Summary

The *FDOT Structures Manual* now encourages the use of Fiber-Reinforced Polymer (FRP) reinforcing for certain concrete bridge elements located in the splash zone of extremely aggressive environments. Pile bent caps are one of the more common bridge elements requiring this design approach. This presentation will summarize the design of Glass FRP reinforced concrete using a typical intermediate pile bent cap example and FDOT’s Mathcad Bent Cap Program v1.0.

Learning objectives

- Awareness of FDOT’s Mathcad Bent Cap Design Program v1.0 capabilities and limitations.
- Awareness of GFRP reinforced concrete design for Flexural and Shear Limit States.
- Understanding of Pile Bent Cap reinforcing strategies for Glass Fiber-Reinforced Polymer (GFRP) bars.
Outline

• Design Guidance for GFRP-RC
• Design Tools for GFRP-RC
• Flexural Design Limit States:
  • Strength
  • Service – Crack Control
  • Service – Sustained Load
  • Fatigue
• Shrinkage & Temperature Reinforcing Design
• Shear Design
• Review: Design guidance & resources
• Where to find more FRP-RC training

GFRP = Glass Fiber-Reinforced Polymer
BFRP = Basalt Fiber-Reinforced Polymer
Design guidance for Bridges


- **Supplemented by**

- **Use associated Material Specifications**
  - *FDOT Spec 932-3* for BFRP & GFRP Rebar (Material Specs)
  - Similar to *ASTM D7957* for GFRP Rebar, (2017)
Design guidance for Buildings (FYI only)

• **ACI CODE-440.11-22**: Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary (2022)

• Uses associated Material Specifications
  • **ASTM D7957** for GFRP Rebar, (2017)
Design Tools for GFRP-RC Design

- **FDOT Design Software**

  - **Bent Cap v1.0** – Includes GFRP 11/1/2018.
  - **Retaining Wall v4.0** – Added GFRP 12/10/2019.
  - **PS Beams v6.2** – Added CFRP-PC/GFRP in v6.0, 10/1/2021.
  - **Box Culvert v5.2** - Added GFRP in v5.0, 5/26/2022.

### Structures Design

**Programs Library**

- **Bent Cap v1.0**
  - 11/07/2018
  - Exe (Zip) (Mathcad 15)
  - Analyzes and designs fixed or pinned bent caps, including lateral loads, in accordance with the AASHTO LRFD Bridge Design Specifications.

- **Retaining Wall v4.0**
  - 06/01/2020
  - Zip (Mathcad 15)
  - Used with [FDOT Standard Plan Index 400-010](https://www.fdot.gov/structures/proglib.shtm) to design and analyze cast-in-place retaining walls in accordance with the AASHTO LRFD Bridge Design Specification.

- **Prestressed Beam v6.2**
  - 05/31/2022
  - Zip (Mathcad 15)
  - Used with [FDOT Standard Plan Index 450-010 to 450-299](https://www.fdot.gov/structures/proglib.shtm) to design simple span prestressed beams (Florida-I, AASHTO, Florida Bulb-T, Florida-U, Florida Double-T, Flat Slab, Inverted-T, FSB) in accordance with the AASHTO LRFD Bridge Design Specification.

- **Box Culvert v5.2**
  - 09/14/2022
  - Zip (Mathcad 15)
  - Used with [FDOT Standard Plan Index 400-289](https://www.fdot.gov/structures/proglib.shtm) to design concrete box culverts, wingwalls, headwalls, and cutoff walls in accordance with the AASHTO LRFD Bridge Design Specification.
Design Tool for GFRP-RC Design

- Bent Cap v1.0

Previously introduced this Mathcad Program at the 2016 FDOT Design Training Expo

US 90/Little River PBES Demonstration - Example Project -

Mathcad Design Program

Comparisons of US 90 Demonstration project designs with new FDOT Mathcad program.

Comparison with two designs recently completed in house, a published FDOT Pile Bent Design Example (June 2016), the SHRP2 Pile-Bent two-column bent cap design example, and analysis with Bentley's RC Pier software showed good correlation of results. Deviations in the results can be explained by the refinements in modeling and loading assumptions for the different designs.

Comparisons of other Design examples with new FDOT Mathcad program
Design Tool for GFRP-RC Design

PART 1: LOAD GENERATOR

PART 2: FRAME ANALYSIS

PART 3: DESIGN & AASHTO BDS CHECKS

Flow Chart

https://www.fdot.gov/structures/proglib.shtm
Design Tool for GFRP-RC Design  • Bent Cap v1.0

Flow Chart  
https://www.fdot.gov/structures/proglib.shtm
Design Tool for GFRP-RC Design

- Bent Cap v1.0

**Flow Chart**

[Flow Chart Image]

https://www.fdot.gov/structures/proglib.shtm
Design Tool for GFRP-RC Design • Bent Cap v1.0

• Part 4 is intended for preliminary design of Precast Bent Cap connections with 3 options.

Part 4 will not be covered in this presentation.

Flow Chart

https://www.fdot.gov/structures/proqlib.shtm
Design Example for Intermediate Pile Bent Cap

- **Inputs - Superstructure**
  - 0 skew
  - Girder = FIB-36 @ 9’ spacing (5 total)
  - Haunch 1” (average)
  - Barrier Height = 36” (single-slope) 430 plf
  - Slab = 8.5” (includes 0.5” sacrificial)
  - Back Span = Forward Span = 87.67’
  - Curb-Curb width = 40’
  - Distance Coping to Roadway Edge = 1.333’
  - No Wearing Surface
  - Additional DL (SIP Forms)
    - Int Beam = 100 plf
    - Ext Beam = 50 plf
Design Example for Pile Bent Cap

• Inputs - Superstructure
  • 0 skew
  • Girder = FIB-36 @ 9’ spacing (5 total)
  • Haunch 1” (average)
  • Barrier Height = 36” (single-slope) 430 plf
  • Slab = 8.5” (includes 0.5” sacrificial)
  • Back Span = Forward Span = 87.67’
  • Curb-Curb width = 40’
  • Distance Coping to Roadway Edge = 1.333’
  • No Wearing Surface
  • Additional DL (SIP Forms)
    • Int Beam = 100 plf
    • Ext Beam = 50 plf

Part 1 - Load Generator
Design Example for Pile Bent Cap

- **Inputs – Substructure Example 1**
  - No. of columns = 5
  - Eff. Length columns = 40’
  - Column Spacing = 9.0’
  - Column Type = 2 (sq.)
  - Column Width = 24”
  - Cap Height = 36”
  - Cap Width = 48”
  - Cap Length = 41.67’
  - Avg. Pedestal Height = 3”
  - Ped. Width = 48”
  - Ped. Length = 44”
  - Bearing Pad Length = 32”
  - $f'c$ Bent Cap = 5.5 ksi
  - $f'c$ Columns = 6.0 ksi
  - Agg. Correction Factor = 1.0
  - Conc. Density for $E_c$ = 0.145 kcf
  - Conc. Density for DL = 0.150 kcf

