FDOT TRANSPORTATION SYMPOSIUM 2019

FRP-RC Design - Part 1

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Adapted from…

Seminar for Composites Australia, December 5, 2018

Design of concrete structures internally reinforced with FRP bars

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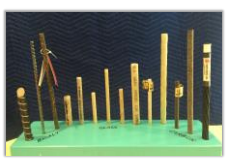
Course Description

Fiber-reinforced polymer (FRP) materials have emerged as an alternative for producing reinforcing bars for concrete structures. Due to other differences in the physical and mechanical behavior of FRP materials versus steel, unique guidance on the engineering and construction of concrete structures reinforced with FRP bars is necessary.



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Learning Objectives

- Understand the mechanical properties of FRP bars
- Describe the behavior of FRP bars
- Describe the design assumptions
- Describe the flexural/shear/compression design procedures of concrete members internally reinforced with FRP bars
- Describe the use of internal FRP bars for serviceability & durability design including long-term deflection
- Review the procedure for determining the development and splice length of FRP bars.

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Content of the Complete Course

FRP-RC Design - Part 1, (50 min.)

This session will introduce concepts for reinforced concrete design with FRP rebar. Topics will address:

- Recent developments and applications
- Different bar and fiber types;
- Design and construction resources;
- Standards and policies;

BFRP-RC Design - Part 2, (50 min.)

This session will introduce FRP rebar that is being standardized under FHWA funded project ***STIC-0004-00A*** with extended FDOT research under BE694, and provide training on the flexural design of beams, slabs, and columns for:

- Design Assumptions and Material Properties
- Ultimate capacity and rebar development length under strength limit states;
- Crack width, sustained load resistance , and deflection under service limit state;

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Content of the Complete Course

BFRP-RC Design - Part 3, (50 min.)

This session continues with FRP rebar from Part 2, covering shear and axial design of columns at the strength limit states for:

- Fatigue resistance under the Fatigue limit state;
- Shear resistance of beams and slabs;
- Axial Resistance of columns;
- Combined axial and flexure loading.

FRP-RC Design - Part 4 *(Not included at FTS - for future training)*:

This session continues with FRP rebar from Part 3, covering detailing and plans preparation:

- Minimum Shrinkage and Temperature Reinforcing
- Bar Bends and Splicing
- Reinforcing Bar Lists
- General Notes & Specifications

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Introduction - Atypical Applications

During the last few years, Universities have been working closely with national & international engineering firms and government departments (including some for FDOT):

- Bridges
- Parking facilities
- Water-treatment plants
- Tunnels
- Retaining walls
- Traffic Barriers
- RC/PC Sheet Piles

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Introduction - Atypical Applications

Examples of major national and international projects using FRP bars:

1) Nipigon Bridge on the Trans-Canada Highway (northwestern Ontario, Canada)
2) Champlain Bridge (Montreal)
3) TTC Subway North Tunnels (Highway 407) (Toronto)
4) Port of Miami Tunnel (Florida - FDOT)
5) Port of Tanger Med II (Morocco)
6) Precast Driven Piles (Florida - FDOT)

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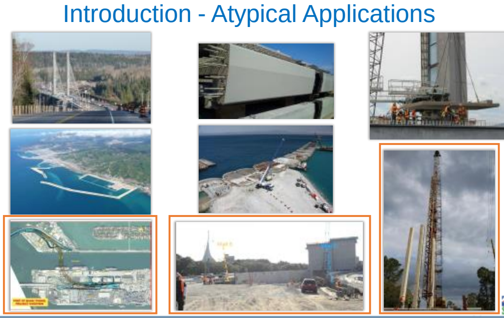
Introduction - Atypical Applications



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Session 1: Materials & Design Specs.

North American Material Specifications and Design Codes for Concrete Structures Reinforced with FRP Bars

Course based on CAN/CSA-S6,-806 & -807
vs. AASHTO BDGS-2 and FDOT Specifications

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Session 1: Materials & Design Specs.

