AASHTO GFRP-Reinforced Concrete Design Training Course

FDOT

UNIVERSITY OF MIAMI

Center for Integration of Composites into Infrastructure

Course Content Areas

1. Introduction & Materials
2. Flexure Response
3. Shear Response
4. Axial Response
5. Case Studies & Field Operations

Course Overview & Expectations

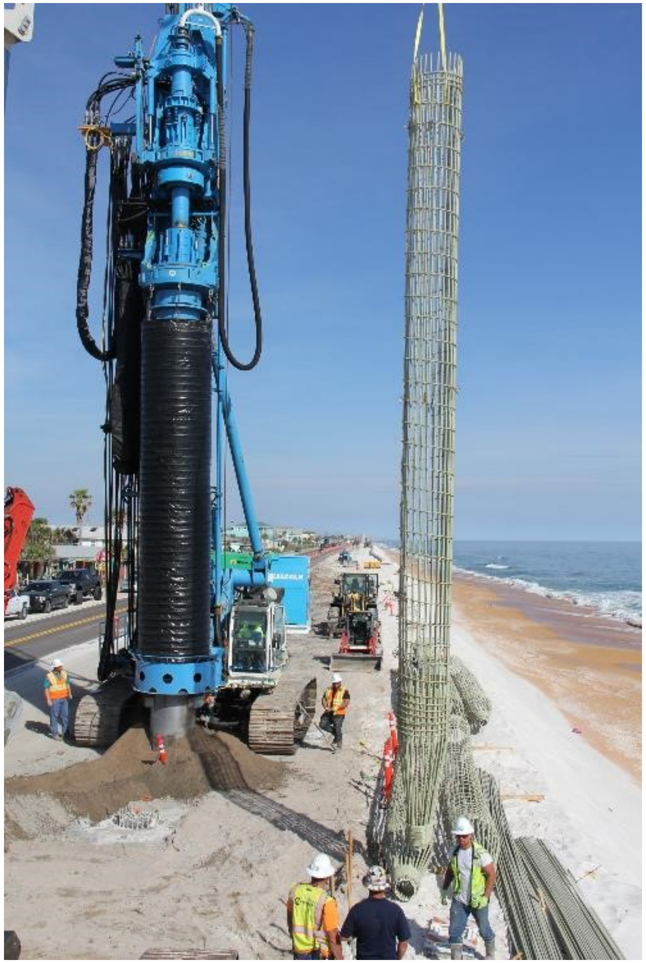
Concepts
- Introduction of concepts
- Understanding of methods
- Use of available resources

Questions & Examples
- Review questions
- Reinforce methods
- Apply concepts

Participation
- Active participation needed
- Ask questions
- Opportunity for discussions

Learning Objectives

- Know what FRP reinforcement is
- Learn the fundamental mechanical properties of FRP bars and bends
- Become aware of some major material-based design provisions of concrete members internally reinforced with **GFRP** bars with particular reference to **AASHTO** and **FDOT** documents
- Become aware of relevant FRP-RC projects in and out of state



Course Content Areas

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1. INTRODUCTION TO FRP-RC & MATERIAL PROPERTIES OF GFRP

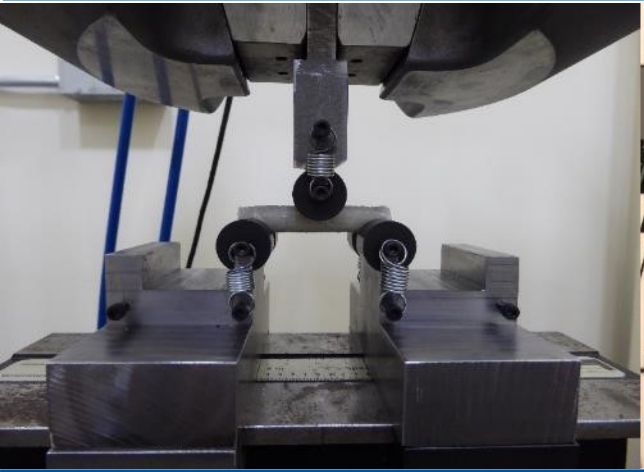

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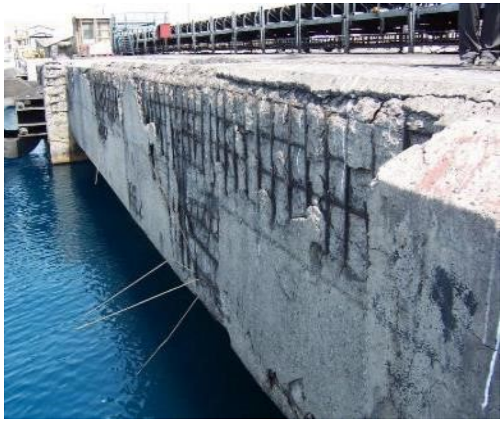
Table of Contents - Intro & Materials

- **Problem Statement**
- Where to Use Glass FRP
- FRP Material Properties
- Durability
- Design Guides and Standards
- Concluding Remarks

Problem Statement

- Failure mechanism for structures exposed to aggressive environments is often corrosion of steel reinforcement

- Traditional corrosion mitigation efforts:
  - ✓ Admixtures
  - ✓ Increase Concrete Cover
  - ✓ Alter Concrete Mix
  - ✓ Membranes & Overlays
  - ✓ Epoxy-Coated, Galvanized or Stainless Steel



SERVICE LIFE OF STRUCTURES GREATLY REDUCED BY CORROSION

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FRP Rebars

Fiber reinforced polymer (FRP) bars as alternative reinforcement for concrete

A composite material system made of:
Fibers + Resin

FRP Rebars

Key Benefits

- Corrosion resistant
- High strength-to-weight ratio
- Ease of application & installation
- Lightweight ¼ the weight of steel
- Transparent to magnetic fields and radar frequencies
- Electrically & thermally non-conductive

FIRST COST COMPARABLE WITH EXPOXY-COATED STEEL

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Where Should FRP Be Used?

- **Concrete structures susceptible to corrosion**
  - Steel corrosion by chlorides
  - Environments that lower concrete pH
  - Structures with minimum concrete cover
- **Concrete structures requiring non-ferrous reinforcement due to**
  - Electro-magnetic considerations
  - Thermal non-conductivity
- **Where machinery will "consume" the reinforced concrete member** (i.e., mining and tunneling)

Ready for Prime Time

- Structural design defined by ***ACI*** & ***AASHTO*** (and *FDOT*)
- Bar properties defined by ***ASTM*** D7957 (and *FDOT*)
- 600+ installations in US & Canada
- Traditional procurement & construction methods

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Types of Fiber in FRP Bars

- Carbon Fiber Reinforced Polymer (CFRP)
- **Glass** Fiber Reinforced Polymer (GFRP)
- Basalt Fiber Reinforced Polymer (BFRP)
- Aramid Fiber Reinforced Polymer (AFRP)

Types of Resin in FRP Bars

Some Thermoset Resins (Only ones allowed for now):
Two-part system composed of resin and hardener resulting in a one-way (irreversible) chemical reaction

- Vinyl Ester
- Epoxy
- Polyester
  Not allowed in structural applications because of poor durability

FRP Bar Types

Several commercially available GFRP solid round bars with different external surface (not standardized) deformations:

- (A & F) Sand coated + helical wrap
- (B) Helically wrapped
- (C) Ribbed
- (D) Sand coated
- (E) Helically grooved

FRP Bar Shapes

- Straight bars

- Bent bars

- Spirals

- Twisted strands (PC use)

Material Specifications

***FDOT* 932-3 and ASTM D7957** specs set minimum QUALIFICATION & QC for Glass (and Basalt)* FRP bars

SECTION 932
NONMETALLIC ACCESSORY MATERIALS
FOR CONCRETE PAVEMENT AND CONCRETE STRUCTURES

932-1 Joint Materials.

