figure 32 Crack pattern for Beam Strengthened without anchorage

Figure 33 Crack pattern for Strengthened beam with anchor bolt

Figure 34 Crack pattern for strengthened beam with U-Wrap

5.2 Failure Mode

The control beams failed by yielding of the steel followed by crushing of the concrete as shown in Figure 35. The strengthened beams using FRP and without anchorage failed by cover delamination as shown in Figure 36. The failure of beams strengthened by anchor bolt failed by cover delamination. Only beams that anchored by u-wrap were failed by debonding of the u-warp from the top side of the beam, as shown in Figure 38.

Figure 35 Failure Mode for the control beam

Figure 36 Failure mode for the strengthened beam without anchorage

Figure 37 Failure mode of strengthened beam with Anchor bolt

Figure 38 Failure mode of the strengthened beam with U-Wrap

Chapter 6: Test Result

An eight beams were tested in the CELB (Civil Engineering Lab Building) in UTA to examine the strengthening of lightweight reinforced concrete beams using carbon fiber reinforced polymer under four-point load tests. Two beams were taken as control specimen, others two beams were taken as strengthened beams without anchorage, others two beams were taken as strengthened beams with anchor bolt anchorage, the last two beams were taken as strengthened beams with U-wrap anchorage. The results in the following sections represent the average of two beams from each category.

6.1 Control beam

The control beams showed typical ductile behavior until failure. The maximum deflection was 29.7mm (1.17 inch) which corresponds to the ultimate load 53.6 kN (12052 lb), as shown in Figure 39.

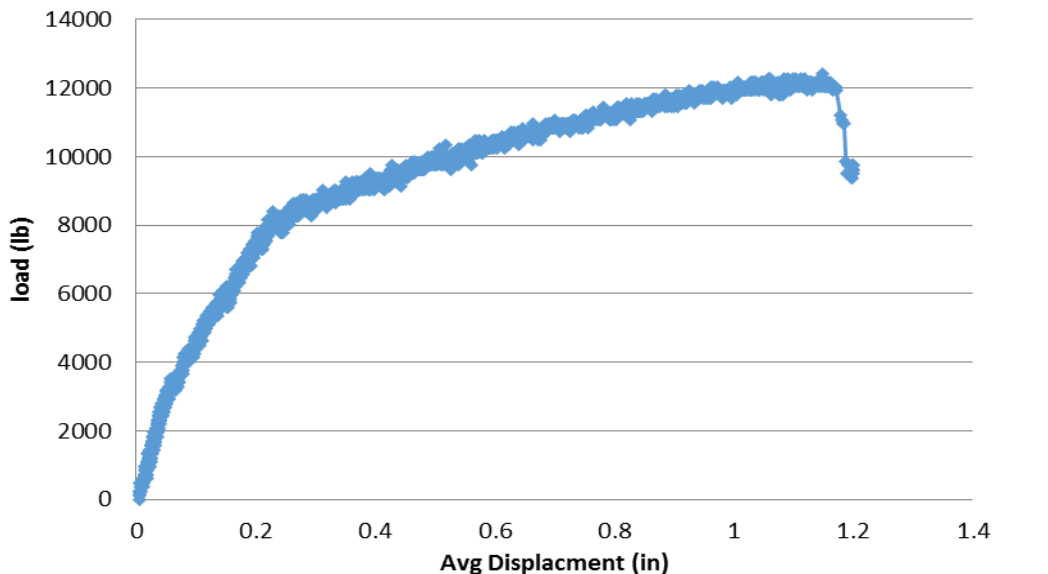**Figure 39 Load VS displacement for B1**

6.2 Strengthened Beam without anchorage

This beams were strengthened by CFRP. No anchorage system was used in these beams but the Epoxy. The failure mode of this beams were cover delamination. The ultimate load was 51.15 kN (1150 lb) and the maximum deflection was12.7 (0.5 inch) as shown in the next Figures 40.

