Evaluation of Beams and Columns Strengthening with Pre-Saturated and Regular CFRP

By

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Abstract
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Structural members such as columns and beams are often subjected to reduced capacity due to errors in design or construction or often due to deterioration with time. The effect of reduction in capacity due to environmental and loading conditions are often the causes for deterioration or complete failure of structures. The main objective of this study is to deliver the effect of using Pre-Saturated Carbon Fiber Reinforced Polymer (CFRP) over regular CFRP Laminates, as an external strengthening material for strength and confinement of these deteriorated structures. The hypothesis was the use of Pre-Saturated CFRP over conventional regular CFRP Wet layup procedure, will lead to an enhancement in workability and efficiency in utilization of composite as strengthening materials. There were several results in past comparing the effectiveness of FRP with different set-up, comparisons with respect to glass and aramid, arrangement of sheet with anchorage number and spacing but not much research has been done in inspecting the variation of Carbon class fibers via change of properties like saturation of laminate to reach optimum capacity of CFRP in retrofitting. Seven beams and ten cylinders has been considered in this research to evaluate the proposed hypothesis. Beams of similar dimensions were considered with one control sample followed by variations in anchorage system to compare the effectiveness of Pre-saturated over Regular CFRP.
Column capacities were compared against Pre-saturated confinement over Regular CFRP confinement with the variation in the number of layers and height-to-diameter ratio. Out of ten samples, five were casted with twelve inch height followed by other five with twenty-four inches of height with similar diameters. The control samples were tested against one and two layers for both type of CFRP confinements.

Three-point bending test was used for beams and axial loading for Columns. Although, column showed increase in strength as per the hypothesis but the beam test results showed variations in strength and ductility, which provided us more grounds for further research and future studies in the behavior of Pre-saturated samples with anchorage devices. The experimental research were further compared with Theoretical computations as per ACI 440 (2017) design guidelines for beams and columns to study the percentage utilization of FRP laminate in the course of study.
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Chapter 01

Introduction

1.1 Background

Externally bonded FRP System as per ACI 440.2R (2017) has been used from mid-1980 to restore or retrofit deteriorated structural member, to resist increase in loading, address construction, or design errors. Bonding of FRP Laminate with adhesive such as resin can be used for strengthening of structural member for different purposes - such as application of FRP in the tension zone of beam can lead to flexure capacity enhancements, wrapping FRP along circumference of column can increase the overall load bearing capacity of column. Along with better performance under loading, FRP also serves as a barrier on concrete surface against corrosion, chemical ingress, water penetration, fire, freeze-thaw damage and thus enhances overall durability of system and its components (such as strands, rebar’s, and ties). The high cost of material (laminate or plate) is compensated by low labor cost and rapid installation.

The major concern though is the underutilization of FRP capacity due to premature debonding of the system from concrete surface. Several attempts have been made to use external anchoring system such as mechanical bolts, CFRP fan anchors and traditional U-Wraps to address such premature failures and increase the overall capacities. ACI 440.2R.17 guidelines has documented these anchorage methods and minimum design requirements that designers has to follow to avoid such premature failures.
1.2 Objectives

The objective of this study is to deliver the effect of using Pre-Saturated Carbon Fiber Reinforced Polymer (CFRP) over regular CFRP Laminates, as an external strengthening material for strength and confinement enhancements and their performance with external anchorage systems such as- mechanical, and fan fiber anchors on beams and layers of confinement for columns. Following are the topics that will be addressed through this research:

- Variations in strength and performance of pre-saturated FRP over regular CFRP Laminate under loading conditions.
- Workability criterion during installation and application of pre-saturated CFRP versus regular CFRP.
- Workability criterion while installation of anchorage systems on pre-saturated FRP over regular CFRP Laminate.
- Variation of strength and performance with respect to change in aspect ratio for the columns.
- Variation of strength with single layer and double layer application of Pre-saturated over regular CFRP Laminate.

1.3 Outline and Organization of Thesis

Hence, to justify the objectives the research has been documented in the following pattern:

Chapter 01 states the background, scope and objectives of the research

Chapter 02 describes the literature review- the previous study on the subject and modification or deviation of current research work with the past studies.

Chapter 03 describes methodologies and material properties used in the course of this research.

Chapter 04 demonstrates the experimental setup for the application of loads on the samples.

Chapter 05 describes the results and mode of failures for the structural members.

Chapter 06 demonstrates conclusion drawn from the course of experiment with the implications in the field of structural engineering
Chapter 02

Literature review

2.1 Background

Retrofitting through Carbon Fiber Reinforced Polymer (CFRP) currently is the most common technique used worldwide. Because of the ease of installation and without any addition of weight to the existing structure, FRP’s have been used in variety of ways to strengthen reinforced concrete beams, columns or slabs. Several guidelines and Journals have been published to document these practical applications such as ACI 440.2R.17 guidelines. However, variety of failure mechanisms has limited the full utilization of CFRP. One of the concern was premature debonding, which initiates from high moment area and propagates towards the end length of CFRP laminate.

Tayyebeh Moamaadi (2014) has conducted a detailed study on Failure mechanisms and parameters that effects FRP debonding on concrete beams and concluded that almost all other mode of failure were initiated directly or indirectly because of FRP debonding in the area of high-localized stress.

Based on the experimental results and evaluations, ACI 440.2R.17 has documented following modes of failures of CFRP on a beam- a) FRP debonding initiation in the region of high moment/shear b) cover delamination near the curtailment of reinforcement or c) debonding due to crack propagation along weak adhesive matrix.

ACI 440.2R.17 defines Cover delamination or FRP debonding occurs when the forces on CFRP are greater than the bonding capacity of FRP-Concrete substrate. All such failures are referred as concrete debonding irrespective whether the failure plane propagates within the FRP-adhesive-substrate region or outside.
To overcome such failures as mentioned in figure 2, ACI 440.2R.17 has recommended following design and practical alternatives based on the recent studies on the topic. To prevent such kind of intermediate crack induced debonding failure, the strain in FRP shall be equal or greater than debonding strain which can be calculated as part of design known as, the debonding length of FRP as of equation 10.1.1 from ACI 440.2R-17

\[ \varepsilon_{fd} = 0.083 \sqrt{\frac{f'c}{nEf_t}} \leq 0.9 \varepsilon_{fu} \]

*Equation 1*

Where

\( \varepsilon_{fd} \) is debonding strain, \( f'c \) is the concrete compressive strength, \( n \) is the number of FRP layers used, \( t_f \) is the thickness of FRP, \( \varepsilon_{fu} \) is the ultimate strain in the FRP.

Thus, the length more than the development length of FRP shall be used to prevent such pre-mature failure leading to the underutilization of FRP system.

*Figure 2 Failure mode with FRP failures as per ACI 440.2R (2017)*
2.3 Overcoming Premature Failures through Installation of Anchors

ACI 440.2R.17, in the recent version has documented the installation of anchors such as mechanical, fan and U-wrap to address the failure due to debonding as documented in figure 3. However not much design backup has been provided to effectively utilize the concept in general civil and construction industry.

