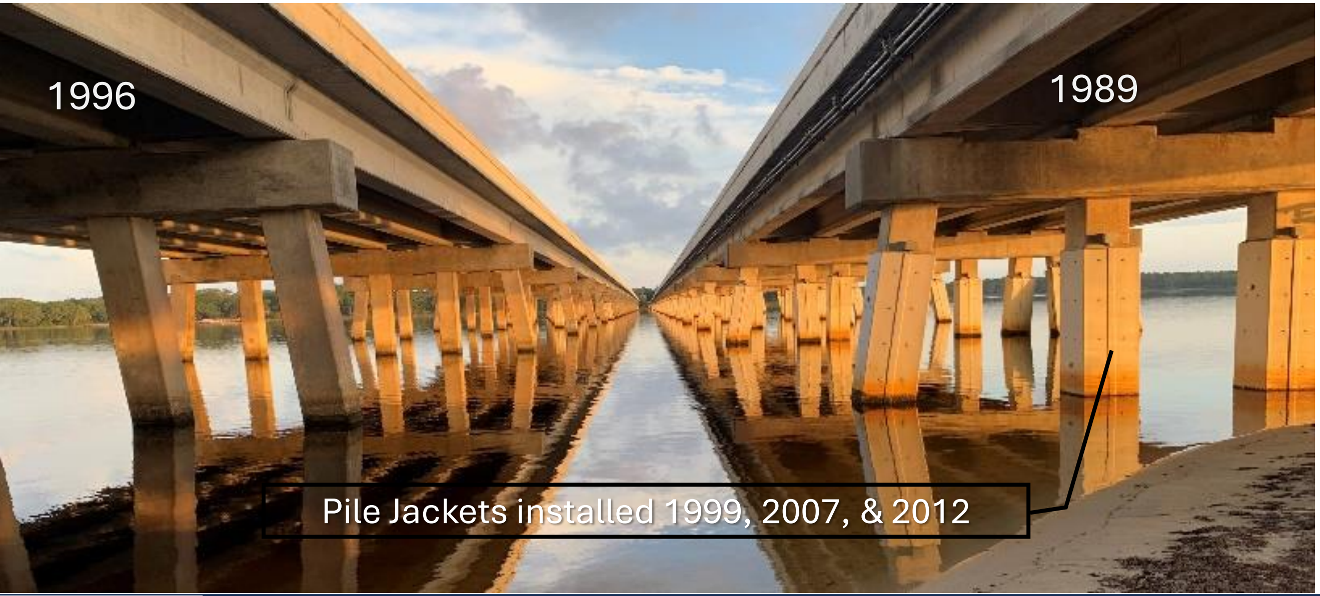
FRP Reinforced Concrete Structures:

10-year update, Lessons Learned, and Emerging Best Practices

(Feb. 10th, 2025)



Steven Nolan, P.E.
State Structures Design Office (Tallahassee, FL.)

2025 FRP Workshop for Tampa Bay Transportation Structures Engineers

Afternoon: (1:15 pm to 3.00 pm) discussion topics/presenters:

- 1:15pm: Design and Construction of Bridges with GFRP & BFRP Rebar – Steven Nolan (45-mins)
- 2:00pm: Example 1 Case Study for FRP-RC/PC Bridge Project: Hamed Kazimi-D7 (15-mins)
- 2:15pm: Example 2 Case Study for FRP-RC/PC Bridge Project: Chris Gooding-PGA (30-mins)
- 2:45pm: Final Q&A, and Closing - Richard Krolewski and Steven Nolan (15-mins)

Featured Bridge:

4th St over Big Island Gap

Schedule

1. Design: Practices and Standards for FRP-RC/PC.
2. Materials: Specifications, Testing, and Qualification.
3. Construction: Example Projects & Lessons Learned.

Speaker Bio:

Steven Nolan, P.E.

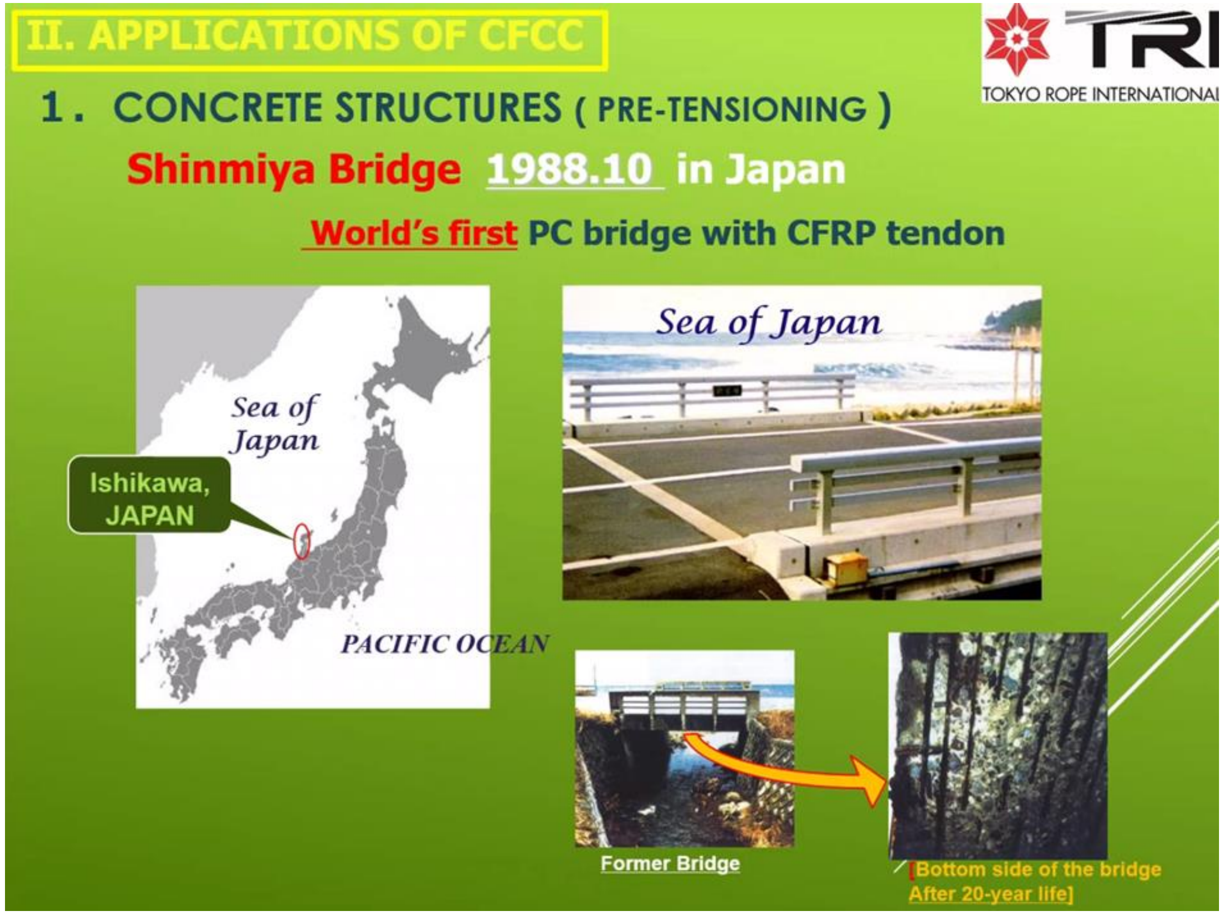
Professional Engineer in Florida since 2003, current technical lead coordinator for Florida DOT for implementation of Fiber-Reinforced Polymer reinforcing and prestressing, stainless-steel prestressing, and UHPC for structural applications. 10-years' experience with development of design guidance for FRP, 31-years' experience with concrete design and construction including 26-years with bridge design specification and standards development. Current member of ***TRB*** committee **AKB10-** Innovative Highway Structures, ***ACI*** 243, 239, 440C & CSAO, ***ASCE***-Structural Engineering Institute, Bridge Engineering Institute, and ***fib*** *(International Federation for Structural Concrete)*.

Background:

- FDOT introduced guidance for the implementation of Fiber-Reinforced Polymer-Reinforced and Prestressed Concrete (FRP-RC & FRP-PC) at the ***2014 Design Training Expo***. We highlighted the planned release of ***Standard Specifications***, ***Structures Manual***, and ***Materials Manual*** updates, and the early design work for the seminal demonstration project - Halls River Bridge.
- Reflecting on 10 years of implementation and the evolution of design guidance, standard specifications and plans, many projects have now been successful completed and continue to be monitored with the goal of improving the state-of-the-practice and cost efficiency.

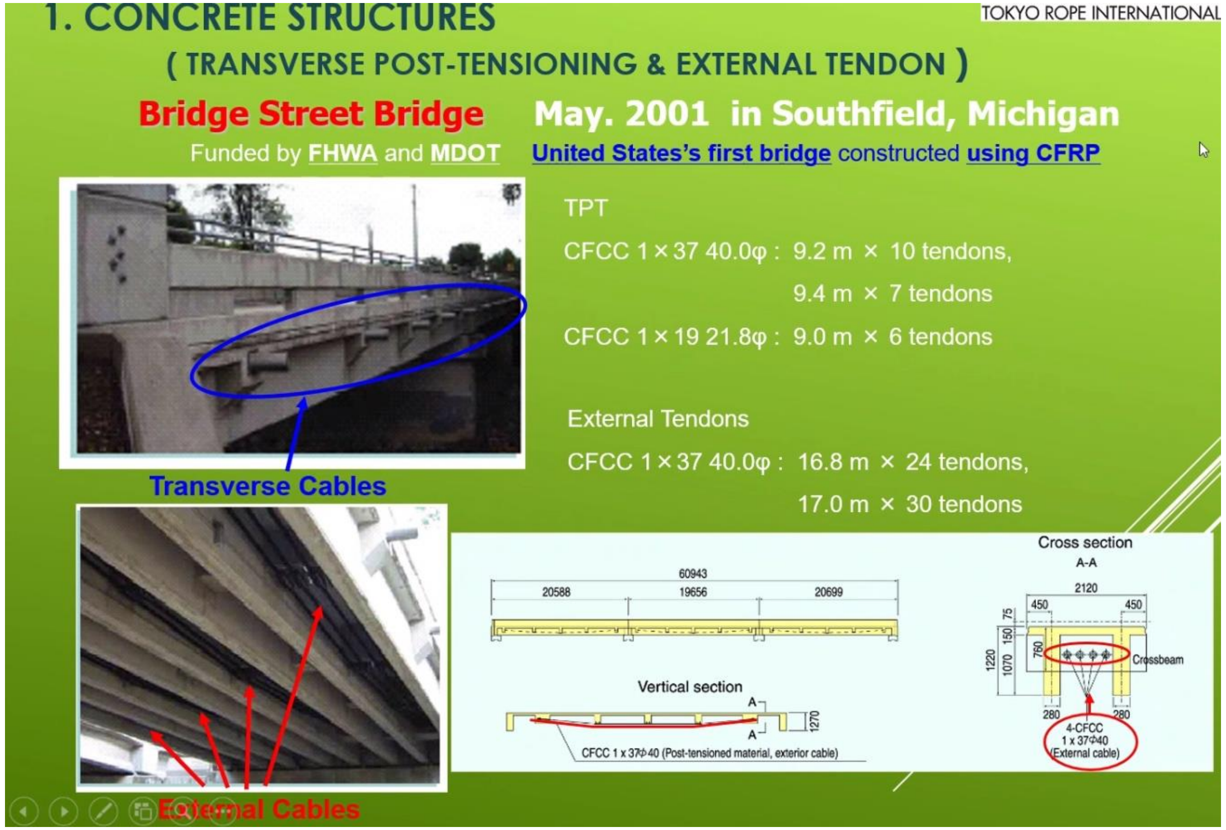
Way Way Back: CFRP Prestressing Strand

- CFCC: Developed in Japan with first prestressed bridge application in 1988



Way Back: CFRP Prestressing Strand

- CFCC: First USA bridge application in Michigan in 2001 – Post-Tensioning

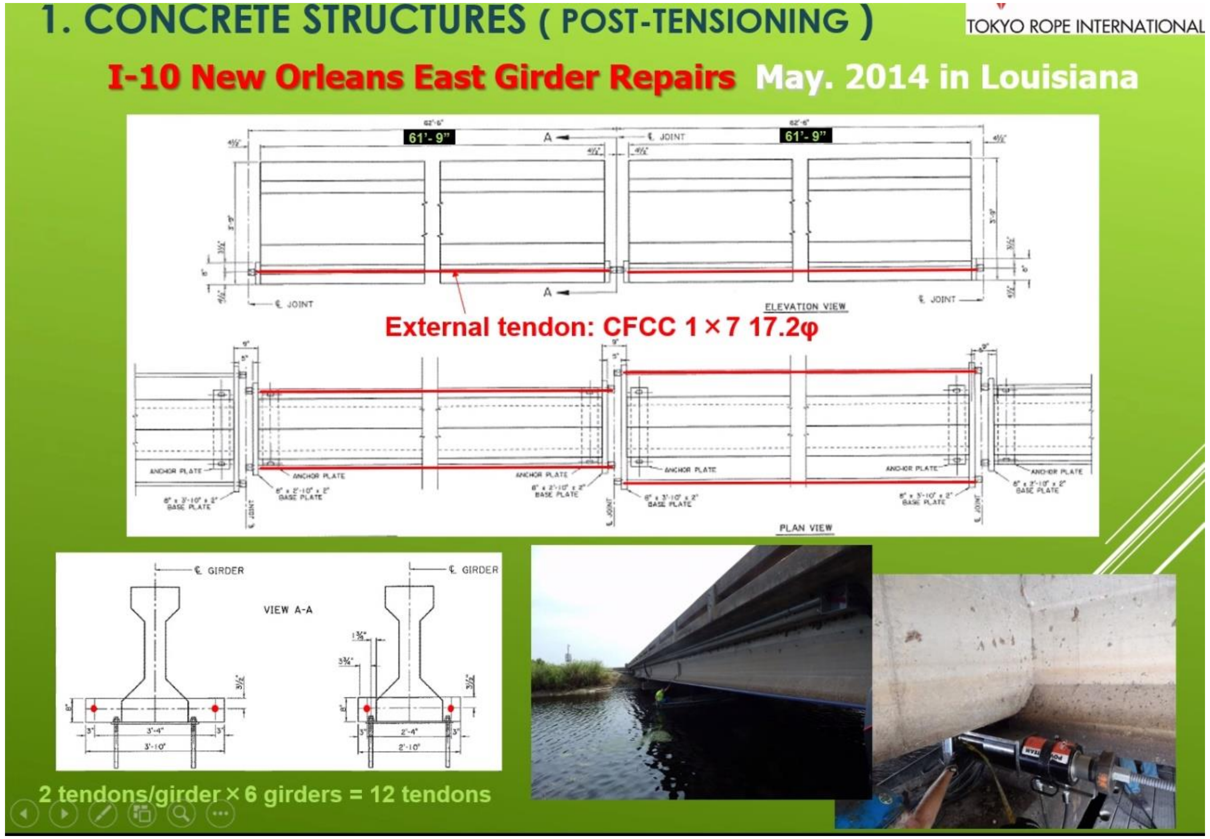


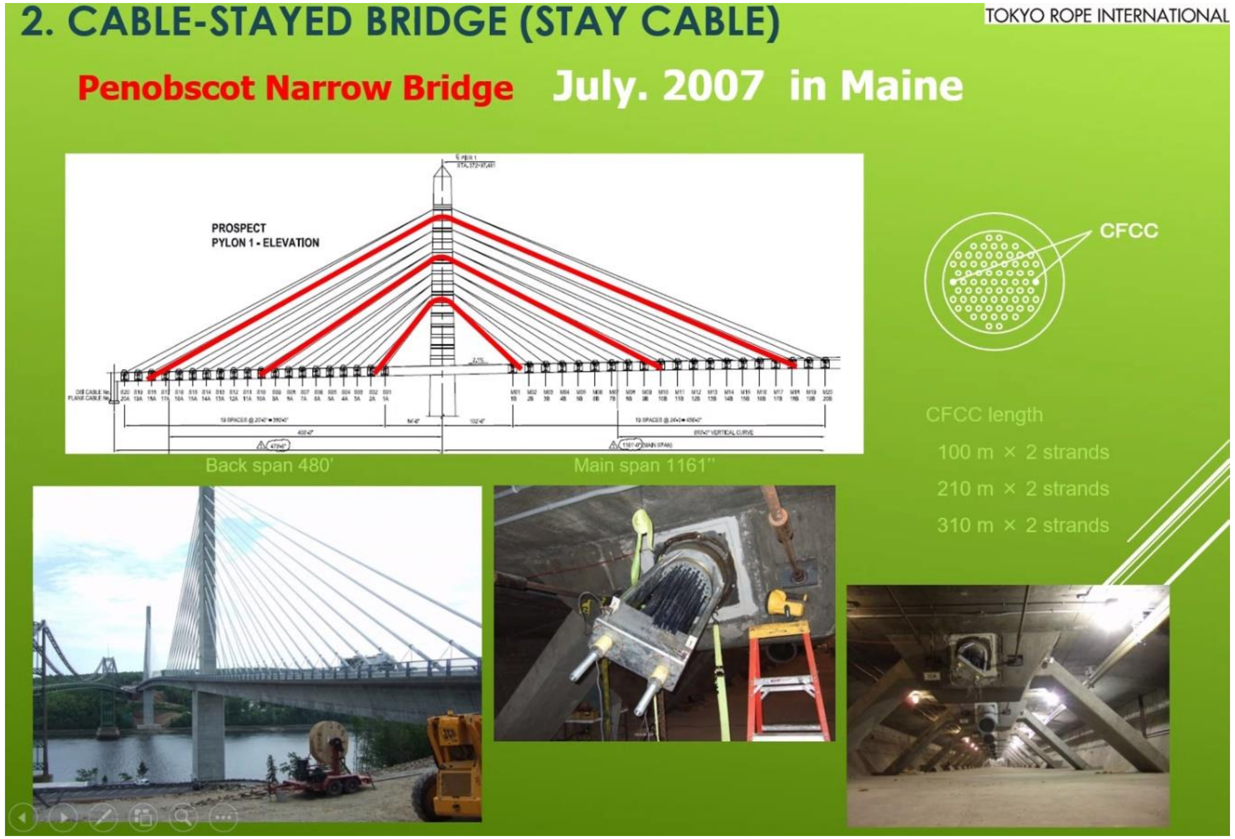
Last Decade+ : CFRP Prestressing Strand

- 2012 (Maine) & 2012-13 (Virginia)