932-1.1 Preformed Joint Filler for Pavement and Structures: Preformed joint filler shall meet the requirements of AASHTO M153 or AASHTO M213, or cellulose fiber types meeting all the requirements of AASHTO M213 ... for the asphalt content) is acceptable provided they contain minimums of 0.2% zinc ... 1.5% waterproofing wax. For AASHTO M153, unless a particular ... Type III may be used.

Preformed joint fillers shall ha... required, and shall be furnished in lengths eq... installed, except that strips which are of a len... joints, or between longitudinal joint and edg...

932-3 Fiber Reinforced Polymer (FRP) Reinforcing Bars.

932-3.1 General: Obtain FRP reinforcing bars from producers currently on the Department's Production Facility Listing. Producers seeking inclusion on the list shall meet the requirements of Section 105.

Use only solid, round, thermoset basalt fiber reinforced polymer (BFRP), glass fiber reinforced polymer (GFRP) or carbon fiber reinforced polymer (CFRP) reinforcing bars. Bars shall be manufactured using pultrusion, variations of pultrusion, or other suitable processes noted in the producer's Quality Control Plan, subject to the approval of the State Materials Office (SMO). For BFRP and CFRP bars only vinyl ester or epoxy resin systems are permitted. For GFRP, use only bars manufactured using vinyl ester resin systems and glass fibers classified as E-CR or R that meet the requirements of ASTM D578.

Return to Table of Contents

Bar manufacturer not known/selected at the design stage

* FDOT only

FRP Bar Sizes

Same as steel bars, specified per ***FDOT* 932-3**, Table 3-1 and ***ASTM* D7957**. Area range (min-max) given for measured values for any surface type

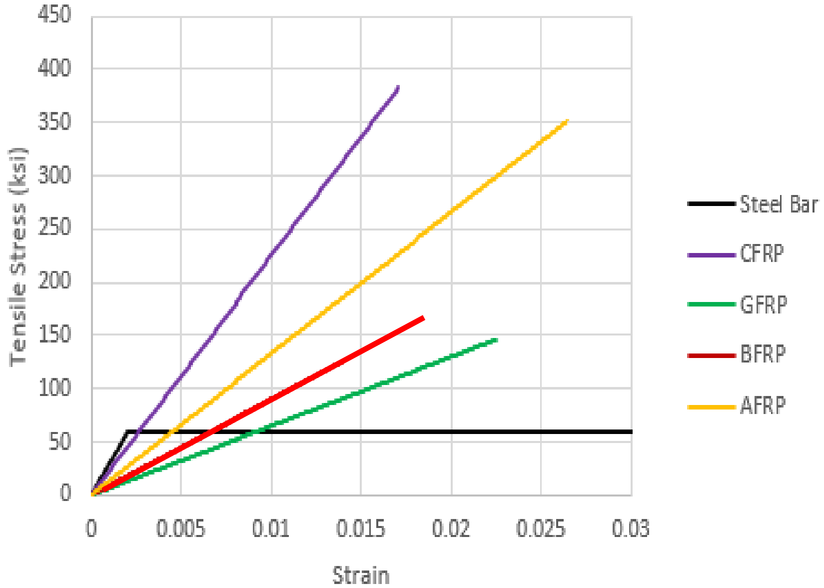
Table 3-1
Sizes and Tensile Loads of FRP Reinforcing Bars

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	BFRP and 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	-

FRP Mechanical Properties

- **Higher tensile strength, but less stiff than steel**
  - ✓ Provides less confinement to concrete and RC members have more deflection than steel-RC
- **Anisotropic behavior**
  - ✓ High strength in the fiber direction
  - ✓ Low shear strength and dowel action (resin dominated)
- **Elastic up to failure - no ductility**
  - ✓ Cannot be used in seismic areas, no plastic hinges formed in RC members

Tensile Stress-Strain Characteristics



Typical Tensile Properties

	Steel	GFRP
Yield Stress ksi (MPa)	40-75 (276-517)	
Guaranteed Tensile Strength, ($f^*_{f,u}$), (Average – 3 sigma) ksi (MPa)		78-160 (534-1240)
Average Elastic Modulus, (E_f) (Average) Ksi (GPa)	29,000 (200)	6,500 – 8,700 (45-60)
Yield Strain, (ε_y)	0.14-0.25%	N/A
Guaranteed Tensile Ultimate Strain, ($\varepsilon^*_{f,u}$)	~10-12%	1.2-2.4%

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Design Tensile Strength

- Design tensile strength and strain are:

$$f_{fu} = C_E f_{fu}^*$$

AASHTO GFRP 2.4.2.1-1

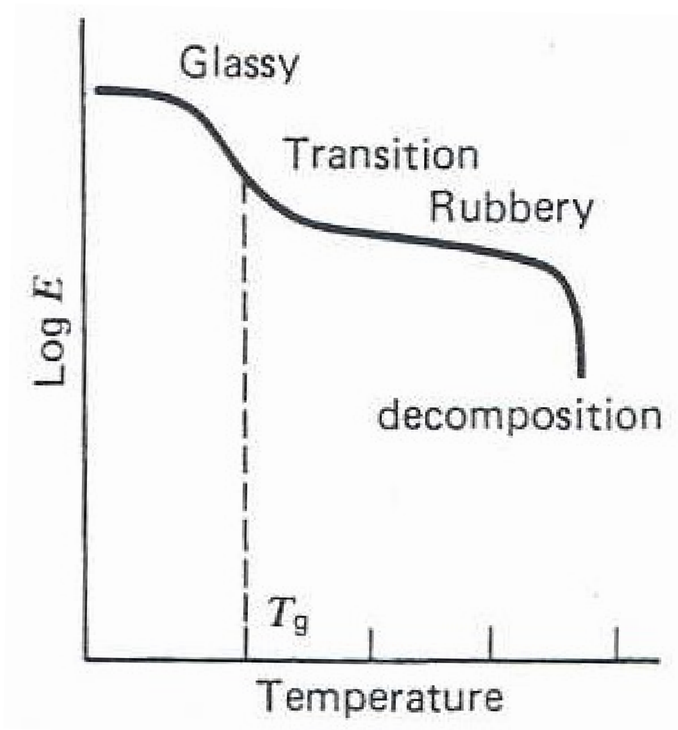
$$\varepsilon_{fu} = C_E \varepsilon_{fu}^*$$

Where C_E is the environmental reduction factor from ***AASHTO*** Table 2.4.2.1-1 (red box) (proposed new factors in ***ACI 440*** in green)

Fiber	Concrete not exposed to earth or weather	Concrete exposed to earth or weather
Glass	0.9 0.8	0.85 0.70

Behavior Function of Temperature

- Thermosets are characterized by **Glass Transition Temperature**, $\boldsymbol{T_g}$
- Resin tensile, compressive, and shear properties diminish when temperatures approach $\boldsymbol{T_g}$
- $\boldsymbol{T_g}$ values of approximately 212 ^oF (100 ^oC) are required for Vinyl Ester typically used GFRP rebars
- $\boldsymbol{T_g}$ lowers as a result of moisture absorption