![Anchor Installation Diagram]

*Figure 3 ACI 440.2R (2017) Recommended anchor installation*

Grelle and Sneed (2013) has reviewed several mechanical anchor types for externally bonded laminates and suggested that with the installation of bolts with metallic plate as in figure 4 can not only delay the debonding or failure of concrete substrate due to normal
tensile forces. In addition, the plate around the bolts increases the area over which shear stress is transferred, which improves the interfacial shear stress transfer.

![Diagram of anchor installation near cover delamination zone.](image)

*Figure 4 anchor installation near cover delamination zone*

![Diagram of typical plate anchorage.](image)

*Figure 5 Grelle and Sneed (2013) suggested bolts with plate system*

Anil and Belgin (2010) conducted experiment on twelve test specimens keeping compressive strength and CFRP bond length constant, to study the effect of the number of applied anchorages, arrangements and types of anchorage on stress distribution. From the experimental results, mentioned in figure 6 and 7 single row arrangements provided
166% more strength than samples without anchors. With staggered arrangement, the increase in strength was 96%.

The study also concluded with the increase in number of anchors beyond certain number will not provide substantial increase in strength but will reduce the contribution of individual anchors.

*Figure 6 Anil and Belgin (2010) anchorage configuration and set-up*
Zhang and Smith (2012), has provided an experimental comparison on the anchor orientation and dowel length required for proper bonding. As shown in figure 8, their study further demonstrates the selection between single and Bow tie configuration of fan anchors along with the influence of dowel angle in overall ductility of the joint and load capacity. FRP fan anchors with fan oriented in the direction of load perform similar manner as the Bow tie although the later enable greater slip between FRP and concrete. Anchors angled with greatest degree relative to the direction of load increased the joint strength by 160%.
as shown in figure 9, however the ductility of joint was decreased at the same time with increase in dowel angle due to brittle failure of anchor and absence of post-peak reserve strength.

Figure 8 Types of Fan anchors

Figure 9 Zhang and Smith (2016) Description of Fan anchor and relation of Dowel angle with respect to strength

Zhang and Smith (2016) further demonstrated that the out-ruling factor for anchor spacing has shown that $L_{\text{end}}$ was much more influential factor than $L_{\text{anchor}}$. The longer $L_{\text{end}}$ generates load plateau for the propagation of de-bonding cracks, this plateau is important for enhancing the ductility of the joint as shown in figure 11. For sufficient length of lend
joint strength were increased and FRP anchor were effectively engaged. $L_{\text{end}}$ has dominating factor in bond strength as compared to $L_{\text{anchor}}$ which was verified through the ultimate load capacities.

Figure 10 Fan anchors dowel and fabric ratios

Figure 11 Zhang and Smith: Influential factors deciding overall anchor strength
2.4 Confinement Enhancement through CFRP

Confinement of reinforced concrete columns through FRP jackets have been used to enhance strength and ductility of columns as shown in figure 12. The increased capacity can improve the immediate peak load resistance i.e. the ultimate capacity.

FRP systems can be used to increase the axial compression strength of concrete members by orienting the fibers traverse to the longitudinal axis of the member. It provides passive confinement remaining unstressed until dilation when cracking of wrapped compression member occurs.

Wrapping with FRP can also provide strength enhancement for a member subjected to combined axial compression and failure. The equations in ACI 440.2R-17 can be applicable to this member when eccentricity in the member is less than 0.1h.

Mirman and ET. Al (1998), describes the effectiveness of circular columns over rectangular by measuring effectiveness as a function of corner radius and jackets hoop strength as
shown in figure 13. The experiment also describes the effectiveness of mechanical shear connectors over adhesive bond to enhance load-bearing capacity by uniform distribution of confinement pressure around circumference of the tube.

Figure 13 Mirman and ET. Al (1998) inference on FRP effectiveness on circular columns over Rectangular columns

Benzaid, ET. Al (2013) further suggested from experimental studies that the CFRP confinement on low strength concrete produces higher capacity when compared with high strength concrete. In addition, with the increasing amount of CFRP sheets, the compressive strength will increase but deformation capacity reduces. The deformation pattern is shown in figure 14

Figure 14 Benzaid, ET. Al (2013), reasons for ineffective CFRP confinement on rectangular columns
2.5 Principal Findings from Literature Review

1. The FRP premature debonding can be avoided by providing strain greater than or equal to FRP debonding strain, which can be calculated from 0.1.1 from ACI 440.2R-17 \( \varepsilon_{fd} = 0.083 \sqrt{\frac{n}{n_{Ef} \cdot t_f}} \leq 0.9 \varepsilon_{fu} \) (equation 1 in this section).

2. As in figure 5 in this section, it can be concluded that anchorage installation can effectively avoid CFRP debonding, by providing support and frictional resistance against debonding. In most of the cases, anchorage installation leads to fracture mode of failure over FRP debonding.

3. As in figure 6 and 7 in this section, Single Row mechanical anchors arrangement provides greater increase in strength when compared with staggered row arrangement, because of their existence in the center of fibers, where maximum stress was concentrated.

4. Further, addition of mechanical anchors over certain number for a constant CFRP strip length will only reduce the stress on individual anchors without any significant increase in overall strength.

5. Figure 8 demonstrates that Single fan anchor in the direction of loading is more effective than Bow tie fan anchor, as the reduction in density of Bow-tie fibers leads to anchor failure before crack propagates to other side of the anchor.

6. Further in this section in figure 11, fan anchor dowel length is more significant factor than fan length, which is outside the hole, for bonding enhancements.

7. As in figure 9, fan anchor effectiveness increases with the increase in dowel angle but with the ductility of joint decrease as observed from brittle failure and omission of post-peak reserve strength. Hence, the optimum dowel angle is 90 degrees for fan anchors.
8. Zhang and Smith (2016) experimentally proved that anchor spacing from the end of beam \((L_{end})\) was much more influential factor than in between anchor spacing \((L_{anchor})\) on the ultimate strength of the joint.

9. Mirman and ET. Al, (1998) and Benzaid, ET. Al (2013) demonstrated that circular column CFRP confinement is more effective than square column confinement due to presence of non-uniform hop strength and corner radius.
Chapter 03

Material Specifications and Methodologies

3.1 Sample Dimensions and Strengths

Unreinforced concrete beams and cylinders were casted to study the comparison on the capacity of Pre-saturated type CFRP over regular CFRP on external strengthening. The compressive strength ($f'_c$) was calculated using average of three cylinders capacity of 4” diameter and 8 inch height dimensions. Following in the table 1, are the dimensions of members considered in this research with their effective compressive strength at the time of testing.

Table 1 Member dimensions and strength

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Dimension (inches)</th>
<th>Concrete strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Beams</td>
<td>Length- 36”</td>
<td>2562.28</td>
</tr>
<tr>
<td></td>
<td>Width- 8”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Height – 8”</td>
<td></td>
</tr>
<tr>
<td>Concrete Columns (1:2)</td>
<td>Diameter – 6”</td>
<td>3914.35</td>
</tr>
<tr>
<td></td>
<td>Height – 12”</td>
<td></td>
</tr>
<tr>
<td>Concrete Columns (1:4)</td>
<td>Diameter – 6”</td>
<td>3914.35</td>
</tr>
<tr>
<td></td>
<td>Height – 24”</td>
<td></td>
</tr>
</tbody>
</table>
The less concrete strength was targeted as the application signifies retrofitting techniques; all the existing old structures are of less concrete strength. Thus, less compressive strength of 2.5 KSI for beams and 3.9 KSI for columns were selected.