Part 1 - Load Generator
Design Example for Pile Bent Cap

- **Inputs – Substructure Example 2**
  - No. of columns = 4
  - Eff. Length columns = 40’
  - Column Spacing = 12.0’
  - Column Type = 2 (sq.)
  - Column Width = 24”
  - Cap Height = 36”
  - Cap Width = 48”
  - Cap Length = 41.67’
  - Avg. Pedestal Height = 3”
  - Ped. Width = 48”
  - Ped. Length = 44”
  - Bearing Pad Length = 32”
  - f’c Bent Cap = 5.5 ksi
  - f’c Columns = 6.0 ksi
  - Agg. Correction Factor = 1.0
  - Conc. Density for $E_c = 0.145$ kcf
  - Conc. Density for DL = 0.150 kcf

Part 1 - Load Generator
Design Example for Pile Bent Cap

**Inputs - Substructure**
- No. of columns = 5 or 4
- Eff. Length columns = 40.0’
- Column Spacing = 9.0’ or 12’
- Column Type = 2 (sq.)
- Column Width = 24”
- Cap Height = 36”
- Cap Width = 48”
- Cap Length = 41.67’
- Avg. Pedestal Height = 3”
- Ped. Width = 48”
- Ped. Length = 44”
- Bearing Pad Length = 32”
- $f’c$ Bent Cap = 5.5 ksi
- $f’c$ Columns = 6.0 ksi
- Agg. Correction Factor = 1.0
- Conc. Density for $E_c = 0.145$ kcf
- Conc. Density for DL = 0.150 kcf

Part 1 - Load Generator
Design Example for Pile Bent Cap

**Additional Input for Centrifugal Force (CE)**
- **Radius of Curvature of traffic lane:** 0 feet
  - Input a Radius of 0 for bridges with no horizontal curve.
- **Highway design speed:** 70 mph
- **The total CE load shall be distributed to bent caps based on the superstructure continuity and the relative stiffness of the bent caps in the direction of CE load.**
- **Distribution Factor for CE load to intermediate bent cap:** 1
  - Minimum 0
  - Maximum 1

**Additional Input for Braking Force (BR)**
- **The total BR load shall be distributed to bent caps based on the superstructure continuity and the relative stiffness of the bent caps in the direction of BR load.**
- **Distribution Factor for BR load to intermediate bent cap:** 0.25
  - Minimum 0
  - Maximum 1
- **Length of bridge for BR load calculation:** 263 feet (typically length of continuous deck)

**Additional Input for Wind on Structure (WS)**
- **Low Member elevation:** 7.9 feet
- **Elevation of low ground or water level:** -1.2 feet
- **Design Wind Speed (mph) per SDG 2.4.1:** 150 mph
- **Total depth of superstructure (barrier, deck, haunch, beam and superelevation):** 8 feet

**Inputs – Additional (CE, BR, & WS)**
- **Radius of Curvature for CE = 0’**
- **Highway Speed for CE = n/a (70 mph)**
- **Distribution CE load = n/a (1.0)**
- **Distribution BR load = 0.25**
- **Length bridge for BR load = 263’**
- **Low Member Elev. = EL. +7.9 (avg.)**
- **Low Water Level or Ground = EL. -1.2**
- **Design Wind Speed = 150 mph**
- **Total Depth of Superstructure = 8.0’**

Part 1 - Load Generator
Design Example for Pile Bent Cap

Additional Input for Water Load (WA)

- 100-year event: parallel to bent-cap = 0 kips
- 100-year event: perpendicular to the bent-cap = 0 kips
- 500-year event: parallel to bent-cap = 0 kips
- 500-year event: perpendicular to the bent-cap = 0 kips

Additional Input for Force Effect due to Uniform Temperature (TU)

- TU load is typically perpendicular to the plane of bent-cap and thus resisted by cantilever columns. Calculation of TU is omitted in current version.
- To consider TU load (e.g. bridges with big skew), directly input the TU load acting on the bent-cap that is under consideration.

The current version only performs transverse loading analysis. However, there are inputs and placeholders for future longitudinal analysis enhancements.

Part 1 - Load Generator

IGNORE THESE FOR THIS EXAMPLE

- 100-year event: parallel to bent-cap = 0 kips
- 100-year event: perp. to bent-cap = 0 kips
- 100-year event: parallel to bent-cap = 0 kips
- 100-year event: perp. to bent-cap = 0 kips
- Longitudinal TU load = 0 kips
Correction needed to Fatigue Load combination:
- Live Load Factor increased from 1.5 to 1.75 in 8th Edition of AASHTO LRFD BDS.
Design Example for Pile Bent Cap

Example 1 – 5 Piles @ 9’ Spacing

Example 2 – 4 Piles @ 12’ Spacing

Part 1 - Load Generator

→ Save Data File
→ Calculate Worksheet

• Visually Check Inputs and Wheel load positioning
Design Example for Pile Bent Cap

- Save Data File
- Calculate Worksheet
- Visually Check Inputs and Wheel load positioning

Example 1 – 5 Piles @ 9’ Spacing

Part 1 - Load Generator
Design Example for Pile Bent Cap

- Inputs – Frame Analysis
  - Top of Column Connection = Pinned or Fixed
  - Beam Load Distribution to Cap = Concentrated or Distributed

Part 2 – Frame Analysis
Design Example for Pile Bent Cap

Part 2 – Frame Analysis

- **Frame Analysis - Inputs**
  - Top of Column Connection = **Pinned** or **Fixed**
  - Beam Load Distribution to Cap = **Concentrated** or **Distributed**

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### Structures Design Guidelines

**Topic No. 625-020-618**

3 - Substructure and Retaining, Noise and Perimeter Walls

**January 2022**

3.5 PILES

3.5.1 Prestressed Concrete Piles (LRFD 5.12.9.4) (Rev. 01/22)

A. For prestressed piling not subjected to significant flexure under service or impact loading, design strand development in accordance with **LRFD 5.9.4.3** and 5.7.2.2.