Last Decade : CFRP Prestressing Strand

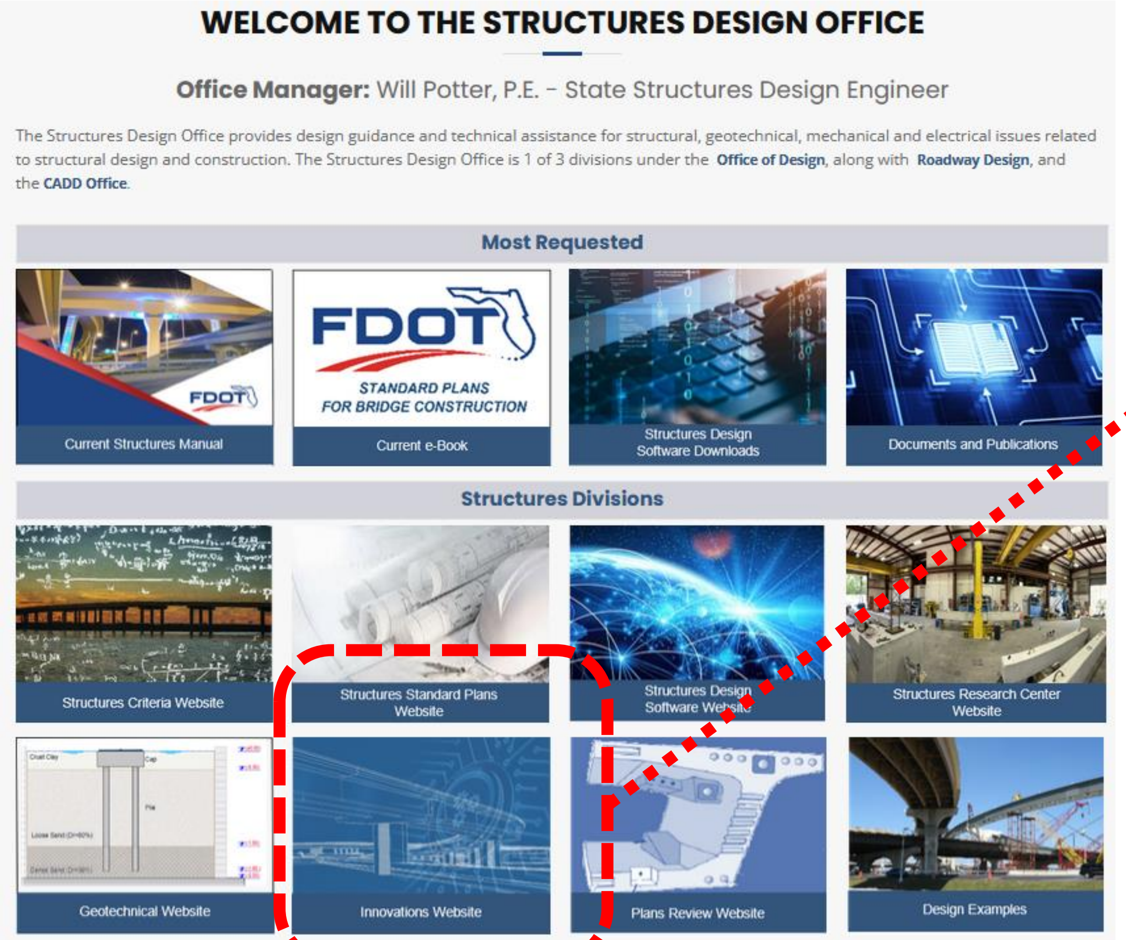
- 2014 (Louisiana) & 2016 (Maine)

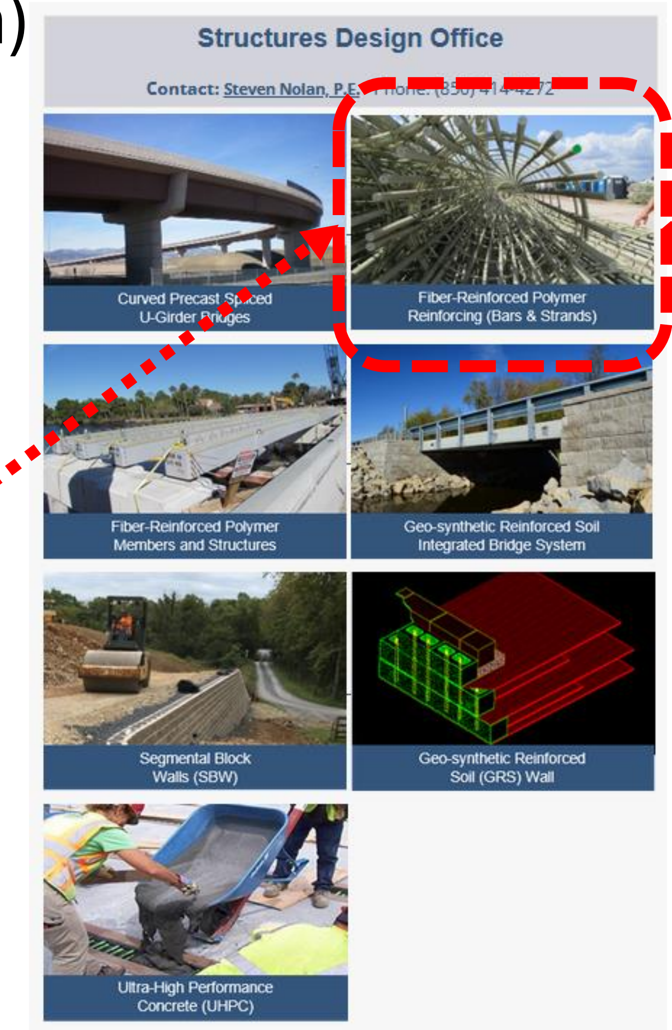




Last Decade : Launched FRP Innovation Webpage

- 2014 FDOT (Invitation to Innovation)





Fiber Reinforced Polymer Reinforcing

Structures Design - Transportation Innovation
Fiber Reinforced Polymer (FRP)
Reinforcing Bars and Strands

- Overview
- Usage Restrictions / Parameters
- Design Criteria
- Specifications
- Standards
- Producer Quality Control Program
- Projects
- Technology Transfer (T^2)
- FDOT Research
- Contact

CFRP Prestressing Strand & more… at FDOT

8/1/1992	Feasibility of Fiberglass Pretensioned Piles in a Marine Environment	Sen, Rajan (USF)
8/1/1995	Durability of CFRP Pretensioned Piles in Marine Environment Volume II	Sen, Rajan (USF)
11/30/1998	Studies on Carbon FRP (CFRP) Prestressed Concrete Bridge Columns and Piles in Marine Environment	Arockiasamy, M. (FAU)

Design: Practices and Standards for FRP-RC/PC

2017 Design Training Expo VS.

2025 FRP Workshop for the Tampa Bay Transportation Structures Engineers

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(Feb. 10th, 2025)

Steven Nolan, P.E.
State Structures Design Office (Tallahassee, FL.)

FRP INSTITUTE 1

FRP Reinforced Concrete Design

Presented in 2017 by: Rick Vallier, P.E.

Updates in 2025 by: Steven Nolan, P.E.

2017 vs. 2024 FRP Reinforced Concrete Outline

Figure 1. Halls River Bridge under construction (a) and existing bridge before demolition (b). [Courtesy of Astaldi Construction]

A. FRP Reinforcing Bars

B. Research

C. Structures Manual

~~D. Design Standards~~

~~E. Developmental Design Standards~~

~~E. Standard Specifications~~

~~F. Challenges~~

A. Reinforcing Bars Spec. 932-4.2 Bar Sizes and Loads

Table 932-8
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	BFRP & GFRP Bars (Type 0)	BFRP & GFRP Bars (Type III)	CFRP (Type II) Single & 7-Wire Strands	CFRP (Type I) Bars
2.1-CFRP	0.21	0.028	0.026	0.042	-	-	7.1	-
2	0.250	0.049	0.046	0.085	6.1	7.4	-	10.3
2.8-CFRP	0.280	0.051	0.048	0.085	-	-	13.1	-
3	0.375	0.11	0.104	0.161	13.2	16.0	-	20.9
3.8-CFRP	0.380	0.09	0.087	0.134	-	-	23.7	-
4	0.500	0.20	0.185	0.263	21.6	27.9	-	33.3
5	0.625	0.31	0.288	0.388	29.1	40.8	-	49.1
6	0.750	0.44	0.415	0.539	40.9	57.3	-	70.7
6.3-CFRP	0.630	0.19	0.184	0.242	-	-	49.8	-
7	0.875	0.60	0.565	0.713	54.1	75.8	-	-
7.7-CFRP	0.770	0.29	0.274	0.355	-	-	74.8	-
8	1.000	0.79	0.738	0.913	66.8	94.9	-	-
9	1.128	1.00	0.934	1.159	82.0	115.0	-	-
10	1.270	1.27	1.154	1.473	98.2	138.7	-	-
11	1.410	1.56	1.500	1.700	105.8	160.0	-	-

A. 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 *(~60%).*
- Low compressive strength of FRP:
  - Design contribution of FRP reinforcement to resist compression is ~~not recommended~~ ignored.
- Modulus of elasticity is low:
  - Due to lower stiffness (*6.5 msi & 8.7 msi*), serviceability often controls the design.
- Creep-rupture threshold is low (~~*25%*~~ *30%* f_u):
  - Sustained high tension can cause fibers to fail after a period of time
  - GFRP is considered more susceptible than CFRP (*70%* f_u).

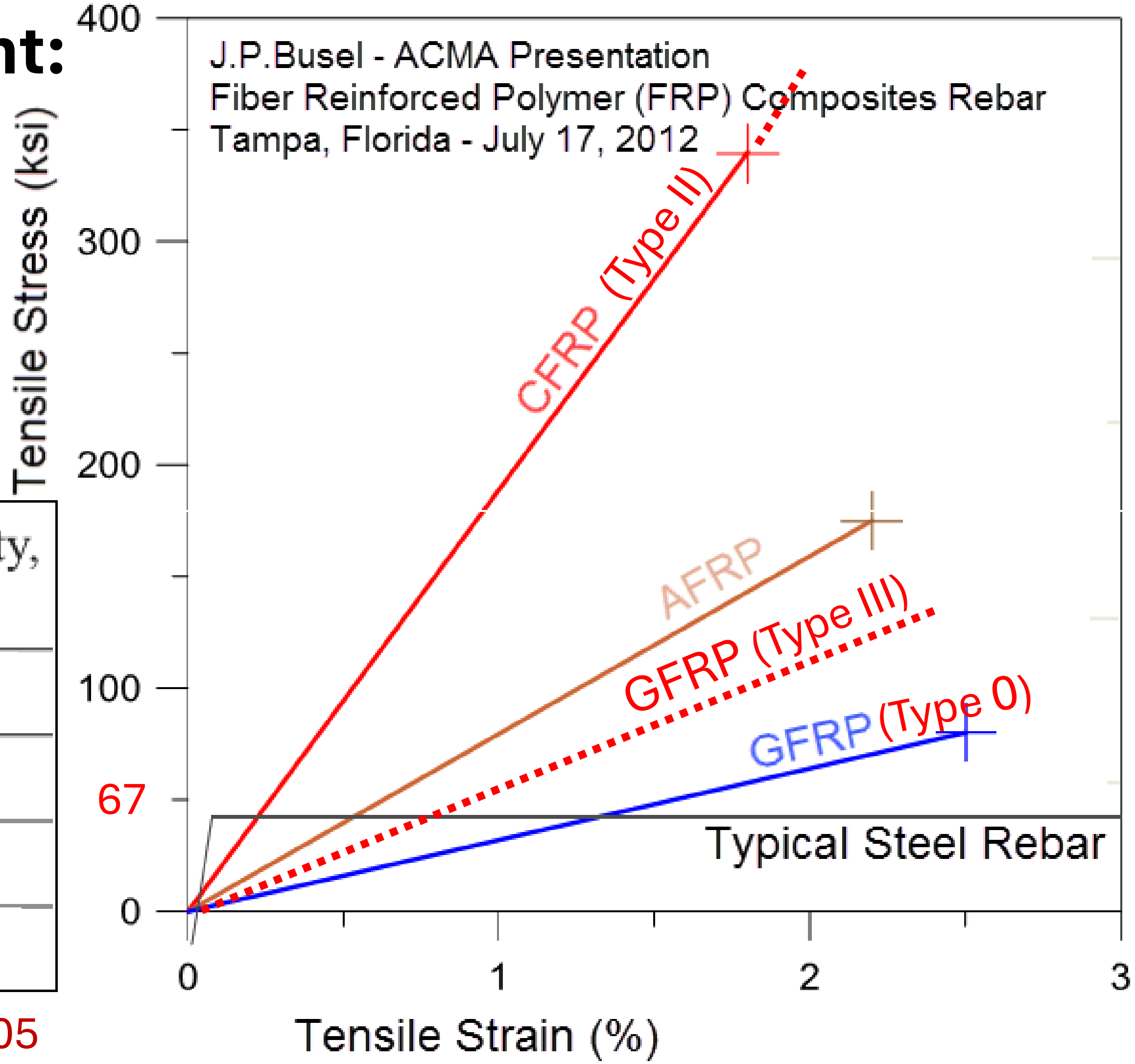
A. Reinforcing Bars

Characteristics of FRP Reinforcement:

- Linear Elastic to Failure
- No Yielding (but higher strain at 60 ksi)
- Higher Ultimate Strength
- Lower Strain at Failure

Bar type	Yield strength f_y or tensile strength f_{fu}, ksi	Modulus of elasticity, ksi
Steel	60	29,000
GFRP	(Type 0) 80 to 120	~~6000~~ 6,500
~~AFRP~~ (Type III)	~~170~~ 105 to 150	~~12,000~~ 8,700
CFRP (Type II)	~~300~~	~~22,000~~ 22,480

From ~~ACI 440.1R-15~~ FDOT Spec 932-4, ASTM D7957 & D8505



A. Reinforcing Bars

FRP Bar Mechanical Characteristics Influenced By:

Pre-Construction

- Manufacturing Process *(FDOT **MM** Chapter 12.1)*
- Rate of Curing
- Quality and Quantity of Constituents

Construction and Post-Construction

- Moisture *(current limitation on BFRP in submerged marine environments. See **FRPG** 2.1)*
- Ultraviolet Exposure *(Spec. 416 limits on exposure)*
- Elevated Temperature *(Fire < T_g)*
- Alkaline, Acidic, Saline Solutions *(C_E = 0.70)*

A. Reinforcing Bars

Characteristics of FRP Reinforcement:

- Endurance time in fire or elevated temperature less than for steel for anchorage zones *(**ACI 440-H** is working on criteria):*
  - 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 temp. (***Tg***)