In addition, for experimental purposes if higher compressive strengths are targeted the total capacity of sample will increase as cracking moment depends on compressive strength (\(f'_c\)) and the machine capacity would be less than required for cracking beams. As specified by manufacturer for each part of 80 lbs., 6 pt. of clean water was added. Their design mix used in this research is as per table 2.

### Table 2 Design Mix used in this research

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (Lb./ft. (^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>3.28</td>
</tr>
<tr>
<td>Water</td>
<td>1.55</td>
</tr>
<tr>
<td>Coarse aggregate (crushed stone with maximum aggregate (\frac{3}{4})”)</td>
<td>8.23</td>
</tr>
<tr>
<td>Fine aggregate (sand)</td>
<td>5.58</td>
</tr>
</tbody>
</table>

The variation in strength of concrete depends is due to the water content and compaction techniques.

### 3.2 Fiber Properties

Carbon type Fiber reinforced polymer were used with the variation of Pre-saturated type and regular CFRP’s for this research to establish the relationship of physical properties alteration on usage of CFRP as external retrofitting material. The fibers are shown in Figure 16 for Pre-saturated and figure 15 shows regular CFRP.
Sika products were used in course of this research and the manufacturer with the products provided their design properties for theoretical calculations.

The variation of Pre-saturation has subsequent effect in the capacity of fiber laminates over traditional CFRP for the same thickness and fiber weight/ inch.

3.2.1.2 Regular CFRP:

An FRP system is defined as the composite laminate which is a created from fibers and resins. The resulting composites are lightweight, corrosion resistant and exhibit high tensile strength, which makes FRP retrofitting advantage over other methods of retrofitting such as steel and Pre-stress as they add additional weight to the structures.
ACI 440.2R.17 provides design equations and examples to calculate the strength added on the structural members due to CFRP which considers following design properties from the manufacturer as shown in Table 3.

Table 3 Regular CFRP Design properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Design Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packaging</td>
<td>24 inch x 300 feet, 12 inch x 300 feet</td>
</tr>
<tr>
<td>Color</td>
<td>Black</td>
</tr>
<tr>
<td>Fiber Direction</td>
<td>0 degrees (unidirectional)</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>$1.05 \times 10^5$ psi (724 MPa)</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>$8.2 \times 10^6$ psi (56500 MPa)</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.02 inch (0.51mm)</td>
</tr>
<tr>
<td>Elongation</td>
<td>1.0%</td>
</tr>
<tr>
<td>Fiber properties</td>
<td>0.065 lbs./inch$^3$ (1.8 gm/cc)</td>
</tr>
</tbody>
</table>
3.2.1.3 Pre-saturated CFRP

These fibers are manufactured as cured laminates, thus they can be added to existing structures without the addition of fiber resin required for saturation, which saves a lot of labor time, cost and addresses the issue of unavailability of clean free surface in the job site for the FRP application. The only additional incentive is the time window for the applicability of the material. The manufacturer has specified a time limit of 2 hours with a total life of shelf storage of a year, which is not in the case of regular CFRP.

![Figure 18 Pre-saturated application in Fort Worth Texas Bridge site](image)

There is slight difference in the thickness of fabric (about 0.001 inches) and almost no difference in fiber distribution properties hence the comparisons for strength enhancements property is valid which is shown in Table 4.
Table 4 Pre-saturated CFRP Design Properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Design Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Time</td>
<td>2 hrs. after file is opened</td>
</tr>
<tr>
<td>Packaging</td>
<td>24 inch x 30 feet (Box of 2 rolls)</td>
</tr>
<tr>
<td>Color</td>
<td>Black</td>
</tr>
<tr>
<td>Fiber Direction</td>
<td>0 degrees (unidirectional)</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>$9.3 \times 10^4$ psi (645 MPa)</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>$8.97 \times 10^6$ psi (61873 MPa)</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.019 inch (0.48mm)</td>
</tr>
<tr>
<td>Elongation</td>
<td>1.04%</td>
</tr>
<tr>
<td>Fiber properties</td>
<td>0.065 lbs./inch3 (1.8 gm/cc)</td>
</tr>
</tbody>
</table>

3.3 Parameters used in this research

The CAD drawings are shown in the table 5, to demonstrate the parameters used for beams and columns in this research. Each parameter is evaluated against both Pre-saturated CFRP and regular CFRP as per Table 5.

Table 5 Cad Drawing for beam and column parameters

<table>
<thead>
<tr>
<th>Designation</th>
<th>Schematics</th>
</tr>
</thead>
</table>

21
<table>
<thead>
<tr>
<th>Beam 01</th>
<th>Control Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 02 (Pre-saturated 117c FRP)</td>
<td>FRP without any anchors</td>
</tr>
<tr>
<td>Beam 03 (Regular FRP)</td>
<td></td>
</tr>
<tr>
<td>Beam 04 (Pre-saturated 117c FRP)</td>
<td>FRP lamination with mechanical Anchors</td>
</tr>
<tr>
<td>Beam 05 (Regular CFRP)</td>
<td></td>
</tr>
<tr>
<td>Beam 06 (Pre-saturated 117c FRP)</td>
<td>FRP Lamination with Fan Anchors</td>
</tr>
<tr>
<td>Beam 07 (Regular CFRP)</td>
<td></td>
</tr>
<tr>
<td>Cylinders</td>
<td></td>
</tr>
<tr>
<td>(Diameter 6&quot; with 5 samples of 12 and 5 samples for 24 inches height)</td>
<td></td>
</tr>
</tbody>
</table>

### 3.3.1 Beam Parameters

Each parameter signifies the research hypothesis of comparison in the strength capacities of Pre-saturated CFRP over regular CFRP laminate when applied externally to the beam.
samples with the variations of the beam with and without anchorages systems. Seven beam samples were used in total with detailed parameter as per table 6:

**Table 6 Beam Parameters**

<table>
<thead>
<tr>
<th>Number of samples</th>
<th>Beam Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>control</td>
</tr>
<tr>
<td>02</td>
<td>One layer Regular CFRP</td>
</tr>
<tr>
<td>03</td>
<td>One layer Pre-saturated CFRP</td>
</tr>
<tr>
<td>04</td>
<td>Fan Anchors Regular CFRP</td>
</tr>
<tr>
<td>05</td>
<td>Fan Anchors Pre-sat CFRP</td>
</tr>
<tr>
<td>06</td>
<td>Mechanical Anchors – Regular CFRP</td>
</tr>
<tr>
<td>07</td>
<td>Mechanical Anchors – Pre-sat CFRP</td>
</tr>
</tbody>
</table>

**3.3.2 Column Parameters**

Columns were casted to study the confinement strength comparison of Pre-saturated CFRP over regular CFRP laminate with the variation in layers of confinement and the height and diameter ratio.