Figure 40 Load VS displacement for B2

Figure 41 Load Vs Strain for B2

6.3 Strengthened Beam with anchor bolt

This beams were strengthened by CFRP. The anchorage system used in these beams was anchor bolt. The failure mode of this beams were cover delamination. The ultimate load was 54.15 kN (12173 lb) and the maximum deflection was 11.9 mm (0.47 inch) as shown in Figures 42.
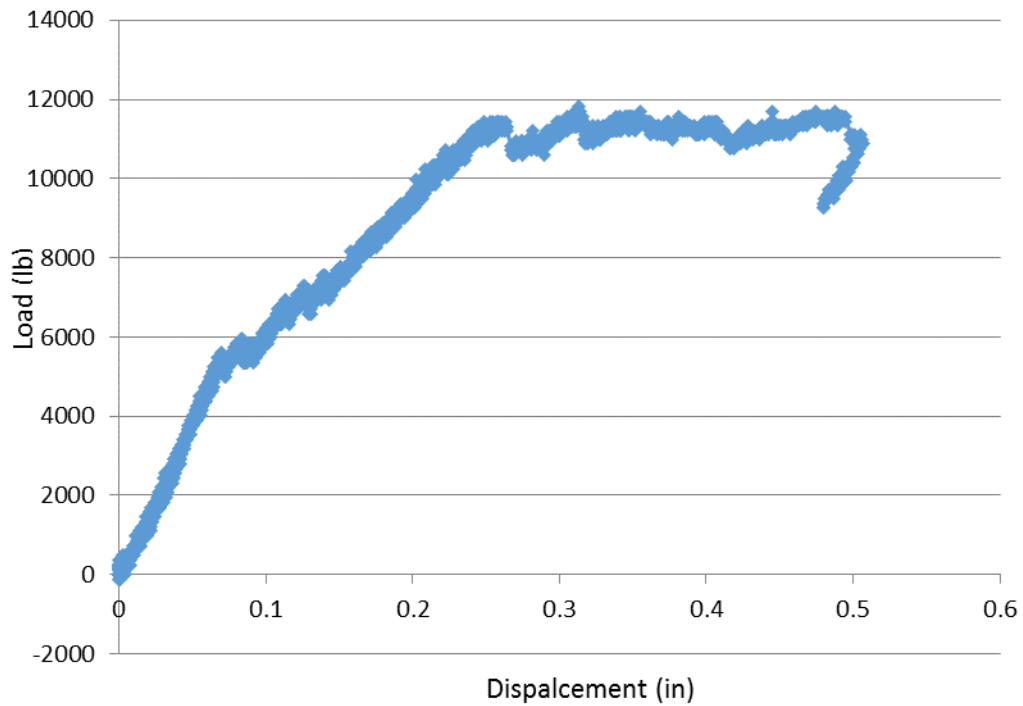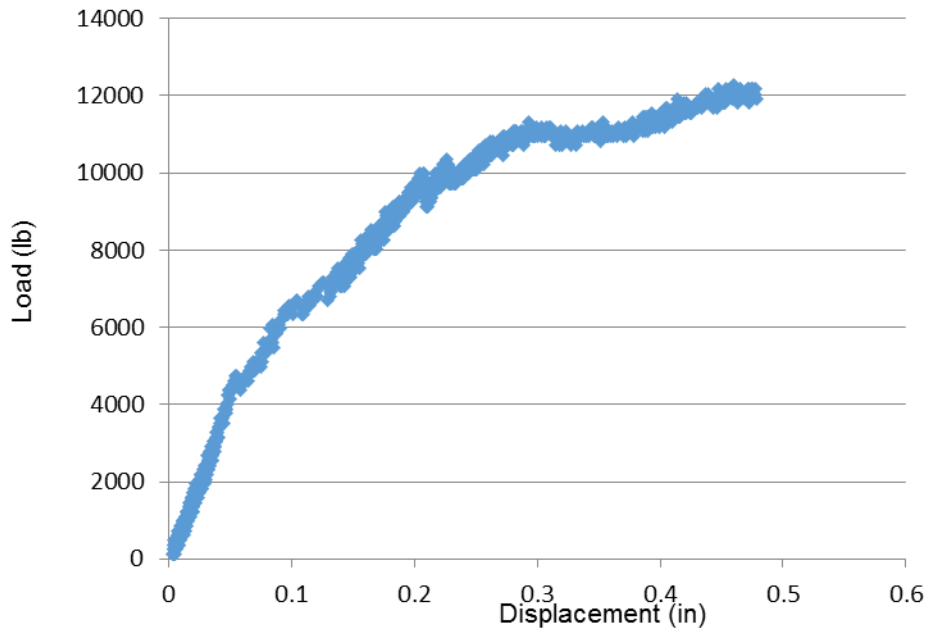
Figure 42 Load Vs Displacement for B3