B. A 1-foot embedment is considered a pinned head condition. For the pinned pile head condition, the strand development must be in accordance with **LRFD 5.9.4.3** and 5.7.2.2.
Part 2 – Frame Analysis

- **Frame Analysis**
  - Calculate Worksheet
  - Select Limit State to view Shear & Moment Envelopes

---

**Table 3.4.1-1—Load Combinations and Load Factors**

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<thead>
<tr>
<th>Load Combination Limit State</th>
<th>DC</th>
<th>DD</th>
<th>DW</th>
<th>EH</th>
<th>EV</th>
<th>ES</th>
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<th>CE</th>
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<th>LS</th>
<th>WA</th>
<th>WS</th>
<th>WL</th>
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<td>Strength II</td>
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<tr>
<td>LL, IM &amp; CE only            + DL for GFRP-RC Only</td>
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</table>

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*Image of a bent cap analysis model with various load combinations and limit states.*

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*Choose a Design Limit State:*
- LS = 1

*Choose a Limit State to Display the Shear and Moment Envelopes*
Design Example for Pile Bent Cap

- Frame Analysis - Inputs
  - Top of Column Connection = Pinned or Fixed
  - Beam Load Distribution to Cap = Concentrated or Distributed

Example 1 – 5 Piles @ 9’ Spacing
Design Example for Pile Bent Cap

*Frame Analysis - Inputs*
- Top of Column Connection = *Pinned* or *Fixed*
- Beam Load Distribution to Cap = *Concentrated* or *Distributed*

**Part 2 – Frame Analysis**

**Example 2 – 4 Piles @ 12’ Spacing**
CONTINUE WITH Example 2 – 12’ Pile Spacing
Using the conditions

- Pinned & Distributed
  (Moment: Strength III)

### Frame Analysis
- Top of Column Connection = Pinned
- Beam Load Distribution to Cap = Distributed

**Example 2 – 4 Piles @ 12’ Spacing**
Design Example for Pile Bent Cap

- Design – GFRP Reinforcing
  → Load Data

**PART 1: LOAD GENERATOR**

**PART 2: FRAME ANALYSIS**

**PART 3: DESIGN & AASHTO BDS CHECKS**

Part 3 – Design & AASHTO Checks

GFRP Design References:
- FDOT Structures Manual Volume 4, 2018
- FDOT Specifications Section 923-3, July, 2018
- AASHTO Bridge Design Specifications for GFRP Reinforced Concrete, 2nd Edition

GFRP Design Properties:
- $H_{cap} = 3\text{ ft}$
- $W_{cap} = 4\text{ ft}$
- $L_{cap} = 41.67\text{ ft}$
- $L_{cap_{ov}} = 2.84\text{ ft}$
- $D_{col} = 0.84\text{ ft}$
- $C = 2$
- $N = 4$
Design Example for Pile Bent Cap

**Inputs - Tapered Ends and Internal Voids**
- N/A for Example 2
- Internal Voids are only intended for precast bents to reduce handling weights.

**Inputs – Support/Pickup Points**
- N/A for Example 2 (precast only)
Design Example for Pile Bent Cap

- **Inputs – GFRP Material & Design Properties**
  - Environmental Reduction Factor = 0.7
  - Tensile Modulus of Elasticity = 6,500 ksi
  - Rebar Properties = *Specification 932-3*

### GFRP Material and Design Properties

- $C_e =$ Environmental reduction factor...
- $E_t =$ Tensile modulus of elasticity...

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>$A_t(Bar) =$</td>
<td>$P_{t}(Bar) =$</td>
</tr>
<tr>
<td>0.049 in² if Bar = 2</td>
<td>6.1 kip if Bar = 2</td>
</tr>
<tr>
<td>0.11 in² if Bar = 3</td>
<td>13.3 kip if Bar = 3</td>
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<td>0.20 in² if Bar = 4</td>
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<td>0.44 in² if Bar = 6</td>
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<td>0.60 in² if Bar = 7</td>
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<td>0.79 in² if Bar = 8</td>
<td>66.8 kip if Bar = 8</td>
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<tr>
<td>1.00 in² if Bar = 9</td>
<td>82.0 kip if Bar = 9</td>
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<tr>
<td>1.27 in² if Bar = 10</td>
<td>98.2 kip if Bar = 10</td>
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</table>

- Tensile Stress of GFRP reinforcing bars
  - $f_{t}(Bar) =$

### Table 932-6

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<thead>
<tr>
<th>Bar Size Designation</th>
<th>Nominal Bar Diameter (in)</th>
<th>Nominal Cross Sectional Area (in²)</th>
<th>Measured Cross-Sectional Area (in²)</th>
<th>Minimum BFRP and GFRP Bars</th>
<th>CFRP (Type II) Single &amp; 7-Wire Strands</th>
<th>CFRP (Type I) Bars</th>
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</tbody>
</table>

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

• Inputs – Critical Section for Negative Moment
  • 1 = at Centerline of Support/Pile
  • 2 = at Face of Support/Pile

Design Loads - Moments and Shears (Torques not considered)

Critical section for shear should be at face of support.

Conservatively take design negative moment at the CL of support. Except for bent caps built integrally with supports (full moment connection), design may be based on the moments at face of support.

Critical section for flexural design:

1 - at center line of support
2 - at face of support

Reinforcement (Symmetrical to CL of Bent Cap)

A few recommendations on bar size and spacing are available to minimize problems during casting.

- Use the same size and spacing of reinforcing for both the negative and positive moment regions. This minimizes construction errors where the top steel is mistakenly placed at the bottom or vice versa.
- If this arrangement is not possible, give preference to maintaining the same spacing between the top and bottom reinforcement. Same grid patterns allow grouted ducts placement and the concrete vibrator to be more effective in reaching the full depth of the cap, especially for multi-layer reinforcing.
**Design Example for Pile Bent Cap**

- **Inputs – GFRP Material & Design Properties**
  - Environmental Reduction Factor = 0.7
  - Tensile Modulus of Elasticity = 6500 ksi
  - Rebar Properties = *Specification 932-3*
  - Rebar Bend Radius = **Index 415-010**

**TABLE 4 Minimum Inside Bend Diameter of Bent Bars**

<table>
<thead>
<tr>
<th>BAR SIZE</th>
<th>D</th>
<th>180° HOOKS</th>
<th>90° HOOKS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A OR G</td>
<td>J</td>
</tr>
<tr>
<td>#3</td>
<td>2 1/4”</td>
<td>5”</td>
<td>3”</td>
</tr>
<tr>
<td>#4</td>
<td>3”</td>
<td>6”</td>
<td>4”</td>
</tr>
<tr>
<td>#5</td>
<td>3 3/4”</td>
<td>7”</td>
<td>5”</td>
</tr>
<tr>
<td>#6</td>
<td>4 1/2”</td>
<td>8”</td>
<td>6”</td>
</tr>
<tr>
<td>#7</td>
<td>5 1/4”</td>
<td>10”</td>
<td>7”</td>
</tr>
<tr>
<td>#8</td>
<td>6”</td>
<td>11”</td>
<td>8”</td>
</tr>
</tbody>
</table>

*Bent bars of designation M29 [9] and M32 [10] are not included in this specification.*
Design Example for Pile Bent Cap

Inputs – Flexural Reinforcement

- Bar Size for Top Reinf (#) - Bars A, B & C
- Distance from c.g. 1\textsuperscript{st} layer to top cap face (t1)
- Distance from c.g. 2\textsuperscript{nd} layer to c.g. 1\textsuperscript{st} layer (t2)