Total ten samples were considered for this research out of which: five samples were casted of height Twelve inches and other five with twenty-four inches of height as per table 7.
<table>
<thead>
<tr>
<th>Number of samples</th>
<th>Column samples 12” Height</th>
<th>Column samples 24” Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>01, 02</td>
<td>control</td>
<td>control</td>
</tr>
<tr>
<td>03, 04</td>
<td>One layer Regular CFRP</td>
<td>One layer Regular CFRP</td>
</tr>
<tr>
<td>05, 06</td>
<td>One layer Pre-saturated CFRP</td>
<td>One layer Pre-saturated CFRP</td>
</tr>
<tr>
<td>07,08</td>
<td>One layer Regular CFRP</td>
<td>two layer Regular CFRP</td>
</tr>
<tr>
<td>09, 10</td>
<td>One layer Pre-saturated CFRP</td>
<td>One layer Pre-saturated CFRP</td>
</tr>
</tbody>
</table>

3.4 Sample Preparation

The samples were prepared with careful consideration on factors effecting the performance of CFRP. The samples preparation was achieved through three stages-

- Stage one, At the time of casting- to control the quality of concrete samples by consolidation and water-cement ratio
- Stage Two, At the time of curing of concrete samples and after the application of CFRP
- Sand Blasting: to provide rough surface for proper bonding of CFRP and concrete
• Stage four, Surface Cleaning: to remove any presence of dirt and voids during CFRP applications and anchorage installation.

3.4.1 Casting of Beam

After careful consideration of parameters, number of beam samples were decided. Seven forms were created of dimensions 36 inch x 8 inch x 8 inch for casting concrete beam samples as shown in figure 19 and 20. The ready mix concrete was used for casting of beams. After casting, the top surface was levelled properly for each beam samples to reduce surface deformity. The samples were properly consolidated with vacuum pumps to avoid segregation. The water cement ratio was monitored on the job site avoid loss of strength and bleeding of concrete. Three samples of concrete were casted to check the compressive strength at the time of testing.

Figure 19 Ready-Mix concrete pouring for beam samples
3.4.2 Casting of Column Samples

Ten Columns form were created of 6 inch diameter out of which five were of twelve inches height and other five were twenty-four (two twelve inch joined head to head). The concrete mixed was prepared in rotating drum concrete mixer as shown in figure 21 with water cement ratio of 0.4. The prepared wet concrete is placed in the forms and with every two layer of concrete pouring, consolidation is provided by tapered rod through 25 blows. The prepared samples were placed in shades as shown in figure 22, covered for proper hydration of cement, and cured using Burlap Curing procedure for 28 days. Three samples of concrete were casted to check the compressive strength at the time of testing.
3.5 Surface Preparation

Before application of FRP Polymer, Concrete surface is prepared by sandblasting as per CSP 3 (Concrete Surface Profile 3) for proper bonding between fiber laminate and concrete surface as shown in figure 23.

The bottom surface of beam with sides are sand blasted considering application of CFRP laminate in the bottom and CFRP U-Wrap around half of beam in all the four directions. The Column surface are sand blasted around circumference for CFRP confinement as well as on the top and bottom face for capping.
Figure 23 Sandblasting on the Concrete surface for FRP application

3.6 Parameters Positioning

The measurement on samples were marked using proper calibrated devices for CFRP application, anchorage installation (drill holes), anchor spacing’s, notch position, notch depth and for support end distances - 2 inches from each side as shown in figure 24. The 15 inches of marking on either side- top and bottom were done so that U-wraps doesn’t fall over supports at the end and support on the top due to provide concentrated loading (three point loading). U-wraps are added on the other side of notch to ensure failure doesn’t propagate on the other un-anchored side of the beam.
3.6.1 Anchorage Installation

For the installation of anchors, the holes were drilled through Drill-Bit of ½ “through 2.5 “deep as shown in figure 25. The standard 2.5” depth is considered for the practical applicability, as beams with reinforcement are considered at 2.5” from concrete surface as per ACI 318-14. The drilled surfaces cleaned by high-pressure air removing all possible dirt, which would otherwise effect bonding of concrete surfaces and FRP Laminate.
3.6.2 Mechanical Anchors

Mechanical anchors are installed in the beams near the regions of maximum moment on the FRP-concrete composite to prolong the failure by increasing the length of load propagation, and hence contribute towards increased strength by ensuring rupture mode of failure over delamination to utilize full capacity of FRP.

The bearing plates were used around mechanical anchors for equal stress distribution and reducing the fibers discontinuity around the slit for mechanical anchors installation. The type of mechanical anchor used was “Wedge anchor” for enhancing the grip in the concrete as shown in figure 26.

Diameter of anchor used = ½ “
Length of anchorage = 2.5”
Bearing plate= 2” x 2”
Figure 26 the Mechanical Anchor used in this Research

The first anchorage location is important to ensure the crack initiation near first anchorage that is why a distance of 4 inches is selected for first anchor spacing compared with 5 inches for second location as shown in figure 27.

Figure 27 Location of mechanical anchors on the b
3.6.3 Fan Anchors

The fan anchors are made from the regular CFRP Sika Wrap-FX as shown in figure 28. The length of 5 inches were used for fan anchor preparation of which 2.5 inches were inserted in the drilled hole which will act as dowel and the other half was bonded on the top of fiber with Sikadur 300. Before inserting the fan in the drilled hole, the hole shall be cleaned completely with high air pressure jet as presence of dirt can affect the capacity of anchors. Epoxy- Sikadur 330 was filled in the drilled holes and anchors are inserted fully immersed in the Sikadur 300. The surface bend joints can be made flexible or rigid with the application of epoxy in the bending corner. For this research, the joint was made fixed.

*Figure 28 Sika Wrap-FX fan anchors*
Figure 29 location of fan anchors

Figure 30 Fan anchor profile on beam samples
The notch as shown in figure 31 was made right at the middle of beam to study the effectiveness of Pre-Saturated and regular CFRP such that the analysis is solely due to material properties of different types of fibers used, instead of depending on other factors like anchors spacing and number.

The notch was made at the center of beam, which was 18 inches from the end and 16 inches from the support. The notch also help the reduction of failure due to interfacial debonding which is the debonding due the shear-moment depth and hence ensure the failure would be due to maximum moment region.

*Figure 31 the notch installation in the center of beam*
3.7 Application of CFRP

3.7.1 Sizing of CFRP Laminate

The FRP epoxy are prepared as per instructions from manufacturer and FRP sheets were cut and prepared as per dimensions as shown in figure 32. Prepared sheets were applied on the concrete surface impregnated by epoxy 330 for regular CFRP and 340 for Pre-saturated CFRP.

![Figure 32 FRP length of 52" and 4" wide including coverage for U-wrap](image)

3.7.2 Wet-layup Procedure for Regular CFRP

Regular FRP were prepared through impregnating 300 Sikadur epoxy. For two layers of regular FRP the between the layers 300 epoxy as applied and the overlap length is maintained 6" all the time as shown in figure 33. Pre-Saturated fabrics were installed directly on the prepared concrete surface and over other layer (in case of two layers).

