FRP Reinforced Concrete Design

Presented by: Rick Vallier, P.E.
FDOT Structures Design Office
Hypothetical Bridge Replacement Project

Structure in an Extremely Aggressive marine environment

- **Plans Preparation Manual (PPM) 2.10.1**
  - Vertical clearance for concrete superstructure over extremely aggressive environments is 12 ft. above the Mean High Water (MHW).

- **Structures Design Guidelines (SDG) 1.4.2**
  - Concrete cover requirements in extremely aggressive environments.

- **Structures Design Guidelines (SDG) 1.4.3**
  - Admixtures for Corrosion Protection: fly ash, slag, silica fume, metakaolin, ultrafine fly ash to reduce permeability.
Alternatives to Carbon Steel Reinforcement

This type of project needs to be considered for corrosion resistant materials.

Two alternatives to carbon steel as concrete reinforcement for corrosion resistance on FDOT projects are:

**Stainless Steel**
- Bar (Spec. 931)
- Strand – HSSS (Spec. 933)

**FRP Reinforcement**
- Bar – GFRP (Spec. 932)
- CFRP (Spec. 932)
- Strand – CFRP (Spec. 933)
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**FRP Reinforcement**
- Bar – GFRP (Spec. 932)
- CFRP (Spec. 932)
- Strand – CFRP (Spec. 933)
# Reinforcing Bars

## FDOT Spec. 932-3.2 Bar Sizes and Loads

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>2</td>
<td>0.250</td>
<td>0.049</td>
<td>0.046</td>
<td>0.085</td>
</tr>
<tr>
<td>3</td>
<td>0.375</td>
<td>0.11</td>
<td>0.104</td>
<td>0.161</td>
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<tr>
<td>4</td>
<td>0.500</td>
<td>0.20</td>
<td>0.185</td>
<td>0.263</td>
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<tr>
<td>5</td>
<td>0.625</td>
<td>0.31</td>
<td>0.288</td>
<td>0.388</td>
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<tr>
<td>6</td>
<td>0.750</td>
<td>0.44</td>
<td>0.415</td>
<td>0.539</td>
</tr>
<tr>
<td>7</td>
<td>0.875</td>
<td>0.60</td>
<td>0.565</td>
<td>0.713</td>
</tr>
<tr>
<td>8</td>
<td>1.000</td>
<td>0.79</td>
<td>0.738</td>
<td>0.913</td>
</tr>
<tr>
<td>9</td>
<td>1.128</td>
<td>1.00</td>
<td>0.934</td>
<td>1.137</td>
</tr>
<tr>
<td>10</td>
<td>1.270</td>
<td>1.27</td>
<td>1.154</td>
<td>1.385</td>
</tr>
</tbody>
</table>
Reinforcing Bars

Characteristics of FRP Reinforcement:

- Polymer resin matrix relatively weak
  - Bond force is transferred through resin to fibers
  - Shear resistance is considered relatively weak
- Low compressive strength of FRP
  - Design of FRP reinforcement to resist compression is not recommended
- Modulus of Elasticity is low
  - Due to lower stiffness, serviceability often controls the design
- Creep-rupture threshold is low
  - Constant tension can cause fibers to fail after a period of time called the endurance time
  - GFRP is considered more susceptible than CFRP
Reinforcing Bars

Characteristics of FRP Reinforcement:

- Linear Elastic to Failure
- No Yielding
- Higher Ultimate Strength
- Lower Strain at Failure

<table>
<thead>
<tr>
<th>Bar Type</th>
<th>Yield Strength $f_y$ or Tensile Strength $f_{tu}$, ksi (MPa)</th>
<th>Modulus of Elasticity, ksi (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>60 (414)</td>
<td>29,000 (200)</td>
</tr>
<tr>
<td>GFRP</td>
<td>80 (552)</td>
<td>6000 (41.4)</td>
</tr>
<tr>
<td>AFRP</td>
<td>170 (1172)</td>
<td>12,000 (82.7)</td>
</tr>
<tr>
<td>CFRP</td>
<td>300 (2070)</td>
<td>22,000 (152)</td>
</tr>
</tbody>
</table>

