AASHTO GFRP-Reinforced Concrete Design Training Course

GoToWebinar by:
Professor Antonio Nanni

Florida Department of Transportation
Office of Design
August 10th, 2020
Design Innovation
9:35 am  **Introduction & Materials** *(Prof. Antonio Nanni)*
   →  **Review Questions** *(Dr. Francisco De Caso)*

10:30 am  **Flexure Response** *(Prof. Antonio Nanni)*
   →  **Review Questions** *(Dr. Francisco De Caso)*
   *** Coffee Break ***
   →  **Design Example: Flat Slab** *(Roberto Rodriguez)*

12:00 pm  **Shear Response** *(Prof. Antonio Nanni)*
   →  **Review Questions** *(Dr. Francisco De Caso)*
   *** Lunch Break (1 hour) ***

1:30 pm  →  **Design Example: Bent Cap** *(Nafiseh Kiani)*

2:00 pm  **Axial Response** *(Prof. Antonio Nanni)*
   →  **Review Questions** *(Dr. Francisco De Caso)*
   →  **Design Example: Soldier Pile** *(Roberto Rodriguez)*
   *** Coffee Break ***

3:00 pm  **Case Studies & Field Operations**
   *(Prof. Nanni & Steve Nolan)*
Introducing our Presenters & Support

Prof. Antonio Nanni  
P.E. PhD.

Dr. Francisco DeCaso  
P.E. PhD.

Roberto Rodriguez,  
P.E. (PhD. Candidate)

Nafiseh Kiani  
(PhD. Candidate)

Alvaro Ruiz,  
(PhD. Candidate)

Christian Steputat,  
P.E. (PhD. Candidate)

Steve Nolan, P.E.
## Support Material - Handouts

[AASHTO GFRP-Reinforced Concrete Design Training Course](#)

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<td>b. NE 23rd Avenue Bridge over Ibis Waterway (FPN 434359-1-52-01)</td>
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<td>c. Hills River Bridge (FPN 430021-1-52-01)</td>
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<td>d. SR A1A Flagler Beach (Segment 3) (FPN 440557-7-52-01)</td>
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### LIST OF COURSE ANNEXES

- Annex A (Section 2.2): LRFD Flat Slab Bridge Design Example
- Annex B (Section 3.2): Intermediate Bent-Cap Analysis & Design
- Annex C (Section 4.0): LRFD Design P-M Diagram of GFRP Reinforced Pile Example
# Support Material - Handouts

## Design Tools from FDOT/AASHTO and Existing Examples

This table provides a list of available tools from FDOT Structures Design (https://www.fdot.gov/structures) located under the Structures Manual section. As a reference when framing and solving the examples, design is focus on the resistance side. Load demand calculation, geotechnical design, etc. are kept to a minimum unless they differ from what traditionally done with steel-RC.

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<tr>
<td></td>
<td>FDOT Structures Manual 4th Edition</td>
<td>Definition of mechanical properties and factorization per existing standards</td>
<td>None</td>
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<tr>
<td>1.B. Definition of material properties and design values when a specific manufacturer and product are selected (value engineering).</td>
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<tr>
<td></td>
<td>FDOT Material Acceptance</td>
<td>Properties as specified by a fictitious manufacturer and fabricated as per existing standards</td>
<td>None</td>
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<td>2.A. Flat slab bridge superstructure</td>
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<td></td>
<td>Mathcad Worksheet for flat slab bridges &amp; LRFD Design Example 2A developed as master's thesis at UM (Internal UM Link)</td>
<td>Most recent version of the Mathcad worksheet used for the 23rd Ave bridge</td>
<td>23rd Ave. Bridge over I-95 (4343501-1-52-01)</td>
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<td>2.B. Deck (empirical &amp; traditional)</td>
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<td></td>
<td>FDOT Girders v5.3 (link) (not including FRP)</td>
<td>Most recent version of the Mathcad spreadsheet developed for FRP-RC girders</td>
<td>None (23rd Street Bridge over I-95) (4343551-1-52-01)</td>
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<td>2.C. Girders</td>
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<td>FDOT Girders v5.4 (link) (not publicly available, modified at UM it includes FRP-RC)</td>
<td>Most recent version of the Mathcad spreadsheet developed for FRP-RC girders</td>
<td>None (23rd Street Bridge over I-95) (4343551-1-52-01)</td>
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<td>2.D. Bent Cap</td>
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<td></td>
<td>FDOT Bent Cap v1.0 (link)</td>
<td>None</td>
<td>None (23rd Street Bridge over I-95) (4343551-1-52-01)</td>
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<tr>
<td>2.E. Railings</td>
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<td>Design Standards Development Report for Highway Railings (GFRP) (Internal UM Link)</td>
<td>Most recent version of the Mathcad spreadsheet used for traffic railings</td>
<td>None (FGDOT development standard available)</td>
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<td>3.A. Precast Pile</td>
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<td></td>
<td>Mathcad Worksheet for FRP-RC precast concrete piles (link)</td>
<td>Design standards exist for FRP with GFRP reinforcement (link) &amp; Developmental standard for square GFRP Prestressed Concrete Pile Splices (link)</td>
<td>None (1Deck)</td>
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## Useful Resources from DOTs

- **Software:**
  - https://www.fdot.gov/structures/ProcLab.shtml
  - FDOT Index:
  - TXDOT Index:
  - ODOT Index:
    - http://www.dot.state.oh.us/Divisions/Engineering/Structures/standard%20drawings/Forms/AllItems.aspx
  - Developmental Index:
  - Structures Manual:
  - Construction and Material spec:
    - https://www.fdot.gov/programmanagement/implementation/specBooks/
  - FRP Projects in Florida:
    - http://www.arcgis.com/apps/proximity/index.html?appid=7680102a09444353ba5f1f1f15662734e4ff
Support Material - Handouts

AASHTO GFRP-Reinforced Concrete Design Training Course
Table of Contents & Course Resources

GENERAL REFERENCES

FDOT Specifications
- FDOT Materials Manual, Section 12.1, Volume II, Fiber Reinforced Polymer Composites
- FDOT Standard Specifications for Road and Bridge Construction, Section 932, Nonmetallic Accessory Materials for Concrete Pavement and Concrete Structures
- FRP Bar Bending Detail, D21310

Railings
- Design Standard Development Report for 32” F Shape Traffic Railing (GFRP Reinforced) (Developmental Index D22426)

Flat Slab
- Approach Slab – GFRP Reinforced (Flexible Pavement Approach) (Developmental Standard D22908)

FDOT Software
- FDOT Structure Design Office – Proglib Library, “Bent Cap v1.0”
  https://www.dot.gov/structures/proglib.shtml
- FDOT Structure Design Office – Proglib Library, “Retaining Wall v4.0 Beta”

Specifications & Design Guides (GFRP)
- ASTM D7957/D7957M-17, Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement
- AASHTO LRFD Bridge Design Guide Specifications for GFRP- Reinforced Concrete 2nd Edition

Books and Papers

COURSE CONTENT REFERENCES


Support Material - Handouts

AASHTO GFRP-Reinforced Concrete Design Training Course
Table of Contents & Course Resources

GENERAL REFERENCES

FDOT Specifications
• FDOT Structures Manual, Volume 4, Fiber Reinforced Polymer Guidelines (FRPG)
• FDOT Materials Manual, Section 12.1, Volume II, Fiber Reinforced Polymer Composites
• FDOT Standard Specifications for Road and Bridge Construction, Section 632, Nonmetallic Accessory Materials for Concrete Pavement and Concrete Structures
• FRP Bar Bending Detail, D21310

Ratings
• Design Standard: Development Report for 32” F Shape Traffic Railing (GFRP Reinforced) (Developmental Index D22420)

Flat Slab
• Approach Slab - GFRP Reinforced (Flexible Pavement Approach) (Developmental Standard D22900)

FDOT Software

Specifications & Design Guides (GFRP)
• ASTM D7857/D7857M-17 Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bar for Concrete Reinforcement
• AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete 2nd Edition
• ACI Committee 440.1R-15, Guide for the Design and Construction of Structural Concrete Reinforced with Fiber Reinforced Polymer Bars

Books and Papers

COURSE CONTENT REFERENCES


Support Material - Workbook

AASHTO GFRP - REINFORCED CONCRETE DESIGN

TRAINING COURSE COMPANION WORKBOOK

PHOTO: Installation of first GFRP pile cage on A1A Flagger beach project, April 2019.

This document has been developed by the University of Miami, College of Engineering Dept. of Civil, Architectural and Environmental Engineering. Contents offered in this document are based on current and available information at the time of its issue and may be subject to revision as additional information becomes available. This companion workbook is for the purposes of demonstration only.
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**PHOTO:** GFRP cage assembly for the Halls River Bridge Project, April 2017.
Other Support Material - FDOT

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

Structures Design

Fiber Reinforced Polymer Reinforcing

2020

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

- FDOT Executive Workshop (January 15, 2020)
- FTS2020 "FRP Reinforced and Prestressed Concrete Designer Training Introduction" (June 30, 2020)
- FDOT/FRP Industry 4th RC/PC Workshop (August 4, 2020)
  - FDOT GFRP-RC Designer Training for Bridges & Structures (August 10, 2020) - Webinar Registration Link
  - FDOT GFRP-RC Designer Training for Bridges & Structures (September 9, 2020) - Webinar Registration Link
CFRP-Prestressed Concrete Designer Training for Bridges & Structures
– Professor Abdeldjelil “DJ” Belarbi, on September 9th, 2020

This 6-hour online training is focused on providing practical designer guidance to FDOT engineers and consultants for structures utilizing Carbon Fiber-Reinforced Polymer (CFRP) Strands for pretensioned bridge beams, bearing piles, and sheet piles. Basic design principles and design examples will be presented for typical FDOT bridge precast elements.

Register Now at:
https://attendee.gotowebinar.com/register/5898046861643311883

There is no cost to attend this webinar training.

A short preview of this training was provided at the June 30th FDOT Transportation Symposium Webinar Series presentation:
FRP Reinforced and Prestressed Concrete Designer Training Introduction
AASHTO GFRP-Reinforced Concrete Design Training Course

Let Us Begin !!
AASHTO GFRP-Reinforced Concrete Design Training Course
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

1. Introduction & Materials
2. Flexure Response
3. Shear Response
4. Axial Response
5. Case Studies & Field Operations
1. INTRODUCTION TO FRP-RC & MATERIAL PROPERTIES OF GFRP
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
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
Table of Contents

- Problem Statement

- Where to Use Glass FRP

- FRP Material Properties

- Durability

- Design Guides and Standards

- Concluding Remarks
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
Table of Contents

• Problem Statement

• Where to Use Glass FRP

• FRP Material Properties

• Durability

• Design Guides and Standards

• Concluding Remarks
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

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

<table>
<thead>
<tr>
<th>Bar Size Designation</th>
<th>Nominal Bar Diameter (in)</th>
<th>Nominal Cross Sectional Area (in²)</th>
<th>Measured Cross-Sectional Area (in²)</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Minimum Guaranteed Tensile Load (kips)</th>
<th>BFRP and GFRP Bars</th>
<th>CFRP Bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.250</td>
<td>0.049</td>
<td>Minimum: 0.046</td>
<td>6.1</td>
<td>10.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum: 0.085</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.375</td>
<td>0.11</td>
<td>Minimum: 0.104</td>
<td>13.2</td>
<td>20.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum: 0.161</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.500</td>
<td>0.20</td>
<td>Minimum: 0.185</td>
<td>21.6</td>
<td>33.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum: 0.263</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.625</td>
<td>0.31</td>
<td>Minimum: 0.288</td>
<td>29.1</td>
<td>49.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum: 0.388</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.750</td>
<td>0.44</td>
<td>Minimum: 0.415</td>
<td>40.9</td>
<td>70.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum: 0.539</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.875</td>
<td>0.60</td>
<td>Minimum: 0.565</td>
<td>54.1</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum: 0.713</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.000</td>
<td>0.79</td>
<td>Minimum: 0.738</td>
<td>66.8</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum: 0.913</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.128</td>
<td>1.00</td>
<td>Minimum: 0.934</td>
<td>82.0</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum: 1.137</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.270</td>
<td>1.27</td>
<td>Minimum: 1.154</td>
<td>98.2</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum: 1.385</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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](image-url)
## Typical Tensile Properties

<table>
<thead>
<tr>
<th></th>
<th>Steel</th>
<th>GFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Yield Stress</strong></td>
<td>40-75 ksi</td>
<td>78-160 ksi</td>
</tr>
<tr>
<td>(ksi (MPa))</td>
<td>(276-517)</td>
<td>(534-1240)</td>
</tr>
<tr>
<td><strong>Guaranteed Tensile Strength, (f_{f,u}^*),</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(Average – 3 sigma)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kinesi (ksi (MPa))</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Average Elastic Modulus, (E_f)</strong></td>
<td>29,000 ksi</td>
<td>6,500 – 8,700 ksi</td>
</tr>
<tr>
<td><em>(Average)</em></td>
<td>(200)</td>
<td>(45-60)</td>
</tr>
<tr>
<td>Kinesi (kinesi (GPa))</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Yield Strain, (ε_y)</strong></td>
<td>0.14-0.25%</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Guaranteed Tensile Ultimate Strain, (ε_{f,u}^*)</strong></td>
<td>~10-12%</td>
<td>1.2-2.4%</td>
</tr>
</tbody>
</table>
Design Tensile Strength

- Design tensile strength and strain are:

\[ f_{fu} = C_E f_u^* \]
\[ \varepsilon_{fu} = C_E \varepsilon_{fu}^* \]

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)

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Concrete not exposed to earth or weather</th>
<th>Concrete exposed to earth or weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>0.9 0.8</td>
<td>0.85 0.70</td>
</tr>
</tbody>
</table>
Behavior Function of Temperature

- Thermosets are characterized by **Glass Transition Temperature**, $T_g$

- Resin tensile, compressive, and shear properties diminish when temperatures approach $T_g$

- $T_g$ values of approximately 212 °F (100 °C) are required for Vinyl Ester typically used GFRP rebars

- $T_g$ lowers as a result of moisture absorption

*Elastic Modulus vs Temperature*
## Summary: GFRP Differences with Steel

<table>
<thead>
<tr>
<th>PROs</th>
<th>CONs</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High longitudinal strength-to-weight ratio</td>
<td>• No yielding</td>
</tr>
<tr>
<td>• Corrosion resistance</td>
<td>• Low transverse strength</td>
</tr>
<tr>
<td>• Electro-magnetic neutrality</td>
<td>• Relatively low modulus</td>
</tr>
<tr>
<td>• Good fatigue endurance</td>
<td>• High CTE perpendicular to fibers</td>
</tr>
<tr>
<td>• Low thermal &amp; electrical conductivity</td>
<td>• Sensitive to UV, moisture &amp; alkaline environment</td>
</tr>
<tr>
<td>• Lightweight</td>
<td>• Susceptible to fire &amp; smoke production</td>
</tr>
</tbody>
</table>
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)
Material Characterization

**Tensile test**

[ASTM D7205]

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

**AASHTO 2.4.2.1:**

\[ f_{fu} \rightarrow \text{Guaranteed tensile strength} = \text{average minus three standard deviations} \]
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.