All the test samples were cured for two weeks for proper bonding between the FRP and concrete surface as shown in figure 35. The room temperature was maintained during curing optimizing the bond. After two weeks, there was no bubble formation on the top of FRP surface implying the perfect bonding of composite.
Figure 33 wet layup procedure on CFRP laminates for regular CFRP samples

Figure 34 application of epoxy—Sikadur 300 on fan anchors
During the application of CFRP the top CFRP surface were levelled from time to time of application by dry roller and scrapper to remove the formation of air bubbles, as these formation's seriously affect the CFRP-concrete bonding and hence the overall capacity.

Figure 35  curing of FRP samples for 2 weeks before load testing
4.1 Beam Set-up

The 3-point loading was applied on all the beam samples as shown in figure 36 and figure 37. The applied load was on the center of roller separation. The roller supports were 32 inches apart due to 2 inches of support distances from each end of the beam. The tensile compression machine was used for testing with a capacity of 500 kips and is calibrated to record the ultimate stress and failure loads. The software program is configured to watch and record the initial loads, which causes the sample to break, or the break force. The machine is calibrated with the top surface of roller support on beams to produce initial zero load and position.

Figure 36 Beam Three-Point loading Setup
To measure vertical deflections with the application of loads, Linear Variable Differential Transformer (LVDT) was used as shown in figure 38 and 39. To compute accurate deflections during loading the top-mid surface of beams were tested by leveler. The un-levelled surface are corrected before applying load, if the alignment is differ by very small amount the surface were grinded but with the presence of substantial alignment, quick cement is added to provide perfect straight surface loading conditions.

Figure 38 LVDT used for vertical deflections
LVDT was placed on side of beam by clamping to concrete box to reach the bottom of the beam for recording vertical deflections. The deflection outputs were recorded via attaching cable from LVDT to the Data Acquisition Box (DAQ), which then records deflections of the sample by converting physical energy into electrical signals.
4.2 Column setup

The columns were placed on top of steel column for the proper levelling and alignment of sample to be tested with machine hydraulic bars as shown in figure 40. Sulfur capping was done on all the column samples to provide levelled top and bottom surface for the load application. The samples were placed in the center of the machine as the machine itself records displacements which are in the direction of loading. The ultimate loads and corresponding displacements were recorded from the Universal tensile compression-testing machine.

![Figure 40 Column setup for axial loading](image)
Chapter 05

Results and Discussions

5.1 Background

Destructive load tests were performed in Civil Engineering Lab at University of Texas at Arlington. Seven Beams and ten cylinders were tested for the evaluation of Pre-saturated and Regular CFRPs applied externally on the concrete samples. Control samples were prepared against all parameters to investigate the changes in strength.

5.2 Beams

The load and stress outputs from 500 kips Universal testing machine for the beams is as per Table 8.

Table 8 Ultimate Load capacities of beams

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sample Description</th>
<th>Experimental Failure Load</th>
<th>Theoretical Failure Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Control</td>
<td>3.99 kips</td>
<td>2.024 kips</td>
</tr>
<tr>
<td>02</td>
<td>Regular one layer</td>
<td>6.46 kips</td>
<td>4.66 kips</td>
</tr>
<tr>
<td>03</td>
<td>Pre-saturated one layer</td>
<td>7.10 kips</td>
<td>4.87 kips</td>
</tr>
<tr>
<td>04</td>
<td>Regular Fan Anchor</td>
<td>6.26 kips</td>
<td>4.66 kips</td>
</tr>
<tr>
<td>05</td>
<td>Pre-saturated Fan Anchor</td>
<td>4.89 kips</td>
<td>4.87 kips</td>
</tr>
<tr>
<td>06</td>
<td>Regular Mechanical Anchor</td>
<td>7.27 kips</td>
<td>4.66 kips</td>
</tr>
<tr>
<td>07</td>
<td>Pre-sat Mechanical Anchor</td>
<td>4.59 kips</td>
<td>4.87 kips</td>
</tr>
</tbody>
</table>
5.3 Discussions for Beam Parameters

5.3.1 Without Anchorage

Failure modes were analyzed to compare the ultimate load capacity with the material performances. For one layer Pre-saturated CFRP the failure mode was Rupture with an ultimate load capacity of 7.10 kips, which was 45.7% higher than theoretical computed values. Whereas, for regular CFRP, the failure was delamination with an ultimate load capacity of 6.46 kips and was 38.62% higher than theoretical computed values. The load and displacement comparing without any anchor sample is shown in figure 41.

\[\text{Figure 41 Load vs Displacement for One-Layer CFRP without anchorage}\]

One layer of FRP strengthening showed strength enhancements for both regular CFRP (6.46 Kips) and Pre-saturated CFRP (7.10 Kips) as compared to control sample. (3.99 kips).
One layer application showed minimal post-reserve strength, i.e. the appearance of peaks in the graphs after reaching its ultimate capacity. Post-reserve strength occurs due to friction between the fiber laminate and concrete surface. The tabulated comparison of result is shown in Table 9.

Table 9 without anchorage Load Discussions

<table>
<thead>
<tr>
<th>Description (one layer)</th>
<th>Pre-saturated CFRP</th>
<th>Regular CFRP</th>
<th>Control Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental capacity</td>
<td>7.10 kips</td>
<td>6.46 kips</td>
<td>3.99 kips</td>
</tr>
<tr>
<td>% difference from control samples</td>
<td>+77.94%</td>
<td>+61.9%</td>
<td>--------</td>
</tr>
<tr>
<td>% difference from theoretical calculations</td>
<td>+45.7%</td>
<td>+38.62%</td>
<td>--------</td>
</tr>
</tbody>
</table>

5.3.1a Regular One-Layer CFRP

The delamination failure was only observed in one layer regular CFRP. The Sample showed an increase capacity of 61.9% from the control sample.
The debonded CFRP clearly showed concrete on the surface of the laminate indicating the bond between CFRP and concrete failed due to the adhesion failure from region of high moment area towards the end.

5.3.1b Pre-Saturated One-Layer CFRP

Pre-saturated one-layer CFRP strengthened beam sample failed by rupture mode. With the rupture crack propagation towards area without U-Wraps.
5.3.2 with Anchorage System:

Two types of anchorage system is considered in these research- Mechanical bolts i.e. “the Wedge type anchor bolts” and Fiber anchorage system that is “CFRP fan fiber”.

5.3.2.1 Mechanical anchors

Two anchor bolts were installed with single row arrangement on the center of 4" fiber laminate. The first anchor was located at 4 inches from center of the beam follower by another mechanical anchor of in between 4” spacing. The anchor bolts were installed with bearing plates for equal stress distribution. The graph comparison is shown in figure 44 with tabulated comparison in Table 10.