From ACI 440.1R-15
Reinforcing Bars

FRP Bar **Mechanical Characteristics** Influenced By:

Pre-Construction
- Manufacturing Process
- Rate of Curing
- Quality and Quantity of Constituents

Construction and Post-Construction
- Moisture
- Ultraviolet Exposure
- Elevated Temperature
- Alkaline, Acidic, Saline Solutions
**Characteristics of FRP Reinforcement:**

- Coefficient of thermal expansion is different in the longitudinal and radial directions
  - Potential for splitting cracks within concrete under temperature increase if concrete confining action is insufficient
  - Ratio of cover to bar diameter greater than 1.6 is considered sufficient to avoid cracking under high temperatures up to 175°F

<table>
<thead>
<tr>
<th>Direction</th>
<th>Steel</th>
<th>GFRP</th>
<th>CFRP</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>6.5</td>
<td>3.3 to 5.6</td>
<td>-4.0 to 0.0</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Transverse</td>
<td>6.5</td>
<td>11.7 to 12.8</td>
<td>41 to 58</td>
<td>4 to 6</td>
</tr>
</tbody>
</table>

From ACI 440.1R-15, Table 4.1.2
Characteristics of FRP Reinforcement:

- Endurance time in fire and elevated temperature less than for steel
  - Reinforcement type, aggregate type, and concrete cover will influence fire performance
  - Tensile, compressive, and shear properties of the resin material diminish as temperature approaches the glass transition temperature (Tg).

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Transition Temperature (Tg)</td>
<td>ASTM E1640 (DMA) or</td>
<td>≥230°F</td>
</tr>
<tr>
<td></td>
<td>ASTM E1356 (DSC)</td>
<td>≥212°F</td>
</tr>
</tbody>
</table>

Reinforcing Bars

Characteristics of FRP Reinforcement:

- **Life cycle costs** likely lower where steel corrosion is a concern
- **Admixtures** for corrosion protection may not be needed:
  - Silica Fume
  - Ultrafine Fly Ash
  - Metakaolin
  - Calcium Nitrite
- **Transportation costs** lower and handling easier for FRP due to light weight
- **Concrete cover** reduction is allowed
Characteristics of FRP Reinforcement:

Bent Bars

- FRP is pultruded from thermoset resin
- FRP is fabricated with bends
  - Sharp bends can be manufactured, but avoid due to potential failure
  - Radius / Bar Diameter ≥ 3
  - Tail Length = 12 x Bar Diameter
  - Field bending not permitted
- Developmental Design Standard D21310 Bar Bending Details
Reinforcing Bars

From Developmental Design Standard D21310:

- **TYPE 1**
- **TYPE 2**
- **TYPE 3**
- **TYPE 4**
- **TYPE 5**
- **TYPE 6**
- **TYPE 7**
- **TYPE 8**
- **TYPE 9** (REFERENCE HOOK DETAILS)
- **TYPE 10** (REFERENCE HOOK DETAILS)
Reinforcing Bars

Complex Shapes:
To Bend FRP Bars:
1) During the pultrusion process, prevent polymerization of the resin at sections to be bent.
2) Bend the section by hand.
2) Place in an oven to complete polymerization.
Reinforcing Bars

**Flexural Strength Design Philosophy**

**Steel Reinforced Concrete Design**
- Tension-Controlled Behavior
- Yielding of Steel Prior to Concrete Crushing Provides Ductility and Warning of Distress

**FRP Reinforced Concrete Design**
- Tension-Controlled Behavior
  - FRP Rupture
- Compression-Controlled Behavior
  - Concrete Crushing prior to FRP Rupture
- Margin of Safety is Higher than for Steel Reinforced Design
Design Assumptions

- Plane sections remain plane
- Flexural strength using equivalent rectangular concrete stress distribution
- Compressive strain in concrete assumed to be 0.003
- Tensile strength of concrete is ignored
- Perfect bond exists between concrete and FRP reinforcement

- Tensile behavior of FRP reinforcement is linear elastic until failure
- Compressive strength of FRP reinforcement is ignored
Reinforcing Bars