Elastic Modulus vs Temperature

Summary: GFRP Differences with Steel

PROs

- High longitudinal strength-to-weight ratio
- Corrosion resistance
- Electro-magnetic neutrality
- Good fatigue endurance
- Low thermal & electrical conductivity
- Lightweight

CONs

- No yielding
- Low transverse strength
- Relatively low modulus
- High CTE perpendicular to fibers
- Sensitive to UV, moisture & alkaline environment
- Susceptible to fire & smoke production

Other Mechanical Properties

Strength of FRP at bend

- FRP bars can be fabricated with bends, however the tensile strength at bend is reduced by about 40%

Compressive behavior of FRP bars

- Reduced strength and stiffness as compared to tensile properties

Shear behavior of FRP bars

- Unidirectional FRP materials have a lower interlaminar shear modulus and shear strength as compared to steel

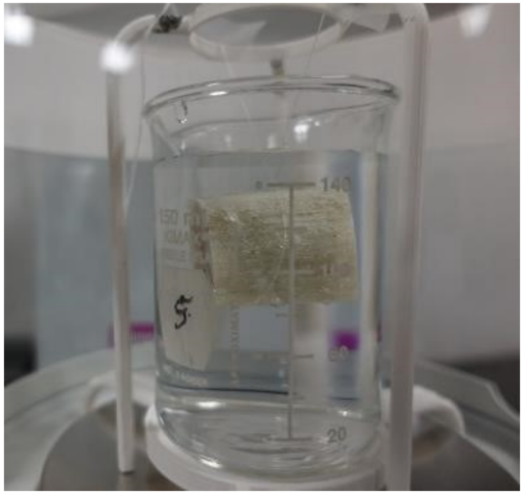
Behavior under sustained and cyclic loading

- FRP bars can undergo creep-rupture under sustained loading and fatigue rupture under cyclic loading

Material Characterization

Moisture absorption
[*ASTM* D570]

Fiber content
[*ASTM* D2484]



Cross-sectional area
[*ASTM* D792]

Minimum requirements**: *FDOT* 932, Table 3.2** (straight bars) **& 3.3** (bent bars)

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Material Characterization

Tensile test
[*ASTM* D7205]

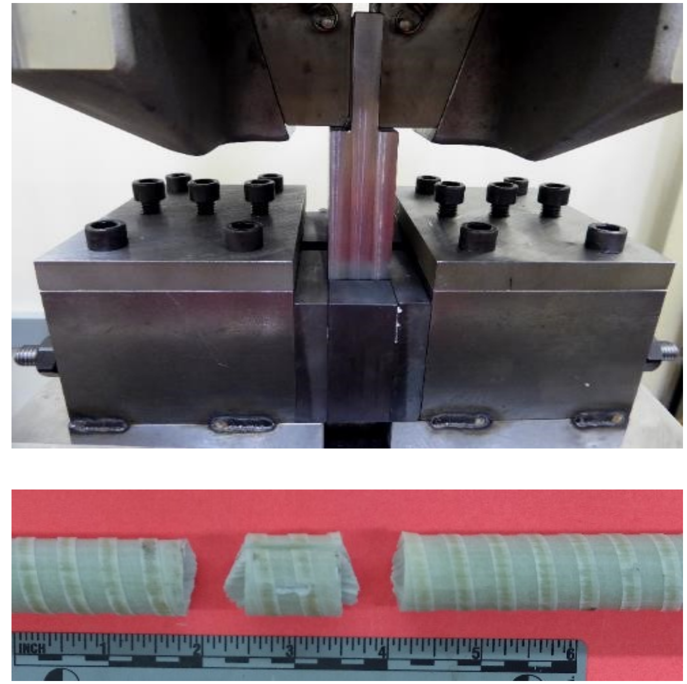
Minimum requirements: ***FDOT* 932, Table 3.2 & 3.3**

AASHTO 2.4.2.1:

f_{fu} → Guaranteed tensile strength = average minus three standard deviations

Material Characterization

Horizontal shear
[*ASTM* D4475]



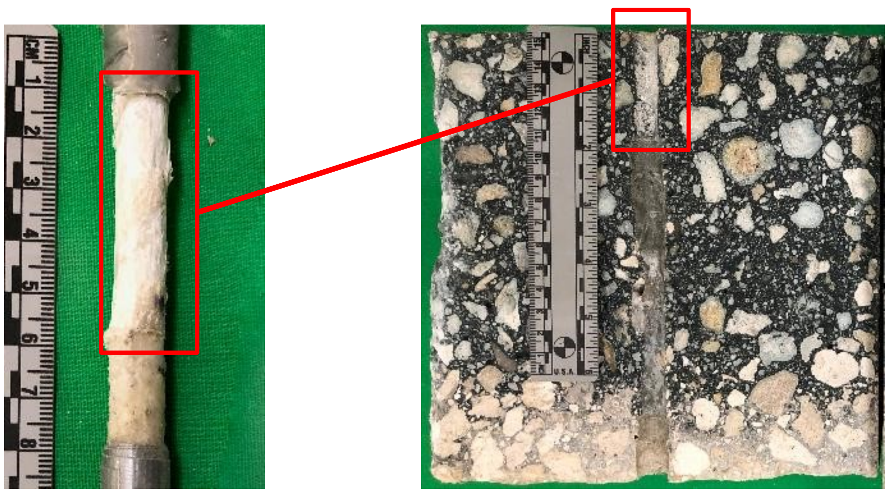
Transverse shear
[*ASTM* D7617]

Minimum requirements: ***FDOT* 932, Table 3.2** (straight bars) **& 3.3** (bent bars)

Material Characterization

Bond-to-concrete
[*ASTM* D7913]

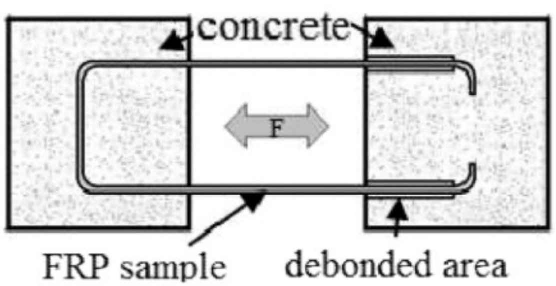
Minimum requirements: ***FDOT* 932, Table 3.2**



Strength of FRP at Bend

- FRP bars can be fabricated with bends; however, the tensile strength of the bend is reduced up to 40% per ***ASTM*** D7957
- Bend internal diameter is larger than for steel
- ***FDOT* 932-3.3** includes additional specifications for properties of FRP bent bars at bend locations

Bar Designation, mm [U.S. Standard]	Minimum Bend Diameter mm [in.]
M6 [2]	38 [1.50]
M10 [3]	58 [2.25]
M13 [4]	76 [3.00]
M16 [5]	96 [3.75]
M19 [6]	114 [4.50]
M22 [7]	134 [5.25]
M25 [8]	152 [6.00]



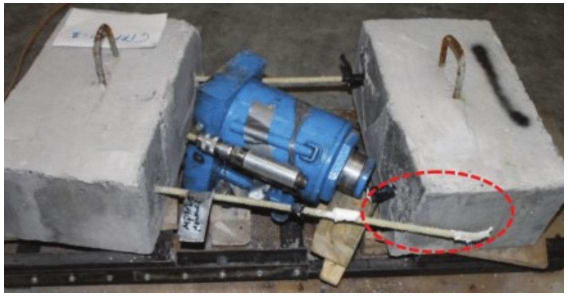


Table of Contents

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- **Durability**
- Design Guides and Standards
- Concluding Remarks

Durability Assessment

Methods used to assess and validate the durability of FRP bars:

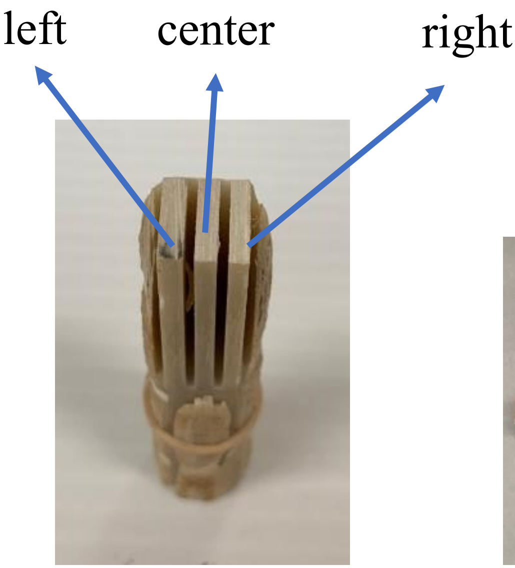
1. Accelerated aging protocols (high temperature; immersion in water w/ or w/o high pH and/or salt)
   → fast

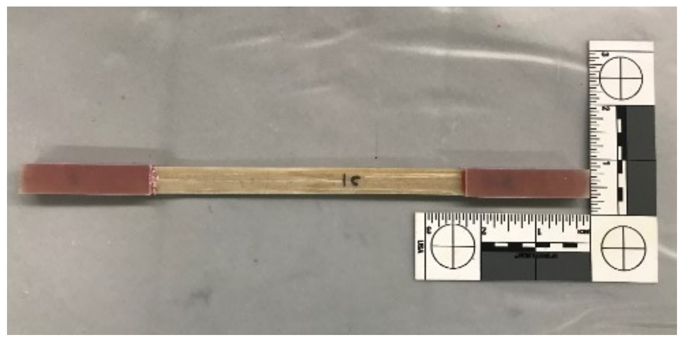
2. Extraction of samples from real life structures
   → slow

GFRP Bars Extracted from Bridges 15-20 Years Old

- Investigation to assess long-term **durability of GFRP bars** after at least 15 years in service
- Cores extracted from **eleven bridges** located across the United States

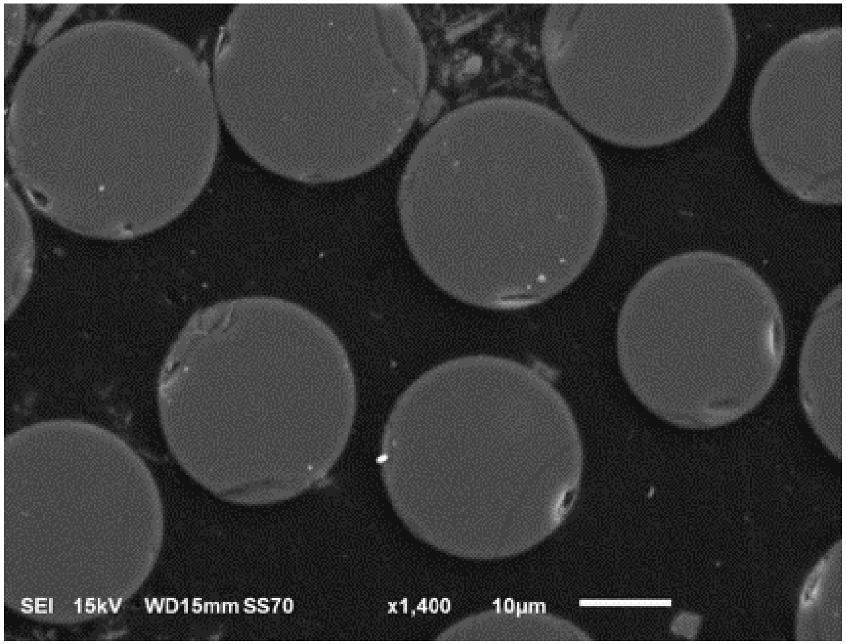
GFRP Bars Extracted from Bridges 15-20 Years Old

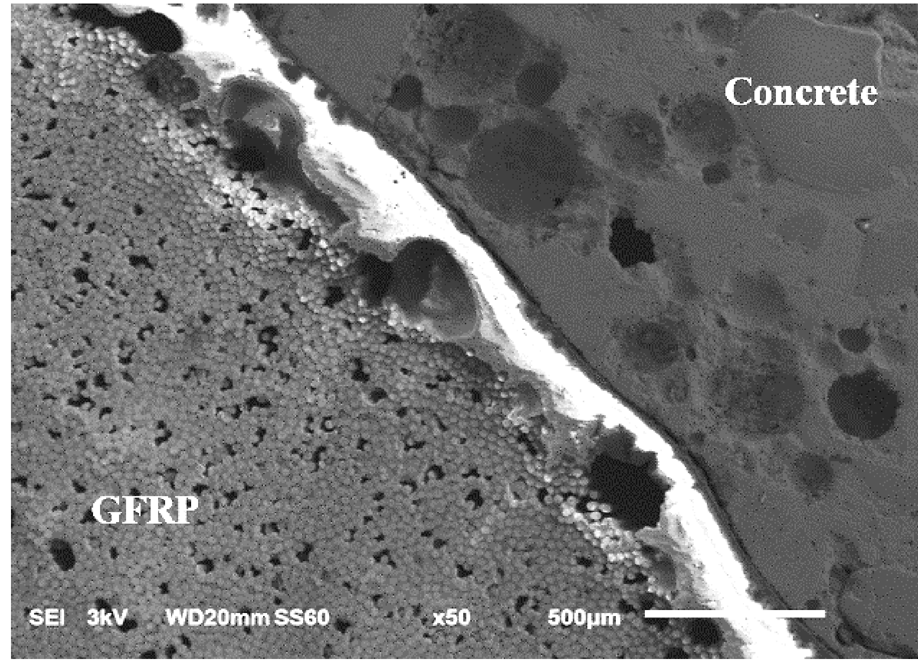




Results indicated reduction in tensile strength of 2.13% over a period of 17 years of service that would correspond to drop in strength of 12.5% over a period of 100 years with degradation rate assumed to be linear

Durability





Source: Long-term Durability of GFRP Reinforcement in Concrete: A Case Study after 15 Years of Service - O. Gooranorimi, E. Dauer, J. Myers, A. Nanni