Figure 43 Load Vs Strain for B3

6.4 Strengthened Beam with U-Wrap

This beams were strengthened by CFRP. The anchorage system used in these beams was anchor bolt. The failure mode of this beams were debonding of the u-wrap. The ultimate load was 60.33 kN (13563 lb) and the maximum deflection was 12.19 (0.48 inch) as shown in Figures 44.

Figure 44 Load Vs Displacement for B4
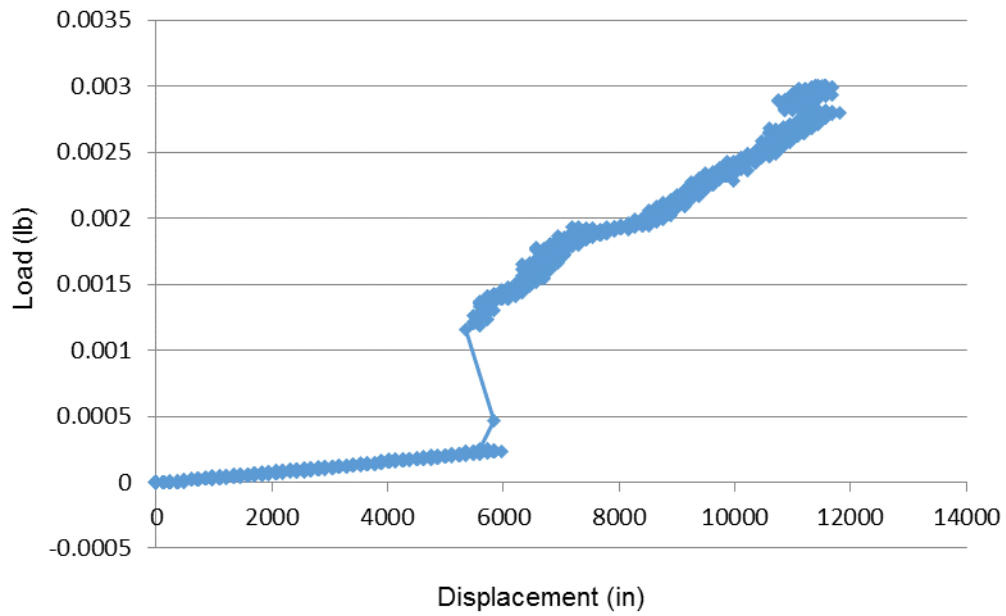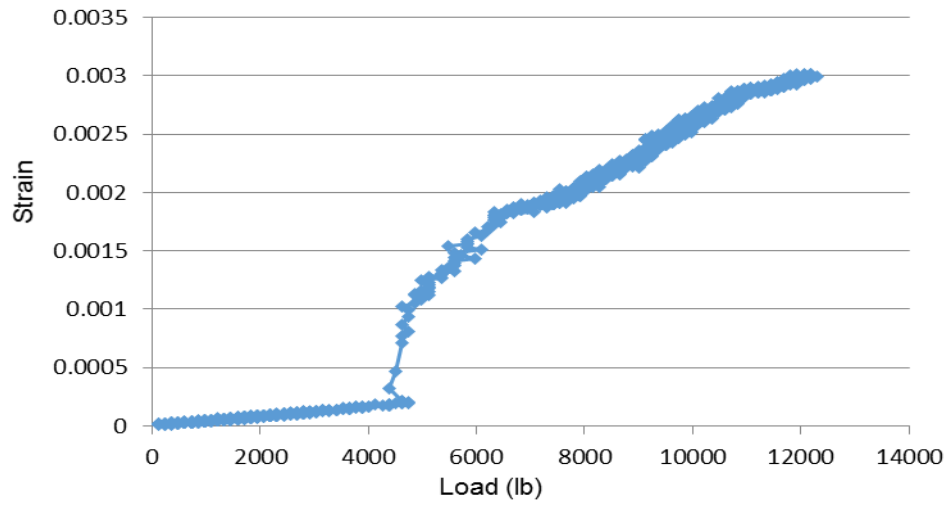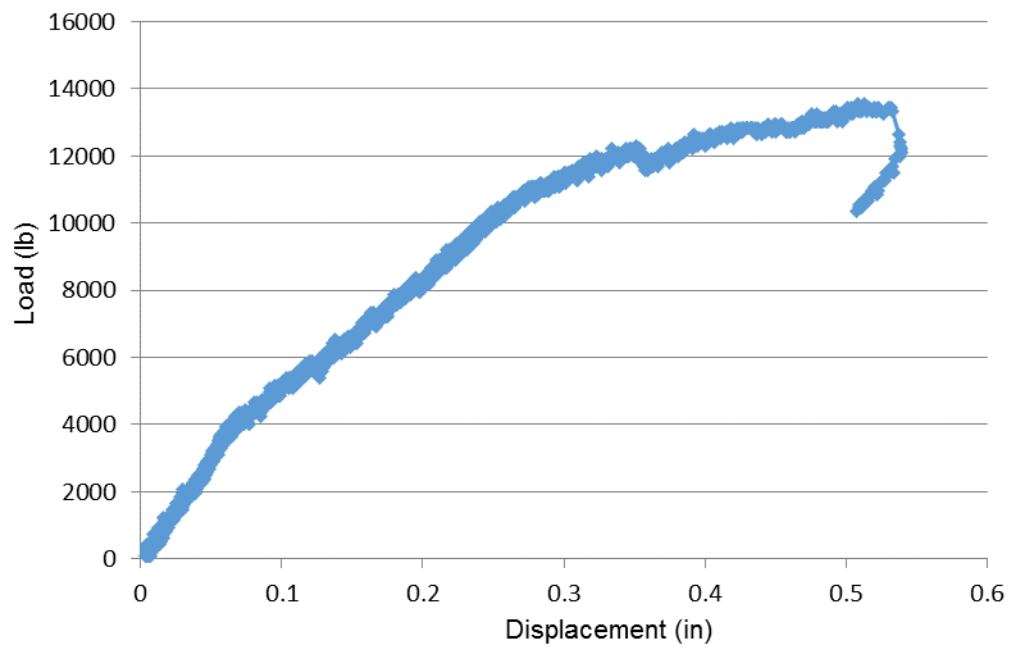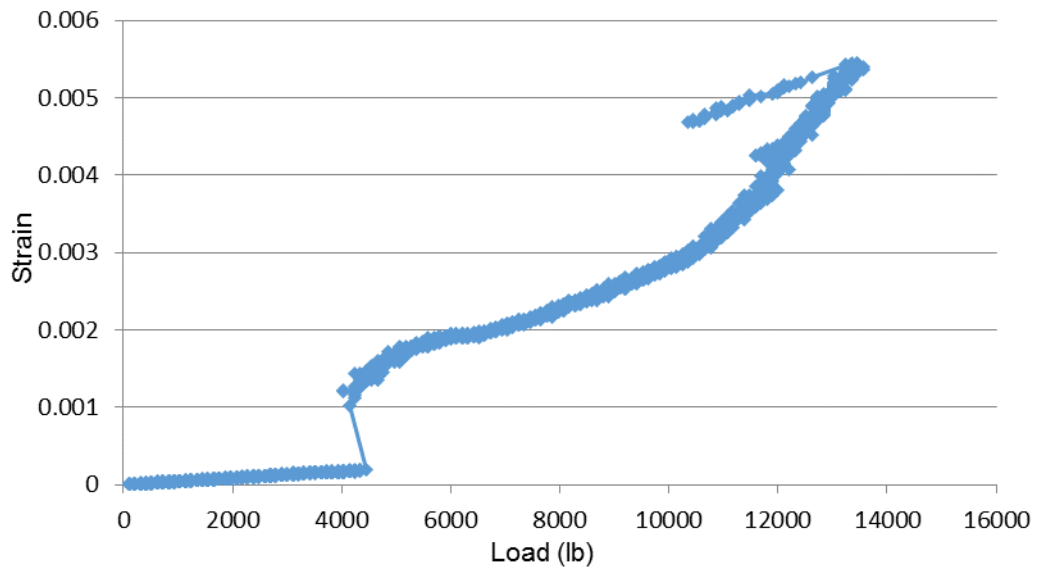
Figure 45 Load Vs Strain for B4

