AASHTO GFRP-Reinforced Concrete Design Training Course

GoToWebinar by:
Professor Antonio Nanni

FDOT
Florida Department of
TRANSPORTATION
Safety, Innovation, Mobility, Attract, Retain & Train

Office of Design
Florida's Transportation Engineers

August 10th, 2020

Design Innovation

FDOT

UNIVERSITY OF MIAMI

Center for Integration of Composites into Infrastructure

Introducing the Schedule

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.

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

Dr. Francisco DeCaso
P.E. PhD.

Nafiseh Kiani
(PhD. Candidate)

Alvaro Ruiz,
(PhD. Candidate)

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

Steve Nolan, P.E.

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COURSE SECTION	TOPIC	TENTATIVE SCHEDULE
1 Nanni	**INTRODUCTION TO FRP-RC & MATERIAL PROPERTIES** a. Problem Statement b. Where to Use Glass FRP c. FRP Material Properties d. Durability e. Design Guides and Standards f. Concluding Remarks	9:30 am
1.1 De Caso	**REVIEW QUESTIONS: Fundamentals** Refer to workbook. Opportunity to actively participate, review concepts, and discussion time	
2 Nanni	**FLEXURE RESPONSE OF GFRP-RC** a. General Considerations b. Bending Moment Capacity c. Serviceability d. Static & Cyclic Fatigue e. Anchorage and Development f. Special Considerations g. Concluding Remarks	10:30 am
2.1 De Caso	**REVIEW QUESTIONS: Fundamentals** Refer to workbook. Opportunity to actively participate, review concepts, and discussion time	
Short Break		
2.2 2.3 2.4 Rodriguez	**DESIGN EXAMPLE: Flat Slab** Step-by-step Flexural design of flat slab. Refer to Annex A, Sections A and B Creep rupture under sustained load. Refer to Annex A, Section D Minimum Reinforcement. Refer to Annex A, Section E	
3 Nanni	**SHEAR RESPONSE OF GFRP-RC** a. General Behavior b. Shear Capacity c. Punching Shear d. Special Considerations e. Concluding Remarks	12:00 am
	Lunch Break	12:30-1:30 (60 min)

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COURSE SECTION	TOPIC	TENTATIVE SCHEDULE
3.1 De Caso	**REVIEW QUESTIONS: Fundamentals** Refer to workbook. Opportunity to review, take notes and discussion	1:30 pm
3.2 Kiani	**DESIGN EXAMPLE: Bent Cap** Refer to Annex B Step-by-step design of flexure and shear bent cap using Mathcad worksheet	
4 Nanni	**AXIAL RESPONSE OF GFRP-RC** a. Strength of GFRP-RC Columns b. Design Considerations c. P-M Diagram Example. Refer to Annex C d. Slenderness Effect e. Concluding Remarks	2:00 pm
4.1 De Caso	**REVIEW QUESTIONS: Fundamentals** Refer to workbook. Opportunity to review, take notes and discussion	
Short Break		
4.2 Rodriguez	**DESIGN EXAMPLE: Solider Pile in Wing Wall** Overview of a soldier pile in a wing wall design with GFRP reinforcement.	
5 Nanni & Nolan	**CASE STUDIES & FIELD OPERATIONS:** a. iDock (Marine Dock) b. NE 23rd Avenue Bridge over Ibis Waterway (FPN 434359-1-52-01) c. Halls River Bridge (FPN 430021-1-52-01) d. SR-A1A Flagler Beach (Segment 3) (FPN 440557-7-52-01) e. FDOT Fast Facts	3:00 pm
	END OF COURSE	4:30 pm

LIST OF COURSE ANNEXES

Annex A (Section 2.2): LFRD 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

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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.

Design Example	Tools from FDOT and other sources		Existing Examples / Description
	Existing	Comments	
1.A. Definition of material properties and design values based on specifications and codes.	• FDOT Structures Manual Volume 4 (Link) • FDOT Materials Manual Section 12 (Link) • FDOT Standard Specifications 932-3 (Link) • FDOT FRP Bar Bending Details (Index D21310) • ASTM D7957/D7957M-17 (Link) • AASHTO LRFD BDGS GFRP-2 (Link)	None	Definition of mechanical properties and factorization per existing standards
1.B. Definition of material properties and design values when a specific manufacturer and product are selected (value engineering).	• FDOT Material Acceptance (Link) • List of certified manufacturers (Link) • List of certified testing labs (Link)	None	Properties as specified by a fictitious manufacturer and factor them as per existing standards
2.A. Flat slab bridge superstructure	• Mathcad Worksheet for flat slab bridges. • LRFD Design Example 2A developed as master's thesis at UM (Internal UM Link)	Most recent version of the Mathcad worksheet used for the 23rd Ave. bridge	• 23rd Ave. Bridge over Ibis Waterway (434359-1-52-01)
3.B. Shallow foundations, pavements, slabs on grade.	• Rectangular Spread Footingv1.1 (Link) (Does not include GFRP) • Approach Slabs – GFRP Reinforced (Flexible Pavement Approach) Index D22900	None	• UM slab on grade for Student Village
3.C. Cantilevered Retaining Wall	• FDOT Retaining Wall v3.3 (Link) (Does not include GFRP) • FDOT Retaining Wall v4.0 (Internal UM Link) (includes GFRP, not publicly available)	None	• UM cantilevered wall for Student Village
3.D Sheet Pile Wall: Cantilevered and tied back	• Precast Concrete CFRP/GFRP Sheet Pile Wall (Index D22440) (Link) • FDOT Retaining Wall v4.0 (Internal UM Link) (includes GFRP, not publicly available, can be adapted to design sheet pile walls)	None	• Anchored and cantilevered sheet pile seawalls for North Miami Beach & other cities/counties

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2.B. Deck (empirical & traditional)	• Refer to Annex A	Most recent version of the Mathcad spreadsheet used for the deck of the Halls River Bridge	• Halls River Bridge (430021-1-52-01) • Toledo Bridge (Ohio) • Calculations for TxDOT index
2.C. Girders	• FDOT Girder v5.3 (Link) (not including FRP) • FDOT Girder v5.4 (not publicly available, modified at UM, includes CFRP-PC) • (can be adapted to design GFRP-RC girders)	Most recent version of the Mathcad spreadsheet developed for FRP-PC girders	*Only GFRP-RC Girders* • Alternative design for the Halls River Bridge (430021-1-52-01) (Rossini et al. 2013)
2.D. Bent Cap	• FDOT Bent Cap v1.0 (Link)	None	• 23rd Street Bridge over Ibis Waterway (434359-1-52-01) • Halls River Bridge (430021-1-52-01)
2.E. Railings	• Design Standards Development Report for 32" F Shape Traffic Railing (GFRP) (Internal UM Link) • Mathcad Worksheets developed for verifying design of concrete barriers with GFRP as master's thesis at UM. (Link) – Official FDOT in development • FDOT GFRP Railing Index D22420 • ODOT Railing Index BR-1-13	Most recent version of the Mathcad spreadsheet used for traffic railings	FDOT developmental standard available
3.A. Precast Pile	• Design standards exist for CFRP with GFRP stirrups piles (Index Series 22600) • Developmental standard for square CFRP Prestressed Concrete Pile Splices (Link)	None	• iDock

USEFUL RESOURCES FROM DOTs

Software:
https://www.fdot.gov/structures/ProgLib.shtm

FDOT Index:
https://www.fdot.gov/roadway/DS/18/STDs.shtm

TxDOT Index:
http://www.dot.state.tx.us/insdtdot/orgchart/cmd/cserve/standard/bridge-e.htm

ODOT Index:
http://www.dot.state.oh.us/Divisions/Engineering/Structures/standard/Bridges/Standard%20Drawings/Forms/AllItems.aspx

Developmental Index:
https://www.fdot.gov/roadway/DS/Dev.shtm#30000

Structures manual:
https://www.fdot.gov/structures/StructuresManual/CurrentRelease/StructuresManual.shtm

Construction and material specs:
https://www.fdot.gov/programmanagement/Implemented/SpecBooks/

FRP Projects in Florida:
http://www.arcgis.com/apps/webappviewer/index.html?id=7800e1da894e433ba81ffac6962349f6

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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 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 D22420)
- Rocchetti, Paolo, "RC Traffic Barrier with GFRP Reinforcement" (2017). *Open Access Theses*. 685. https://scholarlyrepository.miami.edu/oa_theses/685

Flat Slab

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

FDOT Software

- FDOT Structure Design Office – Programs Library, "Bent Cap v1.0", https://www.fdot.gov/structures/proglib.shtm
- FDOT Structure Design Office – Programs Library, "Retaining Wall v4.0 Beta" https://www.fdot.gov/structures/proglib.shtm. Available upon personal request.

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.
- ACI Committee 440.1R-15. Guide for the Design and Construction of Structural Concrete Reinforced with Fiber Reinforced Polymer Bars.

Books and Papers

- Rossini, M., Matta, F., Nolan, S., Potter, W., & Nanni, A. (2019). AASHTO Design Specifications for GFRP-RC Bridges: 2nd Edition. In M. Di Prisco & M. Menegotto (Eds.), Proceedings of Italian Concrete Days 2018. Lecco, IT: Springer International Publishing. https://doi.org/10.1007/978-3-030-23748-6

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Bischoff, P. H. "Member Stiffness for Frame Analysis of GFRP Reinforced Concrete Structures". *39th IABSE Symposium – Engineering the Future, Vancouver, Canada, Sept. 21 – 23, 2017*, pp. 1847-1854.

Bresler, B. (1960) Design criteria for reinforced concrete columns under axial load and biaxial bending. *ACI Journal* 57(5) 481-490.

Cadenazzi, T., Dotelli, G., Rossini, M., Nolan, S., & Nanni, A. (2019). Life-cycle cost and life-cycle assessment analysis at the design stage of a fiber-reinforced polymer-reinforced concrete bridge in Florida. Advances in Civil Engineering Materials, 8(2), 128–151.

De Luca, A. Matta, F., and Nanni, A. (2010). Behavior of Full-Scale Glass Fiber-Reinforced Polymer Reinforced Concrete Columns under Axial Load. *ACI Structural Journal*, 107(5): 589-596

De Luca, A. Matta, Nanni, A. (2009). Behavior of Full-Scale Concrete Columns Internally Reinforced with Glass FRP Bars under Pure Axial Load. *Composites & Polygon*. Tampa: American Composites Manufacturers Association.

De Luca, A., Nardone, F., Matta, F., Nanni, A., Lignola, G. P., and Prota, A. (2011). Structural Evaluation of Full-Scale FRP-Confined Reinforced Concrete Columns. Journal of Composites for Construction, ASCE, 7(1): 112-123

Dietz, D., H., Harik, I. E., and Gesund, H. (2003). Physical properties of glass fiber reinforced polymer rebars in compression. *Journal of Composites for Construction*. Vol 7. No. 4. pp. 363-366.

Guérin, M., Mohamed, H. M., Benmokrane, B., Nanni, A, Shield, C. K. (2018) Eccentric Beh Poly

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Ruiz Emparanza, A., De Caso y Basalo, F., Kampmann, R., Rodrigues de Castro Jalles, P., & Nanni, A. (2019). Durability of Mechanical Properties of GFRP Rebars Exposed to Seawater. 5th International Conference on Sustainable Construction Materials and Technologies (SCMT5). London.

Ruiz Emparanza, A., Kampmann, R., & De Caso y Basalo, F. (2017). State-of-the-Practice of Global Manufacturing of FRP Rebar and Specifications. ACI Fall Convention. Anaheim, CA.

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MacGregor, J. G. (1993). "Design of Slender Concrete Columns – Revisited." *ACI Structural Journal*, 90(S32).

MacGregor, J. G., Breen, J. E., and Pfrang, E. O. (1970). "Design of Slender Concrete Columns." *ACI Journal*.

Mirmiran, A.; Yuan, W.; and Chen, X., 2001, "Design for Slenderness in Concrete Columns Internally Reinforced with Fiber-Reinforced Polymer Bars," *ACI Structural Journal*, V. 98, No. 1, Jan.-Feb., pp. 116-125.

Mohamed, H., Afini, M., Benmokrane, B. (2014) Performance Evaluation of Concrete Columns Reinforced Longitudinally with FRP Bars and Confined with FRP Hoops and Spirals under Axial Load. *Journal of Bridge Engineering*, 19(7).

Rossini, M., Saqan, E., & Nanni, A. (2019). Prediction of the Creep Rupture Strength of GFRP Bars. Construction and Building Materials, 227, 116620(1-11). Retrieved from https://doi.org/10.1016/j.conbuildmat.2019.08.001

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.

Support Material - Workbook

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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

Structures Design / Design Innovation

Fiber Reinforced Polymer Reinforcing

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

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

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**

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Another Training Opportunity

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

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Let Us Begin !!

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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

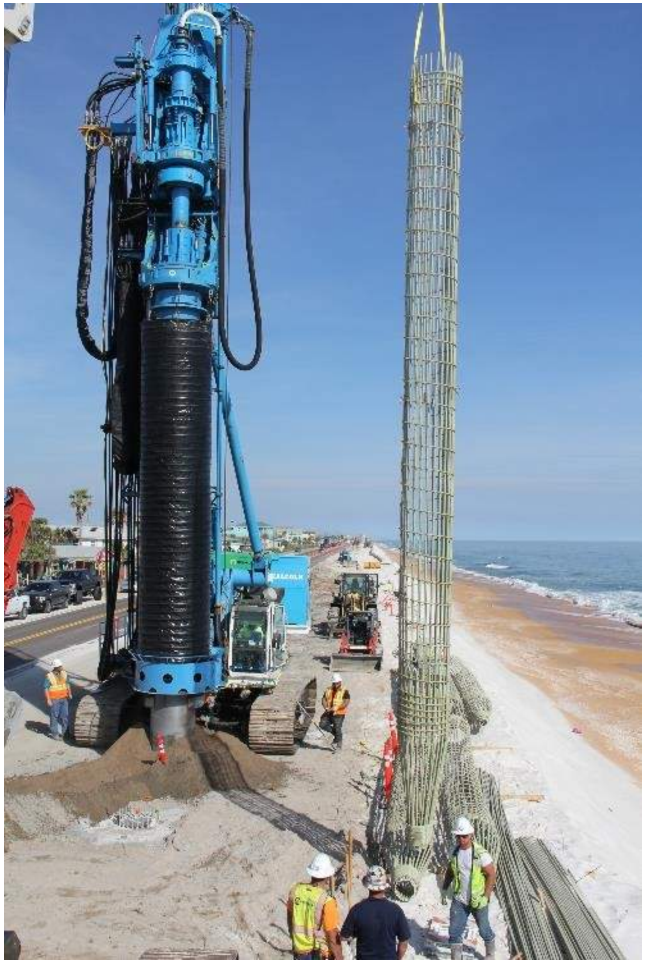
- Review questions
- Reinforce methods
- Apply concepts

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
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5. Case Studies & Field Operations

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

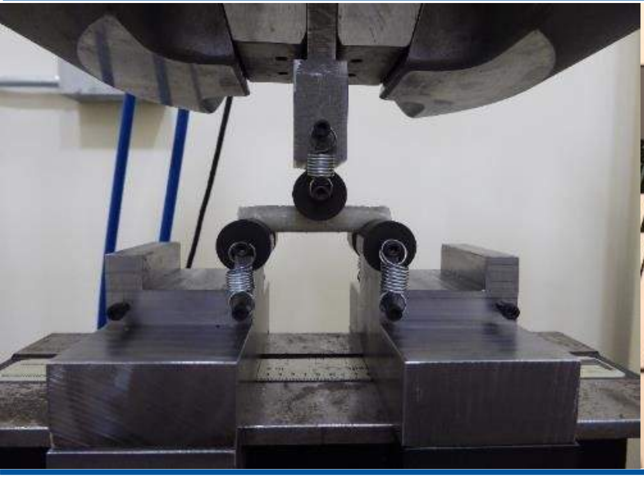

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Table of Contents - Intro & Materials

Problem Statement

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

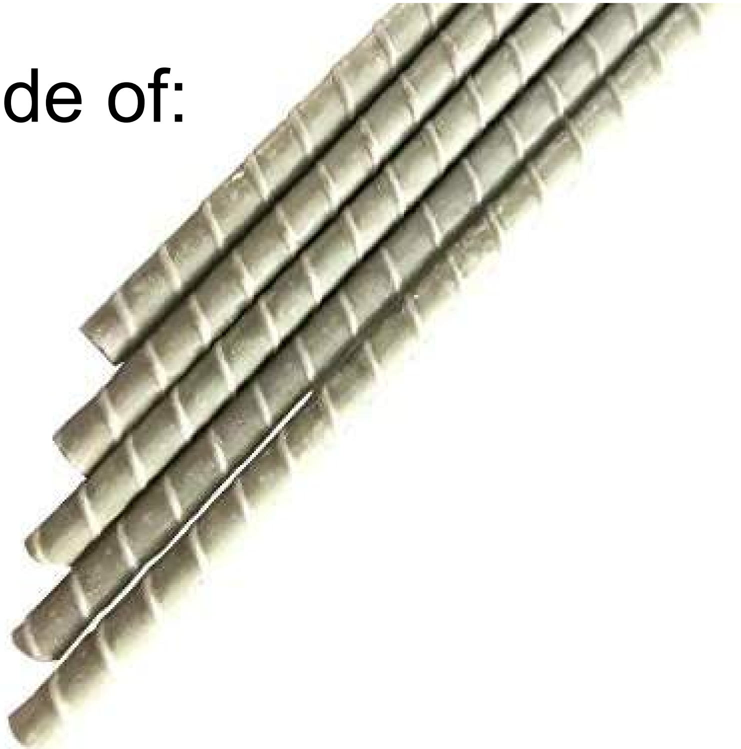
- Traditional corrosion mitigation efforts:
  - ✓ Admixtures
  - ✓ Increase Concrete Cover
  - ✓ Alter Concrete Mix
  - ✓ Membranes & Overlays
  - ✓ Epoxy-Coated, Galvanized or Stainless Steel

SERVICE LIFE OF STRUCTURES GREATLY REDUCED BY CORROSION

FRP Rebars

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

A composite material system made of:
Fibers + Resin



FRP Rebars

Key Benefits

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

FIRST COST COMPARABLE WITH EXPOXY-COATED STEEL

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- 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

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- Problem Statement
- Where to Use Glass FRP
- **FRP Material Properties**
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Types of Fiber in FRP Bars

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

Types of Resin in FRP Bars

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

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

FRP Bar Types

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

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

FRP Bar Shapes

- Straight bars

- Bent bars

- Spirals

- Twisted strands (PC use)

Material Specifications

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

SECTION 932
NONMETALLIC ACCESSORY MATERIALS
FOR CONCRETE PAVEMENT AND CONCRETE STRUCTURES

932-1 Joint Materials.
932-1.1 Preformed Joint Filler for Pavement and Structures: Preformed joint filler shall meet the requirements of AASHTO M153 or AASHTO M213, or cellulose fiber types meeting all the requirements of AASHTO M21 … provided they contain minimums of 0.2% zinc … wax. For AASHTO M153, unless a particular … may be used.
Preformed joint fillers shall ha… required, and shall be furnished in lengths eq… installed, except that strips which are of a len… joints, or between longitudinal joint and edg…

932-3 Fiber Reinforced Polymer (FRP) Reinforcing Bars.
932-3.1 General: Obtain FRP reinforcing bars from producers currently on the Department's Production Facility Listing. Producers seeking inclusion on the list shall meet the requirements of Section 105.
Use only solid, round, thermoset basalt fiber reinforced polymer (BFRP), glass fiber reinforced polymer (GFRP) or carbon fiber reinforced polymer (CFRP) reinforcing bars. Bars shall be manufactured using pultrusion, variations of pultrusion, or other suitable processes noted in the producer's Quality Control Plan, subject to the approval of the State Materials Office (SMO). For BFRP and CFRP bars only vinyl ester or epoxy resin systems are permitted. For GFRP, use only bars manufactured using vinyl ester resin systems and glass fibers classified as E-CR or R that meet the requirements of ASTM D578.

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Bar manufacturer not known/selected at the design stage

* FDOT only

FRP Bar Sizes

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

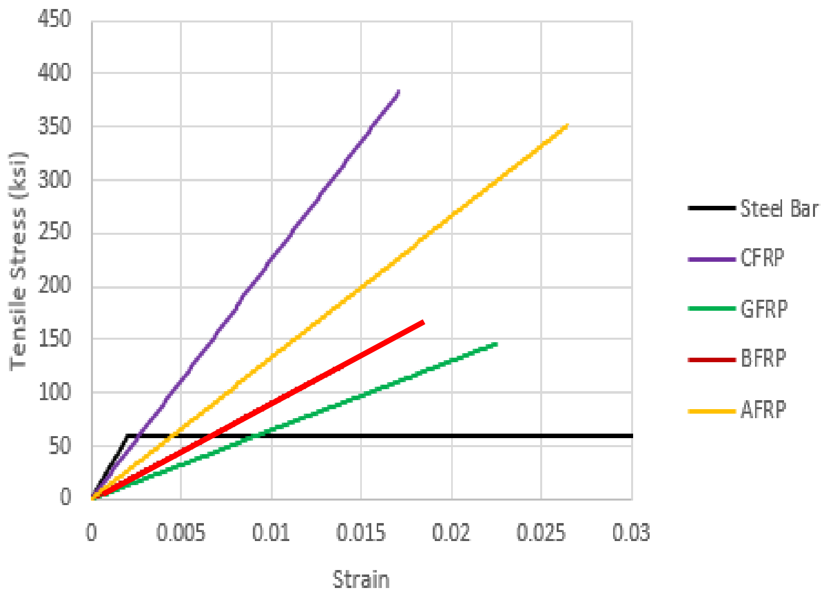
Table 3-1
Sizes and Tensile Loads of FRP Reinforcing Bars

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

FRP Mechanical Properties

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

Tensile Stress-Strain Characteristics



Typical Tensile Properties

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

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Design Tensile Strength

- Design tensile strength and strain are:

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

AASHTO GFRP 2.4.2.1-1

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

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

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

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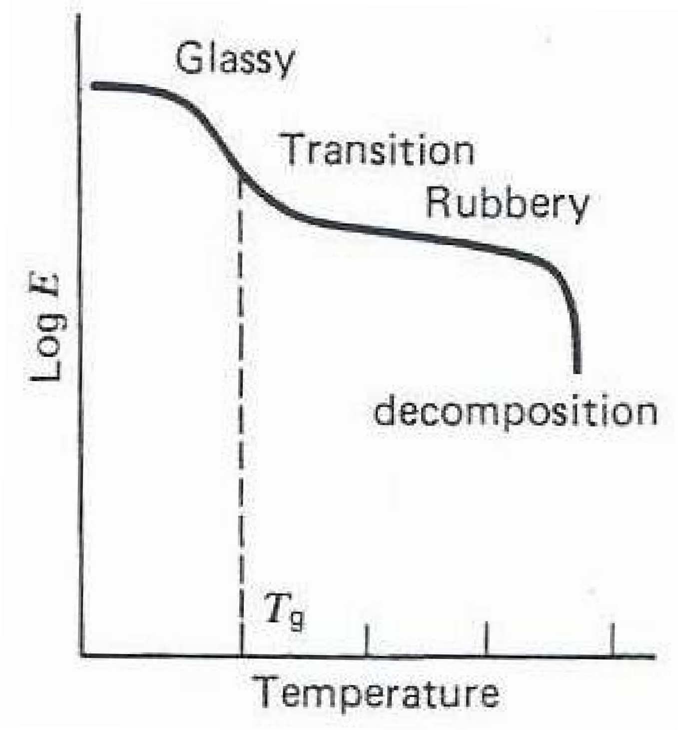
Behavior Function of Temperature

- 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 ^oF (100 ^oC) 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

PROs

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

CONs

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

Other Mechanical Properties

Strength of FRP at bend

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

Compressive behavior of FRP bars

- Reduced strength and stiffness as compared to tensile properties

Shear behavior of FRP bars

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

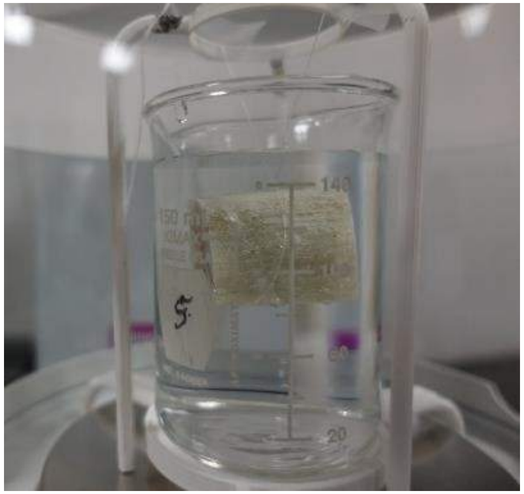
Behavior under sustained and cyclic loading

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

Material Characterization

Moisture absorption
[*ASTM* D570]

Fiber content
[*ASTM* D2484]



Cross-sectional area
[*ASTM* D792]

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

Material Characterization

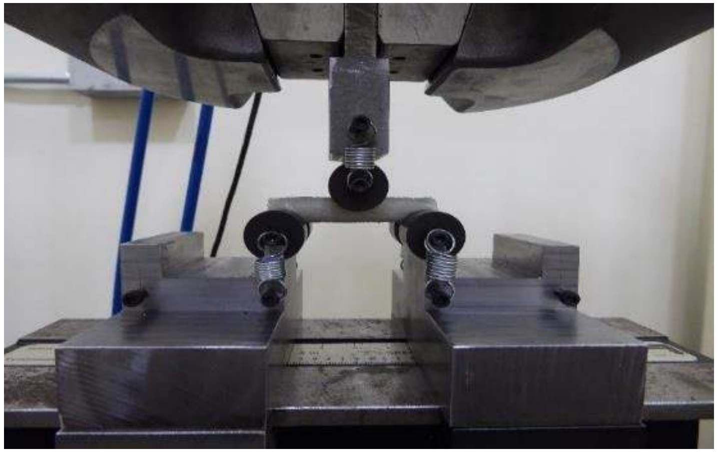
Tensile test
[*ASTM* D7205]

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

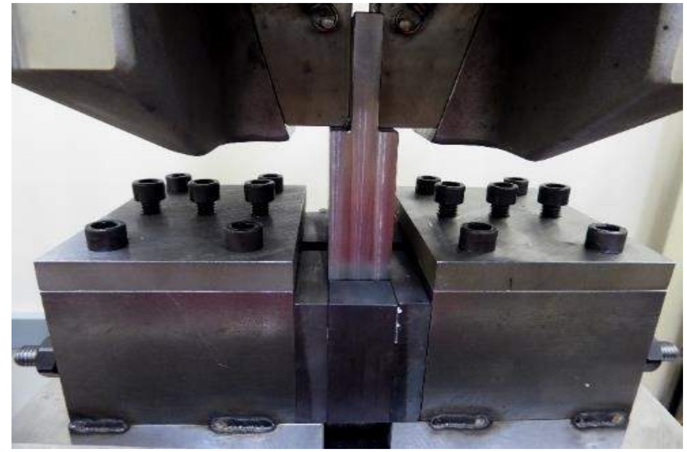
AASHTO 2.4.2.1:

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

Material Characterization



Horizontal shear
[*ASTM* D4475]



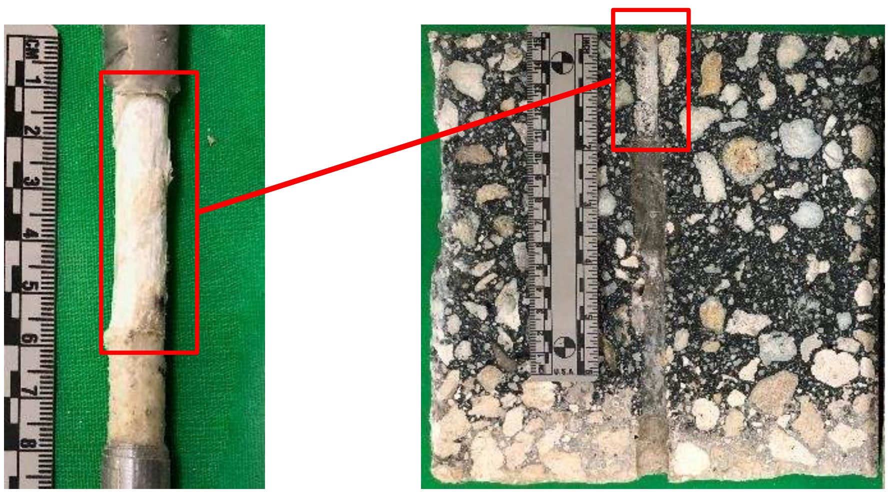
Transverse shear
[*ASTM* D7617]

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

Material Characterization

Bond-to-concrete
[*ASTM* D7913]

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



Strength of FRP at Bend

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

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

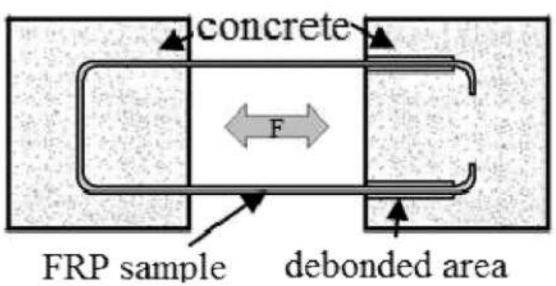


Table of Contents

- 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:

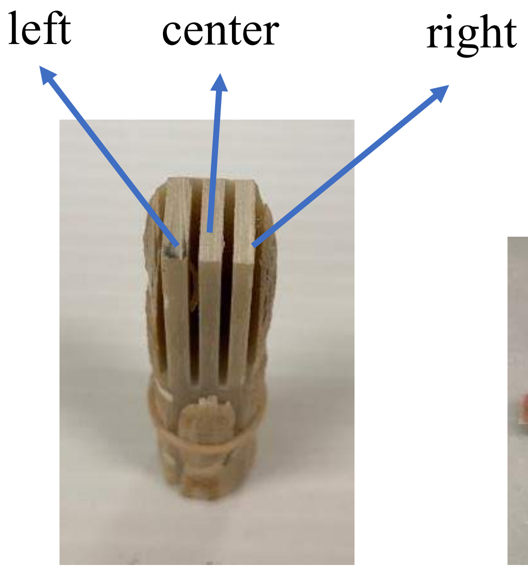
1. Accelerated aging protocols (high temperature; immersion in water w/ or w/o high pH and/or salt)
   → fast

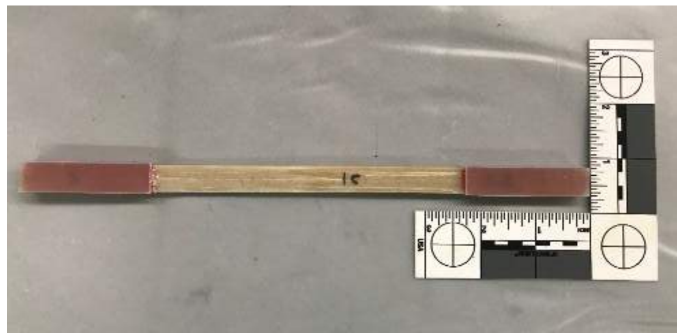
2. Extraction of samples from real life structures
   → slow

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

GFRP Bars Extracted from Bridges 15-20 Years Old





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

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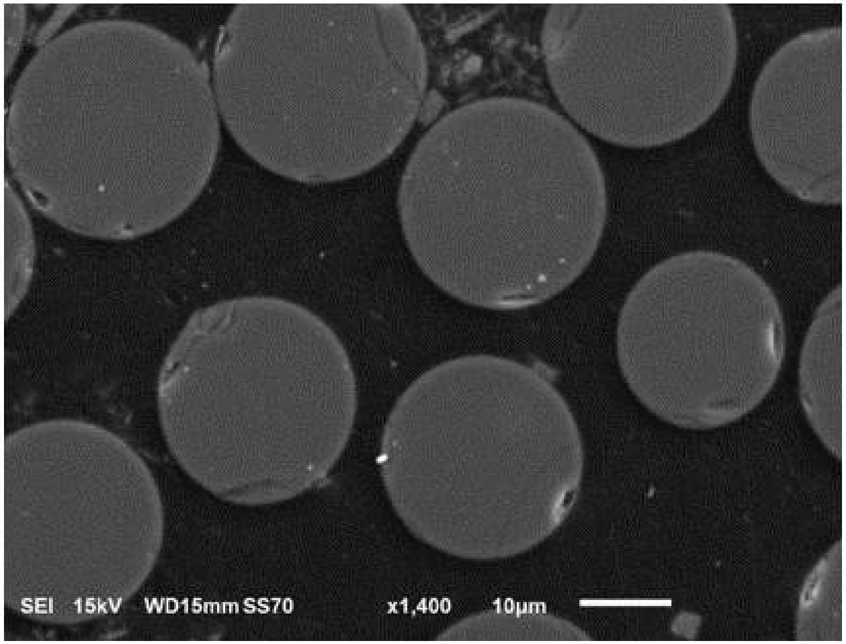
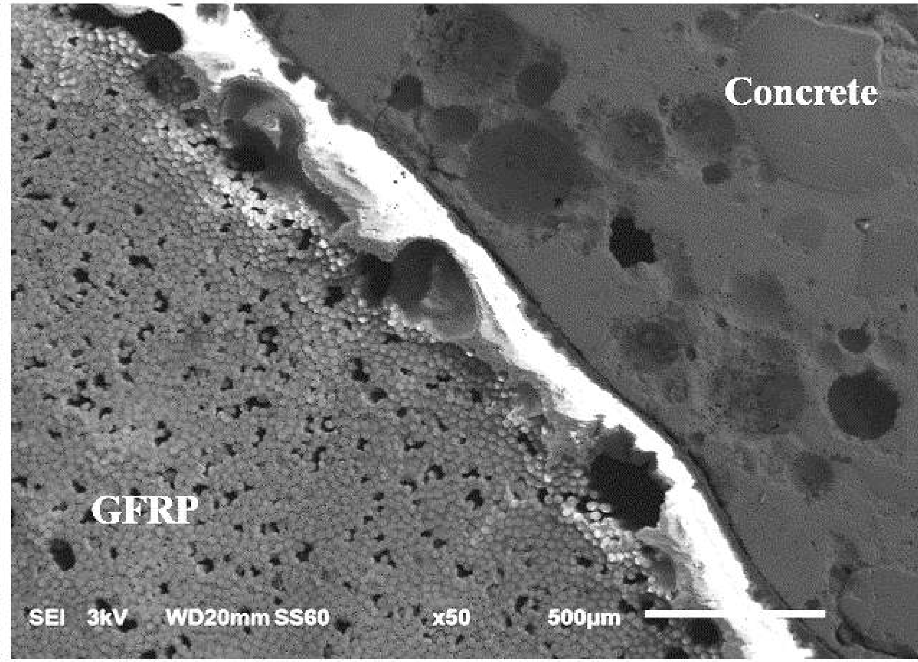
Durability





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

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

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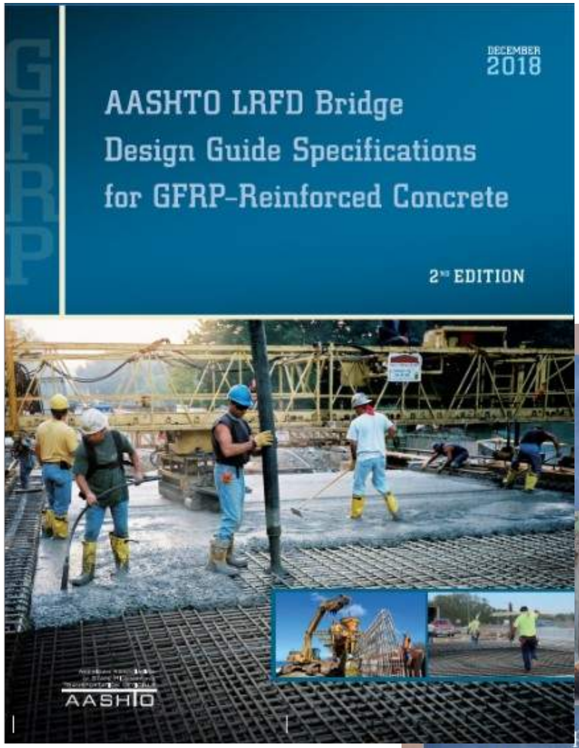
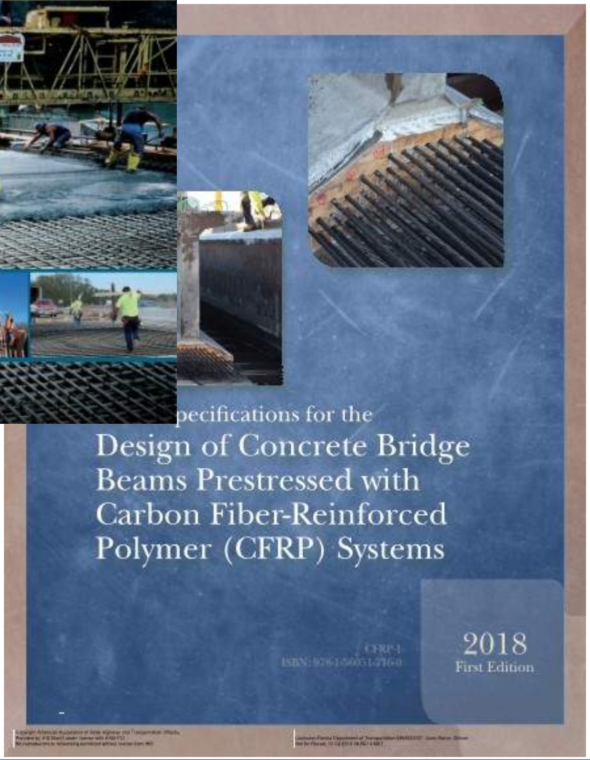
Table of Contents

- 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

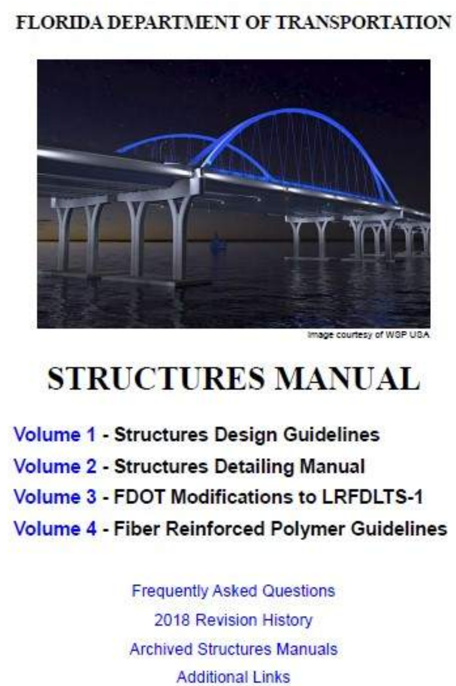


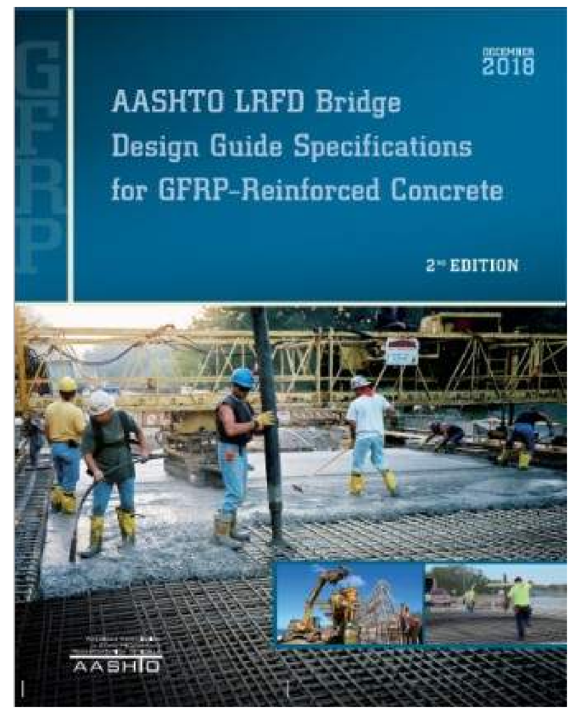


Design Guidance & Tools in Florida

Currently available documents:

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

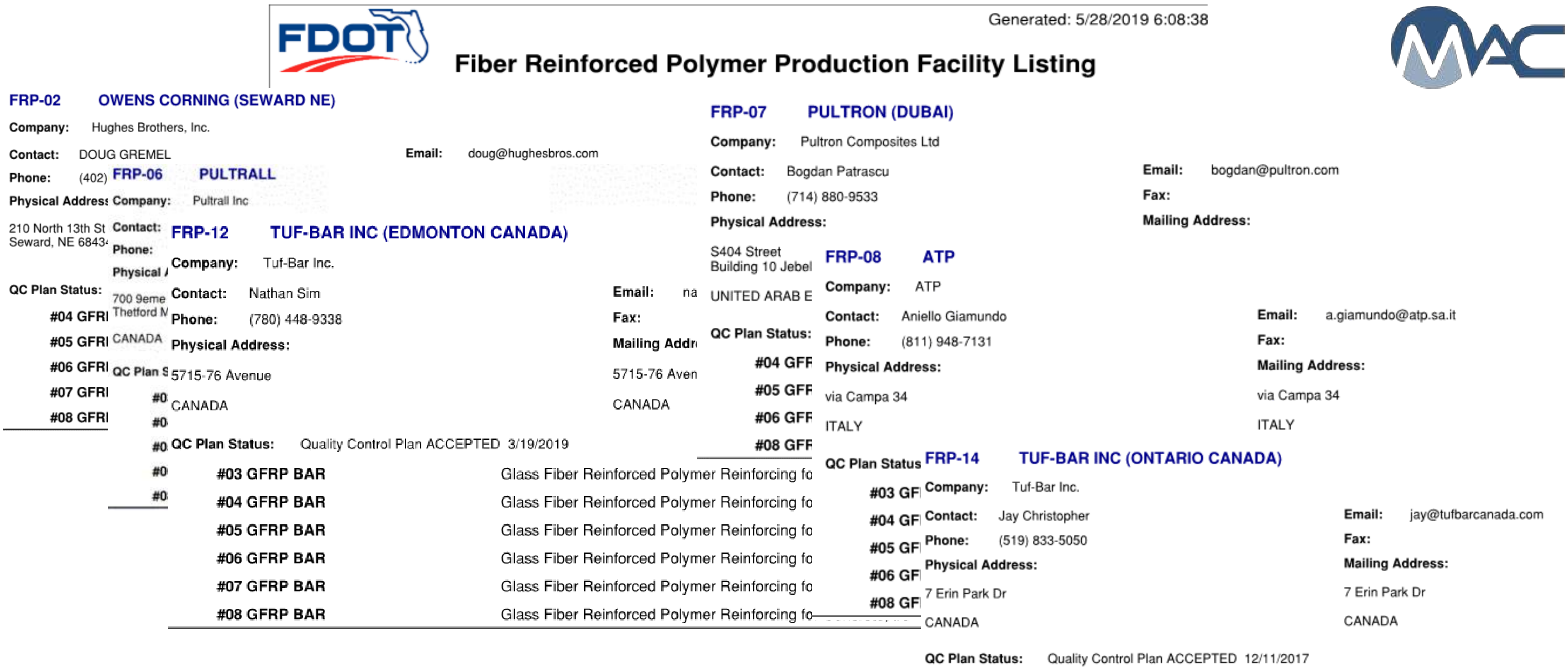




Design Guidance & Tools in Florida

- **Uniform Approval Processes**
  - Manufacturer Approval vs. Product Approval

https://mac.fdot.gov/smoreports



Material Acceptance Criteria

FDOT 932-3 Table 3-4

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

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Design Guidance & Tools In Florida

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

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Prestressed Beam v5.2	11/07/2018	Exe (Zip) (Mathcad 15)	Used with **FDOT Standard Plan Index 450-010 to 450-299** (formerly **Index 20010 to 20299**) to design simple span prestressed beams (Florida-I, AASHTO, Florida Bulb-T, Florida-U, Florida Double-T, Flat Slab, Inverted-T, FSB) in accordance with the AASHTO LRFD Bridge Design Specification.
CFCC-PC/GFRP-RC beta version *(to be included in* ***v6.0*** *with HSSS)*			
Bent Cap v1.0	11/07/2018	Exe (Zip) (Mathcad 15)	Analyzes and designs fixed or pinned bent caps, including lateral loads, in accordance with the AASHTO LRFD Bridge Design Specifications.
GFRP-RC included			
Retaining Wall v4.0	06/01/2020	Zip (Mathcad 15)	Used with **FDOT Standard Plan Index 400-010** (formerly **Index 6010**) to design and analyze cast-in-place retaining walls in accordance with the AASHTO LRFD Bridge Design Specification.
GFRP-RC now included			

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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

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Applied Questions

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

a. Any concrete member susceptible to steel corrosion by chlorides

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

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

d. Applications requiring thermal non-conductivity

e. All the above

Where Should FRP Be Used?