NO SIGN OF BOND DEGRADATION NOR LOSS OF CONTACT AND MECHANICAL PROPERTIES AFTER 15 YEARS IN SERVICE

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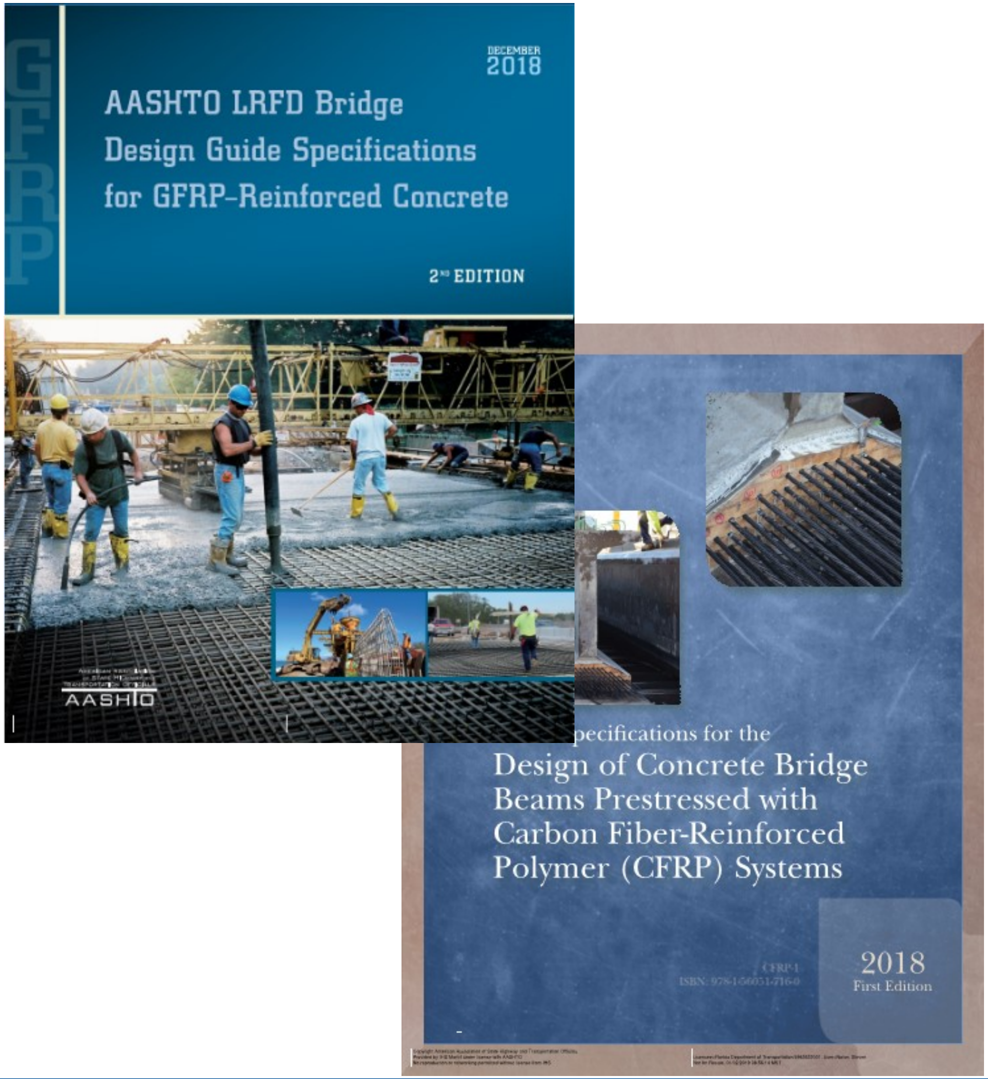
- Problem Statement
- Where to Use Glass FRP
- FRP Material Properties
- Durability
- **Design Guides and Standards**
- Concluding Remarks

Design Guides and Tools

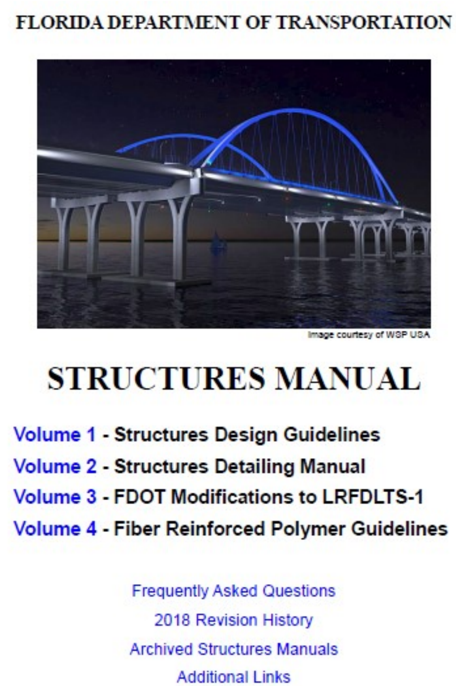
- **Design Guide**
  - Currently available
- **Uniform Approval** Processes
  - Manufacturer Approval vs. Product Approval
- **Reliable Design Tools**
  - Commercial vs. Agency based design programs

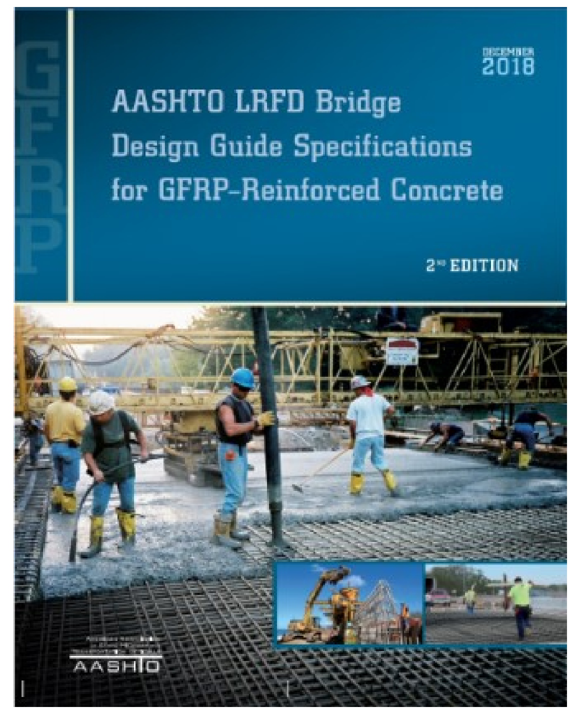


Design Guidance & Tools in Florida

Currently available documents:

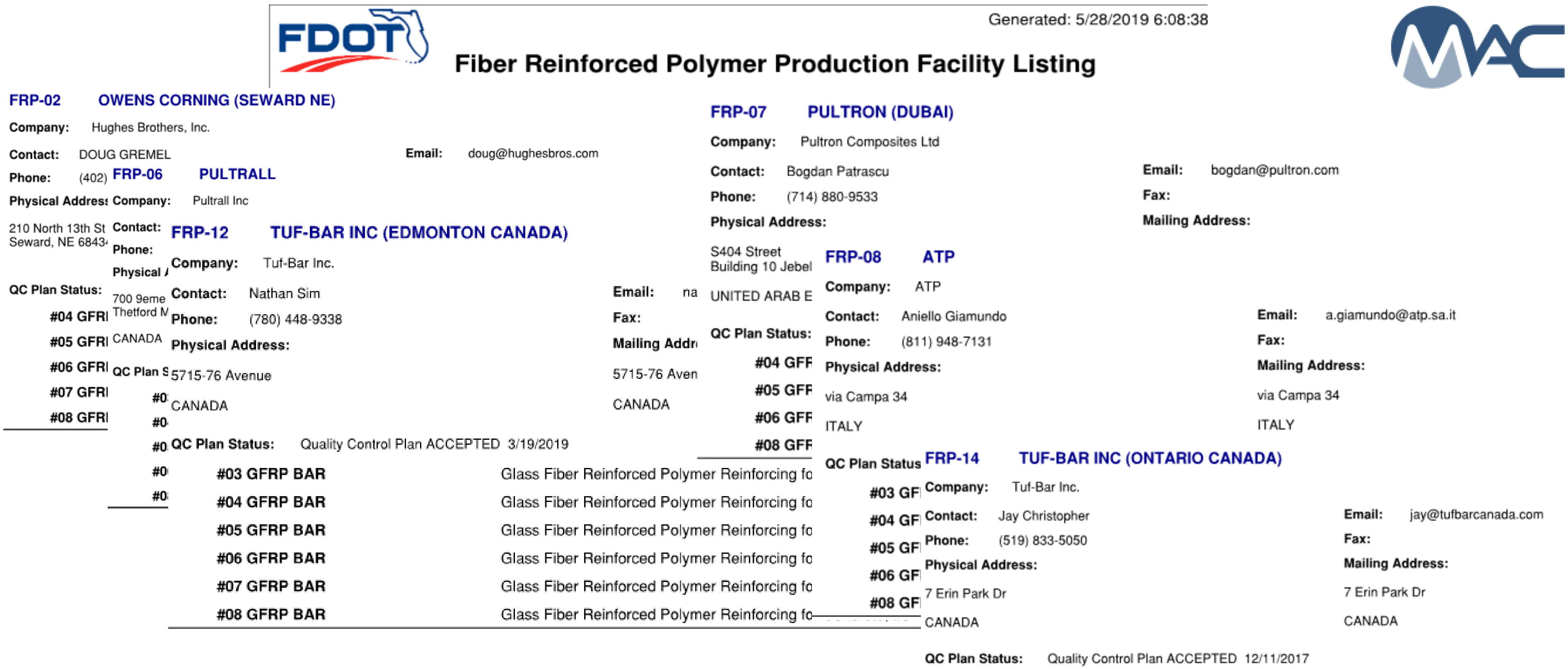
- ***AASHTO***: Only GFRP
- ***FDOT* 932-3**: GFRP and BFRP