Flexural Strength

Concrete:
  Compressive Strength  \( f'c = 5.5 \text{ ksi} \)

No. 8 GFRP – Based on Spec. 932:
  Nominal Bar Area  \( A_f = 0.79 \text{ in}^2 \)
  Minimum Modulus of Elasticity  \( E_f = 6,500 \text{ ksi} \)
  Minimum Guaranteed Tensile Load  66.8 kips

Guaranteed Tensile Strength
  \( f_{fu}^* = \frac{66.8 \text{ kips}}{0.79 \text{ in}^2} = 84.5 \text{ ksi} \)
Reinforcing Bars

Flexural Strength

\[ C_E = \text{Environmental Reduction Factor} = 0.7 \]

(ACI 440.1R-15: Concrete Exposed to Weather)

\[ f_{fu} = \text{Design Tensile Strength of FRP} \]

\[ f_{fu} = C_E \times f_{fu}^* = 0.7 \times 84.5 \text{ ksi} = 59 \text{ ksi} \]
## Reinforcing Bars

### Flexural Strength

<table>
<thead>
<tr>
<th></th>
<th>GFRP</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qty. of No. 8 Bars</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.01090</td>
<td>0.01635</td>
</tr>
<tr>
<td>$\rho$ balanced</td>
<td>0.01519</td>
<td>0.01519</td>
</tr>
<tr>
<td>Control</td>
<td>Tension</td>
<td>Transitioning</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.55</td>
<td>0.57</td>
</tr>
<tr>
<td>$M_n$ (kip-ft)</td>
<td>102</td>
<td>146</td>
</tr>
<tr>
<td>$\phi M_n$ (k-ft)</td>
<td>56</td>
<td>83</td>
</tr>
</tbody>
</table>
## Reinforcing Bars

### Flexural Strength

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<td>83</td>
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</table>
Reinforcing Bars

Flexural Strength

FRP Rupture
Concrete Crushing

Tension Control
Transition
Compression Control

\( \phi \)
\( \rho_f \)
\( \rho_{fb} \)
\( 1.4\rho_{fb} \)
Reinforcing Bars

**Cracking**

AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings

\[ w = 2 \frac{f_{fs} s}{E_f} \beta k_b \sqrt{d_c^2 + \frac{s^2}{4}} \]

\( w = \) maximum crack width
Crack Width Limit = 0.02 in.

**ACI 440.1R-15**

\[ S_{\text{max}} = 1.15 \frac{E_f w}{f_{fs k_b}} - 2.5 c_c \leq 0.92 \frac{E_f w}{f_{fs k_b}} \]

\( S_{\text{max}} = \) maximum bar spacing

**Deflection**

Deflections in FRP Reinforced members tend to be greater in magnitude than structures reinforced similarly with steel.
Reinforcing Bars

Creep Rupture & Fatigue

Limit Stress Levels:

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>GFRP</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creep rupture stress limit</td>
<td>$0.20f_{fu}$</td>
<td>$0.55f_{fu}$</td>
</tr>
</tbody>
</table>

$f_{fs,sus} =$ stress level induced in FRP by sustained service loads

$M_{s,sus} = \frac{n_f d (1-k)}{I_{cr}}$

Similar to Fatigue evaluation.

ACI 440.1R-15
Shear Strength

Resistance factors ($\phi$) for shear = 0.75

Minor modification due to lower stiffness of FRP than steel.

$$V_f = \frac{A_{fv} f_{fv} d}{s}$$

$$V_c = \left(\frac{5}{2} k\right) 2\sqrt{f'_{c}b_w d}$$

$$f_{fv} = 0.004E_f \leq f_{fb}$$
## Reinforcing Bars

### Cost Comparison (Installed Price)

<table>
<thead>
<tr>
<th>Bar Size</th>
<th>Nominal Diameter</th>
<th>Average Unit Costs of Three Bidders on the Halls River Bridge Project</th>
<th>FDOT Structures Manual for BDR Cost Estimating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GFRP Bar</td>
<td>CFRP Bar</td>
</tr>
<tr>
<td>#4</td>
<td>0.500”</td>
<td>$1.18 / LF</td>
<td>$7.99 / LF</td>
</tr>
<tr>
<td>#5</td>
<td>0.625”</td>
<td>$1.37 / LF</td>
<td>$8.34 / LF</td>
</tr>
<tr>
<td>#6</td>
<td>0.750”</td>
<td>$1.55 / LF</td>
<td>-</td>
</tr>
<tr>
<td>#8</td>
<td>1.000”</td>
<td>$2.54 / LF</td>
<td>-</td>
</tr>
</tbody>
</table>