<table>
<thead>
<tr>
<th>Bar Designation, mm [U.S. Standard]</th>
<th>Minimum Bend Diameter mm [In.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6 [2]</td>
<td>38 [1.50]</td>
</tr>
<tr>
<td>M13 [4]</td>
<td>76 [3.00]</td>
</tr>
<tr>
<td>M25 [8]</td>
<td>152 [6.00]</td>
</tr>
</tbody>
</table>
Table of Contents

• Problem Statement
• Where to Use Glass FRP
• FRP Material Properties
• 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
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
Table of Contents

- 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
Currently available documents:

- **AASHTO**: Only GFRP
- **FDOT 932-3**: GFRP and BFRP
## Uniform Approval Processes

- Manufacturer Approval vs. Product Approval

### Fiber Reinforced Polymer Production Facility Listing

<table>
<thead>
<tr>
<th>FRP-02</th>
<th>OWENS CORNING (SEWARD NE)</th>
</tr>
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<tbody>
<tr>
<td>Company:</td>
<td>Hughes Brothers, Inc.</td>
</tr>
<tr>
<td>Contact:</td>
<td>DOUG GREMEL</td>
</tr>
<tr>
<td>Phone:</td>
<td>(402)</td>
</tr>
<tr>
<td>Physical Address:</td>
<td>Pultral Inc.</td>
</tr>
<tr>
<td>QC Plan Status:</td>
<td>#04 GFRP BAR</td>
</tr>
<tr>
<td>QC Plan Status:</td>
<td>Quality Control Plan ACCEPTED 3/19/2019</td>
</tr>
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<table>
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<tr>
<th>FRP-06</th>
<th>PULTRALL</th>
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<tr>
<td>Company:</td>
<td>Pultral Inc.</td>
</tr>
<tr>
<td>Contact:</td>
<td></td>
</tr>
<tr>
<td>Phone:</td>
<td></td>
</tr>
<tr>
<td>Physical Address:</td>
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<td>QC Plan Status:</td>
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<table>
<thead>
<tr>
<th>FRP-07</th>
<th>PULTRON (DUBAI)</th>
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<tbody>
<tr>
<td>Company:</td>
<td>Pultron Composites Ltd</td>
</tr>
<tr>
<td>Contact:</td>
<td>Bogdan Patterau</td>
</tr>
<tr>
<td>Phone:</td>
<td>(714) 880-9533</td>
</tr>
<tr>
<td>Physical Address:</td>
<td>S404 Street Building 10 Jebel</td>
</tr>
<tr>
<td>QC Plan Status:</td>
<td>#04 GFRP BAR</td>
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<th>ATP</th>
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<tr>
<td>Company:</td>
<td>ATP</td>
</tr>
<tr>
<td>Contact:</td>
<td>Antelope Giamundo</td>
</tr>
<tr>
<td>Phone:</td>
<td>(811) 948-7131</td>
</tr>
<tr>
<td>Physical Address:</td>
<td>5715-76 Ave</td>
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<tr>
<td>QC Plan Status:</td>
<td>#04 GFRP BAR</td>
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<th>FRP-12</th>
<th>TUF-BAR INC (EDMONTON CANADA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company:</td>
<td>Tuf-Bar Inc.</td>
</tr>
<tr>
<td>Contact:</td>
<td>Nathan Sim</td>
</tr>
<tr>
<td>Phone:</td>
<td>(780) 948-9338</td>
</tr>
<tr>
<td>Physical Address:</td>
<td>5715-76 Avenue</td>
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<tr>
<td>QC Plan Status:</td>
<td>#04 GFRP BAR</td>
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</table>

<table>
<thead>
<tr>
<th>FRP-14</th>
<th>TUF-BAR INC (ONTARIO CANADA)</th>
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</thead>
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<tr>
<td>Company:</td>
<td>Tuf-Bar Inc.</td>
</tr>
<tr>
<td>Contact:</td>
<td>Jay Christopher</td>
</tr>
<tr>
<td>Phone:</td>
<td>(519) 833-5050</td>
</tr>
<tr>
<td>Physical Address:</td>
<td>7 Erin Park Dr</td>
</tr>
</tbody>
</table>

**Design Guidance & Tools in Florida**

[https://mac.fdot.gov/smoreports](https://mac.fdot.gov/smoreports)
<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Requirement</th>
<th>Straight Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Mass Fraction</td>
<td>ASTM D2584 or ASTM D3171</td>
<td>≥70%</td>
<td>Yes</td>
</tr>
<tr>
<td>Short-Term Moisture Absorption</td>
<td>ASTM D570, Procedure 7.1; 24 hours immersion at 122°F</td>
<td>≤0.25%</td>
<td>Yes</td>
</tr>
<tr>
<td>Glass Transition Temperature</td>
<td>ASTM D7028 (DMA) or ASTM E1356 (DSC; T&lt;sub&gt;m&lt;/sub&gt;) / ASTM D3418 (DSC; T&lt;sub&gt;mg&lt;/sub&gt;)</td>
<td>≥230°F, ≥212°F</td>
<td>Yes</td>
</tr>
<tr>
<td>Degree of Cure</td>
<td>ASTM E2160</td>
<td>≥95% of Total polymerization enthalpy</td>
<td>Yes</td>
</tr>
<tr>
<td>Measured Cross-sectional Area</td>
<td>ASTM D7205</td>
<td>Within range listed in Table 3-1</td>
<td>Yes</td>
</tr>
<tr>
<td>Guaranteed Tensile Load</td>
<td></td>
<td>≥ Value listed in Table 3-1</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Design Guidance & Tools In Florida

• Accessible & Reliable Design Tools
  – Commercial vs. Agency/Institution based design programs

https://www.fdot.gov/structures/proglib.shtm

Structures Design Programs Library

<table>
<thead>
<tr>
<th>Program</th>
<th>Date</th>
<th>File Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prestressed Beam v5.2</td>
<td>11/07/2018</td>
<td>Exe (Zip) (Mathcad 15)</td>
<td>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.</td>
</tr>
<tr>
<td>Bent Cap v1.0</td>
<td>11/07/2018</td>
<td>Exe (Zip) (Mathcad 15)</td>
<td>Analyzes and designs fixed or pinned bent caps, including lateral loads, in accordance with the AASHTO LRFD Bridge Design Specifications.</td>
</tr>
<tr>
<td>Retaining Wall v4.0</td>
<td>06/01/2020</td>
<td>Zip (Mathcad 15)</td>
<td>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.</td>
</tr>
</tbody>
</table>
# Table of Contents

- Problem Statement
- Where to Use Glass FRP
- FRP Material Properties
- Durability
- Design Guides and Standards
- 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
INTRODUCTION TO FRP-RC & MATERIAL PROPERTIES OF GFRP

1.1 Review Questions: Fundamentals
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 electromagnetic 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)
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
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
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
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
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
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

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
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

<table>
<thead>
<tr>
<th>Rebar type</th>
<th>Density (lb./ft(^3))</th>
<th>Nominal weight (lb./ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>#3</td>
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<tr>
<td>GFRP</td>
<td>125</td>
<td>0.38</td>
</tr>
<tr>
<td>Steel</td>
<td>505</td>
<td>0.09</td>
</tr>
</tbody>
</table>
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
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
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
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:
\[ f_{fu} \rightarrow \text{Guaranteed tensile strength} = \text{mean minus three standard deviations} \]
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
1.1.9) At temperatures higher than approximately _______________ the resin of GFRP bars begins to soften.

a. 60 °F

b. 212 °F

c. 1220 °F

d. 2500 °F
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
1.1.9) At temperatures higher than approximately _____________ the resin of GFRP bars begins to soften.

a. 60 °F

b. 212 °F

c. 1220 °F

d. 2500 °F
AASHTO GFRP-Reinforced Concrete Design Training Course
AASHTO GFRP-Reinforced Concrete Design Training Course
Course Outline

1. Introduction & Materials

2. Flexure Response

3. Shear Response

4. Axial Response

5. Case Studies & Field Operations
2. FLEXURE RESPONSE OF GFRP REINFORCED CONCRETE
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• General Considerations

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• Special Considerations

• Concluding Remarks
Flexural Theory

Assumptions:
1. Plane sections remain plane after deformation
2. Ultimate concrete strain is 0.003
3. Tensile strength of concrete and FRP compressive strength are neglected
4. FRP is perfectly bonded to concrete
5. Stress-strain of FRP is linear until failure

Ultimate Flexural Strength and Demand:

\[ M_n = \text{nominal capacity} \]
\[ M_u = \text{factored demand} \]

\[ \phi M_n \geq M_u \]

\( \phi = \text{strength reduction factor} \)  
(does not depend on the mode of failure)

For AASHTO, example

\[ M_u = 1.25M_{DC} + 1.75M_{LL} \]

For ACI, example

\[ M_u = 1.2M_D + 1.6M_L \]
Failure Modes

Compression-controlled: concrete crushing

Concrete Crushing

\[ \beta_1 c = a \]
Failure Modes

Concrete Crushing Failure in GFRP-RC Beam
Failure Modes

**Tension-controlled:** FRP rupture

Concrete stress may be linear or non-linear.

- FRP Rupture
- N.A
- $f'_c$
- $f_{fu}$
- $A_f$
Failure Modes

FRP Rupture Failure in GFRP Reinforced Beam
Failure Modes

**Balanced failure:** simultaneous concrete crushing & FRP rupture

Concrete Crushing

FRP Rupture

\[ f' = 0.85f'_{c,ba} \]

\[ A_f f_{fu} \]

\[ c = c_b \]

\[ \varepsilon_{cu} \]

\[ \varepsilon_{fu} \]

\[ A_f \]

\[ b \]

\[ d \]

\[ N.A \]
General Considerations

• Flexural capacity of an FRP-reinforced flexural member dependent on tension or compression failure modes

• Over or under-reinforced sections are acceptable provided that the strength and serviceability criteria are satisfied

• FRP reinforcement is brittle, but provides warning in terms of large member deflection

• Flexural behavior is not ductile; therefore safety factors are increased (i.e., smaller $\Phi$ factors)
Moment-Curvature Diagrams

<table>
<thead>
<tr>
<th></th>
<th>b (in.)</th>
<th>h (in.)</th>
<th>d (in.)</th>
<th>$A_{\text{reinf.}}$ (in$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>8</td>
<td>15</td>
<td>12.5</td>
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<td>10</td>
<td>18</td>
<td>15.5</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Moment (kip-ft) vs. Curvature (rad/in)

- **(1)** Steel-tension controlled
- **(2)** GFRP-concrete crushing
- **(3)** GFRP-FRP rupture

FDOT
UNIVERSITY OF MIAMI
Center for Integration of Composites into Infrastructure
Balanced Failure

\[
\rho_f = \frac{A_{fb}}{bd}
\]

\[
\rho_{fb} = 0.85 \beta_1 \frac{f_c'}{f_{fu}} \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}}
\]

Where it can be shown that:

\[
C = 0.85 f_c' \beta_1 \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fu}} bd
\]

\[
T = A_{fb} f_{fu} = \rho_{fb} f_{fu} bd
\]
Balanced Reinforcement Ratio

IF $\rho_f < \rho_{fb}$

Rupture of FRP will control failure

IF $\rho_f > \rho_{fb}$

Concrete crushing will control failure

**TYPICAL VALUES FOR $\rho_b$, $\rho_{fb}$**

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho_b$</th>
<th>$\rho_{fb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEEL GRADE 60</td>
<td>$0.0335$</td>
<td>$0.0078$</td>
</tr>
<tr>
<td>GFRP F80-E6</td>
<td>$0.0335$</td>
<td>$0.0078$</td>
</tr>
</tbody>
</table>
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• Concluding Remarks
Nominal Flexural Strength: Compression

Case of **concrete crushing controlling** failure and stress distribution approximated by rectangular stress block

IF $\varepsilon_{ft} < \varepsilon_{fu}$

$$M_n = A_f f_f \left( d - \frac{a}{2} \right)$$  \hspace{1cm} (AASHTO 2.6.3.2.2-1)

WHERE

$$a = \frac{A_f f_f}{0.85 f'_c b}$$  \hspace{1cm} (AASHTO 2.6.3.2.2-2)

$$f_f = \sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85 \beta_1 f'_c}{\rho_f} E_f \varepsilon_{cu} - 0.5 E_f \varepsilon_{cu} \leq f_{fu}}$$  \hspace{1cm} (AASHTO 2.6.3.1-1)
**Nominal Flexural Strength: Tension**

**FRP rupture controlling failure.** Whitney’s Stress block not applicable because $\varepsilon_c < \varepsilon_{cu} = 0.003$. Simplified and conservative procedure is proposed (i.e., $c = c_b$):

IF $\varepsilon_{ft} = \varepsilon_{fu}$

$$M_n = A_f f_{fu} \left( d - \frac{\beta_1 c_b}{2} \right)$$  \hspace{1cm} (AASHTO 2.6.3.2.2.-3)

WHERE

$$c_b = \left( \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fu}} \right) d$$  \hspace{1cm} (AASHTO 2.6.3.2.2.-4)
Strength Reduction Factor (ACI)

\[ \phi = \begin{cases} 
0.55 & \text{for } \rho_f \leq \rho_{fb} \\
0.3 + 0.25 \frac{\rho_f}{\rho_{fb}} & \text{for } \rho_{fb} < \rho_f < 1.4\rho_{fb} \\
0.65 & \text{for } \rho_f \geq 1.4\rho_{fb} 
\end{cases} \]  

(ACI 440 7.2.3)
Strength Reduction Factors (AASHTO)

$\phi$ as a function of strain in GFRP

$$\phi = \begin{cases} 
0.55 & \text{for } \varepsilon_{ft} \leq \varepsilon_{fd} \\
1.55 - \frac{\varepsilon_{ft}}{\varepsilon_{fd}} & \text{for } 0.80\varepsilon_{fd} < \varepsilon_{ft} < \varepsilon_{fd} \\
0.75 & \text{for } \varepsilon_{ft} \geq 0.80\varepsilon_{fd} 
\end{cases}$$

(AASHTO 2.5.5.2)
Minimum longitudinal reinforcement to provide adequate level of protection against sudden failure at formation of first flexural crack

\[
M_r \geq \begin{cases} 
1.33M_u \\
1.6M_{cr} - M_{dnc}\left(\frac{S_c}{S_{nc}} - 1\right)
\end{cases}
\]

- \(f_r\) = modulus of rupture of concrete
- \(M_{dnc}\) = total unfactored dead load moment
- \(S_c\) = section modulus of the extreme fiber of the composite section
- \(S_{nc}\) = section modulus for the extreme fiber of the monolithic or non-composite section

