Study of an Experimental Anchor System - Staple Anchors - for Externally Bonded Frp Laminates Used for the Consolidation and Retrofitting of Reinforced Concrete Structures through an Innovative Double Shear Test Method

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Co-Advisor: Prof. Antonio NANNI

Master Thesis of Thomas CADENAZZI
1. FRP Laminates for Rehabilitation Purposes
2. FRP Anchorage System Purposes
3. Specimen Preparation & Experimental Program
   - Test 1 – Dry CFRP testing
   - Test 2 – Wet CFRP testing (innovative method)
4. Results
   - Failure mode analysis
   - Flat Staples
   - Round Staples
5. Comparisons: Staples vs. Spikes
6. Recommendation on Preliminary Design Previsions
1. **FRP Laminates for Rehabilitation Purposes**

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6. **Recommendation on Preliminary Design Previsions**
FRP Laminates for Rehabilitation Purposes

The Material: Impregnation

Epoxy Resin + Hardening (Amine)

(CNR, 2014)
The Material: Fiber Reinforced Polymers

Carbon Fibers

Epoxy Resin

- High Mechanical Properties
- High Specific Resistance
- Immunity to Corrosion
- High Environmental Resistance
- Lightness
- Cheapness
- Easy to use
- High Adhesion

(CNR, 2014)
CFRP Laminate properties

- Lightness
- High Mechanical Properties
- Immunity to Corrosion

Elastic modulus CFRP 200H: 77.04 GPa
Elastic modulus steel: 210 GPa
The debonding is the loss of adhesion of a thin concrete layer at strain levels much smaller than the ultimate capacity of the composite. Four types of debonding

1) End Debonding

2) Intermediate Debonding

3) Debonding caused by diagonal shear cracks

4) Debonding caused by irregularities and roughness of concrete surface

(Adapted from CNR, 2014)
Anchorage System Purposes

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Anchorage System Purposes

Prevent or delay the interfacial crack opening at the starting of debonding or failure of the concrete substrate

(Grelle & Sneed, 2013)

Shear stresses + “peeling stresses”
Anchorage System Purposes

It should be kept in mind that in flexural elements, peeling stresses also develop along the FRP-concrete interface and their interaction with shear stresses can lead to a reduction in the bond strength of the strengthening system.
Anchorage System Purposes

Intermediate Debonding Direction

End Debonding Direction

(CNR, 2014)
Double-shear test, test of anchorage system characterization

The **force transfer** between FRP plate and concrete substrate takes place primarily through **shear stresses**. **Shear tests** are adopted to determine the **maximum debonding force**.

Due to symmetry and for better control of induced normal stresses, the double-shear test is generally preferred over the single shear test.
Existing types of FRP anchorage systems

1. Anchor Spikes

2. Transverse Wrapping

3. U-Anchors

4. FRP Strips

5. Longitudinal Chase
Existing types of FRP anchorage systems

6. Plate Anchors

7. Bolted Angles

8. Cylindrical Hollow Section
Staple Anchors – Preformed anchorage systems

1) FLAT STAPLE

2) ROUND STAPLE

competitive

1. Low manufacturing costs
2. Easy to apply (preformed elements)
3. High mechanical properties
With the uni-directional fibers of the anchor aligned in a longitudinal way to the flexural FRP sheet, the flat staple anchor is made by carbon fibers pre-impregnated with a particular synthetic resin.
The uni-directional fibers of the anchor are aligned in a longitudinal way to the flexural FRP sheet, covered by an epoxy layer (matrix) that keeps the fibers together.
Round Staples – 2nd Design Idea

1) The under part of the anchor is flat, increasing the area in contact with the FRP laminate.
2) The upper part of the anchor is elliptical. This shape allows the squeezed epoxy in excess to come out laterally, by the legs sides of the anchor.
3) More fibers were concentrated on the bend radius, improving the resistance in this location, where the stresses are more concentrated.
Round Staples – 2nd Design Idea

3D View

Cross-section

0.25"

0.5"
Specimen Preparation & Experimental Program

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The length $l_e$ is called **optimal bond length** and corresponds to the minimal bond length able to carry the maximum anchorage force.