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

Specification 932-4 *https://www.fdot.gov/programmanagement/specs.shtm*

A. Reinforcing Bars

Characteristics of FRP Reinforcement:

- Life cycle costs ~~likely~~ lower where steel corrosion is a concern *(see HRB).*
- SCMs (HRPs) for corrosion protection are ~~may~~ not ~~be~~ needed:
  - Silica Fume
  - Metakaolin
  - Ultrafine Fly Ash
  - ~~Calcium Nitrite~~
- Transportation costs are lower and handling easier for FRP due to light weight *(~25%).*
- Concrete cover reduction is allowed *(see **FRPG** Table 2.2).*

A. Reinforcing Bars

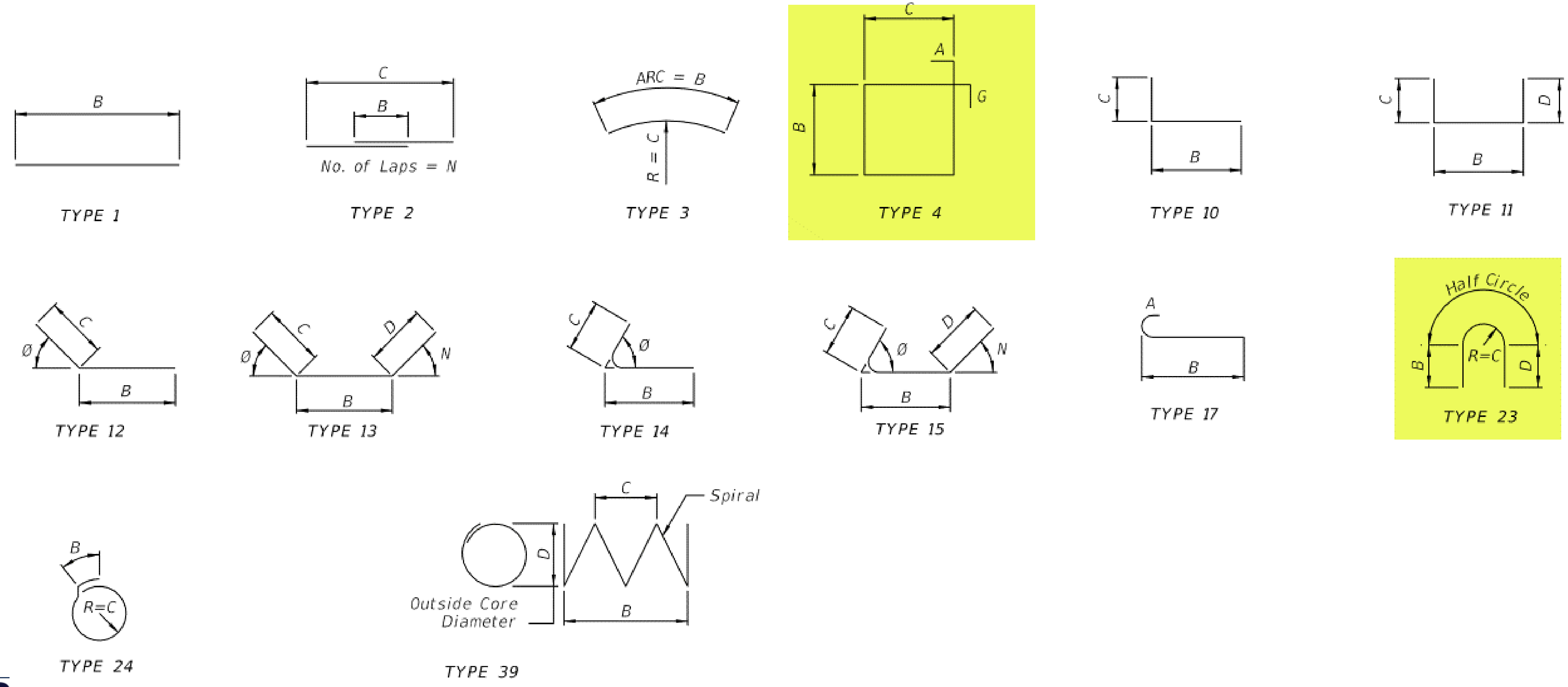
Bent Bars Characteristics:

- FRP is pultruded from thermoset resin *(viable thermoplastic resins are emerging)*
- FRP is fabricated with bends *(thermoplastic and olefin resin will allow controlled thermal bending – NCHRP IDEA-207 validated this):*
  - Sharp bends can be manufactured, but avoided due to potential low stress failure.
  - Bend Radius / Bar Diameter ≥ 3.
  - Tail Length = 12 x Bar Diameter.
  - Field bending not permitted.
- ~~Developmental Design~~ ***Standard Plan Index 415-010*** ~~D21310~~ Bar Bending Details

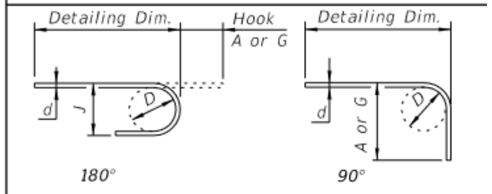
A. Reinforcing Bars

From ~~Developmental Design~~ Standard **Plans Index** **~~D21310~~** **415-010:**

(renumbering to match steel bar bending Index)



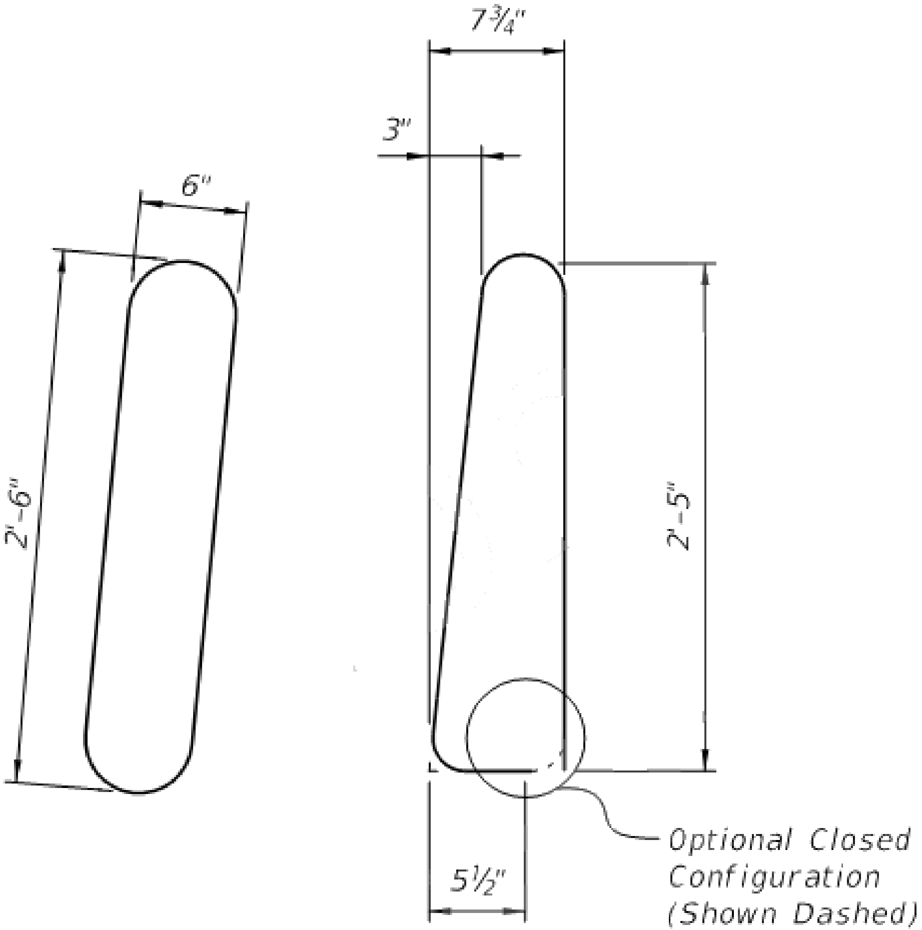
HOOK DETAILS

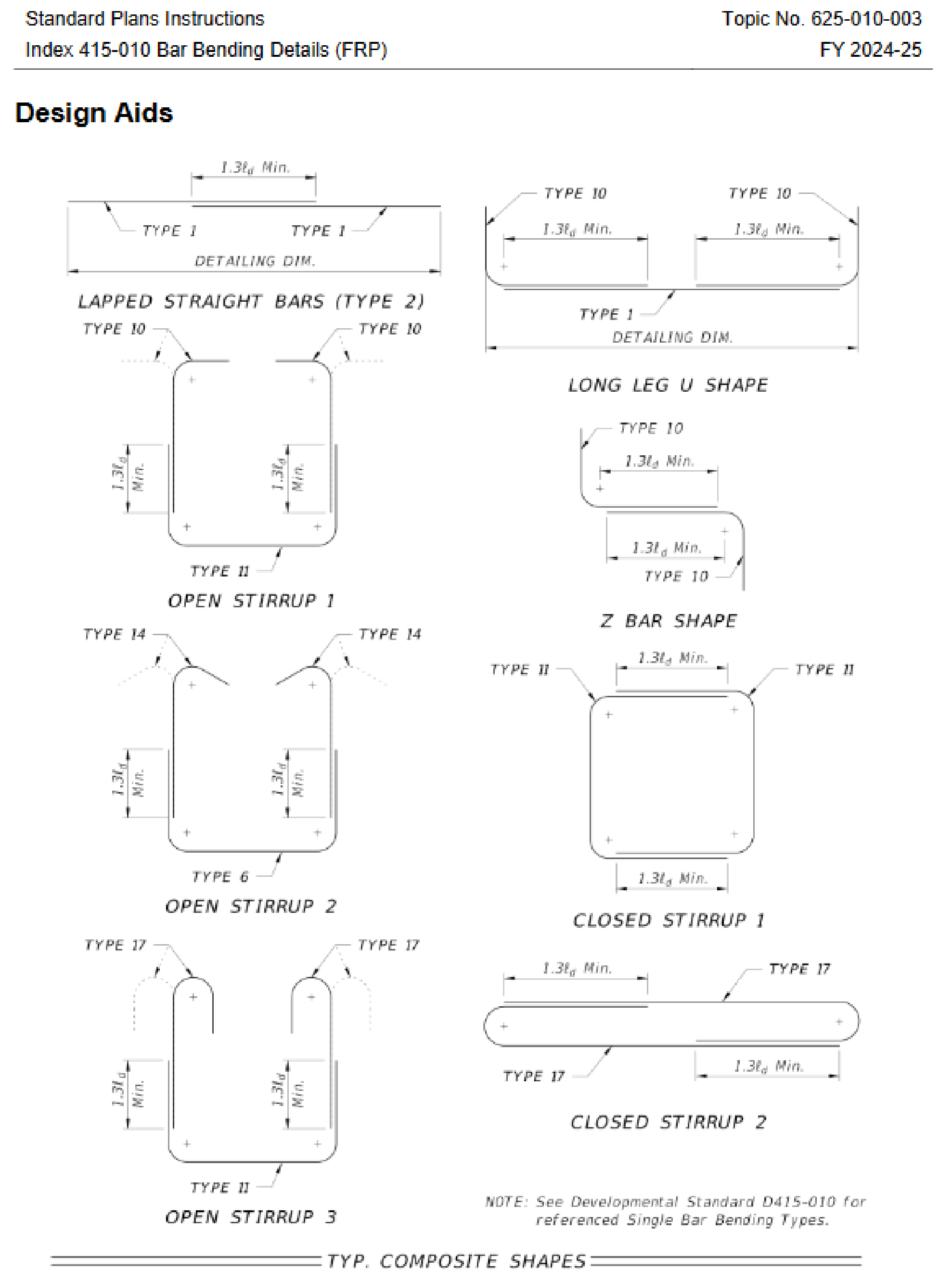


BAR SIZE	D	180° HOOKS A OR G	180° HOOKS J	90° HOOKS A OR G
#3	2¼"	5"	3"	6"
#4	3"	6"	4"	8"
#5	3¾"	7"	5"	10"
#6	4½"	8"	6"	1'-0"
#7	5¼"	10"	7"	1'-2"
#8	6"	11"	8"	1'-4"
STYLE		1		3

A. Reinforcing Bars

Complex Shapes:





A. Reinforcing Bars

1. Steel Reinforcing Bars; cost per pound

Carbon Steel, ASTM A615, Gr. 60 or 75	$1.50
Low-Carbon Chromium Steel, ASTM A1035, Gr. 100	$1.90
Stainless Steel, ASTM A955, Gr. 60 or 75, or ASTM A276, UNS S31653 or S31803	$7.00

2. FRP Reinforcing Bars, ***Specifications*** Section 932-3; cost per linear foot. Add $2.00 per hook, or bend for stirrups, and $2.00 per revolution for circular spirals. Add a lump sum of $5,000 per bar size for each lot of FRP reinforcing bars to account for the cost of testing.

#3	#4	#5	#6	#7	#8	#9	#10	#11
$1.50	$2.00	$2.30	$2.70	$3.50	$4.50	$5.80	$7.20	$8.50

Cost Comparison (Installed Bid Avg. Cost)

Bar Size	Nominal Diameter	Average Unit Costs HRB (3-bids) **		FDOT Structures Manual for BDR Cost Estimating (2025)		
		GFRP Bars 2016	GFRP Bars 2023	GFRP Bars	Grade 60 Steel	Stainless-Steel
#4	0.500”	$1.18 / LF	$1.90 / LF	$2.00 / LF	$~~0.60~~ 1.00 / LF	$~~2.72~~ 4.68 / LF
#5	0.625”	$1.37 / LF	$2.29/ LF	$2.30 / LF	$~~0.94~~ 1.56 / LF	$~~4.19~~ 7.30 / LF
#6	0.750”	$1.55 / LF	$2.71/ LF	$2.70 / LF	$~~1.35~~ 2.25 / LF	$~~5.98~~ 10.53 / LF
#8	1.000”	$2.54 / LF	$4.04/ LF	$4.50 / LF	$~~2.40~~ 4.00 / LF	$~~10.74~~ 18.69 / LF

** 2023 FDOT Bid Avg.

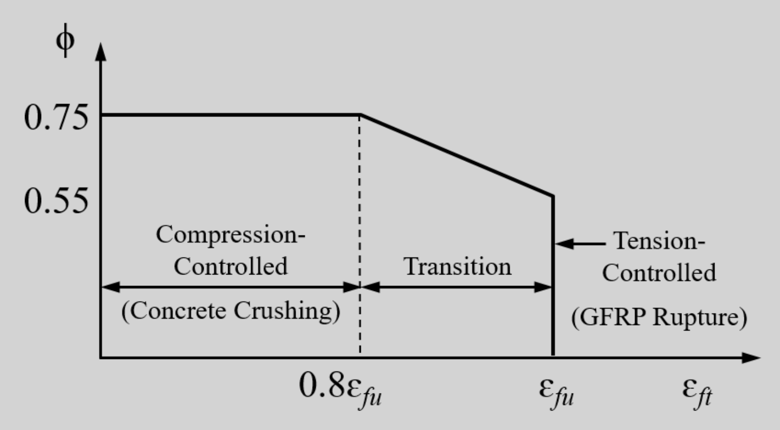
Note: There is not typically a 1:1 substitution of FRP for steel bars.
Black steel bar based on $1.50 ~~$0.90~~ / lb for all bar sizes.
Stainless steel bar based on $7.00 ~~$4.00~~ / lb for all bar sizes.