Illustrative example on ductile and brittle responses
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Serviceability

• Stresses under sustained and cyclic loading must be checked to avoid static (creep-rupture) and cyclic fatigue rupture

• The substitution of FRP for steel on an equal area basis would typically result in larger deflections and wider crack widths

• Deflections under service loads and crack control often govern design
  • Cracking – Excessive crack width is undesirable for aesthetic and other reasons (e.g., prevent leakage that can damage structural concrete)
  • Deflection – Deflections should be within acceptable limits imposed by the use of the structure (e.g., supporting attached nonstructural elements without damage)

• Designing FRP-RC beams for concrete crushing typically satisfies serviceability criteria
Crack Control: Bond Coefficient

Bond coefficient \((k_b)\) accounts for the degree of bond between FRP bar and surrounding concrete in ACI 440. Bond reduction factor \((C_b)\) defined as the inverse of \(k_b\) in AASHTO. Function of surface configuration and materials varies from 70 to 120% of steel bars. 83% assumed in AASHTO 2.6.7.

\[
k_b = \begin{cases} 
> 1 & \text{Worse than steel} \\
< 1 & \text{Better than steel} 
\end{cases}
\]

\[
C_b = \frac{1}{k_b} = \begin{cases} 
> 1 & \text{Better than steel} \\
< 1 & \text{Worse than steel} 
\end{cases}
\]

Testing of GFRP-RC beam using four-point setup
Control of Crack Width

FRP bars are corrosion-resistant; therefore, *larger crack widths* as compared to steel-RC concrete can be tolerated

The maximum crack width \( w \) is:

- **GFRP**: 0.028 in
- **Steel**: 0.017 in

**Indirect approach** controls flexural cracking in terms of maximum bar spacing adopted in AASHTO GFRP 2nd Ed.:

\[
 s_{\text{max}} \leq \min \left( 1.15 \frac{C_b E_f w}{f_{fs}} - 2.5 c_c, 0.92 \frac{C_b E_f w}{f_{fs}} \right) \tag{AASHTO 2.6.7-1}
\]

- \( E_f \) = tensile modulus of elasticity of GFRP reinforcement (ksi)
- \( f_{fs} \) = calculated tensile stress in GFRP reinforcement at the service limit state (ksi)
- \( c_c \) = clear cover, not greater than 2 in. plus half the bar diameter (in.)
Control of Crack Width

For calculated stress level and crack width limit, $d_c$ (concrete cover) shall satisfy:

$$d_c \leq \frac{C_b E_f w}{2 f_{fs} \xi}$$

(AASHTO 2.6.7-2)

$d_c =$ thickness of concrete cover measured from extreme tension fiber to center of flexural GFRP reinforcement located closest thereto (in.)

$E_f =$ tensile modulus of elasticity of GFRP reinforcement (ksi)

$f_{fs} =$ calculated tensile stress in GFRP reinforcement at the service limit state (ksi)

$C_b =$ reduction factor that accounts for the degree of bond between GFRP reinforcing bars and surrounding concrete

$w =$ maximum crack width in a concrete component (in.)

$\xi =$ ratio of distance from neutral axis to extreme tension fiber, $(h - kd)$, to distance from neutral axis to center of tensile reinforcement, $(d - kd)$. 
Shrinkage & Temperature Reinforcement

Area of shrinkage and temperature reinforcement may be divided between each face and shall be:

\[ \rho_{f,st} = \max \left( \frac{3.132}{E_ff_{fd}}; 0.0014 \right) \leq 0.0036 \]

AASHTO GFRP (2.9.6-1)

Spacing:

- \( \leq 3t_{\text{slab}} \) or 12 in.
- Evenly distributed on both surfaces if member is greater than 6 in.

Adapted from FDOT Index 400-010
Shrinkage & Temperature Reinforcement

GFRP-RC retaining wall example:

Properties

Width of Wall Average: 13.4 in.
Height of Wall: 18 ft.
Bar Size of Temp. Reinf. #4
Elastic Modulus of GFRP, $E_f$ 6,500 ksi, 8,700 ksi
Design Tensile Strength, $f_{fd}$ 75.6 ksi, 105 ksi

Minimum Area of S/T Reinf.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$A_s$</td>
<td>0.29 in²/ft</td>
</tr>
<tr>
<td>$A_{f,6500}$</td>
<td>0.58 in²/ft</td>
</tr>
<tr>
<td>$A_{f,8700}$</td>
<td>0.55 in²/ft</td>
</tr>
</tbody>
</table>
Deflections

- AASHTO does not allow deflection control by \textbf{indirect method} (e.g., specifying minimum thickness of a member)

- \textbf{Direct method} of limiting computed deflections:
  
  - Simplified: Effective moment of inertia, $I_e$
  
  - Direct integration of moment curvature relationship

\[ \phi = \frac{\delta^2 y}{\delta x^2} = \frac{M}{EI} \]

\[ y = \int \int \frac{M}{EI} \, dx = \frac{kw l^3}{EI} \]
Deflections: Effective Inertia

Short-Term Loading

The overall (equivalent) flexural stiffness, $E_c I_e$, of a member that has experienced cracking at service varies between $E_c I_g$ an $E_c I_{cr}$

$$I_e = \frac{I_{cr}}{1 - \gamma_d \left( \frac{M_{cr}}{M_a} \right)^2 \left[ 1 - \frac{I_{cr}}{I_g} \right]} \leq I_g$$  \hspace{1cm} \text{AASHTO (2.6.3.2-1)}

$$M_{cr} = f_r \frac{I_g}{\gamma_t}$$  \hspace{1cm} \text{AASHTO (2.6.3.4.2-2 \\
& 2.6.3.4.2-3)}

$$\gamma_d = 1.72 - 0.72 \frac{M_{cr}}{M_a}$$

$M_a$ = maximum moment in a member at the stage deflection is computed, \textit{kip-in}
Long-Term Deflection

The long-term deflection can be calculated from:

\[ \Delta_{(cp+sh)} = \xi (\Delta_i)_{sus} \]

\((\Delta_i)_{sus}\) = short term deflection due to sustained load \((DL + 0.2LL)\)

\(\xi\) = time dependent factor for sustained load, \(2n_f\)

Unless a more exact determination is made, long-term deflection may be:

- If instantaneous deflection is based on \(I_g\): 4.0 \((\Delta_i)_{sus}\)  
- If instantaneous deflection is based on \(I_e\): 3.0 \((\Delta_i)_{sus}\)  

AASHTO GFRP (2.6.3.4.2)
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FRP reinforcing bars subjected to sustained load can suddenly fail after a time period called endurance time. This phenomenon is known as creep rupture (or static fatigue).
# Creep Rupture Reduction Factor

<table>
<thead>
<tr>
<th>AASHTO GFRP-1</th>
<th>AASHTO GFRP-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>2018</td>
</tr>
<tr>
<td>Design of bridges</td>
<td>Design of bridges</td>
</tr>
<tr>
<td>$C_C = 0.20$</td>
<td>$C_C = 0.30$</td>
</tr>
</tbody>
</table>

\[
f_{f,s} = C_E C_C f_{f_u}^*
\]

Creep rupture may govern the design of bridge

Deck of the Halls River Bridge in Homosassa (FL)
State-of-the-art in Creep Rupture

Research shows how current limits are conservative and may be raised as technology advances.

Sustained Load

Sustained load versus logarithmic time-to-failure

→ +50%
From 0.20 to 0.46 using guaranteed unconditioned line
Creep Rupture Provision

Maximum sustained tensile stress in GFRP reinforcement, $f_{fs}$, calculated using **dead loads and live loads** included in **Service I** load combination with live load reduced from 1.0 to 0.2

$$f_{fs} \leq C_c f_{fd}$$

maximum sustained tensile stress in GFRP reinforcement, ksi

where

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

(AASHTO 2.5.3-2)

Creep rupture reduction factor, $C_c$, **shall be equal to 0.3** unless manufacturer can provide a research report following ASTM D7337
Creep Rupture Stress

Based on elastic analysis and the sustained moment, $M_{s,s}$,

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

Where:

- $f_{f,s}$ = stress level induced in the FRP by sustained loads, psi
- $M_{s,s}$ = the moment due to all sustained loads
- $n_f = \frac{E_f}{E_c}$ modular ratio
- $k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2 - \rho_f n_f}$
- $I_{cr} = \frac{bd^3}{3} k^3 + n_f A_f d^2 (1 - k)^2$

(AASHTO 2.5.3-1)
Cyclic Fatigue

The maximum tensile stress in the GFRP reinforcement, $f_{f,f}$, shall satisfy:

$$f_{f,f} \leq C_f C_E f_{f u}^* = C_f f_{fd}$$

where:

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

(AASHTO 2.5.4)

$C_f$ = fatigue rupture reduction factor (set at 0.25 pending future research)

$f_{fd}$ = design tensile strength of GFRP reinforcing bars (Eq. 2.4.2.1-1) (ksi)

$n_f$ = modular ratio ($E_f/E_c$)

$d$ = distance from the extreme compression fiber to centroid of tensile bar (in.)

$k$ = ratio of depth of neutral axis to reinforcement depth

$I_{cr}$ = moment of inertia of transformed cracked section (in$^4$)

$M_{s,f}$ = moment due to dead loads + fatigue load
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Region with flexural cracks

\[ T = A_f f_{fu} \]

Can \( f_{fu} \) be developed in the available length?
GFRP development length is **typically longer compared to steel** and is a function of the tensile stress in the bar

\[
l_d \geq \max \left( \frac{\alpha \frac{f_{fr}}{\sqrt{f'_c}} - 340}{13.6 + \frac{C}{d_b}} d_b; 20d_b \right)\]

where

\( \alpha = 1.5 \) for top bars and \( 1.0 \) for bottom bars

\( f_{fr} \) = the required reinforcing stress

\( C \) = the lesser of the clear cover or \( \frac{1}{2} \) the center to center bar spacing

Note: the value of \( C/d_b \) is limited to a max of 3.5
Development Length of Bent Bars

“Standard hook” consists of the hook itself plus a straight length. Development length for a hooked bar \((l_{dh})\) is measured as shown:

The following expression is recommended:

\[
l_{dh} = \begin{cases} 
63.2 \frac{d_b}{\sqrt{f'_c}} & \text{for } f_{fd} \leq 75 \text{ ksi} \\
\frac{f_{fa} d_b}{1.2 \sqrt{f'_c}} & \text{for } 75 \text{ ksi} < f_{fa} \leq 150 \text{ ksi} \\
126.4 \frac{d_b}{\sqrt{f'_c}} & \text{for } f_{fa} \geq 150 \text{ ksi}
\end{cases}
\]

AASHTO (2.9.7.4.3.1)

\(l_{dh} \geq 12d_b\)

\(l_{dh} \geq 9 \text{ in}\)
Splices

Types of splices currently possible with GFRP bars

- **Lap Splice**

- **Mechanical Splice (Coupler)**

Splicing GFRP bars by mechanical connections is **not permitted** unless the full tensile capacity of the GFRP bar is achieved as substantiated by tensile test data per ASTM D7205
Lap Splices: Two overlapping bars, possibly tied together; staggered to reduce congestion; must overlap by required lap length
Minimum splice length:

For GFRP splices: \[ l_{st} = \begin{cases} 1.3l_d \\ 12 \text{ in} \end{cases} \]

\( l_d \) calculated to provide 25% tensile force

AASHTO (2.9.7.6)
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Special Considerations

Multiple layers and/or differing types of bars

- Due to linear-elastic behavior of FRP, multiple layers cannot be lumped together.
- Stresses need to be computed at each individual layer.

Moment Redistribution

- Plastic hinges shall not be assumed.
- Moment redistribution should not be considered.

AASHTO (2.6.3.2.4)

AASHTO (1.3)
Compression Reinforcement

• FRP has a lower compression strength and stiffness than tensile equivalent properties. Difficult to measure, but higher than concrete

• Any FRP bar in compression should be ignored in design calculations and substituted with an equivalent area of concrete ($n_f = 1$ in compression)

AASHTO Article 1.3
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• Special Considerations

• Concluding Remarks
Concluding Remarks

• Flexural capacity of FRP-reinforced flexural member dependent on tension or compression failure

• FRP reinforcement is brittle, but provides failure warning in terms of member deflection

• Serviceability requirements may govern design. Allowable stresses under sustained or cyclic loading must be checked

• FRP can be placed in compression zones but not be considered in calculations

• Reduced bond properties affect development length and crack control
Questions?

Thank
FLEXURE RESPONSE OF GFRP REINFORCED CONCRETE

2.1 Review Questions: Fundamentals
Review Questions

2.1.1) The substitution of GFRP for steel on an equal area basis would typically result in: _________________________.

a. No difference
b. Larger deflections and wider crack widths
c. Wider crack widths
d. Larger deflections
Moment-Curvature Diagrams

<table>
<thead>
<tr>
<th></th>
<th>b (in.)</th>
<th>h (in.)</th>
<th>d (in.)</th>
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<td>18</td>
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<td>1.2</td>
</tr>
</tbody>
</table>

- (1) Steel-tension controlled
- (2) GFRP-concrete crushing
- (3) GFRP-FRP rupture

---

Curvature (rad/in)

Moment (kip-ft)

Moment $M_n$
Review Questions

2.1.1) The substitution of GFRP for steel on an equal area basis would typically result in: _________________________.

a. No difference

b. Larger deflections and wider crack widths

c. Wider crack widths

d. Larger deflections
2.1.2) When designing structures with FRP the preferred failure mode in flexure is: _________________.

a. FRP rupture

b. Concrete crushing

c. None – it is not safe to design with FRP

d. Debonding between reinforcement and concrete
Failure Modes

Compression-controlled: concrete crushing

\[ \beta_1 c = a \]
2.1.2) When designing structures with GFRP the preferred failure mode in flexure is: _______________________.

a. GFRP rupture

b. Concrete crushing

c. None – it is not safe to design with GFRP

d. Debonding between reinforcement and concrete
2.1.3) In GFRP-RC flexural design the safety factor is increased (Φ is reduced): _______________________.

a. To account for the design of over-reinforced members

b. To consider the long-term behavior

c. To consider the lack of ductility

d. Because a member governed by GFRP bar rupture will have a brittle failure
Strength Reduction Factors (AASHTO)

\[ \phi = \begin{cases} 
0.55 & \text{for } \varepsilon_t \leq \varepsilon_{fd} \\
1.55 - \frac{\varepsilon_t}{\varepsilon_{fd}} & \text{for } 0.80\varepsilon_{fd} < \varepsilon_t < \varepsilon_{fd} \\
0.75 & \text{for } \varepsilon_t \geq 0.80\varepsilon_{fd} 
\end{cases} \]

(AASHTO 2.5.5.2)
2.1.3) In GFRP-RC flexural design the safety factor is increased (Φ is reduced): ________________________.