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

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

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

Applied Questions

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

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

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

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

d. Applications requiring thermal non-conductivity

e. All the above

Applied Questions

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

a. Corrosion resistant

b. Ductility

c. Low thermal and electrical conductivity

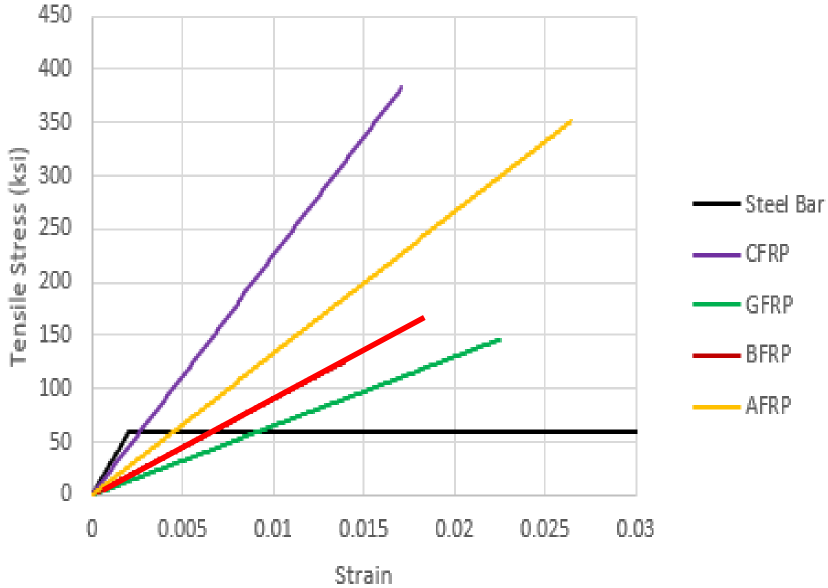
d. Light weight

e. High strength to weight ratio

FRP Mechanical Properties

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

Tensile Stress-Strain Characteristics



Applied Questions

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

a. Corrosion resistant

b. Ductility

c. Low thermal and electrical conductivity

d. Light weight

e. High strength to weight ratio

Applied Questions

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

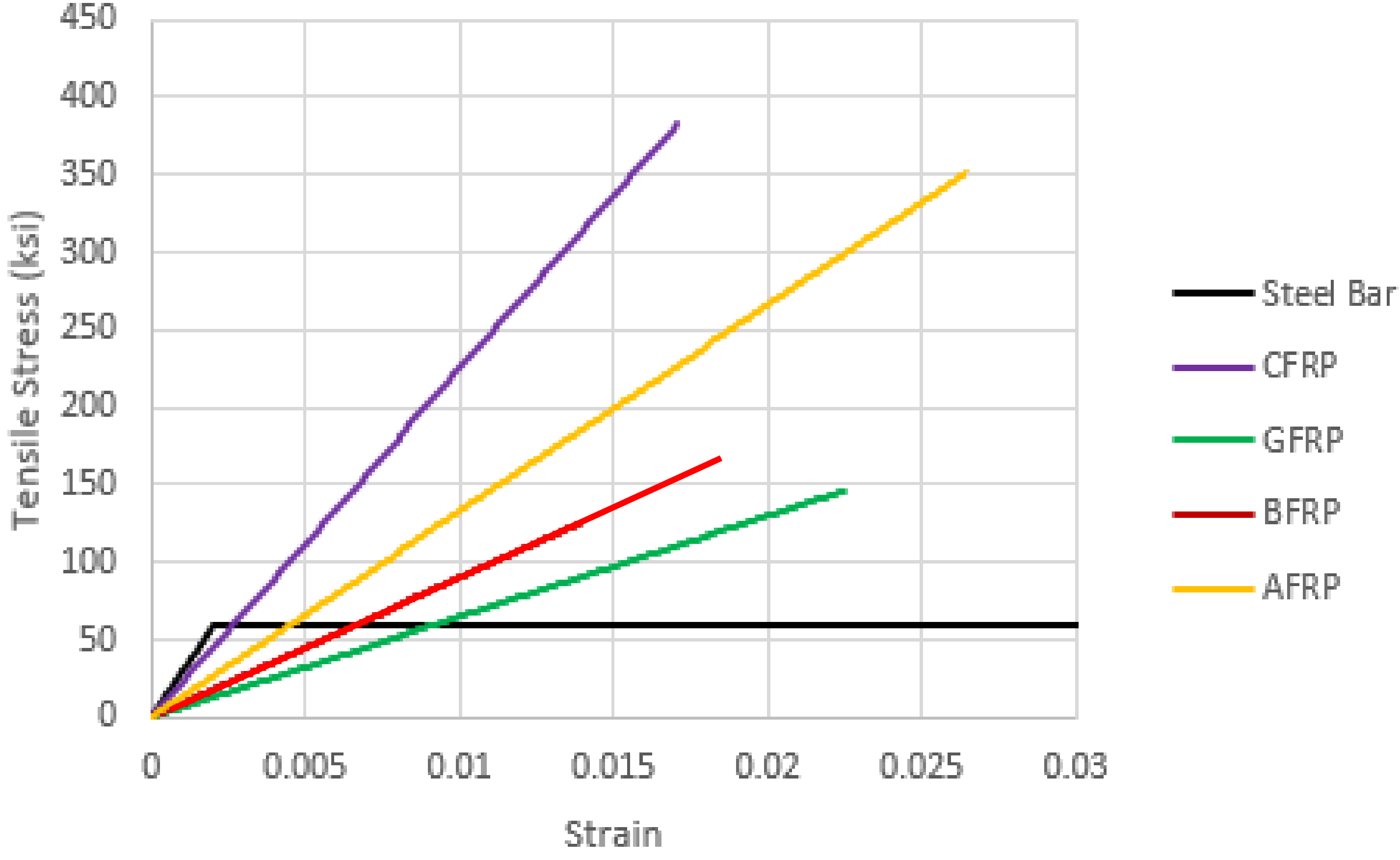
a. 3 to 4 times lower

b. Comparable

c. 2 to 3 times higher

d. 3 to 4 times higher

Applied Questions



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Applied Questions

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

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

b. Comparable

c. 2 to 3 times higher

d. 3 to 4 times higher

Applied Questions

1.1.4) The durability of GFRP rebars __________________.

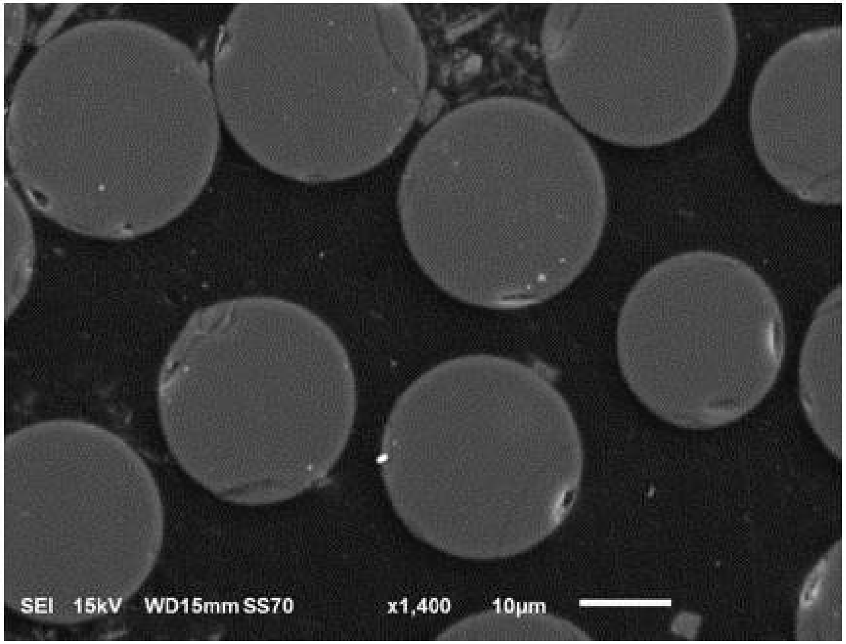
a. Has been proven through accelerated aging protocols and by samples extracted from bridges that have been in service for 15 years

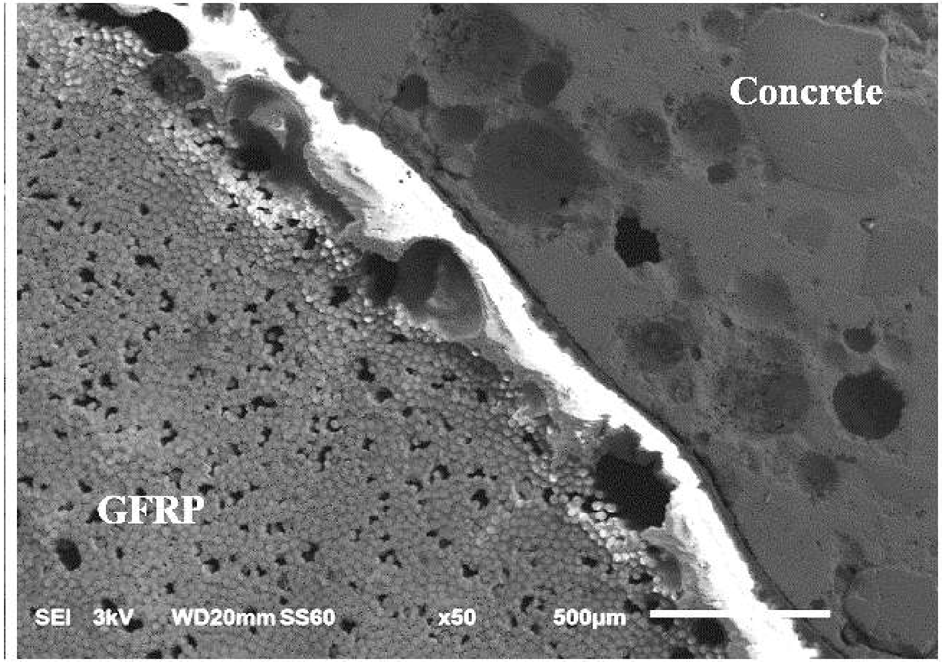
b. Is unknown

c. Is lower than steel

d. a) and c) are true

Durability





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

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Applied Questions

1.1.4) The durability of GFRP rebars ___________________.

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

b. Is unknown

c. Is lower than steel

d. a) and c) are true

Applied Questions

1.1.5) The density of GFRP is about ______________________.

a. About 4 times lighter than steel

b. Similar to that of steel

c. About 4 times heavier than steel

d. Half that of steel

FRP Density

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

Applied Questions

1.1.5) The density of GFRP is about ____________________.

a. **About 4 times lighter than steel**

b. Similar to that of steel

c. About 4 times heavier than steel

d. Half that of steel

Applied Questions

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

a. Transverse

b. Parallel

Transverse vs. Parallel Strength

Parallel - Tensile

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

Transverse - Shear

- > 22ksi
- Almost independent of bar size

Applied Questions

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

a. Transverse

b. Parallel

Applied Questions

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

a. The same as straight GFRP reinforcing bars

b. 40% of the straight GFRP reinforcing bars

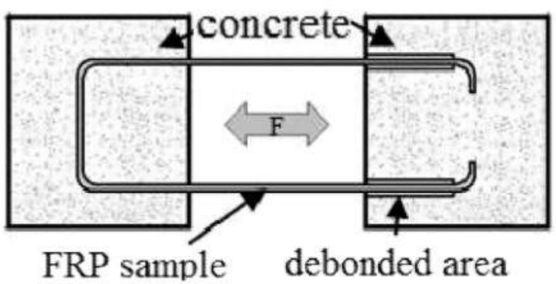
c. 60% of the straight GFRP reinforcing bars

d. 140% of the straight GFRP reinforcing bars

Strength of FRP at Bent

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

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



Applied Questions

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

a. The same as straight GFRP reinforcing bars

b. 40% of the straight GFRP reinforcing bars

c. 60% of the straight GFRP reinforcing bars

d. 140% of the straight GFRP reinforcing bars

Applied Questions

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

a. The mean tensile strength of the sample population

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

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

d. None of the above

Material Characterization

Tensile test
[*ASTM* D7205]

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

AASHTO 2.4.2.1:

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

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Applied Questions

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

a. The mean tensile strength of the sample population

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

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

d. None of the above

Applied Questions

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

a. 60 ^{o}F

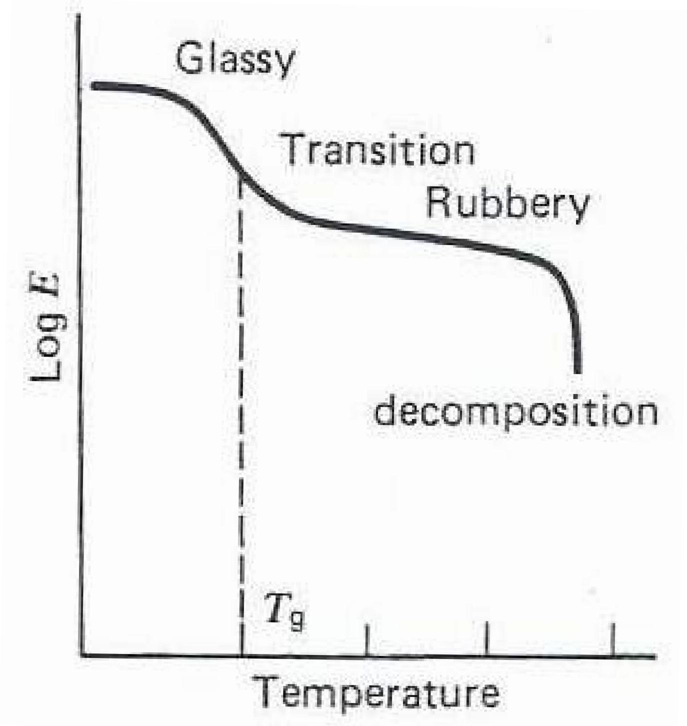
b. 212 ^{o}F

c. 1220 ^{o}F

d. 2500 ^{o}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 ^oF (100 ^oC) for Vinyl Ester typically used GFRP rebars**
- T_g lowers as a result of moisture absorption



Elastic Modulus vs Temperature

Applied Questions

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

a. 60 ^{o}F

b. 212 ^{o}F

c. 1220 ^{o}F

d. 2500 ^{o}F

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AASHTO GFRP-Reinforced Concrete Design Training Course



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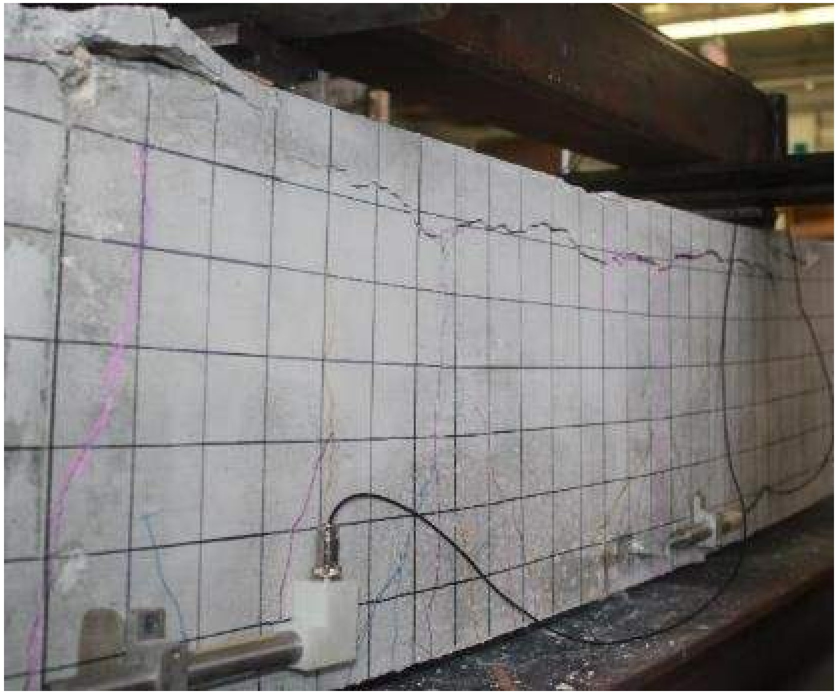
Course Outline

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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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 = nominal capacity

M_u = factored demand

$$\phi M_n \geq M_u$$

ϕ = strength reduction factor (depends on the mode of failure)

For ***AASHTO,*** example

$$M_u = 1.25 M_{DC} + 1.75 M_{LL}$$

For ACI, example

$$M_u = 1.2 M_D + 1.6 M_L$$

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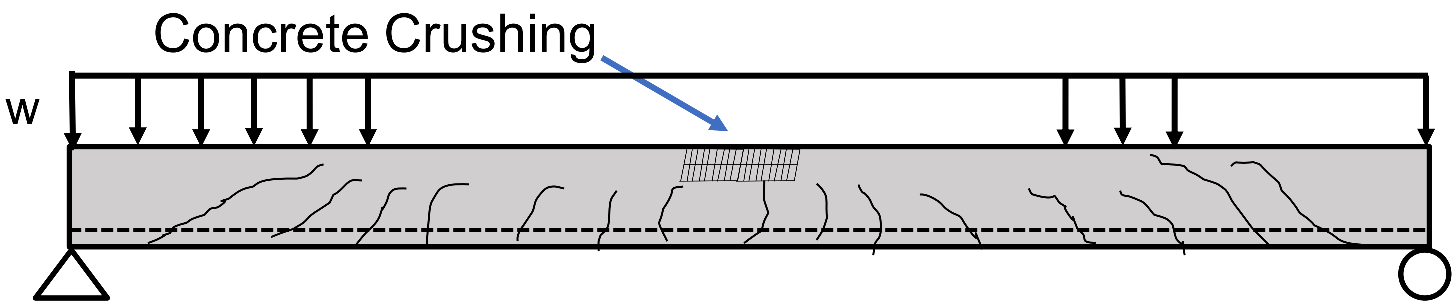
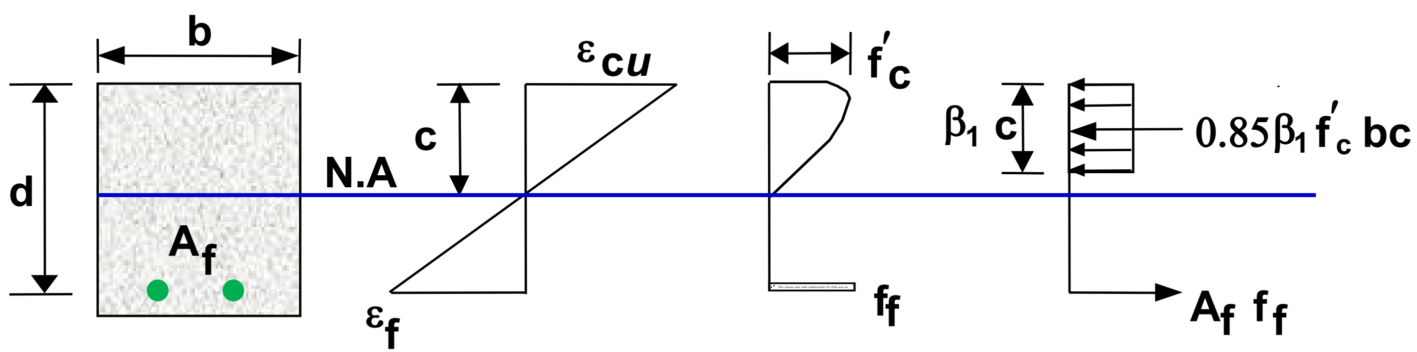
Failure Modes

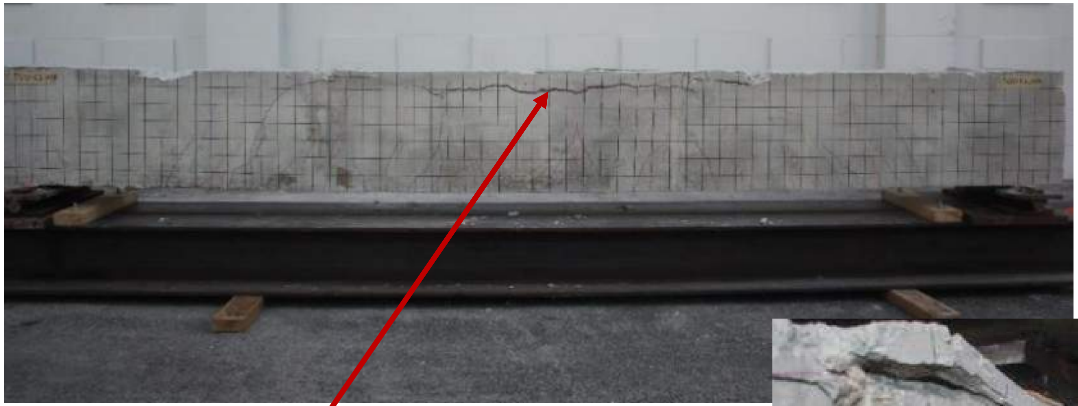
Compression-controlled: concrete crushing

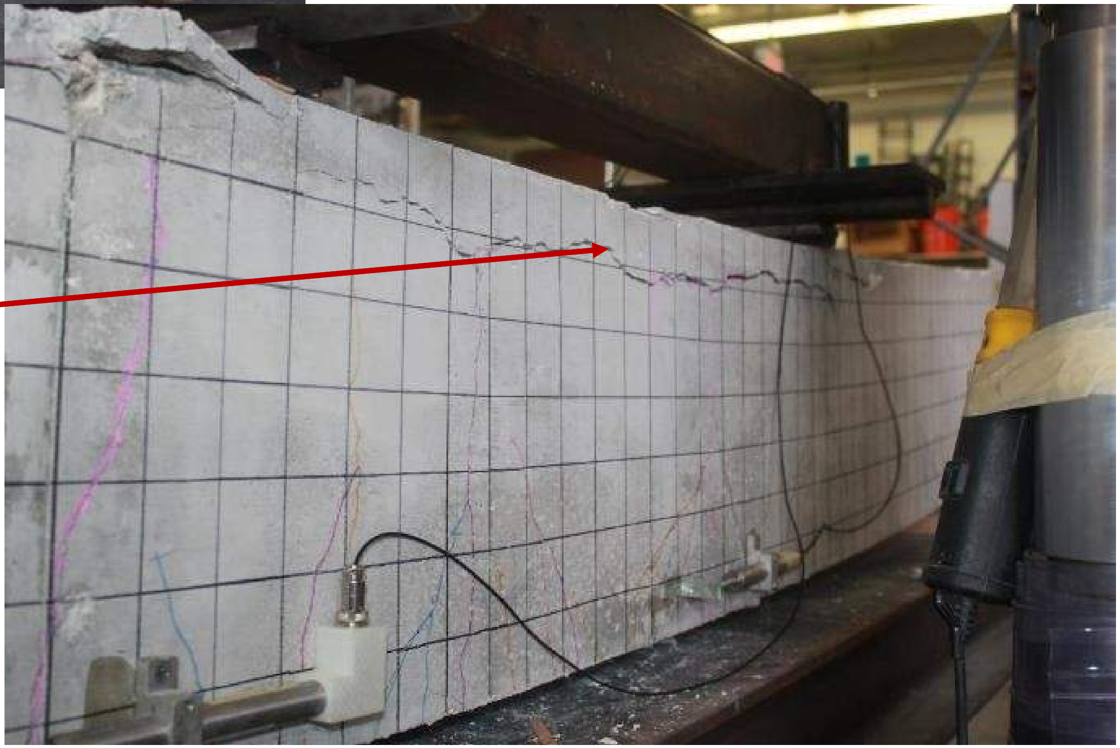




$\beta_1 c = a$

Failure Modes

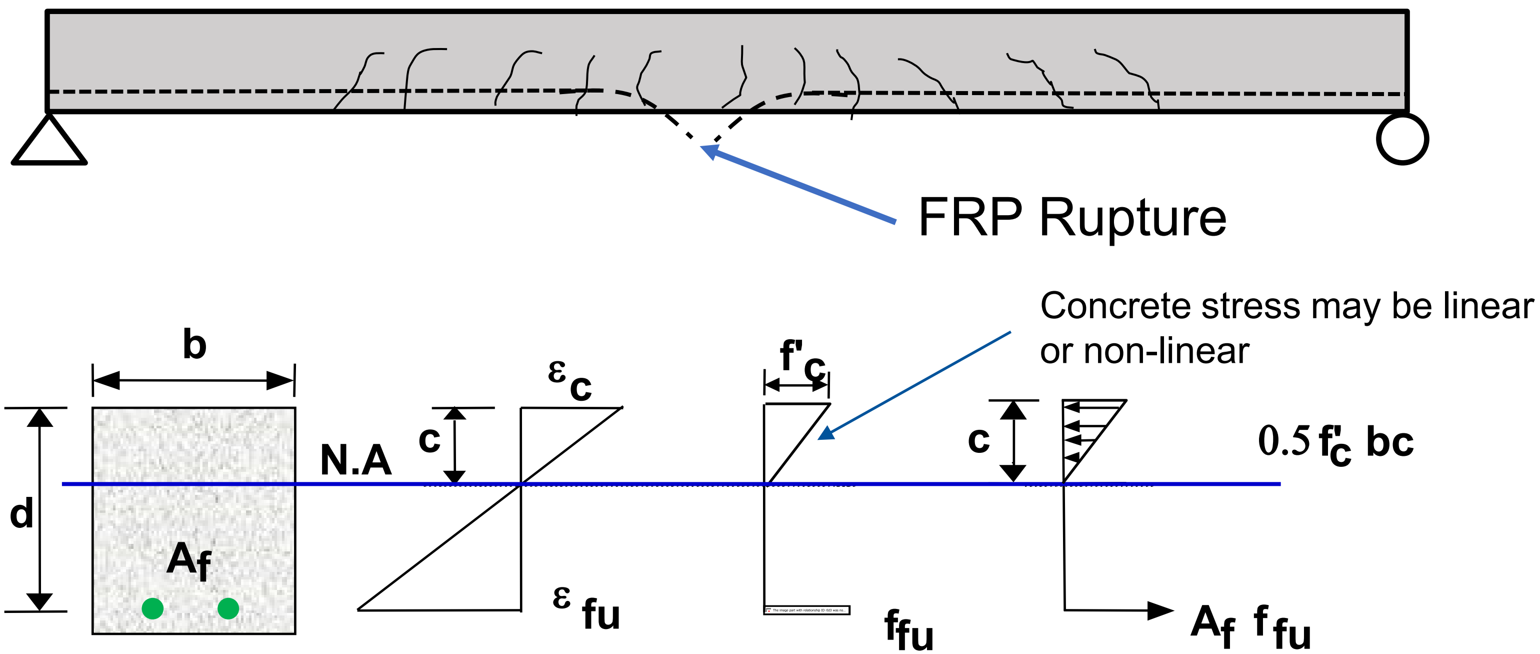




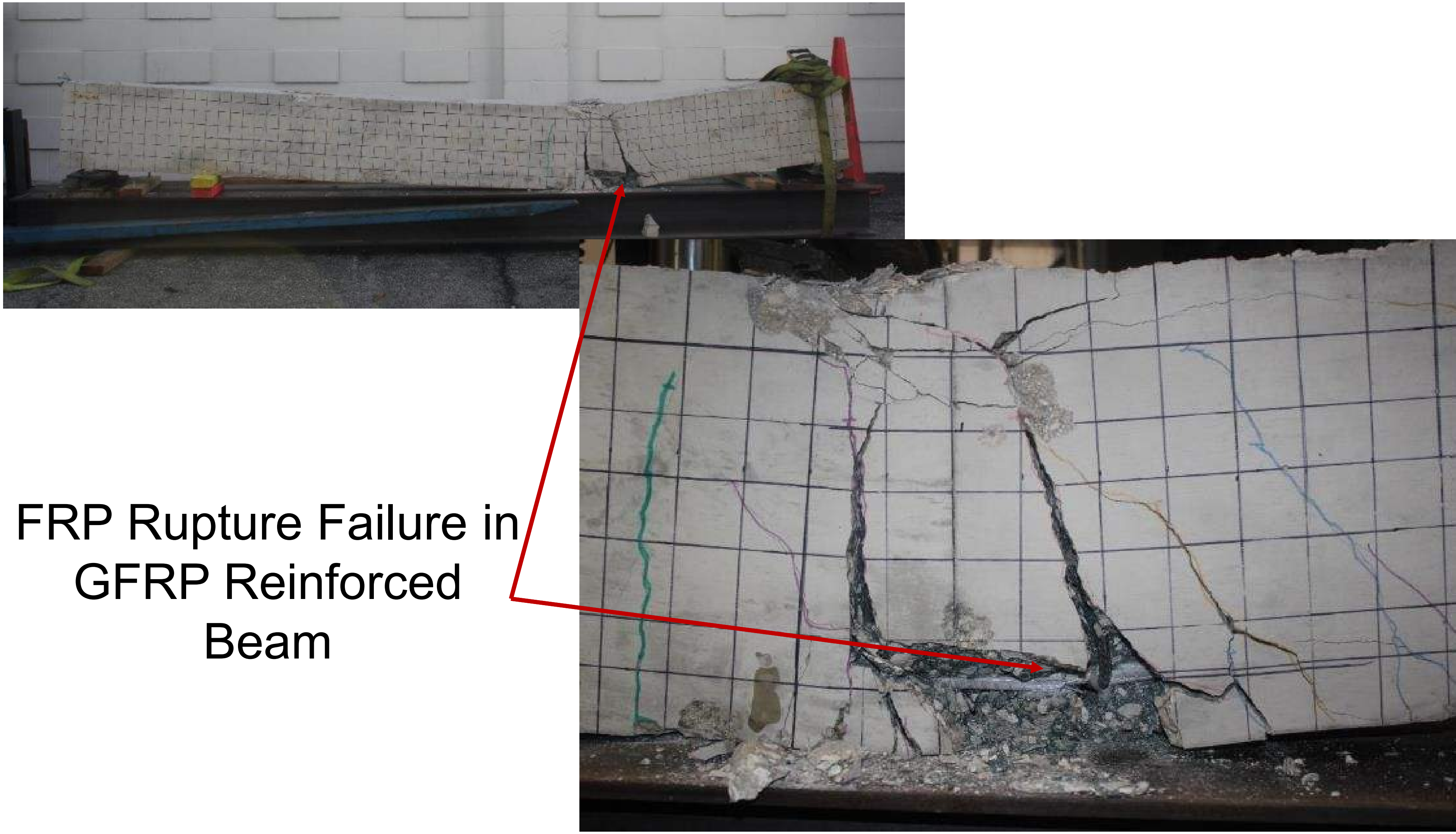
Concrete Crushing Failure in GFRP-RC Beam

Failure Modes

Tension-controlled: FRP rupture



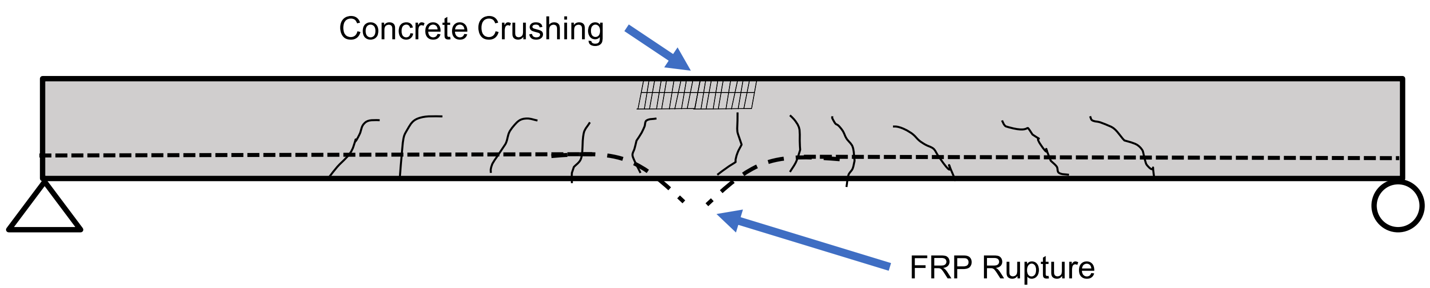
Failure Modes

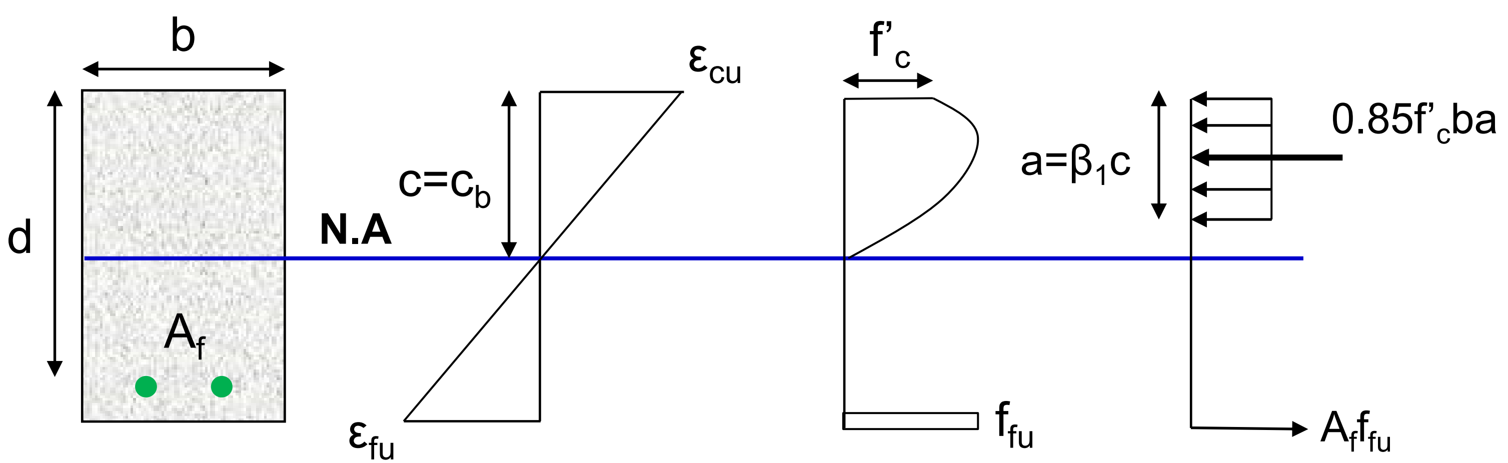


FRP Rupture Failure in GFRP Reinforced Beam

Failure Modes

Balanced failure: simultaneous concrete crushing & FRP rupture

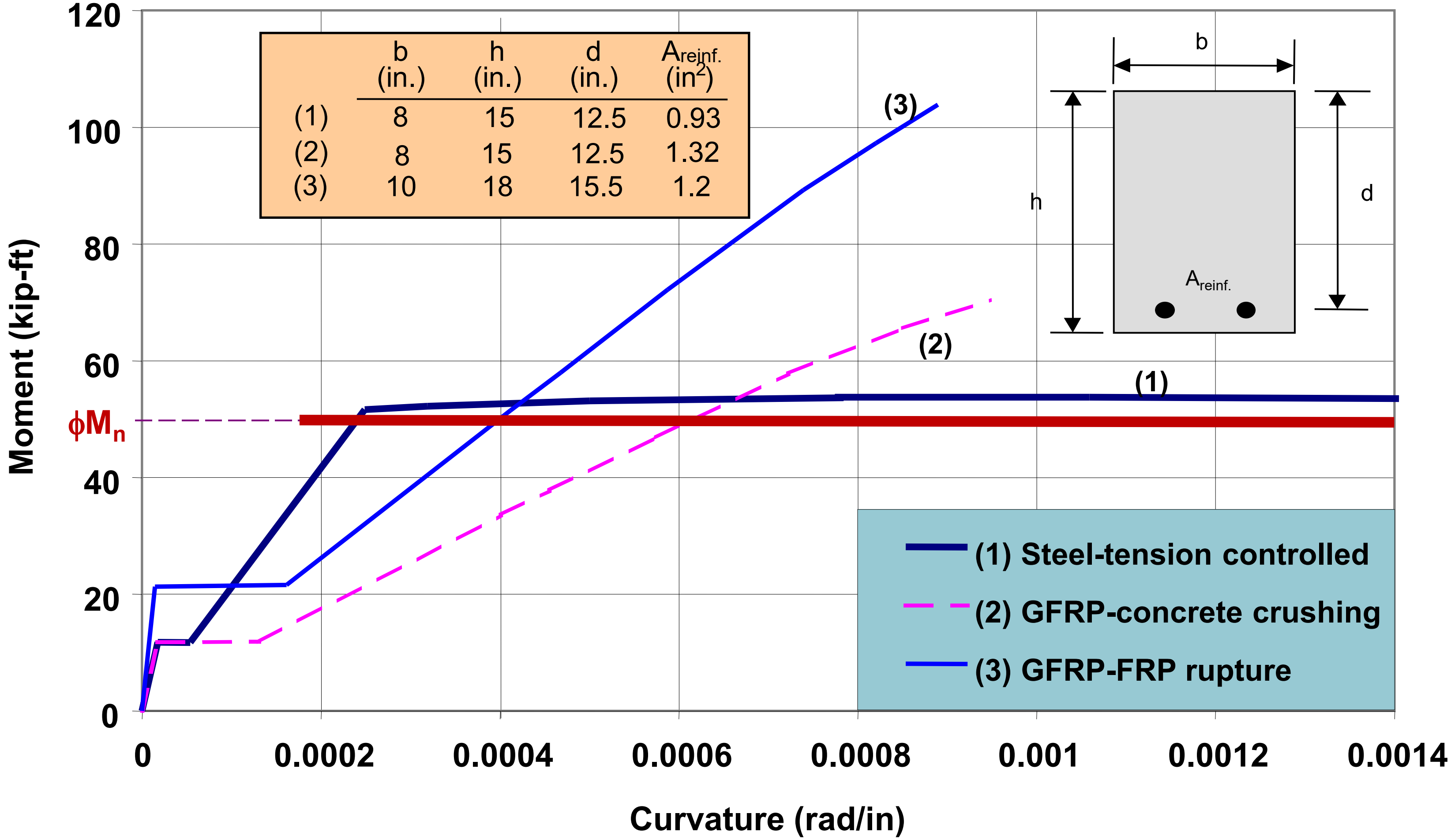




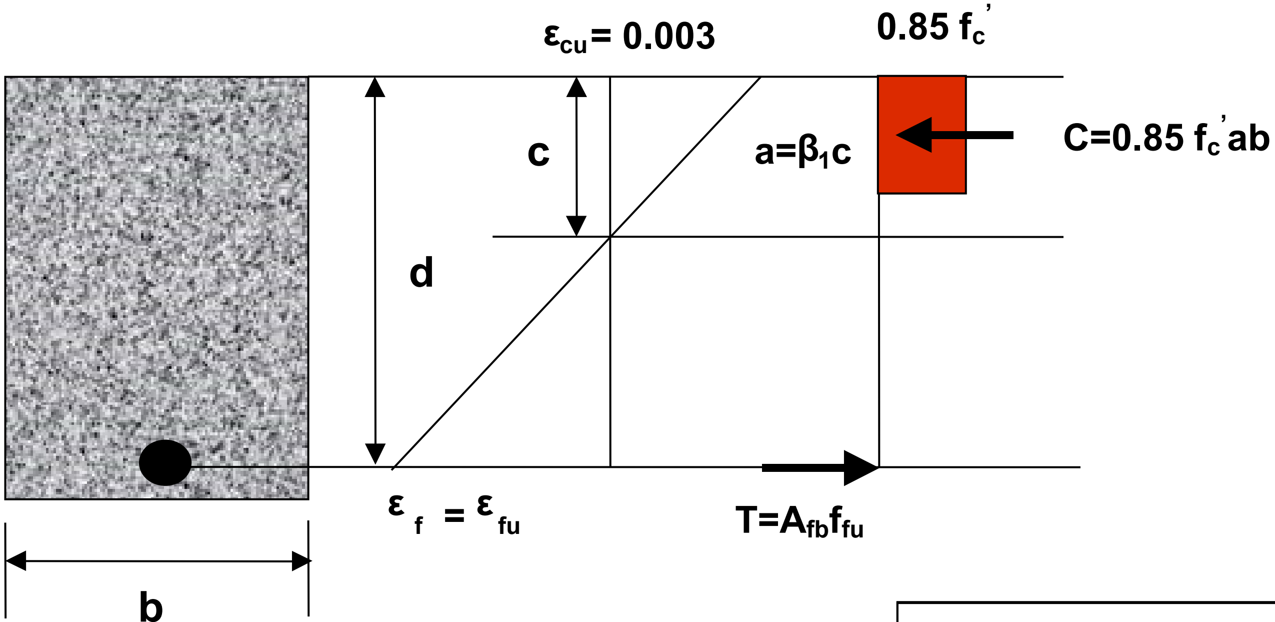
General Considerations

- 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 Φ factors)