$\ell_{ed} = \max \left\{ \frac{1}{Y_{Rd} \cdot f_{bd}} \sqrt{\frac{\pi^2 \cdot \gamma_{f} \cdot t_f \cdot E_f \cdot \Gamma_{fd}}{2}} \cdot 150 \text{ mm} \right\}$
# Shear Test Program

## Data

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ef</td>
<td>Elastic Modulus FRP</td>
<td>77040,00</td>
<td>Mpa</td>
</tr>
<tr>
<td>tf</td>
<td>thickness of FRP</td>
<td>1,02</td>
<td>mm</td>
</tr>
<tr>
<td>FC</td>
<td>Confidence factor</td>
<td>1,00</td>
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</tr>
<tr>
<td>bf</td>
<td>width</td>
<td>152,40</td>
<td>mm</td>
</tr>
<tr>
<td>b</td>
<td>length</td>
<td>254,00</td>
<td>mm</td>
</tr>
<tr>
<td>Kb</td>
<td>geometrical corrective factor</td>
<td>0,94</td>
<td>-</td>
</tr>
<tr>
<td>KG</td>
<td>additional corrective factor for wet lay-up systems</td>
<td>0,04</td>
<td>mm</td>
</tr>
<tr>
<td>fctm</td>
<td>concrete tensile strength</td>
<td>4,13</td>
<td>Mpa</td>
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<tr>
<td>fcm</td>
<td>concrete compressive strength</td>
<td>59,00</td>
<td>Mpa</td>
</tr>
<tr>
<td>Γfd</td>
<td>Design fracture energy</td>
<td>0,41</td>
<td>Mpamm</td>
</tr>
<tr>
<td>su</td>
<td>design bond strength between FRP and concrete</td>
<td>0,25</td>
<td>-</td>
</tr>
<tr>
<td>YRd</td>
<td>Corrective factor (standard)</td>
<td>1,25</td>
<td>-</td>
</tr>
<tr>
<td>fbd</td>
<td>factor fbd</td>
<td>3,27</td>
<td>Mpa</td>
</tr>
</tbody>
</table>

\[
L_{ed} = 97,25 \text{ mm } ( = 3,83 \text{ in.})
\]
Concrete Properties

Calculations on \textit{concrete characterization} and \textit{blocks size}

\[ f'_t = 0.7 \frac{0.27(f'_c)^{2/3}}{1.5} = 0.7 \frac{0.27(59.84)^{2/3}}{1.5} = 1.93 \text{ MPa} \]

\[ A = 10 \text{ in} \cdot 10 \text{ in} = \]

\[ = 254 \text{ mm} \cdot 254 \text{ mm} = 64,516 \text{ mm}^2 \]

\[ P_{\text{max},th} = \frac{f'_t}{1000} \text{ [KPa]} \cdot A = \frac{1.93}{1000} \cdot 64,516 = 124,36 \text{ KN} \]
Specimen Preparation: Concrete Casting & Sandblasting
Concrete Properties

\[ f'_c = \frac{P_m[N]}{A[mm^2]} = \frac{491869N}{8202\text{ mm}^2} = 59.84 \text{ MPa} \]
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Test 1 – Dry CFRP testing
Test 1 – Dry CFRP testing

INSUFFICIENT RESULTS AND NOT RELIABLE
Results test 1

**NOT RELIABLE RESULTS**

- **Different stresses distribution on the dry CFRP**, caused by the not perfectly centered applied load, that brought to a rip in the most stressed fiber, causing the cracking start. It is important to remind that in the dry CFRP, as soon as a little crack occur, this immediately propagate toward the closest dry fibers, leading to the crack of the entire CFRP sheet.
- **The unevenness of adhesive on CFRP sheet out of the bond area**, leading to uneven stress distribution in the CFRP fibers.
- The application of the epoxy resin on CFRP sheet out of the bond area, leading again to uneven stress distribution in the CFRP fibers.
- The **low unbounded area** furnished on the concrete surface (only 1 inch), which could have caused again an **uneven stress distribution** in the CFRP fibers, just out of the bonded area where most of the ruptures occurred.
Specimen Preparation & Experimental Program

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Testing

Aims

I. Find a test which is reliable, repeatable, easy to perform and able to represent the stress state in the real applications

II. Anchors characterization in different configurations

III. Spike anchors comparison
   - Peak load
   - Strains
   - Failure modes
Test 2 – Wet CFRP test preparation

EPS FOAM SHAPES

Mylar sheet
Test 2 – Wet CFRP test preparation

EPS FOAM SHAPES
Test 2 – Wet CFRP test preparation

EPS FOAM SHAPES
Test 2 – Wet CFRP test
1) It represents exactly the real application when the system acts in situ. An interrupted strip of wet CFRP acts as a continuum system.