1. **ACI 440. 1R**: “Guide for the design and Construction of Structural Concrete Reinforced with FRP Bars". *1st Edition in 2001, 2nd Edition in 2003, 3rd Edition in 2006, 4th Edition in 2015, Design Code (ACI 318 in 2020)*.
2. **AASHTO LRFD**: “ Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings“. *1st Edition in 2009, 2nd Edition in 2019*
3. **ASTM D7957-17**: “Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement“. *1st Edition in 2017*
4. **CAN/CSA S6**: "Canadian Highway Bridge Design Code", Section 16 "Fibre Reinforced Polymers (FRP) Structures". *1st Edition in 2000, 2nd Edition in 2006, Supplement S1 in 2010, 3rd Edition in 2014, 4th Edition in 2019*
5. **CAN/CSA S806**: "Design and Construction of Building Components with FRP". *1st Edition in 2002, 2nd Edition in 2012*
6. **CAN/CSA-S807**: “Specifications for Fibre Reinforced Polymers". *1st Edition in 2010, 2nd Edition in 2019*

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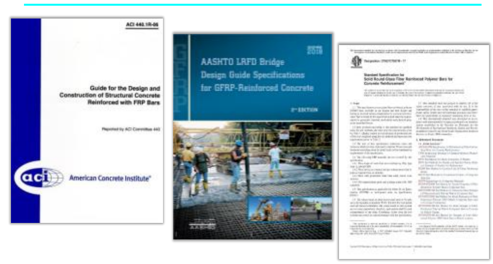
Session 1: Materials & Design Specs.



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Session 1: Materials & Design Specs.

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Session 1: Materials & Design Specs.

- Design principles well established through extensive research and field practice, and experience gained on viability of construction management practices where FRP reinforcement is adopted through traditional low-bid letting processes and competitive bidding from multiple FRP bar suppliers
- Provisions governing testing and evaluation for certification and QC/QA
- Describes permitted constituent materials, limits on constituent volumes, and minimum performance requirements
- Specific properties of FRP reinforcement, design equations and resistance factors, detailing, material and construction specifications
- FRP bar preparation, placement (including cover requirements, reinforcement supports), repair, and field cutting.

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Session 1: Materials & Design

FRP Material Characterizing & Durability Testing

SEM, FTIR, DSC, DMA, Creep/Mechanical, etc.

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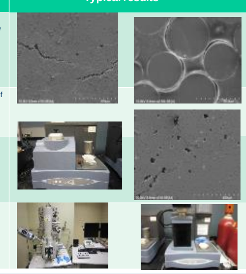
Techniques for assessing physical properties and microstructure of FRP bars

Technique	Principle and objective	Typical results
DSC (Differential Scanning Calorimetry)	Measure the difference in the amount of heat required to increase the temperature of a sample and reference as a function of temperature **Determination of glass transition temperature or softening point (Tg) and cure ratio**	
TMA (Thermomechanical Analysis)	Measure the change of dimension of a sample as a function of temperature **Determination of coefficient of thermal expansion (CET)**	
FTIR (Infrared Spectroscopy)	Provide infrared spectrum of a material (i.e polymeric resin) to detect chemical changes, such as degradation **Detection of chemical degradation of resin, such as hydrolysis**	
SEM (Scanning Electronic microscopy)	Produce images of a sample by scanning it with a focused beam of electrons **Investigation of the morphology, structure, defects (porosity, microcracking, debonding, corrosion, etc.)**	

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Session 1: Materials & Design

Example Structures Laboratory - University of Sherbrooke

New Lab (2009)
Strong floor: 39' x 66'
MTS : 3,600 kip
L-Shape Reaction Walls 39'

Old Lab
Strong floor: 33' x 72'
20 Actuators (50 to 450 kip)

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Session 1: Design & Typ. Applications

Design Considerations

- The designer should understand that a direct substitution between FRP and steel bars is not possible due to differences in mechanical properties of the two materials
- A major difference is that FRP's are linear up to failure and exhibit no ductility or yielding
- Another major difference is that serviceability will be more of a design limitation in FRP reinforced members than with steel. Due to it's lower modulus of elasticity (e.g., GFRP bars), deflection and crack widths will govern the design.