Moment-Curvature Diagrams



Balanced Failure



$$\rho_f = \frac{A_{fb}}{bd}$$

(AASHTO 2.5.3)

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

Where it can be shown that:

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

$$T = A_{fb} f_{fu} \quad = \rho_{fb} f_{fu} bd$$

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 ρ_b , ρ_{fb}	
STEEL GRADE 60	$\rho_b = 0.0335$
GFRP F80-E6	$\rho_{fb} = 0.0078$

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- General Considerations
- **Bending Moment Capacity**
- Serviceability
- Static & Cyclic Fatigue
- Anchorage and Development
- Special Considerations
- Concluding Remarks

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Nominal Flexural Strength: Compression

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

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

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

WHERE

$$a = \frac{A_f f_f}{0.85 f_c' b}$$ **(AASHTO 2.6.3.2.2-2)**

$$f_f = \sqrt{\frac{\left(E_f \varepsilon_{cu}\right)^2}{4} + \frac{0.85\beta_1 f_c'}{\rho_f} E_f \varepsilon_{cu}} - 0.5 E_f \varepsilon_{cu} \leq f_{fu}$$ **(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 $\varepsilon_{ft} = \varepsilon_{fu}$

$$M_n = A_f f_{fu}\left(d - \frac{\beta_1 c_b}{2}\right)$$

(AASHTO 2.6.3.2.2.-3)

WHERE

$$c_b = \left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fu}}\right) d$$

(AASHTO 2.6.3.2.2.-4)

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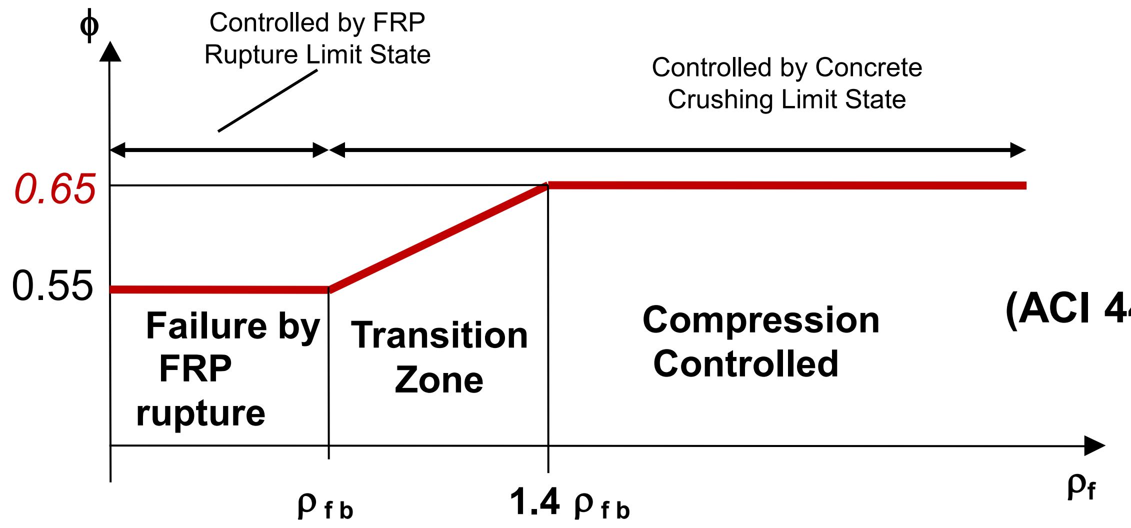
Strength Reduction Factor (ACI)

Φ as a function of GFRP reinforcement ratio



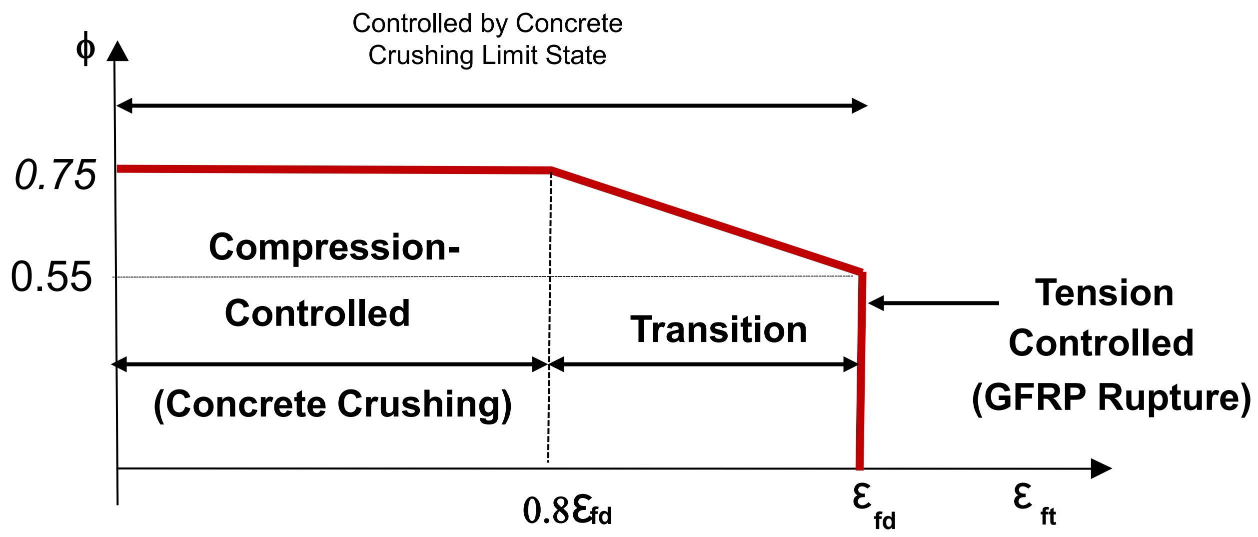
(ACI 440 7.2.3)

$$\phi = \begin{cases} 0.55 \ for \ \rho_f \le \rho_{fb} \\ 0.3 + 0.25\dfrac{\rho_f}{\rho_{fb}} for \ \rho_{fb} < \rho_f < 1.4\rho_{fb} \\ 0.65 \ for \ \rho_f \ge 1.4\rho_{fb} \end{cases}$$

(ACI 440 7.2.3)

Strength Reduction Factors (AASHTO)

Φ as a function of strain in GFRP



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

(AASHTO 2.5.5.2)

Minimum Flexural Reinforcement

Minimum longitudinal reinforcement to provide adequate level of protection against **sudden** failure at formation of first flexural crack

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

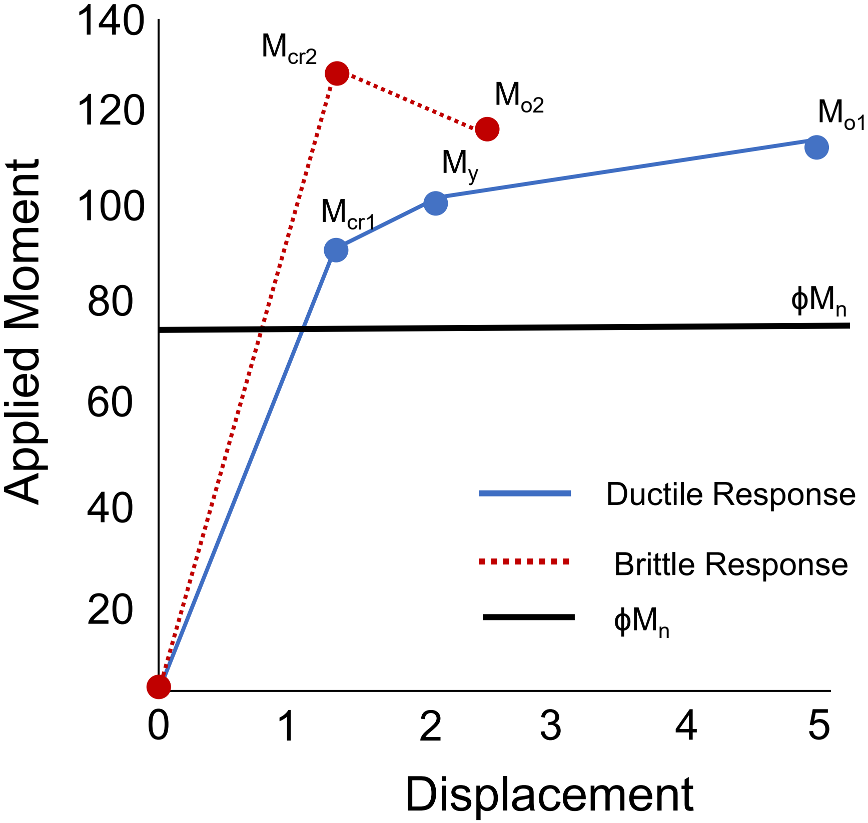
f_r = modulus of rupture of concrete

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

(AASHTO 2.6.3.3-1)



Illustrative example on ductile and brittle responses

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- General Considerations
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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.

$$\boldsymbol{k_b} = \begin{cases} > 1 & Worse\ than\ steel \\ < 1 & Better\ than\ steel \end{cases}$$

$$\boldsymbol{C_b} = \frac{\boldsymbol{1}}{\boldsymbol{k_b}} = \begin{cases} > 1 & Better\ than\ steel \\ < 1 & Worse\ than\ steel \end{cases}$$

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.:

$$s_{max} \leq \min\left(1.15\frac{C_b E_f w}{f_{fs}} - 2.5c_c, 0.92\frac{C_b E_f w}{f_{fs}}\right)$$

(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:

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

(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.)

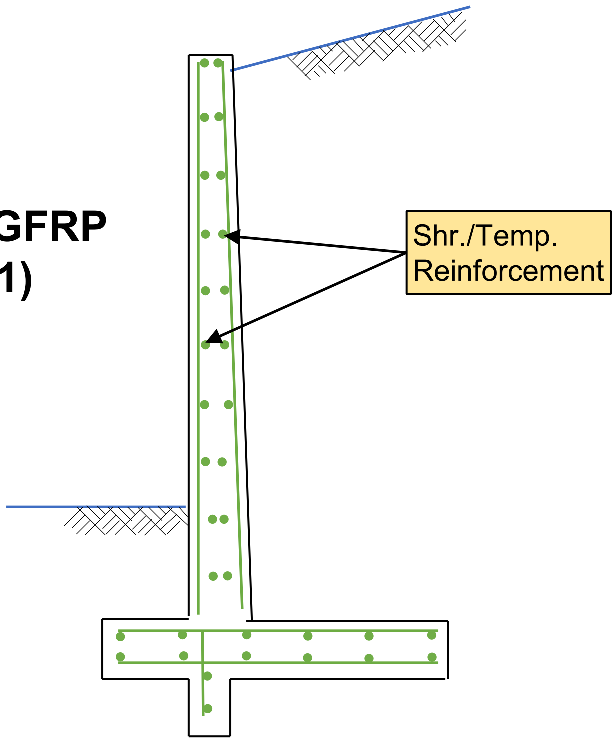
ξ = ratio of distance from neutral axis to extreme tension fiber, $(h - kd)$, to distance from neutral axis to center of tensile reinforcement, $(d - kd)$.

Shrinkage & Temperature Reinforcement

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

$$\rho_{f,st} = \max\left(\frac{3{,}132}{E_f f_{fd}}; 0.0014\right) \leq 0.0036$$

AASHTO GFRP (2.9.6-1)



Adapted from FDOT Index 400-010

Spacing:

- ≤ $3t_{slab}$ or 12 in.
- Evenly distributed on both surfaces if member is greater than 6 in.

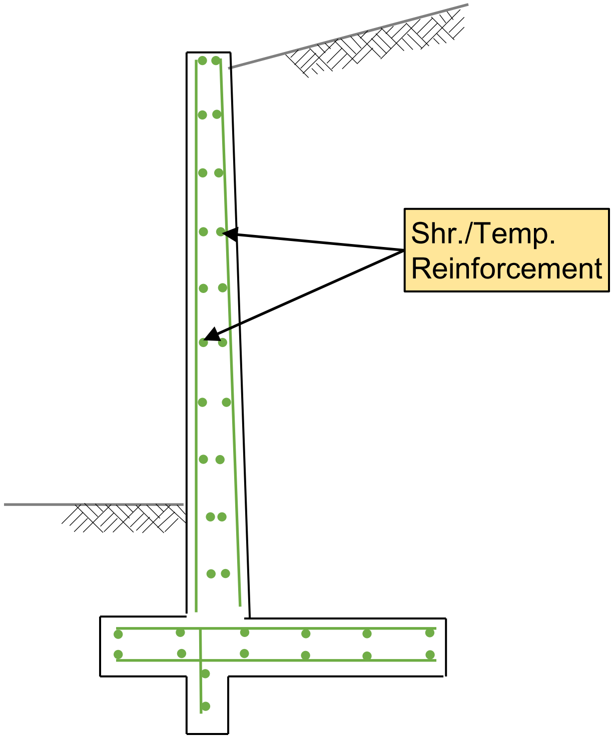
Shrinkage & Temperature Reinforcement

GFRP-RC retaining wall example:

Properties

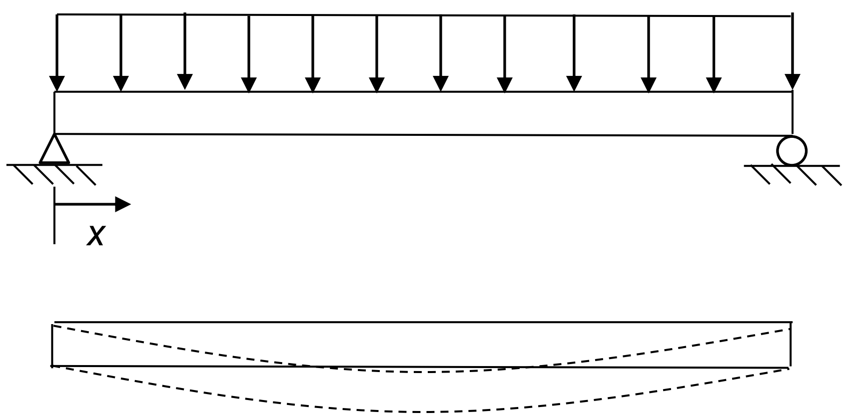
Width of Wall Average:	13.4 in.
Height of Wall:	18 ft.
Bar Size of Temp. Reinf.	#4
Elastic Modulus of GFRP, E_f	6,500 ksi, 8,700 ksi
Design Tensile Strength, f_{fd}	75.6 ksi, 105 ksi

Minimum Area of S/T Reinf.		
A_s	=	0.29 in^2/ft
$A_{f,6500\ ksi}$	=	0.58 in^2/ft
$A_{f,8700\ ksi}$	=	0.55 in^2/ft



Deflections

- AASHTO does not allow deflection control by **indirect method** (e.g., specifying minimum thickness of a member)
- **Direct method** of limiting computed deflections:
  - ✓ Simplified: Effective moment of inertia, I_e
  - ✓ Direct integration of moment curvature relationship



Curvature

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

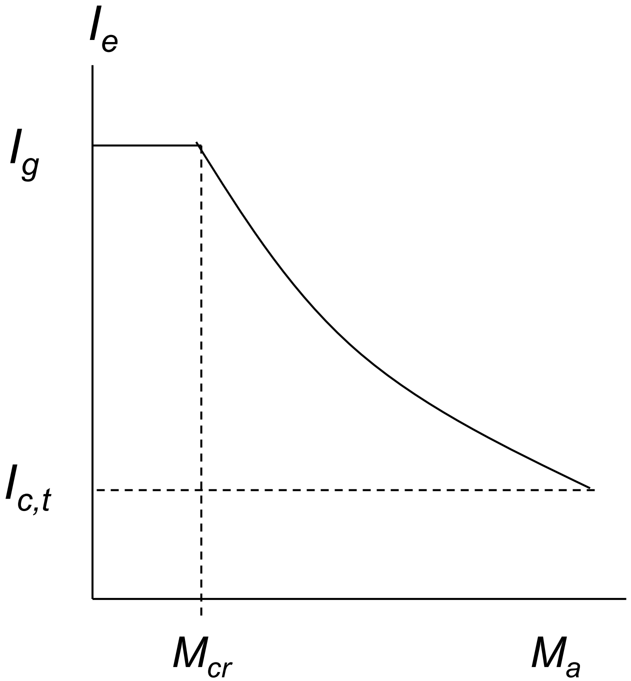
Deflection

$$y = \iint \frac{M}{EI} dx = \frac{kwl^3}{EI}$$

Deflections: Effective Inertia

Short-Term Loading

The overall (equivalent) flexural stiffness, $\boldsymbol{E_cI_e}$, of a member that has experienced cracking at service varies between $\boldsymbol{E_cI_g}$ an $\boldsymbol{E_cI_{cr}}$



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

AASHTO (2.6.3.2-1)

$$M_{cr} = f_r \frac{I_g}{y_t}$$

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, *kip-in*

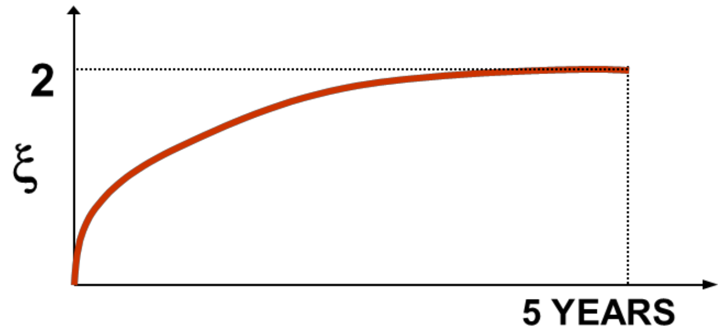
Long-Term Deflection

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*)

ξ = 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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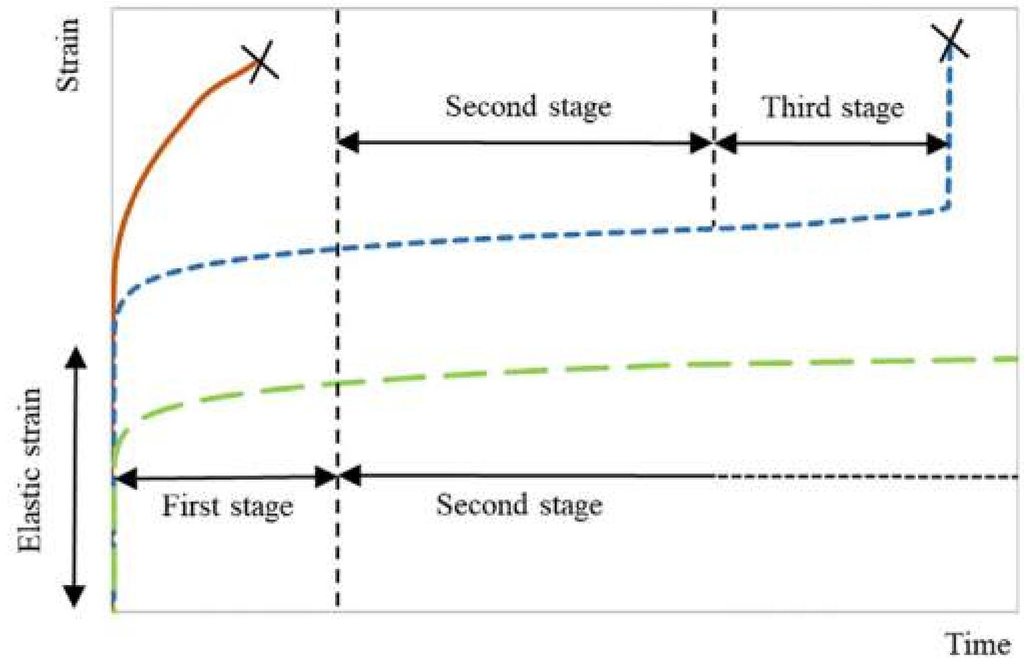
Static Fatigue (Creep Rupture)

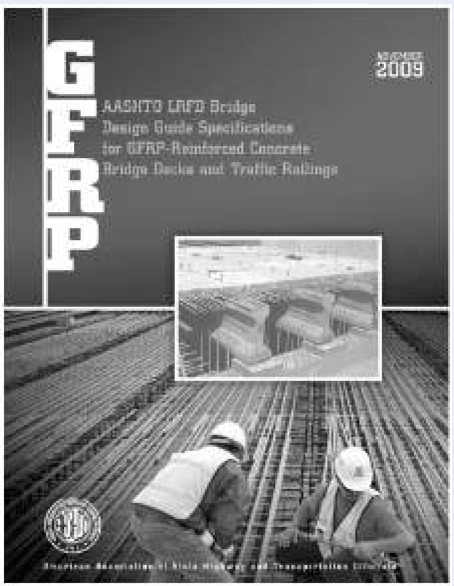
FRP reinforcing bars subjected to sustained load can suddenly fail after a time period called endurance time. This phenomenon is known as creep rupture (or static fatigue)

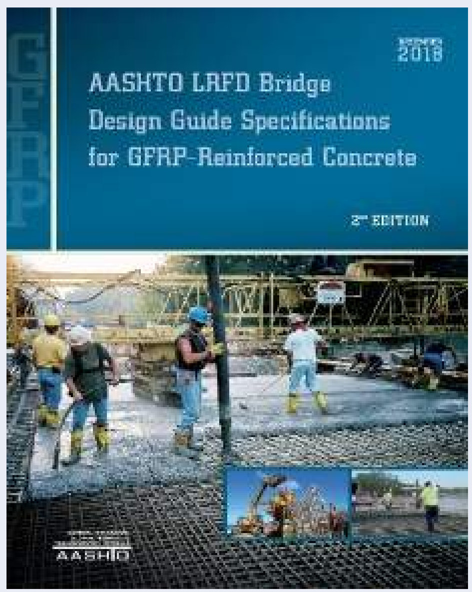


Creep stages in an FRP unidirectional composite

Creep Rupture Reduction Factor

AASHTO GFRP-1	AASHTO GFRP-2
2009	**2018**
Design of bridges	**Design of bridges**
$C_C = 0.20$	$\boldsymbol{C_C = 0.30}$





$$f_{f,s} = C_E C_C f_{fu}^{*}$$

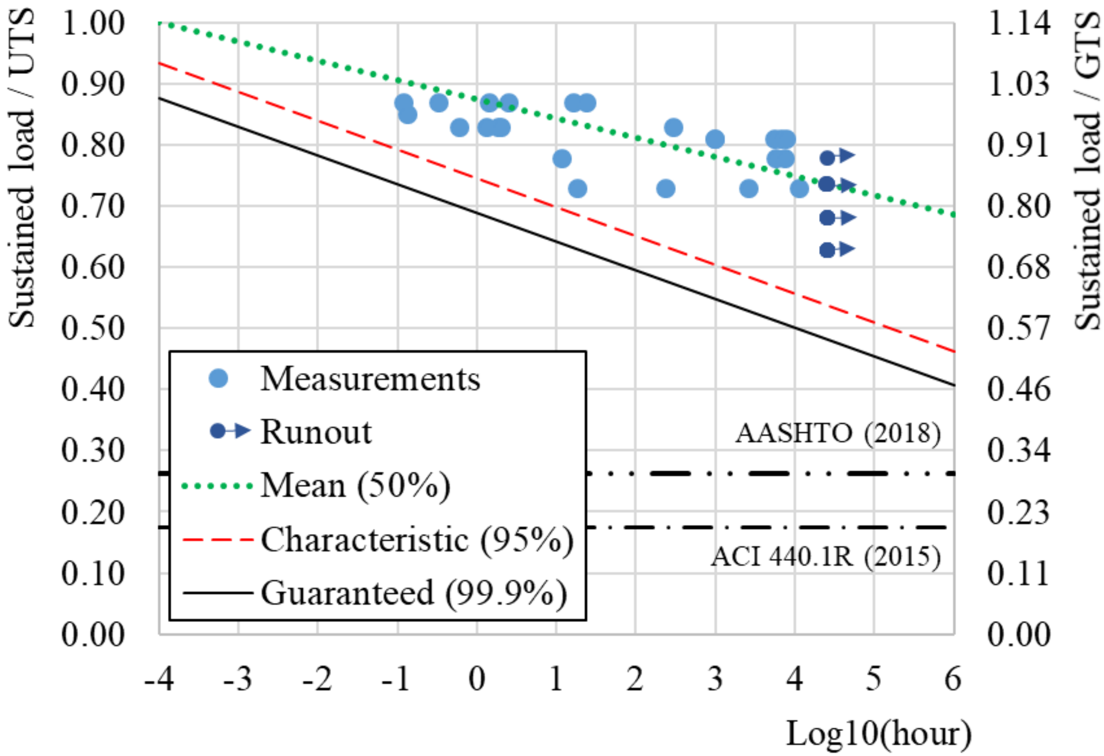
Creep rupture may govern the design of bridge

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 **(AASHTO 2.5.3-1)**

where

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

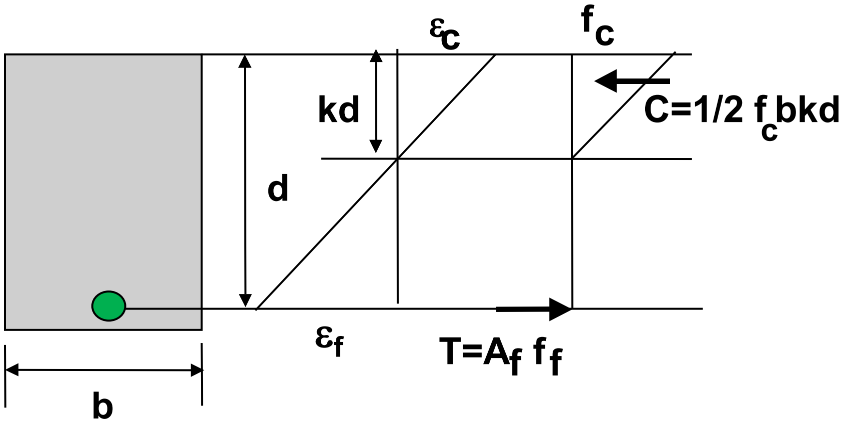
(AASHTO 2.5.3-2)

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 **(AASHTO 2.5.3-1)**

$M_{s,s}$ = the moment due to all sustained loads

$n_f = \frac{E_f}{E_c}$ modular ratio

$$k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f \qquad I_{cr} = \frac{bd^3}{3}k^3 + n_f A_f d^2 (1-k)^2$$

Cyclic Fatigue

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

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

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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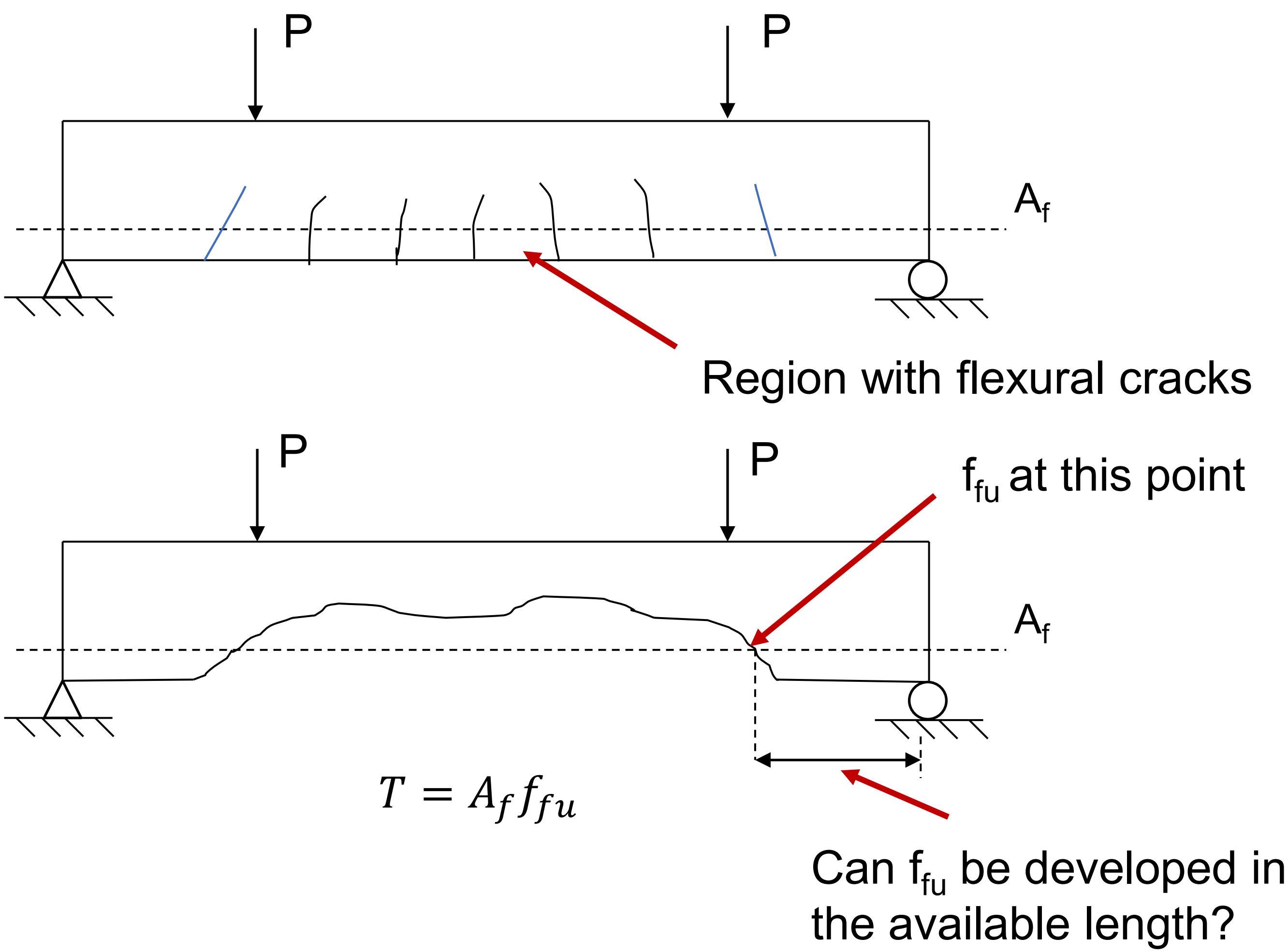
Anchorage Introduction



Development Length of Straight Bars

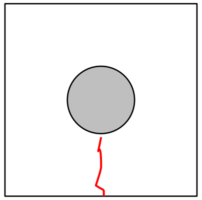
GFRP development length is **typically longer compared to steel** and is a function of the tensile stress in the bar

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

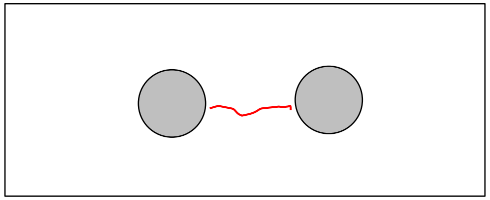
AASHTO (2.9.7.4.1-1)

where

α = 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 ½ the center to center bar spacing
Note: the value of C/d_b is limited to a max of 3.5



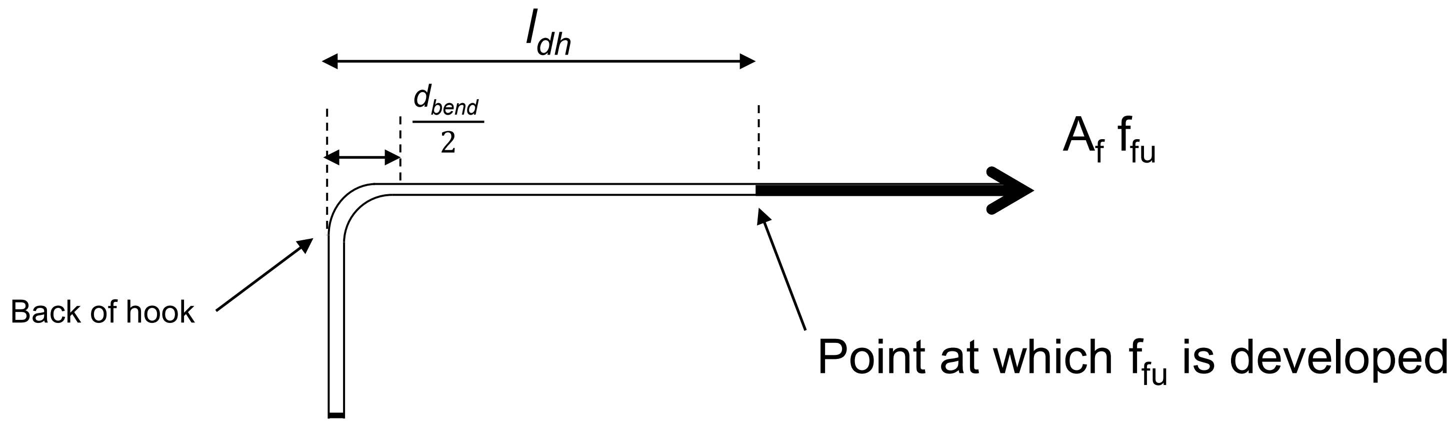
bar-cover



bar-bar

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:

$$l_{dh} = \begin{cases} 63.2\dfrac{d_b}{\sqrt{f_c'}}\ for & f_{fd} \le 75\ ksi \\ \dfrac{f_{fd}}{1.2}\dfrac{d_b}{\sqrt{f_c'}}\ for & 75\ ksi < f_{fd} \le 150\ ksi \\ 126.4\dfrac{d_b}{\sqrt{f_c'}}\ for & f_{fd} \ge 150\ ksi \end{cases}$$

AASHTO (2.9.7.4.3.1)

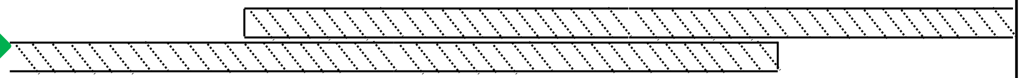
$$l_{dh} \ge 12d_b$$

$$l_{dh} \ge 9\ in$$

Splices

Types of splices currently possible with GFRP bars

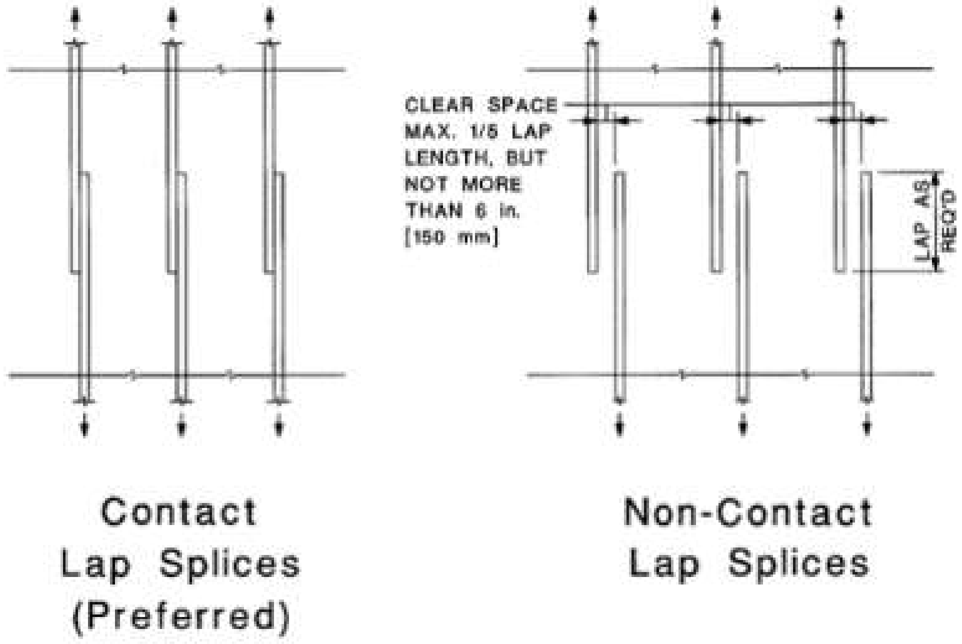
✓ **Lap Splice**



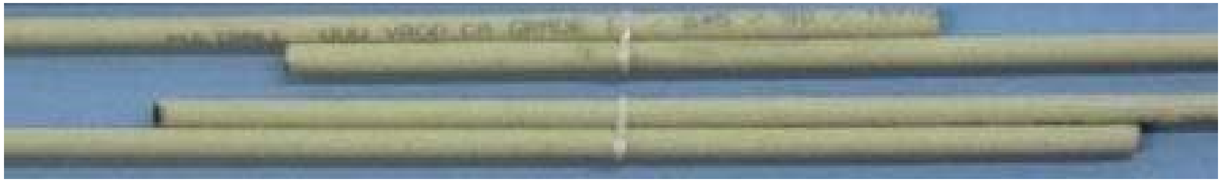
Mechanical Splice (Coupler)

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

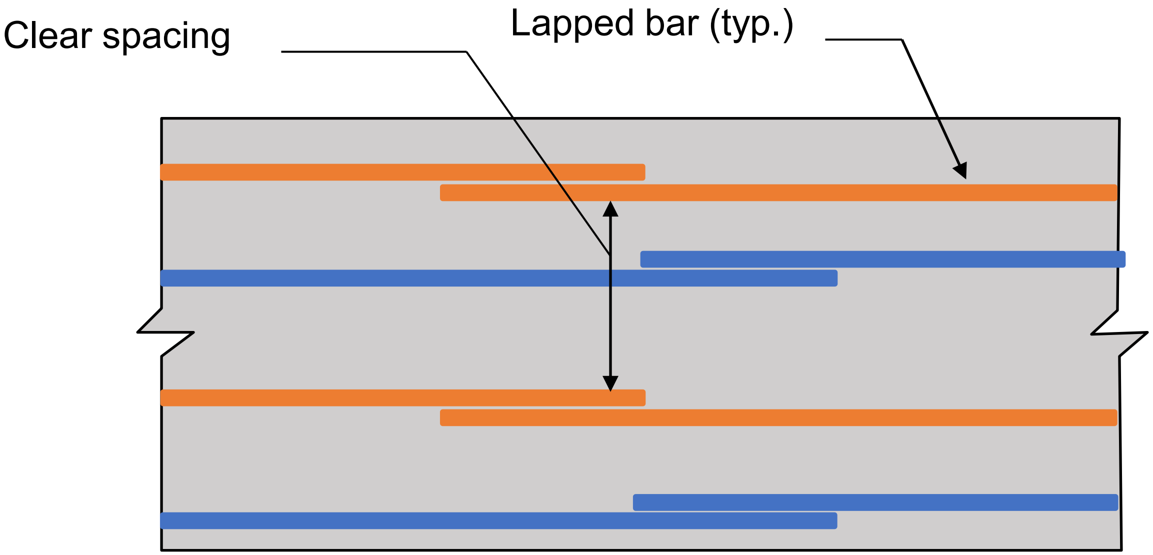


Lap Splices: Two overlapping bars, possibly tied together; staggered to reduce congestion; must overlap by required lap length



Tension Lap Splices

AASHTO spec requires staggered splices to provide redundancy



Clear spacing of lap-spliced bars for determination of l_{st} for staggered splices

Minimum splice length:

No splice class distinction

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

l_d calculated to provide 25% tensile force

AASHTO (2.9.7.6)

Table of Contents

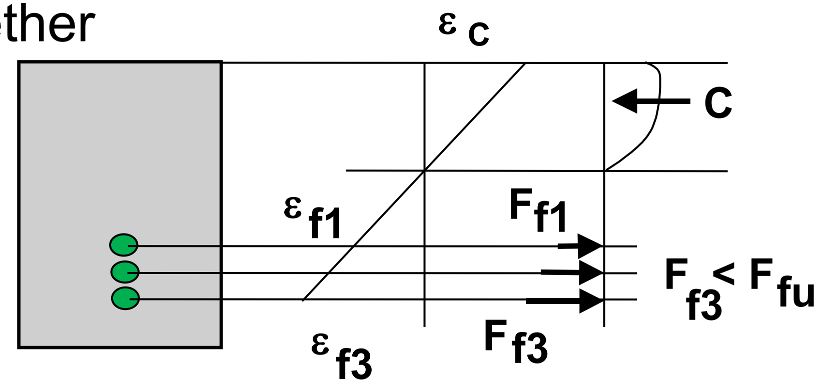
- General Considerations
- Bending Moment Capacity
- Serviceability
- Static & Cyclic Fatigue
- Anchorage and Development
- **Special Considerations**
- Concluding Remarks

Special Considerations

Multiple layers and/or differing types of bars

AASHTO (2.6.3.2.4)

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



Moment Redistribution

AASHTO (1.3)

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

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

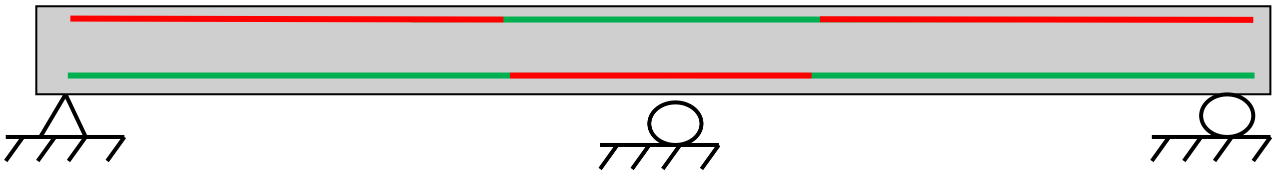


Table of Contents

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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 U

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: ______________________________.