A. 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 through extensive cracking and deformation



FRP Reinforced Concrete Design

- Tension-Controlled Behavior
  - FRP Rupture *(phi = 0.55)* ???
- Compression-Controlled Behavior
  - Concrete Crushing prior to FRP Rupture *(phi = ~~0.65~~ 0.75)*
- "Margin of Safety" is higher than for Steel Reinforced design

A. 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

B. FDOT Research

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

Completed	Title	Researcher	Institution	Research No.
Nov. 2018	**Performance Evaluation** of GFRP Reinforcing Bars Embedded in Concrete Under Aggressive Environments	R. Kampmann	FAMU-FSU	BDV30 977-18
April 2019	**Degradation Mechanisms** and **Service Life Estimation** of FRP Concrete Reinforcements	A. El Safty	UNF	BDV34 977-05
June 2019	Performance Evaluation of Basalt Fiber Reinforced Polymer (BFRP) Reinforcing Bars Embedded in Concrete	R. Kampmann	FAMU-FSU	BVD30 986-01
April 2022	Epoxy Dowel Pile Splice Evaluation with FRP Bars	A. Mehrabi	FIU	BDV29 977-52
Dec. 2020	"Stainless Steel Strands and Lightweight Concrete for Pretensioned Concrete Girders" (w/ GFRP shear stirrups)	M. Roddenberry	FAMU-FSU	BDV30 977-27 (Report A)
July 2022	Improving Testing Protocol and Material Specifications for Basalt Fiber Reinforced Polymer Bars	R. Kampmann	FAMU-FSU	BE694

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

B. FDOT Research - Completed and In-progress

Research and field implementation of FRP materials is ongoing and expanding…

Completion Date	Title	Researcher	Institution	Research No.
Aug. 2022	Development of GFRP Reinforced Single Slope Bridge Rail	G. Consolazio	UF	BDV31 977-110
Dec. 2023	Evaluation of Glass Fiber Reinforced Polymers (GFRP) Spirals in Corrosion Resistant Concrete Piles	S. Jung	FAMU-FSU	BDV30 977-27
~~Feb.~~ Oct. 2025	FSBs With Stainless Steel Strands and GFRP Shear Reinforcement	M. Roddenberry	FAMU-FSU	BED30 977-09
April 2025	*Waterline Pile Cap Footings for Bridges using Large Diameter FRP Reinforcing – Material Characterization and Design*	A. Nanni	UM	BEE76 977-01
May 2025	*HRB Extraction and Physio-Mechanical Testing of FRP Reinforcing Bars from 5-year-old Seawater Concrete Test Blocks on Halls River Bridge Bulkhead*	F. De Caso	UM	BEE76 977-02

C. FDOT Structures Manual

FDOT Design Criteria for FRP:

http://www.fdot.gov/structures

Vol. 1 – SDG

- Bearing Piles – 3.5
- Fender Systems – 3.14
- Structural FRC– 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

C. 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.

C. FDOT Structures Manual

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.

FDM 121.3.2: *"Any component designed using Fiber Reinforced Polymer (FRP) composite materials except components in the Standard Plans"* is designated as **Category 2 Structure/SSDO Review.**

C. FDOT Structures Manual

Volume 4 - Fiber Reinforced Polymer Guidelines *(FRPG)* – Section 2:

Permitted use ~~when approved by the SSDE:~~

- Approach Slabs
- Bridge Decks & Bridge Overlays
- Cast-in-Place Flat Slab Superstructure
- Pile Bent Caps ~~not in direct contact with water~~
- Pile Jackets
- 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 and Copings
- Drainage Structures
- Dowel Bars for Exp. Joints

Note: Other elements will be considered on a case-by-case basis.

C. FDOT Structures Manual

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~~ 2 in.	3 in.
C.I.P. Cantilever Retaining Walls	~~2.5~~ 2 in.	3 in.
MSE Walls	~~2~~ 1.5 in.	3 in.
Bulkheads and Sheet Pile Caps	~~3~~ 2 in.	4 in.

See ***FDOT Structures Manual*** for cover requirements for other components.

http://www.fdot.gov/structures

C. FDOT Structures Manual

GFRP/CFRP Reinforcing Bars – Section 2 – Design Criteria

Design **concrete members** with FRP reinforcement according to:

- *AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete* ~~*ACI 440.1 Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars.*~~

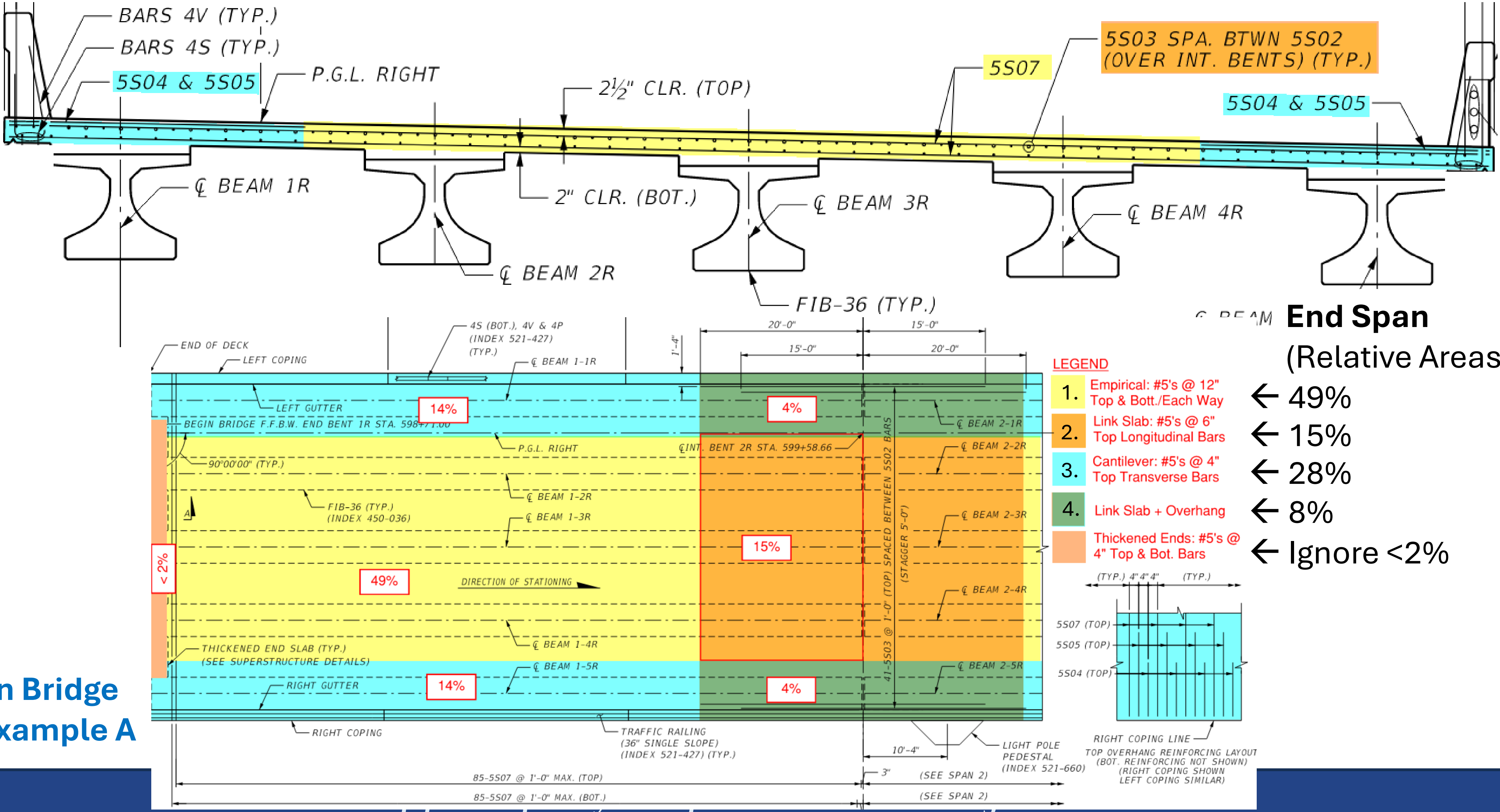
- *AASHTO Guide Specification for the Design of Concrete Bridge Beams Prestressed with CFRP Systems.* ~~*ACI 440.4 Prestressing Concrete Structures with FRP Tendons*~~

Design **Bridge Decks** according to:

- *AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete* ~~*Bridge Decks and Traffic Railings*~~ *(2nd Edition)*

*Use FRP **Mechanical Properties** per FDOT Section 932-4.*

Comparison of Rebar Qty. – Bridge Deck Example A

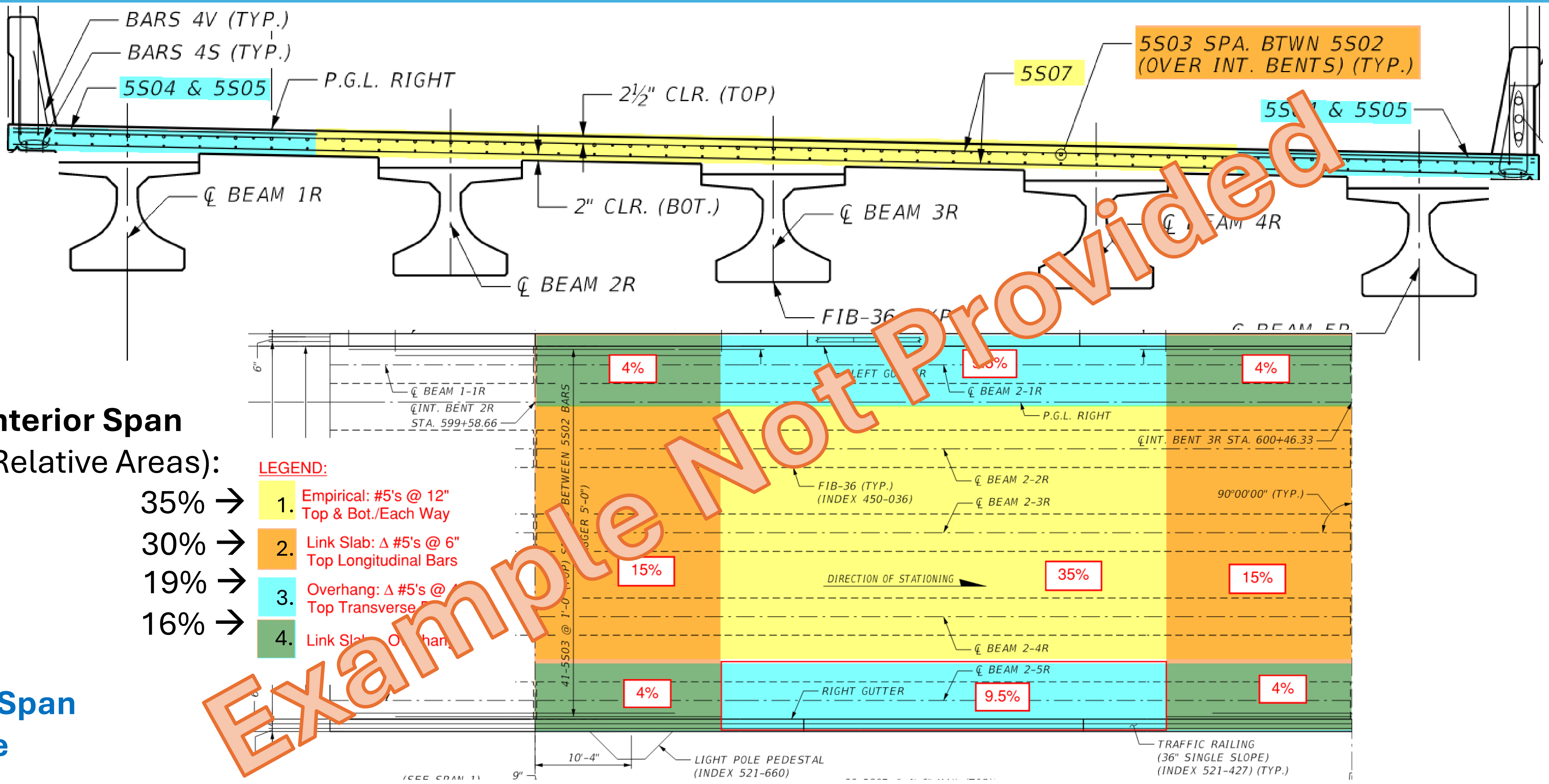


End Span (Relative Areas):

- ← 49%
- ← 15%
- ← 28%
- ← 8%
- ← Ignore <2%

End Span Bridge Deck - Example A

Comparison of Rebar Qty. – Bridge Deck Example B



Interior Span
(Relative Areas):

35% →
30% →
19% →
16% →

LEGEND:

1. Empirical: #5's @ 12" Top & Bot./Each Way
2. Link Slab: Δ #5's @ 6" Top Longitudinal Bars
3. Overhang: Δ #5's @ … Top Transverse …
4. Link Sla… O…hang

Interior Span Example

Comparison of Material Qty. – Deck Area 1 (Example A)

<u>Convention CS-RC</u> *(ASTM A615):*

- Thickness = *8"*
- Concrete Cover = *2"*
- Flexural Depth (#5's) d = *5.7"*
- Empirical ***(AASHTO-BDS)***: Bottom layers = *#5's @ 13.8"* *(0.27 in²/ft)*; Top layers = *#4's @ 13.3"* *(0.18 in²/ft)*
- Empirical ***(FDOT): #5's @ 12"*** **
- Total Rebar ***(AASHTO)***: $A_s = 0.90\ in^2/ft^2$; ***(FDOT)***: $A_s = 1.24\ in^2/ft^2$

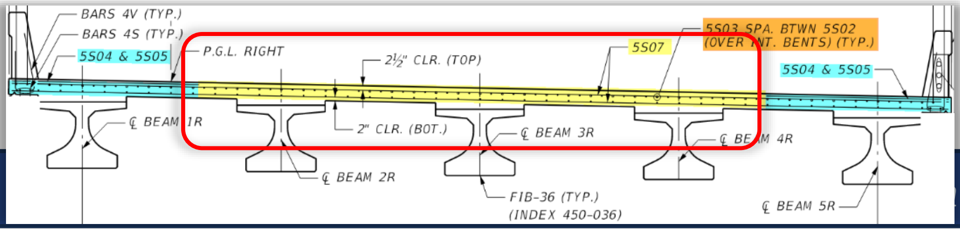
<u>GFRP-RC</u> *(ASTM D8505-23):*

- Thickness = *7"* → $\Delta_{vol.}$ = -12%; Δ_{weight} = -15%
- Concrete Cover = *1"*
- Flexural Depth (#5's) d = *5.7"*
- Empirical ***(AASHTO-GSG)***: ** Bottom transverse layer = *#5's @ 6.5"* *(0.83%)* Other 3-layers = *#5's @ 12"* *(0.35%)*
- Total Rebar: $A_f = 1.50\ in^2/ft^2$ *deck)*

→ Δ_{volume} ***(AASHTO)*** = +67%; Δ_{weight} = -58%

→ Δ_{volume} ***(FDOT)*** = +21%; Δ_{weight} = -70%

End Span Bridge Deck - Example A



Interior Section

*** Minimum bar size and spacing governs*

Comparison of Material Qty. – Deck Area 2 (Example A)

<u>Convention CS-RC</u> *(ASTM A615):*

- Thickness = *8"*
- Concrete Cover = *2"*
- Flexural Depth (#5's) *d* = *5.7"*
- Empirical: ***(AASHTO)***: Bottom layers = #5's @ *13.8"* *(0.27 in²/ft)*; Top transverse = #4's @ 13.3" *(0.18 in²/ft)*; + Top long. = *#5's @ 6"* *(0.62 in²/ft)*
- Empirical: ***(FDOT)***: *3-layers @ #5's @ 12"* ** *(0.31 in²/ft)*;
- Total Rebar ***(AASHTO)***: $A_s = 1.34\ in^2/ft^2$
  (FDOT): $A_s = 1.55\ in^2/ft^2$

<u>GFRP-RC</u> *(ASTM D8505-23):*

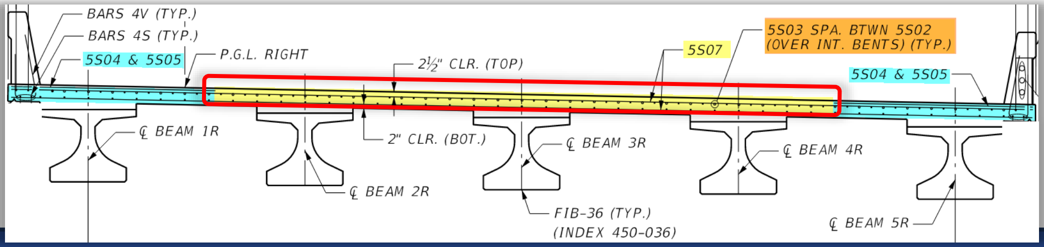
- Thickness = *7"* → $D_{vol.} = -12\%$; $D_{weight} = -15\%$
- Concrete Cover = *1"*
- Flexural Depth (#5's) *d* = *5.7"*
- Empirical ***(FDOT/AASHTO-GSG)***: **Bottom transverse = *#5's @ 6.5"* *(0.83% = 0.57 in²)*; Other 2-layers = *#5's @ 12"* *(0.35% = 0.31 in²)*; + Top long. = *#5's @ 6"* *(0.62 in²/ft)*
- Total Rebar: $A_f = 1.81\ in^2/ft^2$

→ $\Delta_{vol.}$ **(AASHTO)** = +35%; Δ_{weight} = -66 %

→ $\Delta_{vol.}$ **(FDOT)** = +17%; Δ_{weight} = -71 %

End Span Bridge Deck - Example A

Link-Slab Section



*** Minimum bar size and spacing governs*

Comparison of Material Qty. – Deck Area 3 (Example A)

<u>Convention CS-RC</u> *(ASTM A615):*

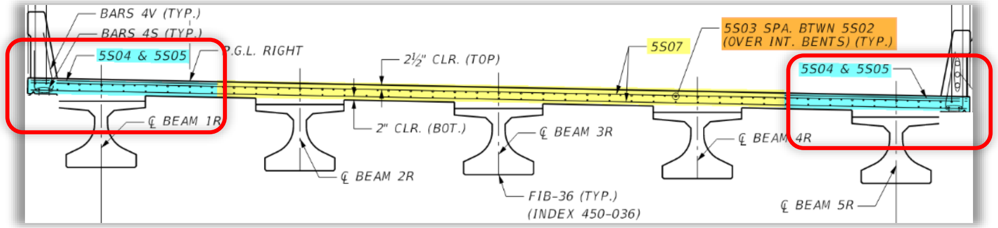
- Thickness = *8”*
- Concrete Cover = *2”*
- Flexural Depth (#5’s) *d = 5.7”*
- Empirical ***(AASHTO-BDS)***: 2~Bot. layers = #5’s @ *13.8” (0.27 in²/ft)*; Top long. = #4’s @ 13.3” *(0.18 in²/ft)*; Top transv. = #4’s + #5’s @ 4” *(0.82 in²/ft)*.
- Empirical ***(FDOT)***: 3-layers #5’s @ 12” ** *(0.31 in²/ft)*; Top Tranv. = #5’s @ 4” *(0.93 in²/ft)*.
- Total Rebar ***(AASHTO)***: A_s = *1.54 in²/ft²*;
  (FDOT): A_s = *1.86 in²/ ft²*.