Design Guidance & Tools in Florida

- **Uniform Approval Processes** https://mac.fdot.gov/smoreports
  - Manufacturer Approval vs. Product Approval



Material Acceptance Criteria

FDOT 932-3 Table 3-4

Property	Test Method	Requirement	Straight Bar
Fiber Mass Fraction	ASTM D2584 or ASTM D3171	≥70%	Yes
Short-Term Moisture Absorption	ASTM D570, Procedure 7.1; 24 hours immersion at 122°F	≤0.25%	Yes
Glass Transition Temperature	ASTM D7028 (DMA) or ASTM E1356 (DSC; T_m)/ ASTM D3418 (DSC; T_{mg})	≥230°F ≥212°F	Yes
Degree of Cure	ASTM E2160	≥95% of Total polymerization enthalpy	Yes
Measured Cross-sectional Area	ASTM D7205	Within range listed in Table 3-1	Yes
Guaranteed Tensile Load		≥ Value listed in Table 3-1	Yes

Design Guidance & Tools In Florida

- **Accessible & Reliable Design Tools**
  - Commercial vs. Agency/Institution based design programs

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Prestressed Beam v5.2	11/07/2018	Exe (Zip) (Mathcad 15)	Used with **FDOT Standard Plan Index 450-010 to 450-299** (formerly **Index 20010 to 20299**) 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.
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** (formerly **Index 6010**) to design and analyze cast-in-place retaining walls in accordance with the AASHTO LRFD Bridge Design Specification.

CFCC-PC/GFRP-RC beta version
*(to be included in **v6.0** with HSSS)*

GFRP-RC included

GFRP-RC now included

Table of Contents

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- **Concluding Remarks**

Concluding Remarks

- There is a strong case for use of FRP in structural concrete exposed to corrosive environment
- FRP anisotropic and linear elastic up to failure
- Material Specifications and Design Guides exist (**ASTM** D7957, ***FDOT***-932, ***AASHTO*** *GFRP*,)
- Accessible design tools exist

Questions?

Thank U

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INTRODUCTION TO FRP-RC & MATERIAL PROPERTIES OF GFRP

1.1 Review Questions: Fundamentals

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Applied Questions

1.1.1) Where could GFRP reinforcement for concrete be most suitable? ___________________________.

a. Any concrete member susceptible to steel corrosion by chlorides

b. Any concrete member requiring non-ferrous reinforcement due to electro-magnetic considerations

c. As an alternative to epoxy, galvanized, or stainless steel rebars

d. Applications requiring thermal non-conductivity

e. All the above

Where Should FRP Be Used?

- **Concrete structures susceptible to corrosion**
  - Steel corrosion by chlorides
  - Aggressive agents that lower concrete pH
  - Structures with minimum cover concrete

- **Concrete structures requiring non-ferrous reinforcement due to**
  - Electro-magnetic considerations
  - **Thermal non-conductivity**

- **Where machinery will "consume" the reinforced concrete member (i.e., mining and tunneling)**

Applied Questions

1.1.1) Where could GFRP reinforcement for concrete be most suitable? ___________________________.

a. Any concrete member susceptible to steel corrosion by chloride ions

b. Any concrete member requiring non-ferrous reinforcement due to electro-magnetic considerations

c. As an alternative to epoxy, galvanized, or stainless steel rebars

d. Applications requiring thermal non-conductivity

e. All the above

Applied Questions

1.1.2) Which of the following is ***not*** applicable to GFRP rebars? ______________________________.

a. Corrosion resistant

b. Ductility

c. Low thermal and electrical conductivity

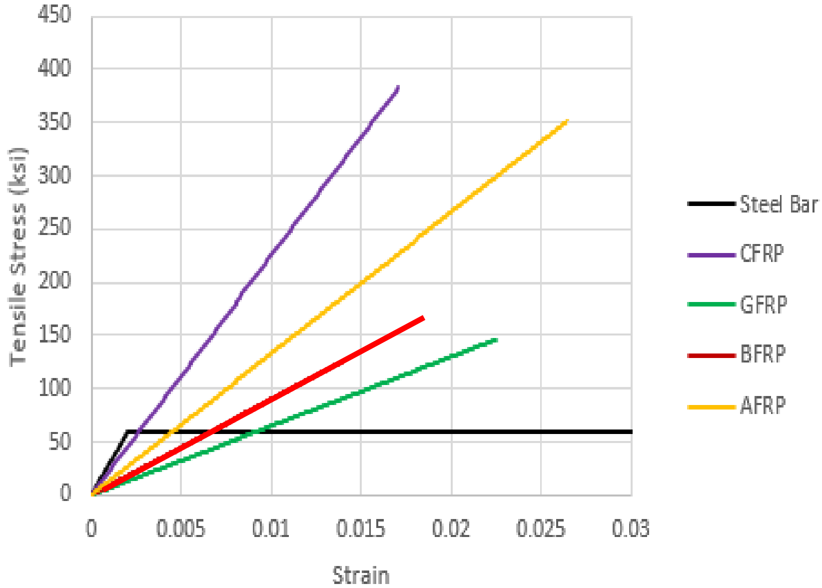
d. Light weight

e. High strength to weight ratio

FRP Mechanical Properties

- Higher tensile strength, but less stiff than steel
  - ✓ Provides less confinement to concrete and RC members have more deflection than steel-RC
- Anisotropic behavior
  - ✓ High strength in the fiber direction
  - ✓ Low shear strength and dowel action (resin dominated)
- Elastic up to failure - no ductility
  - ✓ Cannot be used in seismic areas, no plastic hinges formed in RC members

Tensile Stress-Strain Characteristics



Applied Questions

1.1.2) Which of the following is **not** applicable to GFRP rebars? ___________________________.

a. Corrosion resistant

b. Ductility

c. Low thermal and electrical conductivity

d. Light weight

e. High strength to weight ratio

Applied Questions

1.1.3) The E-modulus of GFRP rebars when compared to steel is approximately ________________________.