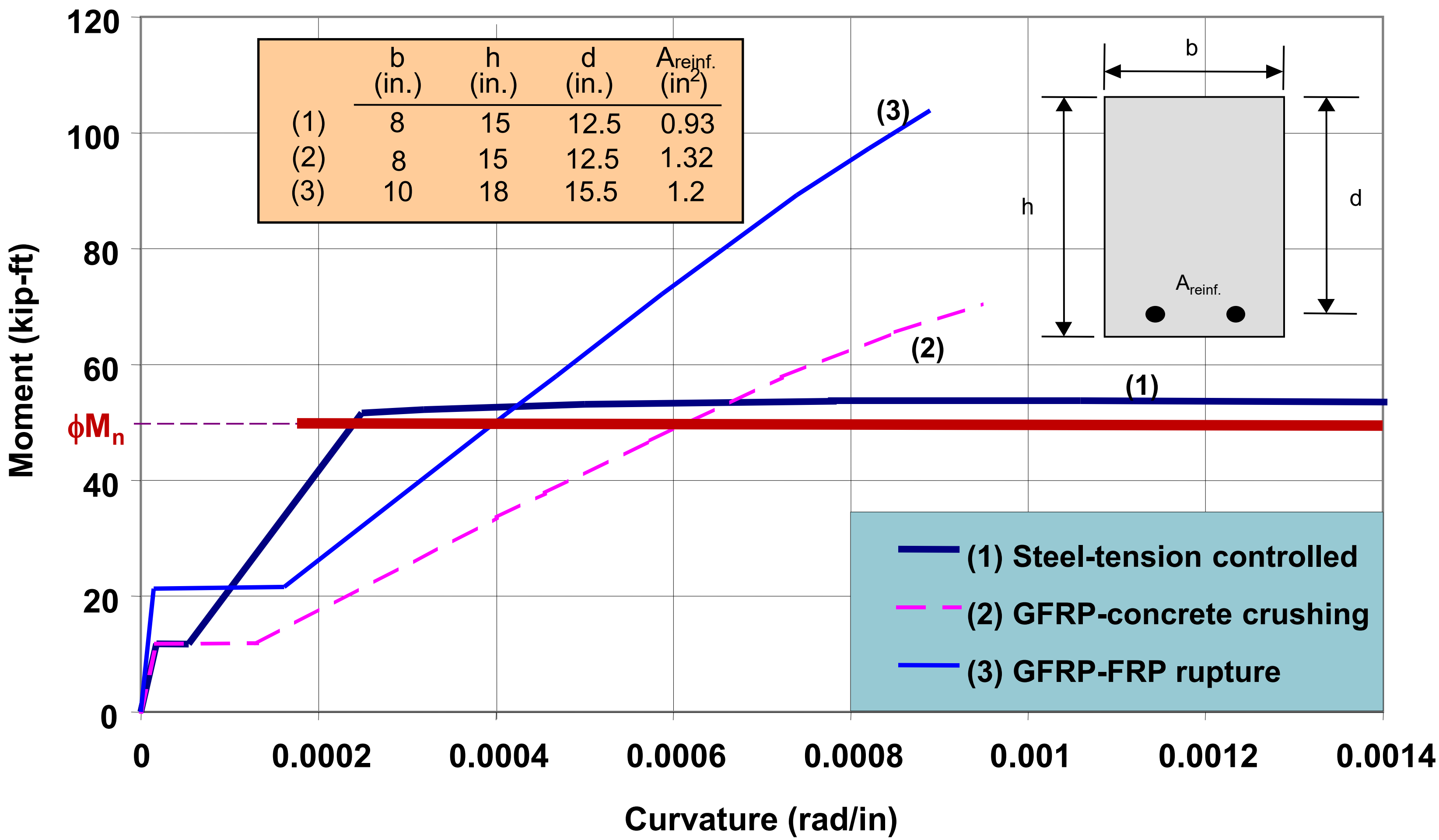
a. No difference

b. Larger deflections and wider crack widths

c. Wider crack widths

d. Larger deflections

Moment-Curvature Diagrams



	b (in.)	h (in.)	d (in.)	$A_{reinf.}$ (in^2)
(1)	8	15	12.5	0.93
(2)	8	15	12.5	1.32
(3)	10	18	15.5	1.2

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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

Review Questions

2.1.2) When designing structures with FRP the preferred failure mode in flexure is: ___________________________.

a. FRP rupture

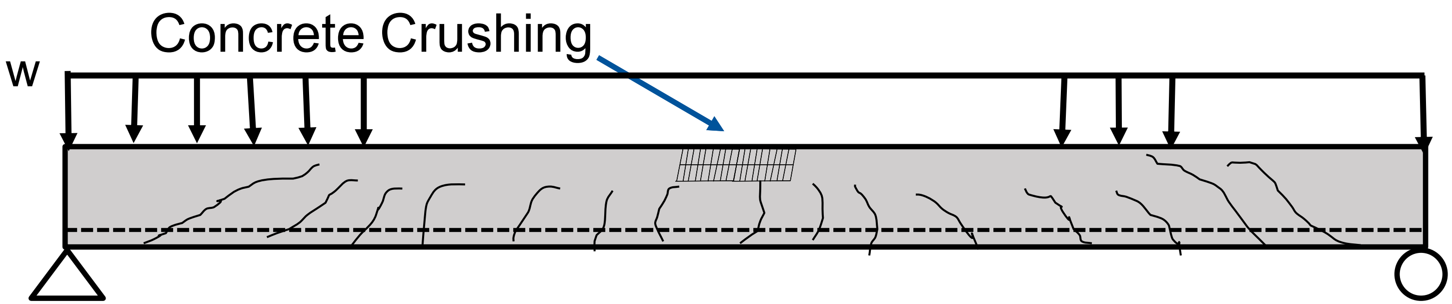
b. Concrete crushing

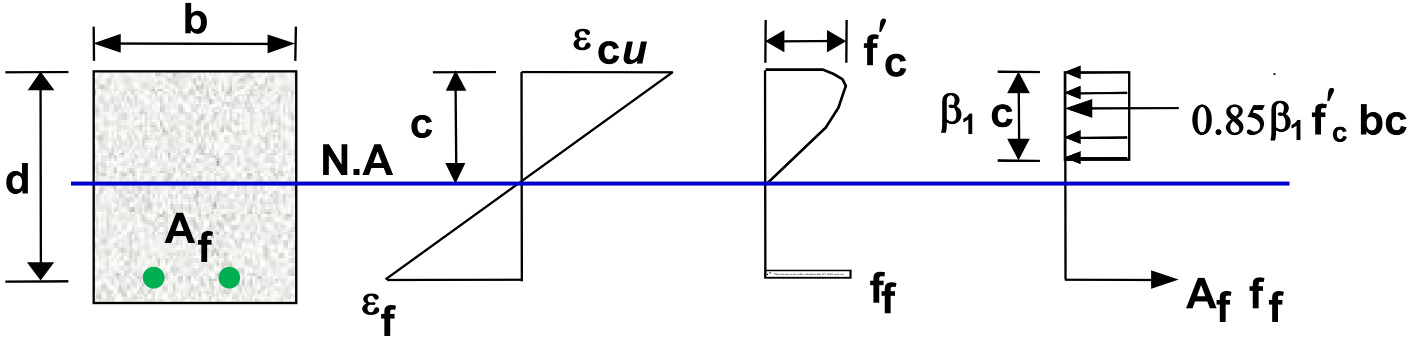
c. None – it is not safe to design with FRP

d. Debonding between reinforcement and concrete

Failure Modes

Compression-controlled: concrete crushing





$\beta_1 c = a$

Review Questions

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

Review Questions

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

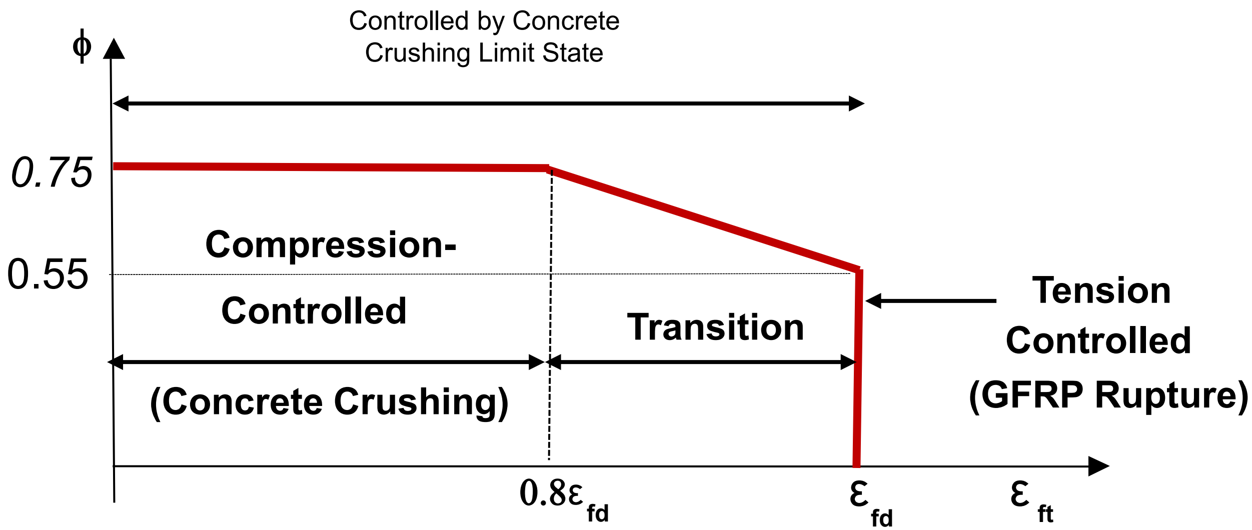
a. To account for the design of over-reinforced members

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)



$$\phi = \begin{cases} 0.55 & for\ \varepsilon_{ft} \le \varepsilon_{fd} \\ 1.55 - \dfrac{\varepsilon_{ft}}{\varepsilon_{fd}} & for \quad 0.80\varepsilon_{fd} < \varepsilon_{ft} < \varepsilon_{fd} \\ 0.75 & for\ \ \varepsilon_{ft} \ge 0.80\varepsilon_{fd} \end{cases}$$

(AASHTO 2.5.5.2)

Review Questions

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

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d. Because a member governed by GFRP bar rupture will have a brittle failure

Review Questions

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 = nominal capacity

M_u = factored capacity

$$\phi M_n \geq M_u$$

ϕ = strength reduction factor (depends on the mode of failure)

For ***AASHTO*** example

$$M_u = 1.25 M_{DC} + 1.75 M_{LL}$$

For ***ACI*** example

$$M_u = 1.2 M_D + 1.6 M_L$$

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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

Review Questions

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

a. The same as the development length of the bar

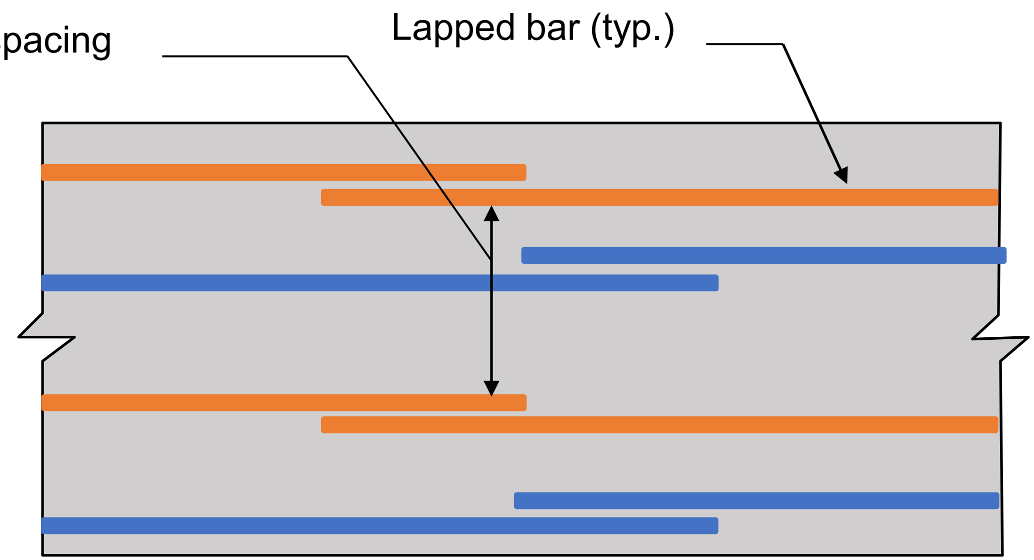
b. 1.25 times the development length of the bar

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



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No splice class distinction

Minimum splice length:

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

l_d calculated to provide 25% tensile force

AASHTO (2.9.7.6)

Review Questions

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

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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

Review Questions

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

AASHTO Table 3.4.1-1

Load Combination Limit State	DC DD DW EH EV ES EL PS CR SH	LL IM CE BR PL LS	WA	WS	WL	FR	TU	TG	SE	Use One of These at a Time				
										EQ	BL	IC	CT	CV
Strength I (unless noted)	γ_p	1.75	1.00	—	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
Strength II	γ_p	1.35	1.00	—	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
Strength III	γ_p	—	1.00	1.40	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
Strength IV	γ_p	—	1.00	—	—	1.00	0.50/1.20	—	—	—	—	—	—	—
Strength V	γ_p	1.35	1.00	0.40	1.0	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
Extreme Event I	γ_p	γ_{EQ}	1.00	—	—	1.00	—	—	—	1.00	—	—	—	—
Extreme Event II	γ_p	0.50	1.00	—	—	1.00	—	—	—	—	1.00	1.00	1.00	1.00
Service I	1.00	1.00	1.00	0.30	1.0	1.00	1.00/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
Service II	1.00	1.30	1.00	—	—	1.00	1.00/1.20	—	—	—	—	—	—	—
Service III	1.00	0.80	1.00	—	—	1.00	1.00/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
Service IV	1.00	—	1.00	0.70	—	1.00	1.00/1.20	—	1.0	—	—	—	—	—
Fatigue I— *LL*, *IM* & *CE* only	—	1.50	—	—	—	—	—	—	—	—	—	—	—	—
Fatigue II— *LL*, *IM* & *CE* only	—	0.75	—	—	—	—	—	—	—	—	—	—	—	—

Load factors are applicable with inclusion of new creep rupture limit state and load factors.

$$1.2DL + 0.2LL$$

Review Questions

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

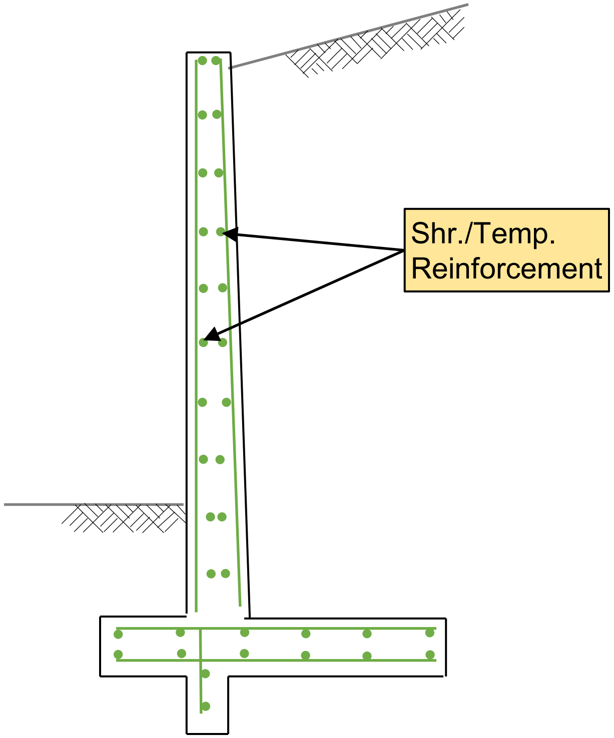
Shrinkage & Temperature Reinforcement

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

Minimum Area of S/T Reinf.	
A_s =	0.29 in^2/ft
$A_{f,6500\ ksi}$ =	0.58 in^2/ft
$A_{f,8700\ ksi}$ =	0.55 in^2/ft



Review Questions

2.1.8) The purpose of shrinkage reinforcement is: ____________________.

a. Distribute load

b. Improve development capacity of FRP

c. Control crack width

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FLEXURE RESPONSE OF GFRP REINFORCED CONCRETE

2.2 Design Example: Flat Slab

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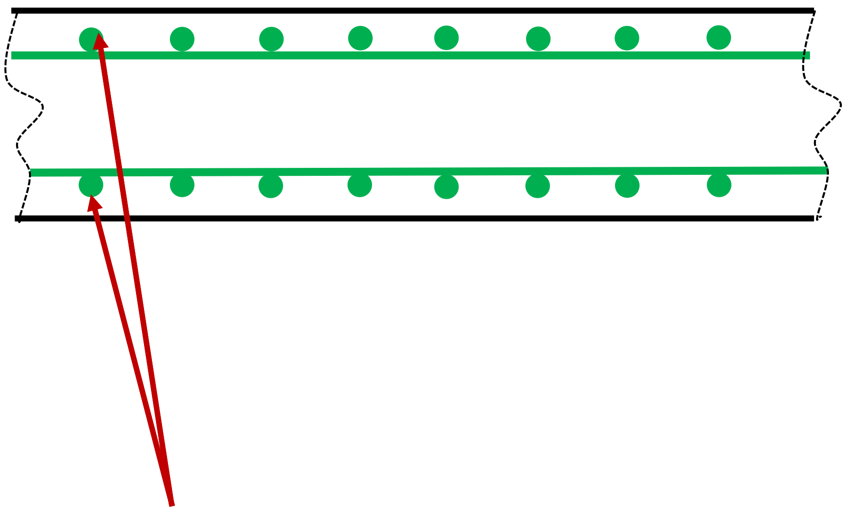
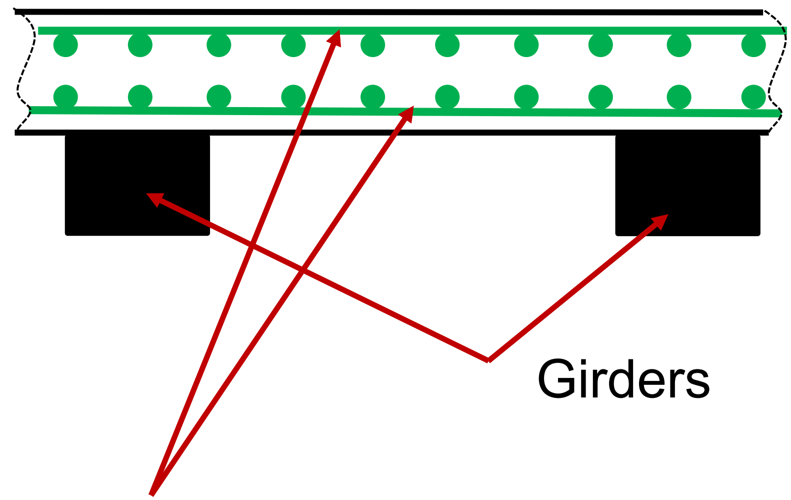
Flat Slab vs. Deck Type

Flat Slab



Longitudinal Bars Provide Flexural Resistance

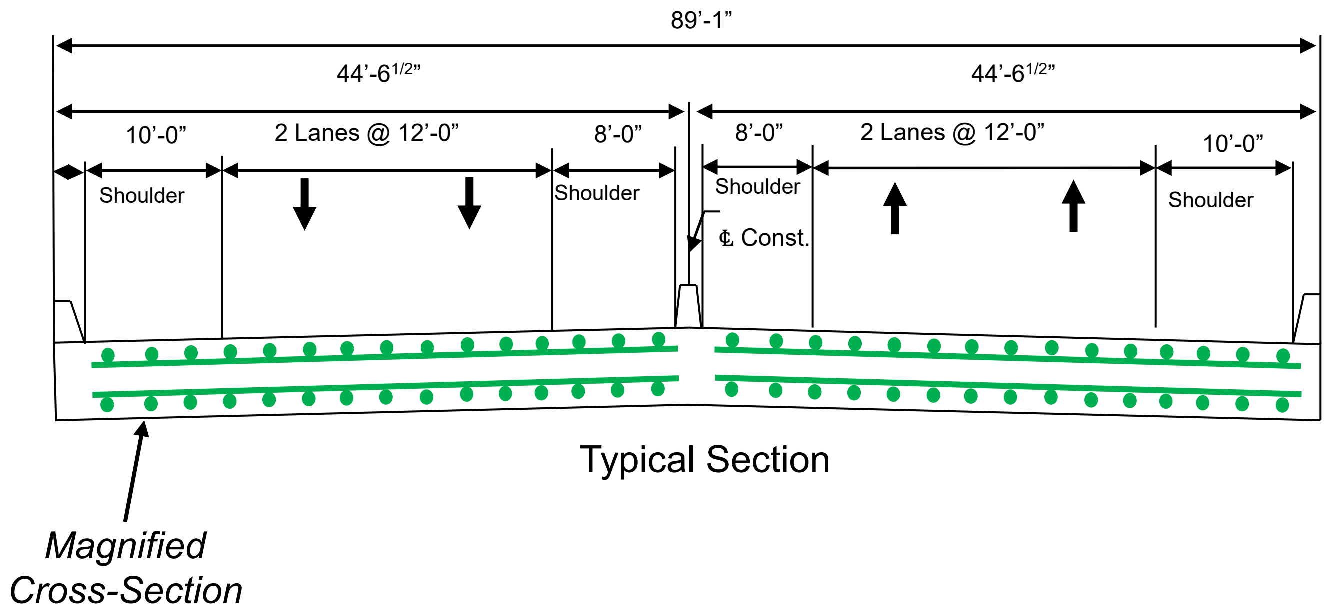
Deck



Transverse Bars Provide Flexural Resistance

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:

$$f_f = \sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85\beta_1 f_c'}{\rho_f} E_f \varepsilon_{cu}} - 0.5 E_f \varepsilon_{cu} \le f_{fd}$$

Check to see if GFRP has ruptured

$f_f < f_{fd}$

No: FRP Rupture

$$c = \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fd}} d$$

$$a = \beta_1 c_b$$

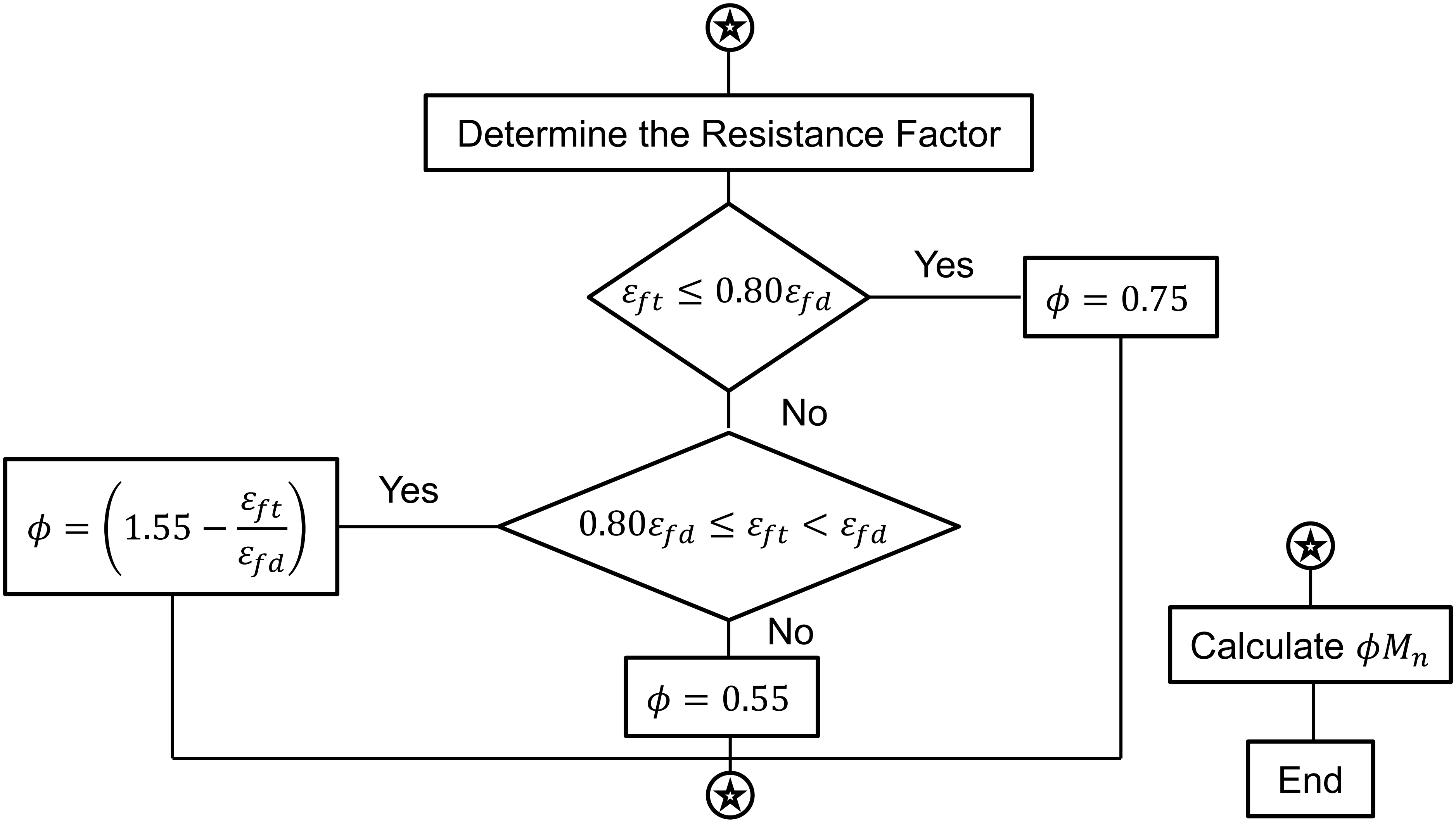
$$M_n = A_f f_{fd}\left(d - \frac{a}{2}\right)$$

Yes: 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

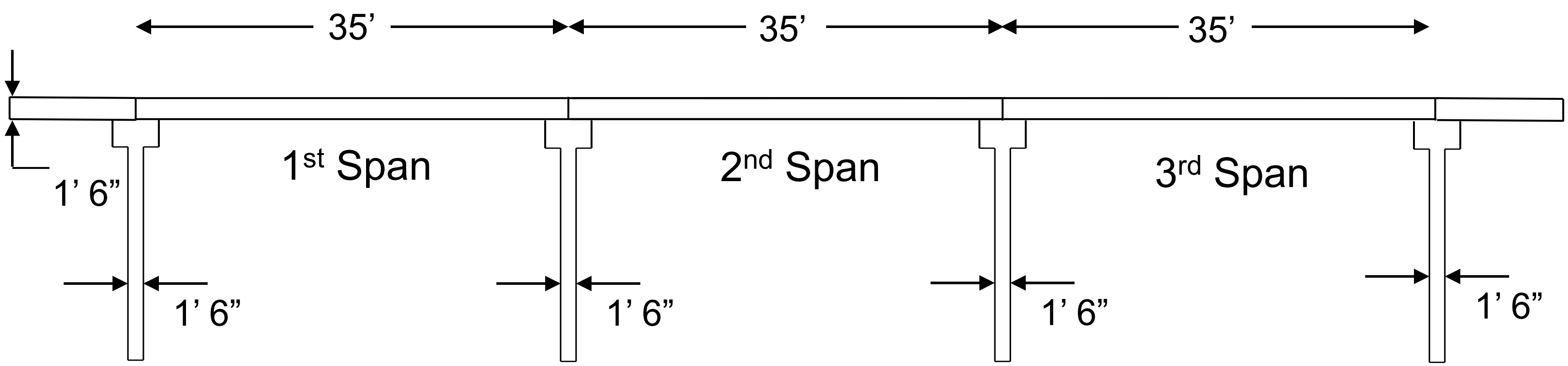


Context

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

$t_{slab} = 18\ inches$ thickness of slab

$b = 12\ inches$ design strip width

$Cover = 2\ inches$ cover for GFRP members

Effective Depth of Reinforcement

$$d_{fl.slab} = 18in - 2in - \frac{1.27in}{2} = 15.9\ inches$$

Primary Reinforcement

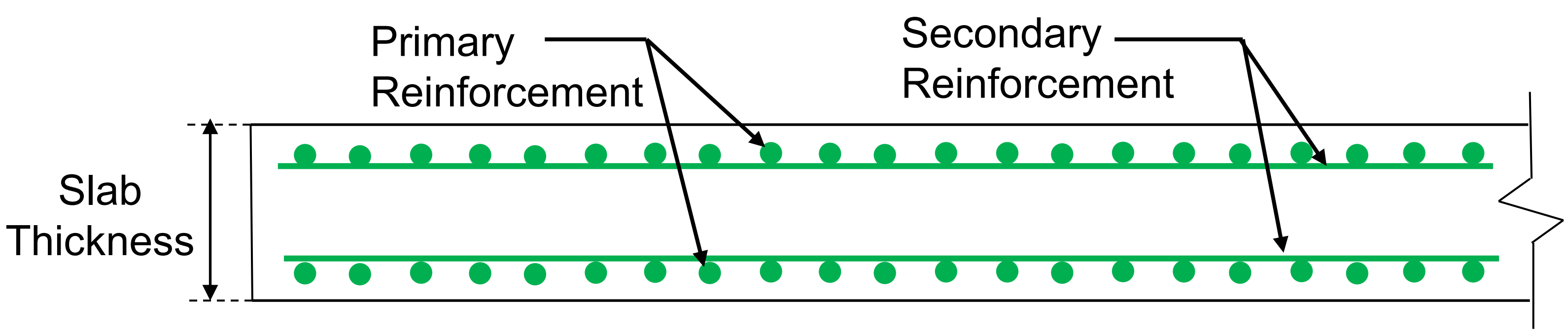
$BarSize_{slab.pr} = 10$

$BarSpace_{slab.pr} = 4\ inches$

Secondary Reinforcement

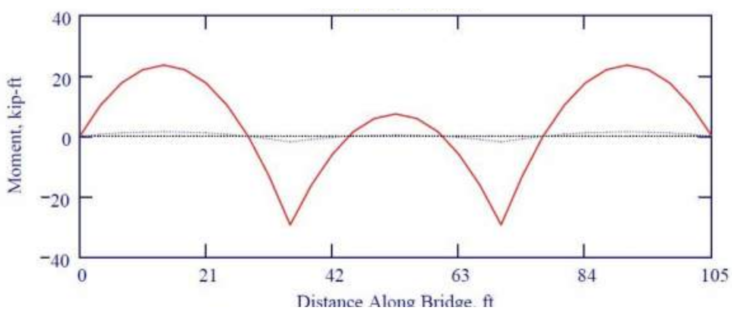
$BarSize_{slab.sec} = 6$

$BarSpace_{slab.sec} = 8\ inches$

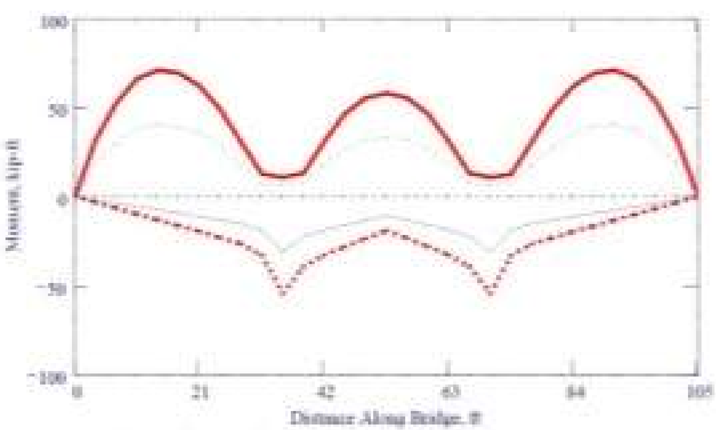


Dead & Live Load Analysis

Dead Load Moments



Strength I & Service I Live Load Moments



Maximum positive moment and corresponding fatigue values

Strength I	$M_{str1.pos} = 100.9\ kip - ft$
Service I	$M_{ser1.pos} = 64.6\ kip - ft$
Live Load Only	$M_{liveLoad.pos} = 39.6\ kip - ft$

Maximum negative moment and corresponding fatigue values

Strength I	$M_{str1.neg} = 93.2\ kip - ft$
Service I	$M_{ser1.neg} = 61.9\ kip - ft$
Live Load Only	$M_{liveLoad.neg} = 39.6\ kip - ft$

Check Primary Reinforcement

Positive Moment Region – Flexural Strength at Support

$$f_c' = 4{,}500\ psi$$

concrete compressive strength

$$\alpha_1 = \max\left(0.75, 0.85 - 0.02(f_c' - 10)\right) = 0.90$$

[AASHTO BDS 5.6.2.2]

$$\beta_1 = 0.85 - 0.05(4.5ksi - 4ksi) = 0.83$$

[AASHTO BDS 5.6.2.2]

<u>Area of primary reinforcement per linear foot</u>

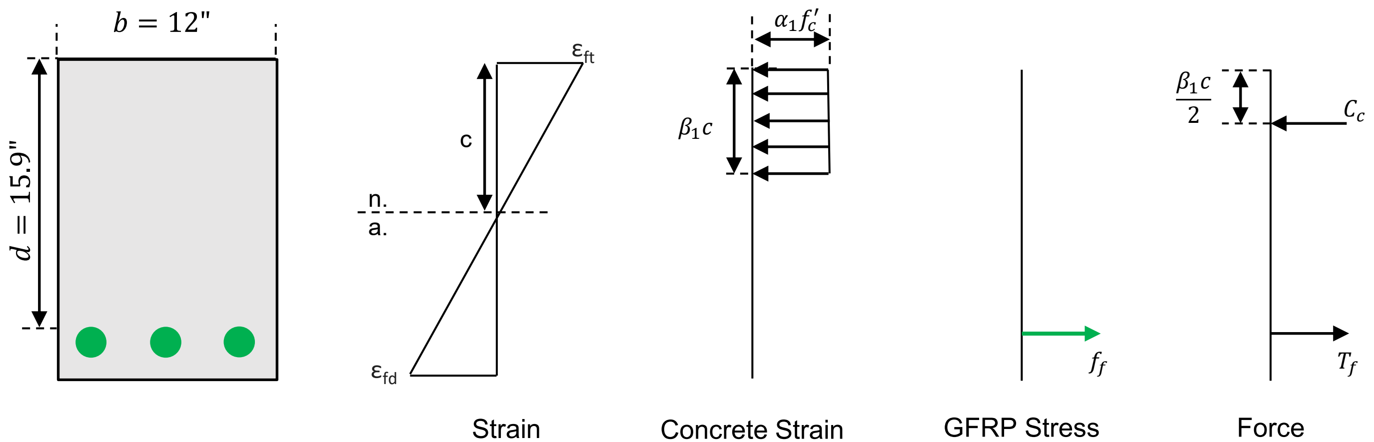
$$A_{fl.slab} = (1.27in^2)\left(\frac{12in}{4in}\right) = 3.8\ in^2$$

area of GFRP reinforcement per foot of negative moment

<u>Reinforcement Ratio</u>

$$\rho_f = \frac{A_f}{b \cdot d} = \frac{3.8in^2}{(1ft)(15.9in)} = 0.02001$$

Check Primary Reinforcement



Effective strength in GFRP reinforcements at strength limit state

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

$$= \sqrt{\frac{(6500ksi \cdot 0.003)}{4} + \frac{0.85(0.83)(4.5)}{0.02001}(6500\ ksi)(0.003)} - 0.5(6500ksi)(0.003) = 46.6ksi$$

$$f_f = \min(f_f, f_{fd}) = \min(46.6ksi, 54.1ksi) \quad = 52.3ksi \quad f_f < f_{fd}$$

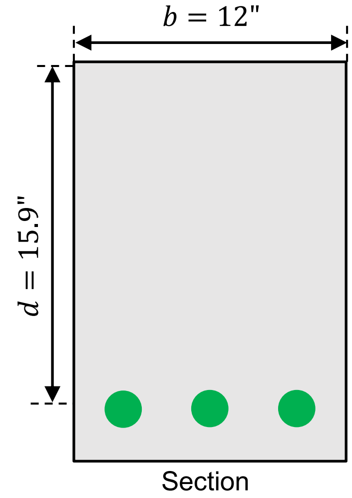
compression controlled

Calculate Resistance Factor

GFRP strain check

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

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



Calculate Resistance Factor for Flexural Strength (GFRP)

$$\phi = \begin{cases} 0.75 & if \quad \varepsilon_{ft} \leq 0.80\varepsilon_{fd} \\ \left(1.55 - \frac{\varepsilon_{ft}}{\varepsilon_{fd}}\right) & if \quad 0.80\varepsilon_{fd} < \varepsilon_{ft} < \varepsilon_{fd} \\ 0.55 & otherwise \end{cases}$$

$$\varepsilon_{ft} \leq 0.00667$$

$$0.00667 \leq \varepsilon_{ft} \leq 0.00833$$

$$\phi = 0.69$$

Check Primary Reinforcement

$$a = \frac{A_f f_f}{0.85 f_c' b} = \frac{(3.8in^2)(52.3ksi)}{0.85(4500psi)(12in)} = 3.9in$$

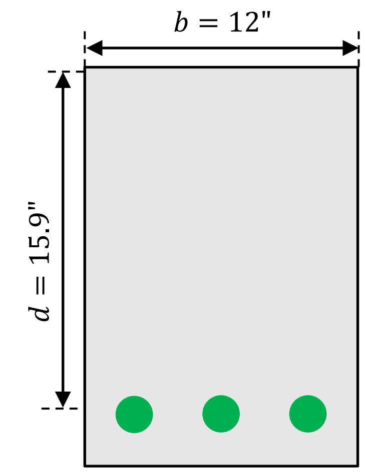
Calculate corresponding moment

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

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

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

$$Demand/Capacity: Moment_{2.slab} = \frac{M_{str1.pos}}{M_{r.2.slab}} = 0.71$$



Section

2.3 Design Example Creep Rupture (Flat Slab)



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Creep Rupture Limit State

Creep Rupture Limit State

$M_{1.creep.slab} = 50.7k - ft$ Sustained loads only

$$E_c = 120{,}000\Phi_{limerock} w_c^{2.0} \sqrt[3]{f_c' \cdot ksi^2} = 4165ksi$$

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

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

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

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

$$f_{f1.creep} = \frac{n \cdot d_{f1.slab}(1 - k_{1.slab})}{I_{cr}} \cdot M_{1.creep.slab}$$

$$= 11.3ksi$$

$$C_c C_E f_{fu} = C_c f_{fd} = (0.3)(54.1ksi)$$

$$C_c f_{fd} = 16.2ksi$$

2.4 Design Example
Minimum Reinforcement
(Flat Slab)

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Minimum Reinforcement

$$f_r = 0.24\sqrt{f'_{c.super} \cdot (ksi)} = 0.51ksi$$

Concrete Modulus of rupture

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

Uncracked concrete section modulus

$$M_{cr.slab} = 1.6f_r S_r = 44.0k - ft$$

Slab cracking moment

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

Minimum required factored flexural resistance

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

Flexural capacity of slab

$$CheckMinReinf_{slab} = if(M_{r.slab} \geq M_{min.slab}, \text{"OK"}, \text{"No Good"})$$

$$CheckMinReinf_{slab} = \text{"OK"}$$

AASHTO GFRP-Reinforced Concrete Design Training Course

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AASHTO GFRP-Reinforced Concrete Design Training Course