<u>GFRP-RC</u> *(ASTM D8505-23):*

- Thickness = *7”* → $\Delta_{vol.}$ = *88%*; Δ_{weight} = *85%*
- Concrete Cover = *1”*
- Flexural Depth (#5’s) *d = 5.7”*
- Empirical ***(AASHTO-GSG)***: Bot. ** transv. = *#5’s @ 6.5” (≥0.83% = 0.57 in²)*; 2~long. layers = *#5’s @ 12” (≥ 0.35% = 0.31 in²)*; Top transv. = *#5’s @ 4” (0.93 in²/ft)*.
- Total Rebar: A_f = *2.12 in²/ft² deck)*
  → Δ_{volume} ***(AASHTO)*** = *+38%*; Δ_{weight} = *-66 %*
  → Δ_{volume} ***(FDOT)*** = *+14%*; Δ_{weight} = *-72 %*

End Span Bridge Deck - Example A

Overhangs (midspan)



*** Minimum bar size and spacing governs*

Comparison of Material Qty. – Deck Area 4 (Example A)

Convention CS-RC *(ASTM A615):*

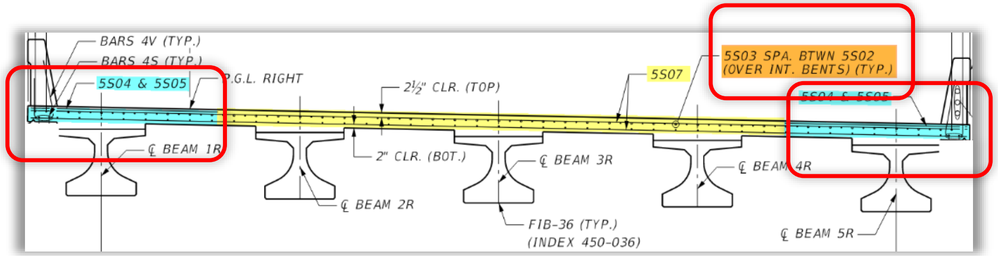
- Thickness = *8"*
- Concrete Cover = *2"*
- Flexural Depth (#5's) *d* = *5.7"*
- Empirical Overhang + Link-Slab ***(AASHTO-BDS)***: 2~Bot. layers = #5's @ *13.8"* *(0.27 in^2/ft)*; Top long. = #4's & #5's @ 6.7" *(0.46 in^2/ft)*; Top transv. = #4's + #5's @ 4" *(0.82 in^2/ft)*.
- Empirical-Link ***(FDOT):*** 2~Bot. layers #5's @ 12" ** *(0.31 in^2/ft)*; Top Tranv. = #5's @ 4" *(0.93 in^2/ft)*. Top. long. = #5's @ 6" *(0.62 in^2/ft)*.
- Total Rebar ***(AASHTO):*** *A_s = 1.82 in^2/ft^2;*
  (FDOT): *A_s = 2.17 in^2/ft^2.*

GFRP-RC *(ASTM D8505-23):*

- Thickness = *7"* → *$\Delta_{vol.}$ = -12%; Δ_{weight} = -15%*
- Concrete Cover = *1"*
- Flexural Depth (#5's) *d* = *5.7"*
- Empirical Overhang + Link-Slab ***(AASHTO-GSG)***: Bot. ** transv. = *#5's @ 6.5"* *(≥0.83% = 0.57 in^2)*; Bot. long. = *#5's @ 12"* *(≥ 0.35% = 0.31 in^2)*; Top transv. = *#5's @ 4"* *(0.93 in^2/ft)*. Top long. = *#5's @ 6"* *(0.62 in^2)*
- Total Rebar: *A_f = 2.69 in^2/ft^2 deck)*
  → *Δ_{volume}* ***(AASHTO)*** *= +48%;* *Δ_{weight} = -67 %*
  → *Δ_{volume}* ***(FDOT)*** *= +24%;* *Δ_{weight} = -69 %*

End Span Bridge Deck - Example A

Overhangs @ Link-Slab



*** Minimum bar size and spacing governs*

Comparison of Material Quantities – Example A Summary

<u>Convention CS-RC</u> *(ASTM A615):*

- **Example A** (End Span Rebar)
  - Empirical (AASHTO): As= 0.49*0.90 + 0.15*1.34 + 0.28*1.54 + 0.08*1.82 = **1.22 in^2/ ft^2**
  - Empirical (FDOT): A_s = 0.49*1.24 + 0.15*1.55 + 0.28*1.86 + 0.08*2.17 = **1.53 in^2/ ft^2**

<u>GFRP-RC</u> *(ASTM D8505-23):*

- **Example A** (End Span Rebar)
  - Empirical (both): As= 0.49*1.50 + 0.15*1.81 + 0.28*2.12 + 0.08*2.69 = **1.82 in^2/ ft^2**

*** Minimum bar size and spacing governs*

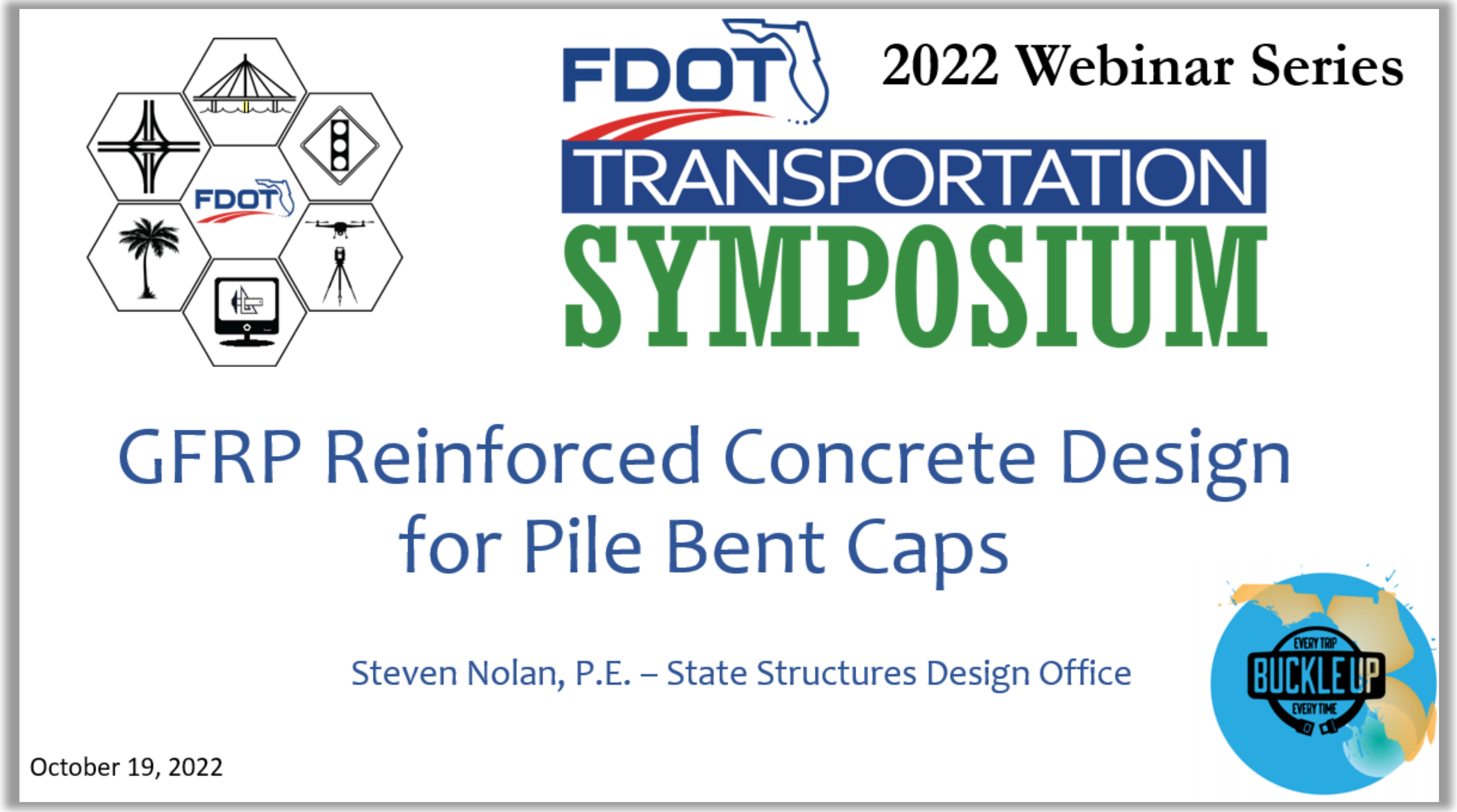
End Span Bridge Deck - Example A

*Concrete → $\Delta_{vol.}$ **(AASHTO)** = -12%; Δ_{weight} = -15% for GFRP-RC*

*Rebar → Δ_{volume} **(AASHTO)** = +49%; Δ_{weight} = -63 %.*

*Rebar → Δ_{volume} **(FDOT)** = +19%; Δ_{weight} = -70 %.*

Comparison of Rebar Qty. – Pile Bent Cap Example C



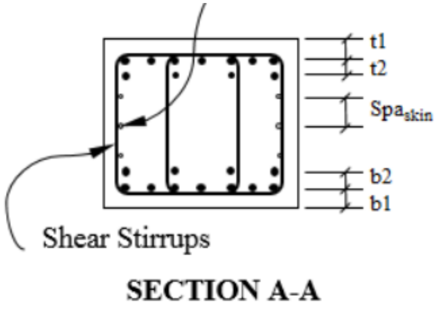
https://transportationsymposium.fdot.gov/Attendee/PastWebinars2022

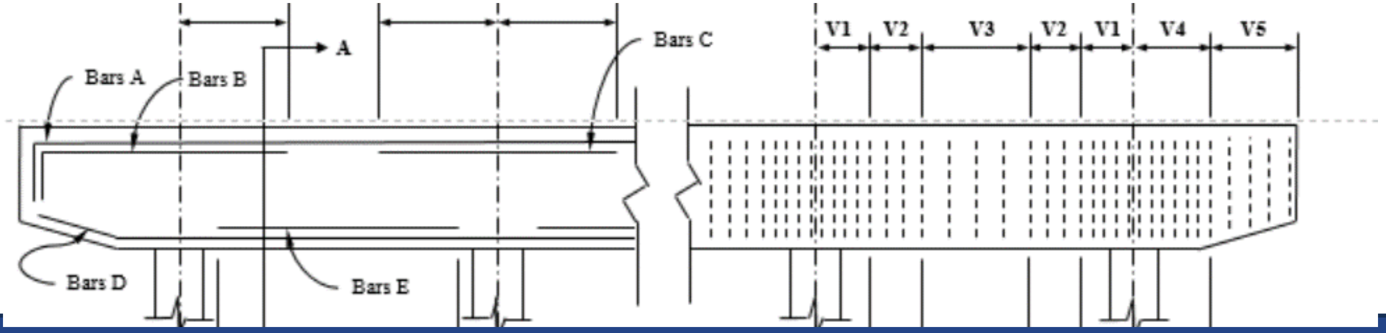
10/20/2022	GFRP Reinforced Concrete Design for Pile Bent Caps	Presentation

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)**

Rebar Location	GFRP-RC (Type 0) 3-ft Deep Cap (E_f = 6,500 ksi)	GFRP-RC 3-ft Deep Cap (E_f = 7,250 ksi)	GFRP-RC (Type III) 3-ft Deep Cap (E_f = 8,700 ksi)
Bars A - Flexural Top	**6 ~ #8's** (A_f = 4.7 in^2)	**7 ~ #7's** (A_f = 4.2 in^2)	**6 ~ #7's** (A_f = 3.6 in^2)
Bars D & E - Flexural Bottom	**8 ~ #8's** (A_f = 6.3 in^2)	**7 ~ #8's** (A_f = 5.5 in^2)	**6 ~ #8's** (A_f = 4.7 in^2)
Bars V3 - Shear Stirrups	**4-legs #5 at 11" sp.** (A_f = 1.4 in^2/ft)	**4-legs #5 at 13" sp.** (A_f = 1.1 in^2/ft)	**4-legs #4 at 10" sp.** (A_f = 1.0 in^2/ft)

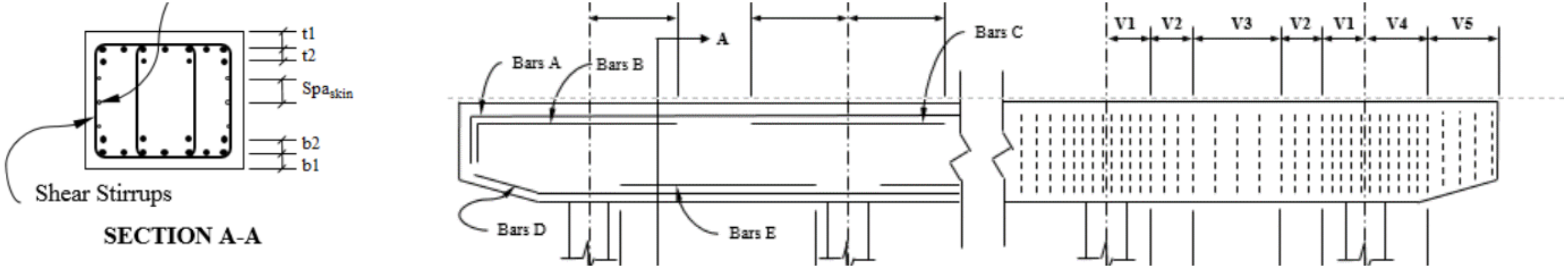




Design Example for Pile Bent Cap Summary

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

Rebar Location	GFRP-RC (Type 0) 3-ft Deep Cap	*Δvolume* Type 0 or (Type III)	Steel-RC 3-ft Deep Cap
Bars A - Flexural Top	**6 ~ #8's** (A_f = 4.7 in^2)	*+80% or (+38%)*	**6 ~ #6's** (A_s = 2.6 in^2)
Bars D & E - Flexural Bottom	**8 ~ #8's** (A_f = 6.3 in^2)	*+50% or (+12%)*	**7 ~ #7's** (A_s = 4.2 in^2)
Bars V3 - Shear Stirrups	**4-legs #5 at 11" sp.** (A_f = 1.4 in^2/ft)	*+75% or (+25%)*	**4-legs #4 at 12" sp.** (A_s = 0.8 in^2)