**Note:** There is not 1:1 substitution of FRP for steel bars. Black steel bar based on $0.90 / lb for all bar sizes. Stainless steel bar based on $4.00 / lb for all bar sizes.
FDOT Structures Manual

FDOT Design Criteria for FRP:

**Vol. 1 – SDG**
- Bearing Piles – 3.5
- Fender Systems – 3.14
- Structural Fiber Reinforcement – 3.17
- BDR Cost Estimating – 9.2
  - Bearing Piles
  - Sheet Pile

**Vol. 2 – SDM**
- Fender Systems – 24

**Vol. 4 – FRPG**
- Reinforcing Bars – 2
- Strands – 3
- Strengthening – 4
- Pultruded Shapes – 5
- VIP Shapes – 6
- Thermoplastic Shapes – 7

[http://www.fdot.gov/structures](http://www.fdot.gov/structures)
FDOT Design Criteria for using FRP Composites:

The Structures Manual implements *basic design guidelines* for FRP composites in specific applications.

As is the case with all structural materials, the engineer must practice the *appropriate standard of care* when designing components using FRP composites.
Research and field implementation of FRP materials is ongoing and design recommendations continue to evolve.

<table>
<thead>
<tr>
<th>Completion Date</th>
<th>Title</th>
<th>Researcher</th>
<th>Institution</th>
<th>Research No.</th>
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</thead>
<tbody>
<tr>
<td>5/31/2018</td>
<td>Performance Evaluation of GFRP Reinforcing Bars Embedded in Concrete Under Aggressive Environments</td>
<td>R. Kampmann</td>
<td>FSU</td>
<td>BDV30 977-18</td>
</tr>
<tr>
<td>3/31/2018</td>
<td>Degradation Mechanisms and Service Life Estimation of FRP Concrete Reinforcements</td>
<td>A. El Safty</td>
<td>UNF</td>
<td>BDV34 977-05</td>
</tr>
</tbody>
</table>

http://www.fdot.gov/research

Halls River Bridge Replacement Project
Homosasss, Florida

http://www.fdot.gov/structures/innovation/FRP.shtm
Unless otherwise stated within the FRPG, the use of FRP composites requires approval of the State Structures Design Office.

Obtain concept approval before proceeding with any design effort.

After concept is approved, submit the design to the State Structures Design Office for review.

PPM 26.3.2: Structures with any component designed using FRP composite materials is a Category 2 Structure.
Permitted use of FRP reinforcement without prior approval by the State Structures Design Engineer:

- **GFRP/CFRP** reinforcing bars used for expansion joints in junction slabs when paired with a keyed joint
- **CFRP/GFRP Prestressed Concrete Bearing Pile**
  Design Standards (22600 Series)
- **CFRP/GFRP Prestressed Concrete Sheet Pile Wall**
  Design Standard 22440

**ALTERNATE STRAND PATTERNS**

- 4 ~ 0.6" Ø, CFRP 7-Strand, at 42 kips
- 4 ~ ½" Ø, CFRP Single-Strand, at 41 kips

From Design Standard 22612

12” Pile Cross Section
<table>
<thead>
<tr>
<th>Pile Location</th>
<th>Minimum Pile Size (inches)</th>
<th>Minimum Cylinder Pile Diameter (inches)</th>
<th>Material Properties for All Pile Sizes¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vehicular Bridges</td>
<td>Pedestrian Bridges &amp; Fishing Piers</td>
<td>Strand Type</td>
</tr>
<tr>
<td>Pile Bents</td>
<td></td>
<td></td>
<td>Carbon steel, Spec 933</td>
</tr>
<tr>
<td>New Construction</td>
<td>24²</td>
<td>18³</td>
<td>54³</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>14</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>Stainless steel, Spec 933</td>
<td>Stainless steel, Spec 931</td>
<td>Stainless steel, Spec 931</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>14</td>
<td>54</td>
</tr>
<tr>
<td>Footings</td>
<td>On land or in water (waterline or mudline) in environments that are Extremely Aggressive due to chlorides</td>
<td>24²</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>On land or in water in all other environments</td>
<td>18</td>
<td>14</td>
</tr>
</tbody>
</table>
## Table 3.5.1-1