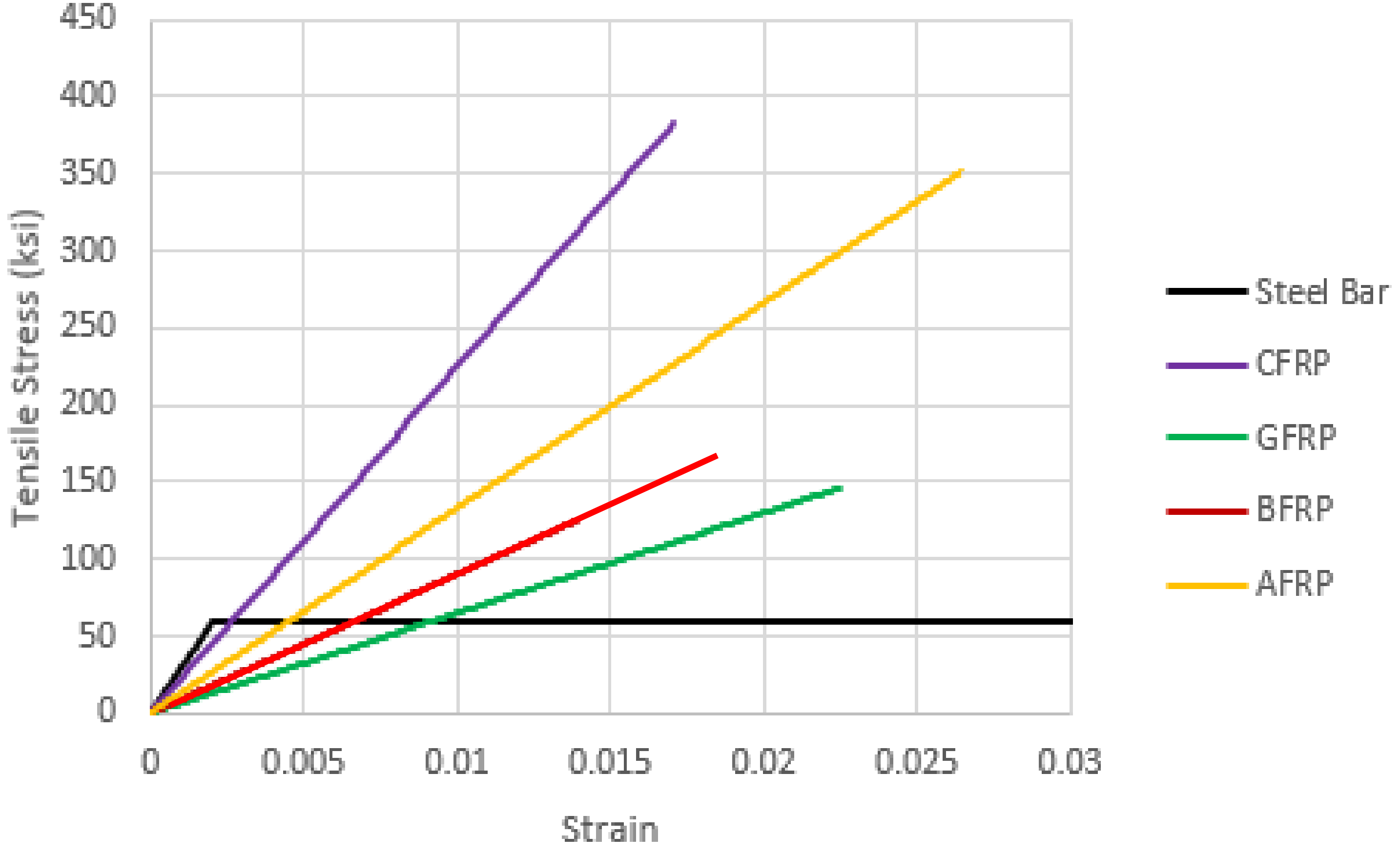
a. 3 to 4 times lower

b. Comparable

c. 2 to 3 times higher

d. 3 to 4 times higher

Applied Questions



Applied Questions

1.1.3) The E-modulus of GFRP rebars when compared to steel is approximately ___________________________.

a. **3 to 4 times lower** (6.5-8.7 msi compared to 29 msi)

b. Comparable

c. 2 to 3 times higher

d. 3 to 4 times higher

Applied Questions

1.1.4) The durability of GFRP rebars _________________.

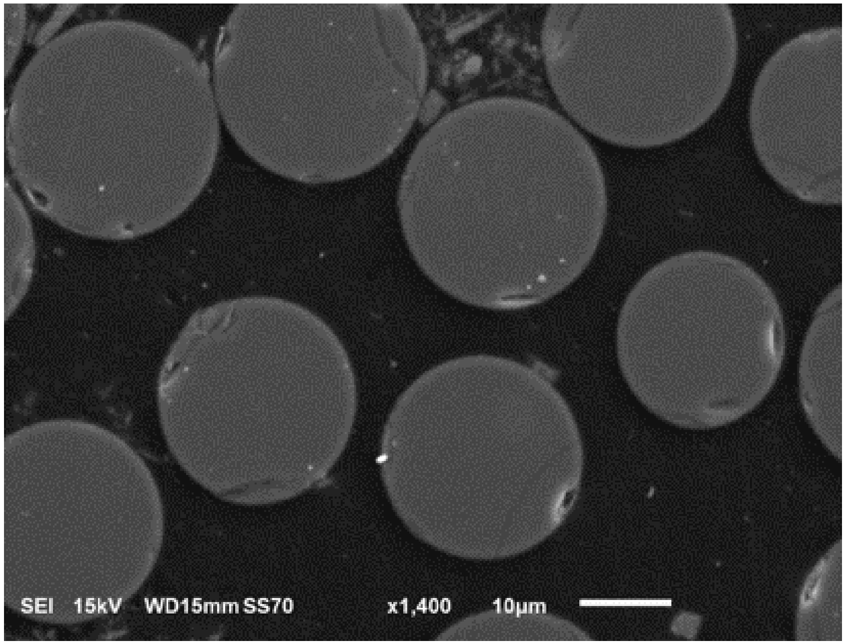
a. Has been proven through accelerated aging protocols and by samples extracted from bridges that have been in service for 15 years

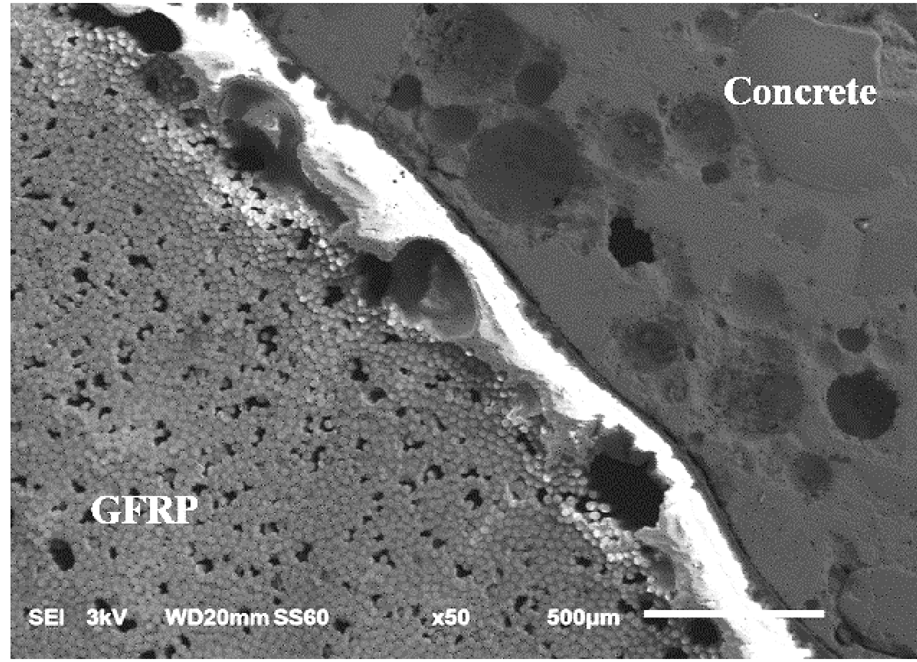
b. Is unknown

c. Is lower than steel

d. a) and c) are true

Durability





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Applied Questions

1.1.4) The durability of GFRP rebars ____________________.