Chapter 7: Discussions

In this experiment, three different anchor system were used to increase the bonding between the CFRP and the concrete: without Anchorage, Anchor bolt and U-Wrap. Each system has a different effect on the beams behavior, ultimate load and deflection. As discussed in the following sections

7.1 Beams Strength Analysis

Comparison values are shown in Table 5 to present the differences in the strength between the strengthened beams and the control beams.

Table 5 Comparison of strength for all Beams

Beam	Theoretical Failure load kN (Lb)	Experimental Failure load kN (lb)	Maximum Deflection mm (in)	Percent of increase in strength comparing to control beam from Experiment
B1	51.9 (11670)	53.6 (12052)	29.7(1.17)	NA
B2	66.7(15000)	51.44(11560)	12.7(0.5)	-4.1%
B3	66.7(15000)	54.14(12173)	11.94(0.47)	+1.00%
B4	66.7(15000)	60.1(13512)	12.19(0.48)	+12.11%

7.1.1 B1 vs B2

As shown in table above the failure load of B2 was 51.44 kN (11560 Lb) at deflection 12.7 mm (0.5 in). The maximum load of this type of beams which strengthened using CFRP without anchorage was less than the control beam by 4.00% because of the cover delamination of the beam. The CFRP layer is not utilized efficiently in this beams since the value of the strain 0.00299 as shown in the Figure 41 which is less than the maximum strain of the cured CFRP which is 0.01.

7.1.2 B1 vs B3

The failure load of B3 was 43.2 kN (12173 Lb) with a deflection equal to 11.94 mm (0.47 in). The maximum load of this type of beams which strengthened using CFRP anchor bolt anchorage was more than the control beam by 1.00% only. The failure mode of these beams were cover delamination which means that the concrete cover was delaminated from the beam. The actual strain in the FRP is 0.003 but the maximum permissible strain of the cured FRP is 0.01, so the FRP layer can hold more strength up to rupture of FRP. In order to increase the strength of the beams, the development length of the FRP layer should be increased as discussed in section (7.4), and the depth of the anchor bolt should be increased.

7.1.3 B1 vs B4

The failure load of B4 was 60.1kN (13512 Lb) at deflection 12.19 mm (0.48 in). The maximum load of this type of beams which strengthened using CFRP with U-Wrap anchorage was more than the control beam by 12.11%. The failure mode of these beams were debonding of the U-Wrap. The actual strain in the FRP is 0.005 but the maximum permissible strain of the cured FRP is 0.01, so the FRP layer can hold more strength up to rupture of FRP. The value of strain is more than others strengthened beams, so the FRP layer was more efficient than others. This shows that the using of U-Wrap in anchorage will increase the capacity of the strengthened beams due to confinement of the concrete.

7.2 Analysis of Deflection

The comparison of the deflection between un-strengthened beam and strengthened beams are shown in Figure 46. It is obvious from Figure 46 that the CFRP reduce the deflection of the beams compared to unstrengthen beams. This means that the stiffness of the beams are increased accordingly. At the same load the deflection in the control beams is more than the deflection in the strengthened beams using CFRP with any types of anchorage.