Construction: Example Projects & Lessons Learned

Projects with Fast-Facts Sheet

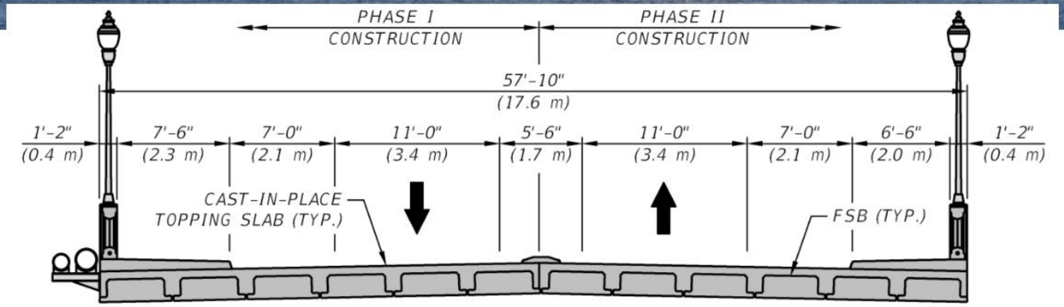
- 4th St North over Big Island Gap (D7) ***– In-house Design.***
- 40th Ave NE over Placido Bayou (D7)
- Arthur Drive over Lynn Haven Bayou (D3)
- Bakers Haulover Cut Bulkhead Replacement (D6)
- Bimini Dr Bridge on Duck Key (D6)
- Cedar Key Bulkhead Rehab (D2)
- Halls River Bridge (D7) ***– In-house Design.***
- Key West Bight Ferry Terminal Extension (D7)
- NE 23rd Ave over Ibis Waterway (D6)
- PortMiami Tunnel Retaining Walls (D6)
- South Maydell Dr over Palm River (D7)
- SR-A1A Flagler Beach Seawall (Segment 3) (D5)
- SR-A1A over Myrtle Creek and Simpson Creek (D2)
- SR-5 (US-17) over Trout River (D2)
- SR-5 (US 41) over Morning Star and Sunset Waterways (D1)
- SR-30 over St Joe Inlet (D3)
- SR-45 (US 41) over North Creek (D1)
- SR 112/I-195 Over Westshore Waterway (D5)
- SR-312 over Matanzas River (D2)
- SR-520 over Indian River Bulkhead Rehab (D5)
- Sunshine Skyway Seawall Rehabilitation (D7)
- UM Innovation Bridge
- UM Fate Bridge
- UM I-Dock
- US-1 over Cow Key Channel (D6)

Upcoming Bridge and Seawall Projects

- D2: US1/King St over San Sebastian River (437428-1)
- D2: St. Augustine A1A/Avenida Menendez Seawall replacement (428271-2)
- D2: CR 357 over Shired Creek (437402-1)
- D3: CR30A over Western Lake (443331-1)
- D3: CR30B/Indian Lagoon (441185-2)
- D3: CR 372/Surf Road over Otter Creek Rise (442951-1)
- D4: US 1/Jupiter Federal Observation Platform (428400-2)
- D4: SR-A1A North Causeway Bridge Observation Platform (429936-2)
- D4: 17th St/Indian River, East End-Vero (446106-2)
- D4: SR 5/US 1 Over Earman River (442891-1) ***– In-house Design.***
- D5: SR-A1A Seawalls - Flagler Beach & Nth Volusia Co. (452443-1 & 452444-1)
- D5: Barracuda Blvd New Smyrna (437935-1) ***– In-house Design.***
- D5: 5th Street over Yacht Club Cut (437936-1)
- D5: US1 over Pellicer Ck (447118-1)
- D6: FKOSH Bridge Replacement… (448206-1 & (448207-1)

Construction: D7 Example Project

- **40th Ave NE over Placido Bayou (FPID: 443600-1)**



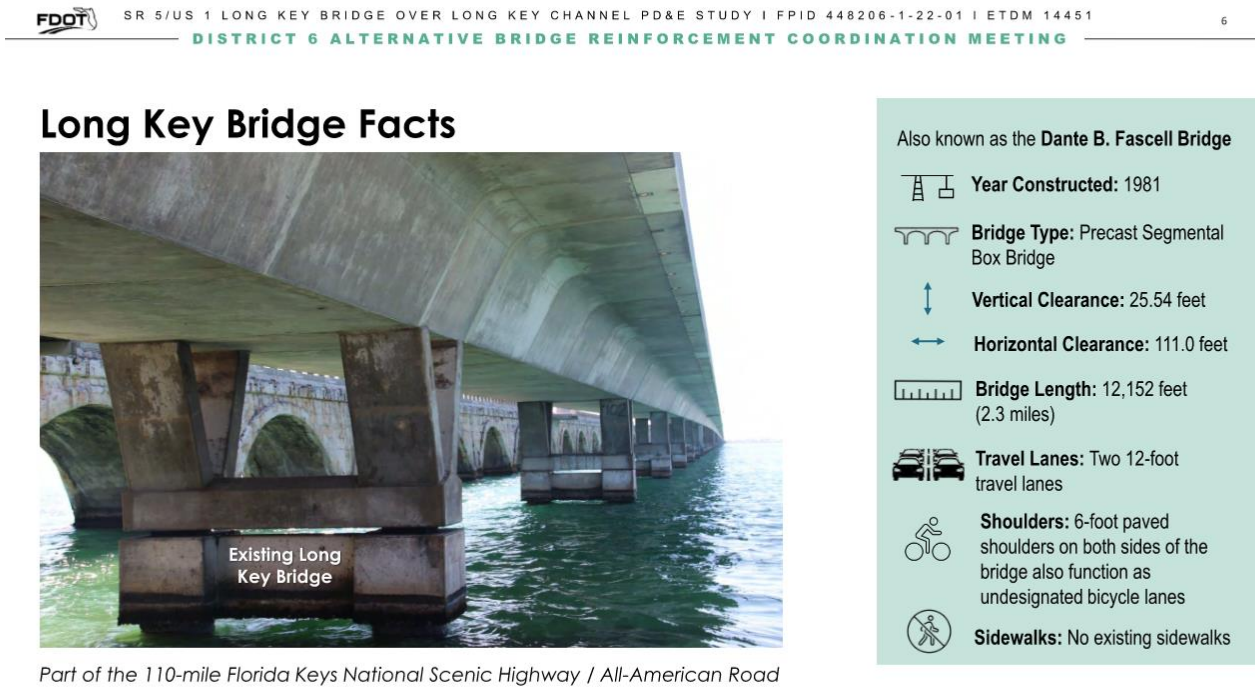
- **4th St North over Big Island Gap (FPID: 430500-1)**

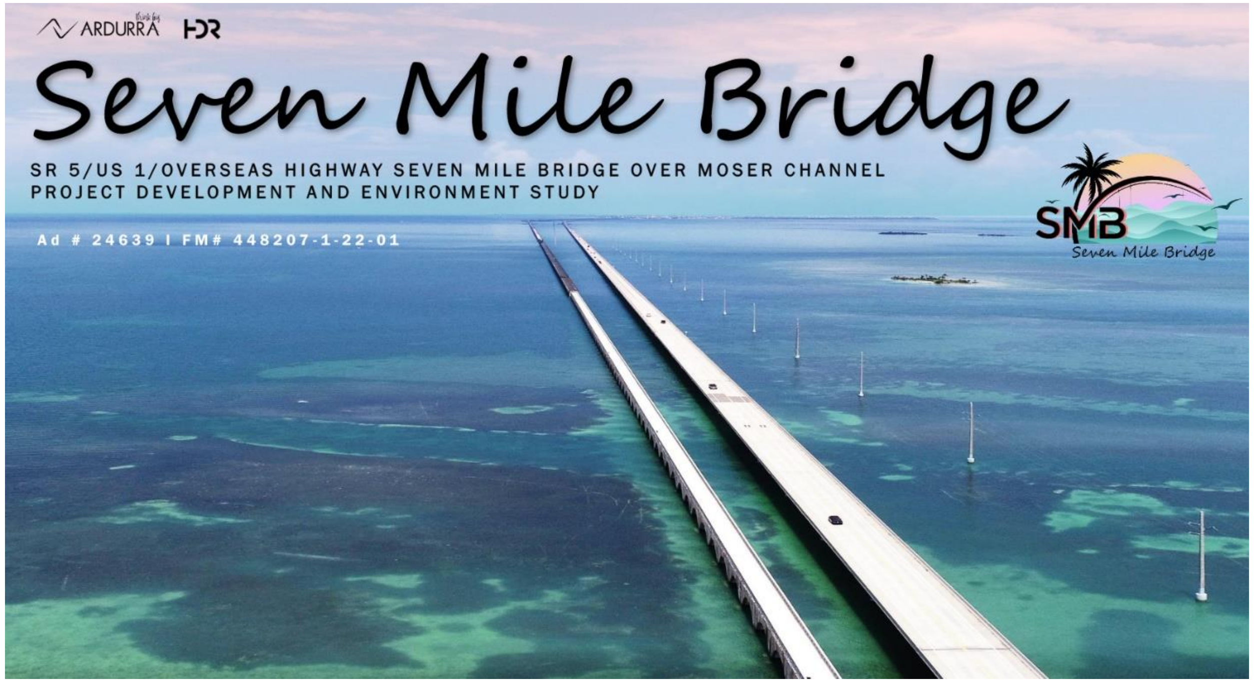
In-house Design

Future Construction: D6 Example Projects

- Long Key Bridge Replacement (448206-1 & (448207-1)

- Seven Mile Bridge Replacement (448207-1)



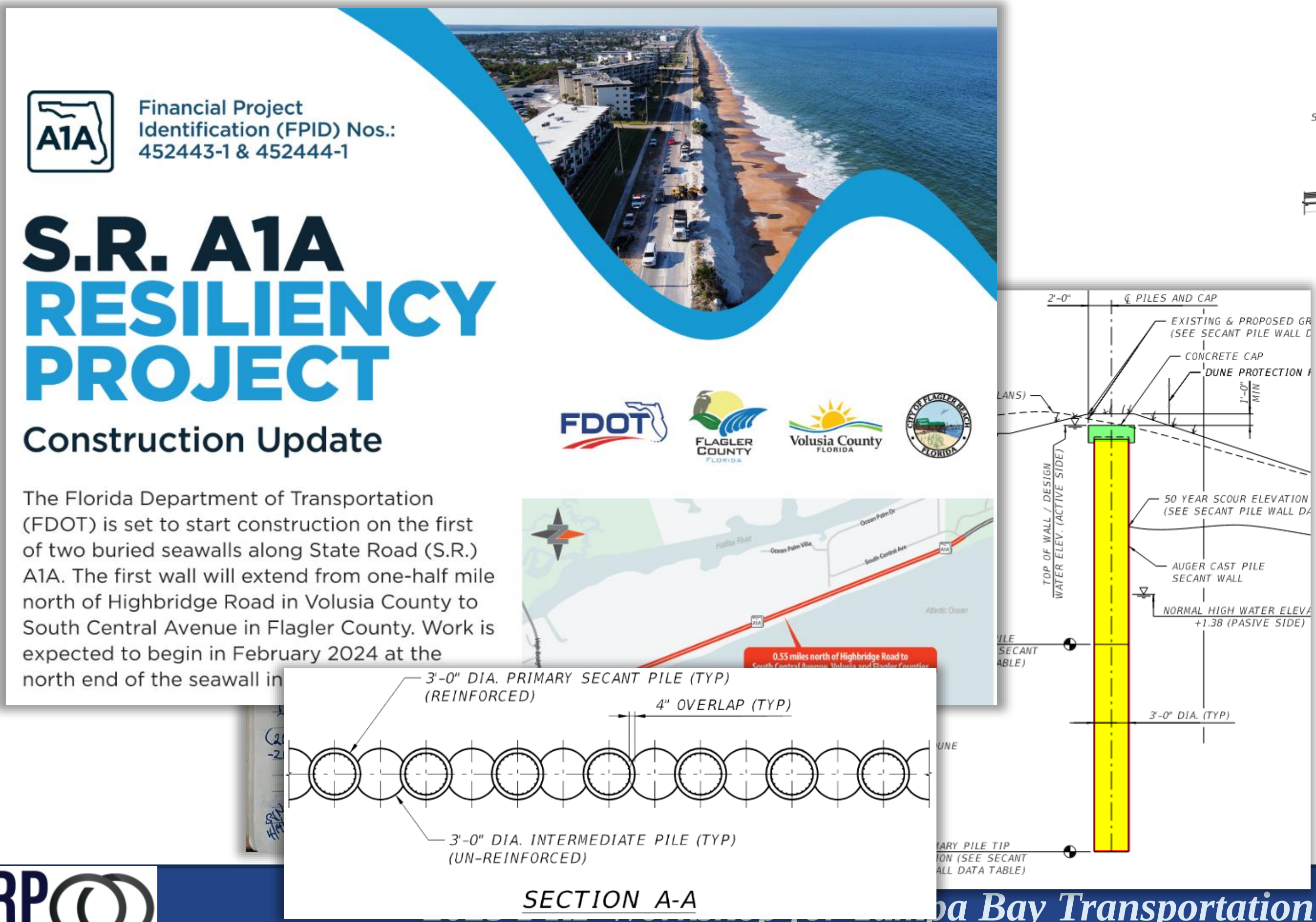


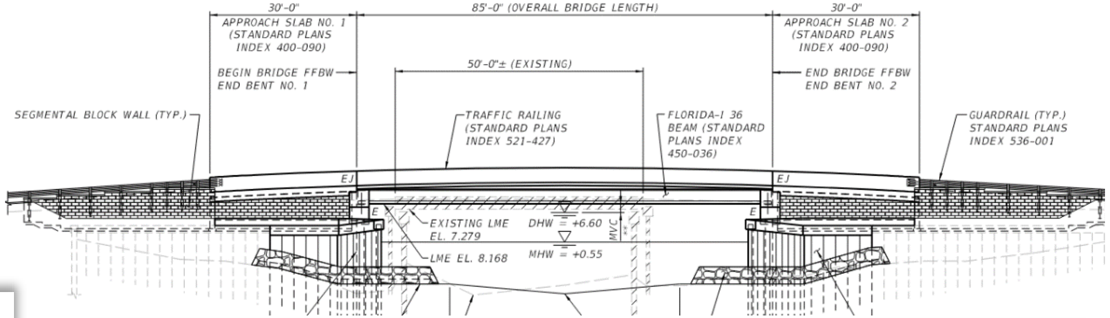
Letting Date: 03/15/2027

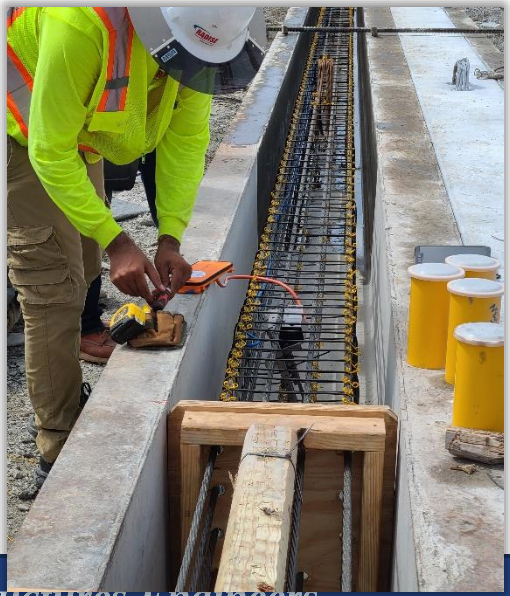
Letting Date: 03/11/2030

Construction: D5 Example Projects

- SR-A1A Seawalls - Flagler Beach & Nth Volusia Co. (452443-1 & 452444-1)
- Barracuda Blvd over Canal Bradano (437935-1) *In-house Design*