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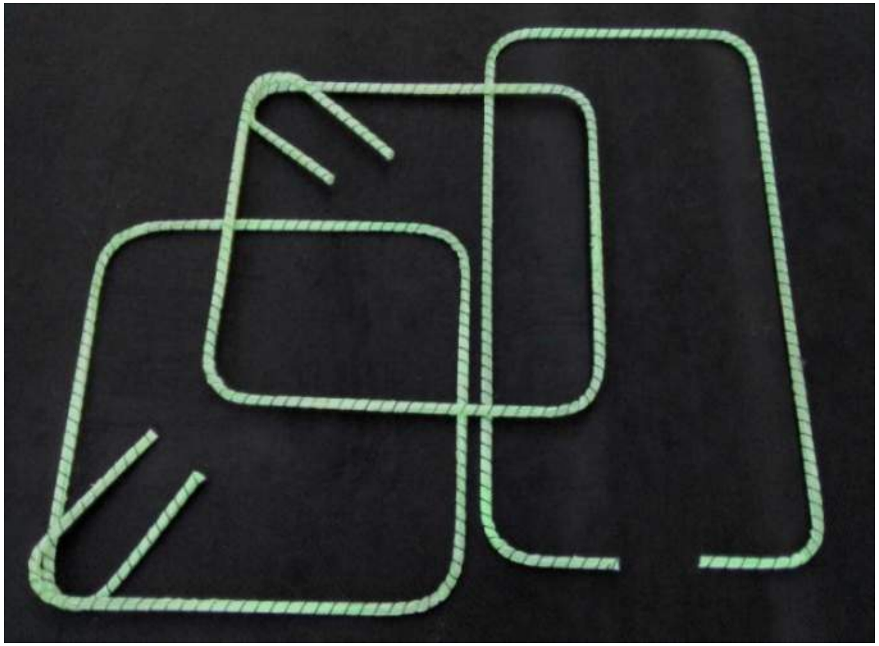
Course Outline

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



3. SHEAR RESPONSE OF GFRP REINFORCED CONCRETE

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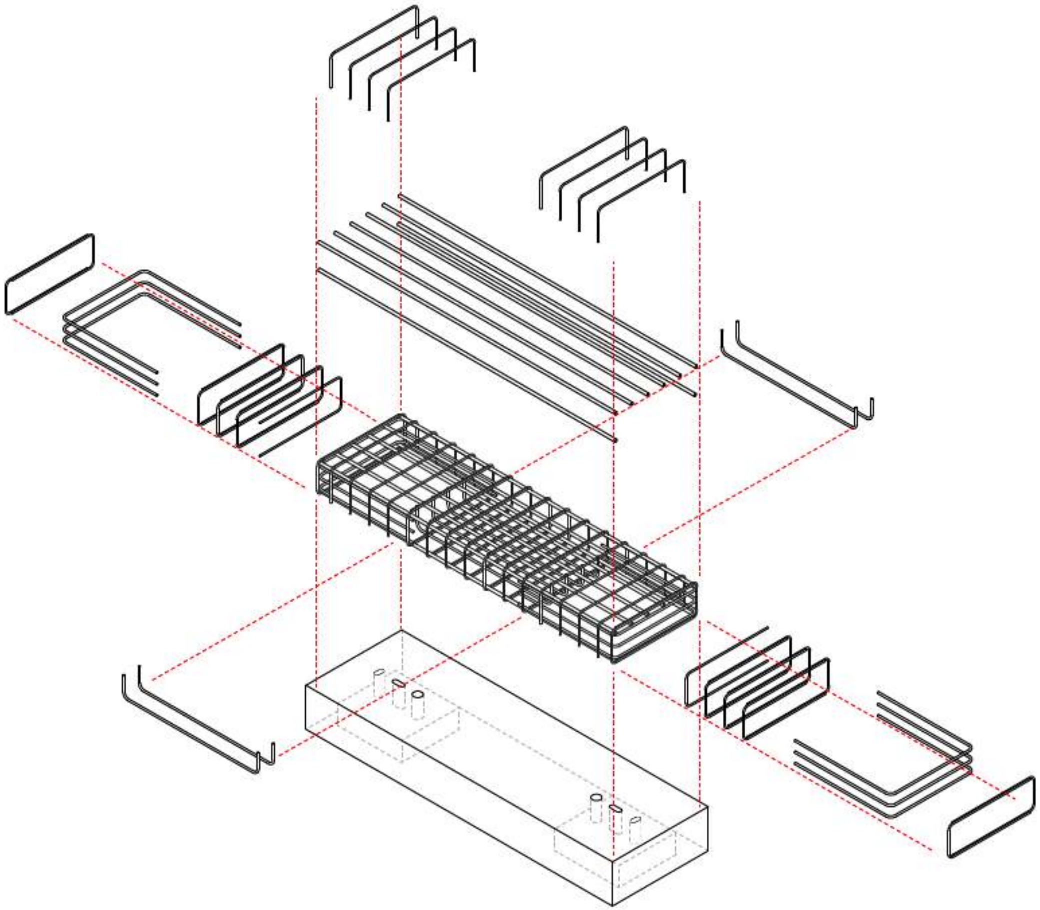
Table of Contents

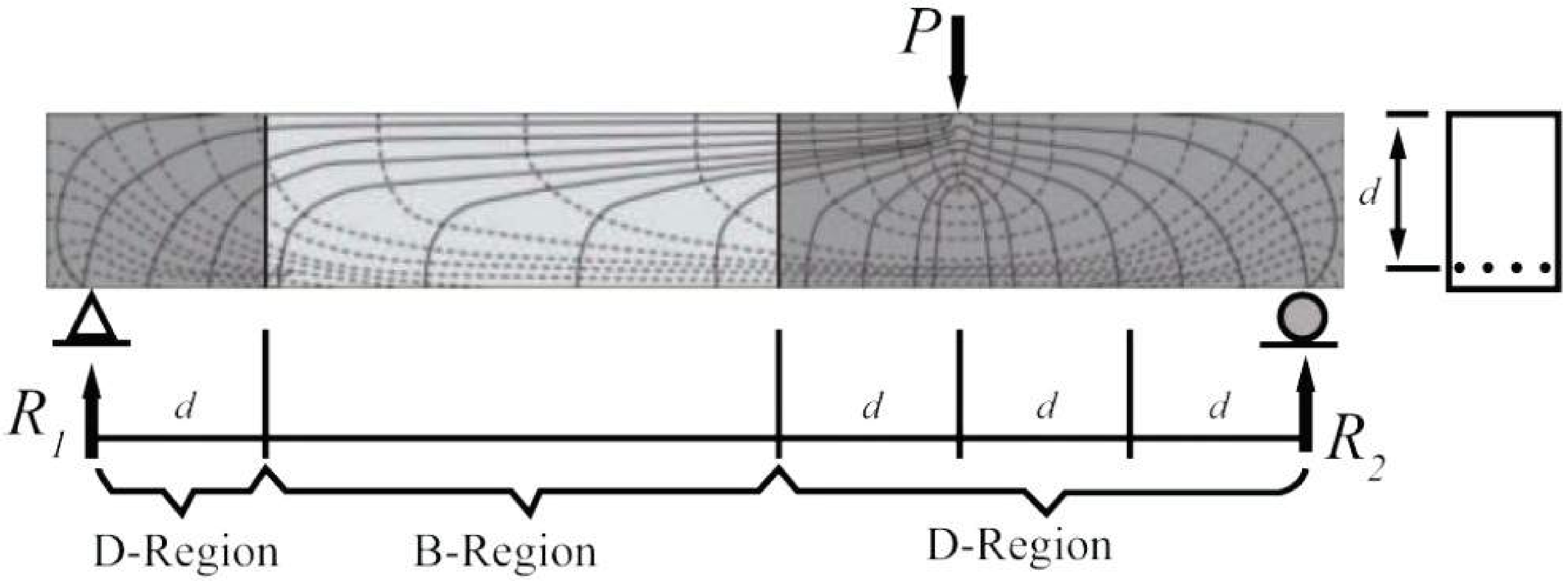
- **General Behavior**
- Shear Capacity
- Punching Shear
- Special Considerations
- Concluding Remarks



Uncracked Section

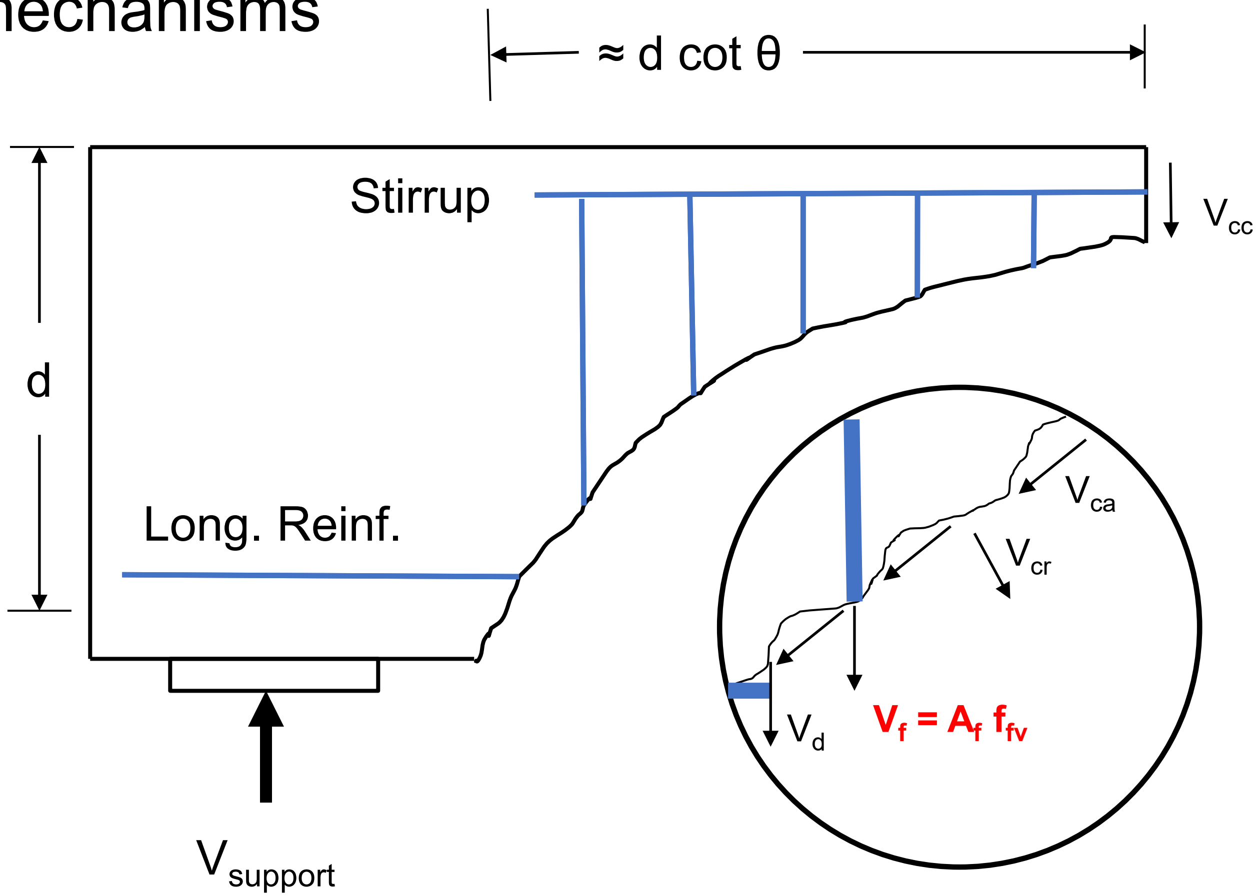
In **uncracked sections**, shear is carried by the concrete itself

Typically, shear crack starts from a flexural crack once the cracking moment exceeds the cracking strength of concrete (tensile rupture)



Cracked Section

In **cracked sections**, shear is carried by complex transfer mechanisms



V_{cc} : Compression Zone Contribution

V_d : Dowel Action

V_{ca} : Aggregate Interlock

V_{cr} : Residual Tensile Strength of Concrete

V_f : GFRP Stirrup Contribution

Components of Shear Resistance in Structural Concrete Beams

Shear Failure

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 $V_u \leq \phi \, V_n$ $\phi = 0.75$

Nominal Shear Resistance $V_n = V_c + V_f$

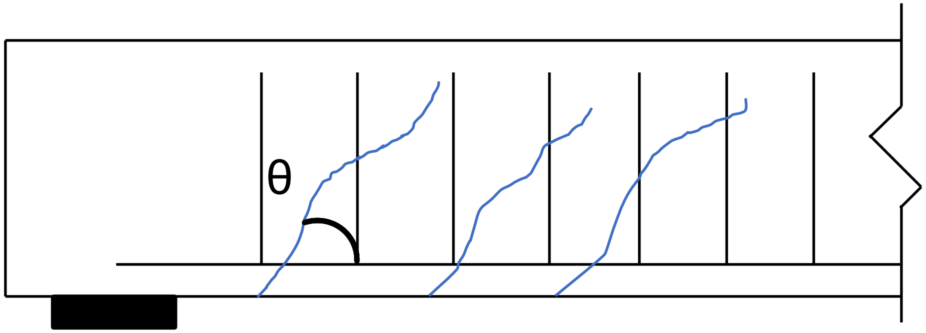
Shear Resistance of Concrete $V_c = 0.0316\beta\sqrt{f_c'}b_v d_v$

(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)



β and ***θ*** 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 β and θ

β: Factor indicating ability of diagonally cracked concrete to transmit tension and shear
θ: Angle of inclination of diagonal compressive stresses

- **Simplified Method** $\beta = 5k$ $\theta = 45°$ ***(AASHTO 2.7.3.6.1)***

$$k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$$

k: ratio of depth of neutral axis to depth of flexural reinforcement ***(AASHTO 2.5.3-4)***

- **General Method** $\theta = 29 + 3500\varepsilon_f$ ***(AASHTO 2.7.3.6.2-3)***

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

$$\beta = \frac{4.8}{1 + 750\varepsilon_f}$$

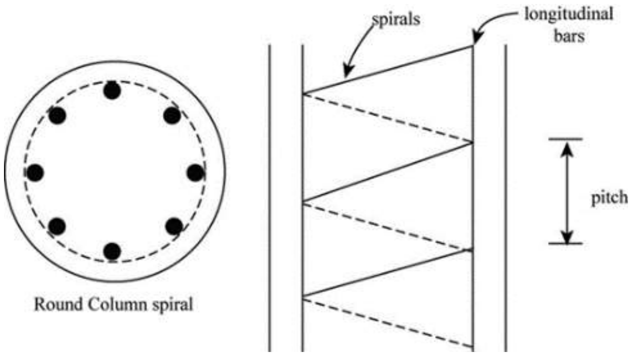
-Sections without minimum transverse reinforcement ***(AASHTO 2.7.3.6.2-2)***

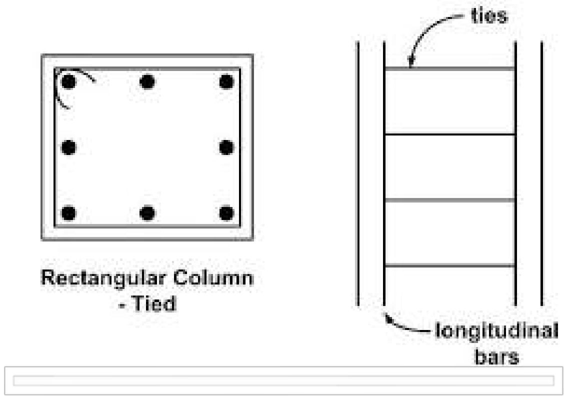
$$\beta = \left(\frac{4.8}{1 + 750\varepsilon_f}\right)\left(\frac{51}{39 + s_{xe}}\right)$$

ε_f: longitudinal tensile strain of the GFRP
s_{xe}: crack spacing as influenced by aggregate size ***(AASHTO 2.7.3.6.2-7)***

Types of Transverse Reinforcement

- Stirrups or ties
- Spirals or hoops





Shear resistance of FRP reinforcement when using spirals

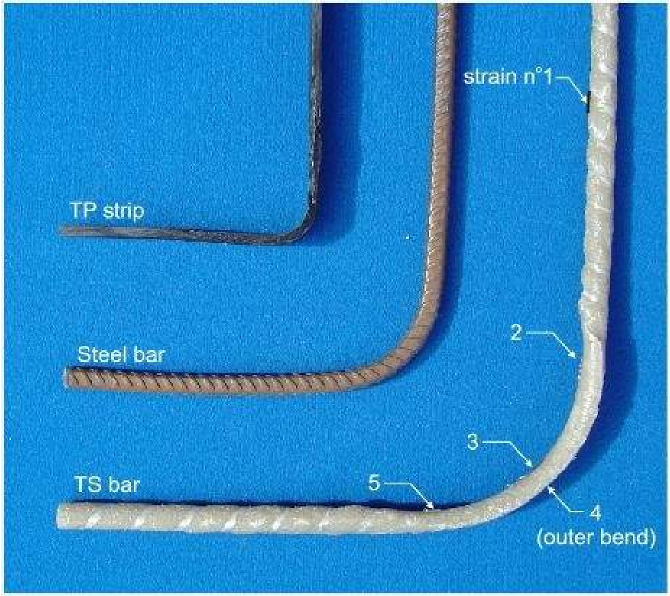
$$V_f = \frac{A_{fv} f_{fv} d_v (cot\theta + cot\alpha) sin\alpha}{s}$$ ***(AASHTO 2.7.3.5)***

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 $f_{f,sd}$

$$f_{f,sd} = min(f_{fv}, f_{fb}, f_{fd})$$ ***(AASHTO 2.7.3.5)***



Tensile Strength of GFRP for Shear Design

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

← Typically governs for GFRP

Tensile Strength of GFRP at Bends

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

r_b = internal radius of bend of reinforcing bar
d_b = diameter of reinforcing bar

Tensile Strength of GFRP

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

← **FDOT 932-3** requires this to ≥ 60% of straight bars for qualification

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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

$$A_{fv,min} \geq 0.05 \frac{b_v s}{f_{fv}}$$ ***(AASHTO 2.7.2.4-1)***

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

$$S \leq Min\,\{0.5d\,, 24\ in.\}$$ ***(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

r_b= bend radius
d_b=bar diameter

TABLE 4 Minimum Inside Bend Diameter of Bent Bars[A]

Bar Designation, mm [U.S. Standard]	Minimum Bend Diameter mm [in.]
M6 [2]	38 [1.50]
M10 [3]	58 [2.25]
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M16 [5]	96 [3.75]
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M25 [8]	152 [6.00]

(ASTM D7957)

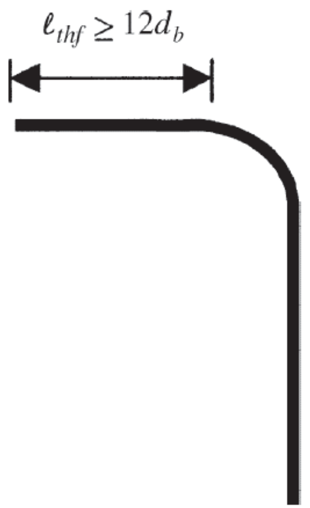

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Table of Contents

- 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
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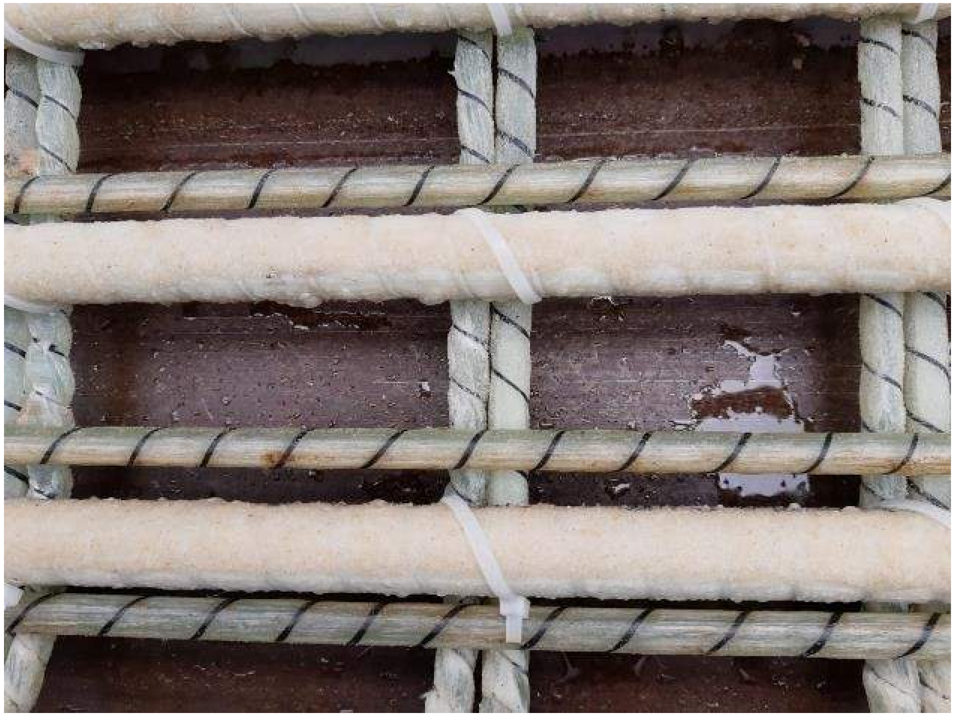
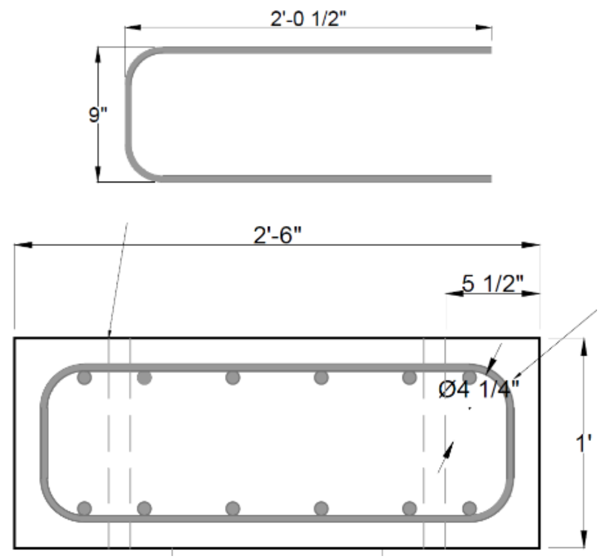
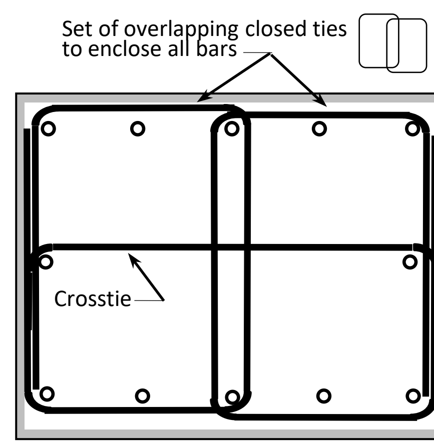
- **Special Considerations**
- Concluding Remarks



Special Considerations

- **90-degree bends** instead of 135-degree
- Typically **two overlapping "C or U" stirrups** are used instead of a closed loop stirrup





Special Considerations

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

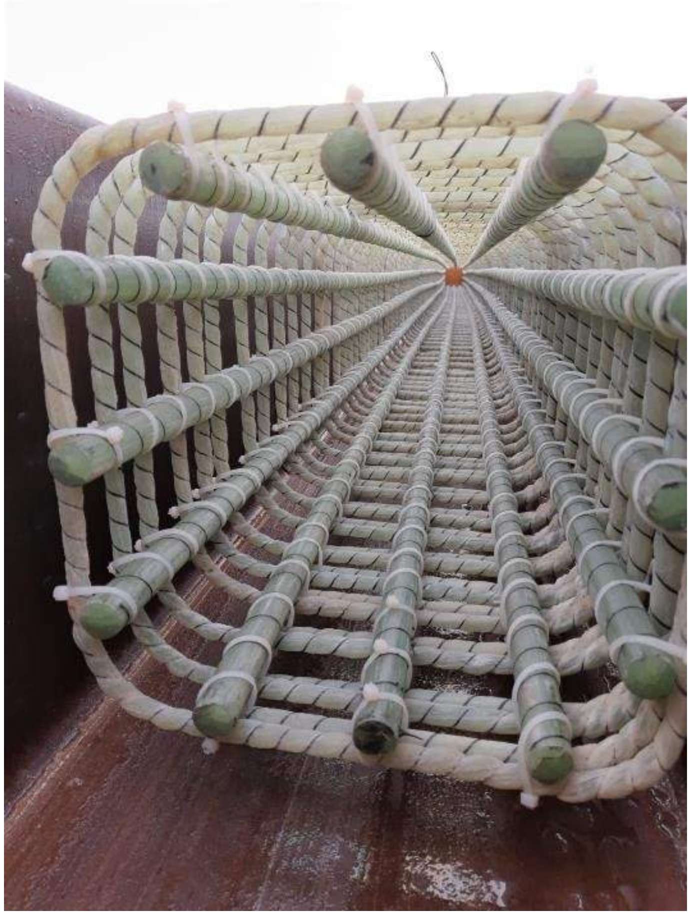
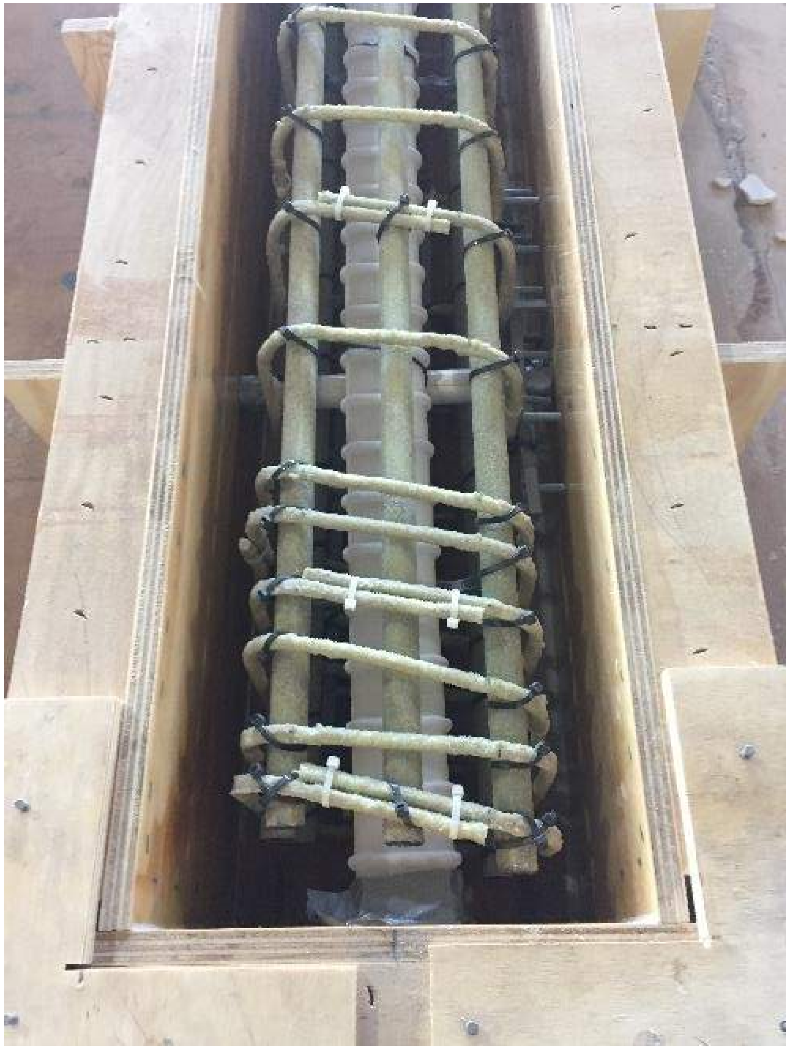


Table of Contents



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



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Review Questions

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

$$A_{fv,min} \geq 0.05 \frac{b_v s}{f_{fv}}$$

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

$$S \leq Min\,\{0.5d\,, 24in.\}$$

(AASHTO 2.7.2.6)

Review Questions

3.1.1) For GFRP stirrups, does the maximum amount of transverse reinforcement requirement similar to steel-RC still apply: ___________________________.

a. True

b. False

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

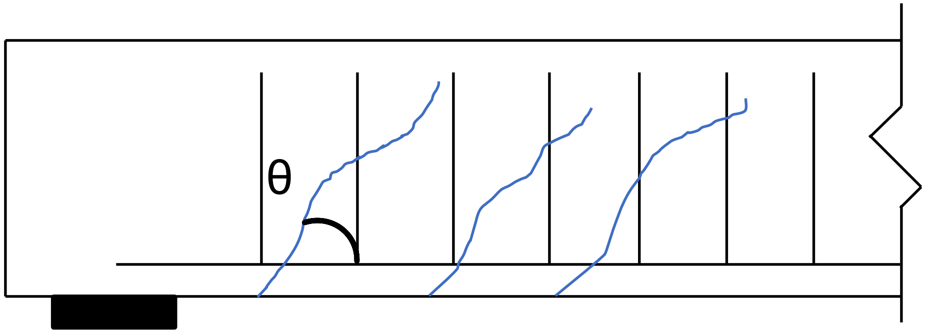
Shear Capacity

Ultimate Limit State $V_u \leq \phi\, V_n$ $\phi = 0.75$

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)***

Shear Resistance of GFRP Stirrups $V_f = \dfrac{A_{fv}\, f_{fv}\, d_v \cot(\theta)}{s}$ ***(AASHTO 2.7.3.5)***



β and θ 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

Review Questions

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= bend radius
d_b=bar diameter

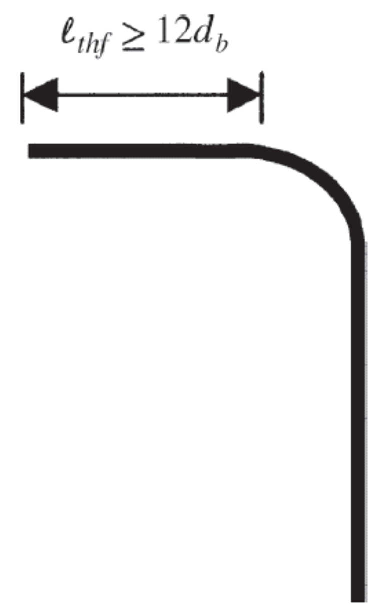


TABLE 4 Minimum Inside Bend Diameter of Bent Bars[A]

Bar Designation, mm [U.S. Standard]	Minimum Bend Diameter mm [in.]
M6 [2]	38 [1.50]
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M22 [7]	134 [5.25]
M25 [8]	152 [6.00]

(ASTM D7957)

Review Questions

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

Review Questions

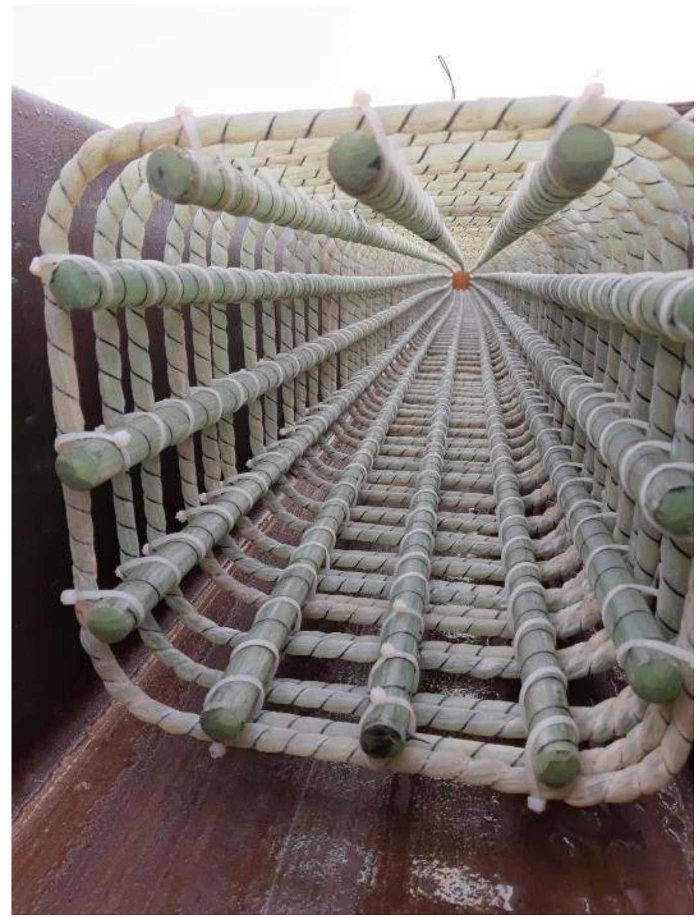
3.1.4) GFRP stirrups can be bent on site with EOR approval?

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

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 minimum of $r_b/d_b = 3$

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

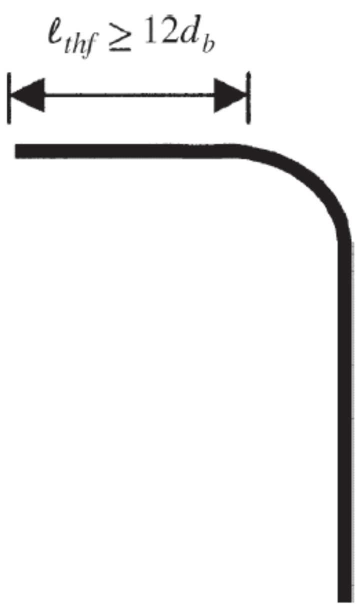
c. Smaller than required for steel reinforcement due to lower elastic modulus

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= bend radius
d_b=bar diameter



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M19 [6]	114 [4.50]
M22 [7]	134 [5.25]
M25 [8]	152 [6.00]

(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

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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

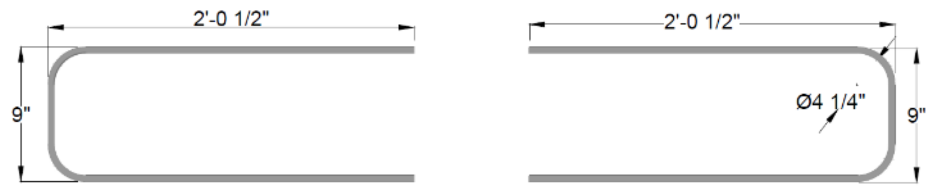
c. Closed stirrup, providing the tails overlap

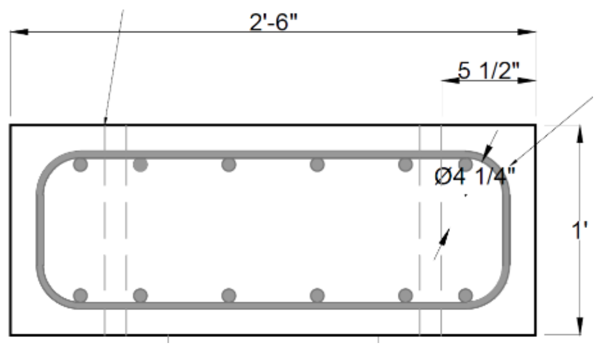
d. L shapes for end hooks

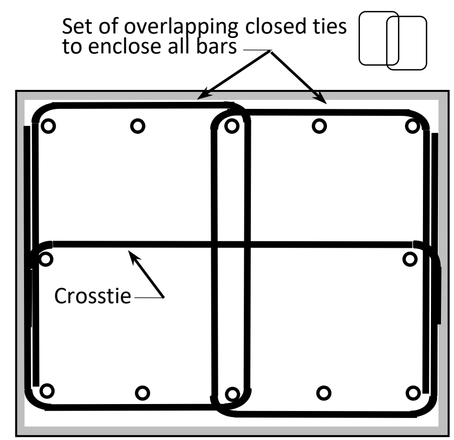
e. Special bends for complex shapes

Special Considerations

- **90-degree bends** instead of 135-degree
- Typically **two overlapping "C or U" stirrups** are used instead of a closed loop stirrup.







Applied 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**

Review Questions

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

$$A_{fv,min} \geq 0.05 \frac{b_v s}{f_{fv}}$$

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

$$S \leq Min\,\{0.5d\,,24in.\}$$

(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)

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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 ($f_{f,sd}$)

$$f_{f,sd} = min(f_{fv}, f_{fb}, f_{fd})$$

Shear Design Flowchart

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 $A_{fv} \geq A_{fv.min}$

$$A_{fv,min} \geq 0.05 \frac{b_v s}{f_{fv}}$$

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

$$V_u \leq V_r = \phi\, V_n = 0.75(V_c + V_f)$$

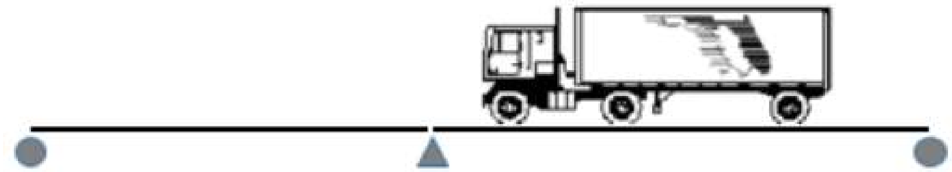
Check spacing of GFRP stirrups

$$S = Min\,\{0.5d\,,24in.\}$$

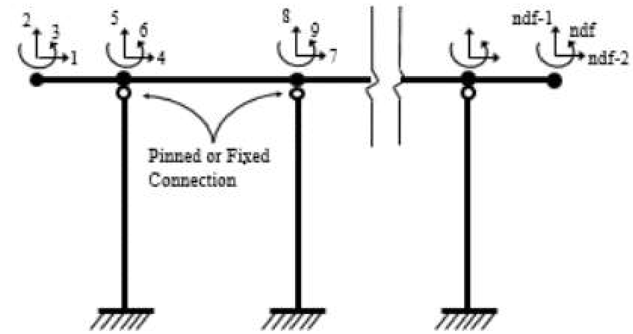
Finish

Bent Cap- Halls River Bridge

Part 1: Load Generator

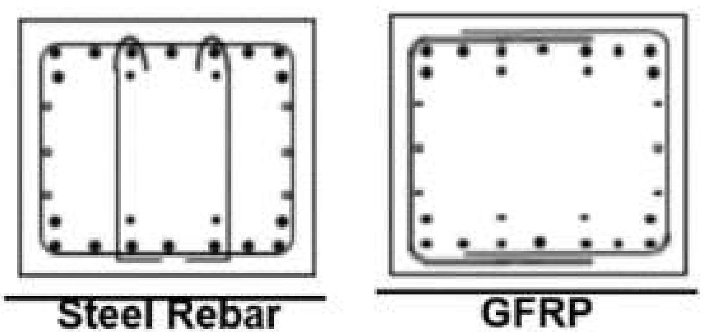


Part 2: Frame Analysis



Bent Cap Analysis Model

Part 3: Design & AASHTO Checks



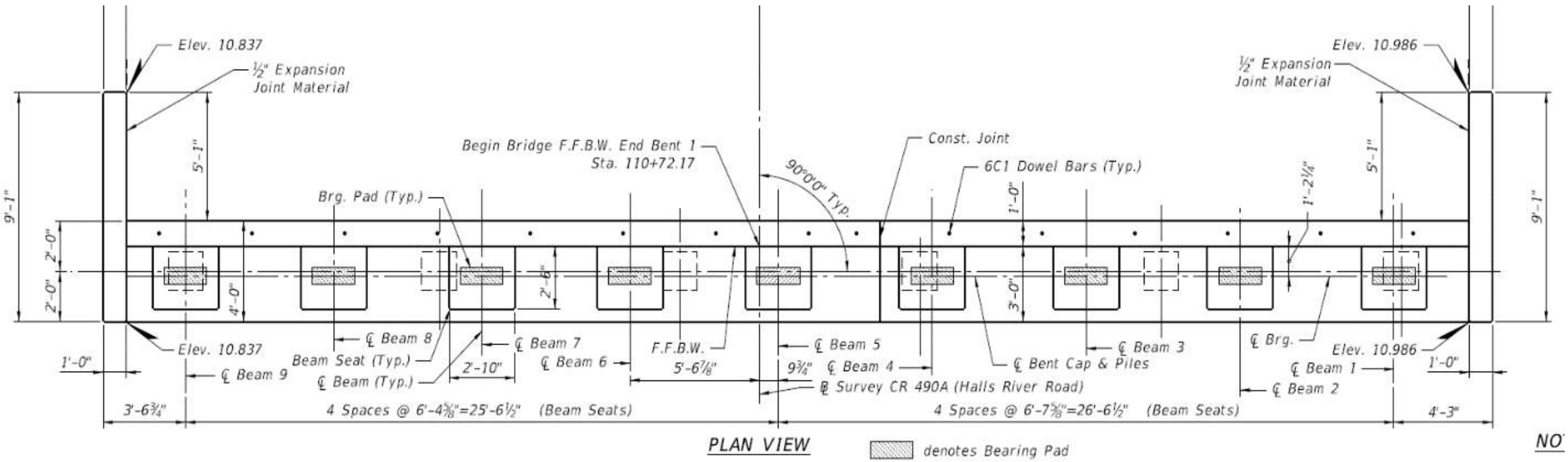
Bent Cap- Halls River Bridge

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.