a. To account for the design of over-reinforced members

b. To consider the long-term behavior

c. To consider the lack of ductility

d. Because a member governed by GFRP bar rupture will have a brittle failure
2.1.4) A member governed by GFRP bar rupture will have a brittle failure: ________________________________.

a. True

b. False
Failure Modes

FRP Rupture Failure in GFRP Reinforced Beam
Review Questions

2.1.4) A member governed by GFRP bar rupture will have a brittle failure: ________________________________.

a. True

b. False
Review Questions

2.1.5) For the flexural design of GFRP-RC members which of the following assumptions is false:

a. Plane sections remain plane after deformation

b. Tensile strength of concrete is not neglected

c. Stress-strain of FRP is linear until failure

d. FRP is completely bonded to concrete
Flexural Theory

Assumptions:
1. Plane sections remains plane after deformation
2. Ultimate concrete strain is 0.003
3. Tensile strength of concrete is neglected
4. FRP is perfectly bonded to concrete
5. Stress-strain of FRP is linear until failure

Ultimate Flexural Strength:

- $M_n = \text{nominal capacity}$
- $M_u = \text{factored capacity}$
- $\phi M_n \geq M_u$

For AASHTO example

\[ M_u = 1.25M_{DC} + 1.75M_{LL} \]

For ACI example

\[ M_u = 1.2M_D + 1.6M_L \]
2.1.5) For the flexural design of GFRP-RC members which of the following assumptions **is false**:

a. Plane sections remain plane after deformation

b. **Tensile strength of concrete is not neglected**

c. Stress-strain of FRP is linear until failure

d. FRP is completely bonded to concrete
Review Questions

2.1.6) Tension lap splice for GFRP bars is: ________________.

a. The same as the development length of the bar
b. 1.25 times the development length of the bar
c. 1.30 times the development length of the bar
d. 1.60 times the development length of the bar
Tension Lap Splices

AASHTO specification requires staggered splices to provide redundancy

Minimum splice length:

For GFRP splices:  \[ l_{st} = \begin{cases} 1.3l_d \\ 12 \text{ in} \end{cases} \]

\( l_d \) calculated to provide 25% tensile force

AASHTO (2.9.7.6)
2.1.6) Tension lap splice for GFRP bars is: ________________.

a. The same as the development length of the bar
b. 1.25 times the development length of the bar
c. **1.30 times the development length of the bar**
d. 1.60 times the development length of the bar
2.1.7) When designing with GFRP the load factors are:
______________________________.

a. Higher than the ones used when designing steel RC
b. Lower than the ones used when designing steel RC
c. The same as the ones used when designing steel RC
d. Not defined yet
Load factors are applicable with inclusion of new creep rupture limit state and load factors. 1.2DL + 0.2LL
2.1.7) When designing with FRP the load factors are:
______________________________.

a. Higher than the ones used when designing steel RC
b. Lower than the ones used when designing steel RC
c. The same as the ones used when designing steel RC
d. Not defined yet
Review Questions

2.1.8) The purpose of shrinkage/temperature reinforcement is: ____________________________.

a. Distribute load

b. Improve development capacity of GFRP

c. Control crack width

d. Reduce member thickness
Shrinkage & Temperature Reinforcement

GFRP reinforced retaining wall example:

**Properties**

- **Width of Wall Average:** 13.38 inches
- **Height of Wall:** 18 feet
- **Bar Size of Temp. Reinf.:** 4
- **Elastic Modulus of GFRP, \( E_f \):** 6500 ksi, 8700 ksi
- **Design Tensile Strength, \( f_{fd} \):** 75.6 ksi, 105 ksi

<table>
<thead>
<tr>
<th>Minimum Area of S/T Reinf.</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_s ) =</td>
<td>0.29 in(^2)/ft</td>
</tr>
<tr>
<td>( A_{f,6500 \text{ ksi}} ) =</td>
<td>0.58 in(^2)/ft</td>
</tr>
<tr>
<td>( A_{f,8700 \text{ ksi}} ) =</td>
<td>0.55 in(^2)/ft</td>
</tr>
</tbody>
</table>
Review Questions

2.1.8) The purpose of shrinkage reinforcement is: _____________________.

a. Distribute load

b. Improve development capacity of FRP

c. Control crack width

d. Reduce member thickness
FLEXURE RESPONSE OF GFRP REINFORCED CONCRETE

2.2 Design Example: Flat Slab
Flat Slab vs. Deck Type

**Flat Slab**

- Longitudinal Bars Provide Flexural Resistance

**Deck**

- Transverse Bars Provide Flexural Resistance
- Girders
Objectives

• Demonstrate the design of a FLAT SLAB bridge superstructure utilizing method prescribed by AASHTO

• Show calculations with emphasis on flexural design for positive moment
Analysis of Flexural Member with GFRP

Given \( A_f, d, b, f_{fd} \)

Determine \( \rho = \frac{A_f}{bd} \)

Calculate stress in GFRP reinforcement at nominal flexural resistance:

\[
f_f = \sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85 \beta_1 f'_c}{\rho_f} E_f \varepsilon_{cu} - 0.5 E_f \varepsilon_{cu}} \leq f_{fd}
\]

Check to see if GFRP has ruptured

FRP Rupture

\[
c = \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fd}} d
\]

\[
a = \beta_1 c_b
\]

\[
M_n = A_f f_{fd} \left( d - \frac{a}{2} \right)
\]

Concrete Crushing

\[
a = \frac{A_f f_f}{0.85 f'_c b}
\]

\[
M_n = A_f f_f \left( d - \frac{a}{2} \right)
\]
Analysis of Flexural Member with GFRP

Determine the Resistance Factor

- If $\varepsilon_f \leq 0.80\varepsilon_{fd}$, then $\phi = 0.75$. Yes
- If $0.80\varepsilon_{fd} \leq \varepsilon_f < \varepsilon_{fd}$, then
  - Yes: $\phi = 0.55$
  - No: Calculate $\phi M_n$

End
Context
GFRP Slab Design

Bridge Geometry

Dimension of Bridge in Front View

Overall bridge length = 105 ft

Bridge design span length = 35 ft

Ideal span range: up to 40 ft
GFRP Reinforcement Properties

Geometric Properties

\[ t_{slab} = 18 \text{ inches} \] thickness of slab

\[ b = 12 \text{ inches} \] design strip width

\[ \text{Cover} = 2 \text{ inches} \] cover for GFRP members

Effective Depth of Reinforcement

\[ d_{fl,slab} = 18in - 2in - \frac{1.27in}{2} = 15.9 \text{ inches} \]

Primary Reinforcement

\[ BarSize_{slab.pr} = 10 \]

\[ BarSpace_{slab.pr} = 4 \text{ inches} \]

Secondary Reinforcement

\[ BarSize_{slab.sec} = 6 \]

\[ BarSpace_{slab.sec} = 8 \text{ inches} \]
Dead & Live Load Analysis

Maximum positive moment and corresponding fatigue values

- **Strength I**
  - $M_{str1.pos} = 100.9 \text{ kip} - \text{ft}$

- **Service I**
  - $M_{ser1.pos} = 64.6 \text{ kip} - \text{ft}$

- **Live Load Only**
  - $M_{liveLoad.pos} = 39.6 \text{ kip} - \text{ft}$

Maximum negative moment and corresponding fatigue values

- **Strength I**
  - $M_{str1.neg} = 93.2 \text{ kip} - \text{ft}$

- **Service I**
  - $M_{ser1.neg} = 61.9 \text{ kip} - \text{ft}$

- **Live Load Only**
  - $M_{liveLoad.neg} = 39.6 \text{ kip} - \text{ft}$
Check Primary Reinforcement

Positive Moment Region – Flexural Strength at Support

\[ f'_c = 4,500 \, \text{psi} \]

\[ \alpha_1 = \max(0.75, 0.85 - 0.02(f'_c - 10)) = 0.90 \]

\[ \beta_1 = 0.85 - 0.05(4.5 \text{ksi} - 4 \text{ksi}) = 0.83 \]

Area of primary reinforcement per linear foot

\[ A_{f_{l\text{-}slab}} = (1.27 \text{in}^2) \left( \frac{12 \text{in}}{4 \text{in}} \right) = 3.8 \text{ in}^2 \]

Reinforcement Ratio

\[ \rho_f = \frac{A_f}{b \cdot d} = \frac{3.8 \text{in}^2}{(1\text{ft})(15.9\text{in})} = 0.02001 \]
Check Primary Reinforcement

Effective strength in GFRP reinforcements at strength limit state

\[ f_f = \min(f_f, f_{fd}) = \min(46.6 \text{ksi}, 54.1 \text{ksi}) = 52.3 \text{ksi} \]

\[ f_f < f_{fd} \quad \text{compression controlled} \]
Calculate Resistance Factor

**GFRP strain check**

\[\varepsilon_{ft} = \frac{f_f}{E_f} = \frac{52.3 ksi}{6500 ksi} = 0.00716\]

\[\varepsilon_{fd} = \frac{f_{fd}}{E_f} = \frac{54.1 ksi}{6500 ksi} = 0.00833\]

**Calculate Resistance Factor for Flexural Strength (GFRP)**

\[\phi = \begin{cases} 
0.75 & \text{if } \varepsilon_{ft} \leq 0.80\varepsilon_{fd} \\
1.55 - \frac{\varepsilon_{ft}}{\varepsilon_{fd}} & \text{if } 0.80\varepsilon_{fd} < \varepsilon_{ft} < \varepsilon_{fd} \\
0.55 & \text{otherwise}
\end{cases}\]

\[\phi = 0.69\]
Check Primary Reinforcement

\[ a = \frac{A_ff}{0.85f'_c b} = \frac{(3.8in^2)(52.3ksi)}{0.85(4500psi)(12in)} = 3.9in \]

**Calculate corresponding moment**

\[ M_n = A_ffd \left( d - \frac{a}{2} \right) \]

\[ M_n = (3.8in^2)(46.6ksi) \left( 15.9in - \frac{3.9in}{2} \right) = 205.9k - ft \]

\[ M_r = \phi M_n = (0.69)(224.3k - ft) = 142.1k - ft \]

**Demand/Capacity:**

\[ \frac{M_{str1.pos}}{M_{r,2,slab}} = 0.71 \]
2.3 Design Example Creep Rupture (Flat Slab)
Creep Rupture Limit State

\[ M_{1, \text{creep.slab}} = 50.7k - ft \quad \text{Sustained loads only} \]

\[ E_c = 120,000 \Phi \text{limerock} w_c^{2.03} \sqrt{f'_c \cdot ksi^2} = 4165ksi \]

\[ n = \frac{E_f}{E_c} = \frac{6500ksi}{4165ksi} = 1.6 \]

\[ k = \sqrt{2pn - (pn)^2 - pn} = \sqrt{2(0.02) - (0.02 \cdot 1.6)^2 - (0.02)(1.6)} = 0.2 \]

\[ I_{cr} = \frac{bd^3}{3} k^3 + nAst(d - kd)^2 = \]

\[ = \frac{(12in)(15.9in)^3}{3} (0.2)^3 + (1.6)(3.8in^2)(15.9in - 0.2 \cdot 15.9in^2)^2 = 1108in^4 \]

\[ f_{f1, \text{creep}} = \frac{n \cdot d_{f1, \text{slab}}(1 - k_{1, \text{slab}})}{I_{cr}} \cdot M_{1, \text{creep.slab}} = 11.3ksi \]

\[ C_c C_{Ef_{fu}} = C_c f_{fd} = (0.3)(54.1ksi) \quad C_c f_{fd} = 16.2ksi \]
2.4 Design Example
Minimum Reinforcement (Flat Slab)
Minimum Reinforcement

\[ f_r = 0.24 \sqrt{f'_{c,super} \cdot (ksi)} = 0.51 ksi \]

\[ S_r = \frac{t_{slab}^3}{6} b = 648 in^3 \]

\[ M_{cr,slab} = 1.6f_r S_r = 44.0 k - ft \]

\[ M_{min,slab} = \min(1.33M_{str1.pos}, M_{cr,slab}) = 44.0 k - ft \]

\[ M_{r,slab} = \min(M_{r,pos}, M_{r,neg}) = 142.1 k - ft \]

\[ \text{CheckMinReinf}_{slab} = \text{if} (M_{r,slab} \geq M_{min,slab}, "OK","No Good") \]

\[ \text{CheckMinReinf}_{slab} = "OK" \]
AASHTO GFRP-Reinforced Concrete Design Training Course
Course Outline

1. Introduction & Materials

2. Flexure Response

3. Shear Response

4. Axial Response

5. Case Studies & Field Operations
3. SHEAR RESPONSE OF GFRP REINFORCED CONCRETE
Table of Contents

• General Behavior
• Shear Capacity
• Punching Shear
• Special Considerations
• Concluding Remarks
Uncracked Section

In **uncracked sections**, shear is carried by the concrete itself.

Typically, shear crack starts from a flexural crack once the cracking moment exceeds the cracking strength of concrete (tensile rupture).
In cracked sections, shear is carried by complex transfer mechanisms.

\[ \approx d \cot \theta \]

\[ V_{cc} : \text{Compression Zone Contribution} \]
\[ V_{d} : \text{Dowel Action} \]
\[ V_{ca} : \text{Aggregate Interlock} \]
\[ V_{cr} : \text{Residual Tensile Strength of Concrete} \]
\[ V_f : \text{GFRP Stirrup Contribution} \]

Components of Shear Resistance in Structural Concrete Beams
Shear failure modes of members with FRP stirrups

- **Shear-tension failure mode**
  (controlled by the rupture of FRP shear reinforcement)

- **Shear-compression failure mode**
  (controlled by the crushing of the concrete web)
RC with FRP Shear Reinforcement

- Low modulus of elasticity
- High tensile strength and no yield point
- Tensile strength of the bent portion lower than the straight portion
- Low transverse shear resistance (i.e., low dowel action of flexural bars)
- Larger crack widths compared to steel (i.e., lower N.A. depth)

Substitution of FRP for steel on an equal area basis would typically result in **lower shear strength** in both shear reinforced and non-shear reinforced members.
Table of Contents

• General Behavior

• **Shear Capacity**

• Punching Shear

• Special Considerations

• Concluding Remarks
Shear Capacity

Ultimate Limit State

\[ V_u \leq \phi V_n \quad \phi = 0.75 \]

Nominal Shear Resistance

\[ V_n = V_c + V_f \]

Shear Resistance of Concrete

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

(AASHTO 2.7.3.4-1)

Shear Resistance of GFRP Stirrups

\[ V_f = \frac{A_{fv} f_{fv} d_v \cot(\theta)}{s} \]

(AASHTO 2.7.3.5-1)

\[ \beta \] and \[ \theta \] are function of the level of strain in the reinforcement (MCFT*), but align to ACI values if the simplified method is used.

