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.

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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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  CFRP (Spec. 932)
- Strand – CFRP (Spec. 933)

Reinforcing Bars

FDOT Spec. 932-3.2 Bar Sizes and Loads

Table 3-1
Sizes and Tensile Loads of FRP Reinforcing Bars

Bar Size Designation	Nominal Bar Diameter (in)	Nominal Cross Sectional Area (in^2)	Measured Cross-Sectional Area (in^2)		Minimum Guaranteed Tensile Load (kips)	
			Minimum	Maximum	GFRP Bars	CFRP Bars
2	0.250	0.049	0.046	0.085	6.1	10.3
3	0.375	0.11	0.104	0.161	13.2	20.9
4	0.500	0.20	0.185	0.263	21.6	33.3
5	0.625	0.31	0.288	0.388	29.1	49.1
6	0.750	0.44	0.415	0.539	40.9	70.7
7	0.875	0.60	0.565	0.713	54.1	-
8	1.000	0.79	0.738	0.913	66.8	-
9	1.128	1.00	0.934	1.137	82.0	-
10	1.270	1.27	1.154	1.385	98.2	-

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

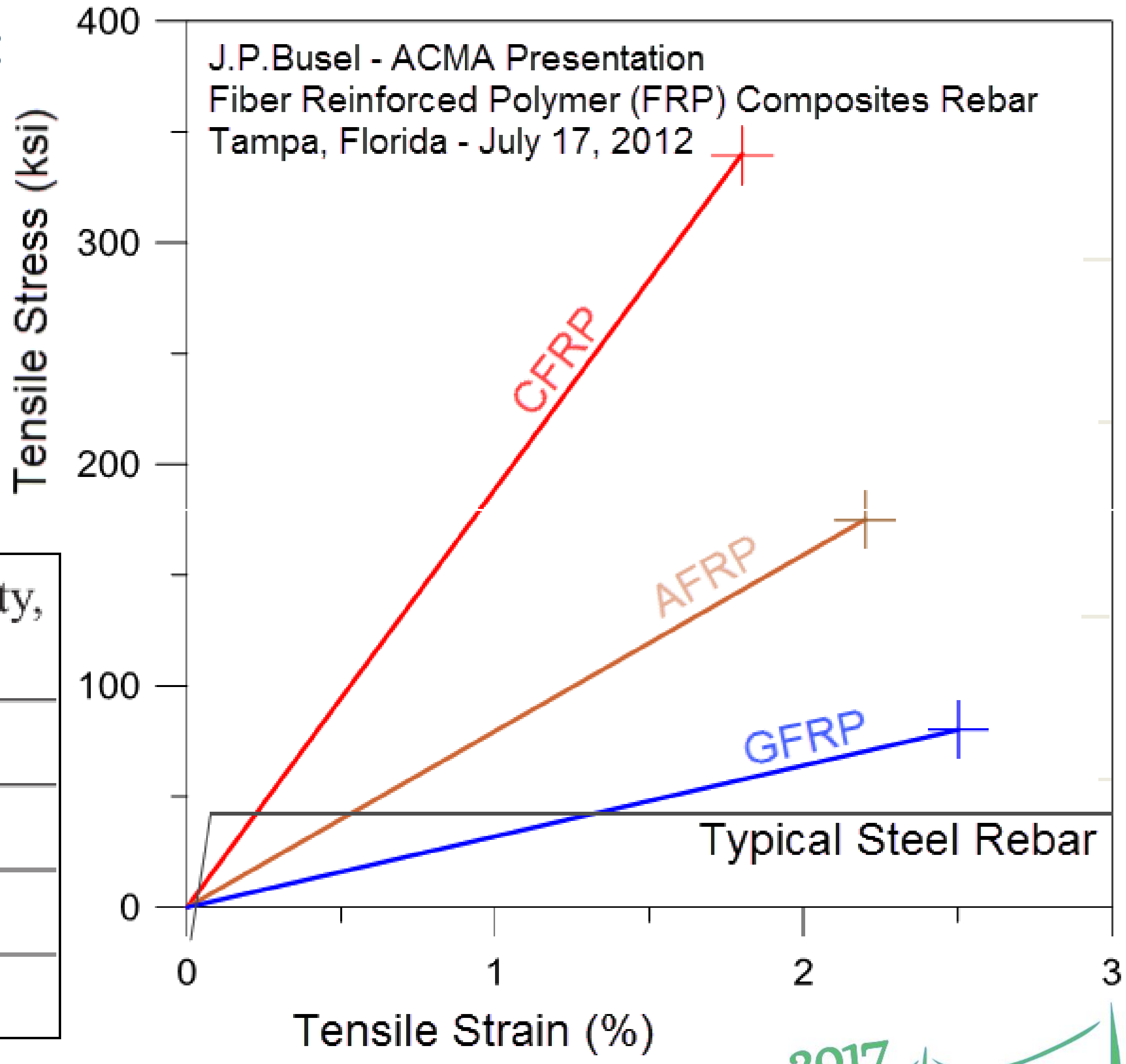
Reinforcing Bars

Characteristics of FRP Reinforcement:

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