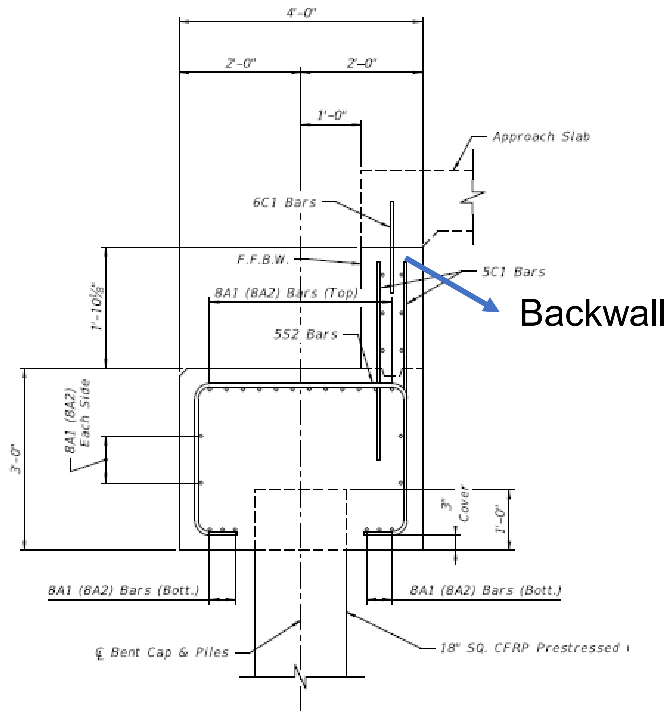


Bent Cap- Halls River Bridge

Part 1: Load Generator

Input Data

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



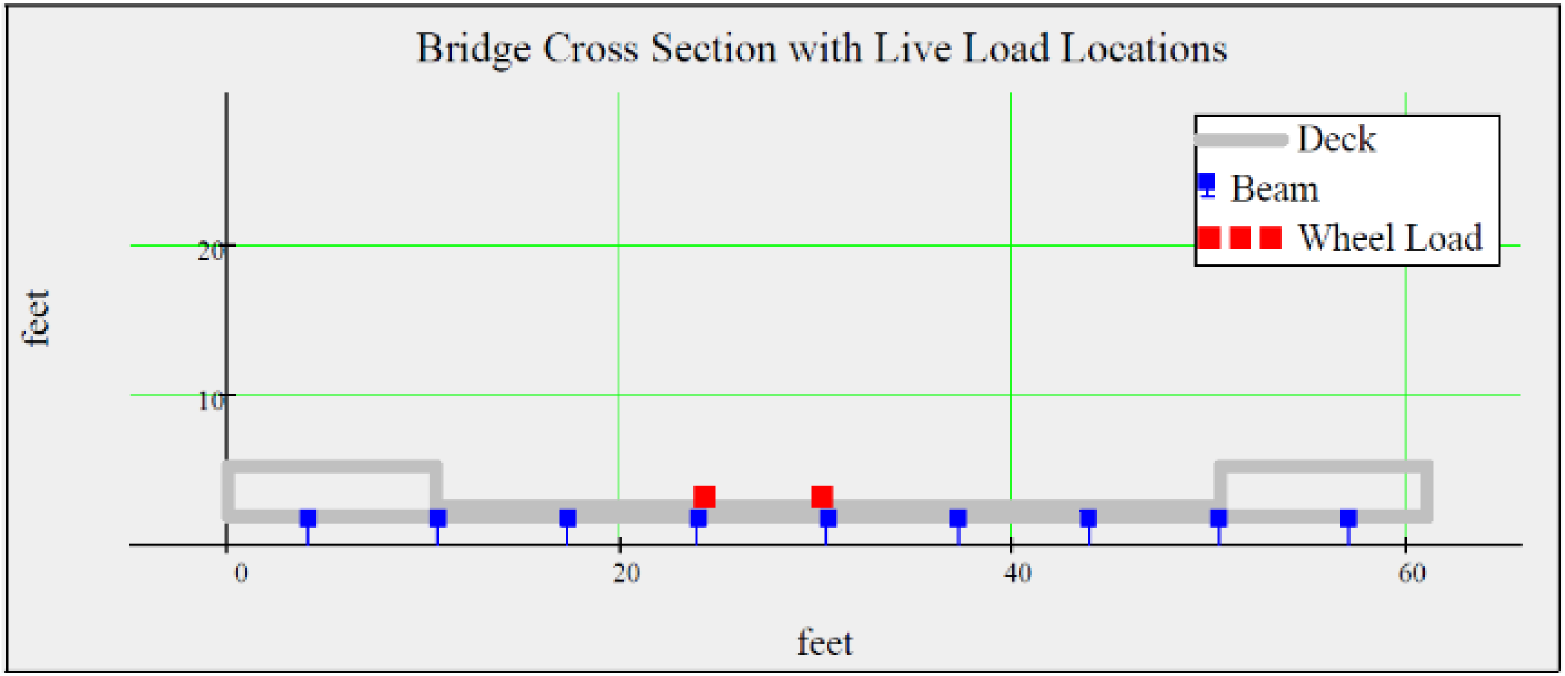
SECTION A-A

Beam Seat reinforcing not shown for clarity.

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

$$P_{LL.beam}{}^{T} = (0.0 \;\; 0.0 \;\; 0.0 \;\; 59.5 \;\; 59.9 \;\; 0.0 \;\; 0.0 \;\; 0.0 \;\; 0.0)\cdot kip$$

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)

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

Factored total load perpendicular to cap (z)

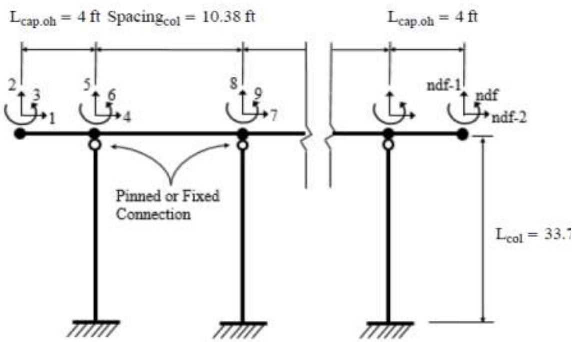
$$P_{cap.z} = \begin{pmatrix} 80.32 \\ 8.07 \\ 66.43 \\ 49.65 \\ 36.72 \\ 0 \\ 80.32 \\ 8.07 \\ 66.43 \\ 0 \end{pmatrix} \cdot kip$$

Load cases per LRFD

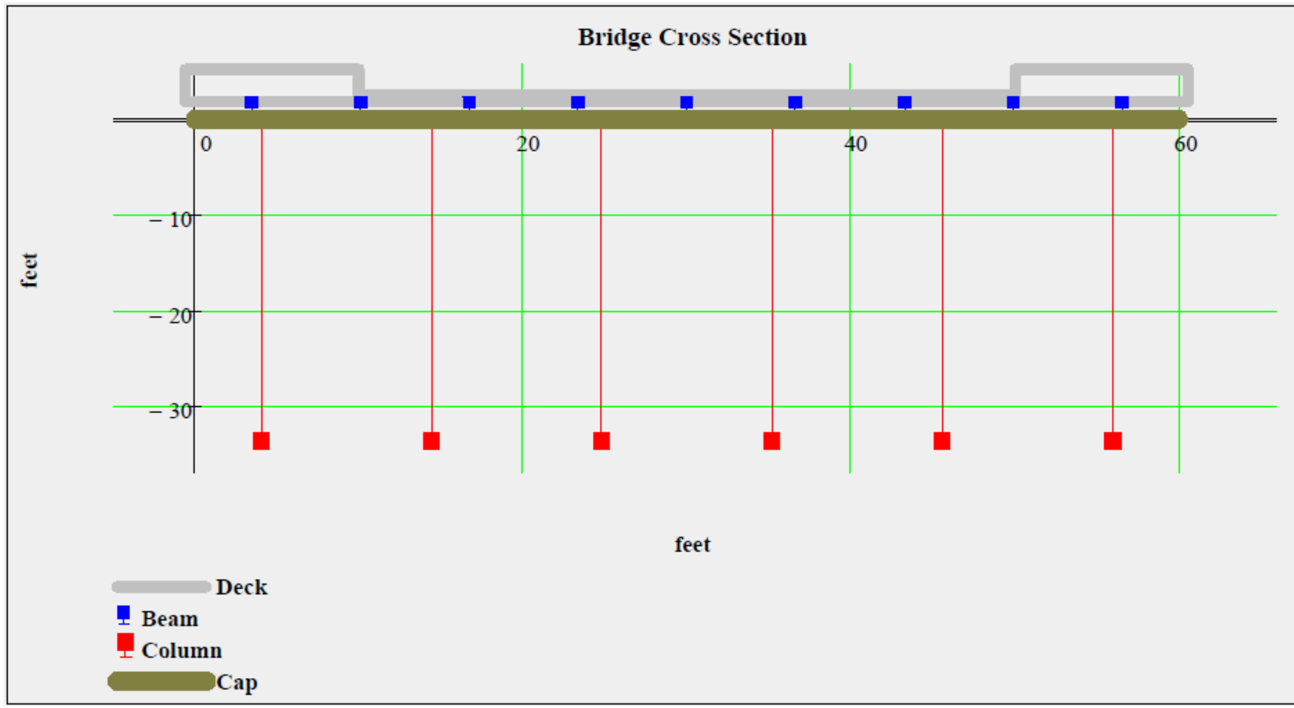
$$\begin{pmatrix} \text{"Strength I max vertical"} \\ \text{"Strength III max vertical"} \\ \text{"Strength V max vertical"} \\ \text{"Service I"} \\ \text{"Service III"} \\ \text{"Sustained load: DL+0.2LL"} \\ \text{"Strength I min vertical"} \\ \text{"Strength III min vertical"} \\ \text{"Strength V min vertical"} \\ \text{"DL+Fatigue I"} \end{pmatrix}$$

Part 2: Frame Analysis

Connection of columns to bent cap (Fixed or Pinned)	Fixed
Beam load	Distributed

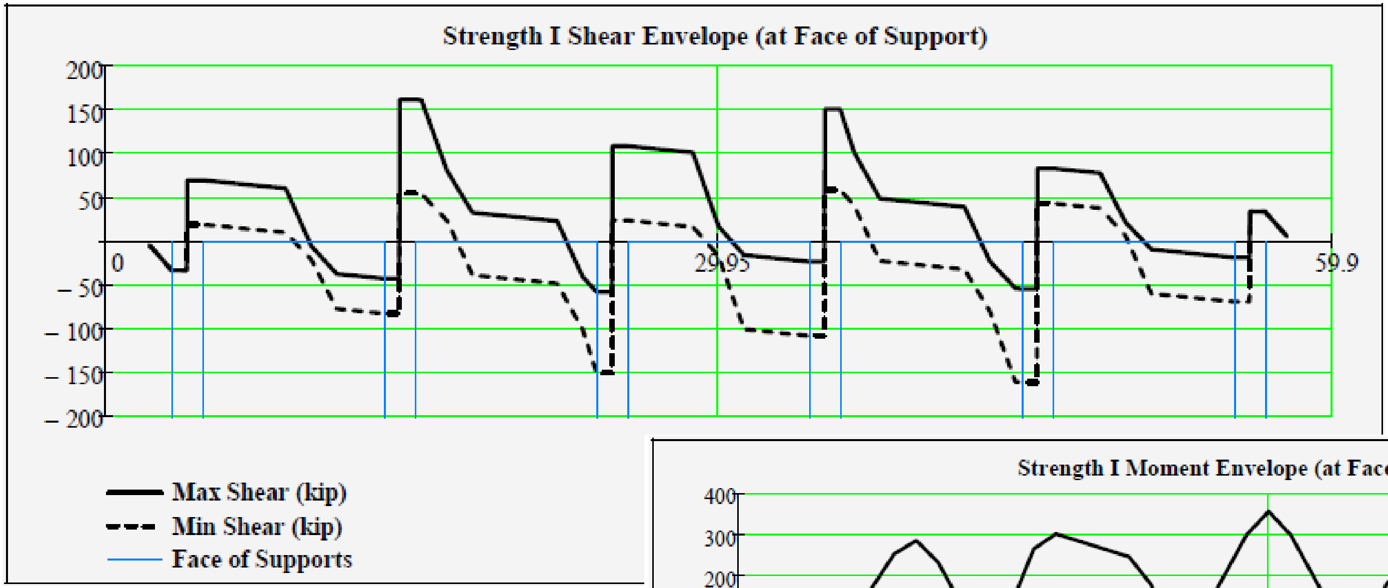


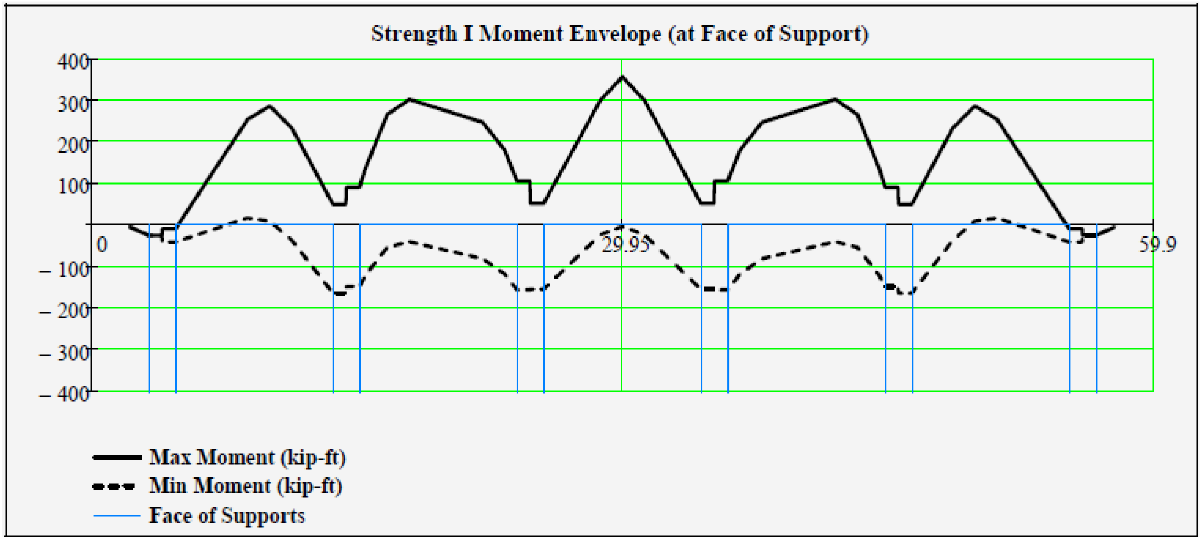
Bent Cap Analysis Model



Part 2: Frame Analysis

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





Part 3: GFRP Design & AASHTO Checks

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

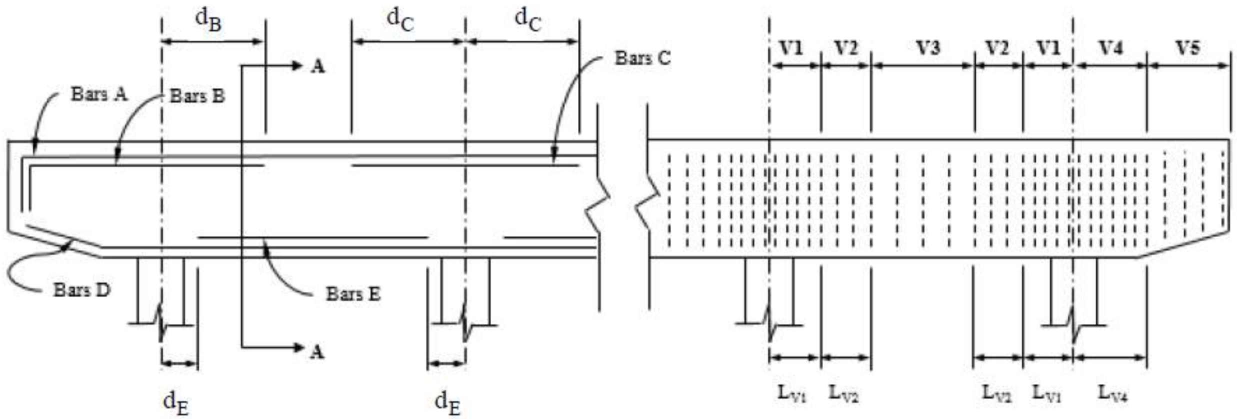
Shear Reinforcement

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.



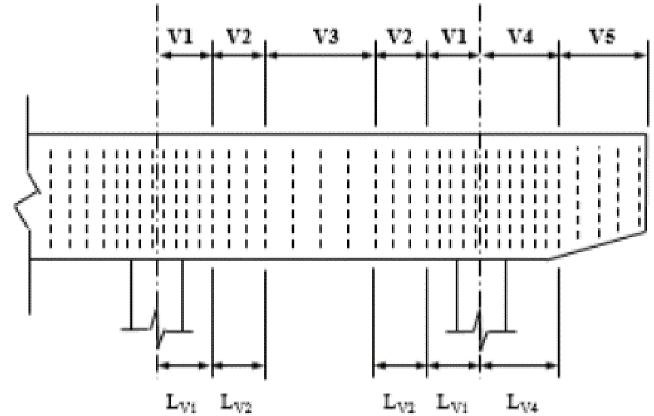
Part 3: GFRP Design & AASHTO Checks

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.

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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

$\beta = 5k$ ***(AASHTO 2.7.3.6.1)***

Shear Resistance of GFRP Reinforcement

$$V_f = \frac{A_{fv}\, f_{fv}\, d_v \cot(\theta)}{s} = 137\ kip$$

The Maximum Demand to Capacity Ratio

$V_u = 162\ kip$

$V_r = 0.75\ (64.75 + 137) = 151 kip$

$$\boldsymbol{max\ \frac{V_u}{V_r} = 1.07}$$

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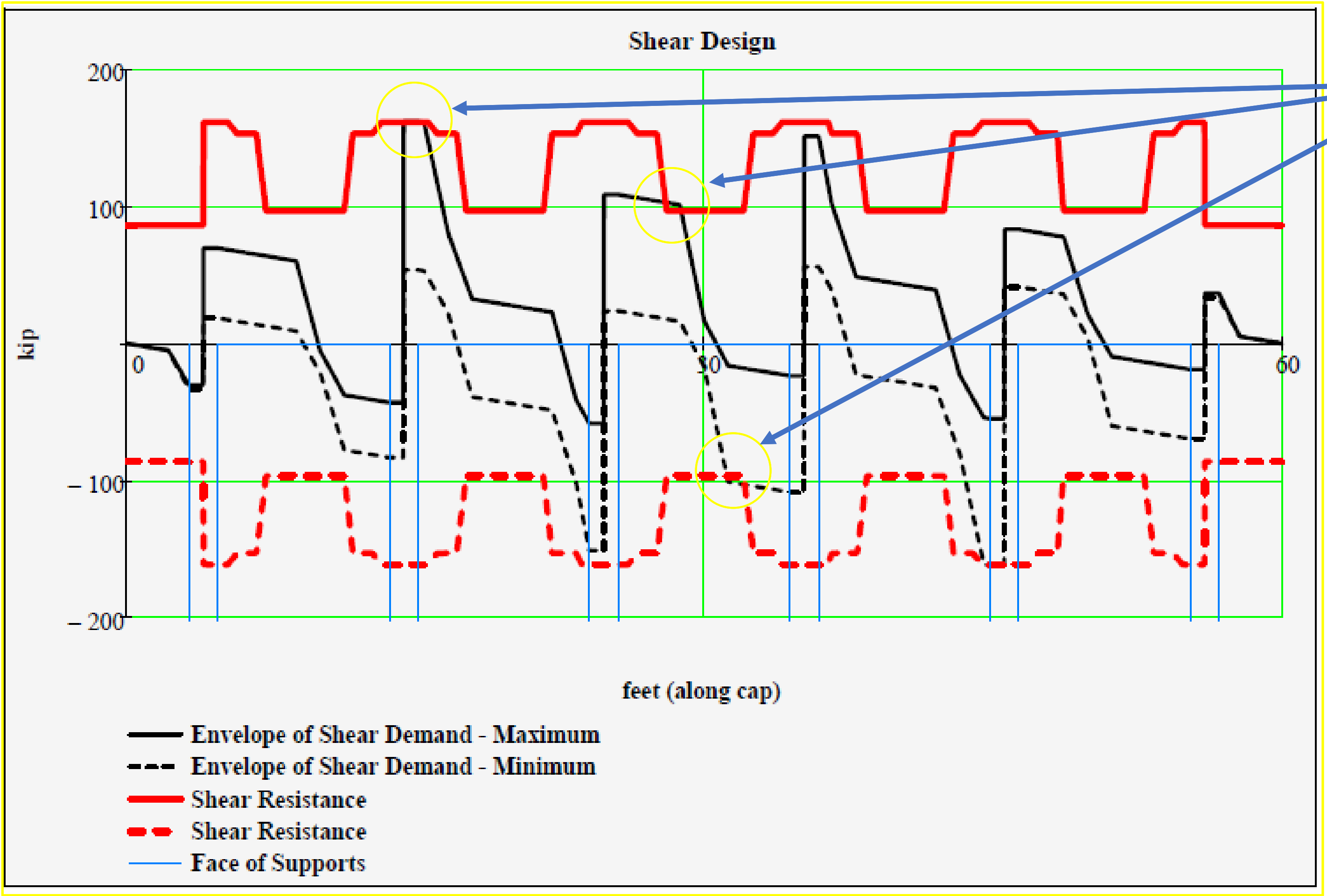
Shear Design Example



Problem areas

Maximum demand to capacity ratio = 1.07

AASHTO GFRP-Reinforced Concrete Design Training Course

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AASHTO GFRP-Reinforced Concrete Design Training Course



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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

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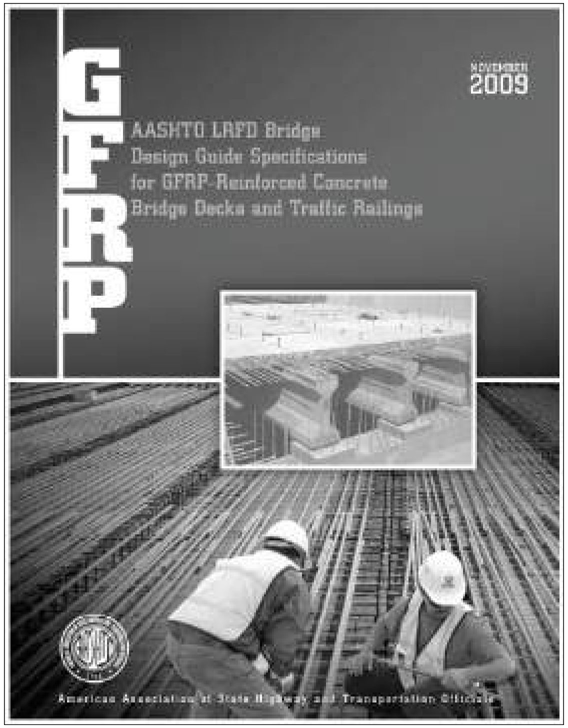
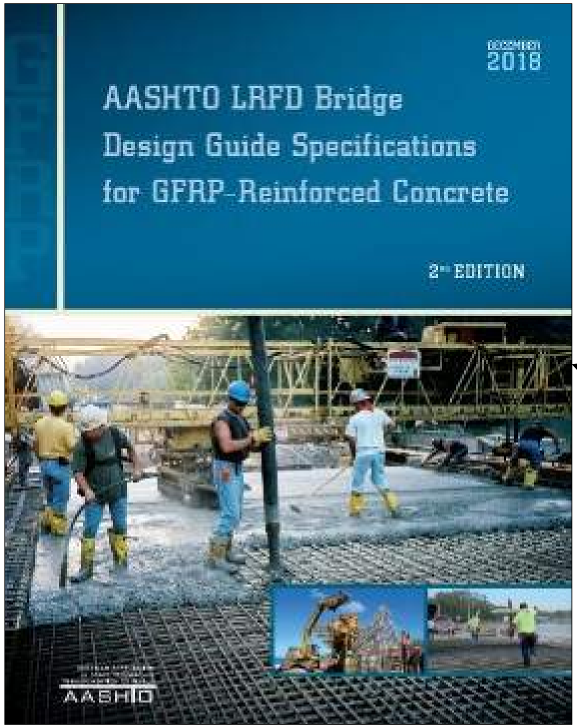
Table of Contents – Axial & More

Design Codes



AASHTO GFRP 1st Ed.

(No provisions included)



AASHTO GFRP 2nd Ed.

(Provisions included)

Only US guide/code including compression members

Introduction – Pure Compression

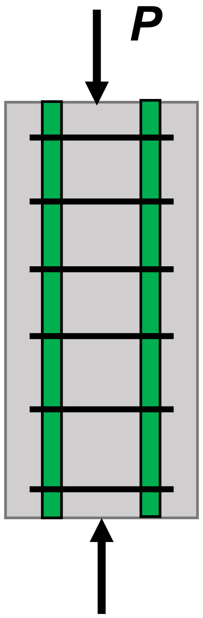
Review of Steel-RC Columns

$$P_o = P_c + P_s = 0.85f_c'(A_g - A_s) + f_y A_s$$

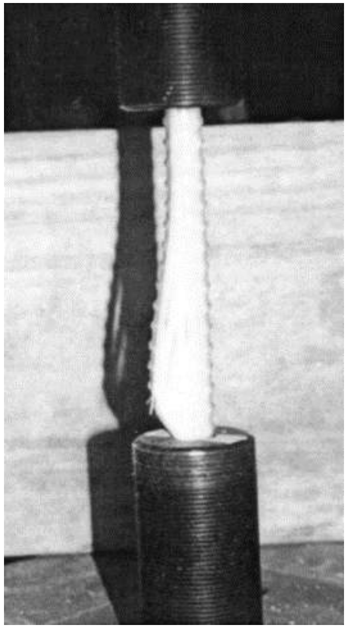
Basic Concept for GFRP-RC Columns

$$P_o = P_c + P_f = 0.85f_c'(A_g - A_f) + \cancel{f_f A_f}$$

(**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 Compressive Resistance - AASHTO

Factored Pure Compressive Resistance - AASHTO

$$P_r = \phi P_n$$ **(AASHTO GFRP 2.6.4.2-1)**

- For members with spiral or hoop reinforcements

$$P_n = 0.85[0.85 f_c'(A_g - A_f)]$$ **(AASHTO GFRP 2.6.4.2-2)**

- For members with tie reinforcement

$$P_n = 0.80[0.85 f_c'(A_g - A_f)]$$ **(AASHTO GFRP 2.6.4.2-3)**

A_f = area of GFRP reinforcement (in^2)
A_g = gross area of section (in^2)
f'_c = specified compressive (ksi)
P_n = nominal axial resistance, without flexure (kips)
P_r = factored axial resistance, without flexure (kips)

Factored Tensile Resistance - AASHTO

Factored Pure Tensile Resistance - AASHTO

$$P_r = \phi P_n$$ **(AASHTO GFRP 2.6.6.2-1)**

in which:

$$P_n = f_{fd} A_f$$ **(AASHTO GFRP 2.6.6.2-2)**

$$f_{fd} = C_E f_{fu}$$ **(AASHTO GFRP 2.4.2.1-1)**

where:

A_f = area of GFRP reinforcement (in^2)

f_{fd} = 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

Design Considerations

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):

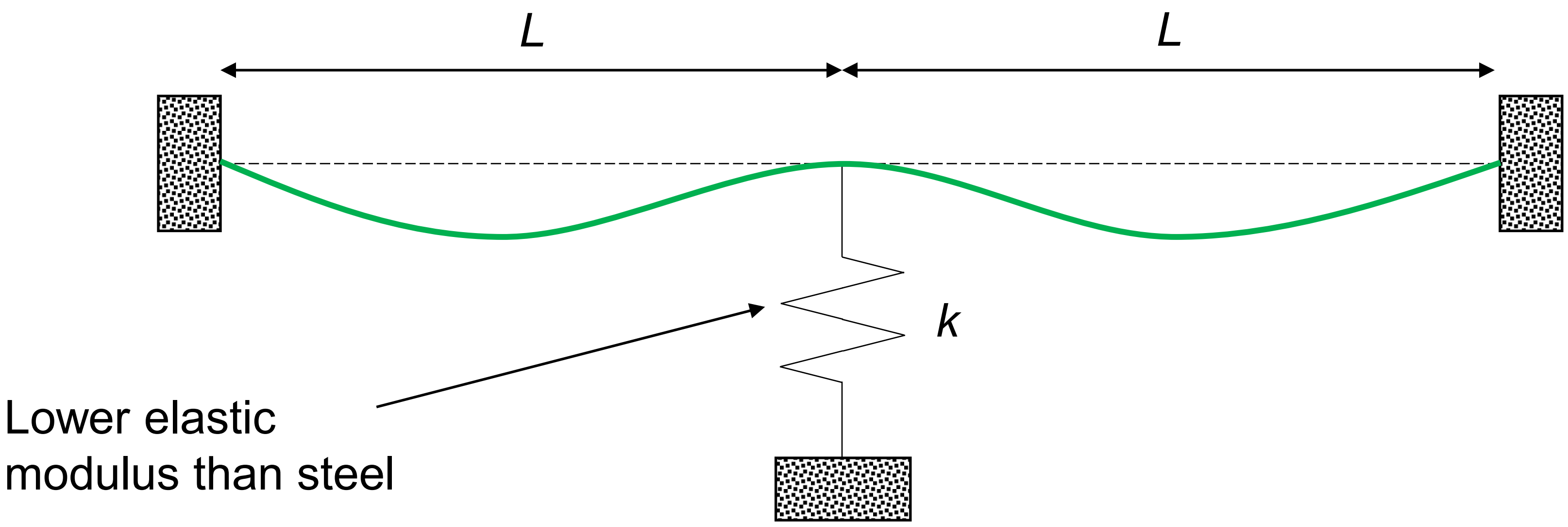
$$\varepsilon_{fd} = \min(\varepsilon_{fu}, 0.010)$$

and

$$f_{fd} = \min(f_{fu}, 0.010E_f)$$

Design Considerations

Limits on maximum spacing of Transverse Reinforcement: confinement, buckling of longitudinal reinforcement



Theoretical:

$$s_{max} \approx 14d_b$$

AASHTO GFRP 4.7.5.4 – Tied Members

$$s_{max} = min\begin{cases} least\ dimension\ of\ column \\ d/4 \\ 12\ inches \end{cases}$$

Table of Contents

Context

GFRP Cage Assembly, Casting and Installation of RC Piles

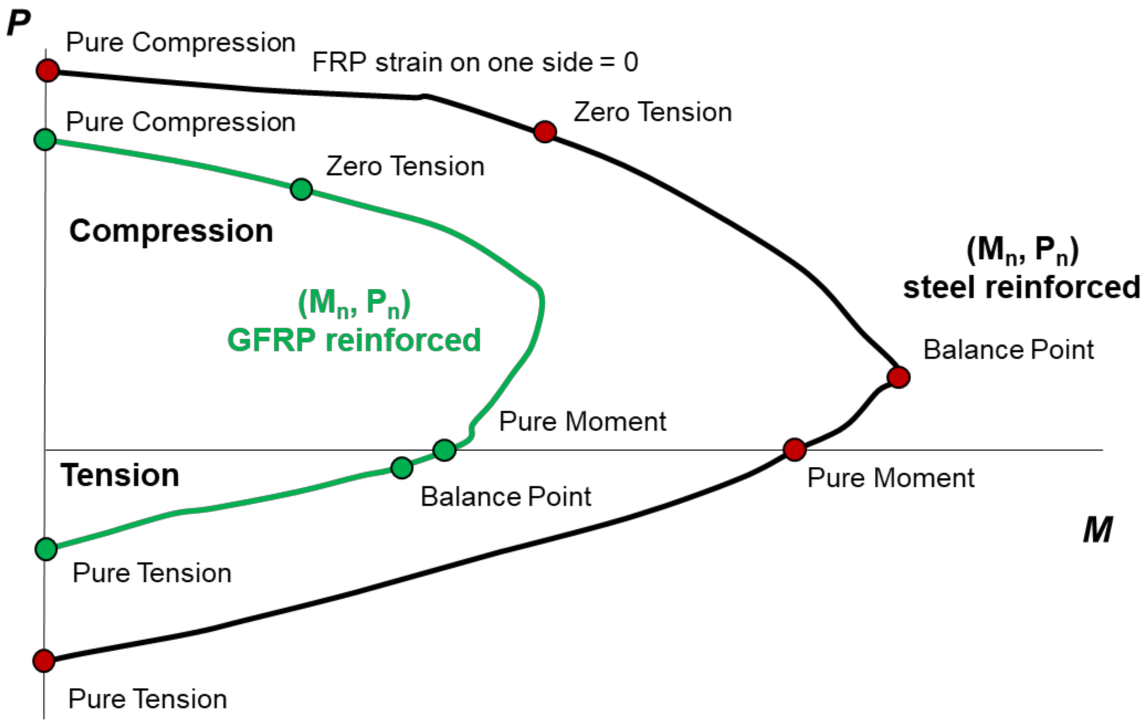
Combined P-M Failure Modes

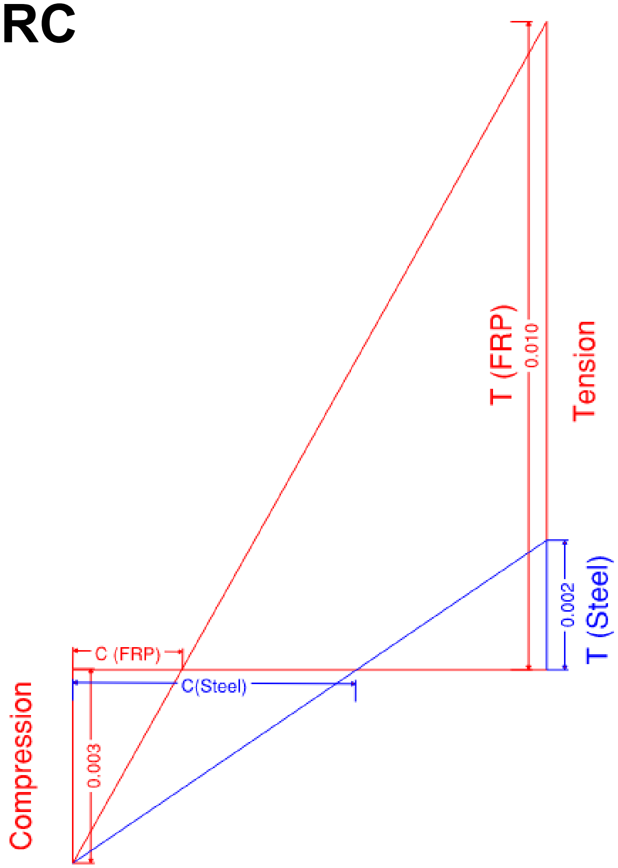
Rectangular Concrete Column Failure with GFRP Bars and Ties (Guérin et al., 2018)

Compression Side Side View Tension Side

Developing P-M Interaction Diagram

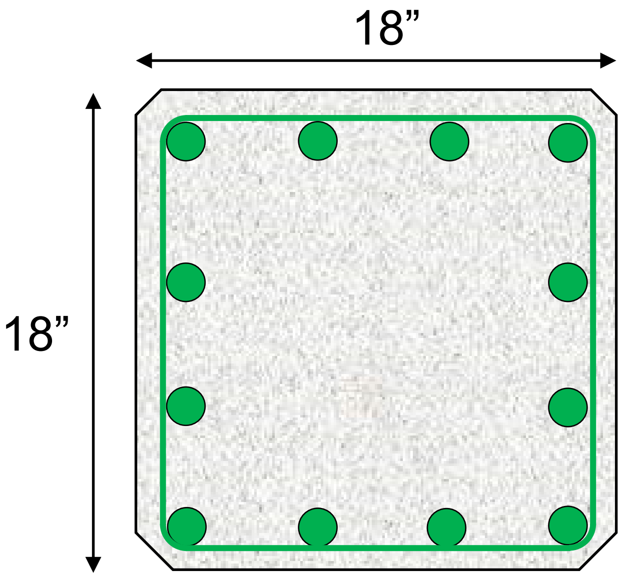
Schematic P-M diagram for two identical columns having the same amounts of GFRP and steel reinforcement. Include the following five points. Note location of **balance point for GFRP-RC**





Developing P-M Interaction Diagram

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



Equivalent FDOT standard index non-prestressed

18”x18”, 12 GFRP bars

f'_c = 5,000 psi

E_f = 6,500 ksi E_c= 4,291 ksi

f_{fd} = 59.2 ksi ε_{fd} = 0.00911

12 - #8 GFRP bars evenly spaced

Include the following points:

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

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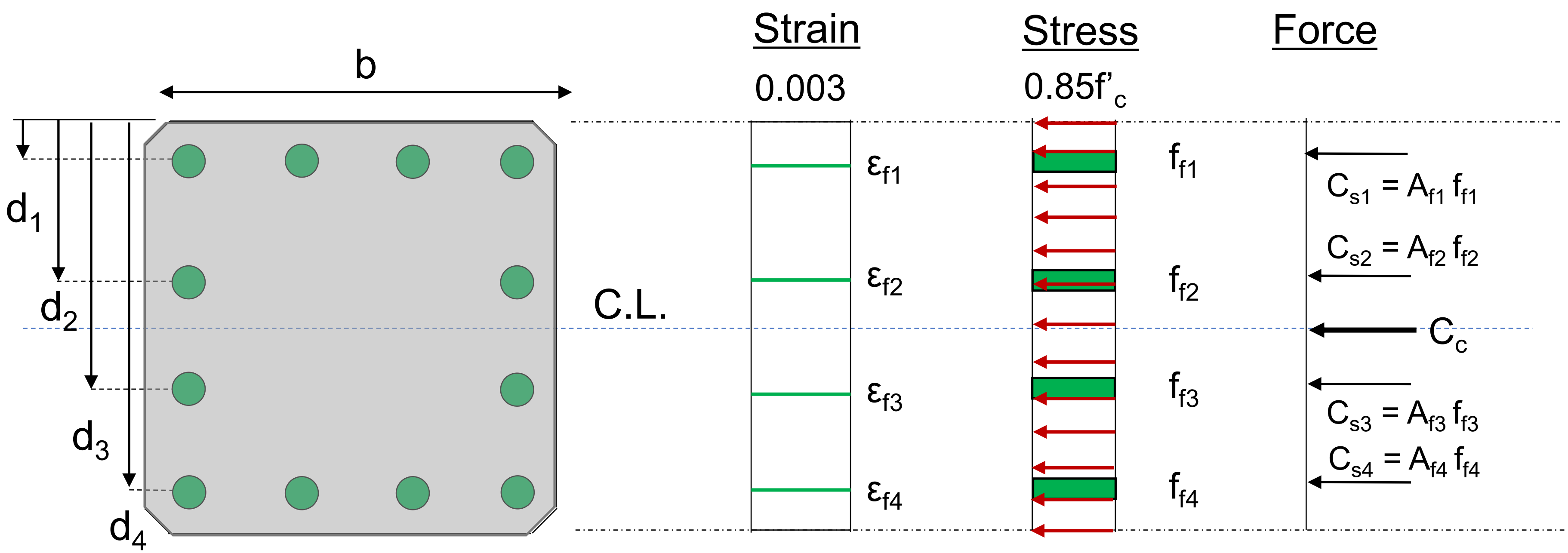
Developing P-M Interaction Diagram

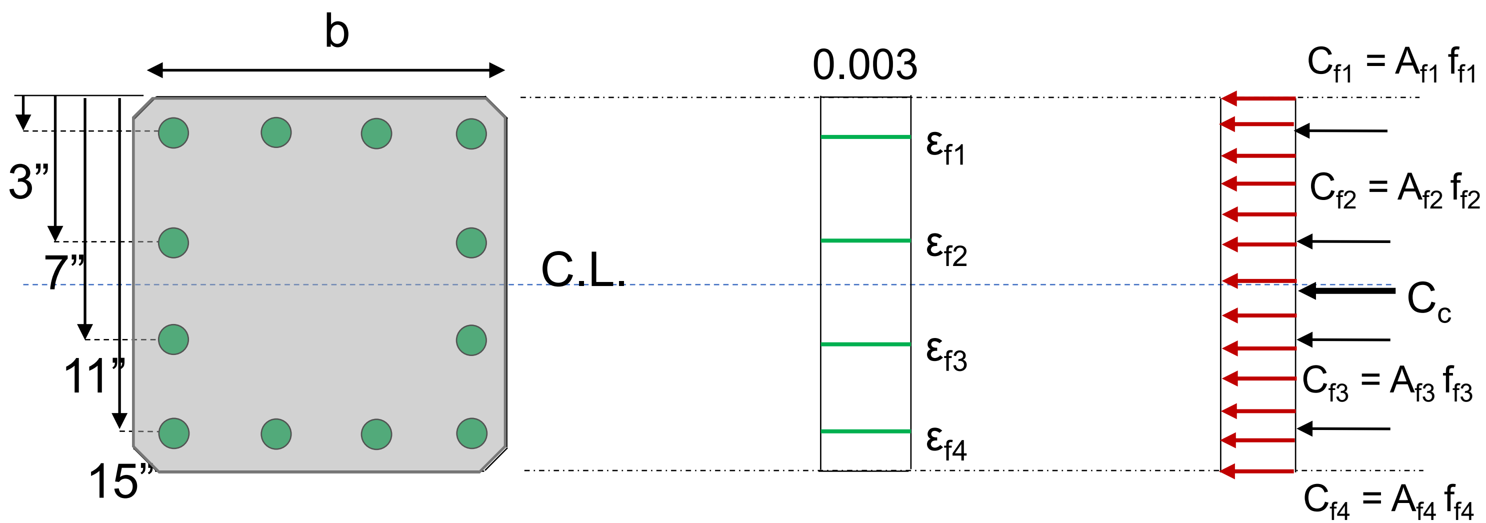
Pure Compression

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



Developing P-M Interaction Diagram

Pure Compression



Moment at this point: $M = 0\ k - in$

Should we add this term?