- Bar Size for Bottom Reinf (#) - Bars D & E
- Distance from c.g. 1\textsuperscript{st} layer to bottom cap face (b1)
- Distance from c.g. 2\textsuperscript{nd} layer to c.g. 1\textsuperscript{st} layer (b2)

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

- **Inputs – Flexural Top Reinforcement**
  - For simplicity only use Bars A for pile bent caps
  - Bars B and C are intended for large multi-column piers
Part 3 – Design & AASHTO Checks

Design Example for Pile Bent Cap

**Bars D: Continuous Bottom Reinforcement**
- Bars D placed in 1st Layer
- Bars D placed in 2nd Layer

- Number of bars, $=Bar_{D1}$
- Number of bars, $=Bar_{D2}$

**Bars E: Supplemental Bottom Reinforcement Centered on Interior Spans**
- Distance from CL of column to end of Bars E (in.), $d_E$
- Development Length not considered in current version, input distance to portion that is considered fully developed

- Bars E placed in 1st Layer
- Bars E placed in 2nd Layer

- Number of bars, $=Bar_{E1}$
- Number of bars, $=Bar_{E2}$

**Inputs – Flexural Bottom Reinforcement**
- Bars D – along the outside of piles
- Bars E – between piles
Design Example for Pile Bent Cap

**Inputs – Concrete Cover**

- See *Structures Manual, Vol.4 - FRPG 2.3.E*
- Side Concrete Cover = 2”
- Bottom & Top cover previously set by “1st layer c.g.”

Concrete cover on the two sides (in.)

**Spacing of Flexural Reinforcement**

For crack control check, the bar spacing is calculated assuming a uniform distribution of bars on the 1st layer. Designer/user to calculate the actual spacing of bars if bars are not evenly distributed or bundled together. The maximum allowable spacing is plotted along the cap under the “Crack Control” section and the maximum allowable spacing at the most critical cap section is reported at the end of the program.

**Flexural reinforcement**

**Part 3 – Design & AASHTO Checks**
Design Example for Pile Bent Cap

• **Inputs Shear Reinforcement**
  - Only use Zone 3 spacing for simplicity b/w piles
  - Only use Zone 5 spacing for simplicity b/w piles

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

<table>
<thead>
<tr>
<th>Summary of LRFD and SDG Checks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Positive Moment</strong></td>
</tr>
<tr>
<td>Check (M_{f, pos} ) = “OK”</td>
</tr>
<tr>
<td>( \text{max}(\text{DCR}_{M, pos}) = 0.80 )</td>
</tr>
<tr>
<td>Check (\min A_{f, bot} ) = “OK”</td>
</tr>
<tr>
<td>( \text{max}(\text{Crack}<em>{W</em>{set, bot}}) = 0.024 \text{ in} )</td>
</tr>
<tr>
<td>Check (\text{crack control bot} ) = “OK”</td>
</tr>
<tr>
<td>( \text{max}(\text{CrackW}_{set, bot}) = 0.032 \text{ in} )</td>
</tr>
<tr>
<td>Check (\text{crack} ) = “OK”</td>
</tr>
<tr>
<td>( \text{max}(f_{\text{crb}, bot}) = 9.36 \text{ ksi} )</td>
</tr>
<tr>
<td>Check (\text{fatigue} ) = “OK”</td>
</tr>
<tr>
<td>( \text{max}(f_{\text{fat}, bot}) = 12.97 \text{ ksi} )</td>
</tr>
<tr>
<td>( C_r f_{fs, pos} = 14.8 \text{ ksi} )</td>
</tr>
<tr>
<td><strong>Negative Moment</strong></td>
</tr>
<tr>
<td>Check (M_{f, neg} ) = “OK”</td>
</tr>
<tr>
<td>( \text{max}(\text{DCR}_{M, neg}) = 0.88 )</td>
</tr>
<tr>
<td>Check (\min A_{f, top} ) = “NG”</td>
</tr>
<tr>
<td>Check (\text{crack control top} ) = “NG, bar spacing exceeds maximum”</td>
</tr>
<tr>
<td>( \text{max}(\text{CrackW}_{set, top}) = 0.032 \text{ in} )</td>
</tr>
<tr>
<td>Check (\text{crack} ) = “OK”</td>
</tr>
<tr>
<td>( \text{max}(f_{\text{crb}, top}) = 14.74 \text{ ksi} )</td>
</tr>
<tr>
<td>Check (\text{fatigue} ) = “NG”</td>
</tr>
<tr>
<td>( \text{max}(f_{\text{fat}, top}) = 16.3 \text{ ksi} )</td>
</tr>
<tr>
<td>( C_r f_{fs, neg} = 14.8 \text{ ksi} )</td>
</tr>
</tbody>
</table>

- **Output – Flexure (Pos. & Neg. Moment)**
  - Neg. for Min. Cracking Moment – **No Good**
  - Neg. for Service I Crack Control – **No Good**
  - Neg. for Fatigue Check – **No Good**

→ **Need to Revise Input**

![Negative Moment Reinf.](image-url)
Design Example for Pile Bent Cap

- **Output – Flexure (Pos. & Neg. Moment)**
  - Strength Limit State OK for loading.
  - $\phi M_{n,\text{pos}} = 952 \text{ kip-ft}$
  - $\phi M_{n,\text{neg}} = 634 \text{ kip-ft}$

**Compression-Controlled (Concrete Crushing)**

$$f_t = \frac{\left(E_e e_m\right)^2}{4} + \frac{0.85 f'\rho}{f_t} - 0.5E_e e_m \leq f_t$$

(2.6.3.1-1)

$$M_n = A_nf_t \left( d - \frac{a}{2} \right)$$

(2.6.3.2.1-1)

in which:

$$a = \frac{A_nf_t}{0.85 f'_t b}$$

(2.6.3.2.2-1)

**Tension-Controlled (GFRP Bar Rupture)**

$$M_n = A_nf_M \left( d - \frac{\beta c_s}{2} \right)$$

(2.6.3.2.2-3)

in which:

$$c_s = \left( \frac{\varepsilon_{cm}}{\varepsilon_{cm} + \varepsilon_{gd}} \right) d$$

(2.6.3.2.2-4)
Design Example for Pile Bent Cap

- Output – Flexure (Pos. & Neg. Moment)
  - Negative Cracking Moment – No Good
  - $1.33 \times \mu = 1013 \text{ kip-ft}$
  - $1.6 \times M_{cr} = 739 \text{ kip-ft} \quad \leftarrow \text{controls}$
  - $\Omega M_{neg} = 634 \text{ kip-ft} < \min(1.33 \mu, 1.6 M_{cr}), \text{ NG}$
    - Add approx. 20% more reinforcing