2) Impregnating the carbon fibers with an epoxy resin allows the latter to behave as a matrix, which means to keep the fibers straight, transferring evenly the stresses to them, avoiding intensifications or different stresses distribution along all the CFRP strip.
Results

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6 Failure modes:

A. Rupture as delamination of the CFRP sheet
B. Slippage of the CFRP sheet beneath the anchor, without their ruptures
C. Slippage of the CFRP sheet beneath the anchor, with the rupture of the CFRP sheet
D. Rupture of the anchor with the delamination of the CFRP
E. Rupture of the concrete substrate and rupture of the anchor
F. Rupture of the concrete substrate without the rupture of the anchor
A. Rupture as delamination of the CFRP sheet

Rupture by debonding of the CFRP sheet at the adhesive-to-concrete interface. Only the benchmarks presented this type of failure. That is due to the fact that of the absence of an anchorage system.

PREVALENT ON BENCHMARKS
Failure mode analysis

B. Slippage of the CFRP sheet beneath the anchor, without their ruptures

Debonding of the CFRP sheet at the adhesive-to-concrete interface, followed literally by a slippage of the CFRP sheet beneath the anchor, as to mean an insufficient adhesive-to-concrete and anchor-to-CFRP interface.

ACCIDENTAL, OBSERVED ONLY IN ONE SPECIMEN
C. Slippage of the CFRP sheet beneath the anchor, with the rupture of the CFRP sheet

The sheet has developed its full strength (readings of good strains level around 0.7-0.8%), with a good anchor resistance. **The failure mode C is ideal for determining the sufficiency of the anchors** and develop guidelines for anchor design.
D. Rupture of the anchor with the delamination of the CFRP

The failure of the anchor indicates that anchors do not have sufficient capacity to develop the full strength of the CFRP sheet and is generally an undesirable failure mode. Failure mode D was observed only for the round staple anchor.
Failure mode analysis

E. Rupture of the concrete substrate and rupture of the anchor

The rupture of the concrete always initiated first at one end, where the leg of the round staple was embedded; after this, immediately the opposite leg of the anchor took the entire stress, breaking again the anchor along the bend radius.
Failure mode analysis

F. Rupture of the concrete substrate without the rupture of the anchor

The failure was due entirely to the rupture of the concrete substrate. Since the maximum shear capacity of the non-reinforced concrete was reached, the anchor was still performing well, assuming that it could have been achieved a higher load.
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# Results test 2 - Flat staples