![Figure 44 Load vs Displacement graph for mechanical anchorage](image-url)
Table 10 with mechanical anchorage Load Discussions

<table>
<thead>
<tr>
<th>Description (one layer)</th>
<th>Pre-saturated CFRP</th>
<th>Regular CFRP</th>
<th>Control sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental capacity</td>
<td>7.27 kips</td>
<td>4.59 kips</td>
<td>3.99 kips</td>
</tr>
<tr>
<td>% difference from control samples</td>
<td>+82.22%</td>
<td>+15.03%</td>
<td>--</td>
</tr>
<tr>
<td>% difference from without anchorage</td>
<td>+12.53%</td>
<td>-35.35%</td>
<td>--</td>
</tr>
</tbody>
</table>

5.3.2.1a Regular CFRP with mechanical anchors

The regular CFRP with mechanical anchors showed a capacity of 7.27 kips, which was the highest capacity among all samples and showed an increase of 82.22% when compared to the control sample. The failure mode for regular CFRP with maximum rupture length (near the first anchorage) as shown in figure 45.
The anchorage installation proved to be effective with a gain in strength of 12.5%. In addition, has eliminated delamination failure, which is seen earlier in regular CFRP without any anchorage.

**5.3.2.1b Pre-saturated CFRP with Mechanical Anchors**

The pre-saturated CFRP with mechanical anchors has seen a reduction of 0.06% in strength when compared with theoretical design value. Hence, the mechanical anchors were not as effective as regular CFRP mechanical anchor. A significantly large reduction of strength of 35.35% occurred when compared with unanchored sample. The rupture was near the notch as shown in figure 46.
Although there was no strength enhancement of mechanical anchors on Pre-saturated CFRP, there was tremendous gain in ductility. Which clearly demonstrates the engaging of mechanical anchors in load capacity but an incompatibility with Pre-saturated fibers.

5.3.2.2 Fan Anchors

The installation of fan anchors on CFRP has not shown any strength enhancement for both Pre-saturated and regular CFRP when compared to their single layer application without any anchorage.

The graph for load and displacement comparing both Pre-saturated and regular CFRP is shown in figure 47 with the value comparison in Table 11.
Figure 47 Load vs Displacement for fan anchors

Table 11 fan anchorage Load Discussion

<table>
<thead>
<tr>
<th>Description (one layer)</th>
<th>Pre-saturated CFRP</th>
<th>Regular CFRP</th>
<th>Control sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental capacity</td>
<td>6.26 kips</td>
<td>4.89 kips</td>
<td>3.99 kips</td>
</tr>
<tr>
<td>%difference from control</td>
<td>+56.8%</td>
<td>+22.5%</td>
<td>----</td>
</tr>
<tr>
<td>%difference without anchorage</td>
<td>-0.03%</td>
<td>-31.12%</td>
<td>----</td>
</tr>
</tbody>
</table>
Fan anchors were not effective for pre-saturated CFRP, both in displacement and flexural strength. But, for regular CFRP, fan anchors have provided gain in ductility and post-reserve strength after reaching ultimate capacity (post-reserve strength is secondary peaks after the beam reaches the optimum capacity which is due to the friction between fibers in laminate and concrete surface).

5.3.2.2a Regular CFRP with Fan Anchors

The installation of regular fan anchors have shown an increase in capacity of 6.26 kips, which is more than 56.89% when compared with the theoretical design strength. On the other hand a loss of 0.03% occurred when compared with no anchorage. The failure mode was rupture right near the Notch as shown in figure 48.

5.3.2.2b Pre-saturated CFRP with Fan Anchors

The installation of fan anchors on Pre-saturated has shown no gain in strength and ductility. In fact, a loss of strength of 31.12% occurred when compared with no anchorage.
5.4 Effective Rupture Length

The varying length of rupture failure for different beam has direct impact on the overall capacity of beams. The maximum load occurred when the rupture failure reaches the first anchorage location as marked in figure 49.

On the other hand, the load capacity for members were reduced when the rupture takes place right near the notch. In addition, Pre-saturated CFRP has shown maximum strength without any anchorage system whereas regular CFRP has shown tremendous gain in strength when applied with mechanical anchors.

Figure 49 length of rupture and delamination influence in overall capacity
Table 12: Comparison of all beam samples from control sample

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sample Description</th>
<th>Failure Load</th>
<th>% Strength from control</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Control</td>
<td>3.99 kips</td>
<td>------</td>
</tr>
<tr>
<td>02</td>
<td>117 C one layer</td>
<td>6.46 kips</td>
<td>61.9%</td>
</tr>
<tr>
<td>03</td>
<td>Pre-saturated one layer</td>
<td>7.10 kips</td>
<td>77.94%</td>
</tr>
<tr>
<td>04</td>
<td>117 C Fan Anchor</td>
<td>6.26 kips</td>
<td>56.8%</td>
</tr>
<tr>
<td>05</td>
<td>Pre-saturated Fan Anchor</td>
<td>4.89 kips</td>
<td>22.5%</td>
</tr>
<tr>
<td>06</td>
<td>117 C Mechanical Anchor</td>
<td>7.27 kips</td>
<td>82.2%</td>
</tr>
<tr>
<td>07</td>
<td>Pre-saturated Mechanical Anchor</td>
<td>4.59 kips</td>
<td>15.03%</td>
</tr>
</tbody>
</table>

Figure 50: Load VS Displacement Graph for all Beam samples
5.5 Columns

Ten columns were tested in axial loading condition. Samples were placed in the center of Universal testing machine with a capacity of 500 kips to record the ultimate load capacities.

5.5.1 Twelve-inch Height Samples

The column samples of 12” height and 6” diameter makes an aspect ratio of 1:2. The samples behave like traditional bulkier columns by undergoing crushing and splitting with the application of load. The results are shown in table 13 followed by the graph in figure 51.

Table 13 twelve inch height columns load capacities

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sample Description</th>
<th>Experimental Failure Load</th>
<th>Theoretical Failure load</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Control sample</td>
<td>70.6 kips</td>
<td>48.938 Kips</td>
</tr>
<tr>
<td>02</td>
<td>117 C one layer</td>
<td>112 kips</td>
<td>61.36 kips</td>
</tr>
<tr>
<td>03</td>
<td>117 C two layer</td>
<td>153 kips</td>
<td>122.72 kips</td>
</tr>
<tr>
<td>04</td>
<td>Pre saturated one layer</td>
<td>123 kips</td>
<td>62.34 Kips</td>
</tr>
<tr>
<td>05</td>
<td>Pre saturated Two layer</td>
<td>164.14 kips</td>
<td>124.68 Kips</td>
</tr>
</tbody>
</table>
The mode of failure has strong impact on the recorded ultimate capacities of column samples.

The development of crack at the failure load by machine for 12 inches and 24 inches column samples were with different modes of failure in one layer and two layer of regular CFRP and Pre-Saturated CFRP.

*Figure 51 Load Vs Displacement for 12" column samples*
5.5.1a Single-Layer CFRP

One layer Regular CFRP in figure 52, underwent FRP hoop failure, which is the most common type of failure. The failure initiated both in the inner end of FRP as well with the rupture outside the overlapping zone. Local stiffness and non-uniform deformation of concrete might be the reason of failure.