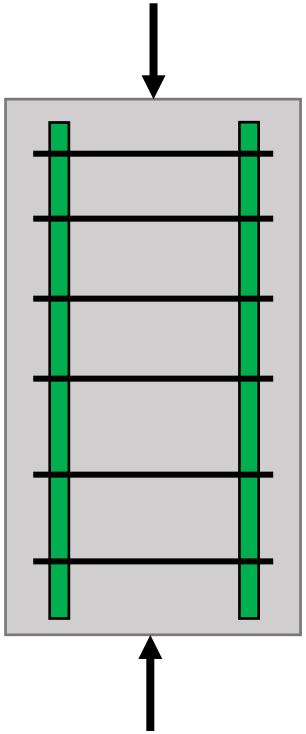
Capacity in pure compression: $P = \mathbf{0.85 f'_c (A_g - A_f)} + A_{f,tot}(\varepsilon_{cu} E_c)$

$$\boldsymbol{C_c} = (0.85)(5ksi)(324in^2 - 9.48in^2) = \mathbf{1337\ k}$$ (**AASHTO GFRP 2.6.4.2**)

Developing P-M Interaction Diagram

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: $A_{f,tot}(\varepsilon_{cu}E_c)$



Developing P-M Interaction Diagram

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

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

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

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

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

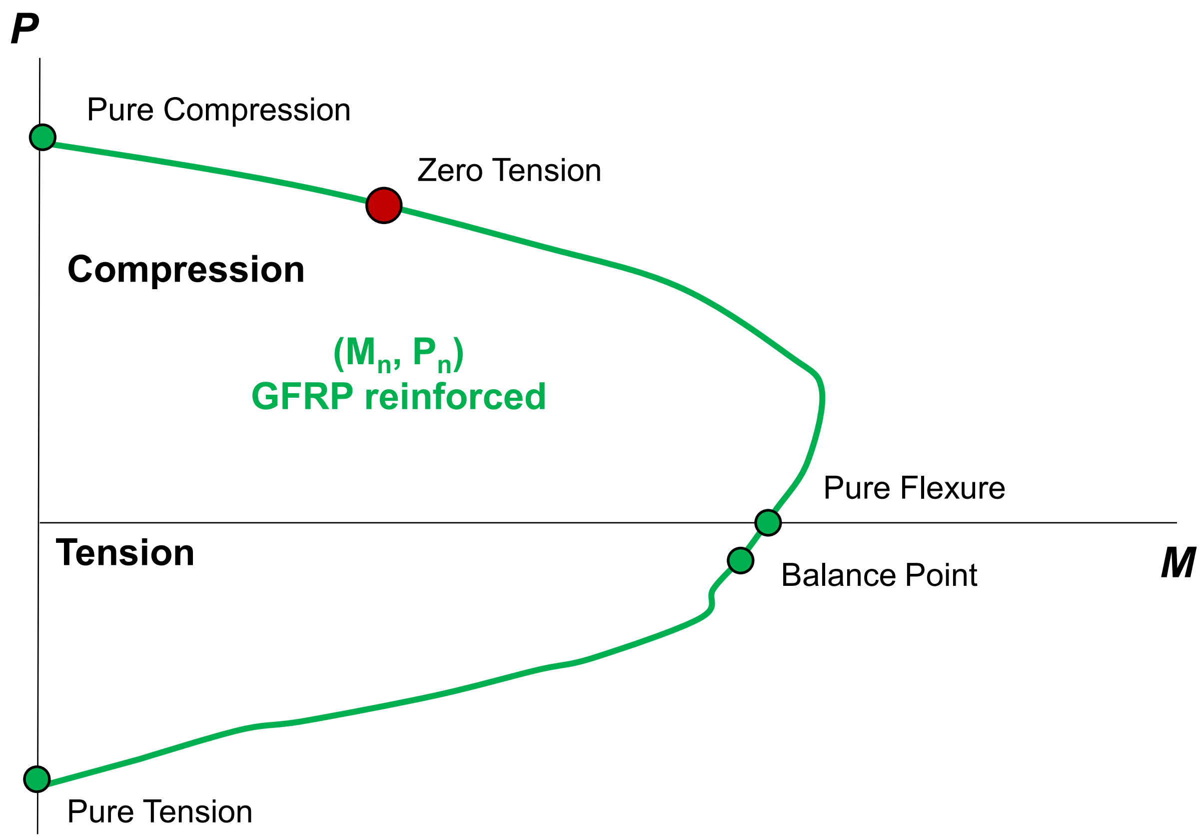
Adding all forces:

$$P = 1337k + 40.7k + 20.3k + 20.3k + 40.7k = \mathbf{1459\ k}$$

9% increase over current AASHTO equation

Developing P-M Interaction Diagram

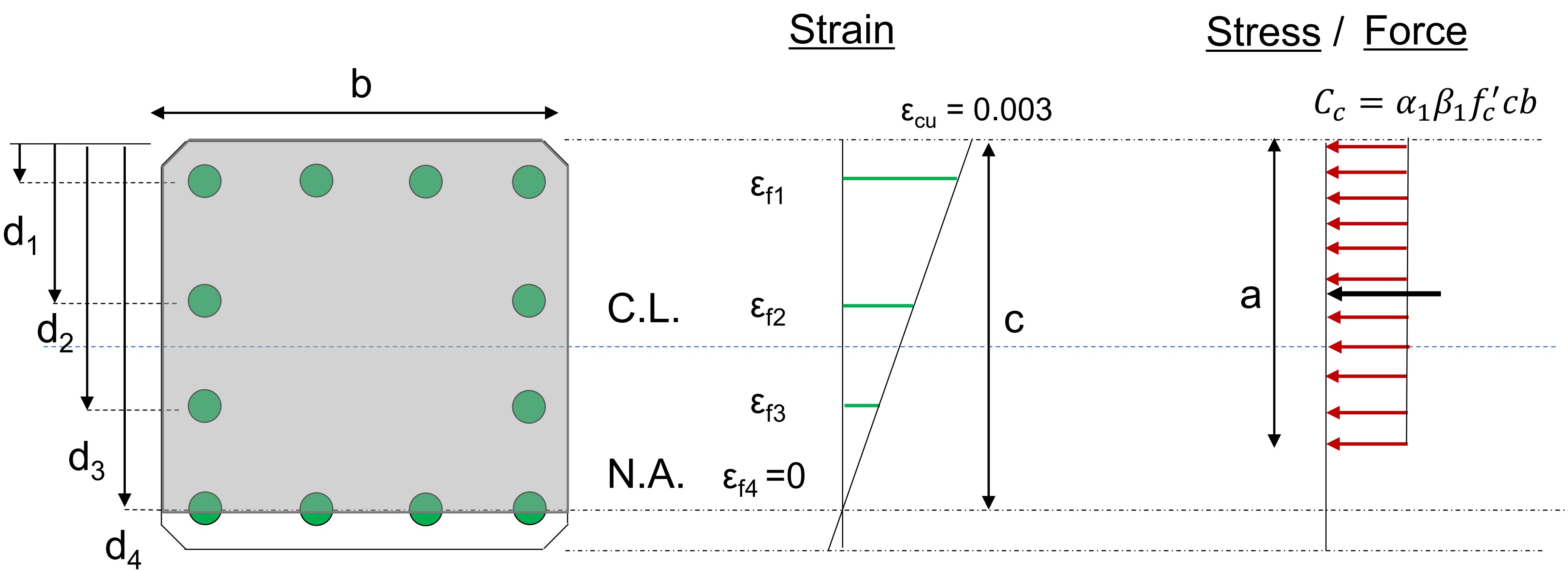
Next point: Zero tension on the extreme GFRP bar layer



Developing P-M Interaction Diagram

Zero Tension

Point where there is zero tension in the bottom reinforcement layer



Developing P-M Interaction Diagram

Zero Tension

$c = d$ neutral axis

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

$T_{f4} = 0\ kip$ *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

$$P = \sum F = C_c \qquad = 918k$$

Developing P-M Interaction Diagram

Zero Tension (Continued)

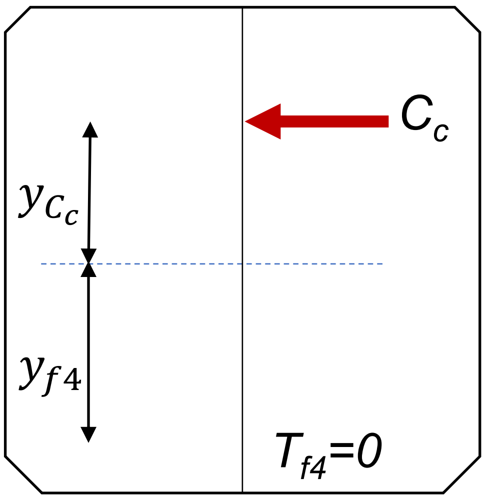
Calculate distance of forces from center line and then solve using for moment

Concrete level:

$$y_{C_c} = y_{N.A.} - \frac{\beta_1 c}{2}$$
$$= 9in - \frac{(0.8)(15in)}{2} = 3in$$

4th Level:

$$y_{f4} = d_4 - y_{N.A.} = 15in - 9in = 6in$$

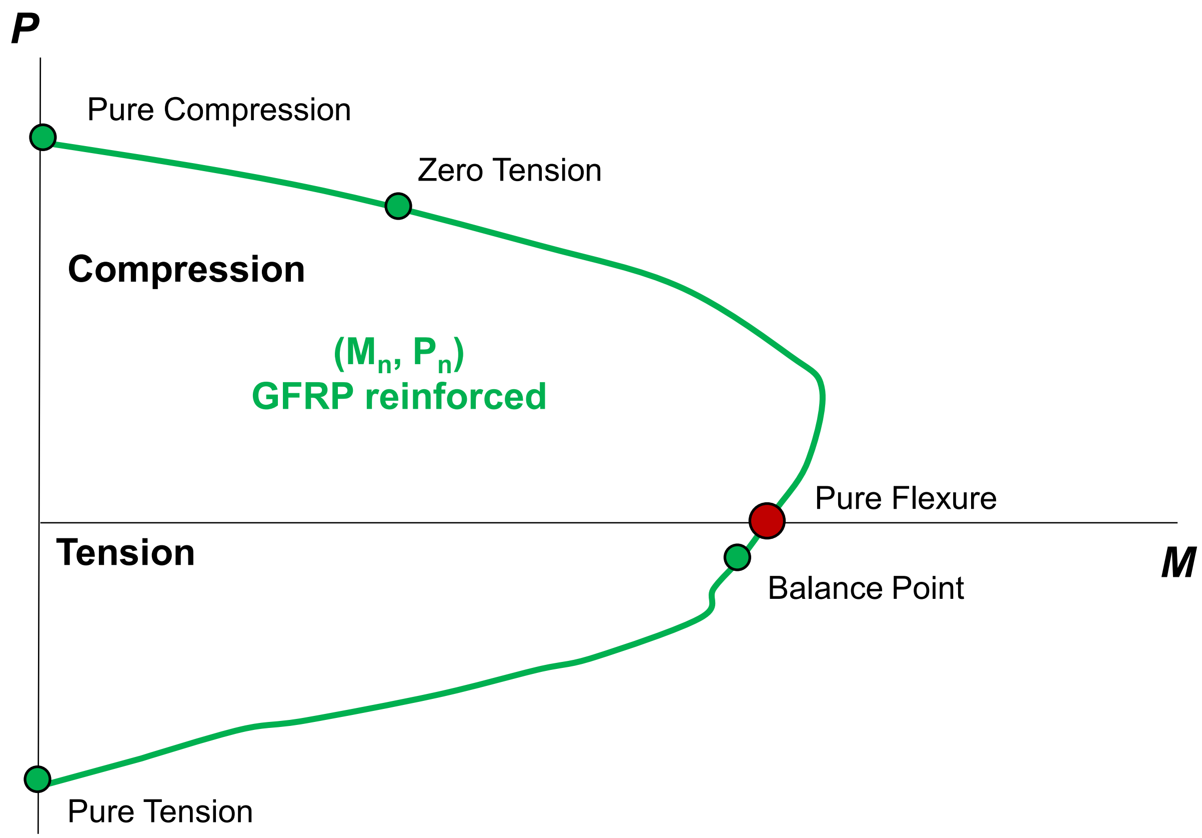


Taking moments

$$M = y_{Cc}F_{Cc} + y_{f4}T_{f4} = 918k(3in) + 0k(6in) = 229\ k-ft$$

Developing P-M Interaction Diagram

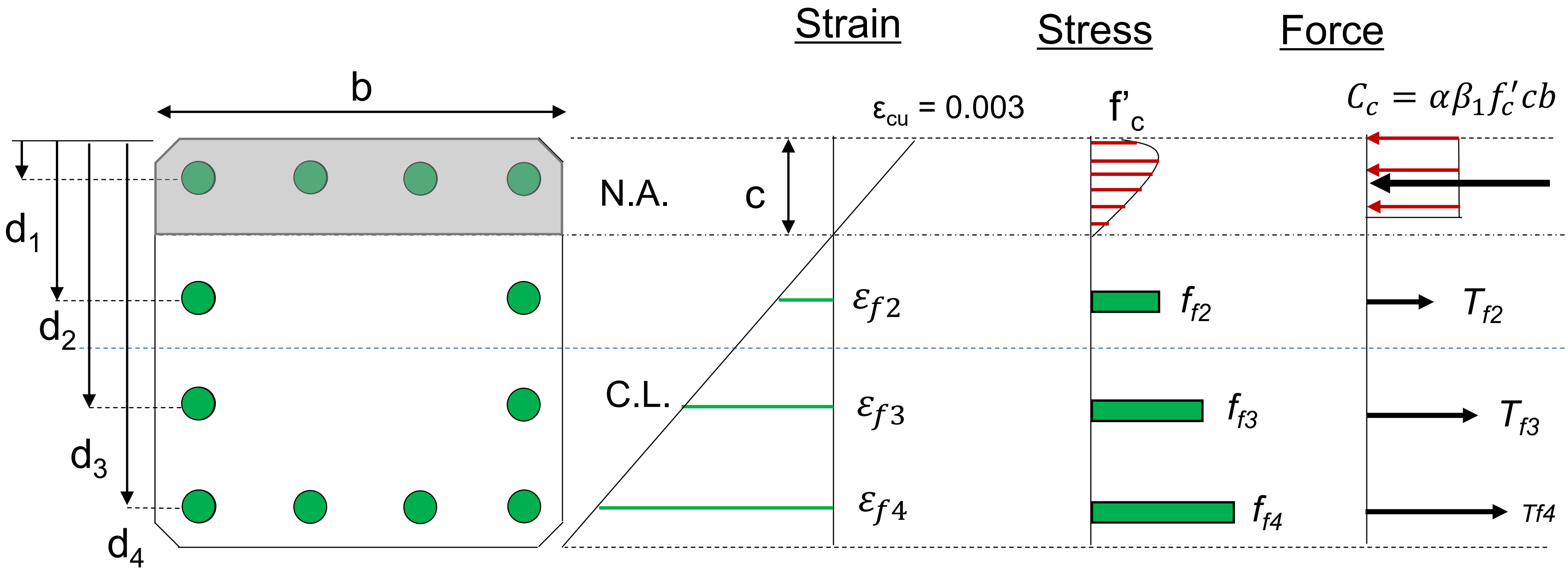
Next point: Pure flexure (P= zero)



Developing P-M Interaction Diagram

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)



$T_f = A_f \varepsilon_f E_f$

Developing P-M Interaction Diagram

Pure Flexure

$$P = \sum F = C_c + T_{f2} + T_{f3} + T_{f4} = 0k$$

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

$$C_c = 0.85(0.8)(5ksi)(18in)c = 61.2c$$

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:

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

$$\mathrm{c} = 4.01in.$$

Pure Flexure (Continued)

Calculate the Moment: Sum moments around center line

Concrete lever arms:

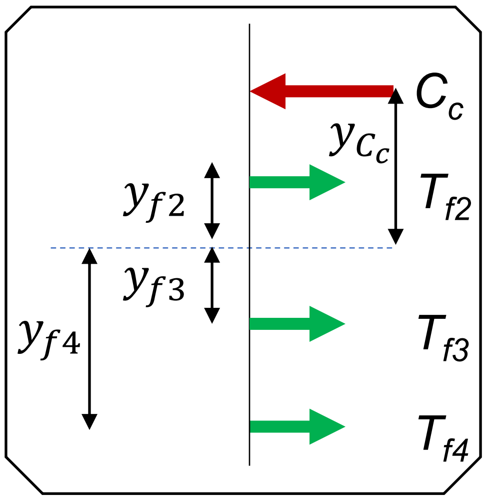
Summing Moments Around Cente

$$y_{C_c} = y_{N.A.} - \frac{\beta_1 c}{2} = 9in - \frac{(0.8)(4.01in)}{2} = 7.4in$$

$$y_{f2} = y_{N.A.} - d_2 = 9in - 7in = 2in$$

$$y_{f3} = d_3 - y_{N.A.} = 11in - 9in = 2in$$

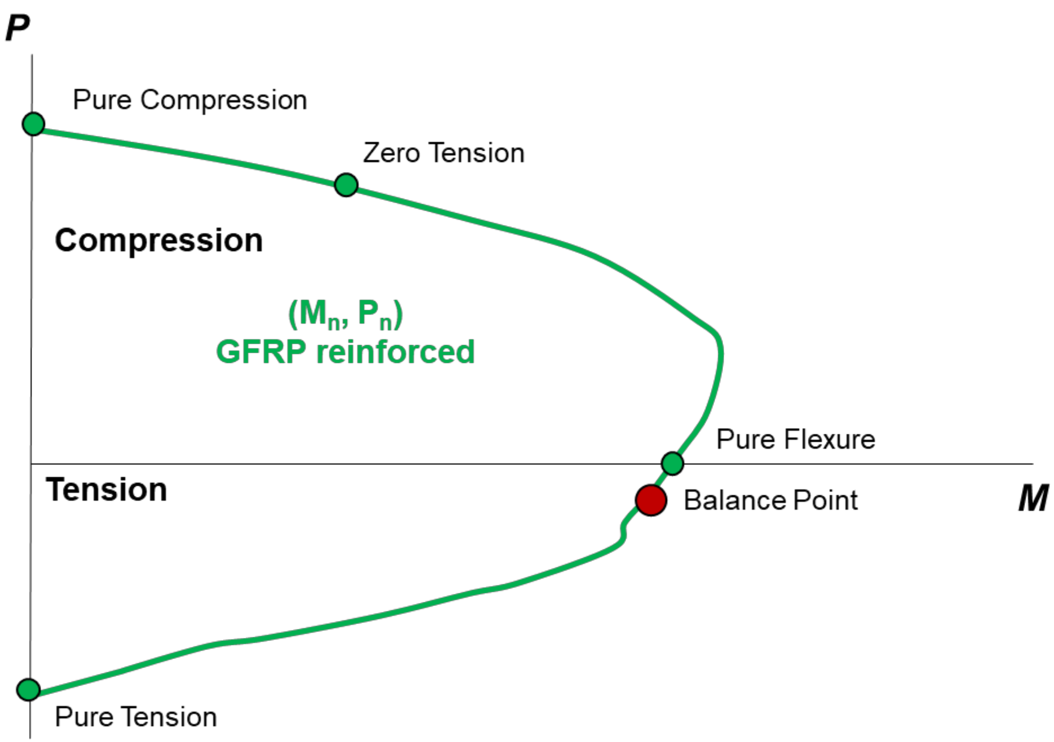
$$y_{f4} = d_4 - y_{N.A.} = 15in - 9in = 6in$$

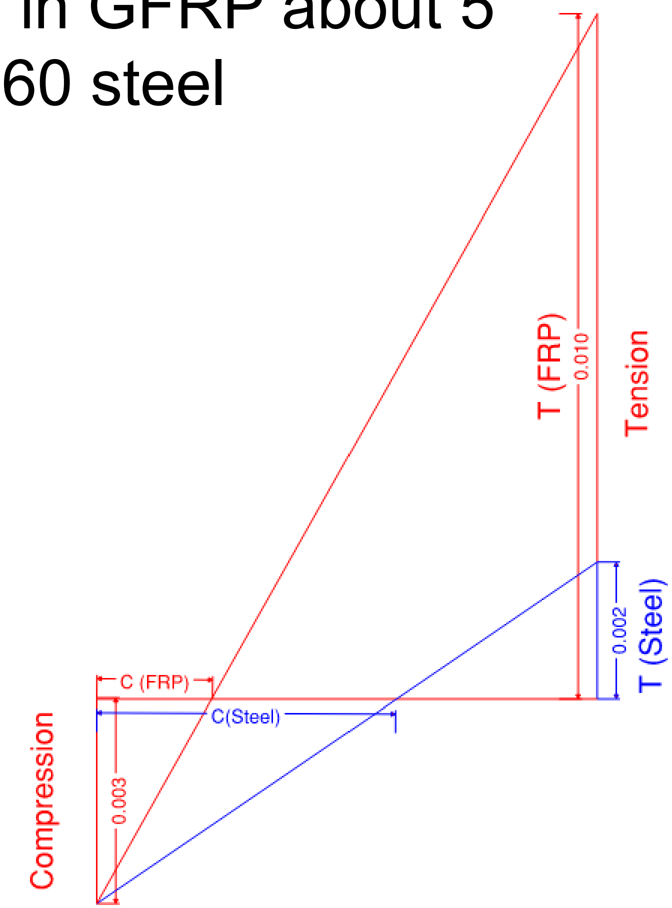


$$M = y_{Cc}C_c + y_{f2}T_{f2} + y_{f3}T_{f3} + y_{f4}T_{f4} = 231\ k - ft$$

Developing P-M Interaction Diagram

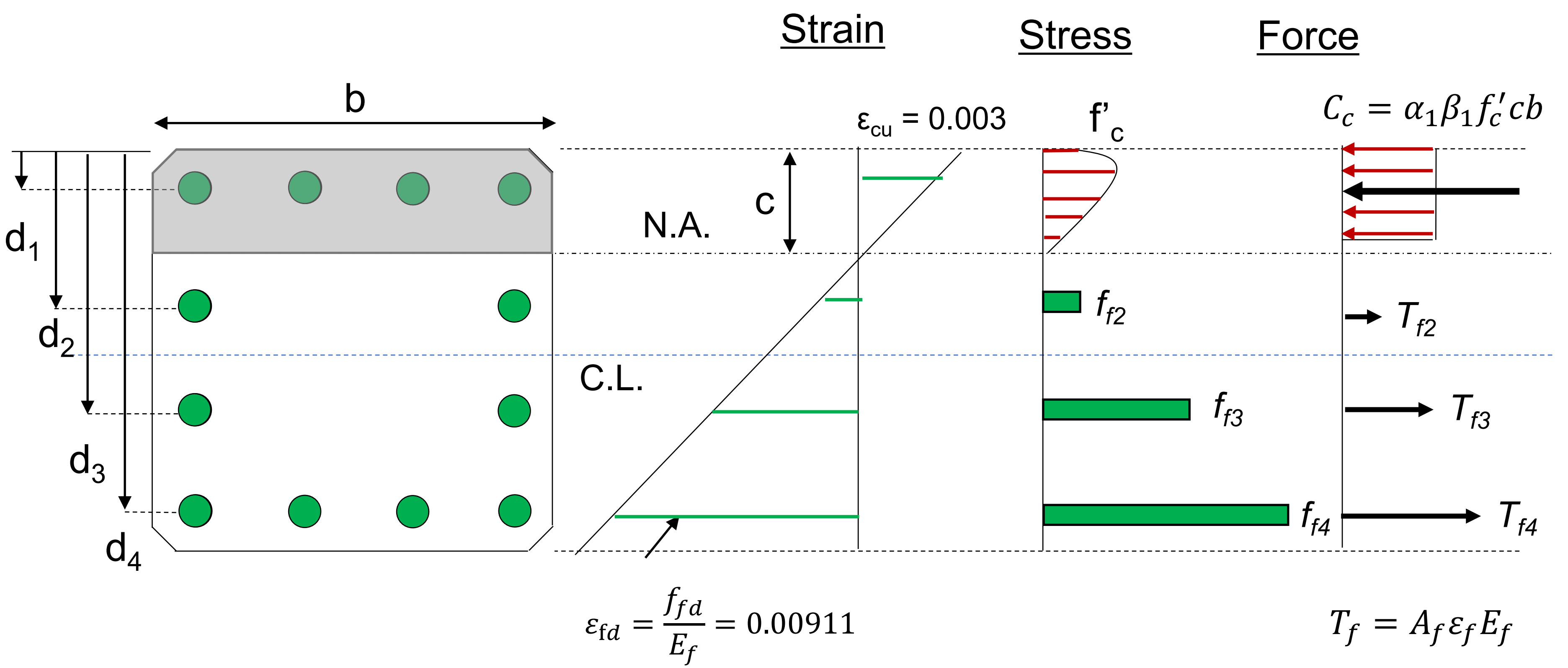
Next point: Balance failure, simultaneous GFRP rupture and concrete crushing. Design failure strain in GFRP about 5 times larger than yield strain for Grade 60 steel





Developing P-M Interaction Diagram

Balance Point: strain, stress and force distribution (equivalent stress block)

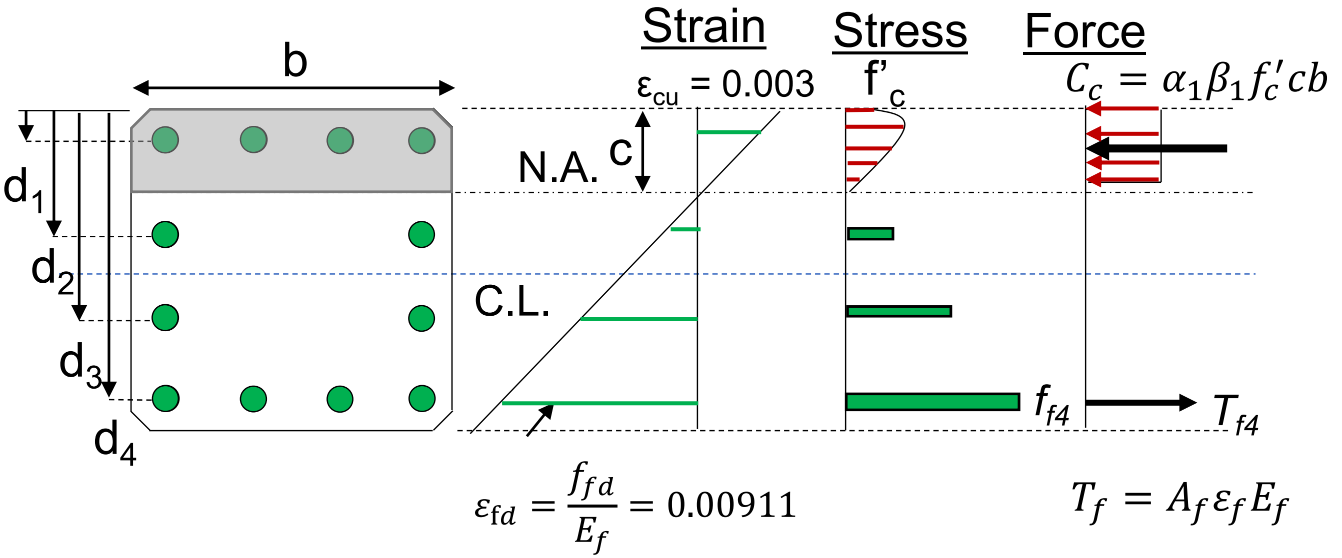


Developing P-M Interaction Diagram

Balance Point

d_1=3"; d_2=7";

d_3=11"; d_4=15"



Find the neutral axis:

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

$$c = (15in)\left(\frac{0.003}{0.00911 + 0.003}\right) = 3.72in$$

Developing P-M Interaction Diagram

Calculate GFRP strain and stresses:

Second layer GFRP strain

$$\varepsilon_{f2} = \varepsilon_{cu}\left(\frac{c - d_2}{c}\right) = 0.003\left(\frac{3.72in - 7in}{3.72in}\right) = -0.00265$$

$$f_{f2} = E_f \varepsilon_{f2} = (6500ksi)(-0.00265) = -17.2\ ksi$$

Third layer GFRP strain

$$\varepsilon_{f3} = \varepsilon_{cu}\left(\frac{c - d_3}{c}\right) = 0.003\left(\frac{3.72in - 11in}{3.72in}\right) = -0.00588$$

$$f_{f3} = E_f \varepsilon_{f3} = (6500ksi)(-0.00588) = -38.2\ ksi$$

Fourth layer GFRP strain

$$\varepsilon_{f4} = \varepsilon_{cu}\left(\frac{c - d_4}{c}\right) = 0.003\left(\frac{3.72in - 15in}{3.72in}\right) = -0.00911$$

$$f_{f4} = E_f \varepsilon_{f4} = (6500ksi)(-0.00911) = -59.2\ ksi = \mathbf{f_{fd}}$$

Developing P-M Interaction Diagram

Balance Point (Continued)

Calculate the Forces:

$$C_c = (b \cdot a)\alpha_1 \beta_1 f_c'$$

$$C_c = (18in \cdot 0.85 \cdot 3.72in)(0.8)(5ksi) = 277.5k$$

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

Sum forces by multiplying GFRP stress by areas

$$P = 277.5k - (17.2ksi)(1.58in^2) - (38.2ksi)(1.58in^2) - (59.2ksi)(3.16in^2)$$

$P = -47.1k$

Balance point occurs when axial load is tension

Developing P-M Interaction Diagram

Calculate the Moment: Sum moments around section centerline

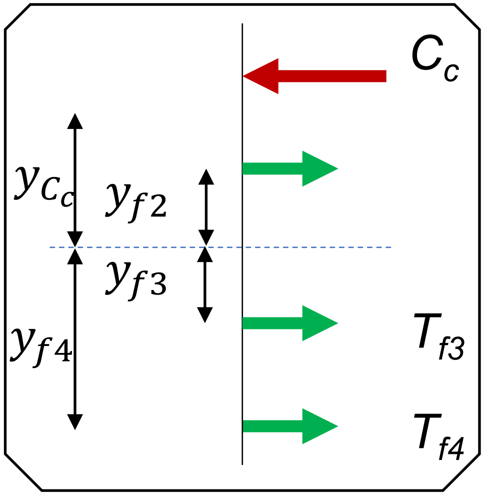
Concrete and GFRP bars lever arms:

$$y_{C_c} = y_{N.A.} - \frac{\beta_1 c}{2} = 9in - \frac{(0.8)(3.72in)}{2} = 7.5in$$

$$y_{f2} = y_{N.A.} - d_2 = 9in - 7in = 2in$$

$$y_{f3} = d_3 - y_{N.A.} = 11in - 9in = 2in$$

$$y_{f4} = d_4 - y_{N.A.} = 15in - 9in = 6in$$

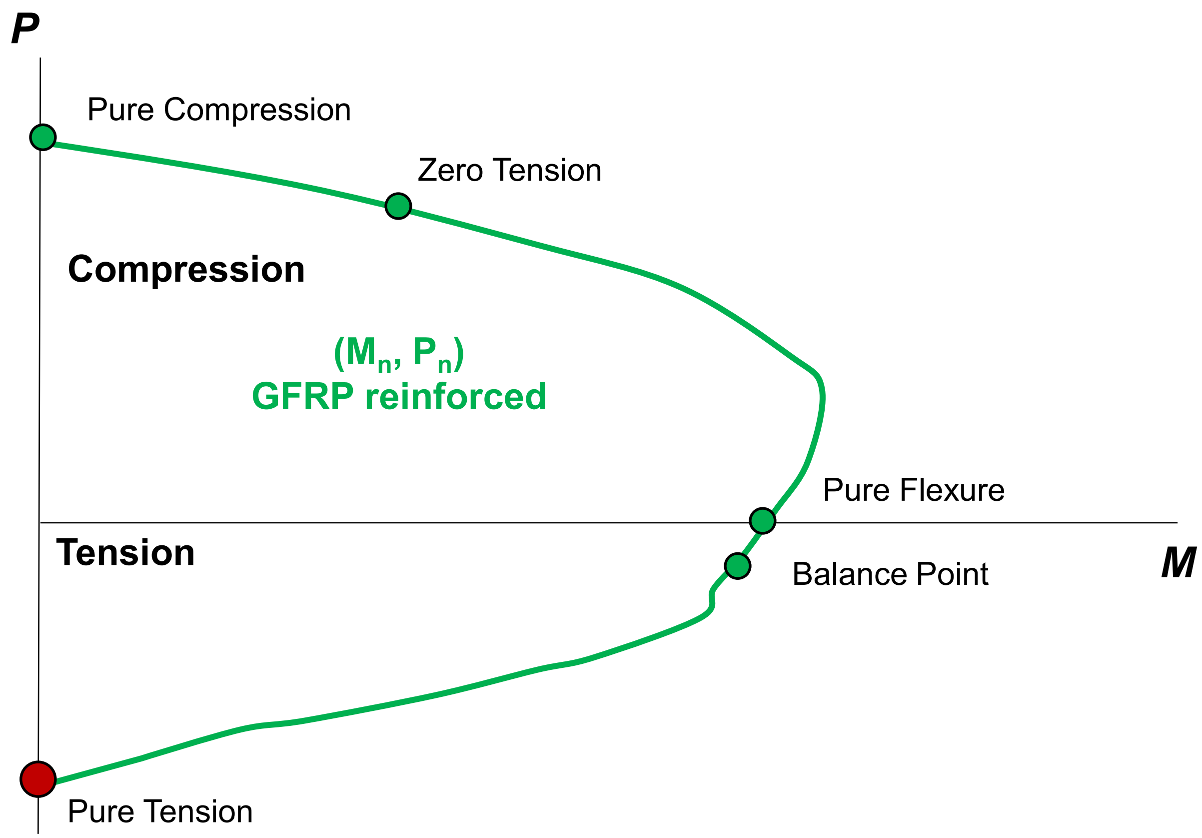


Summing Moments Around Center Line

$$M = C_c y_{C_c} - y_{f2} T_{f2} + y_{f2} T_{f3} + y_{f4} T_{f4} = 241\ k - ft$$

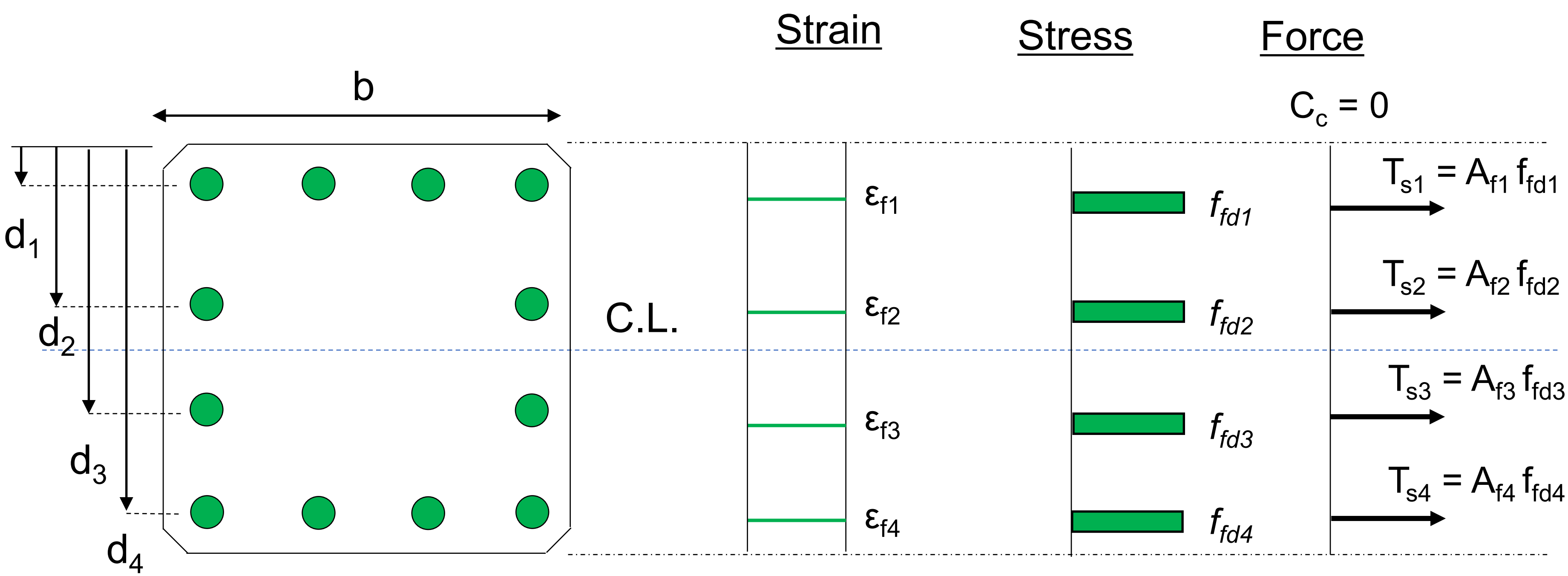
Developing P-M Interaction Diagram

Next point: Pure axial tension. There is no concrete contribution



Zero Moment (Tension)

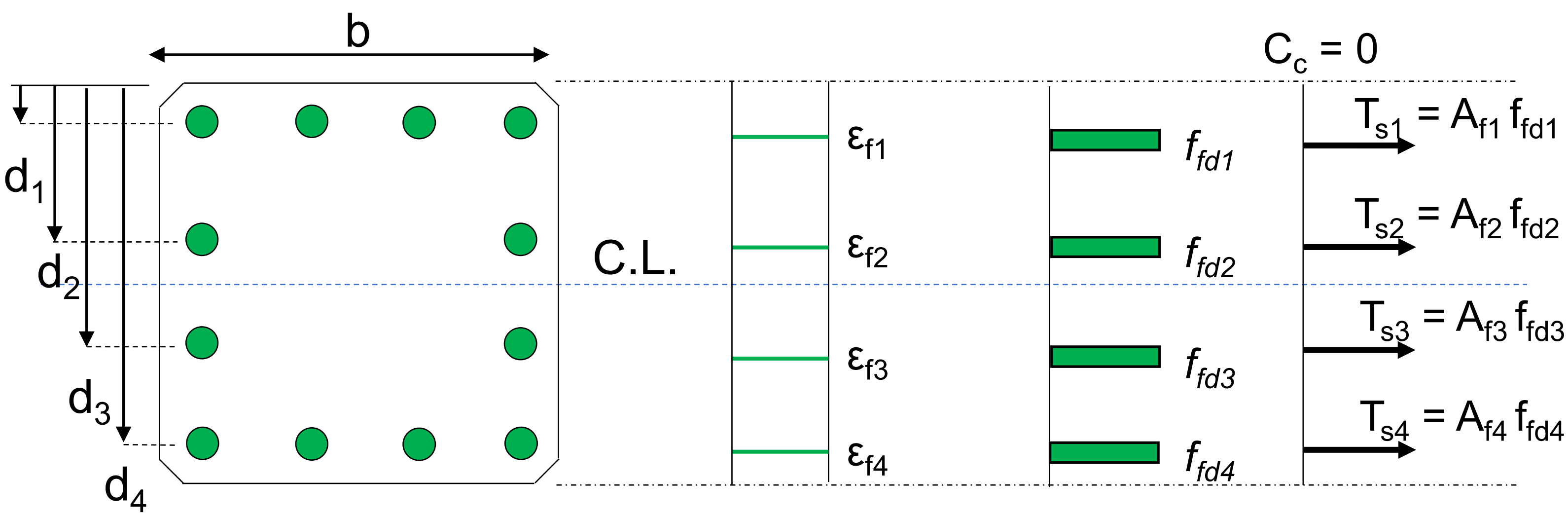
The first point is tension only, so the concrete is assumed to not contribute



$$\varepsilon_f = \varepsilon_{fd}$$

Developing P-M Interaction Diagram

Zero Moment (Tension)



$$\varepsilon_f = \varepsilon_{fd}$$

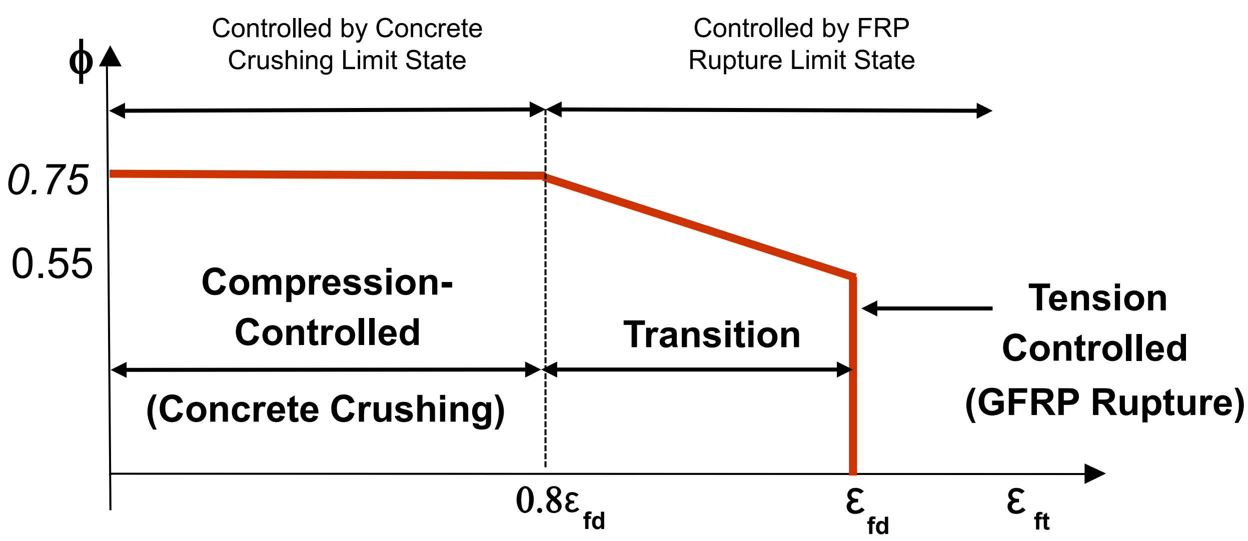
Calculate force components assuming all GFRP bars rupture