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Anchor's dimensions</th>
<th>P/2 [KN]</th>
<th>Increase in Peak Load [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BENCHMARKS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2_BM_001</td>
<td>No anchor</td>
<td>29,01</td>
<td>-19,68%</td>
</tr>
<tr>
<td>T2_BM_002</td>
<td>No anchor</td>
<td>37,88</td>
<td>4,91%</td>
</tr>
<tr>
<td>T2_BM_003</td>
<td>No anchor</td>
<td>41,45</td>
<td>14,77%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>36,11</td>
<td>0,00%</td>
</tr>
<tr>
<td><strong>FLAT STAPLES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2_FS_3W_001</td>
<td>3&quot;W - 1&quot;D</td>
<td>55,37</td>
<td>53,34%</td>
</tr>
<tr>
<td>T2_FS_3W_002</td>
<td>3&quot;W - 1&quot;D</td>
<td>62,26</td>
<td>72,41%</td>
</tr>
<tr>
<td>T2_FS_3W_003</td>
<td>3&quot;W - 1&quot;D</td>
<td>81,62</td>
<td>126,01%</td>
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<td><strong>Average</strong></td>
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<td>66,42</td>
<td>83,92%</td>
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<tr>
<td>T2_FS_2W_001</td>
<td>2&quot;W - 1&quot;D</td>
<td>54,78</td>
<td>51,69%</td>
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<td>T2_FS_2W_002</td>
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<td>66,98</td>
<td>85,49%</td>
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<tr>
<td>T2_FS_2W_003</td>
<td>2&quot;W - 1&quot;D</td>
<td>64,88</td>
<td>79,65%</td>
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<tr>
<td><strong>Average</strong></td>
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<td>62,21</td>
<td>72,28%</td>
</tr>
<tr>
<td>T2_FS_1W_001</td>
<td>1&quot;W - 1&quot;D</td>
<td>57,18</td>
<td>58,34%</td>
</tr>
<tr>
<td>T2_FS_1W_002</td>
<td>1&quot;W - 1&quot;D</td>
<td>55,69</td>
<td>54,21%</td>
</tr>
<tr>
<td>T2_FS_1W_003</td>
<td>1&quot;W - 1&quot;D</td>
<td>59,17</td>
<td>63,84%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
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<td>57,35</td>
<td>58,80%</td>
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</tbody>
</table>
Results test 2

FLAT STAPLE 2W_1D_001

Left Side - Perpendicular strains

FRP Strain

FRP Width (in)

Strains at peak load [KN]

54.78 43.75
26.75 16.45
8.93 5.14

FLAT STAPLE 2W_1D_001
Results test 2

FLAT STAPLE 2W_1D_001

Left side - Parallel strains

Strains at peak load [KN]
- 54.78
- 43.75
- 26.75
- 16.45
- 8.93
- 5.14

FRP Strain vs FRP Length (in)
Results test 2

**FLAT STAPLE 2W_1D_001**

![Graph showing load vs. FRP strain for different samples labeled F1, F2, F3, F4, and F5.]
Progressive behavior of the debonding crack, which initiated at the loaded end (readings of the SG2, SG3, SG4) and propagated towards the free end, behind the anchor as the reading of the SG5.
Results test 2

AVERAGE INCREASE – PEAK LOADS
Results test 2

PERCENTUAL INCREASE - PEAK LOADS

- Width 1: 58.80%
- Width 2: 72.28%
- Width 3: 83.92%
Results

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### Results test 2 - Round staples

#### Shear test n.2 (WET FRP)

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Anchor's dimensions</th>
<th>P/2 [KN]</th>
<th>Increase in Peak Load [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BENCHMARKS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2_BM_001</td>
<td>No anchor</td>
<td>29,01</td>
<td>-19,68%</td>
</tr>
<tr>
<td>T2_BM_002</td>
<td>No anchor</td>
<td>37,88</td>
<td>4,91%</td>
</tr>
<tr>
<td>T2_BM_003</td>
<td>No anchor</td>
<td>41,45</td>
<td>14,77%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>36,11</td>
<td>0,00%</td>
</tr>
<tr>
<td><strong>ROUND STAPLES</strong></td>
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<td></td>
</tr>
<tr>
<td>RS_2D_001</td>
<td>2&quot;D_OLD</td>
<td>30,75</td>
<td>-14,86%</td>
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<tr>
<td>RS_2D_002</td>
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<td>36,49</td>
<td>1,05%</td>
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<tr>
<td>RS_2D_003</td>
<td>2&quot;D_NEW</td>
<td>49,13</td>
<td>36,06%</td>
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<tr>
<td><strong>Average</strong></td>
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<td>49,13</td>
<td>36,06%</td>
</tr>
<tr>
<td>RS_1D_001</td>
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<td>46,34</td>
<td>28,31%</td>
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<tr>
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<td>59,20</td>
<td>63,94%</td>
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<td>52,31</td>
<td>44,86%</td>
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<td>45,70%</td>
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<td><strong>Average</strong></td>
<td></td>
<td>65,61</td>
<td>81,70%</td>
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</table>
Results test 2

AVERAGE INCREASE – PEAK LOADS
Results test 2

PERCENTUAL INCREASE - PEAK LOADS

PERCENTAGE [%]