On the other hand, one layer pre-saturated CFRP as in figure 53 experienced Rupture failure from top to mid-height of the column, resulting in higher load capacities.
5.5.1b Two Layer CFRP

The Two layer Pre-saturated CFRP as in figure 54, failed in rupture with higher load capacity as compared to one layer. Two layer laminate also were effective in reducing the intensity of concrete failure whereas regular CFRP failed due to concrete crushing.

![Figure 54 Double layer regular CFRP (12’’)](image1)
![Figure 55 Double layer Pre-sat CFRP (12’’)](image2)

5.5.2 24” Height Samples

The column samples of 24” height and 6” diameter makes an aspect ratio of 1:4. With the application of load the location of failure was different for regular CFRP and Pre-saturated CFRP as shown in figure 56 and Table 14.
Table 14 twenty-four inch height columns load capacities

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sample Description</th>
<th>Experimental Failure Load</th>
<th>Theoretical Failure Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>06</td>
<td>Control sample</td>
<td>129 kips</td>
<td>48.938 Kips</td>
</tr>
<tr>
<td>07</td>
<td>117 C one layer</td>
<td>112.3 kips</td>
<td>61.36 kips</td>
</tr>
<tr>
<td>08</td>
<td>117 C two layer</td>
<td>123 kips</td>
<td>122.72 kips</td>
</tr>
<tr>
<td>09</td>
<td>Pre saturated one layer</td>
<td>191 kips</td>
<td>62.34 Kips</td>
</tr>
<tr>
<td>10</td>
<td>Pre saturated Two layer</td>
<td>199 kips</td>
<td>124.68 Kips</td>
</tr>
</tbody>
</table>

Figure 56 load Vs Displacement for 24” column samples
5.5.2a Single Layer CFRP

One layer Regular CFRP in figure 57 failed in debonding. Hence, the strength has reduced by 14.8% as compared to control sample. The primary factor for column debonding may include overlap length and application process of FRP. Other factors include bending and axial stiffness of FRP laminate, seize of column or due to mechanical properties and thickness of adhesive.

One layer Pre-saturated CFRP as in figure 58 on the other hand failed in rupture from mid-height toward top. The gain in strength for this case was 48.06% as compared to control sample.
5.5.2b Two Layer CFRP

Double layer Pre-saturated CFRP as in figure 59 showed maximum gain in strength among all samples. The strength enhancement for these samples was 54.2% when compared to control sample. In addition, the failure mode was rupture with failure of one layer in the mid height.

Regular CFRP two layer in figure 60 failed by debonding with rupture in the outer end of CFRP. Although when compared with one layer the strength has increased to 0.09%. However, due to debonding, the overall strength has reduced to 0.04% when compared with control sample.
As the length of column increases, the failure starts shifting towards the bottom of the column as the involvement of moment along with the axial loading starts acting as shown in figure 61. For bulky column usually the failure is splitting type, from the center of sample but with the change in aspect ratio (diameter: height) the failure changes to cone type failure which is complete detachment of upper or lower cone portion of the cylinder, further into the category also known as circumferential hoop stress failure.

Figure 61 Reason of Failure of CFRP on the bottom of Long Columns
5.6 Aspect-ratio and Strength

Table 15 clearly shows that the pre-saturated has shown the progressive gain in strength for all parameters (for both 1:2 and 1:4). Hence, Pre-saturated CFRP has proven as effective retrofitting material in confinement.

However, Regular CFRP were only effective for height twice as diameter. Any, further increase in height leads to failure due to axial and bending stiffness of FRP laminate (FRP debonding).

Table 15 Comparison of loads from aspect ratios

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>1:1 Aspect Ratio</th>
<th>1:2 Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control sample</td>
<td>70.6 kips</td>
<td>109 kips</td>
</tr>
<tr>
<td>One layer pre-saturated</td>
<td>+74.22%</td>
<td>+75.22%</td>
</tr>
<tr>
<td>Two layer pre saturated</td>
<td>+132.45%</td>
<td>+82.5%</td>
</tr>
<tr>
<td>One layer Regular FRP</td>
<td>+58.6%</td>
<td>-12.9%</td>
</tr>
<tr>
<td>Two layer Regular FRP</td>
<td>+116.71%</td>
<td>-4.65%</td>
</tr>
</tbody>
</table>

The gain in strength of pre-saturated was small in aspect ratio of 1:4 due to involvement of only one layer of CFRP in rupture as compared to rupture failure of both layers in 1:2 aspect columns.

The results can be generalized for regular columns, but the effect of eccentricity shall be considered for bigger diameters’. Thus the gain in strength may be lesser than what is observed in this research.
Chapter 06

Conclusions and Recommendations

6.1 Conclusions

- The rupture mode of failure was dominant in Pre-saturated CFRP.
- Though, Pre-saturated performs for higher capacity in single layer (77.96% increase in strength from control specimen). The addition of anchorage leads to lower load capacity. The possible expiration would be the dis-continuation of saturated fibers near anchorage of mechanical and fan anchors. The bonding capacity of Pre-saturated CFRP with fan anchors (fan anchors were made from the regular CFRP) and mechanical anchors (metals) might be the reason failure of anchorage. Further research is needed to study the interaction of pre-saturated with FRP of different properties (density, thickness and saturation).
- The installation of Mechanical anchors is easy and cheap as available in general store as compared with fan anchors. The fan fibers are very expensive and require skilled labor for installation. Also, the bonding of fan fibers highly depends on epoxy application on the drilled holes as well on the top of fibers.
- The columns capacity highly depends on number of layers, as installation of anchors is not possible in column as column reinforcement cage is complicated and near the cover. Thus, it may introduce corrosion on the column rebars.
- However, the saturated FRP is easy to apply but the resin Sikadur 340 application is dense and difficult to work with. Also the fabric is fragile and easily distorted as compared to regular FRP.
- Fiber waviness- a localized appearance of fibers deviation from general straight fiber line was observed while cutting and laying the Pre-saturated laminate. As
per ACI 440.2R.17 even a small distortion, say 5 degrees seriously affect the fiber capacity.

- The orientation and placement of fan anchors with the loading direction in three point loading. The previous research were done as 4 point loading on FRP Fan anchors. The sharp moment region of three point loading might not provide sufficient time for fan anchors to engage in loading.

- The pre-saturated CFRP performs well in confinement for all samples as compared to the performance in bending.

- The effect of change in aspect ratio is efficient for pre-saturated columns than compared with regular CFRP.

6.2 Recommendations for Future Studies:

- Further use of neoprene pad for capping instead of sulfur capping has proven to provide better friction between the loading from machine and the sample. Thus, account for results that are more accurate.

- Use of high strength concrete is recommended with mixing steel or engineering fibers in the mix to study the impact of concrete strength in FRP debonding.

- Use of Reinforced beams, will provide a better understanding on the study of crack patterns as the failure won't be brittle and cracks can be marked to understand the patterns initiation and development of minor cracks due to debonding.

- Incorporation of U-Wrap, as an additional anchorage. Since TX-Dot approves the use of U-Wrap as effective anchorage for FRP, the use of U-Wrap will provide a better comparative analysis on the subject of most effective and economical anchoring system.
• Since there was problem with trimming of Pre-Saturated fabric during installation, further research shall be performed to study the difference in effectiveness of full-length fabric and the fabric with shorter width.