Bar type	Yield strength f_y or tensile strength f_{fu}, ksi (MPa)	Modulus of elasticity, ksi (GPa)
Steel	60 (414)	29,000 (200)
GFRP	80 (552)	6000 (41.4)
AFRP	170 (1172)	12,000 (82.7)
CFRP	300 (2070)	22,000 (152)

From ACI 440.1R-15



Reinforcing Bars

FRP Bar <u>Mechanical Characteristics</u> 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

Reinforcing Bars

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

Coefficient of Thermal Expansion x 10 -6/°F				
Direction	**Steel**	**GFRP**	**CFRP**	**Concrete**
Longitudinal	6.5	3.3 to 5.6	-4.0 to 0.0	4 to 6
Transverse	6.5	11.7 to 12.8	41 to 58	4 to 6

From ACI 440.1R-15, Table 4.1.2

Reinforcing Bars

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).

Property	Test Method	Requirement
Glass Transition Temperature (Tg)	ASTM E1640 (DMA) or ASTM E1356 (DSC)	≥230°F ≥212°F

Specification 932-3 http://www.fdot.gov/programmanagement

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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

Reinforcing Bars

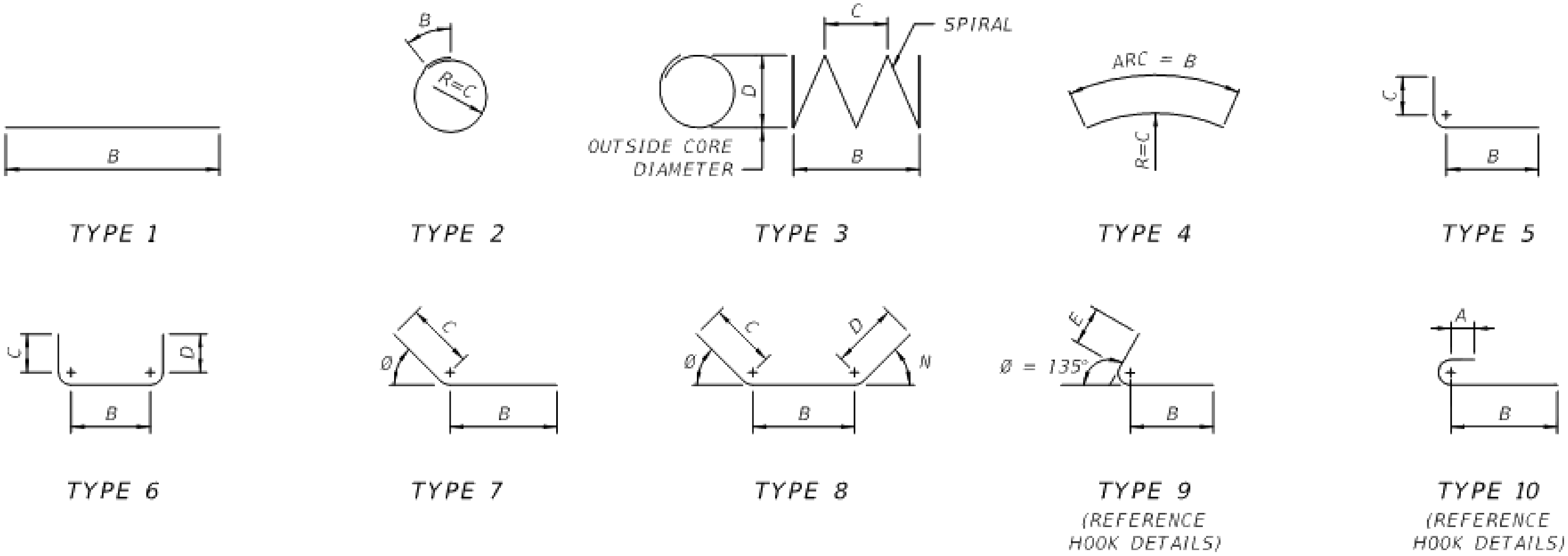
Characteristics of FRP Reinforcement:

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:



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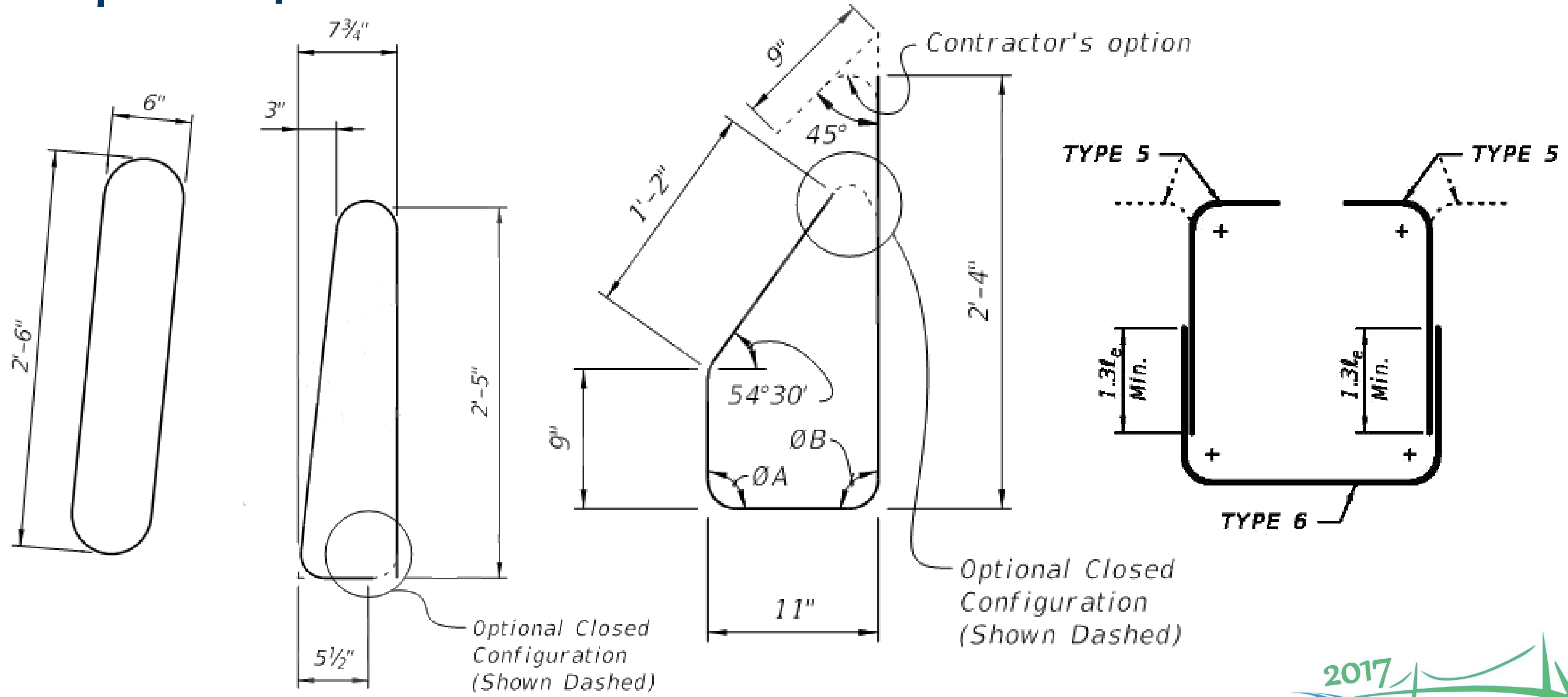
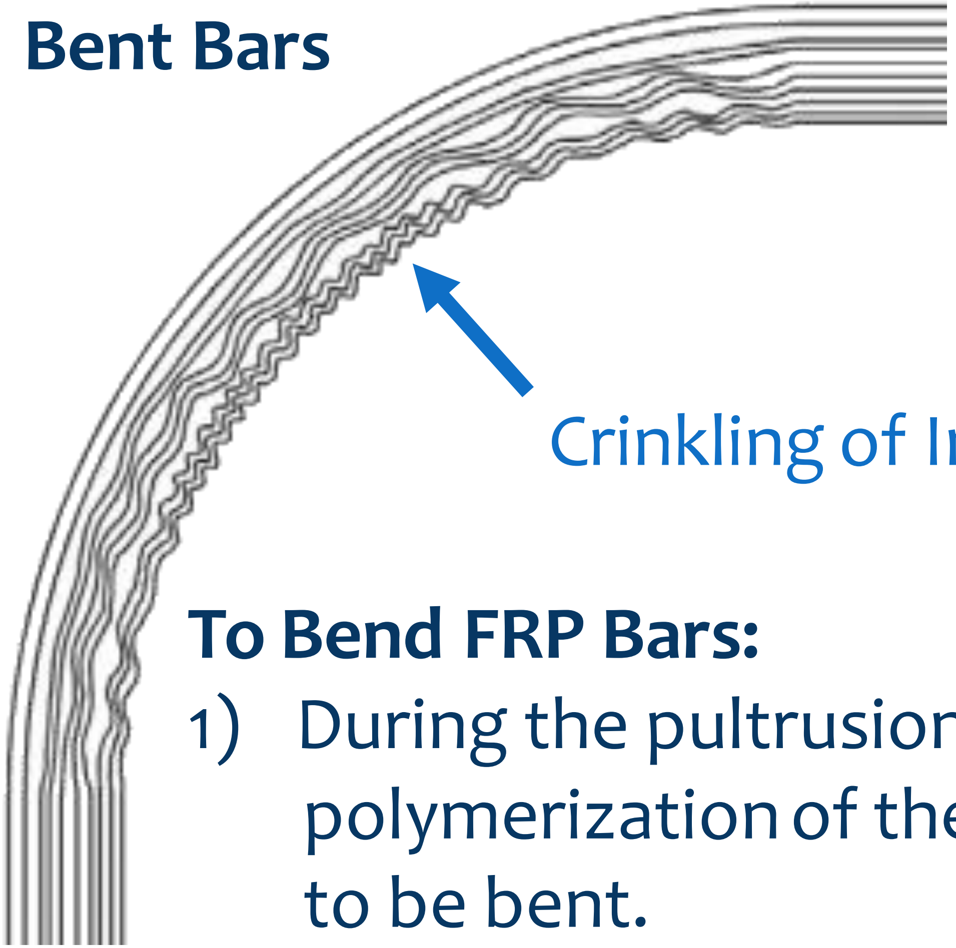
Reinforcing Bars

Complex Shapes:



Reinforcing Bars

Bent Bars



Crinkling of Inner Fibers

To Bend FRP Bars:

1) During the pultrusion process, prevent polymerization of the resin at sections to be bent.
1) 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

Reinforcing Bars

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 $f'c = 5.5$ ksi

No. 8 GFRP – Based on Spec. 932:

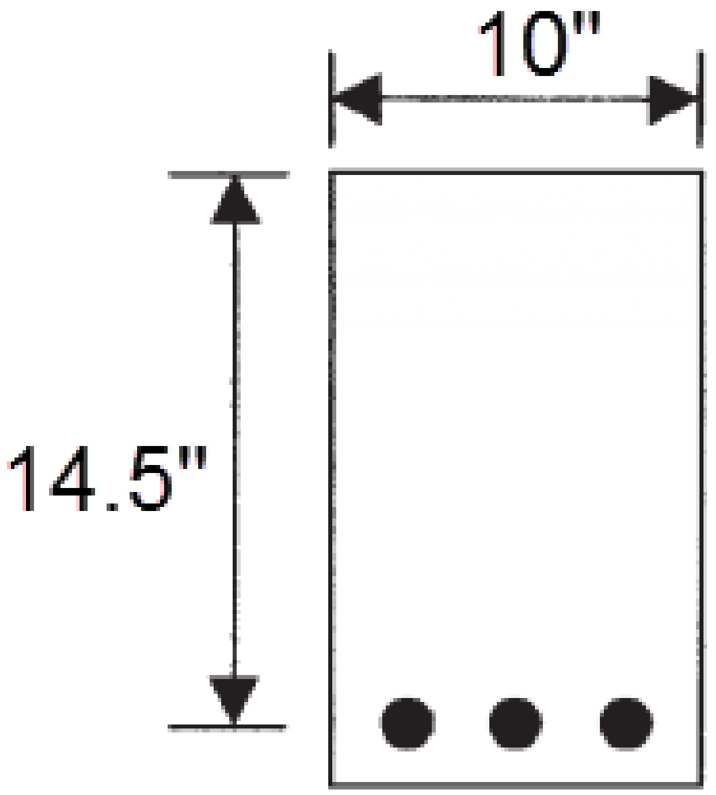
Nominal Bar Area $A_f = 0.79$ in^2

Minimum Modulus of Elasticity $E_f = 6{,}500$ ksi

Minimum Guaranteed Tensile Load 66.8 kips

Guaranteed Tensile Strength

$f_{fu}^* = 66.8$ kips / 0.79 in^2 = 84.5 ksi



Reinforcing Bars

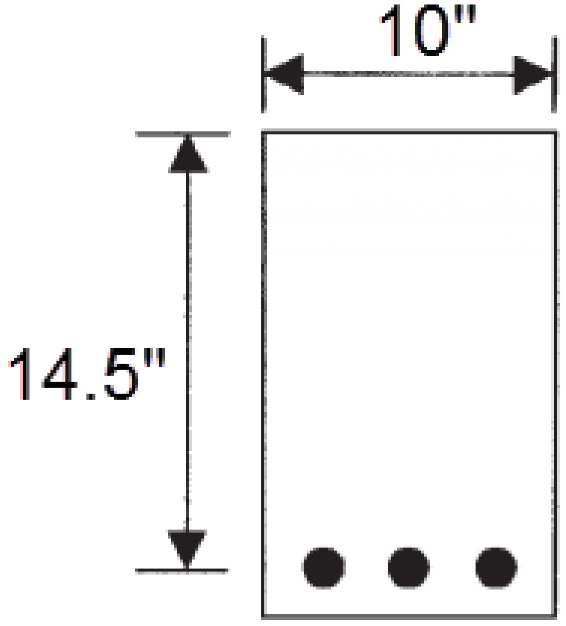
Flexural Strength

C_E = Environmental Reduction Factor = 0.7

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

f_{fu} = 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

	GFRP			Steel
Qty. of No. 8 Bars	2	3	4	2
ρ	0.01090	0.01635	0.02179	0.01090
ρ balanced	0.01519	0.01519	0.01519	0.03574
Control	Tension	Transitioning	Compression	Tension
ϕ	0.55	0.57	0.65	0.9
Mn (kip-ft)	102	146	163	107
ϕMn (k-ft)	56	83	106	96