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Session 1: Design & Typ. Applications

Where should FRP Concrete Reinforcing be used?

- Any concrete member susceptible to steel corrosion by chloride ions
- Any concrete member requiring non-ferrous reinforcement due to electro-magnetic considerations, e.g. tolling plaza
- As an alternative to epoxy, galvanized, or stainless-steel rebars
- Where machinery will "consume" the reinforced member (i.e., mining and tunneling)
- Applications requiring thermal non-conductivity

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Session 1: Design & Typ. Applications

Civil and Building Applications

Concrete exposed to de-icing chlorides or salt sprays:

- Bridge decks
- Approach slabs
- Barrier walls
- Railroad crossings
- Salt storage facilities
- Retaining walls
- Parking Garages
- Seawalls, piles and piers
- Marine structures

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Session 1: Design & Typ. Applications

Tunneling Softeyes

London, UK

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Session 1: Design & Typ. Applications

Marine Structures

Corrosion of the steel reinforcement caused concrete delamination

Dry-Docks

Pearl Harbor, Hawaii

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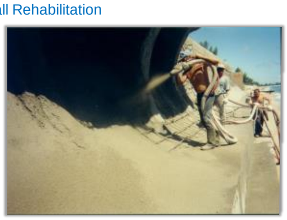
Session 1: Design & Typ. Applications

Marine Structures

Seawall Rehabilitation



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Session 1: Design & Typ. Applications

Bridge Railings

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Session 1: Design & Typ. Applications

Electromagnetic Applications

- MRI rooms in hospitals
- Airport radio & compass calibration pads
- Electrical high voltage transformer vaults
- Concrete near high voltage cables and substations
- Electronic tolling plaza pavements and traffic barriers

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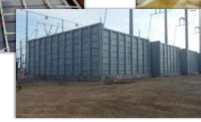
Session 1: Design & Typ. Applications

Electric Utilities

Wall Protection System

- *Protect key transformer sites on the energy grid from ballistics, explosions and fire without requiring grounding of reinforcement*



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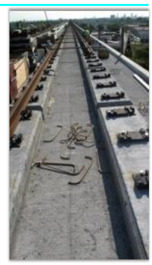
Session 1: Design & Typ. Applications

Electrified Rail Isolation

Miami MetroRail: 2.4 miles of elevated rail

- *Rail Plinths 100% reinforced with GFRP Bars*



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Session 1: Design & Typ. Applications

FRP Rebar Use in Concrete Bridges in USA

- 65 Bridges – 27 States

Colorado	2
Connecticut	1
Florida	8
Georgia	2
Indiana	1
Iowa	2
Kansas	1
Kentucky	2
Mass	1
Maine	4
Michigan	2
Minnesota	1
Missouri	6
Nebraska	1

New Hampshire	1
New York	3
North Carolina	1
Ohio	4
Oregon	1
PA/NJ	1
Pennsylvania	1
Texas	3
Utah	2
Vermont	1
Virginia	1
West Virginia	9
Wisconson	3

Applications		
Deck only	Deck, parapet, barrier, enclosure, and/or sidewalk	Parapet, barrier, enclosure, and/or sidewalk
56	5	4

Source: ACMA, 2016

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Session 1: Design & Typ. Applications

FRP Rebar Use in Concrete Bridges in Canada

- 202 Bridges – 5 provinces

	Rebar	Deck only	Deck, parapet, barrier, enclosure, and/or sidewalk	Parapet, barrier, enclosure, and/or sidewalk
Bridges in Canada	202	167	23	12

Source: ACMA, 2016

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Session 1: Design & Typ. Applications

Nipigon River Cable-Stayed Bridge *(Canada)*

- The First Deck Slab Reinforced with GFRP Bars in Cable Stayed Bridge

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Session 1: Design & Typ. Applications