*Modified Compression Field Theory
Factor $\beta$ and $\theta$

$\beta$: Factor indicating ability of diagonally cracked concrete to transmit tension and shear

$\theta$: Angle of inclination of diagonal compressive stresses

- **Simplified Method**
  \[ \beta = 5k \quad \theta = 45^\circ \]  
  \[ k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2 - \rho_f n_f} \]
  
  $k$: ratio of depth of neutral axis to depth of flexural reinforcement  
  (AASHTO 2.5.3-4)

- **General Method**
  \[ \theta = 29 + 3500\varepsilon_f \]  
  \[ \beta = \frac{4.8}{1 + 750\varepsilon_f} \]  
  \[ \beta = \left(\frac{4.8}{1 + 750\varepsilon_f}\right)\left(\frac{51}{39 + s_{xe}}\right) \]

- Sections with minimum transverse reinforcement  
  (AASHTO 2.7.3.6.2-1)

- Sections without minimum transverse reinforcement  
  (AASHTO 2.7.3.6.2-2)

$\varepsilon_f$: longitudinal tensile strain of the GFRP

$s_{xe}$: crack spacing as influenced by aggregate size  
(AASHTO 2.7.3.6.2-7)
Transverse Reinforcement

Types of Transverse Reinforcement

• Stirrups or ties
• Spirals or hoops

Shear resistance of FRP reinforcement when using spirals

\[ V_f = \frac{A_{f_v} f_{f_v} d_v (\cot \theta + \cot \alpha) \sin \alpha}{s} \]  

(AASHTO 2.7.3.5)

S: Pitch of spiral
α: Angle of inclination of transverse reinforcement to longitudinal axis
θ: Angle between a strut and the longitudinal axis of a member
Design Tensile Strength

Design Tensile Strength for Shear $f_{f, sd}$

$$f_{f, sd} = \min(f_{fv}, f_{fb}, f_{fa}) \quad \text{(AASHTO 2.7.3.5)}$$

Tensile Strength of GFRP for Shear Design

$$f_{fv} = 0.004E_f \leq f_{fb} \quad \leftarrow \text{Typically governs for GFRP}$$

Tensile Strength of GFRP at Bends

$$f_{fb} = \left(0.05 \frac{r_b}{d_b} + 0.3\right) f_{fu} \leq f_{fu}$$

Tensile Strength of GFRP

$$f_{fa} = C_E f_{fu} \quad \leftarrow \text{FDOT 932-3 requires this to } \geq 60\% \text{ of straight bars for qualification}$$

$r_b =$ internal radius of bend of reinforcing bar
$d_b =$ diameter of reinforcing bar
Transverse Reinforcement

- For any member required when: \( V_u > \frac{\phi V_c}{2} \)
- Except for the slabs and footings: \( V_u > \phi V_c \)

Minimum GFRP Transverse Reinforcement

\[ A_{f_v,min} \geq 0.05 \frac{b_v s}{f_{f_v}} \]  \hspace{1cm} \text{(AASHTO 2.7.2.4-1)}

Maximum GFRP Transverse Reinforcement

\[ V_f \leq 0.25 \sqrt{f' c b_v d_v} \]  \hspace{1cm} \text{(AASHTO 2.7.2.5)}

Maximum Spacing of Transverse Reinforcement

\[ S \leq \text{Min} \{0.5d, 24 \text{ in.}\} \]  \hspace{1cm} \text{(AASHTO 2.7.2.6)}
FRP Stirrups

- GFRP stirrups should be provided with 90-degree hooks

- Required tail length for GFRP stirrups: \( L_{thf} \geq 12d_b \) (AASHTO C2.10.2.3.2)

- Maximum tensile strain in FRP shear reinforcement: 0.004 (AASHTO 2.7.3.5-2)

- A minimum \( \frac{r_b}{d_b} = 3 \) is recommended

\[
\frac{r_b}{d_b} = \text{bend radius} \\
\frac{d_b}{d_b} = \text{bar diameter}
\]

<table>
<thead>
<tr>
<th>Bar Designation, mm [U.S. Standard]</th>
<th>Minimum Bend Diameter mm [in.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6 [2]</td>
<td>38 [1.50]</td>
</tr>
<tr>
<td>M13 [4]</td>
<td>76 [3.00]</td>
</tr>
<tr>
<td>M25 [8]</td>
<td>152 [6.00]</td>
</tr>
</tbody>
</table>

(ASM D7957)
Table of Contents

• General Behavior

• Shear Capacity

• Punching Shear

• Special Considerations

• Concluding Remarks
Punching Shear

Shear Resistance of the Concrete

Two-way shear \[ V_c = 0.316k \sqrt{f'_c} b_0 d_v \]  

(AASHTO 2.10.5.1.3)

k: ratio of depth of neutral axis to depth of flexural reinforcement

\( b_0 \): computed \( \frac{d}{2} \) away from the column face

For Members with Transverse Reinforcement

\[ V_f = \frac{A_{fv} f_{fv} d_v}{S} \]  

(AASHTO 2.10.5.1.3)
Table of Contents

- General Behavior
- Shear Capacity
- Punching Shear
- Special Considerations
- Concluding Remarks
Special Considerations

- **90-degree bends** instead of 135-degree bends

- Typically **two overlapping “C or U” stirrups** are used instead of a closed loop stirrup

![Diagram of stirrup design](image)
Special Considerations

• Field bending or straightening of GFRP bars **not possible**

• All stirrups are **pre-bent**
Table of Contents

• General Behavior
• Shear Capacity
• Punching Shear
• Special Considerations

• Concluding Remarks
Concluding Remarks

• Shear equations and structural theory remain mostly the same as for conventional steel-RC

• The contribution of both concrete and stirrups to shear capacity is reduced in FRP-RC

• Closer stirrup spacing because of lower strength and stiffness

• Strength of FRP stirrups is reduced at bends

• A limit on FRP stirrup strain is imposed because of crack width concerns

• Complex bent shapes are currently not available, but technology is advancing
Questions?

Thank U
SHEAR RESPONSE OF GFRP REINFORCED CONCRETE

3.1 Review Questions: Fundamentals
3.1.1) For GFRP stirrups, does the maximum amount of transverse reinforcement requirement similar to steel-RC still apply: ____________________________.

a. True

b. False
Transverse Reinforcement

- Required when:
  \[ V_u > \frac{\phi V_c}{2} \]

- For the slabs and footings:
  \[ V_u > \phi V_c \]

Minimum GFRP Transverse Reinforcement

\[ A_{fv,\text{min}} \geq 0.05 \frac{b_v s}{f_{fv}} \]

Maximum GFRP Transverse Reinforcement

\[ V_f \leq 0.25 \sqrt{f'_c b_v d_v} \]  
(AASHTO 2.7.2.5)

Maximum Spacing of Transverse Reinforcement

\[ S \leq \text{Min} \{0.5d, 24\text{in.}\} \]  
(AASHTO 2.7.2.6)
3.1.1) For GFRP stirrups, does the maximum amount of transverse reinforcement requirement similar to steel-RC still apply: ________________________________.

a. True

b. False
3.1.2) The shear strength of GFRP-RC members:
____________________.

a. Is comparable to the shear strength of steel-RC members
b. Is lower than the shear strength of steel-RC members
c. Is higher than to the shear strength of steel-RC members
d. Cannot be compared to the shear strength of steel-RC members
Shear Capacity

Ultimate Limit State

\[ V_u \leq \phi V_n \quad \phi = 0.75 \]

Nominal Shear Resistance

\[ V_n = V_c + V_f \]

Shear Resistance of Concrete

\[ V_c = 0.0316\beta \sqrt{f'_c} b_v d_v \]  \hspace{1cm} (AASHTO 2.7.3.4)

Shear Resistance of GFRP Stirrups

\[ V_f = \frac{A_{fv} f_{fv} d_v \cot(\theta)}{s} \]  \hspace{1cm} (AASHTO 2.7.3.5)

\[ \beta \text{ and } \theta \text{ are a function of the level of strain in the reinforcement (MCFT) but aligns to ACI values if the simplified method is used} \]
Review Questions

3.1.2) The shear strength of GFRP-RC members:
________________________.

a. Is comparable to the shear strength of steel-RC members

b. Is lower than the shear strength of steel-RC members

c. Is higher than to the shear strength of steel-RC members

d. Cannot be compared to the shear strength of steel-RC members
3.1.3) The required tail length of GFRP stirrups is at least equal to or more than: ________________________.

a. 4 times the bar diameter
b. 8 times the bar diameter
c. 12 times the bar diameter
d. 16 times the bar diameter
FRP Stirrups

• GFRP stirrups should be provided with 90-degree hooks

• Required tail length for GFRP stirrups: \( L_{thf} \geq 12d_b \) (AASHTO C2.10.2.3.2)

• Maximum tensile strain in FRP shear reinforcement: 0.004 (AASHTO 2.7.3.5-2)

• A minimum \( \frac{r_b}{d_b} = 3 \) is recommended
  
  \[ r_b = \text{bend radius} \]
  
  \[ d_b = \text{bar diameter} \]

\[ \ell_{thf} \geq 12d_b \]

<table>
<thead>
<tr>
<th>TABLE 4 Minimum Inside Bend Diameter of Bent Bars(^A)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bar Designation, mm [U.S. Standard]</strong></td>
</tr>
<tr>
<td>M6 [2]</td>
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<td>M25 [8]</td>
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</tbody>
</table>

\(^A\) (ASTM D7957)
3.1.3) The required tail length of GFRP stirrups is at least equal to or more than: ____________________________.

a. 4 times the bar diameter

b. 8 times the bar diameter

c. 12 times the bar diameter

d. 16 times the bar diameter
3.1.4) GFRP stirrups can be bent on site with EOR approval?

a. True

b. False
Special Considerations

- Field bending or straightening of GFRP bars **not possible**
- All stirrups are **pre-bent**
Review Questions

3.1.4) GFRP stirrups can be bent on site with EOR approval?

a. True

b. False
3.1.5) The minimum bent radius allowed for a GFRP stirrup is generally __________. (Select all that apply)

a. Larger than required for steel, with a minimum of $r_b/d_b = 3$

b. Can be equivalent to steel, if verified by manufacturer

c. Smaller than required for steel reinforcement due to lower elastic modulus

d. Dependent on field bending and cannot be prescribed
FRP Stirrups

- GFRP stirrups should be provided with 90-degree hooks.

- Required tail length for GFRP stirrups: \( L_{thf} \geq 12d_b \) (AASHTO C2.10.2.3.2)

- Maximum tensile strain in FRP shear reinforcement: 0.004 (ACI 440.1R8.3)

- A minimum \( \frac{r_b}{d_b} = 3 \) is recommended.

\[ r_b = \text{bend radius} \]
\[ d_b = \text{bar diameter} \]

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

<table>
<thead>
<tr>
<th>Bar Designation, mm [U.S. Standard]</th>
<th>Minimum Bend Diameter mm [in.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6 [2]</td>
<td>38 [1.50]</td>
</tr>
<tr>
<td>M13 [4]</td>
<td>76 [3.00]</td>
</tr>
<tr>
<td>M25 [8]</td>
<td>152 [6.00]</td>
</tr>
</tbody>
</table>

(ASTM D7957)
Review Questions

3.1.5) The minimum bent radius allowed for a GFRP stirrup is generally __________. (Select all that apply)

a. Larger than required for steel, with a min. of \( r_b/d_b = 3 \)

b. Can be equivalent to steel, if verified by manufacturer

c. Smaller than required for steel reinforcement due to lower elastic modulus

d. Dependent on field bending and cannot be prescribed
Review Questions

3.1.6) When designing GFRP shear reinforcement, the following shapes are possible to manufacturer: __________. (Select all that apply)

a. Two C’s
b. Two U’s
c. Closed stirrup, providing the tails overlap
d. L shapes for end hooks
e. Special bends for complex shapes
Special Considerations

- **90-degree bends** instead of 135-degree

- Typically **two overlapping “C or U” stirrups** are used instead of a closed loop stirrup.
3.1.6. When designing GFRP shear reinforcement, the following shapes are possible to manufacturer: ___________. (Select all that apply)

a. Two C’s
b. Two U’s
c. Closed stirrup, providing the tails overlap
d. L shapes for end hooks
e. Special bends for complex shapes
3.1.7) The maximum spacing of transverse GFRP reinforcement is generally ___________.

a. 12 in.

b. 24 in.

c. 0.5d

d. Minimum value of 0.5d* or 24in.

* Flexural reinforcement depth
Transverse Reinforcement

- Required when:
  \[ V_u > \frac{\phi V_c}{2} \]
- For the slabs and footings:
  \[ V_u > \phi V_c \]

Minimum GFRP Transverse Reinforcement

\[ A_{f_v,\text{min}} \geq 0.05 \frac{b_v S}{f_{f_v}} \]

Maximum GFRP Transverse Reinforcement

\[ V_f \leq 0.25\sqrt{f'_c b_v d_v} \]  \( \text{(AASHTO 2.7.2.5)} \)

Maximum Spacing of Transverse Reinforcement

\[ S \leq \text{Min} \{0.5d, 24\text{in.}\} \]  \( \text{(AASHTO 2.7.2.6)} \)
Review Questions

3.1.7) The maximum spacing of GFRP transverse reinforcement is generally __________.

a. 12 in.
b. 24 in.
c. 0.5 d

d. Minimum value of 0.5d* or 24in.

*Flexural reinforcement depth
SHEAR RESPONSE OF GFRP REINFORCED CONCRETE

3.2 Design Example: Bent Cap (Halls River Bridge)
Shear Design Flowchart

Shear Design

\[ V_u \leq V_r = \phi V_n = 0.75(V_c + V_f) \]

Find nominal shear resistance of the concrete \((V_c)\)

\[ V_c = 0.0316 \beta \sqrt{f'_c} b_v d_v \]

Find shear strength of transverse reinforcement \((f_{f, sd})\)

\[ f_{f, sd} = \min(f_{fv}, f_{fb}, f_{fd}) \]
Find design tensile strength of GFRP ($f_{fd}$)

$$f_{fd} = C_E \cdot f_{fu}$$

Find design tensile strength of bent ($f_{fb}$)

$$f_{fb} = \min\left(0.05 \frac{r_b}{d_b} + 0.3, 1\right) f_{fd}$$

Find tensile strength of GFRP for shear design ($f_{fv}$)

$$f_{fv} = \min(0.004E_f, f_{fb})$$
Shear Design Flowchart

Select $A_{fv} \geq A_{fv,\text{min}}$

$$A_{fv,\text{min}} \geq 0.05 \frac{b_{v}s}{f_{fv}}$$

Find shear resistance of GFRP ($V_f$)

$$V_f = \frac{A_{fv} f_{fv} d_v \cot(\theta)}{s}$$

Find nominal shear strength

$$V_n = V_c + V_f$$
Shear Design Flowchart

Check shear design

\[ V_u \leq V_r = \phi \ V_n = 0.75(\ V_c + \ V_f) \]

Check spacing of GFRP stirrups

\[ S = Min\{0.5d, 24\text{in.}\} \]

Finish
Bent Cap- Halls River Bridge

Part 1: Load Generator

Part 2: Frame Analysis

Part 3: Design & AASHTO Checks
Bent Cap- Halls River Bridge

Part 1: Load Generator

Input Data

Number of columns 6
Column spacing 10.38 ft.
Column width 18 in.