Table 6 Stiffness Comparison

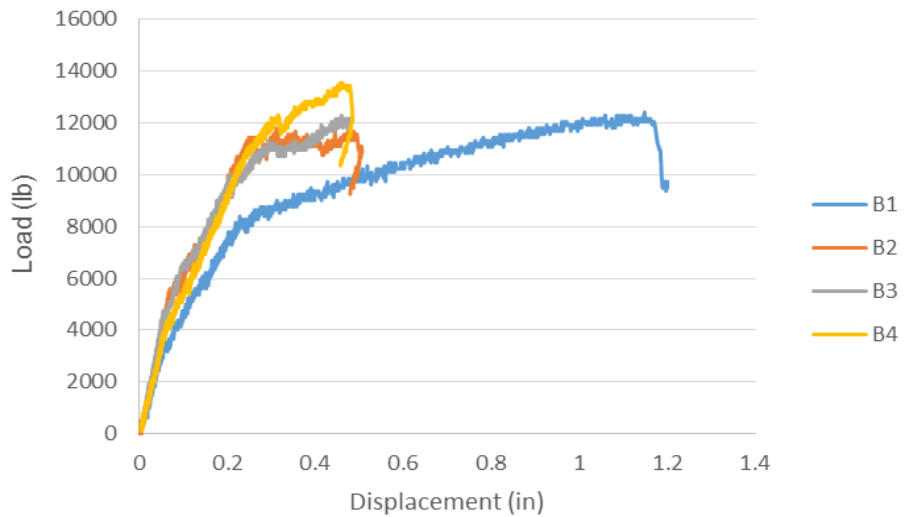|	**Un-strengthened**	**Strengthened**	**Percent of Stiffness increase**
Stiffness kN/mm(lb/in)	2.66 (15218)	6.04 (34500)	126 %

Figure 46 Deflection

7.3 The importance of anchorage

Another concern that CFRP sheet is affecting is the deflection which varies for each type of anchorage. As shown in the figure (7-4) the deflection for each type of the anchorage is unique. This is due to the change in the bonding efficiency between the FRP and the concrete.

Using anchor bolts show increase in the strength comparing to control beams and strengthened beams without anchorage. This increment in the strength is because of the increase of bonding efficiency between FRP and concrete which help to prevent the premature debonding of the FRP layer or delay it. On the other hand, using U-wrap anchorage increase the strength comparing to other types of anchorage, U-wrap is installed perpendicularly to the longitudinal beam axis at the end of the FRP layer and wrapped on beam sides to make confining for the concrete in that area. Confining concrete at the ends of the FRP helps to delay the cracks and increase the anchorage of the FRP layer. Increasing in the anchorage bond between concrete and FRP is important, since in some cases no enough length to increase the FRP length.

7.4 Cover Delamination

One of the failures mode of external FRP strengthening is cover delamination. This type of failure occur at the end of the FRP layer because of the normal stress developed at the ends. The stress along the FRP layers is not uniform as shown in Figure 47. The steel reinforcement help to break the bond horizontally between concrete above and below the steel, and the concrete cover delaminate from the beam.

Cover delamination can be prevented using anchorage which is U-Wrap. Another way to prevent the cover delamination and debonding is by locating the end of FRP as close to region of zero moment as possible.
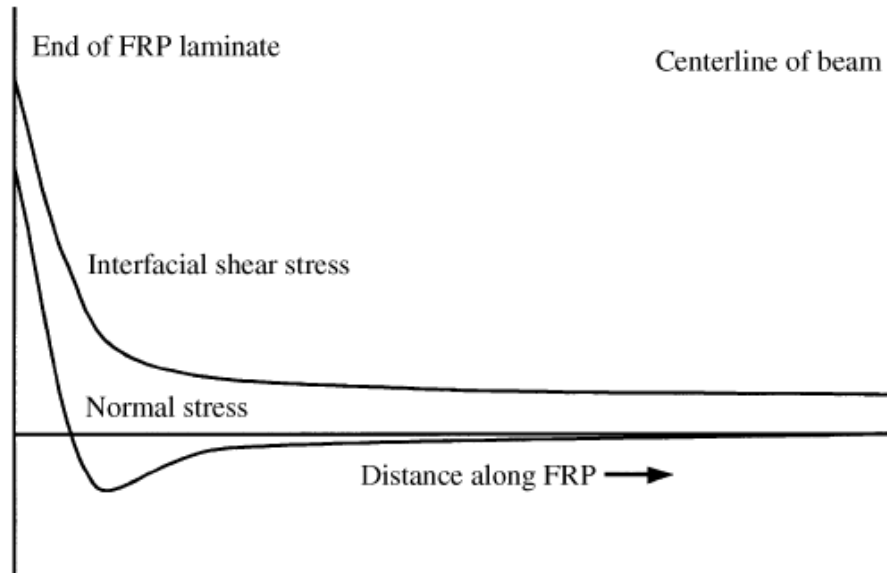
Figure 47 Conceptual interfacial shear and normal stress (Roberts and Haji-Kazemi 1989; Malek et al. 1998)