***Nipigon River Cable-Stayed Bridge** (cont.)*

- 2012-2017
- ~827 ft. (252m) in length
- two-span, four lanes
- 480 precast concrete panels (10 ft. x 23 ft.)
- High Performance concrete
- Panel joint filled with UHPFRC
- Many partners

Session 1: Design & Typ. Applications

***Halls River Bridge Replacement**, Florida, USA*

Session 1: Design & Typ. Applications

***Halls River Bridge Replacement** (cont.)*

- **Owner:** Citrus County, Designer: FDOT, Funding: FHWA
- **Location:** Homosassa, FL (north of Tampa)
- **Superstructure**: GFRP Bars: Deck, Barriers & Approach Slabs
  - 186 ft. overall bridge length, 58 ft. wide
  - 5 spans (37 ft.), continuous deck, simple span beams
- **Substructure:** CFRP Pre-stressed Piles; Bent Caps: GFRP Bars
- **Sheet Pile Walls**: CFRP Sheet Piles; Wall Cap: GFRP Bars
- **Contractor Bid Cost** - $6.016 Million (Structures = $4M; $2M Roadway & Utilities)
  - Bridge Cost = $218 / sq. ft. (Conventional Construction = $166 / sq.ft.)
- **Accelerated Construction Potential**
  - Lighter Materials – Beams and Rebar
  - Faster Transportation and Delivery – reduced construction time ??

Session 1: FRP Rebar Properties

***FRP Reinforcing Bars** - Typically produced by pultrusion process and its variations*

Session 1: FRP Rebar Properties

FRP Bar Types

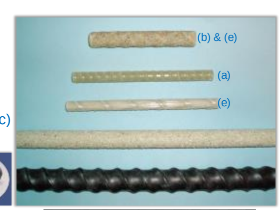
- Materials
  - Glass / vinyl ester
  - Carbon / epoxy
  - Basalt / epoxy/vinylester
  - Aramid / vinyl ester
- Forms
  - Solid round

Session 1: FRP Rebar Properties

FRP Bar Types

External Surface:

- Ribbed (a)
- Sand Coated (b)
- Wrapped and Sand Coated (c)
- Deformed (d)
- Helical (e)
- Grooved (g)
- Hollow core (h)



Session 1: FRP Rebar Properties

Differences from Steel

- High longitudinal strength to weight ratio
- Corrosion-resistant
- Electro-magnetic neutrality (glass/basalt/aramid)
- High fatigue endurance (carbon)
- Low thermal and electrical conductivity (glass/basalt)
- Light weight (1/4 steel)

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Session 1: FRP Rebar Properties

Differences from Steel (cont.)

- No yielding before failure
- Low transverse strength
- Relatively low modulus (glass/basalt/aramid)
- Some susceptible to UV
- Sensitive to moisture (aramid)
- Sensitive to alkaline environment (glass/basalt)
- High CTE perpendicular to the fibers
- Susceptible to fire and smoke production

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Session 1: FRP Rebar Properties

FRP Mechanical Properties and Behavior

- *FRP is anisotropic*
  - High strength only in the fiber direction
  - Anisotropic behavior affects shear strength, dowel action and bond performance
- *FRP does not exhibit yielding: is elastic until failure*
  - Design accounts for lack of ductility

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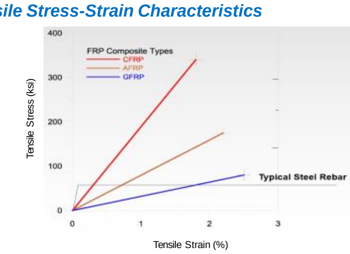
Session 1: FRP Rebar Properties

Tensile Stress-Strain Characteristics



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Session 1: FRP Rebar Properties

Tensile Stress-Strain Characteristics

	Steel	GFRP	CFRP	AFRP
Yield Stress ksi (MPa)	40-75 (276-520)	N/A	N/A	N/A
Tensile Strength ksi (MPa)	70-100 (483-690)	70-230 (483-1585)	87-535 (600-3700)	250-368 (1725-2540)
Elastic Modulus X 10^3 ksi (GPa)	29 (200)	5.1 - 8.6 (40-60)	15.9 – 24 (109-165)	6.0 - 18.2 (41-125)
Yield Strain %	0.14-0.25	N/A	N/A	N/A