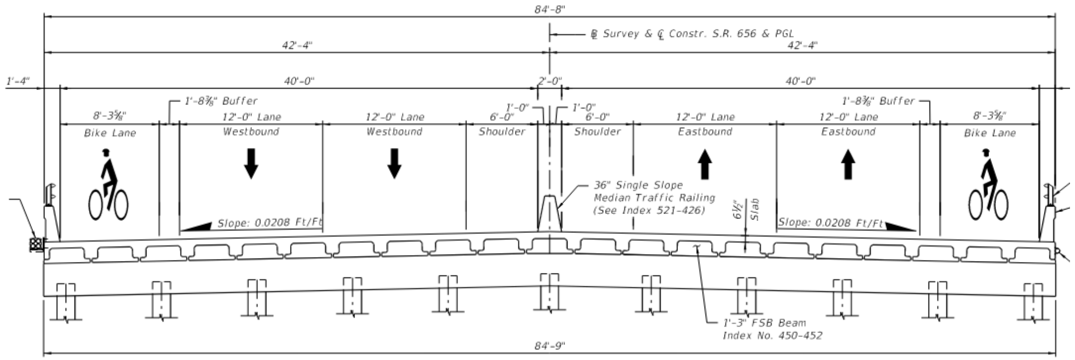


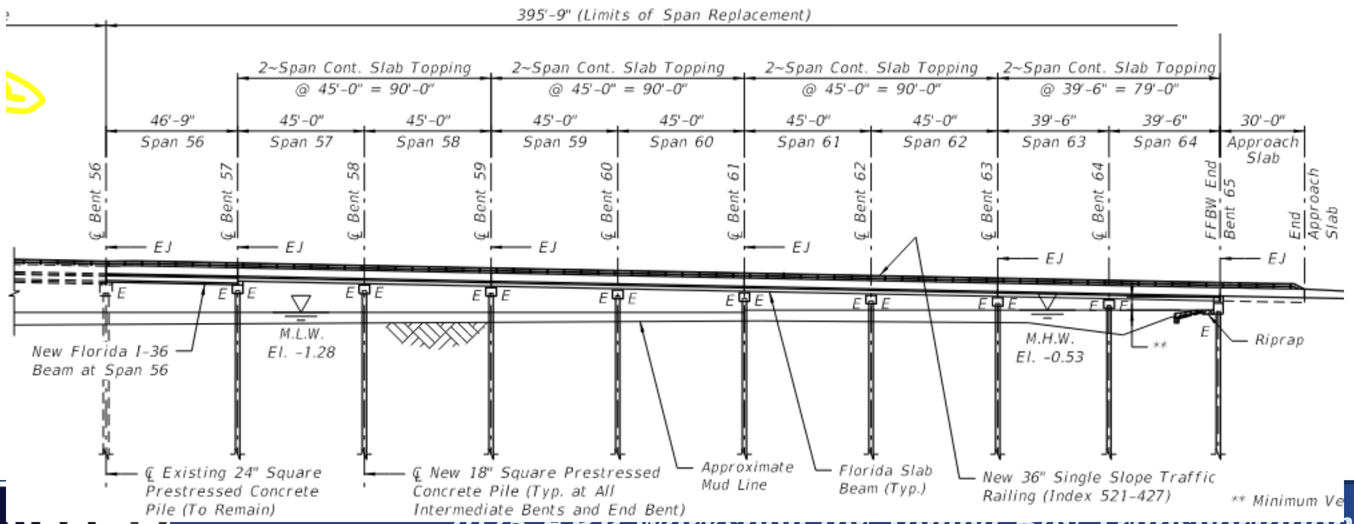




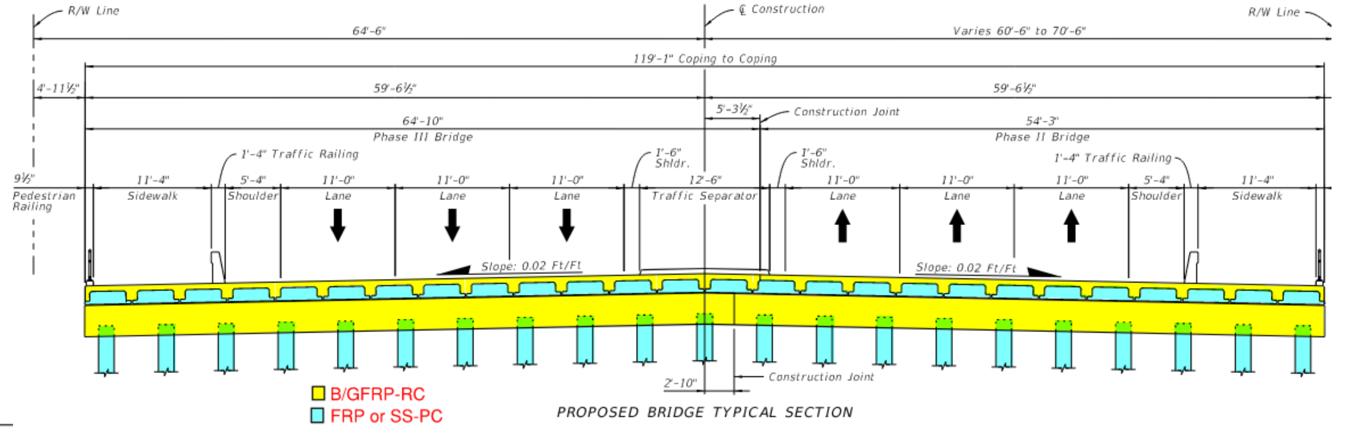
Construction: D4 Example Projects

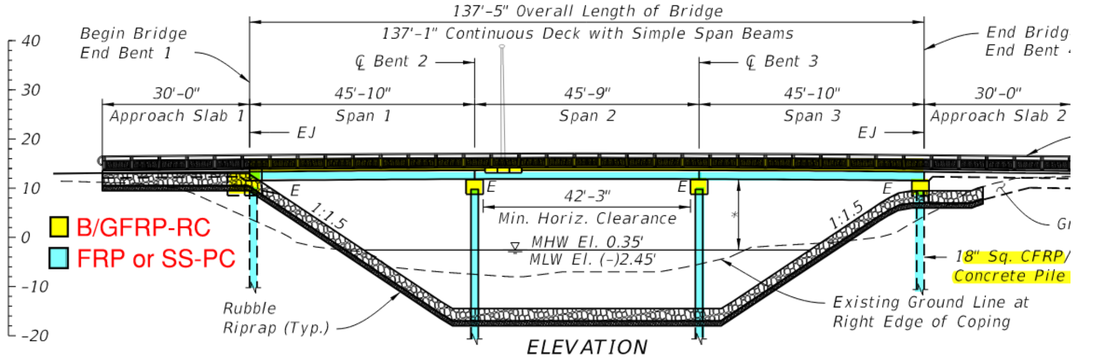
- 17th St/Indian River, East End-Vero (446106-2)





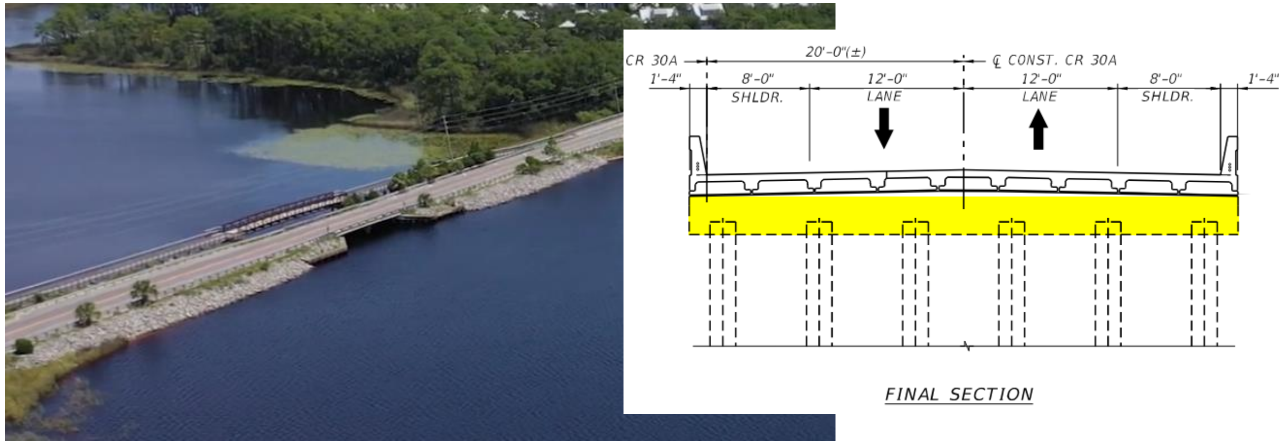
- SR 5/US 1 Over Earman River (442891-1) *In-house Design*

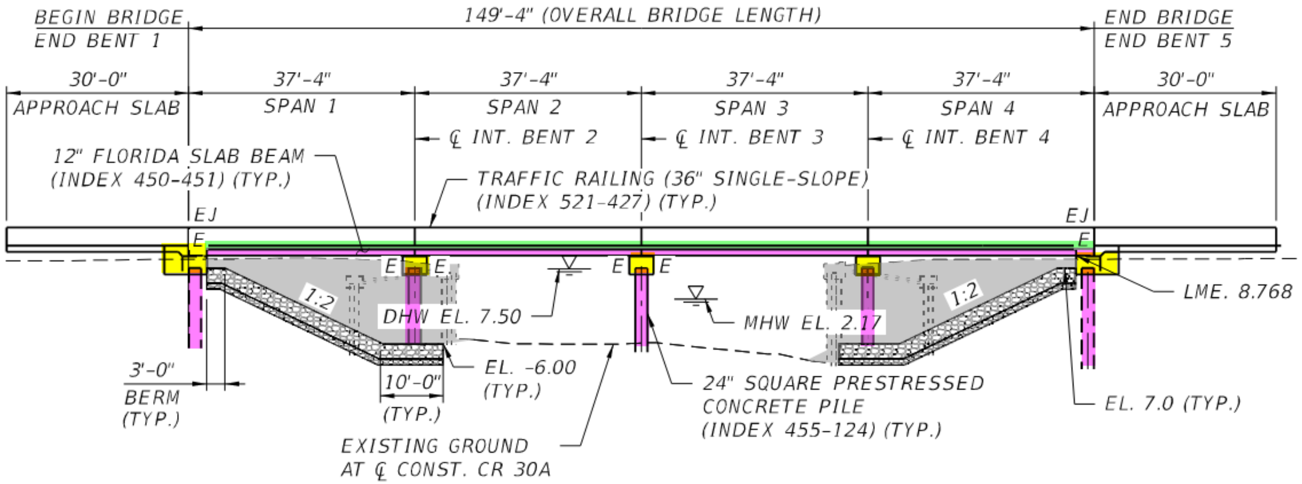




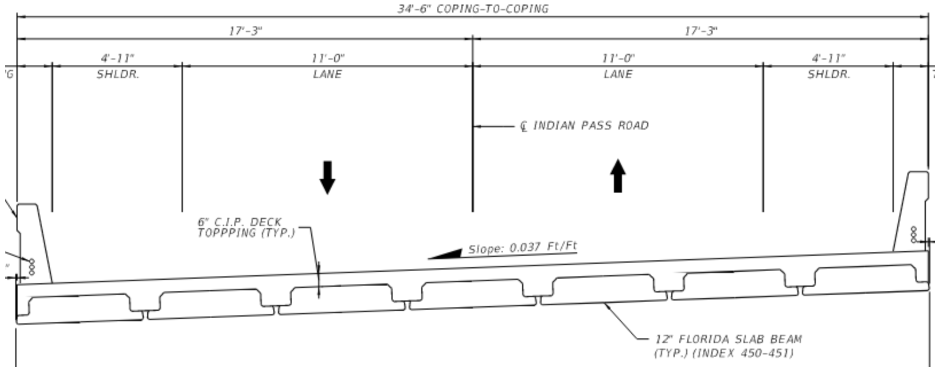
Construction: D3 Example Projects

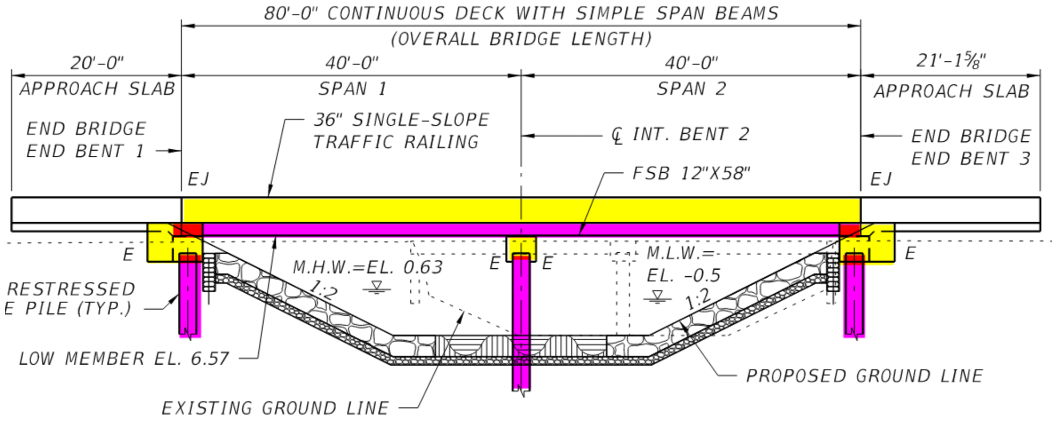
- CR30A over Western Lake (443331-1)





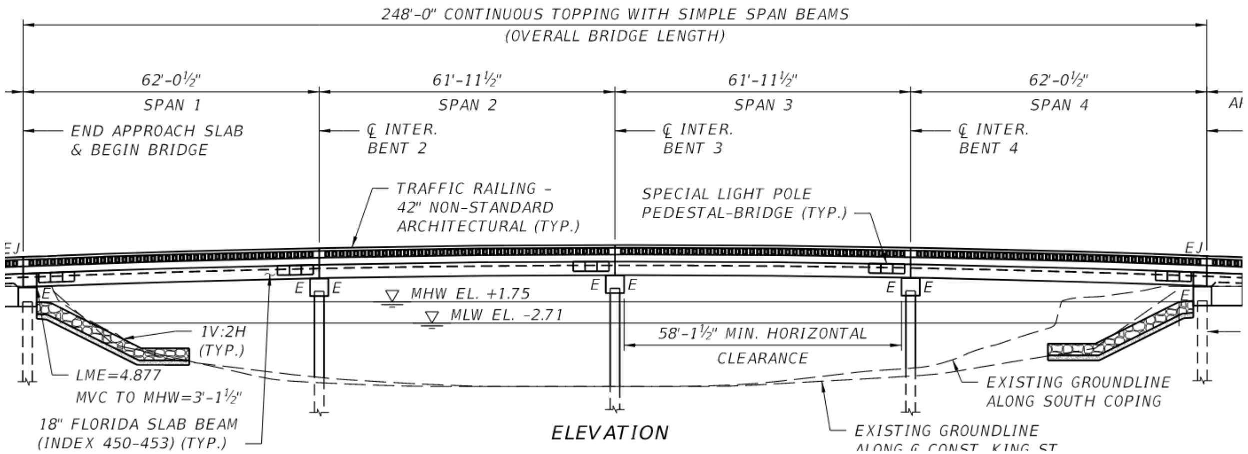
- CR30B/Indian Lagoon (441185-2)

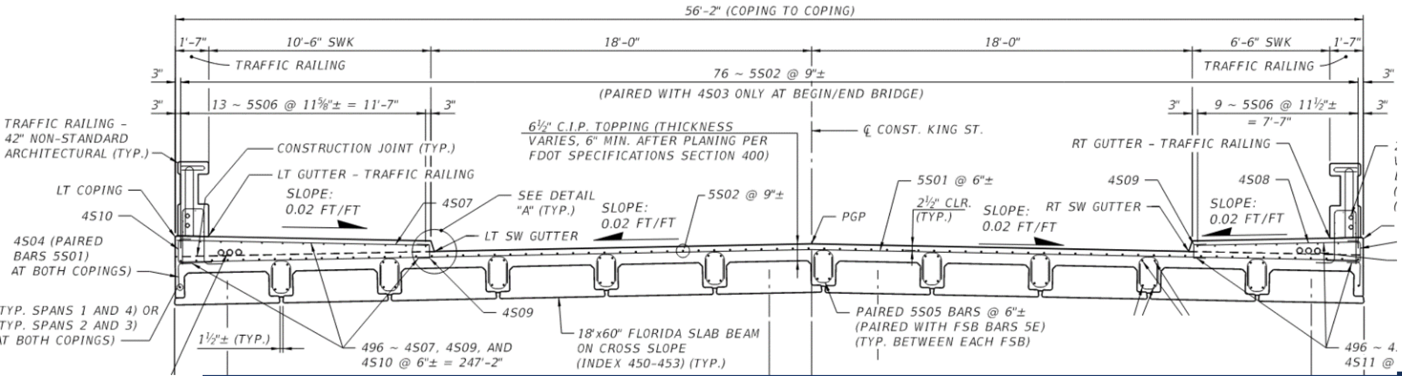




Future Construction: D2 Example Projects

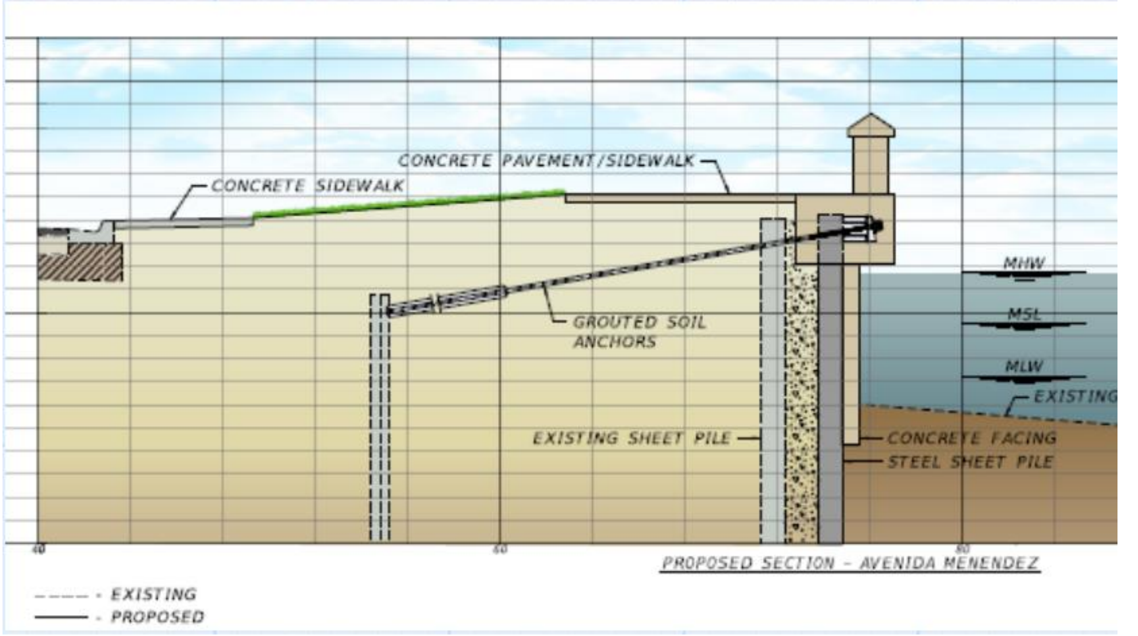
- US1/King St over San Sebastian River (437428-1)





- St. Augustine A1A/Avenida Menendez Seawall Replacement (428271-2)

Figure 2 - Proposed Bulkhead Typical Section



Construction: D1 Example Projects

- Skyway Rest Area (437635-1, 437973-1 & 438528-1), **E1P44**, **Fast-Facts:** bulkhead cap replacement; xCR-sheet pile wall extension & traffic railings – **status:** complete.