• Anchorage application near the highest moment zone shall be further studied to capture the rupture length and overall enhancement of load capacity.
Appendix A

Theoretical Calculation For Control and Strengthened Beams
The Ultimate capacity of structural members

A.1 Calculation for Control and strengthened Beams

The member capacity of structure components were calculated by following the design examples as per ACI 440.2R (2017). For comparisons with the experimental loads, the support distances of 2 inches were considered. Three point loading as per figure 62.

\[ P \times X = \text{Moment computed from equations (ACI 318 for control samples and ACI 440.2R (2017) for beams strengthened with FRP)} \]

![Figure 62 Load Location with respect to support](image)

Beam Properties Considered

Length of beam = 36 inches

Width of beam = 8 inches
Height of beam = 8 inches

For concrete strength up to 4000 psi, $\beta_1 = 0.85$ (as experimental compressive strength is 2562.28 psi)

Since No reinforcements is used, the moment capacity of beam will be equal to the cracking moment

Cracking Moment =

$$M_{cr} = \frac{f_r I g}{Y_t}$$  \hspace{1cm} \text{Equation 2}

Rupture strength =

$$f_r = 7.5\sqrt{f'}$$  \hspace{1cm} \text{Equation 3}

$F_r = 379.681$ psi

$Y_+ = 8/2$ inches $= 4$ inches

Thus $M_{cr} = 32.3994$ kips-inch

Considering 2 inches of end separation, the distance from the point of load application is 16 inches

Thus $P \times 16$ inch $= 32.3994$ kips-inch

$P = 2.024$ kips

Calculating the moments through FRP strengthening

Moment equation for FRP strengthening as per ACI 440.2R.17

Area of fiber, $A_f = n^* t^* w^f$

$$M_{nf} = A_f \times f_{fe} \left( d - \frac{\beta^1 \times c}{2} \right)$$  \hspace{1cm} \text{Equation 5}
Table 16 Design properties of Laminate used in calculations

<table>
<thead>
<tr>
<th>Manufacturer's Reported Properties</th>
<th>Regular CRFP</th>
<th>Pre-saturated FRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>$t_f$</td>
<td>0.02 inches</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>$f_{fu}^*$</td>
<td>105 KSI</td>
</tr>
<tr>
<td>Rupture strain</td>
<td>$\varepsilon_{fu}$</td>
<td>1%</td>
</tr>
<tr>
<td>Modulus of Elasticity of FRP Laminates</td>
<td>$E_{fu}$</td>
<td>8200 KSI</td>
</tr>
<tr>
<td>Area of Fiber</td>
<td>$A_f = \frac{n^* t_f^*}{W_f}$</td>
<td>0.08 inch$^2$</td>
</tr>
</tbody>
</table>

Stress level in FRP is calculated as

\[
\frac{f}{f_e} = E \frac{\varepsilon}{f_e} \tag{Equation 6}
\]

Estimate the depth, $c = 0.20 \times d$
Considering the ultimate values for strain
\[ \epsilon_{fu} = C \epsilon_{fu} \]
*Equation 7*

Concrete strain at failure
\[ \beta_1 = \frac{4\epsilon_c' - \epsilon_c}{6\epsilon_c' - 2\epsilon_c} \]
*Equation 8*

<table>
<thead>
<tr>
<th>values calculated from equations</th>
<th>Regular CFRP</th>
<th>Pre-saturated CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{fe} ) (equation 7)</td>
<td>0.00855</td>
<td>0.008892</td>
</tr>
<tr>
<td>( E_f ) (Given, design property)</td>
<td>8200 KSI</td>
<td>8973 KSI</td>
</tr>
<tr>
<td>( F_{fe} ) (equation 6)</td>
<td>70.11 KSI</td>
<td>79.787 KSI</td>
</tr>
<tr>
<td>( \beta_1 ) (equation 8)</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>( M_{mf} ) (equation 5)</td>
<td>42.178 kips-inch</td>
<td>45.6 kips-inch</td>
</tr>
</tbody>
</table>

**A.2 Columns**

The column strength as
\[ F_c = 3914.35 \text{ psi} \]

Area of circular column of diameter 6 inches
\[ A_g = \pi \times 3^2 \]
\( \phi = 0.65 \)

So column without any strengthening = \( P \)

\[ P = \phi \times A \times g \times F \times c \quad \text{Equation 9} \]

Column strengthened with FRP

\[ \phi P_n = \phi 0.8(0.85f_{cc'}(A_g - A_{st}) + f_y A_{st}) \quad \text{Equation 10} \]

The confined concrete strength

\[ f_{cc} = f'_{c} + w_f \times 3.3 \times \kappa_a \times f_l \quad \text{Equation 11} \]

Where \( f'_{c} \) is the confined concrete strength

\( W_f \) is the wrapping reduction factor as per ACI 440.2R.17 which is taken as 0.95 and \( \kappa_a \)

for circular cylinder is taken as 1 (confined cross sectional area factor).

\( f_l \) is the confinement pressure which is calculated as

\[ f_l = \frac{2Efntf \cdot \varepsilon_{fe}}{D} \quad \text{Equation 12} \]

<table>
<thead>
<tr>
<th>Description</th>
<th>Regular CFRP</th>
<th>Pre-Saturated CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confinement pressure ( f_l )</td>
<td>0.317</td>
<td>0.342</td>
</tr>
</tbody>
</table>

*Table 18 the computed confinement strength for different FRP laminates*

After considering, the computed value of the factors in the equations following is the calculated capacity of columns without confinement, with regular confinement and Pre-saturated confinement.
Table 19 theoretical computed column capacities

<table>
<thead>
<tr>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Phi )</td>
<td>0.65</td>
</tr>
<tr>
<td>( f_{cc} )</td>
<td>3914.35Psi</td>
</tr>
<tr>
<td>( A_g )</td>
<td>28.2857 Inch(^2)</td>
</tr>
<tr>
<td>Axial capacity for concrete</td>
<td>48938.3 psi</td>
</tr>
<tr>
<td>Axial capacity with regular CFRP</td>
<td>6136.29 Psi</td>
</tr>
<tr>
<td>Axial capacity with Pre-saturated CFRP</td>
<td>6234.29 Psi</td>
</tr>
</tbody>
</table>

For the additional layers, conservatively the number of layers of confinement multiplies with the theoretical values of confinement.
References


3. Building Code Requirements for Structural Concrete (ACI 318M-08) and Commentary (ACI 318R-08). American Concrete Institute, 2008.


5. Circular and Square Concrete Columns Externally Confined by CFRP Composite: Experimental Investigation and Effective Strength Models. (n.d.). Retrieved March 31, 2018, from https://hal.archives-ouvertes.fr/hal-00782084


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Preeti Pandey, graduated with a degree of Masters in science in Structures and Applied Mechanics from University of Texas at Arlington in May, 2018. She completed her bachelors in Civil Engineering from India in May, 2016. This Research was the part of her completion of Master’s thesis in University of Texas at Arlington. She is pursuing her career in Structural Engineering and her area of interest includes- Building Design, Bridge Design and Restoration/Retrofitting of structures.