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Session 1: FRP Rebar Properties

Factors Affecting Material Characteristics

- Fiber volume
- Type of fibers
- Type of resin
- Fiber orientation/straightness
- Quality control during manufacturing
- Rate of curing
- Void content
- Service temperature

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Session 1: FRP Rebar Properties

***Typical Densities** of reinforcing bars*

	Steel	GFRP	CFRP	AFRP
lb./ft³ (g/cm3)	493 (7.90)	78 – 131 (1.25-2.10)	93 – 100 (1.50-1.60)	78 – 88 (1.25-1.40)

Session 1: FRP Rebar Properties

***Coefficient of Thermal Expansion** (CTE) 10^{-6} / °F (x 10-6 / °C)*

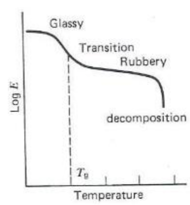
Material	Longitudinal Direction	Transverse
Concrete	4 ~ 6 (7.2 to 10.8)	4 ~ 6 (7.2 to 10.8)
Steel	6.5 (11.7)	6.5 (11.7)
GFRP	3.5 ~ 5.6 (6.0 to 10.0)	≈ 30 (40)
CFRP	-4 ~ 0 (-9.0 to 0.0)	41 ~ 58 (74 to 104)
AFRP	-3.3 ~ -1.1 (-6 to-2)	33 ~ 44 (60 to 80)

Values of CTE differ between FRP materials and concrete and most relevant is the difference in the transverse bar direction

Session 1: FRP Rebar Properties

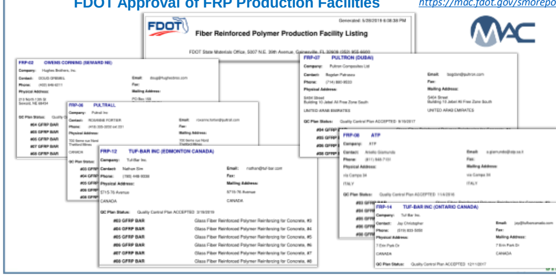
Effect of High Temperatures

- Resins will soften due to excessive heat
- Tensile, compressive, and shear properties of the resin diminish when temperatures approach the Glass Transition Temperature, T_g
- T_g values are approximately 230-240ºF (*110-115 ºC)* for vinyl ester resins which are typically used with GFRP rebar



Session 1: FRP Rebar Acceptance

FDOT Approval of FRP Production Facilities https://mac.fdot.gov/smoreports



Session 1: FRP Rebar Acceptance

At least five Canadian GFRP bar manufacturers qualified their products in accordance with ***CAN/CSA S807*** and obtained approvals from end-users and government authorities (such as MTO and MTQ):

1. B&B FRP Manufacturing, Inc. (MSTBAR)
2. BP Composites, Inc. (TUF-BAR) *
3. Fiberline Composites Canada, Inc. (COMBAR)
4. Pultrall, Inc. (V-ROD) *
5. Tempcorp, Inc. (TEMBAR)

** Also approved for FDOT use.*

Other reputable manufactures supply North America:

USA: Marshall Composite Technologies Inc. (C-BAR); Composite Rebar Technologies Inc. (CRT); Basalt World (No Rust Rebar); Owens Corning (ASLAN formally Hughes Brothers Inc.)*
Europe: FiReP International AG (Switzerland), Asamer (Austria), Magmatech Ltd (United Kingdom); Sireg; ATP (Italy)*
Elsewhere: Galen (Russia); Pultron Composites Ltd. (MATEENBAR, NZ and Dubia)*