Number of beams 9
Beam spacing 6.63 ft.
Beam width 24 in.
Beam height 21 in.
Beam self weight 181 plf.
Bent Cap- Halls River Bridge

Part 1: Load Generator

Input Data

Cap height 36 in.
Cap width 48 in.
Cap length 59.9 ft.

Dead load of wearing surfaces and utilities 165 lb./ft.
Additional dead load of structural and nonstructural attachments 20 lb./ft.
Part 1: Load Generator

Bridge cross section with live load locations generated by MathCad program

Beam Live Loads

\[ P_{LL, beam}^T = (0.0 \ 0.0 \ 0.0 \ 59.5 \ 59.9 \ 0.0 \ 0.0 \ 0.0 \ 0.0) \text{-kip} \]
Part 1: Load Generator

Summary of factored loads on cap generated by Mathcad

Mathcad worksheet computes all loads on the bent cap from the beam reactions. Live loads are generated for each beam using the lever rule and tributary area methods.

Factored total load parallel to cap (x)

\[
P_{cap.x} = \begin{pmatrix} 0 \\ 11.37 \\ 8.02 \\ 7.01 \\ 0 \\ 0 \\ 0 \\ 11.37 \\ 8.02 \\ 0 \end{pmatrix} \cdot \text{kip}
\]

Factored total load perpendicular to cap (z)

\[
P_{cap.z} = \begin{pmatrix} 80.32 \\ 8.07 \\ 66.43 \\ 49.65 \\ 36.72 \\ 0 \\ 80.32 \\ 8.07 \\ 66.43 \\ 0 \end{pmatrix} \cdot \text{kip}
\]

Load cases per LRFD

- "Strength I max vertical"
- "Strength III max vertical"
- "Strength V max vertical"
  - "Service I"
  - "Service III"
- "Sustained load: DL+0.2LL"
- "Strength I min vertical"
- "Strength III min vertical"
- "Strength V min vertical"
- "DL+Fatigue I"
Part 2: Frame Analysis

Connection of columns to bent cap (Fixed or Pinned)

Beam load

Fixed
Distributed
Part 2: Frame Analysis

Shear and Moment Diagrams for Limit State Strength I (max vertical load)

Strength I Shear Envelope (at Face of Support)

Strength I Moment Envelope (at Face of Support)
Part 3: GFRP Design & AASHTO Checks

Environmental reduction factor ($C_E$) 0.7
Tensile modulus of elasticity ($E_t$) 6,500 ksi

**Shear Reinforcement**

**Zone V1**
- Size of stirrup bar 4
- No. of bar legs 4
- Spacing 4 in.
- Length of Zone V1 ($L_{v1}$) 36 in.

**Zone V2**
- Size of stirrup bar 4
- No. of bar legs 4
- Spacing 8 in.
- Length of Zone V2 ($L_{v2}$) 36 in.
Part 3: GFRP Design & AASHTO Checks

Zone V3
Size of stirrup bar 4
No. of bar legs 4
Spacing 12 in.

Zone V4 (Cap overhang)
Size of stirrup bar 4
No. of bar legs 4
Spacing 12 in.
Length of Zone V4 ($L_{v4}$) 36 in.

Zone V5 (Cap overhang)
Size of stirrup bar 4
No. of bar legs 4
Spacing 12 in.
Shear Design Example

Nominal Shear Resistance of the Concrete

\[ V_c = 0.0316\beta \sqrt{f'_c} b_v d_v = 64.75 \text{ kip} \]

Simplified method for concrete sections not subjected to axial tension

\[ \beta = 5k \quad (AASHTO \ 2.7.3.6.1) \]

Shear Resistance of GFRP Reinforcement

\[ V_f = \frac{A_{fv} f_{fv} d_v \cot(\theta)}{s} = 137 \text{ kip} \]

The Maximum Demand to Capacity Ratio

\[ V_u = 162 \text{ kip} \]
\[ V_r = 0.75 \times (64.75 + 137) = 151 \text{ kip} \]
\[ \max \frac{V_u}{V_r} = 1.07 \]
Shear Design Example

Problem areas

Maximum demand to capacity ratio = 1.07
AASHTO GFRP-Reinforced Concrete Design Training Course
AASHTO GFRP-Reinforced Concrete Design Training Course
Course Outline

1. Introduction & Materials
2. Flexure Response
3. Shear Response
4. Axial Response
5. Case Studies & Field Operations
4. AXIAL RESPONSE OF GFRP REINFORCED CONCRETE
Table of Contents – Axial & More

• Strength of GFRP-RC Columns

• Design Considerations

• P-M Diagram Example

• Slenderness Effect

• Concluding Remarks
Design Codes

AASHTO GFRP 1\textsuperscript{st} Ed.
(No provisions included)

AASHTO GFRP 2\textsuperscript{nd} Ed.
(Provisions included)

Only US guide/code including compression members
Introduction – Pure Compression

Review of Steel-RC Columns

\[ P_o = P_c + P_s = 0.85 f'_c (A_g - A_s) + f_y A_s \]

Basic Concept for GFRP-RC Columns

\[ P_o = P_c + P_f = 0.85 f'_c (A_g - A_f) + f_f A_f \]

(AASHTO GFRP 2.6.4.2)

As reported in Afifi et al. (2014) and Mohamed et al., (2014), mechanical properties of GFRP in compression exceed those of concrete and therefore, equivalency could be assumed.

GFRP bar loaded in compression (Deitz, Harik, and Gesund, 2003)
Axial Loading Failure Modes

Column test at NIST  
12-in Tie Spacing  
3-in Tie Spacing

Behavior of Full-Scale Concrete Columns Internally Reinforced with Glass FRP Bars under Pure Axial Load (De Luca, et al., 2009)
Axial Loading Failure Modes

GFRP-RC Columns After Failure

Circular Concrete Columns with GFRP Longitudinal Bars, Hoops, or Spirals under Axial Loads (University of Sherbrooke; courtesy of Prof. Brahim Benmokrane)
Factored Pure Compressive Resistance - AASHTO

\[ P_r = \phi P_n \]

- For members with spiral or hoop reinforcements

\[ P_n = 0.85 \left[ 0.85 f'_c (A_g - A_f) \right] \]

- For members with tie reinforcement

\[ P_n = 0.80 \left[ 0.85 f'_c (A_g - A_f) \right] \]

\[ A_f = \text{area of GFRP reinforcement (in}^2\text{)} \]
\[ A_g = \text{gross area of section (in}^2\text{)} \]
\[ f'_c = \text{specified compressive (ksi)} \]
\[ P_n = \text{nominal axial resistance, without flexure (kips)} \]
\[ P_r = \text{factored axial resistance, without flexure (kips)} \]
Factored Pure Tensile Resistance - AASHTO

\[ P_r = \phi P_n \]  
(AASHTO GFRP 2.6.6.2-1)

in which:

\[ P_n = f_{fa} A_f \]  
(AASHTO GFRP 2.6.6.2-2)

\[ f_{fa} = C_E f_{fu} \]  
(AASHTO GFRP 2.4.2.1-1)

where:

- \( A_f \) = area of GFRP reinforcement (in²)
- \( f_{fa} \) = design tensile strength of GFRP reinforcing bars considering reductions for service environment (ksi)
- \( P_n \) = nominal axial resistance (kip)
Table of Contents

• Strength of GFRP-RC Columns

• Design Considerations

• P-M Diagram Example

• Slenderness Effect

• Concluding Remarks
**Minimum & Maximum Longitudinal Reinforcement**

Minimum and maximum area of the longitudinal GFRP reinforcing shall be:

\[
0.01 \leq A_f / A_g \leq 0.08
\]

AASHTO GFRP 4.5.6

Provision adopted for GFRP-RC are analogous to Steel-RC design provisions in AASHTO & ACI

**Limit on Maximum Tensile Strain in GFRP**

To avoid strains that lead to unacceptable deformation and loss of stiffness of the column (Jawaheri & Nanni, 2013):

\[
e_{fd} = \min(e_{fu}, 0.010) \quad \text{and} \quad f_{fd} = \min(f_{fu}, 0.010E_f)
\]
Limits on maximum spacing of Transverse Reinforcement: confinement, buckling of longitudinal reinforcement

Lower elastic modulus than steel

Theoretical:

\[ s_{\text{max}} \approx 14d_b \]

AASHTO GFRP 4.7.5.4 – Tied Members

\[ s_{\text{max}} = \min \left\{ \frac{\text{least dimension of column}}{d/4}, 12 \text{ inches} \right\} \]
Table of Contents

• Strength of GFRP-RC Columns

• Design Considerations

• P-M Diagram Example

• Slenderness Effect

• Concluding Remarks
Context

GFRP Cage Assembly, Casting and Installation of RC Piles
Combined P-M Failure Modes

Rectangular Concrete Column Failure with GFRP Bars and Ties (Guérin et al., 2018)
Schematic P-M diagram for two identical columns having the same amounts of GFRP and steel reinforcement. Include the following five points. Note location of **balance point for GFRP-RC**.
Developing P-M Interaction Diagram

Create a P-M interaction diagram for the following tied column section:

\[ f'_c = 5,000 \text{ psi} \]
\[ E_f = 6,500 \text{ ksi} \quad E_c = 4,291 \text{ ksi} \]
\[ f_{fd} = 59.2 \text{ ksi} \quad \varepsilon_{fd} = 0.00911 \]
12 - #8 GFRP bars evenly spaced

Include the following points:

- Pure compression
- Zero tension
- Pure flexure
- Balance point
- Pure tension

Equivalent FDOT standard index
non-prestressed

18”x18”, 12 GFRP bars
Developing P-M Interaction Diagram

Pure Compression

Strain in GFRP reinforcement cannot exceed the strain maximum strain in concrete (0.003). Contribution of GFRP in compression is difficult assess, show zero and non-zero contribution

\[ \varepsilon_f = 0.003 \]

\[ f = 0.85f'_c \]
Developing P-M Interaction Diagram

Pure Compression

Moment at this point: \[ M = 0 \text{ k} - \text{in} \]

Capacity in pure compression: \[ P = 0.85f'_c(A_g - A_f) + A_{f,tot}(\varepsilon_{cu}E_c) \]

\[ C_c = (0.85)(5\text{ksi})(324\text{in}^2 - 9.48\text{in}^2) = 1337 \text{ k} \] (AASHTO GFRP 2.6.4.2)
Discussion on contribution of GFRP in Compression

- Current AASHTO provisions do not account for GFRP compression contribution
- Force up to 0.003 compressive strain times a stiffness conservatively equal to that of concrete is appropriate
- For pure compression: $A_{f,\text{tot}}(\varepsilon_{cu}E_c)$
Developing P-M Interaction Diagram

Adding the compressive component of GFRP reinforcement ($\varepsilon_f = 0.003$)

\[
C_{f1} = 4(0.79in^2)(4291ksi)(0.003) \frac{(18" - 0")}{18"} = 40.7k
\]

\[
C_{f2} = 2(0.79in^2)(4291ksi)(0.003) \frac{(18" - 0")}{18"} = 20.3k
\]

\[
C_{f3} = 2(0.79in^2)(4291ksi)(0.003) \frac{(18" - 0")}{18"} = 20.3k
\]

\[
C_{f4} = 4(0.79in^2)(4291ksi)(0.003) \frac{(18" - 0")}{18"} = 40.7k
\]

Adding all forces:

\[
P = 1337k + 40.7k + 20.3k + 20.3k + 40.7k = 1459k
\]

9% increase over current AASHTO equation
Next point: Zero tension on the extreme GFRP bar layer

Developing P-M Interaction Diagram

(P, M)

Zero Tension

Pure Compression

GFRP reinforced

Pure Tension

Pure Flexure

Balance Point
Developing P-M Interaction Diagram

Zero Tension

Point where there is zero tension in the bottom reinforcement layer

\[ \varepsilon_{f4} = 0 \]

\( \varepsilon_{f3} \)

\( \varepsilon_{f2} \)

\( \varepsilon_{f1} \)

\( \varepsilon_{cu} = 0.003 \)

\( C_c = \alpha \beta f'_c c_b \)

\( d_1 \)

\( d_2 \)

\( d_3 \)

\( d_4 \)

b

C.L.

N.A.
Developing P-M Interaction Diagram

**Zero Tension**

\[ c = d \text{ } \text{ } \text{neutral axis} \]

Strain at bottom GFRP reinforcement layer is zero
GFRP bars in compression are treated as concrete

\[ T_{f4} = 0 \text{kip} \text{ } \text{zero tension} \]

Calculate the force in concrete

\[ C_c = (b \cdot a)\alpha_1 f'_c = (b \cdot \beta_1 c)\alpha_1 f'_c = (18in \cdot 0.80 \cdot 15in)(0.85)(5ksi) = 918kip \]

Calculate the axial force

\[ P = \sum F = C_c = 918k \]
Zero Tension (Continued)

Calculate distance of forces from center line and then solve using for moment

Concrete level:

\[ y_{Cc} = y_{N.A.} - \frac{\beta_1 c}{2} \]
\[ = 9\text{in} - \frac{(0.8)(15\text{in})}{2} = 3\text{in} \]

4th Level:

\[ y_{f4} = d_4 - y_{N.A.} = 15\text{in} - 9\text{in} = 6\text{in} \]

Taking moments

\[ M = y_{Cc} F_{Cc} + y_{f4} T_{f4} = 918k(3\text{in}) + 0k(6\text{in}) = 229k \text{ ft} \]
Next point: Pure flexure (P= zero)
Pure Flexure

Pure flexure occurs when axial load is zero and the failure mode is governed by concrete crushing (potentially also by GFRP failure depending on cross-section)

\[ C_c = \alpha \beta_1 f'_c cb \]

\[ T_f = A_f \varepsilon_f E_f \]
Developing P-M Interaction Diagram

Pure Flexure

\[ P = \sum F = C_c + T_{f2} + T_{f3} + T_{f4} = 0 \text{k} \]

Calculate forces in terms of \( c \), and then solve by imposing horizontal equilibrium

\[ T_{f2} = 2 \cdot (0.79in^2)(6500ksi)(0.003) \left( \frac{c - 7in}{c} \right) \]

\[ T_{f3} = 2 \cdot (0.79in^2)(6500ksi)(0.003) \left( \frac{c - 11in}{c} \right) \]

\[ T_{f4} = 4 \cdot (0.79in^2)(6500ksi)(0.003) \left( \frac{c - 15in}{c} \right) \]
Developing P-M Interaction Diagram

\[ C_c = 0.85(0.8)(5\text{ksi})(18\text{in})c = 61.2c \]

Solving for \( c \):

\[ T_{f2} = 30.8 \left( \frac{c - 7}{c} \right) \]

\[ T_{f3} = 30.8 \left( \frac{c - 11}{c} \right) \]

\[ T_{f4} = 61.6 \left( \frac{c - 15}{c} \right) \]