The area of U-Wrap can be calculated from the following equations:

$$A_{fanchor} = \frac{(A_f f_{fu})_{longitudinal}}{(E_f \kappa_v \varepsilon_{fu})_{anchor}}$$

Where:

$$\kappa_v = \frac{k_1 k_2 L_e}{468 \varepsilon_{fu}} \leq 0.75 \text{ in.-lb } \text{In.-lb}$$

$$L_e = \frac{2500}{(n_f t_f E_f)^{0.58}} in.-lb \text{ In.-lb}$$

$$\kappa_2 = \begin{cases} \frac{d_{fv} - L_e}{d_{fv}} \text{ for U-wrap} \\ \frac{d_{fv} - 2L_e}{d_{fv}} \text{ for two sides bonded} \end{cases}$$

51

In order to prevent cover delamination failure the cutoff point for the FRP layer should be determined. A single layer of FRP should be cutoff at a distance equal to l_{df} past the cracking moment M_{cr} point along the span as shown in the Figure 48.

l_{df} :can be calculated from the following equation:

$$l_{df} = 0.057 \sqrt{\frac{nE_f t_f}{\sqrt{f'_c}}} \text{ in.-lb}$$

$$l_{df} = 2.87 \text{ in.}$$
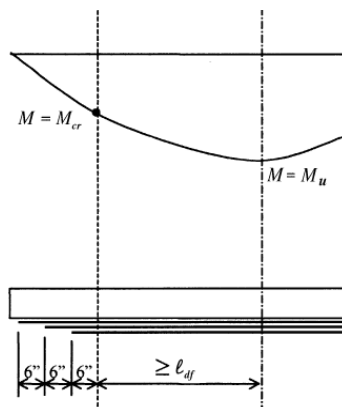$$A_{fanchor} = 0.46 \text{ in}^2$$

Figure 48 Development Length

Chapter 8: Conclusion and Recommendations

8.1 Conclusion

This research studied the effect of FRP to strengthen the lightweight reinforced concrete beams. The following conclusion were obtained from this research:

- The lightweight reinforced concrete beams strengthened with CFRP layer have exhibit an appreciable increment in flexural strength compared to control beam.

- The B3 beams exhibit 1.00% increase in the strength comparing to control beams.

- The B4 beams exhibit 12.11% increase in the strength comparing to control beams.

- The flexure anchorage prevent of delay the deboning of the FRP.

- Most of the strengthened beams failed by cover delamination with no rupture in the CFRP sheet.

- Only beams with U-wrap anchorage failed by debonding of the u-wrap.

- The strengthened beams show 126% increase in the stiffness comparing to un-strengthened beams.

8.2 Recommendations and Future work

- More research are needed in order to find the best anchorage system to utilize the full capacity of the FRP.

- Using others methods to increase the strength of the substrate layer in order to hold the tension force coming from FRP.

- Beams with larger dimensions should be investigated using longer anchorage system inside the concrete.

Appendix A

Theoretical Calculation for control beams and strengthened Beams
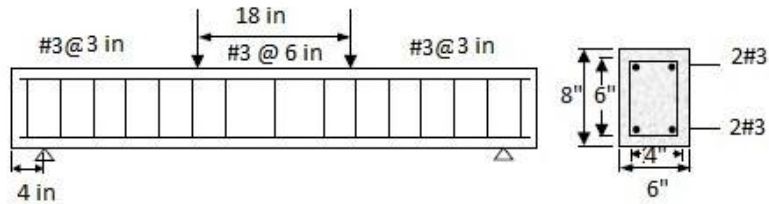
Figure 49 Beam Reinforcement

The figure above shows the dimension of the tested beam in order to calculate the theoretical values of the nominal moment and nominal load that beams can hold before failure.

Follow ACI-318 code to calculate the nominal strength of the tested beams.