Session 1: FRP Rebar Acceptance

***Qualification Tests per GFRP Bar Size** (FDOT Spec 932; CSA S807-10)*

1. Tensile Strength & Modulus at room temp.: *15*, 24 samples*
2. Tensile Strength & Modulus at cold temp.: *n/a, 24 samples*
3. Fiber Content: *15*, 9 samples*
4. Bond Strength: *15, 24 samples*
5. Transverse Shear Strength: *15, 24 samples*
6. Strength of bent bars: *15*, 24 samples*
7. Transverse Coeff. Thermal Expansion: *n/a, 9 samples*
8. Void Content: *n/a, 9 samples*
9. Water Absorption: *15*, 15 samples*
10. Cure Ratio/Polymerization: *9*, 15 samples*
11. Glass Transition Temperature: *9*, 15 samples*
12. Alkaline Resistance without/load: *15, 24 samples*
13. Alkaline Resistance with/load: *15, 24 samples*
14. Creep Rupture: *n/a, 24 samples*

** FDOT project level testing @ 3 per bar size*

Session 1: FRP Rebar Development

Development of FRP Bar Solutions in North America

- GFRP Bars
- CFRP Bars
- GFRP & CFRP Stirrups
- GFRP & CFRP Spirals & Hoops
- GFRP Bent Bars
- GFRP Headed Bars
- GFRP Dowels
- GFRP Adhesive Anchors
- BFRP Bars (recently)

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Session 1: FRP Rebar Development

Grades of FRP Bars in Canada

(CAN CSA S807-10)

 Specification for fibre-reinforced polymers

Table 2
Grades of FRP bars and grids corresponding to their minimum modulus of elasticity, GPa
(See Clause 8.3 and Table 3)

Designation	Grade I Individual bars	Grade I Bars in a grid	Grade II Individual bars	Grade II Bars in a grid	Grade III Individual bars	Grade III Bars in a grid
AFRP	50	40	70	60	90	80
CFRP	80	70	110	100	140	130
GFRP	40	30	50	40	60	50

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Session 1: FRP Rebar Development

Grades of FRP Bars in Florida *(FDOT Spec 932-3, similar to ASTM D7957)*

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

Bar Size Designation	Nominal Bar Diameter (in)	Nominal Cross Sectional Area (in²)	Measured Cross-Sectional Area (in²)		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	-

$E_f \geq 6{,}500$ ksi $E_f \geq 18{,}000$ ksi

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Session 1: FRP Rebar Development

Improving Properties of FRP Bars in North America

Glass FRP Bars (High Modulus and High Strength)

1. *Guaranteed Tensile Strength up to 175 ksi (1,200 MPa)*
2. *Modulus of Elasticity up to 9,000 ksi (60 GPa)*

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Session 1: FRP Rebar Development

Improving FRP Bars in North America

Carbon FRP Bars:

1. *Guaranteed Tensile Strength up to 290 ksi (2,000 MPa)*
2. *Modulus of Elasticity up to 20,000 ksi (135 GPa)*

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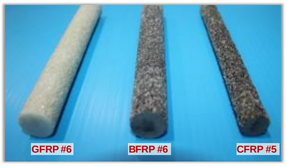
Session 1: FRP Rebar Development

Improving FRP Bars in North America

Basalt FRP Bars (High Modulus and High Strength)

1. *Guaranteed Tensile strength up to 200 ksi (1400 MPa) ?*
2. *Modulus of elasticity up to 9,000+ ksi (64-75 GPa)*



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Session 1: FRP Rebar Development

Bent Bars & Complex Shapes in North America

FRP Stirrups




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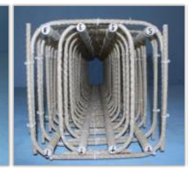
Session 1: FRP Rebar Development

Bent Bars & Complex Shapes in North America

FRP Ties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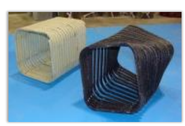
Session 1: FRP Rebar Development

Bent Bars & Complex Shapes in North America

FRP Spirals and Hoops



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Session 1: FRP Rebar Development

Bent Bars in North America

GFRP Bent Bars


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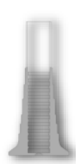
Session 1: FRP Rebar Development

Other FRP Solutions in North America

Glass FRP Headed bars





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Session 1:

End of Session

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Questions

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