Reinforcing Bars

Flexural Strength

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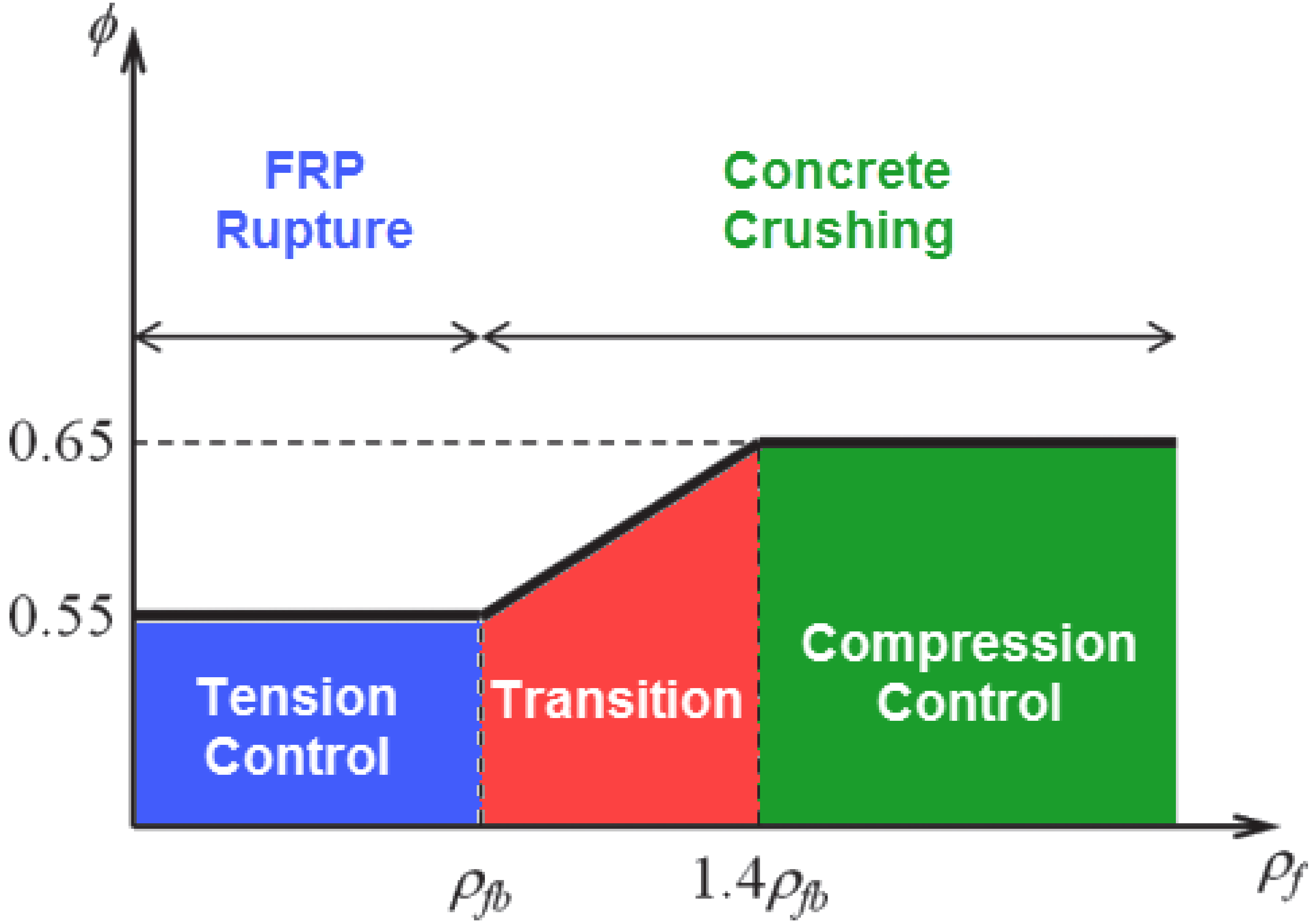
Reinforcing Bars

Flexural Strength



Reinforcing Bars

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

w = maximum crack width
Crack Width Limit = 0.02 in.

$$w = 2\frac{f_{f,s}}{E_f}\beta k_b\sqrt{d_c^2 + \frac{s^2}{4}}$$

ACI 440.1R-15

S max = maximum bar spacing

$$s_{max} = 1.15\frac{E_f w}{f_{fs}k_b} - 2.5c_c \leq 0.92\frac{E_f w}{f_{fs}k_b}$$

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

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Reinforcing Bars

Creep Rupture & Fatigue

ACI 440.1R-15

Limit Stress Levels:

Fiber type	GFRP	CFRP
Creep rupture stress limit $f_{fs,sus}$	$0.20f_{fu}$	$0.55f_{fu}$

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

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

Similar to Fatigue evaluation.