2.6.3.3—Limits for Reinforcement

There is no maximum reinforcement limit. Unless otherwise specified by the Owner, at any section of a noncompression-controlled flexural component, the amount of tensile reinforcement shall be adequate to develop a factored flexural resistance, $M_{n}$, greater than or equal to the lesser of the following:

- $1.33$ times the factored moment required by the applicable strength load combination specified in Table 3.4.1-1 of the AASHTO LRFD Bridge Design Specifications.

\[ 1.6 f_c S_c - M_{min} \left( \frac{S_{ce}}{S_{c}} - 1 \right) \quad (2.6.3.3-1) \]
Design Example for Pile Bent Cap

• Output – Flexure (Pos. & Neg. Moment)
  • Service I Limit State (Crack Control):
    • Max. Allowed Bot. Bar Spacing = 3.79 in.
    • Bot. Spacing (b/w piles) = 2.96 in. ⇨ OK
    • Max. Allowed Top Bar Spacing = 2.15 in.
    • Top Spacing = 4.61 in. ⇨ NG
      • AASHTO & ACI provides this check in terms of bar spacing, but it is easier to visualize & graph by converting to crack width.

Equation 2.6.7-1 is based on ACI 440.1R which uses a simplified conversion of the 1999 Frosch crack width equation.

Part 3 – Design & AASHTO Checks
Part 3 – Design & AASHTO Checks

- **Output – Flexure (Pos. & Neg. Moment)**
  - Service I Limit State (Crack Control) cont.:
  - Max. allowed crack width = 0.28 in.  
  - Bot. Crack Width (max) = 0.024 in.  
    → **OK**
  - Top Crack Width (max) = 0.032 in.  
    → **NG**

- Provide closer spacing or increase area of reinforcing for top reinforcing to reduce tensile stress.

**A NEW CRACK WIDTH EQUATION**

Frosch observed that a significant shortcoming of the Gergely-Lutz and Kaar-Mattock equations is that they were both developed empirically using statistical analysis techniques on experimental data that was limited in the range of concrete covers investigated. In fact, he noted that only three test specimens had concrete covers greater than 2.5 inches.

Frosch developed the following simple, theoretically-derived equation to predict crack widths that could be used regardless of the actual concrete cover:

\[
\text{Crack Width (in)} = 2 \frac{f_t}{E_t} \rho \sqrt{(d_y)^2 + \left(\frac{s}{2}\right)^2}
\]

(4) Frosch, R.J. “Another Look at Cracking and Crack Control in Reinforced Concrete.” *ACI Structural Journal*, 96(3), 1999, pp. 437–442.
Design Example for Pile Bent Cap

- **Output – Flexure (Pos. & Neg. Moment)**
  - Service I Limit State (Crack Control) cont.:
  - Max. allowed crack width = 0.28 in.
  - Bot. Crack Width (max) = 0.024 in. \(\leftarrow\) OK
  - Top Crack Width (max) = 0.032 in. \(\leftarrow\) NG

A direct conversion of **AASHTO Guide Spec Eq. 2.6.7-1**, provides slightly more conservative widths as shown by the red plot lines in this graph.

\[
s \leq \min \left( 1.15 \frac{C_y E_y w}{f_{fs}} - 2.5c_y, 0.92 \frac{C_y E_y w}{f_{fs}} \right) \quad (2.6.7-1)
\]
Design Example for Pile Bent Cap

Creep Rupture Limit State [AASHTO BDS for GFRP 2.5.3]

To avoid creep rupture of the FRP reinforcement under sustained stresses or failure due to cyclic stresses and fatigue of the FRP reinforcement, the stress levels in the FRP under these stress conditions should be limited.

- Output – Flexure (Pos. & Neg. Moment)
  - Service Limit State (Creep Rupture):
    \[ f_{f,x} \leq C_c f_{fd} \]  
    (2.5.3-1)
    - Max. allowed bar stress = 17.8 ksi
    - Bot. Stress (max) = 9.4 ksi \(\rightarrow\) OK
    - Top Stress (max) = 12.3 ksi \(\rightarrow\) OK

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

Fatigue Limit State [AASHTO BDS for GFRP 2.5.4]

\[ C_r = 0.25 \]

Fatigue rupture stress limit of GFRP

\[ \text{FatigueLimit}_{\text{pos}} = C_r \cdot f_{\text{fat, pos}} \]
\[ \max(\text{FatigueLimit}_{\text{pos}}) = 14.8 \text{ ksi} \]

\[ \text{FatigueLimit}_{\text{neg}} = C_r \cdot f_{\text{fat, neg}} \]
\[ \max(\text{FatigueLimit}_{\text{neg}}) = 14.8 \text{ ksi} \]

Stress in the bottom reinforcing due to sustained load (DL = 1.5FatigueLL)

\[ f_{\text{Fat, bot}} = f_f \left( \max(M_{\text{Fat, bot}}, d_{\text{pos}}, d_{\text{cap}}, k_{\text{pos}}, S_{\text{cap}}, k_{\text{neg}}, f_{\text{fat, pos}}, M_{\text{cr}}) \right) \]
\[ \max(f_{\text{Fat, bot}}) = 12.97 \text{ ksi} \]

Stress in the top reinforcing due to sustained load (DL = 1.5FatigueLL)

\[ f_{\text{Fat, top}} = f_f \left( -\min(M_{\text{Fat, top}}, d_{\text{neg}}, d_{\text{cap}}, k_{\text{neg}}, S_{\text{cap}}, k_{\text{pos}}, f_{\text{fat, neg}}, M_{\text{cr}}) \right) \]
\[ \max(f_{\text{Fat, top}}) = 16.3 \text{ ksi} \]

Fatigue Limit State:

\[ f_{f, f} \leq C_j f_{\text{fat}} \quad (2.5.4-1) \]

- Max. allowed bar stress = 14.8 ksi  \( \leftarrow \text{OK} \)
- Bot. Stress (max) = 13.0 ksi  \( \leftarrow \text{OK} \)
- Top Stress (max) = 16.3 ksi  \( \leftarrow \text{NG} \)

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

Skin Reinforcement [LRFD 5.7.3.4]

\[ d_{t,\text{pos}} = \frac{H_{\text{cap}}}{b_1} = 2.73 \text{ ft} \]
\[ d_{t,\text{neg}} = \frac{H_{\text{cap}}}{t_1} = 2.73 \text{ ft} \]

Check skin.reinf = \text{if}(d_{t,\text{pos}} \geq 3 \text{ ft} \lor d_{t,\text{neg}} \geq 3 \text{ ft}, "Skin Reinf Required", "Skin Reinf Not Required")

Check_skin.reinf = "Skin Reinf Not Required"

Size of bar

\[ \text{Bar# skin} = 5 \]
\[ \#Bars\text{ skin} = 4 \]

If \( d_t \) of nonprestressed members exceeds 3.0 ft, longitudinal skin reinforcement shall be uniformly distributed along both side faces of the component for a distance \( d_t/2 \) nearest the flexural tension reinforcement. The area of skin reinforcement, \( A_d \), in in.\(^2\)/ft of height on each side face shall satisfy:

\[ A_d \geq 0.012 \ (d_t - 30) \quad (5.6.7-3) \]

where:

\[ d_t = \text{distance from the extreme compression fiber to the centroid of extreme tension steel element (in.)} \]

• **Output – Flexure (Pos. & Neg. Moment)**

Skin Reinforcement (based on **LRFD BDS**):

• Not Required, since \( d_t < 3 \)-ft

• Provide anyway #5’s, need for Shrinkage & Temperature reinforcing on side face.