0,00% 10,00% 20,00% 30,00% 40,00% 50,00% 60,00% 70,00% 80,00% 90,00%

R.S_1D  D.R.S_1D

45,70% 81,70%
Comparisons: Staples vs. Spikes

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**Peak load interpretation**

<table>
<thead>
<tr>
<th>Anchor's type</th>
<th>Anchor's Configuration</th>
<th>Peak Load [KN]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spike anchors</strong></td>
<td>60 degrees fan opening</td>
<td>57,8</td>
</tr>
<tr>
<td></td>
<td>90 degrees fan opening</td>
<td>66,38</td>
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<tr>
<td><strong>Flat staple anchors</strong></td>
<td>1 in. width – 1 in. depth</td>
<td>57,35</td>
</tr>
<tr>
<td></td>
<td>2 in. width - 1 in. depth</td>
<td>62,21</td>
</tr>
<tr>
<td></td>
<td>3 in. width - 1 in. depth</td>
<td>66,42</td>
</tr>
<tr>
<td><strong>Round staple anchors</strong></td>
<td>Single conf. - 1 in. depth</td>
<td>52,62</td>
</tr>
<tr>
<td></td>
<td>Double conf. - 1 in. depth</td>
<td>65,61</td>
</tr>
</tbody>
</table>
Strain interpretation – Spike anchors

- $\varepsilon = 0.06\%; L = 50.8\,\text{mm}
- $\varepsilon = 0.86\%; L = 101.6\,\text{mm}$
- $\varepsilon = 0.05\%; L = 20.3\,\text{mm}$
- $\varepsilon = 0.70\%; L = 132.1\,\text{mm}$
Strain interpretation – Flat staples

\[ \varepsilon = 0.58\% \]
Strain interpretation – Round staples
Failure modes - comparison

**SPIKE ANCHORS**

**FLAT STAPLE**
Recommendation on Preliminary Design Previsions

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Results - Discussions

Based on:

- **Dispersion of the results** (a low COV observed mainly in the 2-inches flat staple anchorage system).
- **Type of rupture** (the ideal failure mode is the failure mode C, which represents the full strength developed by the CFRP laminate).
- **Strains interpretation** (highest values of the strains are obviously preferred).
- **Peak load** significantly high.

We can say that the best configurations are:

- The 2-inches width, 1-inch depth anchor, for the flat staple anchorage system.
- The double round staple configuration, with 1-inch depth, for the round staple anchorage system.
Results - Discussions

FLAT STAPLES: 2-inches width

- 3-inches width anchor → **Concrete failure** (high concrete strength! 59MPa of f’c)
- The 2-inches width anchor → Delamination and rupture of the FRP laminate, without the anchor rupture (in two cases: mixed rupture of concrete and the FRP laminate).
- Excellent stresses distribution and relevant values of the strains → 2-inches width anchor is sufficient to develop the full strength of the FRP laminate
Results - Discussions

ROUND STAPLES: The double round staple configuration

- 24.7% increase of peak load compared to the single configuration
- Increase of the strain values → develop the full strength of the FRP laminate
- Better resistance through the work of both the anchors (without their rupture)
Future studies

- Changing values of depth \( \rightarrow \) **Pull-out stresses**

Finally, thanks to the results obtained in this research, tests should be conducted on beams, as follows:

- One anchor 2-inches width, 1-inch depth on each end, on a 6” FRP sheet width.

- A double round staple configuration, 1-inch depth on each end, always on a 6” FRP sheet – width.
Aims

I. Find a test which is reliable, repeatable, easy to perform and able to represent the stress state in the real applications

II. Anchors characterization in different configurations

III. Spike anchors comparison

   o Peak load

   o Strains

   o Failure modes
Thank you for your attention
Voids & Durability Hazard

Thermal Camera

Thomas Cadenazzi
Voids & Durability Hazard

Thermal Camera
Surface and anchors’ hole preparation
Surface and anchors’ hole preparation
Anchors sizes

\[ A_{fan} = \frac{(r + R)w_{fan}}{2} \cos\left(\frac{\alpha}{2}\right) - \frac{rd}{2} \cos\left(\frac{\alpha}{2}\right) - \frac{\pi d^2}{8} + \frac{2}{3} p w_{fan} \]

Area \(60\) degrees fan opening \(= 7,55 \text{ in}^2 = 48,71 \text{ cm}^2\)

Area \(90\) degrees fan opening \(= 10,15 \text{ in}^2 = 65,48 \text{ cm}^2\)
Anchors sizes

Flat staples

Length = 6 in. = 15.24 cm

Width = Variable = ?