a. **Has been proven through accelerated aging protocols and by samples extracted from bridges that have been in service for 15 years**

b. Is unknown

c. Is lower than steel

d. a) and c) are true

Applied Questions

1.1.5) The density of GFRP is about ____________________.

a. About 4 times lighter than steel

b. Similar to that of steel

c. About 4 times heavier than steel

d. Half that of steel

FRP Density

Rebar type	Density ($lb./ft^3$)	Nominal weight (lb./ft)		
		#3	#5	#8
GFRP	125	0.38	1.05	2.68
Steel	505	0.09	0.26	0.66

Applied Questions

1.1.5) The density of GFRP is about ______________________.

a. About 4 times lighter than steel

b. Similar to that of steel

c. About 4 times heavier than steel

d. Half that of steel

Applied Questions

1.1.6) FRP has higher strength in the direction _________________ to the fibers.

a. Transverse

b. Parallel

Transverse vs. Parallel Strength

Parallel - Tensile

- 70 ksi to >150 ksi
- Strength varies per bar size (shear lag effect)

Transverse - Shear

- > 22ksi
- Almost independent of bar size

Applied Questions

1.1.6) FRP has higher strength in the direction ________________ to the fibers.

a. Transverse

b. Parallel

Applied Questions

1.1.7) The tensile strength of GFRP reinforcing bars with bend should be at minimum ___________________________.

a. The same as straight GFRP reinforcing bars

b. 40% of the straight GFRP reinforcing bars

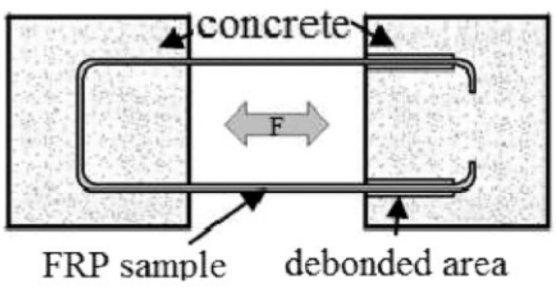
c. 60% of the straight GFRP reinforcing bars

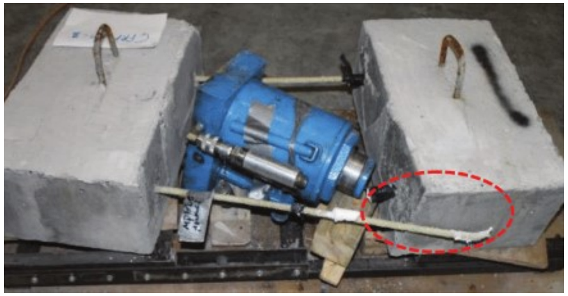
d. 140% of the straight GFRP reinforcing bars

Strength of FRP at Bent

- FRP bars can be fabricated with bends, however the tensile strength of the bend is reduced up to 60% per ***ASTM*** D7957
- Bend radius is larger than for steel
- ***ASTM*** D7914 includes specifications for strength of FRP bent bars in bend locations

Bar Designation, mm [U.S. Standard]	Minimum Bend Diameter mm [in.]
M6 [2]	38 [1.50]
M10 [3]	58 [2.25]
M13 [4]	76 [3.00]
M16 [5]	96 [3.75]
M19 [6]	114 [4.50]
M22 [7]	134 [5.25]
M25 [8]	152 [6.00]





Applied Questions

1.1.7) The tensile strength of GFRP reinforcing bars with bend should be at minimum ___________________________.

a. The same as straight GFRP reinforcing bars

b. 40% of the straight GFRP reinforcing bars

c. 60% of the straight GFRP reinforcing bars

d. 140% of the straight GFRP reinforcing bars

Applied Questions

1.1.8) The guaranteed tensile strength of a GFRP bar as provided by the manufacturer is ____________________________.

a. The mean tensile strength of the sample population

b. The mean tensile strength of the sample population minus three standard deviations

c. The mean tensile strength of the sample population minus two standard deviations

d. None of the above

Material Characterization

Tensile test [*ASTM* D7205]

Minimum requirements**: *FDOT* 932-3, Table 3.2 & 3.3**

AASHTO 2.4.2.1:

f_{fu} → Guaranteed tensile strength = mean minus three standard deviations

Applied Questions

1.1.8) The guaranteed tensile strength of a GFRP bar as provided by the manufacturer is ___________________________.

a. The mean tensile strength of the sample population

b. The mean tensile strength of the sample population minus three standard deviations

c. The mean tensile strength of the sample population minus two standard deviations

d. None of the above

Applied Questions

1.1.9) At temperatures higher than approximately ______________ the resin of GFRP bars begins to soften.

a. 60 ^oF

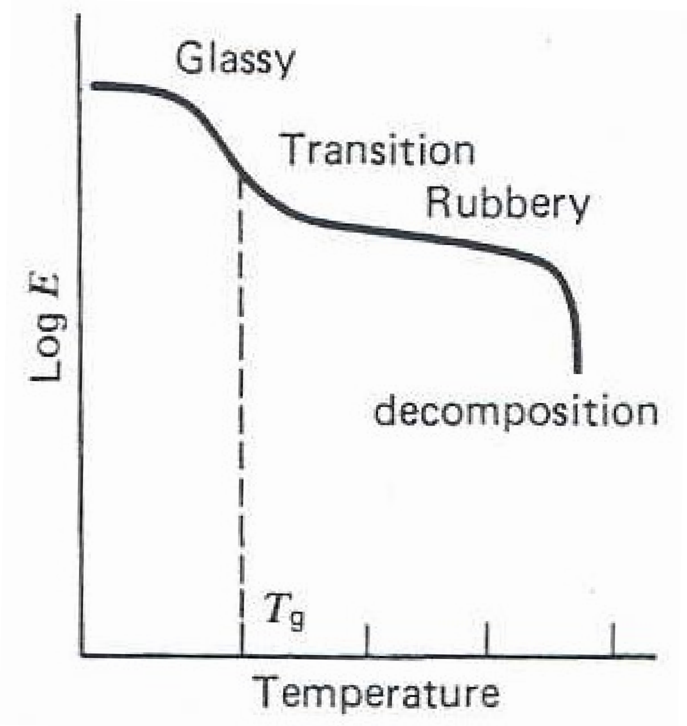
b. 212 ^oF

c. 1220 ^oF

d. 2500 ^oF

Behavior at High Temperatures

- Thermosets are characterized by Glass Transition Temperature, T_g
- Resin tensile, compressive, and shear properties diminish when temperatures approach T_g
- **T_g values are approximately 212 °F (100 °C) for Vinyl Ester typically used GFRP rebars**
- T_g lowers as a result of moisture absorption



Elastic Modulus vs Temperature

Applied Questions

1.1.9) At temperatures higher than approximately ______________ the resin of GFRP bars begins to soften.

a. 60 ^{o}F

b. 212 ^{o}F

c. 1220 ^{o}F

d. 2500 ^{o}F

AASHTO GFRP-Reinforced Concrete Design Training Course



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