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

Shrinkage and Temperature Reinforcement [AASHTO BDS for GFRP 2.9.6]

For conservatism, use the lowest $f_{tk}$ for the calculation of the minimum shrinkage and temperature reinforcement ratio

- $f_{tk, pos} = 57.4$ ksi
- $f_{tk, neg} = 59.19$ ksi
- $f_{tk, skin} = f_{tk}(Bar# skin) = 65.71$ ksi
- $maxBar = max(Bar#V1, Bar#V2, Bar#V3, Bar#V4, Bar#V5) = 5$
- $f_{tk, shear} = f_{tk}(maxBar) = 65.71$ ksi
- $f_{tk, ts} = \min(f_{tk, pos}, f_{tk, neg}, f_{tk, skin}, f_{tk, shear}) = 57.4$ ksi

- $f_{ts, min} = 0.44 \text{ sq.in/ft}$
- $f_{ts, max} = 0.80 \text{ sq.in/ft (on side face)}$

Strength of Positive Reinforcement
Strength of Negative Reinforcement
Strength of Skin Reinforcement
Lowest Strength of Shear Reinforcement
Maximum bar size of Shear Reinforcement

Design strength for calculation of Shrinkage and Temperature Reinforcement Ratio (Lowest Strength of All Reinforcement for conservatism)

- $\rho_{f,ul} = 0.0018 \times \frac{600}{f_{tk, min} E_f} \geq 0.0014$ (C2.9.6-1)

Shrinkage & Temp. Reinforcement Area:
- Min. Required = 0.44 sq.in/ft
- Min. Provided = 0.80 sq.in/ft (on side face)

and not less than 0.0014 (ACI, 2014). These provisions are modified accounting for the tensile modulus of elasticity and strength of shrinkage and temperature GFRP reinforcement:

Area of required minimum shrinkage and temperature reinforcement per foot [LRFD 5.10.8]

Area of reinforcement near top surface
Area of reinforcement near bottom surface
Area of reinforcement near side surface

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

Shrinkage and Temperature Reinforcement [AASHTO BDS for GFRP 2.9.6]

... continued

Check $\text{Shrink\&Temp\_Reinf} = "OK"

$\text{Spa}_{\text{shrink\_req}} = 12$ in

$\text{Spa}_{\text{shrink\_top}} = \frac{W_{\text{cap}}}{\text{Bars}_{\text{A1}}} = 4.8$ in

$\text{Spa}_{\text{shrink\_bot}} = \frac{W_{\text{cap}}}{\text{Bars}_{\text{D1}}} = 12$ in

$\text{Spa}_{\text{shrink\_side}} = \text{Spa}_{\text{shrink\_skin}} = 10$ in

$\text{Spa}_{\text{shrink\_shear}} = \text{max}(\text{Spa}_{\text{shrink\_top}}, \text{Spa}_{\text{shrink\_bot}}, \text{Spa}_{\text{shrink\_side}}, \text{Spa}_{\text{shrink\_shear}}) = 12$ in

$\text{Spa}_{\text{shrink}} = \frac{\text{Spa}_{\text{shrink\_top}}}{\text{Spa}_{\text{shrink\_req}}} = 1.00$

$\text{Spa}_{\text{shrink\_req}} = \text{max}(\text{Spa}_{\text{shrink\_top}}, \text{Spa}_{\text{shrink\_bot}}, \text{Spa}_{\text{shrink\_side}}, \text{Spa}_{\text{shrink\_shear}}) = 12$ in

Check $\text{SpaShrink\_Reinf} = "\text{NG}"$ if $\text{Spa}_{\text{shrink\_req}} > 1.005$

$\text{Check\_SpaShrink\_Reinf} = "\text{OK}"$

$\text{Critical spacing}$

$\rho_{f,sl} = \max\left(\frac{3.132}{E_f f_{fd}}; 0.0014\right) \leq 0.0036$ (2.9.6-1)

The spacing of GFRP reinforcing bars used as shrinkage and temperature reinforcement shall not exceed three times the slab thickness or 12 in., whichever is less.

$\rho_{f,sl} = 0.0018 \times \frac{60}{f_{\text{fd}} E_f} \geq 0.0014$ (C2.9.6-1)

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

Recall from our Initial Design attempt:

**Summary of LRFD and SDG Checks**

**Positive Moment**
- Check\(_{M_r, pos}\) = "OK"
  \[ \max(DCR_{M, pos}) = 0.80 \]
- Check\(_{\text{min}A, bot}\) = "OK"
- Check\(_{\text{crack, control, bot}}\) = "OK"
  \[ \max(\text{CrackW}_{\text{setl, bot}}) = 0.024 \text{ in} \]
- Check\(_{\text{creep, bot}}\) = "OK"
  \[ \max(f'_{\text{SL, bot}}) = 9.36 \text{ ksi} \]
- Check\(_{\text{fatigue, bot}}\) = "OK"
  \[ \max(f'_{\text{Fat, bot}}) = 12.97 \text{ ksi} \]
  \[ C_f f'_{\text{fat, pos}} = 14.8 \text{ ksi} \]

**Negative Moment**
- Check\(_{M_r, neg}\) = "OK"
  \[ \max(DCR_{M, neg}) = 0.88 \]
- Check\(_{\text{min}A, top}\) = "NG"
- Check\(_{\text{crack, control, top}}\) = "NG, bar spacing exceeds maximum"
  \[ \max(\text{CrackW}_{\text{setl, top}}) = 0.032 \text{ in} \]
- Check\(_{\text{creep, top}}\) = "OK"
  \[ \max(f'_{\text{SL, top}}) = 14.74 \text{ ksi} \]
- Check\(_{\text{fatigue, top}}\) = "NG"
  \[ \max(f'_{\text{Fat, top}}) = 16.3 \text{ ksi} \]
  \[ C_f f'_{\text{fat, neg}} = 14.8 \text{ ksi} \]

- The maximum demand to capacity ratio
- The maximum crack width
- The maximum stress under sustained load (DL=0.2LL)
- The maximum stress under fatigue (DL=1.75LL, fatigue)
- Fatigue stress limit

- **Output – Flexure (Pos. & Neg. Moment)**
  - Neg. for Min. Cracking Moment – No Good
  - Neg. for Service I Crack Control – No Good
  - Neg. for Fatigue Check – No Good

- Revise Input

Negative Moment Reinf.