Reinforcing Bars

Shear Strength

ACI 440.1R-15

Resistance factors (ϕ) for shear = 0.75

Minor modification due to lower stiffness of FRP than steel.

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

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

$$f_{fv} = 0.004E_f \leq f_{fb}$$

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Reinforcing Bars

Cost Comparison (Installed Price)

Bar Size	Nominal Diameter	Average Unit Costs of Three Bidders on the Halls River Bridge Project		FDOT Structures Manual for BDR Cost Estimating	
		GFRP Bar	CFRP Bar	Grade 60 Steel Bar	Stainless Steel
#4	0.500"	$1.18 / LF	$7.99 / LF	$0.60 / LF	$2.72 / LF
#5	0.625"	$1.37 / LF	$8.34 / LF	$0.94 / LF	$4.19 / LF
#6	0.750"	$1.55 / LF	-	$1.35 / LF	$5.98 / LF
#8	1.000"	$2.54 / LF	-	$2.40 / LF	$10.74 / LF

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

Topic No. 625-020-018 January 2017

FLORIDA DEPARTMENT OF TRANSPORTATION

FDOT STRUCTURES MANUAL

Volume 1 - Structures Design Guidelines
Volume 2 - Structures Detailing Manual
Volume 3 - FDOT Modifications to LRFDLTS-1
Volume 4 - Fiber Reinforced Polymer Guidelines

http://www.fdot.gov/structures

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

FDOT Structures Manual

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.

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Research and field implementation of FRP materials is ongoing and design recommendations continue to evolve.

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

http://www.fdot.gov/research

Halls River Bridge Replacement Project

Homosassa, Florida

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

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Volume 4 - Fiber Reinforced Polymer Guidelines (FRPG)

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.

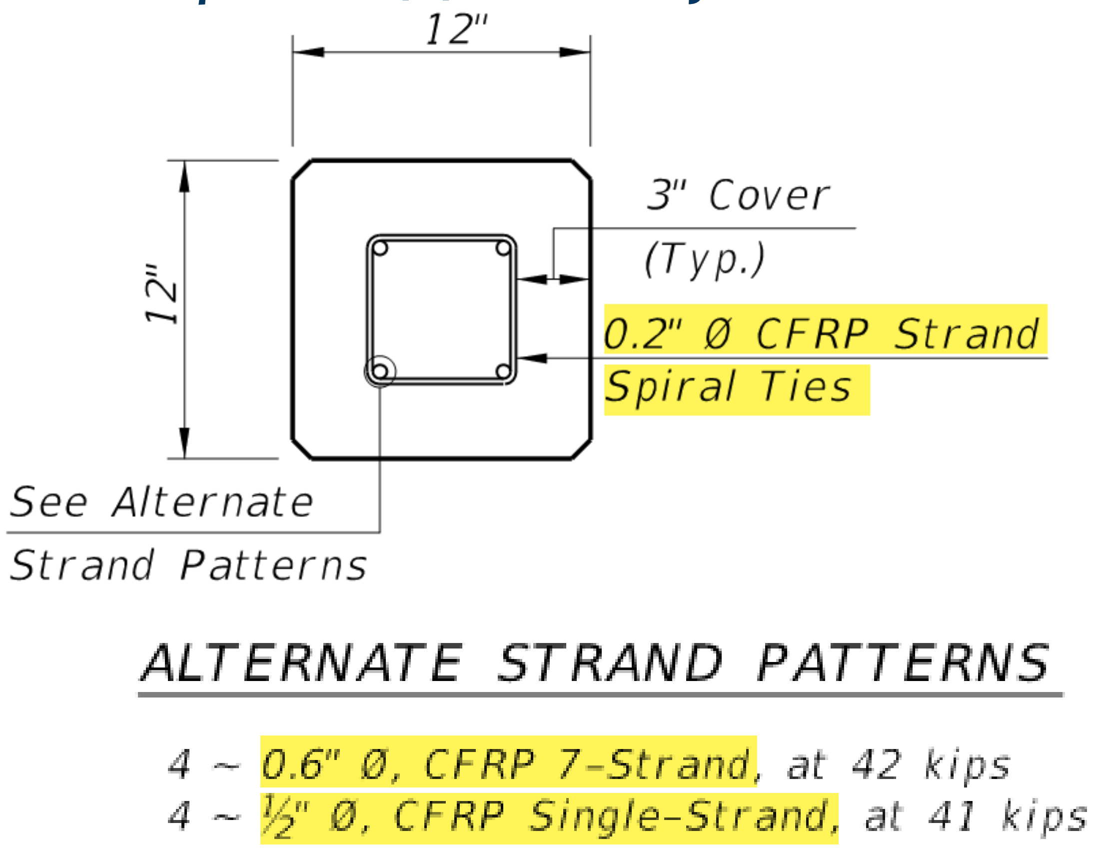
PPM 26.3.2: Structures with any component designed using FRP composite materials is a Category 2 Structure.