<table>
<thead>
<tr>
<th>Pile Location</th>
<th>Minimum Square Pile Size (inches)</th>
<th>Minimum Cylinder Pile Diameter (inches)</th>
<th>Material Properties for All Pile Sizes&lt;sup&gt;1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vehicular Bridges</td>
<td>Pedestrian Bridges &amp; Fishing Piers</td>
<td>Strand Type</td>
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<td></td>
<td></td>
<td>Carbon steel, Spec 933</td>
</tr>
<tr>
<td>On land or in water in environments that are Extremely Aggressive due to chlorides</td>
<td>24&lt;sup&gt;2&lt;/sup&gt;</td>
<td>18</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>New Construction</td>
<td></td>
<td>Carbon steel, Spec 933</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>14</td>
<td>54</td>
</tr>
<tr>
<td>On land or in water in all other environments</td>
<td>18</td>
<td>14</td>
<td>54</td>
</tr>
<tr>
<td>Footings</td>
<td></td>
<td></td>
<td>Carbon steel, Spec 933</td>
</tr>
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<td>In water (waterline or mudline) in environments that are Extremely Aggressive due to chlorides</td>
<td>24&lt;sup&gt;2&lt;/sup&gt;</td>
<td>18</td>
<td>54</td>
</tr>
<tr>
<td>On land or in water (waterline or mudline) in all other environments</td>
<td>18</td>
<td>14</td>
<td>54</td>
</tr>
</tbody>
</table>
See FRPG for permitted use when approved by the State Structures Design Engineer:

- Approach Slabs
- Bridge Decks
- Bridge Overlays
- Cast-in-Place Flat Slab Superstructure
- Pile Bent Caps not in direct contact with water
- Pier Columns and Caps not in direct contact with water
- Retaining Walls, Noise Walls, Perimeter Walls
- Traffic Railings
- Pedestrian/Bicycle Railings
- Bulkheads and Bulkhead Copings
- MSE Wall Panels
- Drainage Structures
- Concrete Sheet Piles

Note: Other locations will be considered on a case-by-case basis.
Concrete Cover Requirements in Extremely Aggressive Environments

<table>
<thead>
<tr>
<th>Component</th>
<th>FRP Cover Requirements</th>
<th>Steel Cover Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Surface Cast Against Earth</td>
<td>3 in.</td>
<td>4.5 in.</td>
</tr>
<tr>
<td>Box Culverts</td>
<td>2.5 in.</td>
<td>3 in.</td>
</tr>
<tr>
<td>C.I.P. Cantilever Retaining Walls</td>
<td>2.5 in.</td>
<td>3 in.</td>
</tr>
<tr>
<td>MSE Walls</td>
<td>2 in.</td>
<td>3 in.</td>
</tr>
<tr>
<td>Bulkheads and Sheet Pile Caps</td>
<td>3 in.</td>
<td>4 in.</td>
</tr>
</tbody>
</table>

See FDOT Structures Manual for cover requirements for other components. [http://www.fdot.gov/structures](http://www.fdot.gov/structures)
GFRP/CFRP Reinforcing Bars – Section 2 – Design Criteria

Design **concrete members** with FRP reinforcement according to:
- ACI 440.1 Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars
- ACI 440.4 Prestressing Concrete Structures with FRP Tendons

Design **Bridge Decks** according to:
- AASHTO LRFD Bridge Design Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings

Use FRP **Mechanical Properties** per:
- FDOT Specifications Section 932-3 FRP Reinforcing Bars
Thank You

Rick Vallier, P.E.
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Rick.Vallier@dot.state.fl.us
www.fdot.gov