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

- Revise Inputs – Flexural Top Reinforcement
  - Number of Bars A: change from 10 to 12

Bars A: Continuous Top Reinforcement

Bars A placed in 1st Layer

10
Number of bars, \( #Bars_{A1} \)

0
Number of bars, \( #Bars_{A2} \)

Bars A placed in 2nd Layer

12
Number of bars, \( #Bars_{A1} \)

0
Number of bars, \( #Bars_{A2} \)

Flexural reinforcement

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

From Revised Design:

- Revised Output – Flexure (Pos. & Neg. Moment)
- All OK!
Design Example for Pile Bent Cap

Part 3 – Design & AASHTO Checks

- Check Output – Shear Reinforcement
  - DCR = 2.40 \( \Leftarrow \text{No Good!} \)
  - Revise
- Shear resistance is lower for both \( V_c \) & \( V_f \) than steel-RC design.

2.7.3.3—Nominal Shear Resistance

The nominal shear resistance, \( V_n \), shall be determined as:

\[
V_n = V_c + V_f
\]

(2.7.3.3-1)

Using Simplified Method for determining \( \beta \) and \( \theta \)

\[
V_c = 0.0316 \beta \sqrt{f_c' b_d d_v}
\]

(2.7.3.4-1)

- \( \beta = 5.0k \)
  where the ratio of depth of neutral axis to reinforcement depth, \( k \), may be calculated using Eq. 2.5.3-4.
- \( \theta = 45^\circ \)
**Design Example for Pile Bent Cap**

### Summary of LRFD and SDG Checks

<table>
<thead>
<tr>
<th>Positive Moment</th>
<th>Negative Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check Output</td>
<td>DCR = 2.40</td>
</tr>
<tr>
<td>Shear Reinforcement</td>
<td>No Good!</td>
</tr>
<tr>
<td>Revise Spacing or Size</td>
<td></td>
</tr>
<tr>
<td>Shear Reinf. Design Stress is Limited by Elastic Modulus not Bent Bar Strength</td>
<td></td>
</tr>
<tr>
<td>0.004E_f = 26 ksi</td>
<td>Governs!</td>
</tr>
<tr>
<td>(0.05r_b/d_b + 0.3)f_fd = 31.5 ksi</td>
<td></td>
</tr>
</tbody>
</table>

**Part 3 – Design & AASHTO Checks**

#### 2.7.3.5 — Procedure for Determining Shear Resistance Provided by Transverse Reinforcement

When using stirrups or hoops perpendicular to the longitudinal axis of the member, the nominal shear resistance provided by the transverse reinforcement, \( V_f \), shall be calculated as:

\[
V_f = \frac{A_{ho} f_{ho} d_s \cot \theta}{s}
\]

in which:

\[
f_{ho} = 0.004E_f \leq f_{yd}
\]

\[
f_{yd} = \left(0.05 r_b + 0.3\right) f_{yd} \leq f_{yd}
\]
Design Example for Pile Bent Cap

- Recall Original Inputs for Shear Reinforcement
  - Zone V3 - #5 @ 6” sp. (4 legs) $\Leftarrow$ No Good
  - Zone V5 - #5 @ 6” sp. (4 legs) $\Leftarrow$ OK

- Revision-1 Inputs Shear Reinforcement - Zone 3
  - Try Zone V3 - #5 @ 3” sp. (4 legs)
  - DCR = 1.41 $\Leftarrow$ still No Good

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap

• Recall Revision-1 Inputs for Shear Reinforcement
  - Zone V3 - #5 @ 3” sp. (4 legs) ← No Good
  - Zone V5 - #5 @ 6” sp. (4 legs) ← OK

• Revision-2 Inputs Shear Reinforcement - Zone 3
  - Try Zone V3 - #6 @ 3” sp. (4 legs)
  - DCR = 1.04 ← Still No Good & too congested!

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap (3-ft height cap)

- Recall Revision-2 Inputs for Shear Reinforcement
  - Zone V3 - #6 @ 3” sp. (4 legs) ➞ No Good
  - Zone V5 - #5 @ 6” sp. (4 legs) ➞ OK

- Revision-3 Inputs Shear Reinforcement - Zone 3
  - Try Zone V3 - #6 @ 4” sp. (6 legs)
  - DCR = 0.94 ➞ OK, however a better design approach would be to thicken the bent cap to 4-ft.
Design Example for Pile Bent Cap (4-ft height cap)

- Recall 3-ft Cap Inputs for Shear Reinforcement
  - Zone V3 - #6 @ 4” sp. (6 legs) \(\leftarrow\) OK
  - Zone V5 - #5 @ 6” sp. (4 legs) \(\leftarrow\) OK

- Revise 4-ft Cap Shear Reinforcement - Zone 3
  - Try Zone V3 - #6 @ 4” sp. (4 legs)
  - DCR = 0.96 \(\leftarrow\) OK

You should also be able to reduce some of the flexural reinforcing with the deeper cap!

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap (Shear Stirrups)

- **Shear Stirrup Configurations (2 or 4-Leg)**

Initial FDOT project details (used Side Lap-Splice with pairs of U-Bars – “Type 11” FDOT Bar Bend)

Better Detail uses Top & Bottom laps. Better anchorage, but results in congestion in 4-leg stirrups due to 4 bar overlap). Similar to SPI 415-010 “Design Aid”

Now Recommend using “Type 4” FDOT Bar Bend. Being added to **FY 2023-24 Standard Plans Index 415-010**
Design Example for Pile Bent Cap (Summary)

- Comparison of different design alternates for 4-piles @ 12-ft spacing (Example 2)

<table>
<thead>
<tr>
<th>Rebar Location</th>
<th>GFRP-RC 3-ft Deep Cap</th>
<th>GFRP-RC 4-ft Deep Cap</th>
<th>Steel-RC 3-ft Deep Cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bars A - Flexural Top</td>
<td>12 ~ #8’s (A_f = 9.5 in²)</td>
<td>9 ~ #8’s (A_f = 7.1 in²)</td>
<td>7 ~ #8’s (A_s = 5.5 in²)</td>
</tr>
<tr>
<td>Bars D &amp; E - Flexural Bottom</td>
<td>15 ~ #8’s (A_f = 11.9 in²)</td>
<td>16 ~ #8’s (A_f = 12.6 in²)</td>
<td>8 ~ #8’s (A_s = 6.3 in²)</td>
</tr>
<tr>
<td>Bars V3 - Shear Stirrups</td>
<td>6-legs #6 at 4&quot; sp. (A_f = 7.9 in²/ft)</td>
<td>4-legs #6 at 4&quot; sp. (A_f = 5.3 in²)</td>
<td>4-legs #5 at 9&quot; sp. (A_s = 1.7 in²)</td>
</tr>
</tbody>
</table>