FDOT Structures Manual

Volume 4 - Fiber Reinforced Polymer Guidelines (FRPG) – Sections 2 & 3

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



From Design Standard 22612
12" Pile Cross Section

FDOT Structures Manual

Volume 1 – Structures Design Guidelines – Table 3.5.1-1

Pile Location			Minimum Square Pile Size (inches)		Minimum Cylinder Pile Diameter (inches)	Material Properties for All Pile Sizes[1]		
			Vehicular Bridges	Pedestrian Bridges & Fishing Piers		Strand Type	Spiral Type	Reinforcing Bar Type
Pile Bents	On land or in water in environments that are Extremely Aggressive due to chlorides	Widenings	24[2]	18	54	Carbon steel, Spec 933	Carbon steel, Spec 931	Carbon steel, Spec 931
		New Construction	24[3]	18[3]	54[3]	Carbon steel, Spec 933	Carbon steel, Spec 931	Carbon steel, Spec 931
			18	14	54	CFRP, Spec 933	CFRP, Spec 932	GFRP or CFRP, Spec 932
						Stainless steel, Spec 933	Stainless steel, Spec 931	Stainless steel, Spec 931
	On land or in water in all other environments		18	14	54	Carbon steel, Spec 933	Carbon steel, Spec 931	Carbon steel, Spec 931
Footings	In water (waterline or mudline) in environments that are Extremely Aggressive due to chlorides		24[2]	18	54	Carbon steel, Spec 933	Carbon steel, Spec 931	Carbon steel, Spec 931
	On land or in water (waterline or mudline) in all other environments		18	14	54	Carbon steel, Spec 933	Carbon steel, Spec 931	Carbon steel, Spec 931

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Volume 1 – Structures Design Guidelines – Table 3.5.1-1

Pile Location			Minimum Square Pile Size (inches): Vehicular Bridges	Minimum Square Pile Size (inches): Pedestrian Bridges & Fishing Piers	Minimum Cylinder Pile Diameter (inches)	Material Properties for All Pile Sizes[1]: Strand Type	Material Properties for All Pile Sizes[1]: Spiral Type	Material Properties for All Pile Sizes[1]: Reinforcing Bar Type
Pile Bents	On land or in water in environments that are Extremely Aggressive due to chlorides	Widenings	24[2]	18	54	Carbon steel, Spec 933	Carbon steel, Spec 931	Carbon steel, Spec 931
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Volume 4 - Fiber Reinforced Polymer Guidelines (FRPG) – Section 2

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.

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FDOT Structures Manual – Vol. 4 FRPG 2.3

Concrete Cover Requirements in Extremely Aggressive Environments

Component	FRP Cover Requirements	Steel Cover Requirements
External Surface Cast Against Earth	3 in.	4.5 in.
Box Culverts	2.5 in.	3 in.
C.I.P. Cantilever Retaining Walls	2.5 in.	3 in.
MSE Walls	2 in.	3 in.
Bulkheads and Sheet Pile Caps	3 in.	4 in.

See FDOT Structures Manual for cover requirements for other components.
http://www.fdot.gov/structures

FDOT Structures Manual

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.
FDOT Structures Design Office
Rick.Vallier@dot.state.fl.us
www.fdot.gov

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