Substituting into equilibrium equation:

\[ 30.8 \left( \frac{c - 7}{c} \right) + 30.8 \left( \frac{c - 11}{c} \right) + 61.6 \left( \frac{c - 15}{c} \right) + 61.2c = 0 \]

\[ c = 4.01\text{in.} \]
Pure Flexure (Continued)

Calculate the Moment: Sum moments around center line

Concrete lever arms:

\[ y_{cc} = y_{N.A.} - \beta_1 c = 9\text{in} - \frac{(0.8)(4.01\text{in})}{2} = 7.4\text{in} \]

\[ y_{f2} = y_{N.A.} - d_2 = 9\text{in} - 7\text{in} = 2\text{in} \]

\[ y_{f3} = d_3 - y_{N.A.} = 11\text{in} - 9\text{in} = 2\text{in} \]

\[ y_{f4} = d_4 - y_{N.A.} = 15\text{in} - 9\text{in} = 6\text{in} \]

\[ M = y_{cc}C_c + y_{f2}T_{f2} + y_{f3}T_{f3} + y_{f4}T_{f4} = 231 \text{ k-ft} \]
Developing P-M Interaction Diagram

Next point: Balance failure, simultaneous GFRP rupture and concrete crushing. Design failure strain in GFRP about 5 times larger than yield strain for Grade 60 steel.
Balance Point: strain, stress and force distribution (equivalent stress block)

\[ C_c = \alpha_1 \beta_1 f_c' cb \]

\[ \epsilon_{cu} = 0.003 \]

\[ f'c \]

\[ f_{f2} \]

\[ f_{f3} \]

\[ f_{f4} \]

\[ \epsilon_{fd} = \frac{f_{fd}}{E_f} = 0.00911 \]

\[ T_f = A_f \epsilon_f E_f \]
Developing P-M Interaction Diagram

Balance Point

\[ d_1 = 3” \text{; } d_2 = 7” \text{; } d_3 = 11” \text{; } d_4 = 15” \]

Find the neutral axis:

\[
c = d \left( \frac{\varepsilon_{cu}}{\varepsilon_{fd} + \varepsilon_{cu}} \right) 
\]

\[
c = (15 \text{in}) \left( \frac{0.003}{0.00911 + 0.003} \right) = 3.72 \text{in}
\]
Developing P-M Interaction Diagram

Calculate GFRP strain and stresses:

Second layer GFRP strain
\[
\varepsilon_{f2} = \varepsilon_{cu} \left( \frac{c - d_2}{c} \right) = 0.003 \left( \frac{3.72\text{in} - 7\text{in}}{3.72\text{in}} \right) = -0.00265
\]
\[
f_{f2} = E_f \varepsilon_{f2} = (6500\text{ksi})(-0.00265) = -17.2\text{ ksi}
\]

Third layer GFRP strain
\[
\varepsilon_{f3} = \varepsilon_{cu} \left( \frac{c - d_3}{c} \right) = 0.003 \left( \frac{3.72\text{in} - 11\text{in}}{3.72\text{in}} \right) = -0.00588
\]
\[
f_{f3} = E_f \varepsilon_{f3} = (6500\text{ksi})(-0.00588) = -38.2\text{ ksi}
\]

Fourth layer GFRP strain
\[
\varepsilon_{f4} = \varepsilon_{cu} \left( \frac{c - d_4}{c} \right) = 0.003 \left( \frac{3.72\text{in} - 15\text{in}}{3.72\text{in}} \right) = -0.00911
\]
\[
f_{f4} = E_f \varepsilon_{f4} = (6500\text{ksi})(-0.00911) = -59.2\text{ ksi} = f_{fd}
\]
Developing P-M Interaction Diagram

Balance Point (Continued)

Calculate the Forces:

\[ C_c = (b \cdot a)\alpha_1\beta_1 f'_c \]

\[ C_c = (18\text{in} \cdot 0.85 \cdot 3.72\text{in})(0.8)(5\text{ksi}) = 277.5k \]

\[ P = \sum F = C_c + T_{f2} + T_{f3} + T_{f4} \]

Sum forces by multiplying GFRP stress by areas

\[ P = 277.5k - (17.2\text{ksi})(1.58\text{in}^2) - (38.2\text{ksi})(1.58\text{in}^2) - (59.2\text{ksi})(3.16\text{in}^2) \]

\[ P = -47.1k \]

Balance point occurs when axial load is tension
Developing P-M Interaction Diagram

**Calculate the Moment:** Sum moments around section centerline

*Concrete and GFRP bars lever arms:*

\[ y_{Cc} = y_{N.A.} - \frac{\beta_1 c}{2} = 9\text{in} - \frac{(0.8)(3.72\text{in})}{2} = 7.5\text{in} \]

\[ y_{f2} = y_{N.A.} - d_2 = 9\text{in} - 7\text{in} = 2\text{in} \]

\[ y_{f3} = d_3 - y_{N.A.} = 11\text{in} - 9\text{in} = 2\text{in} \]

\[ y_{f4} = d_4 - y_{N.A.} = 15\text{in} - 9\text{in} = 6\text{in} \]

**Summing Moments Around Center Line**

\[ M = C_c y_{Cc} - y_{f2} T_{f2} + y_{f2} T_{f3} + y_{f4} T_{f4} = 241 \text{ k-ft} \]
Next point: Pure axial tension. There is no concrete contribution
Zero Moment (Tension)

The first point is tension only, so the concrete is assumed to not contribute.

\[ \epsilon_f = \epsilon_{fd} \]
Developing P-M Interaction Diagram

Zero Moment (Tension)

Calculate force components assuming all GFRP bars rupture

\[ P = \sum F = F_{f1} + F_{f2} + F_{f3} + F_{f4} \]

\[ P = 12(0.79in^2)(59.2ksi) = 561.1kip \]

\[ M = 0kip - ft \]
AASHTO Resistance Factor for GFRP

The safety factor $\Phi$ needs to be calculated for each moment-axial load combination (as each P-M point has a different stress in tension reinforcement)
Developing P-M Interaction Diagram

Limiting the factored compressive load:  
\[ P_{n,\text{max}} = 0.80[0.85(5\text{ksi})(324in^2 - 9.48in^2)] \]

\[ P_{n,\text{max}} = 1070.6\text{kip} \]

<table>
<thead>
<tr>
<th>Point</th>
<th>( M_n )</th>
<th>( P_n )</th>
<th>( \phi )</th>
<th>( \phi M_n )</th>
<th>( \phi P_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Compression</td>
<td>0 k-ft</td>
<td>1070 k</td>
<td>0.75</td>
<td>0 k-ft</td>
<td>802 k</td>
</tr>
<tr>
<td>Zero Tension</td>
<td>229 k-ft</td>
<td>918 k</td>
<td>0.75</td>
<td>172 k-ft</td>
<td>689 k</td>
</tr>
<tr>
<td>Pure Moment</td>
<td>231 k-ft</td>
<td>0 k</td>
<td>0.64</td>
<td>148 k-ft</td>
<td>0 k</td>
</tr>
<tr>
<td>Balance Point</td>
<td>241 k-ft</td>
<td>-47 k</td>
<td>0.55</td>
<td>133 k-ft</td>
<td>-26 k</td>
</tr>
<tr>
<td>Pure Tension</td>
<td>0 k-ft</td>
<td>-561 k</td>
<td>0.55</td>
<td>0 k-ft</td>
<td>-309 k</td>
</tr>
</tbody>
</table>
Developing P-M Interaction Diagram

P-M Diagram for factored and unfactored values

Unfactored P-M diagram for different assumptions on GFRP compression contribution
Table of Contents

• Strength of GFRP-RC Columns
• Design Considerations
• P-M Diagram Example

• Slenderness Effect

• Concluding Remarks
Slenderness Effect

Slender Columns

As column bends, there is an out-of-plane deflection ($\Delta$). $\Delta$ will cause second-order moment

$$M_{2nd\,order} = P\Delta$$

This second-order moment is in addition to any other moment applied to the column and decreases the strength of the overall column.

By definition, a column is considered slender when this second order moment decreases the capacity by more than 5%.

$$\frac{P_{long}}{P_{short}} \leq 0.95$$

Criterion
Determination of $EI$

Flexural stiffness, $EI$, ad effective length, $kL$, are the parameters determining the slenderness effect.

GFRP-RC columns are affected more by slenderness due to smaller $EI$.

Jawaheri & Nanni, 2017 offer both simplified and detailed expressions for $EI$ analogous to ACI 318-14:

**Simplified**

$$EI = \frac{0.2E_c I_g}{1 + \beta_{dns}} + 0.03E_c I_g$$

**Detailed**

$$EI = \frac{0.2E_c I_g}{1 + \beta_{dns}} + 0.75E_f I_f$$

where

$$\beta_{dns} = \frac{P_{u,\text{sustained}}}{P_u}$$
Design Considerations

Slenderness Ratio

Mirmiran et al., 2001 showed that, for GFRP-RC columns not braced against side-way, the limit should be reduced to 17

(a) Sway permitted

\[
\frac{kL}{r} \leq 22 \quad \text{(ACI 318-14)} \quad \rightarrow \quad \frac{kL}{r} \leq 17
\]

(b) Braced

\[
\frac{kL}{r} \leq 34 + 12 \left(\frac{M_1}{M_2}\right) \leq 40 \quad \text{(ACI 318-14)} \quad \rightarrow \quad \frac{kL}{r} \leq 29 + 12 \left(\frac{M_1}{M_2}\right) \leq 30
\]

\(M_1/M_2\) is negative if column is bent in single curvature, and positive for double curvature
Alignment Charts

The coefficient $k$ can be determined through the use of alignment charts based on relative stiffness of framing members.

ψₐ and ψₐ are found based upon members framing into joint

\[
\phi_i = \frac{\sum \left(\frac{EI}{L}\right)_{\text{column}}}{\sum \left(\frac{EI}{L}\right)_{\text{beam}}}
\]

(a) Nonsway Frames  (b) Sway Frames
## Determination of EI

For GFRP reinforced concrete members, stiffness of restraining members needs approximation. Values are provided below in the table.

\[
\varphi_i = \frac{\sum \left(\frac{EI}{L}\right)_{\text{column}}}{\sum \left(\frac{mEI}{L}\right)_{\text{beam}}}
\]

<table>
<thead>
<tr>
<th>Member and condition</th>
<th>Moment of Inertia</th>
<th>Cross-sectional area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns</td>
<td>0.40I_g</td>
<td></td>
</tr>
<tr>
<td>Walls</td>
<td></td>
<td>1.0A_g</td>
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<tr>
<td>Uncracked</td>
<td>0.40I_g</td>
<td></td>
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<tr>
<td>Cracked</td>
<td>0.15I_g</td>
<td></td>
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<tr>
<td>Beams</td>
<td>0.15I_g</td>
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</tr>
<tr>
<td>Flat plates and flat slabs</td>
<td>0.15I_g</td>
<td></td>
</tr>
</tbody>
</table>

Table of Contents

• Strength of GFRP-RC Columns

• Design Considerations

• P-M Diagram Example

• Slenderness Effect

• Concluding Remarks
Concluding Remarks

• Elastic modulus of GFRP in compression matches that of concrete (conservative assumption)

• Transverse reinforcement spacing affected by smaller elastic modulus of GFRP

• Minimum longitudinal GFRP reinforcement ratio for columns same as for steel

• P-M diagram can be constructed using similar procedure as for steel-RC columns

• GFRP-RC not appropriate for seismic application
Questions?

Thank U
AXIAL RESPONSE OF GFRP REINFORCED CONCRETE

4.1 Review Questions: Fundamentals
Applied Question

4.1.1) The compressive capacity of GFRP reinforcement ________________.

a. Is used to improve ductility

b. Is used to satisfy maximum strain requirements of AASHTO

c. Is not considered for low loads

d. Can be used in design up until a concrete strain of 0.003
Introduction

Review of Steel RC Columns

\[ P_o = P_c + P_s = 0.85 f_c'(A_g - A_s) + f_y A_s \]

Basic Concept for GFRP RC Columns

\[ P_o = P_c + P_s = 0.85 f_c'(A_g - A_s) + f_y A_s \]

As reported in reference, the mechanical properties of GFRP exceed those of concrete and therefore, equivalency can be assumed.

GFRP bar loaded in compression (Deitz, Harik, and Gesund, 2003)
4.1.1) The compressive capacity of GFRP reinforcement ______________________.

a. Is used to improve ductility

b. Is used to satisfy maximum strain requirements of AASHTO

c. Is not considered for low loads

d. Can be used in design up until a concrete strain of 0.003
4.1.2) Compared to steel reinforced columns, the transverse spacing requirements for GFRP reinforced columns are the same.

a. True

a. False
Design Considerations

Limits on Maximum Spacing of Transverse Reinforcement: confinement, buckling of longitudinal reinforcement

Lower elastic modulus than steel

Theoretical:

\[ s_{\text{max}} \approx 14d_b \]

AASHTO 4.7.5.4 – Tied Members

\[ s_{\text{max}} = \min \left\{ \frac{\text{least dimension of column}}{4}, 12 \text{ inches} \right\} \]
Applied Question

4.1.2) Compared to steel reinforced columns, the transverse spacing requirements for GFRP reinforced columns are the same.

a. True

b. False
Applied Question

4.1.3) Compared to steel reinforced columns, the ultimate tensile capacity is reduced.

a. True

b. False
Developing P-M Interaction Diagram

Schematic P-M diagram for two identical columns having the same amounts of GFRP and steel reinforcement.
4.1.3) Compared to steel reinforced columns, the ultimate tensile capacity is reduced.

a. True

b. False
4.1.4) When constructing a moment-interaction diagram for a GFRP reinforced column, the balance points refers to:

a. The point at which the GFRP reinforcement yields and concrete crushes
b. The point at which the GFRP reinforcement ruptures and concrete crushes
c. The point at which the GFRP reinforcement yields before concrete crushes
d. The point at which the concrete crushes, but the GFRP reinforcement has not ruptured.
Developing P-M Interaction Diagram

Balance Point

Balance point is when concrete crushes and tension reinforcement ruptures simultaneously. (Since there is no yielding of GFRP)

\[ \varepsilon_{\text{tu}} = 0.003 \]

\[ f'_{c} \]

\[ C_c = \alpha_1 \beta_1 f'_{c} c_b \]

\[ \varepsilon_{\text{tu}} = \frac{f_{d}}{E_f} \]

\[ T_f = A_f \varepsilon_f E_f \]
When constructing a moment-interaction diagram for a GFRP reinforced column, the balance points refers to:

a. The point at which the GFRP reinforcement yields and concrete crushes

b. The point at which the GFRP reinforcement ruptures and concrete crushes

c. The point at which the GFRP reinforcement yields before concrete crushes

d. The point at which the concrete crushes, but the GFRP reinforcement has not ruptured.
4.1.5) When designing a slender GFRP reinforced column, special considerations should be made to determining slenderness ratio and EI?