1) Width = 1 in = 25.4 cm
2) Width = 2 in = 5.8 cm
3) Width = 3 in = 7.62 cm

Area \text{1 in.width} = 6 \text{ in}^2 = 38.71 \text{ cm}^2
Area \text{2 in.width} = 12 \text{ in}^2 = 77.42 \text{ cm}^2
Area \text{3 in.width} = 18 \text{ in}^2 = 116.13 \text{ cm}^2
Anchors sizes

Round staples

Length = 6 in. = 15.24 cm
Width = 0.5 in. = 1.27 cm
Area = 3 in² = 19.35 cm²

Sandwich configuration
Sandwich configuration – round staples
Anchors sizes

Round staples

Length = 6 in. = 15.24 cm
Width = 0.5 in. = 1.27 cm
Area = 3 in.² = 19.35 cm²

Sandwich configuration

\[ \sigma = E \cdot \varepsilon \rightarrow \frac{P}{A} = E \cdot \varepsilon \]

\[ \rightarrow P = E \cdot \varepsilon \cdot A \]

\[ A \uparrow \rightarrow P \uparrow \]

N.B. CFRP sheet thickness = 1 mm
Fixed at 1”. Infact 1” of anchors depth is sufficient and ideal for a main reason:

The rebar interaction!

Since most of the worldwide regulations give some minimum requirements for the concrete cover (see table 4.1), a 1” depth, while anchoring an FRP reinforcement, would not be a problem of interact and damage the internal reinforcement of a slab.
EPS FOAM SHAPES
Steel support cut

Section A-A

- Upper plate
- Lower plate

Front view

- A

Dimensions:
- 18
- 14
- 13
- 10
- 0.5
- 2.89
- 18
Existing types of FRP anchorage systems

1. Anchor Spikes
2. Transverse Wrapping
3. U-Anchors
4. FRP Strips
5. Longitudinal Chase
6. Plate Anchors
7. Bolted Angles
8. Cylindrical Hollow Section
Anchor Spikes

Figure 1.9 - 90° anchor spikes

Complete fan ➔ P

Single fan ➔ P

Single fan (Reverse) ➔ P

Double fan ➔ P

\[ h \]

\[ \beta \]

\[ \alpha \]
Transverse wrapping is usually in the form of discrete strips situated along the laminate length or at its end. The fiber orientation can be perpendicular to the longitudinal axis or inclined with a certain angle.
A U-Anchor is installed in a groove made in the concrete surface onto which or adjacent to where the strengthening FRP sheets are placed. The FRP sheets are then pressed into the groove that is filled with epoxy, sometimes in combination with steel bars.
Fiber reinforced polymer strips are a very simple type of anchorage, installed on the top of the FRP sheet used to strengthen the reinforced concrete member. They are typically installed perpendicular to the direction of the force of the strengthening FRP sheets and for this reason they have limited efficiency.
The groove is filled in with epoxy resin and, in some cases, a steel or FRP bar is embedded. The FRP sheet is bonded to the concrete and over the top of the groove. This anchorage system is based on the concept that the interfacial shear stresses are better distributed to a larger area of concrete through the mechanical properties of the epoxy resin poured into the groove.
Plate Anchors

This anchorage system is made up of FRP sheets anchored to the plates (metallic or composite plates), which are either bolted or bonded to the concrete substrate. This configuration allows transferring the shear stress to the FRP–plate interface.
Installed in 90° joints. Usually, the FRP is laid around the joint, the angle is bonded to the FRP in the joint and bolted to the concrete either through or around the FRP sheet. Even if bolted angles have several limitations, as the problem of corrosion (they are made of steel) or the problem of stress concentration in the FRP (due to the 90° corner), they are frequently used because steel angle shapes are easy to obtain and require little fabrication.
Designed for 90° joints applications, this type of anchorage is composed of a steel pipe bolted through the FRP at a 45° angle in order to eliminate the potential for local stress concentrations at the 90° corner.
1. prevent or delay the interfacial crack opening at the starting of debonding or failure of the concrete substrate