- US41 over Morning Star & Sunset Waterways (435390-1), **T1742**, **Fast-Facts:** Link-slab details (GFRP & BFRP) – 2/27/19 letting, (Bid Tabs) – **status:** completed 10/30/20.

- US41 over North Creek (433550-3), **T1747**, **Fast-Facts:** piles (HSSS-PC), wall panels, flat-slab, traffic railings, 8/28/19 letting (Bid Tabs) – **status**: completed 7/7/21.

More Information: - ASPIRE® article Winter 2025

CREATIVE CONCRETE CONSTRUCTION

Corrosion-Resistant Fiber-Reinforced Polymer Reinforcement for Concrete Structures

by Steven Nolan, Florida Department of Transportation, Matthew Chynoweth, RS&H, and Dr. Antonio Nanni and Dr. Francisco De Caso, University of Miami

An article in the July–August 1993 issue of *PCI Journal* opens with the observation, "By the 1980s, the technology that spawned the original AASHTO I-beams was 30 years old. The beams had more than met their intended goals, but times were changing: sophisticated structural analysis, improved materials and fabricating techniques, and advanced construction methods were being introduced at a rapid pace."[1] Readers today may note that this opening statement does not mention durability, resilience, or sustainability. Perhaps the author felt confident that the durability challenges for reinforced and prestressed concrete had been resolved, especially considering a 50-year nominal design life. It is not surprising that "resilience" and "sustainability" were not mentioned; these terms as currently used were absent from our lexicon in the early 1990s.

Increased Target Service Life

In 1994, the first edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[2] increased the nominal design life from 50 to 75 years. This change was partially based on the performance of existing bridge stock, but it also reflected the reality of a growing bridge inventory, which exceeded 570,000 structures in 1990 and could not affordably be replaced every 50 years.[3] By this time, a longer design life was feasible because the industry had improved its understanding of the mechanisms involved in the corrosion of steel reinforcement and how they are exacerbated by long-term chloride diffusion and carbonation.[4]

Three decades later, the U.S. highway bridge inventory exceeds 623,000 bridges.[5] Another notable development is that bridge deck areas are often much greater than in the past, due to capacity and safety improvements such as additional travel lanes, wider roadway and bicycle shoulders, and additions of sidewalks on many non-limited-access bridges. Furthermore, increasing urbanization, managed lanes, and a generally more constrained roadway network have resulted in significant increase in the associated earth-retaining and water-conveyance structures, which are also predominantly reinforced concrete, including precast concrete. Additionally, there have been significant advancements in reinforced concrete structural materials technologies, such as fiber-reinforced polymers (FRP), high-strength stainless-steel strands and reinforcing bars, and ultra-high-performance, steel-fiber-reinforced concrete. Simultaneously, societal expectations for safety, maintainability, and reliability are increasing, while the intensity of both natural and human made shocks and stressors from the surrounding environment are also on the rise.[6,7]

With sufficient concrete cover, good detailing, and appropriate workmanship practices, uncracked high-performance concrete and carbon-steel reinforcement typically provide adequate durability to achieve a 75-year target service life. However, asset managers and bridge owners still face susbstantial durability challenges, including mitigating in-service concrete cracking (especially for bridge decks in colder regions), achieving corrosion resistance in low-level trestle bridges in coastal areas, and meeting target service-life expectations of 100 to 150 years.

One solution to such challenges is the use of extremely corrosion-resistant reinforcement. Of the available material classes that could meet an enhanced (100-year) target service life in an extremely corrosive environment, FRP reinforcing bar and prestressing strands are one practical solution and are the focus of this article.[8] A follow-up article presenting state-of-the-art stainless-steel reinforcing bar and strand reinforcement as another viable option is planned as part 2 of this series.

Developments in FRP Reinforcement

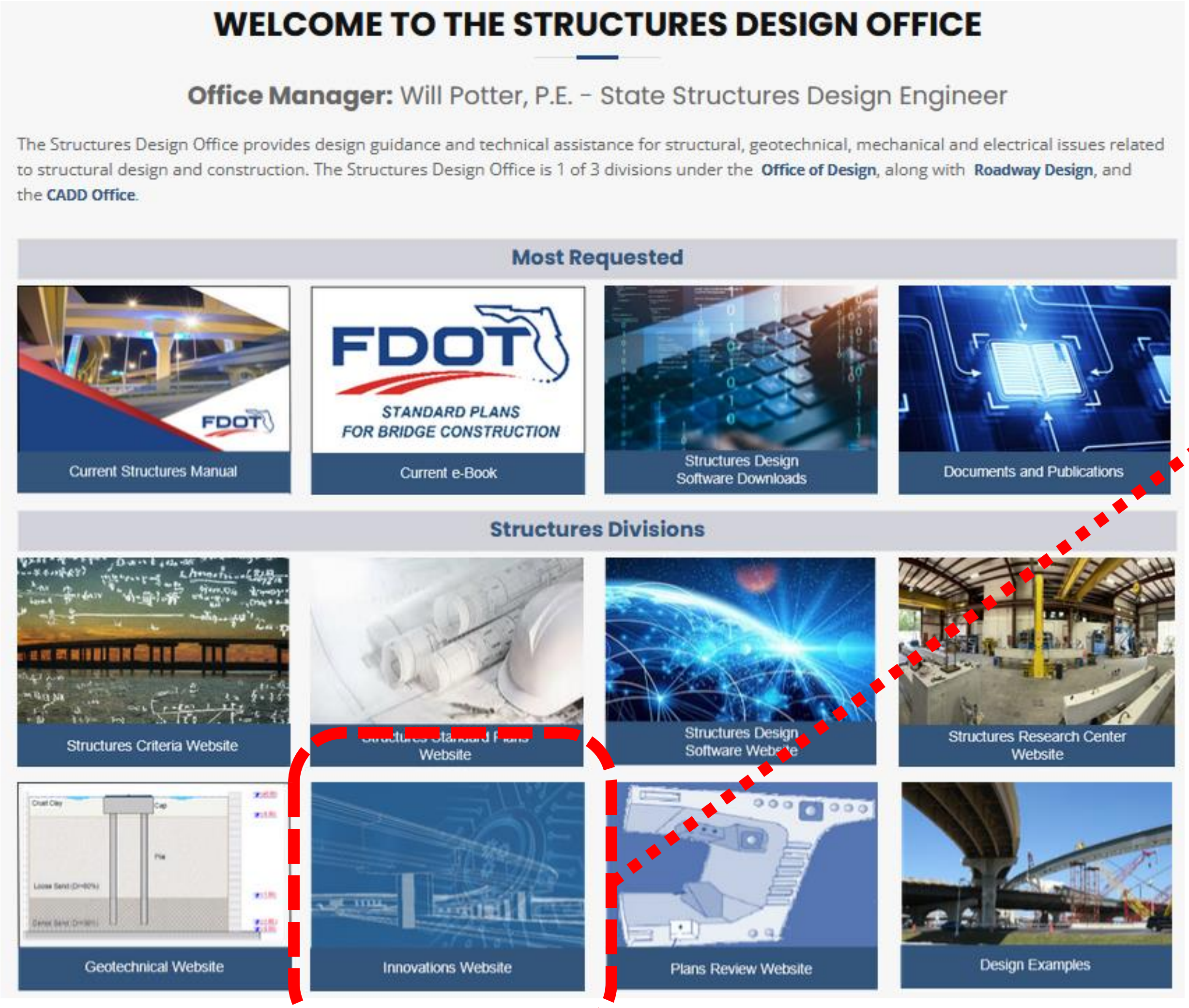
Many developments have occurred since our article, "Glass Fiber-Reinforced Polymer (GFRP) Reinforcement for Bridge Structures," in the Summer 2020 issue of *ASPIRE*®. The following are worth highlighting:

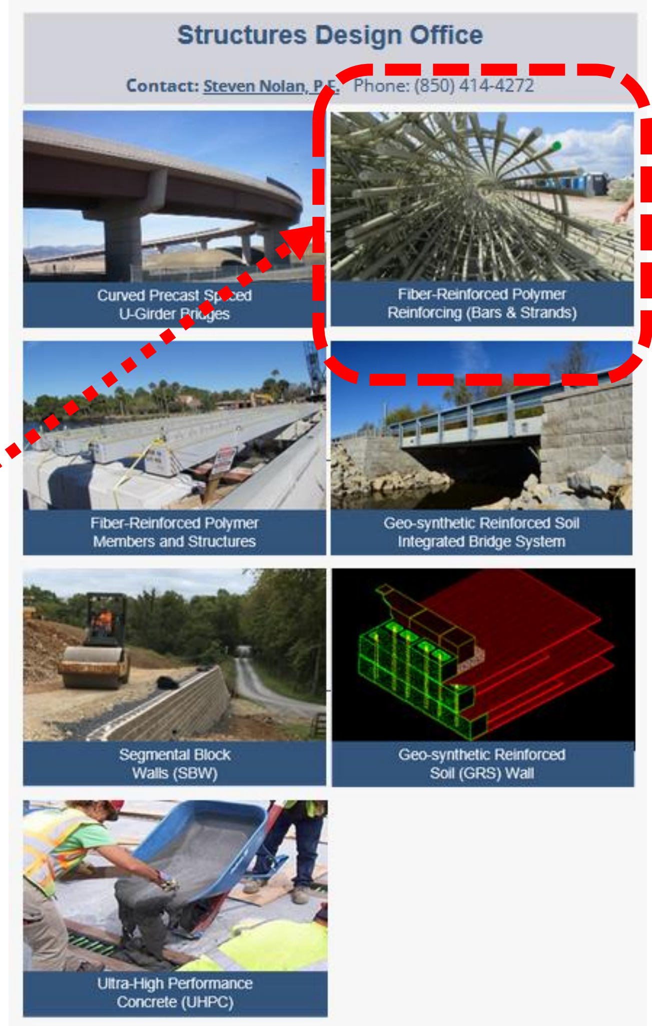
- The publication of the American Concrete Institute's *Building Code Requirements for Structural Concrete with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary* (ACI CODE-440.11-22)[9]

The 17th Street Bridge replacement over Indian River in Vero Beach, Fla., includes 168 prestressed concrete Florida slab beams with fiber-reinforced-polymer reinforcement. The 45-ft long beams use carbon-fiber-reinforced-polymer strands and glass-fiber-reinforced-polymer auxiliary reinforcement. All Photos: Florida Department of Transportation.

The Florida slab beams, piles, and bent caps of a low-level observation deck at the U.S. Route 1 bridge replacement in Jupiter, Fla., have carbon-fiber-reinforced-polymer prestressing strands and glass-fiber-reinforced-polymer reinforcement.

More Info: FRP RC/PC Design Innovation Webpage





Fiber Reinforced Polymer Reinforcing

Structures Design - Transportation Innovation
Fiber Reinforced Polymer (FRP)
Reinforcing Bars and Strands

- Overview
- Usage Restrictions / Parameters
- Design Criteria
- Specifications
- Standards
- Producer Quality Control Program
- Projects
- Technology Transfer (T^2)
- FDOT Research
- Contact

Safety Message

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Florida Dept. of Transportation

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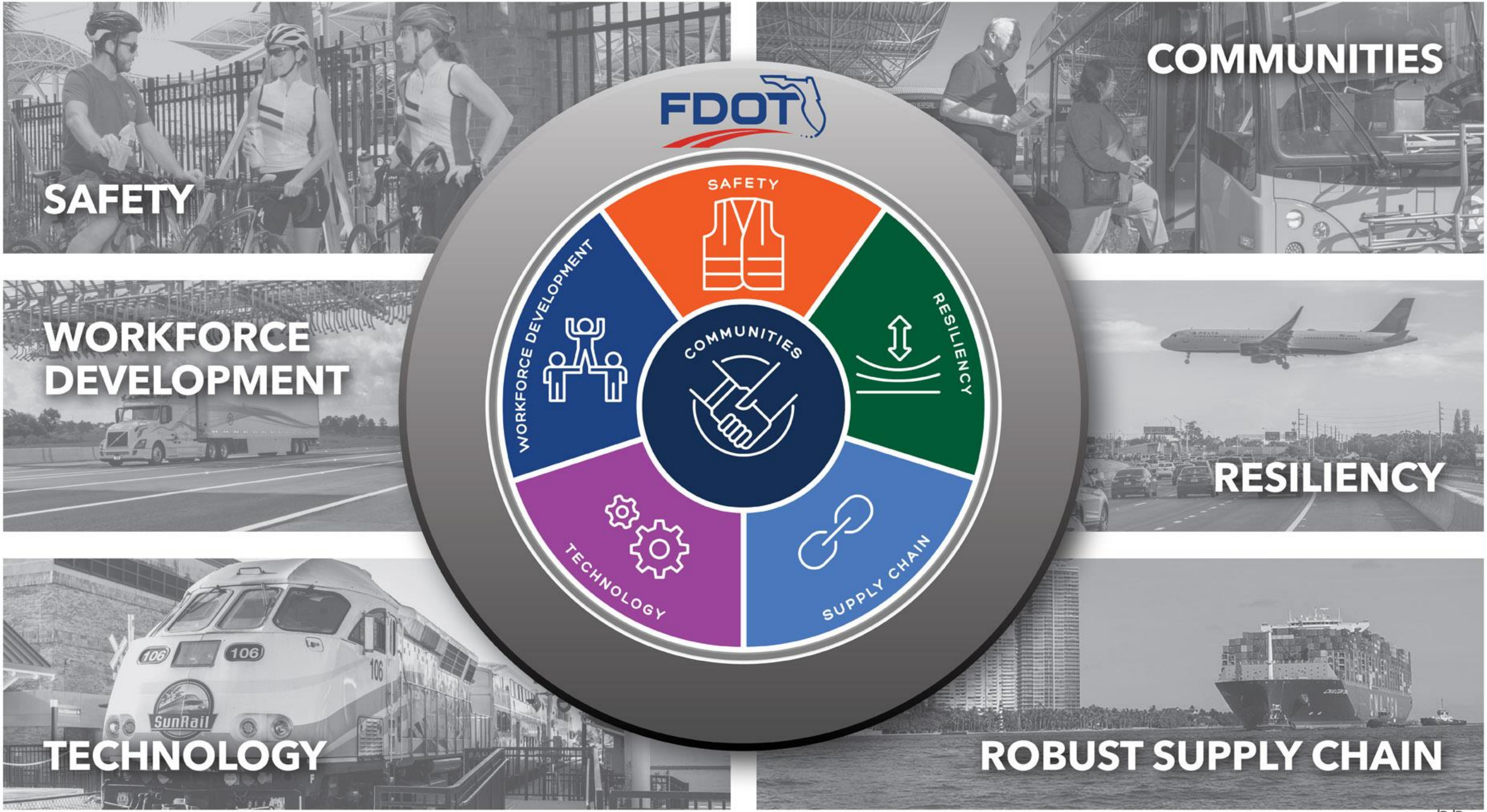
Office #: 850-414-4272

Website: *https://www.fdot.gov/design/Innovation/*


SAFETY
COMMUNITIES
WORKFORCE DEVELOPMENT
RESILIENCY
TECHNOLOGY
ROBUST SUPPLY CHAIN
FDOT
SAFETY
RESILIENCY
SUPPLY CHAIN
TECHNOLOGY
WORKFORCE DEVELOPMENT
COMMUNITIES
SunRail
106