a. True

b. False
Determination of EI

Effect of Creep

Jawaheri & Nanni, 2017 offer both simplified and detailed expressions analogous to ACI 318-14:

**Simplified**

\[
EI = \frac{0.2E_cI_g}{1 + \beta_{ans}} + 0.03E_cI_g
\]

**Detailed**

\[
EI = \frac{0.2E_cI_g}{1 + \beta_{ans}} + 0.75E_fI_f
\]

where \( \beta_{ans} = \frac{P_{u,sustained}}{P_u} \)
4.1.5) When designing a slender GFRP reinforced column, special considerations should be made to determining slenderness ratio and EI?

a. True

b. False
AXIAL RESPONSE OF GFRP REINFORCED CONCRETE

4.2 Design Example: Solider Pile in Wing Wall
Consider the following example:

GFRP-RC Piles
Pile Example

Cross Section

Soil Properties

\[ \gamma = 110 \text{ pcf} \]
\[ \phi = 30 \text{ degrees} \]
\[ c = 0 \text{ ksf} \]
Pile Example

\[ P_{cap} = Pile\ Spacing \times Cap_{Height} \times Cap_{Width} \times \gamma_c \]

**Distributed Force** = Resultant Earth Pressure \times Pile Spacing
Laterally Loaded Pile Model

Ground Surface

$P_{\text{cap}}$

$p$-z spring

$t$-z spring

$Q$-z spring
Pile Example

Laterally Loaded Pile Results

Shear

Moment

Axial

Lateral Deflection

Max: 15.3 kip  \hspace{1cm} 97.4 kip-ft  \hspace{1cm} 87.7 kip  \hspace{1cm} 0.301 in
Min: -22.9 kip  \hspace{1cm} -33.4 kip-ft  \hspace{1cm} -63.0 kip  \hspace{1cm} -0.037 in
Pile Example

Plotting Demand Point in P-M Diagram

P-M Diagram (GFRP-RC Pile)
Questions?
AASHTO GFRP-Reinforced Concrete Design Training Course
Course Outline

1. Introduction & Materials
2. Flexure Response
3. Shear Response
4. Axial Response
5. Case Studies & Field Operations
5. CASE STUDIES & FIELD OPERATIONS
Table of Contents – Case Studies

• iDock (Marine Dock)

• NE 23rd Avenue Bridge over Ibis Waterway (FPN 434359-1-52-01)

• Halls River Bridge (HRB) (FPN 430021-1-52-01)

• SR-A1A Flagler Beach (Segment 3), (FPN 440557-7-52-01)

• FDOT Fast Facts
iDock Construction Intent - Miami, Florida

• Replacement of hurricane Irma-damaged dock with GFRP-RC precast concrete components, CIP BFRP-RC continuity pour and GFRP gratings

• Provide a demo prototype for precast-concrete dock modular-system, that exhibits extended durability and resilience to extreme events
Traditional vs. Innovative Approach

- **Traditional:** precast steel-PC piles and cast in-place RC caps with timber decking

- **Innovative:** precast modular-units with rapid assembly time with GFRP & BFRP reinforcement to eliminate corrosion-related maintenance and provide higher resistance
iDock Design

Four-span bridge-type dock with precast GFRP-RC driven piles, GFRP-RC pile-bent caps and slab-beams. Continuity CIP pour with BFRP bars and mesh
Precast Construction
Precast Construction

Slab

Pile Cap

Pile
Precast Construction
Pile-Driving and Slab Installation

**Piles** installed in original steel-PC pile locations

Pile-Driving at iDock

Precast Slab-Beam installed in sections after cap placement
iDock Precast Element Installation
iDock Connections (Cap-Slab)

- GFRP dowel bars (greenish) connecting horizontal to vertical components
- BFRP (darker color) bars for flexural continuity
- Connection cast in place to interlock precast components and create continuity over the four spans
Dowels, Placement and Testing

GFRP Dowels

Slab-Beam with Grating

Cylinder Testing

Placement of Components and Material Testing for Q/A
Conclusions and Remarks

Components employed for the iDock project:

- 8 precast GFRP-RC Driven Piles [12x12 in. x 24 ft.]
- 4 precast GFRP-RC Pile-Bent Caps [12x30 in. x 8 ft.]
- 8 precast GFRP-RC Slab-Beams [8x33 in. x 10 to 12 ft.]
Primary Benefits Realized/Expected:

- FRP reinforcement eliminates the need for deep concrete cover, concrete mixture additives, and waterproofing sealants needed for reinforcement corrosion protection.

- Lightweight reinforcement allows for significantly lower labor and equipment costs due to ease of handling and transportation savings.

- Additional owner benefits include an extended service life and significantly reduced maintenance costs.
Table of Contents – Case Studies

• iDock (Marine Dock)

• **NE 23rd Avenue Bridge over Ibis Waterway (FPN 434359-1-52-01)** Under construction

• Halls River Bridge (HRB) (FPN 430021-1-52-01)

• SR-A1A Flagler Beach (Segment 3), (FPN 440557-7-52-01)

• FDOT Fast Facts
Ibis Waterway – A No-steel Bridge

- IBIS-Waterway located at Lighthouse Point, Broward County, Florida
- Project consists of replacing existing bridge sub- and superstructure, while adding intermediate-bents
- Total CFRP-PC and GFRP-RC construction.
- First GFRP-RC 3-span continuous flat-slab bridge in Florida
- First time use of two experimental partially-prestressed GFRP piles
Three-span IBIS-Waterway bridge with CIP flat-slab, CIP caps, precast PC panels and piles
Production of Experimental GFRP Piles

Partially-prestressed GFRP piles

Cutting of GFRP tendons

- 18x18 in. cross-section
- 53 ft. long
- 12 prestressed #4 GFRP bars
- 12 unstressed #8 GFRP bars

Casting of piles at Gate Precast Company in Jacksonville, FL
#4 GFRP bars (220 ft. long) uncoiled & coupled to 7-wire steel strands to reach length of the prestressing bed (about 430 ft.)
Pile-Driving in “very dense” Soil Conditions

Pile alignment via template construction to allow for FDOT specified tolerances

Initiation of pile driving with needed soil predrilling

Pile installation challenging due to power lines and tight site conditions
GFRP-RC Intermediate Bent Cap Beams

GFRP cage assemblies with spliced-bars at intermediate pile locations. GFRP bars inspected and lab-tested for Q/A
GFRP-RC Intermediate Bent Cap Beams

Completing assembly and forming

Casting completed and forms stripped
Learning Outcomes from IBIS Waterway

• Geotechnical challenges at site

• Experimental GFRP partially-prestressed piles successfully fabricated and driven

• Construction progressing as planned
Table of Contents – Case Studies

• iDock (Marine Dock)

• NE 23rd Avenue Bridge over Ibis Waterway (FPN 434359-1-52-01)

• Halls River Bridge (HRB) (FPN 430021-1-52-01)

• SR-A1A Flagler Beach (Segment 3) (FPN 440557-7-52-01)

• FDOT Fast Facts
First of a Kind 5-span Bridge

FRP PC/RC Structure

- FDOT replacement project / County Owner
- Five 37-ft. spans
- CFRP-PC piles and sheet piles
- GFRP-RC bulkheads, deck and railings
- Proprietary girders
Halls River Bridge

Prototype for Future FRP Bridge-Projects
Sheet Piles: CFRP-PC/GFRP-RC (FDOT Index D22440)

- CFRP Strands (8 Ø 0.6 in.)
- GFRP Ties (#4 @ 4 in.)
- C40/45 (12 x 30 in.)
- 13 to 26 ft. depth
- Cantilever or tied-back
Bent Caps: GFRP-RC (FDOT Software Bent Cap v1.0)

- GFRP Bars (12 #8 T&B)
- GFRP Ties (#5 @ 5 in.)
- C38 (48 x 36 in.)
- 10 ft. long
- Cast-in-place
Deck: GFRP-RC (AASHTO GFRP 2\textsuperscript{nd} Edition)

- GFRP Bars (Top & Bottom)
- Primary: #6 @ 4.5 in.
- Secondary: #6 @ 6 in.
- C30/37 (8.5 in. depth)
- 6.5 ft. girder spacing
- Cast-in-place
Learning Outcomes from Halls River Bridge

- FRP Sub/Superstructure (1st Project)
- 100+ Year Service Life
- Prototype for future FDOT Bridges

- HSCS/GFRP Hybrid (1st Project)
- Performance monitoring
Table of Contents – Case Studies

• iDock (Marine Dock)

• NE 23rd Avenue Bridge over Ibis Waterway (FPN 434359-1-52-01)

• Halls River Bridge (FPN 430021-1-52-01)

• SR-A1A Flagler Beach (Segment 3) (FPN 440557-7-52-01)

• FDOT Fast Facts
Flagler Beach, FL (SR-A1A) Damage & Recovery
GFRP Design for Secant-Pile Seawall

- 4920-ft. long secant pile seawall
- First FDOT project with about 1.5 million linear feet of GFRP bars
- Secant piles in high chloride content sand, high water table and periodically exposed to salt spray
GFRP bar site delivery and storage

- Straight bars, bent bars, hoops and toe bent bars
- Site storage and protective measures from elements
GFRP Bars - Cage Assembly
GFRP Bars - Cage Assembly

- Cages constructed with 25 #8 GFRP bars, spiral ties and “toe-end”
- GFRP cages were 38-ft. in length
Guide Wall for GFRP Secant-Piles

Guide wall trench boxes installed to assure pile alignment

Secant-piles installed via guide wall form

Removal of steel formwork prior to drilling secant-piles
Concrete Grouting of GFRP Secant-Piles

Concrete grouting of Secant-piles

Secant-pile cages delivered to pile-drilling area and ready for installation

1,847 Secant-piles installed. 5,000 linear feet of pile-cap
Flagler Beach - GFRP pile cage installation

GFRP cage installation

Auger-cast primary piles 36 in. in diameter and 36 ft. long
Secondary piles 18 ft. long
Continuous pile-cap and dune restoration

Pile-cap placement and dune restoration/re-establishment

Project completed in 4½ months
Aspects of GFRP Use

**PROs**
- Quick installation
- Light weight
- Assembly time savings
- “Toe” or “No-Toe” option
- GFRP cages remain in-place, i.e., “no flotation”

**CONs**
- Bent-shapes need to be pre-fabricated by pultruder
- No on-site bending of GFRP
- “Skin-itching” (protective clothes should be worn)
- More GFRP than black steel bars are needed
Learning Outcomes from SR-A1A

• No Secant-Pile cage alterations needed. Installed all 1,847 piles as per design-phase
• Quick and reliable installation in soft to medium dense sands
• GFRP cage assemblies resulted, in up to 52% time savings over “black steel”
• Toe assemblies may be removed in future projects
• Less noise pollution through Secant-Pile installation vs. Sheet-Pile installation
Table of Contents – Case Studies

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• Halls River Bridge (FPN 430021-1-52-01)
• SR-A1A Flagler Beach (Segment 3), (FPN 440557-7-52-01)
• FDOT Fast Facts
Structures Design

Structures Design / Design Innovation
Fiber Reinforced Polymer Reinforcing

Structures Design - Transportation Innovation
Fiber Reinforced Polymer (FRP)
Reinforcing Bars and Strands
Multiple online resources available

Overview
Usage Restrictions / Parameters
Design Criteria
Specifications
Standards
Producer Quality Control Program
Projects
Technology Transfer (T²)
FDOT Research
Contact

www.fdot.gov/structures/innovation
Fast-Fact sheets for selected FDOT and affiliated projects in Florida (completed and under construction)
Fast Facts:

Glass Fiber Reinforced Polymer

Project Location: FDOT District Two
Duval County
Jacksonville, Florida

Agency: Florida Department of Transportation

URL: [http://www.fdot.gov/structures/innovation/FRP.shtml](http://www.fdot.gov/structures/innovation/FRP.shtml)

Project Name: US-17 (SR-5) Over Trout River
Bridge No. 720011
FPID: 426169-1

Project Description: Bridge Substructure Rehabilitation

Project Purpose & Need: Bridge Inspection Reports identified concrete deterioration in the substructure. Work activities included removal of existing Pile Jackets and installation of new Pile Jackets and Pier Footing Jackets with Impressed Current Cathodic Protection (ICCP). Glass Fiber Reinforced Polymer (GFRP) dowels and reinforcement were used in select locations.
Fast Facts:

| Project Location: | FDOT District Two  
|                  | Levy County  
|                  | Cedar Key, Florida |
| Agency:          | Florida Department of Transportation |
| URL:             | [http://www.fdot.gov/structures/innovation/FRP.shtml](http://www.fdot.gov/structures/innovation/FRP.shtml) |
| Project Name:    | SR 24 over Number Three Channel  
|                  | Bridge No. 340003  
|                  | FPID: 426169-1 |
| Project Description: | Rehabilitation of three bridges in Cedar Key |
| Project Purpose & Need: | Bridge Inspection Reports identified deterioration, including evidence of corroded steel reinforcement in the bulkhead cap on bridge 340003. Work activities included removal of the existing bulkhead cap and installation of a new bulkhead cap with GFRP reinforcement. |
Fast Facts:
Glass Fiber Reinforced Polymer

Project Location: Coral Gables, Florida
Agency: University of Miami
URL: http://www.fdot.gov/structures/innovation/FRP.shtm
Project Name: Innovation Pedestrian Bridge
Project Description: Although this pedestrian bridge is a simple, single-span, 70 ft.-long construction, it offers a number of features intended to ensure a 75-year service life to its owner, the University of Miami. The bridge consists of the following concrete elements reinforced with FRP: auger-cast piles; cast-in-place pile caps and back walls; precast prestressed girders; and, cast-in-place deck topping and curbs. Stainless steel is used for the bearing plates of the girders, the anchor bolts for the lamp posts, and the railings.

Project Purpose & Need: The University of Miami deliberately chose this type of structure to demonstrate its commitment to innovation and sustainability for a pedestrian bridge used by students to access the sports and intermural fields on campus.
Fast Facts:
Glass Fiber Reinforced Polymer

Project Location: Coral Gables, Florida
Agency: University of Miami
URL: http://www.fl.dot.gov/structures/innovation/FRP.shtml

Project Name: Fate Pedestrian Bridge
Project Description: This three-span pedestrian bridge with a short cantilever end allows for the crossing of the Lake Osceola at the University of Miami, Coral Gables Campus.

Project Purpose & Need: Designed by renowned Arquitectonica, the Fate Bridge not only connects two sides of the campus, but also intends to become itself a place for gathering and reflection. The silhouette of the bridge with its variable cross-section is like an extension of the water surface. The bridge with an embedded monitoring system is a living laboratory to educate engineering and architecture students.
Questions?

Thank U
AASHTO GFRP-Reinforced Concrete Design Training Course