1 - Following the procedure assume that the steel strain exceeds the yield strain, and thus, the stress in the tension reinforcement equals the yield strength. Compute the steel tension force:

As = 2 No. 8 bars = 2 * 0.11 in.2 = 0.22 in^2

T = Asfy = 0.22 in^2 * 60 ksi = 13.2 kips

The assumption that will be checked in step 3

2 - For concrete strengths, up to and including 4000 psi

β1 = 0.85

For 4000 psi - 8000 psi

β1 = 0.85 - 0.05 $\dfrac{f_c'-4000\,psi}{1000\,psi}$

$\beta1 = 0.85 - 0.05 \dfrac{4200-4000\,psi}{1000\,psi} = 0.84$

$\alpha = \beta1*c = \dfrac{A_s f_y}{0.85 f_c' b} = \dfrac{13.2}{0.85x6x4.2} = 0.616$ in

3 - Check that the tension steel is yielding. The yield strain is

$$\varepsilon_y = \dfrac{f_y}{E_s} = \dfrac{60ksi}{29{,}000ksi} = 0.00207$$

From above $c = \dfrac{\alpha}{\beta_1} = 0.73$

Now, use strain compatibility:

$$\varepsilon_s = \left(\dfrac{d-c}{c}\right)\varepsilon_{cu}$$

$$= \left(\dfrac{6.5-0.73}{0.73}\right)0.003 = 0.0237 >> 0.002 \text{ assumbtion used is correct}$$

4- Compute Mn

$$M_n = A_s f_y \left(d - \tfrac{a}{2}\right)$$

Using

$$M_n = 13.2\left(6.5 - \tfrac{0.616}{2}\right) = 9.32 kN.m(81.7k.ft)$$

$P_n = \dfrac{M_n}{2} x\ 14$ =51.9 kN (11.67 kips)

Strengthened Beams:

With the same dimensions of the previous calculated beam. Strengthened beams using FRP layer exhibit increase in the strength coming from the FRP layer.

Assuming elastic

According to the strain distribution shown in Figure above for any assumed depth to the neutral axis c, the strain level in FRP (ϵf), can be computed from the following equation:

Equation 1 $\varepsilon_f = \left(\frac{h-c}{c}\right)\varepsilon_{cu} \le \varepsilon_{fu}$

where (ϵcu) represents maximum usable compressive strain in concrete, h represents overall thickness of a member in inch , c represents distance from extreme compression fiber to the neutral axis in inch and ϵfu represents design rupture strain of FRP. The stress level in the CFRP, ff, can be found from the strain level in the CFRP assuming elastic behavior

Equation 2 : $f_f = E_f \varepsilon_f$

where Ef is the tensile modulus of elasticity of CFRP in psi. Based on the strain level in the CFRP, the strain level in tension steel ϵs can be found from

Equation 3 : $\varepsilon_s = \left(\frac{d-c}{h-c}\right)\varepsilon_f$

Where d is the depth of tension steel in inch. Also, for compression steel

:

Equation 4 : $\varepsilon_s' = \left(\frac{d'-c}{h-c}\right)\varepsilon_f$

With the strain and stress level in the CFRP and steel reinforcement determined for the
assumed neutral axis depth, internal force equilibrium may be checked using

Equation 5 : $c = \frac{A_s + A_f f_f + A_s' f_s'}{0.85 f_c' \beta_1 b}$

Where

As: is the are of steel in in2

Af : is the area of FRP

As' is the area of compression steel

Fc': the compressive strength of concrete in psi,

b :is the width of concrete cross section in inch

The actual neutral axis depth c is found by

Simultaneously satisfying Equations (1)–(5), then establishing internal force equilibrium

and strain compatibility.

The nominal flexural strength of the section with

FRP external reinforcement Mu can be computed from

$$M_u = A_s f_s (d - \frac{\beta_1 c}{2}) + \psi A_f f_f (h - \frac{\beta_1 c}{2}) + A_s' f_s' (d' - \frac{\beta_1 c}{2})$$

Where: ψ is an addition reduction factor of the flexural strength contribution of FRP.

The Nominal Moment is 134970.25 lb-in =15.25 kN-m

Pn = 2 *Mn / X = 14996.7 lb = 66.7 kN

The Nominal Load is 66.7 kN(15 kips)

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