2. increases the total available interfacial shear stress transfer

transfer length is less than the effective bond length, usually due to the geometric conditions of the structural member
1. prevent or delay the interfacial crack opening at the starting of debonding or failure of the concrete substrate

2. increases the total available interfacial shear stress transfer

3. provides a load transfer mechanism at critical locations of structural members (such as at the location of an interface between two orthogonal structural members) where no bond length is available beyond the critical section.
Anchorage System Purposes

(CNR, 2014)
### Results test 1

#### Shear test n.1 (DRY CFRP)

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Anchor's dimensions</th>
<th>P [KN]</th>
<th>P/2 [KN]</th>
<th>Increase in Peak Load [%]</th>
<th>Rupture Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BENCHMARKS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1_BM_001</td>
<td>No anchor</td>
<td>45,80</td>
<td>22,90</td>
<td>34,53%</td>
<td>G</td>
</tr>
<tr>
<td>T1_BM_002</td>
<td>No anchor</td>
<td>22,29</td>
<td>11,15</td>
<td>-34,53%</td>
<td>G</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>34,05</td>
<td>17,02</td>
<td>0,00%</td>
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<tr>
<td>T1_FS_3W_2D_001</td>
<td>3&quot;W - 2&quot;D</td>
<td>39,33</td>
<td>16,16</td>
<td>-5,06%</td>
<td>G</td>
</tr>
<tr>
<td>T1_FS_3W_2D_002</td>
<td>3&quot;W - 2&quot;D</td>
<td>88,04</td>
<td>44,02</td>
<td>158,57%</td>
<td>G/C</td>
</tr>
<tr>
<td>T1_FS_3W_2D_003</td>
<td>3&quot;W - 2&quot;D</td>
<td>61,16</td>
<td>30,58</td>
<td>79,62%</td>
<td>G</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>60,51</td>
<td>30,25</td>
<td>158,57%</td>
<td></td>
</tr>
<tr>
<td>T1_FS_3W_1D_001</td>
<td>3&quot;W - 1&quot;D</td>
<td>67,11</td>
<td>33,56</td>
<td>97,11%</td>
<td>G</td>
</tr>
<tr>
<td>T1_FS_3W_1D_002</td>
<td>3&quot;W - 1&quot;D</td>
<td>83,55</td>
<td>41,78</td>
<td>145,40%</td>
<td>G/C</td>
</tr>
<tr>
<td>T1_FS_3W_1D_003</td>
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<td>67,31</td>
<td>33,65</td>
<td>97,68%</td>
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<tr>
<td><strong>Average</strong></td>
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<td>72,66</td>
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<td>1,5&quot;W - 2&quot;D</td>
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<td>80,91%</td>
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<tr>
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<td>1,5&quot;W - 2&quot;D</td>
<td>34,25</td>
<td>17,12</td>
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<tr>
<td>T1_FS_1,5W_2D_003</td>
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<td>86,35</td>
<td>43,18</td>
<td>153,62%</td>
<td>G/C</td>
</tr>
<tr>
<td><strong>Average</strong></td>
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<td>60,73</td>
<td>30,37</td>
<td>153,62%</td>
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<tr>
<td>T1_FS_1,5W_1D_001</td>
<td>1,5&quot;W - 1&quot;D</td>
<td>59,67</td>
<td>29,83</td>
<td>75,25%</td>
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<td>43,20</td>
<td>153,78%</td>
<td>G/C</td>
</tr>
<tr>
<td>T1_FS_1,5W_1D_003</td>
<td>1,5&quot;W - 1&quot;D</td>
<td>64,89</td>
<td>32,44</td>
<td>90,57%</td>
<td>G</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>70,32</td>
<td>35,16</td>
<td>153,78%</td>
<td></td>
</tr>
</tbody>
</table>
Thank you for your attention