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap (Summary)

- Comparison of different design alternates for 5-piles @ 9-ft spacing (Example 1)

<table>
<thead>
<tr>
<th>Rebar Location</th>
<th>GFRP-RC 3-ft Deep Cap</th>
<th>Steel-RC 3-ft Deep Cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bars A - Flexural Top</td>
<td>6 ~ #8’s</td>
<td>6 ~ #6’s</td>
</tr>
<tr>
<td></td>
<td>($A_f = 4.7 \text{ in}^2$)</td>
<td>($A_s = 2.6 \text{ in}^2$)</td>
</tr>
<tr>
<td>Bars D &amp; E - Flexural</td>
<td>8 ~ #8’s</td>
<td>7 ~ #7’s</td>
</tr>
<tr>
<td>Bottom</td>
<td>($A_f = 6.3 \text{ in}^2$)</td>
<td>($A_s = 4.2 \text{ in}^2$)</td>
</tr>
<tr>
<td>Bars V3 - Shear Stirrups</td>
<td>4-legs #5 at 11&quot; sp.</td>
<td>4-legs #4 at 12&quot; sp.</td>
</tr>
<tr>
<td></td>
<td>($A_f = 1.4 \text{ in}^2/\text{ft}$)</td>
<td>($A_s = 0.8 \text{ in}^2$)</td>
</tr>
</tbody>
</table>

Part 3 – Design & AASHTO Checks
Design Example for Pile Bent Cap (Summary)

- Comparison of different design alternates for 5-piles @ 9-ft spacing (Example 1) – Higher Modulus GFRP Rebar (Ef = 6,500 psi to 8,700 psi for future enhancements to ASTM D7957)

<table>
<thead>
<tr>
<th>Rebar Location</th>
<th>GFRP-RC 3-ft Deep Cap (Ef = 6500 ksi)</th>
<th>GFRP-RC 3-ft Deep Cap (Ef = 7250 ksi)</th>
<th>GFRP-RC 3-ft Deep Cap (Ef = 8700 ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bars A - Flexural Top</td>
<td>6 ~ #8’s (Af = 4.7 in²)</td>
<td>7 ~ #7’s (Af = 4.2 in²)</td>
<td>6 ~ #7’s (Af = 3.6 in²)</td>
</tr>
<tr>
<td>Bars D &amp; E - Flexural Bottom</td>
<td>8 ~ #8’s (Af = 6.3 in²)</td>
<td>7 ~ #8’s (Af = 5.5 in²)</td>
<td>6 ~ #8’s (Af = 4.7 in²)</td>
</tr>
<tr>
<td>Bars V3 - Shear Stirrups</td>
<td>4-legs #5 at 11&quot; sp. (Af = 1.4 in²/ft)</td>
<td>4-legs #5 at 13&quot; sp. (Af = 1.1 in²/ft)</td>
<td>4-legs #4 at 10&quot; sp. (Af = 1.0 in²/ft)</td>
</tr>
</tbody>
</table>

Part 3 – Design & AASHTO Checks
Review: Design guidance & resources

• FDOT Design Guidance – *FRPG Chapter 2*

[Image of FDOT Design Guidance]

[Image of AASHTO Design Guide]

• AASHTO Design Guide Specifications for GFRP-RC

[Image of AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete]

https://www.fdot.gov/structures/structuresmanual/currentrelease/structuresmanual.shtm

Part 4 - Review
Review: Design guidance & resources

• Materials & Construction

Materials Acceptance and Certification System

- Production Facility
  - Aggregate Production Facility Listing
  - All Producers (Excel)
  - Approved Aggregate Products For Friction Course
  - Approved Aggregate Products From Mines or Terminals Listing
  - Approved Products at Expired Mines or Terminals
  - Asphalt Production Facility Listing
  - Asphalt Recycled Products
  - Asphalt Targets
  - Cementitious Materials Production Facility Listing
  - Coatings Production Facility Listing
  - Fiber Reinforced Polymer Production Facility Listing

https://mac.fdot.gov/smoreports

Sections 415, 450, 932-3 & 933

https://www.fdot.gov/programmanagement/Implemented/SpecBooks/default.shtm

Part 4 - Review
Where to find more FRP-RC info & training

https://www.fdot.gov/structures
Where to find more FRP-RC training

Structures Design
Structures Design / Design Innovation
Fiber Reinforced Polymer Reinforcing

Overview
The deterioration of reinforcing and prestressing steels in structures. In addition to being exposed to weather, corrosive environments such as marine locations and concrete paths for the agents of the aggressive environments. An innovative approach to connect reinforcement with Fiber Reinforced Polymer (FRP) reinforcement from materials or fibers held in a polymeric resin matrix such as glass (GFRP), basalt (BFRP) or carbon (CFRP). A surface treatment for reinforcing and the concrete.

Part 4 - Review

https://www.fdot.gov/structures/innovation/FRP.shtm

Structures Design Office
FDOT 2020 GFRP-RC Design Training Course

Meeting Information

- Training Dates: August 10, 2020
- Location: FDOT - Hosted Online via GoToWebinar

AASHTO GFRP-Reinforced Concrete Design Training Course

GoToWebinar by: Professor Antonio Nanni

Begins at 9:30 am

- Video Recording: [FDOT GFRP-RC Designer Training for Bridges and Structures](GoTo Drag)

Presentation Slides:
- Introduction & Materials
- Project Examples
- Case Studies
- Fracture Mechanics
- Final Presentation

TDOT 2020 Workshop 1063 (Jan 12, 2020):
- Externally Bonded Wraps
- FRP Design Tools, CBB Implementation & Pedestrian Bridges

FDOT Executive Workshop (January 15, 2020)
- FTS2020 "FRP Reinforced and Prestressed Concrete Designer Training Intensive"
- FDOT/FRP Industry 4th RC/PC Workshop (August 4, 2020)

FDOT GFRP-RC Designer Training for Bridges & Structures (August 10, 2020)

FDOT CFRP-PC Designer Training for Bridges & Structures (September 9, 2020)
- CMX 2020 - Infrastructure Education: Presentations-Advancements in composite infrastructure
GFRP-Reinforced Concrete Design for Bridges

Lead Speaker: Prof. Antonio Nanni
Co-Speaker: Dr. Francisco De Caso

Department of Civil, Architectural & Environmental Engineering
University of Miami

https://www.fdot.gov/structures/innovation/fdot-2020-gfrp-rc-design-course
Questions

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