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

$$P = 12(0.79in^2)(59.2ksi) = 561.1kip$$

$$\mathrm{M} = 0kip - ft$$

AASHTO Resistance Factor for GFRP



The safety factor Φ 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:

0.85 = spiral or hoop reinforcement
0.80 = tie reinforcement

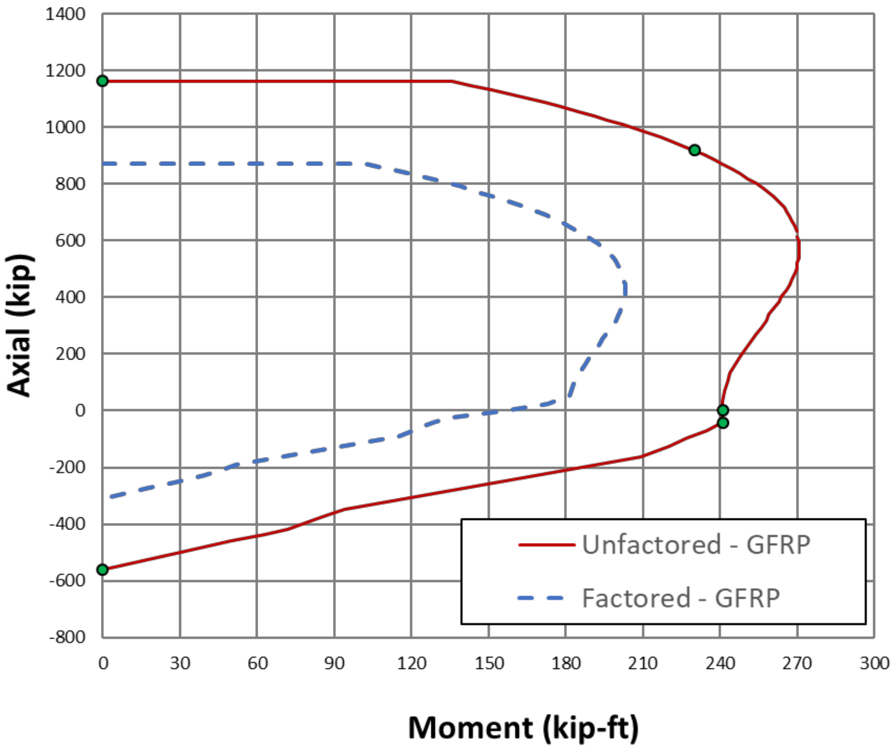
$$P_{n,.max} = 0.80[0.85(5ksi)(324in^2 - 9.48in^2)]$$

$$P_{n,.max} = 1070.6kip$$

Point	M_n	P_n	ϕ	ϕM_n	ϕP_n
Pure Compression	0 k-ft	1070 k	0.75	0 k-ft	802 k
Zero Tension	229 k-ft	918 k	0.75	172 k-ft	689 k
Pure Moment	231 k-ft	0 k	0.64	148 k-ft	0 k
Balance Point	241 k-ft	-47 k	0.55	133 k-ft	-26 k
Pure Tension	0 k-ft	-561 k	0.55	0 k-ft	-309 k

Developing P-M Interaction Diagram

P-M Diagram for factored and unfactored values



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

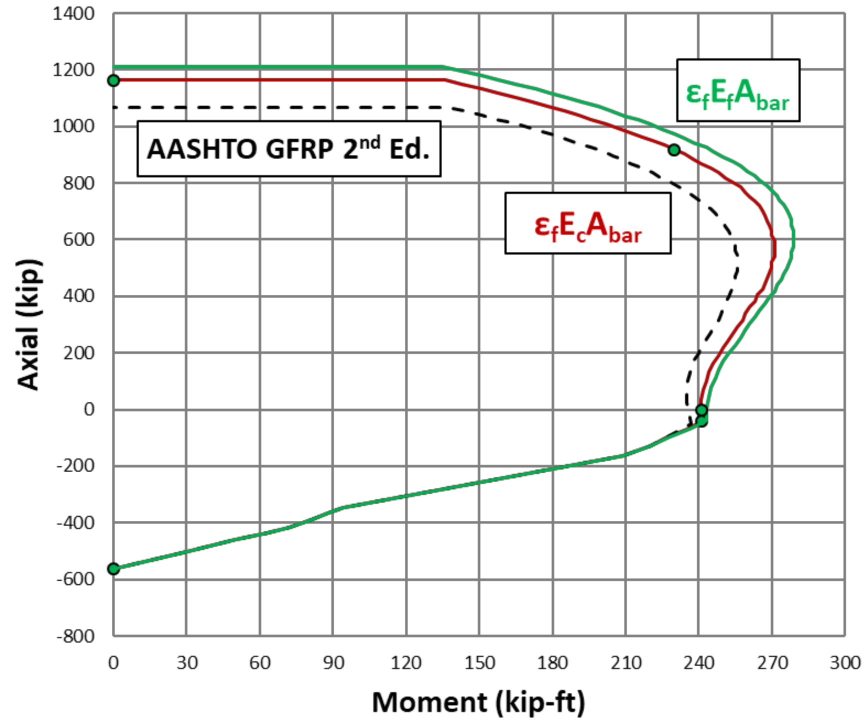
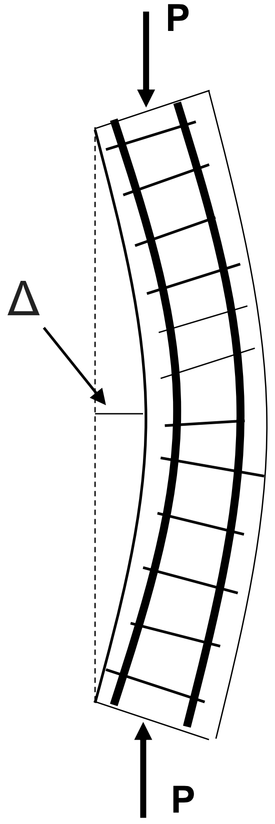


Table of Contents

- 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 (Δ). Δ 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%

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

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

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

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

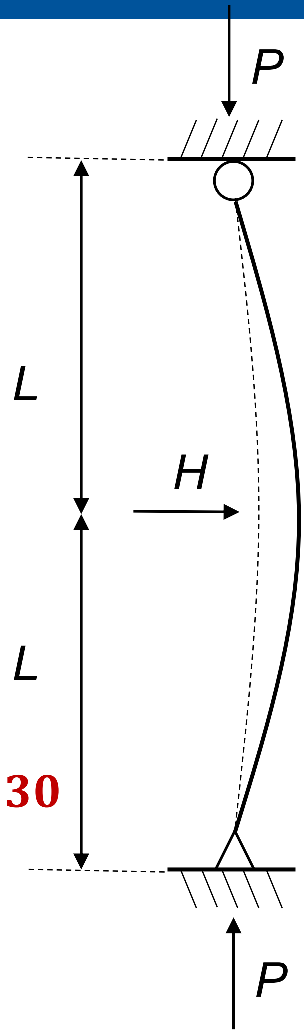
(a) Sway permitted

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

(b) Braced

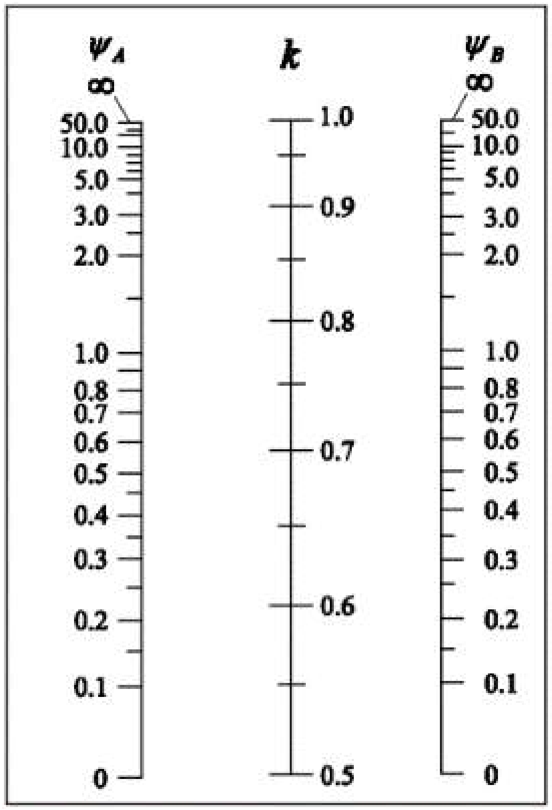
$$\frac{kL}{r} \leq 34 + 12\left(\frac{M_1}{M_2}\right) \leq 40 \quad \text{(ACI 318-14)} \quad \rightarrow \quad \frac{kL}{r} \leq \mathbf{29} + 12\left(\frac{M_1}{M_2}\right) \leq \mathbf{30}$$

M_1/M_2 is negative if column is bent in single curvature, and positive for double curvature

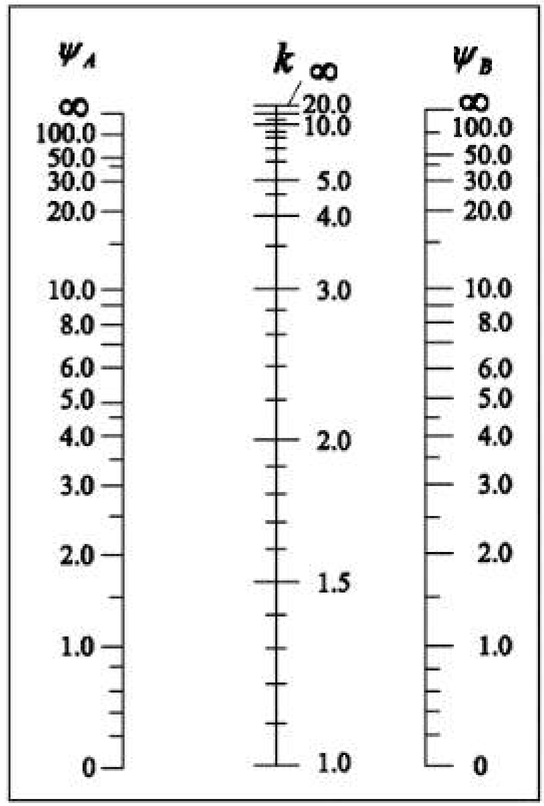


Alignment Charts

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

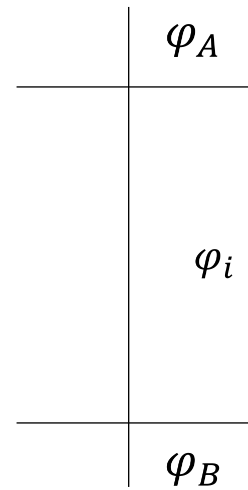


(a) Nonsway Frames



(b) Sway Frames

ψ_A and ψ_B are found based upon members framing into joint



$$\varphi_i = \frac{\sum \left(\frac{EI}{L}\right)_{column}}{\sum \left(\frac{EI}{L}\right)_{beam}}$$

Determination of EI

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

φ_A

$$\varphi_i = \frac{\sum\left(\frac{EI}{L}\right)_{column}}{\sum\left(m\frac{EI}{L}\right)_{beam}}$$

φ_B

Member and condition		Moment of Inertia	Cross-sectional area
Columns		$0.40I_g$	$1.0A_g$
Walls	Uncracked	$0.40I_g$	
	Cracked	$0.15I_g$	
Beams		$0.15I_g$	
Flat plates and flat slabs		$0.15I_g$	

Approved by ACI 440 committee adapting Bischoff (2017) for expected range of reinforcing ratios and elastic modulus. Jawaheri, H. & Nanni, A., (2017) provide further information.

Table of Contents

- Strength of GFRP-RC Columns
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- **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

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AXIAL RESPONSE OF GFRP REINFORCED CONCRETE

4.1 Review Questions: *Fundamentals*

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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

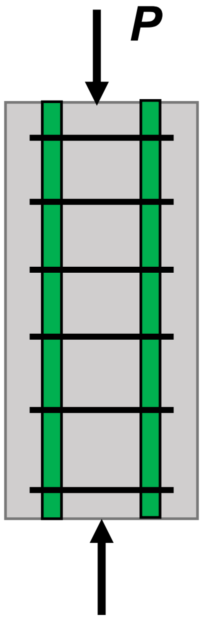
Introduction

Review of Steel RC Columns

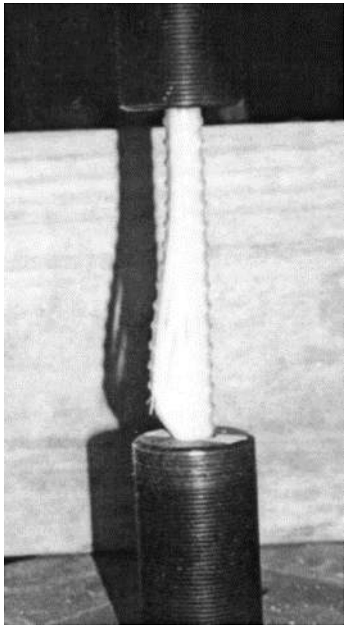
$$P_o = P_c + P_s = 0.85f_c'(A_g - A_s) + f_y A_s$$

Basic Concept for GFRP RC Columns

$$P_o = P_c + P_s = 0.85f_c'(A_g - A_s) + \cancel{f_y A_s}$$



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)

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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

Applied Question

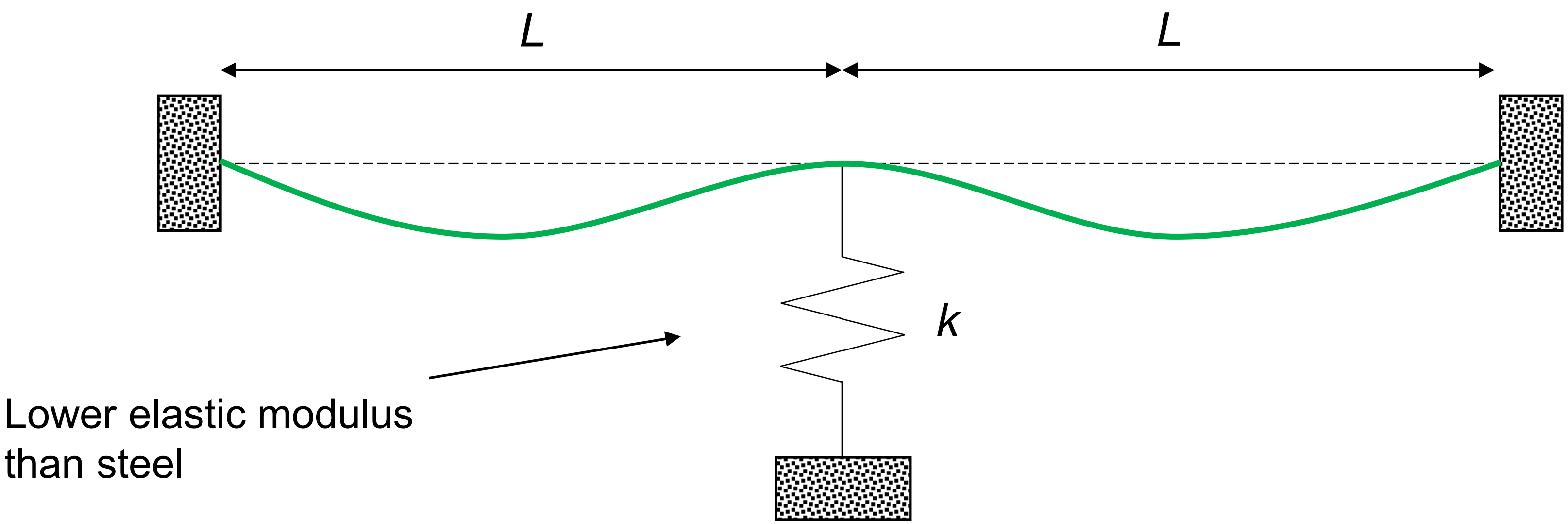
4.1.2) Compared to steel reinforced columns, the transverse spacing requirements for GFRP reinforced columns are the same.

a. True

a. False

Design Considerations

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



Theoretical:

$$s_{max} \approx 14d_b$$

AASHTO 4.7.5.4 – Tied Members

$$s_{max} = min\begin{cases} least\ dimension\ of\ column \\ d/4 \\ 12\ inches \end{cases}$$

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

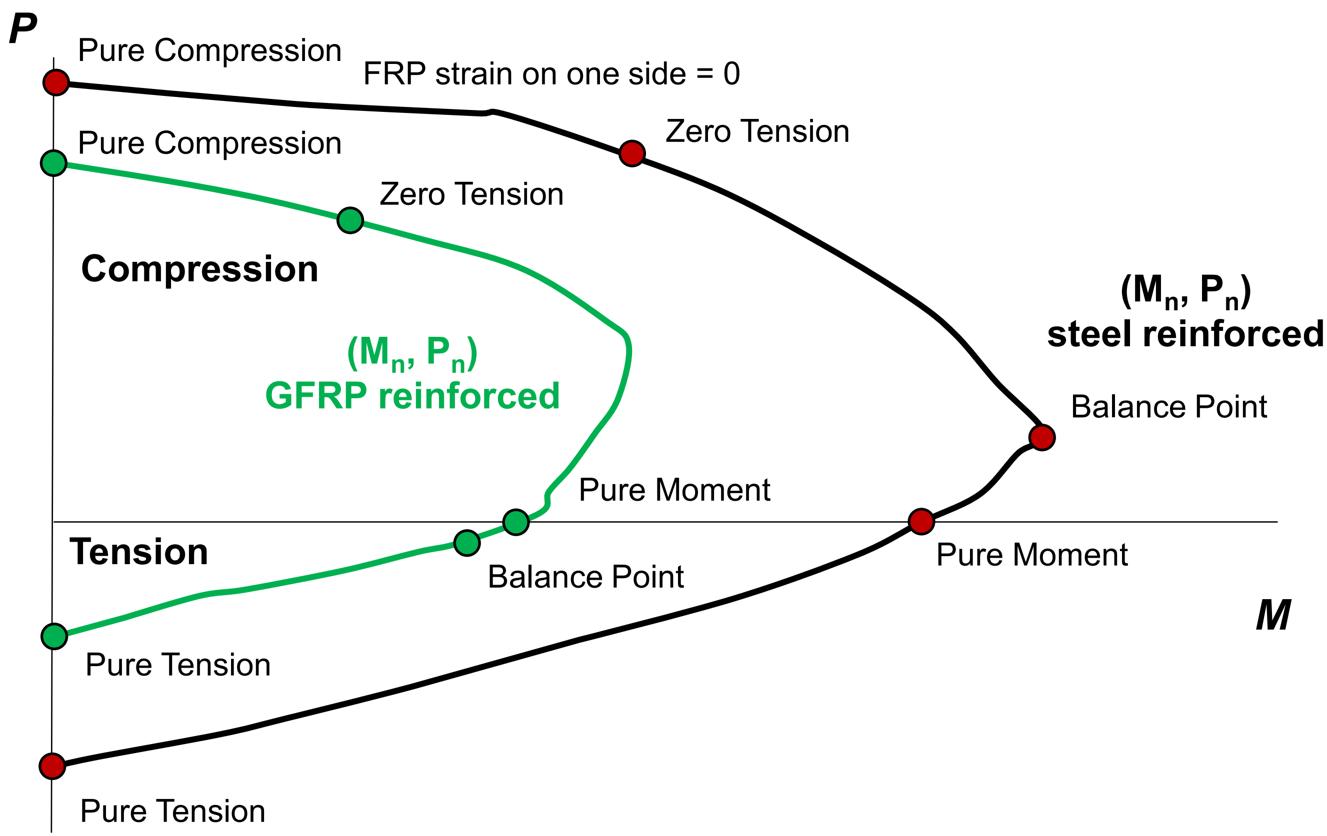
4.1.3) Compared to steel reinforced columns, the ultimate tensile capacity is reduced.

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



Applied Question

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

a. True

b. False

Applied Question

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

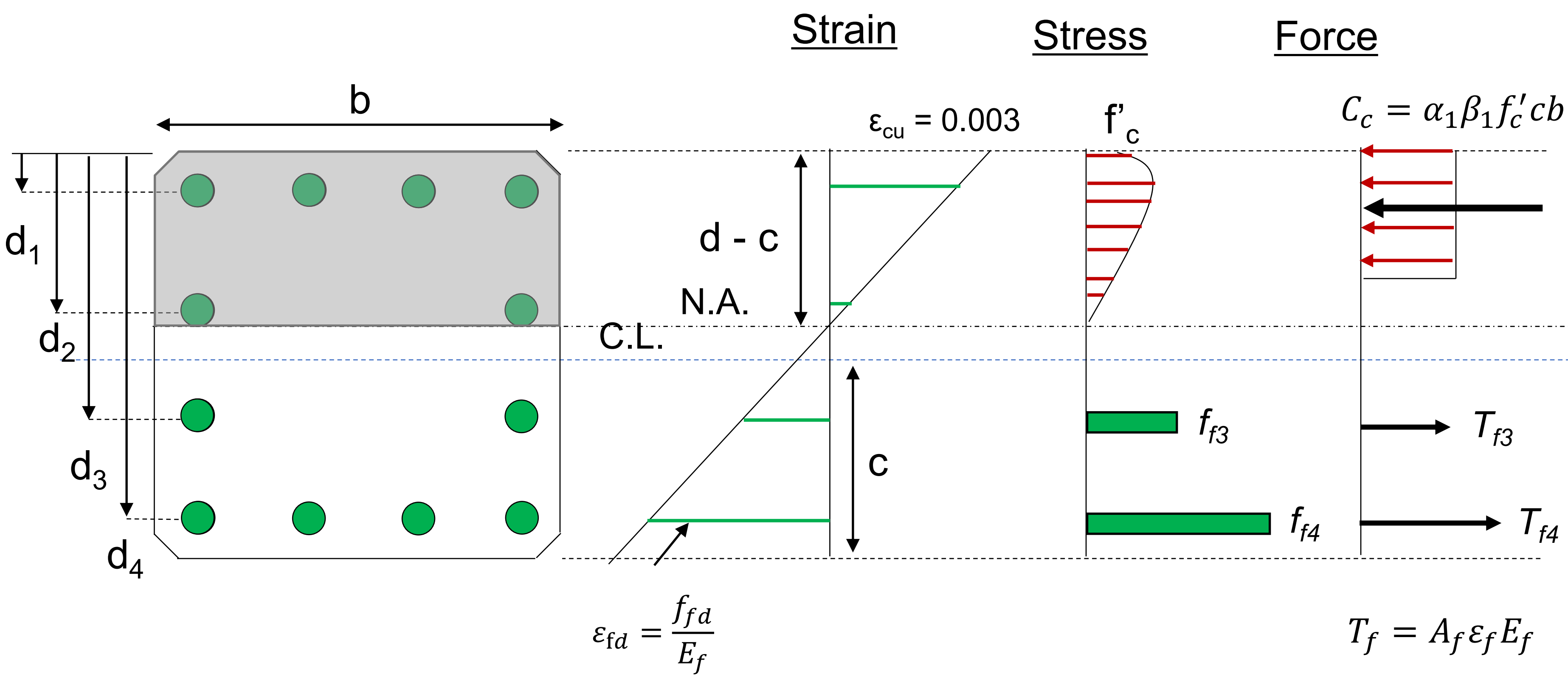
c. The point at which the GFRP reinforcement yields before concrete crushes

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)



Applied Question

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.

Applied Question

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

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

Detailed

$$EI = \frac{0.2E_cI_g}{1 + \beta_{dns}} + 0.75E_fI_f$$

where

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

Applied Question

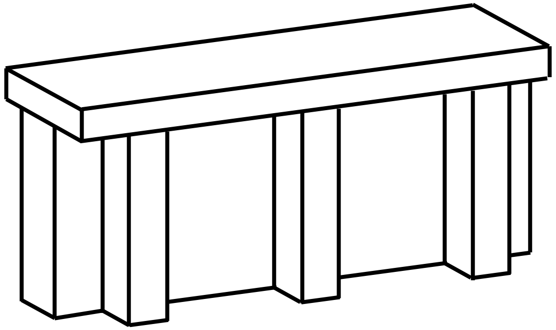
4.1.5) When designing a slender GFRP reinforced column, special considerations should be made to determining slenderness ratio and EI?

a. True

b. False

AXIAL RESPONSE OF GFRP REINFORCED CONCRETE

4.2 Design Example: Solider Pile in Wing Wall



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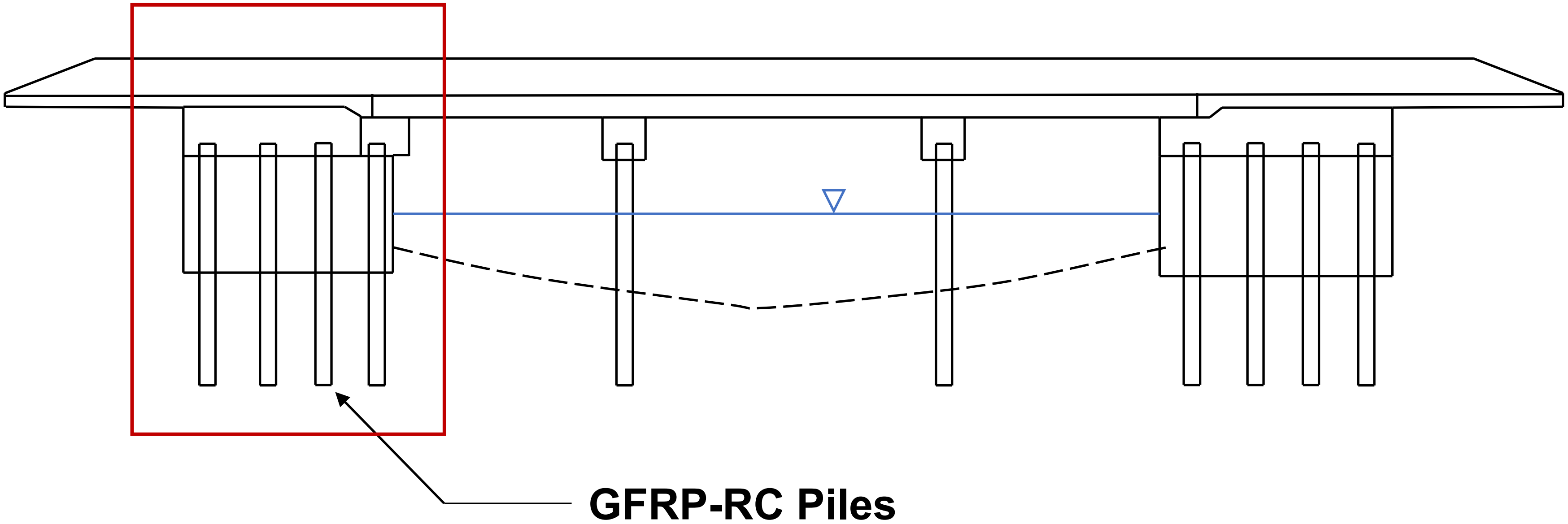
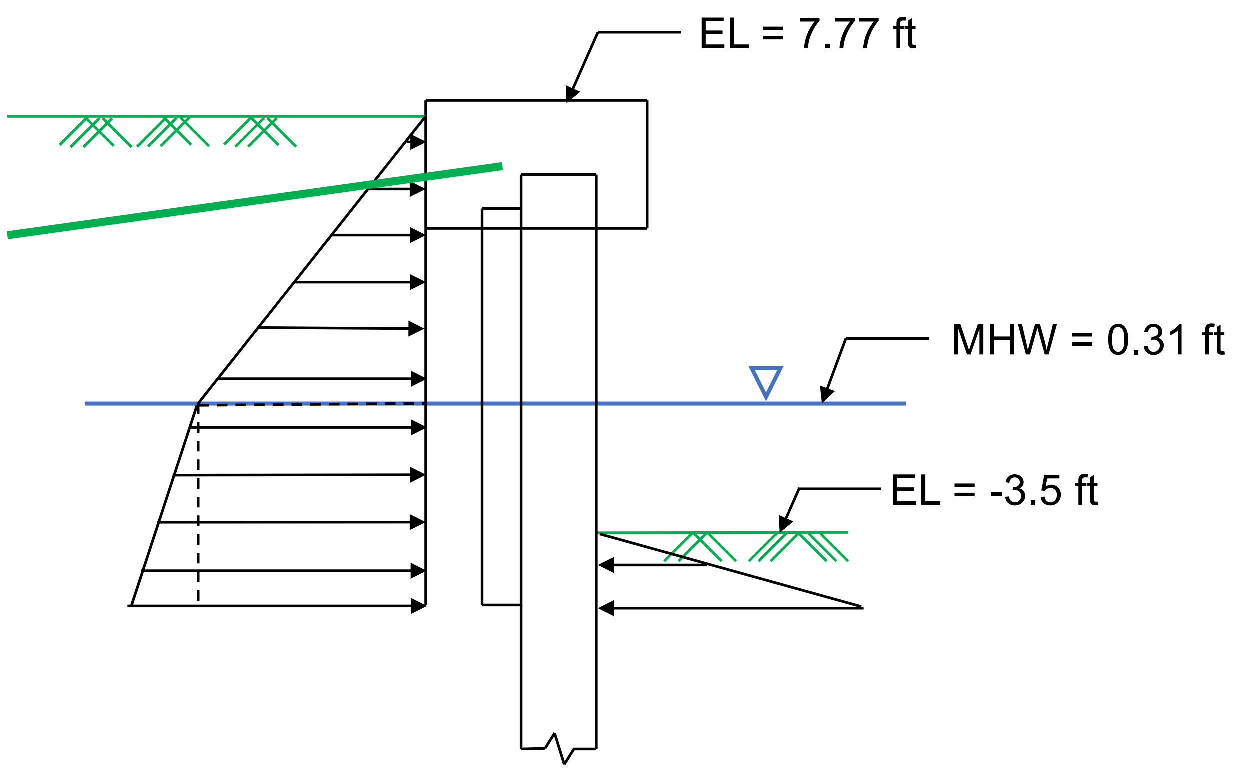
Pile Example

Consider the following example:



Pile Example



Cross Section

Soil Properties

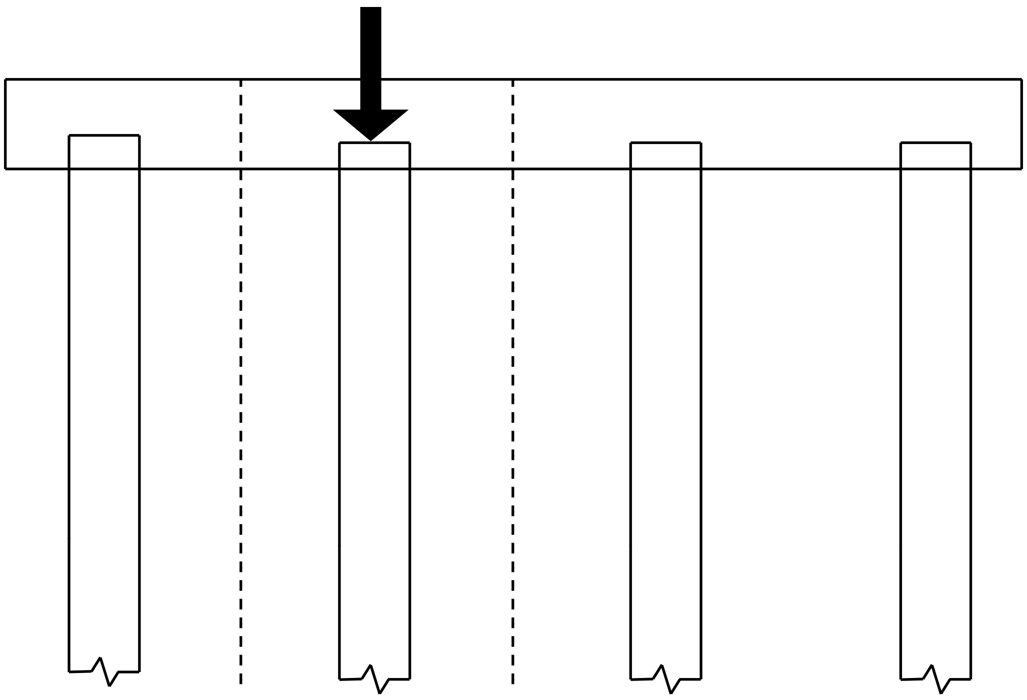
$$\gamma = 110\ pcf$$

$$\phi = 30\ degrees$$

$$c = 0\ ksf$$

Pile Example

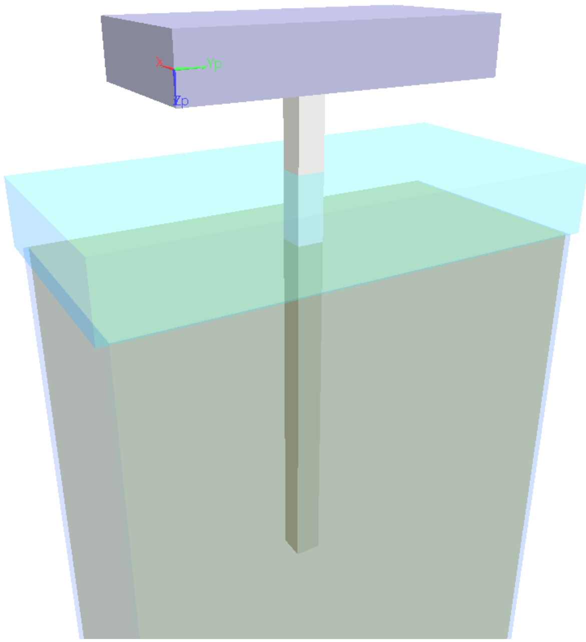
$$P_{cap} = Pile\ Spacing \times Cap_{Height} \times Cap_{Width} \times \gamma_c$$

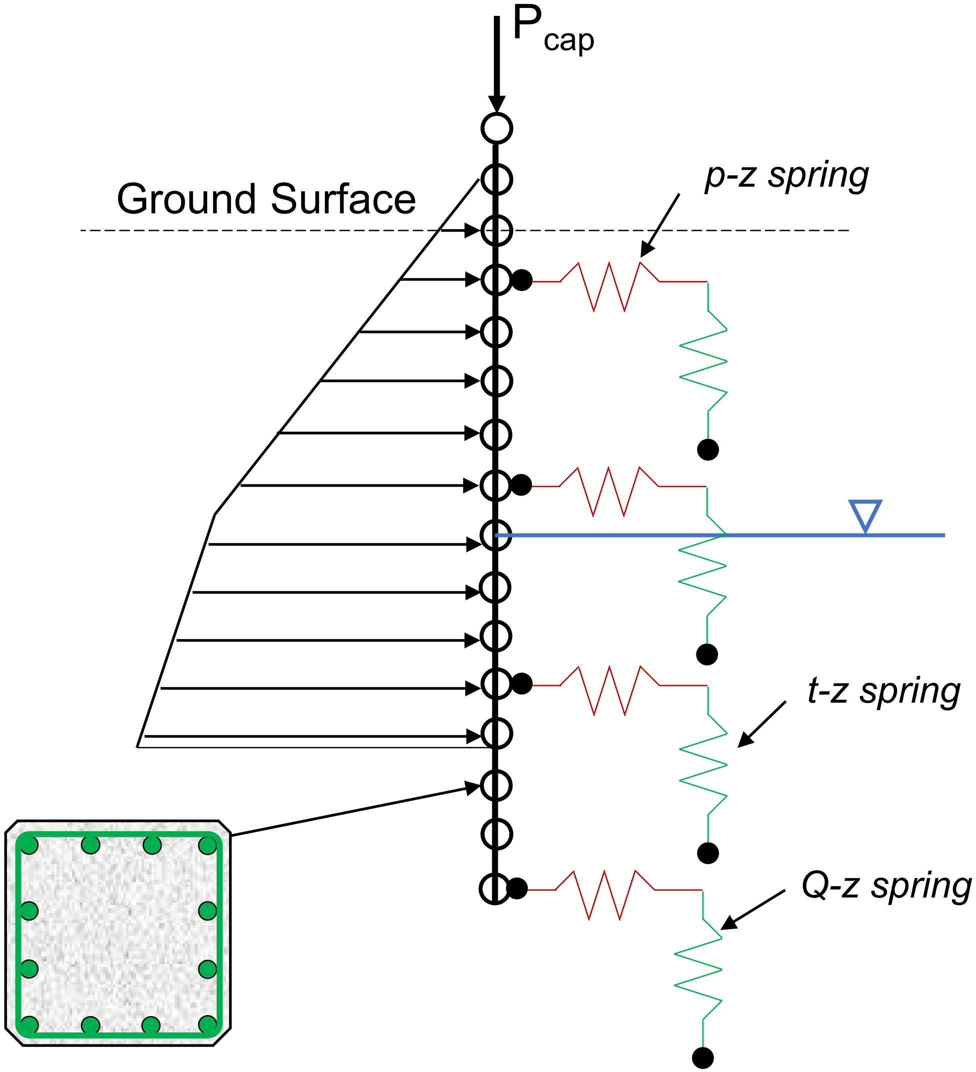


$$Distributed\ Force = Resultant\ Earth\ Pressure \times Pile\ Spacing$$

Pile Example

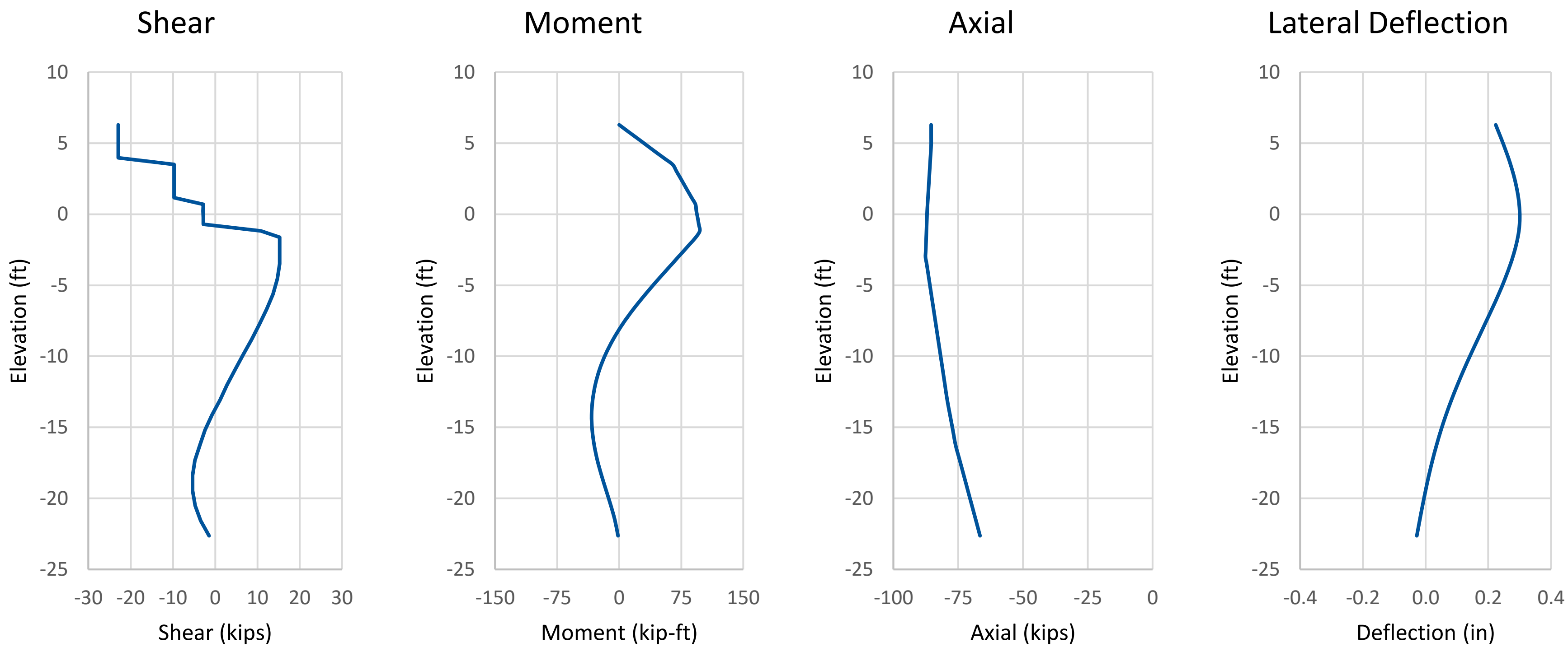
Laterally Loaded Pile Model





Pile Example

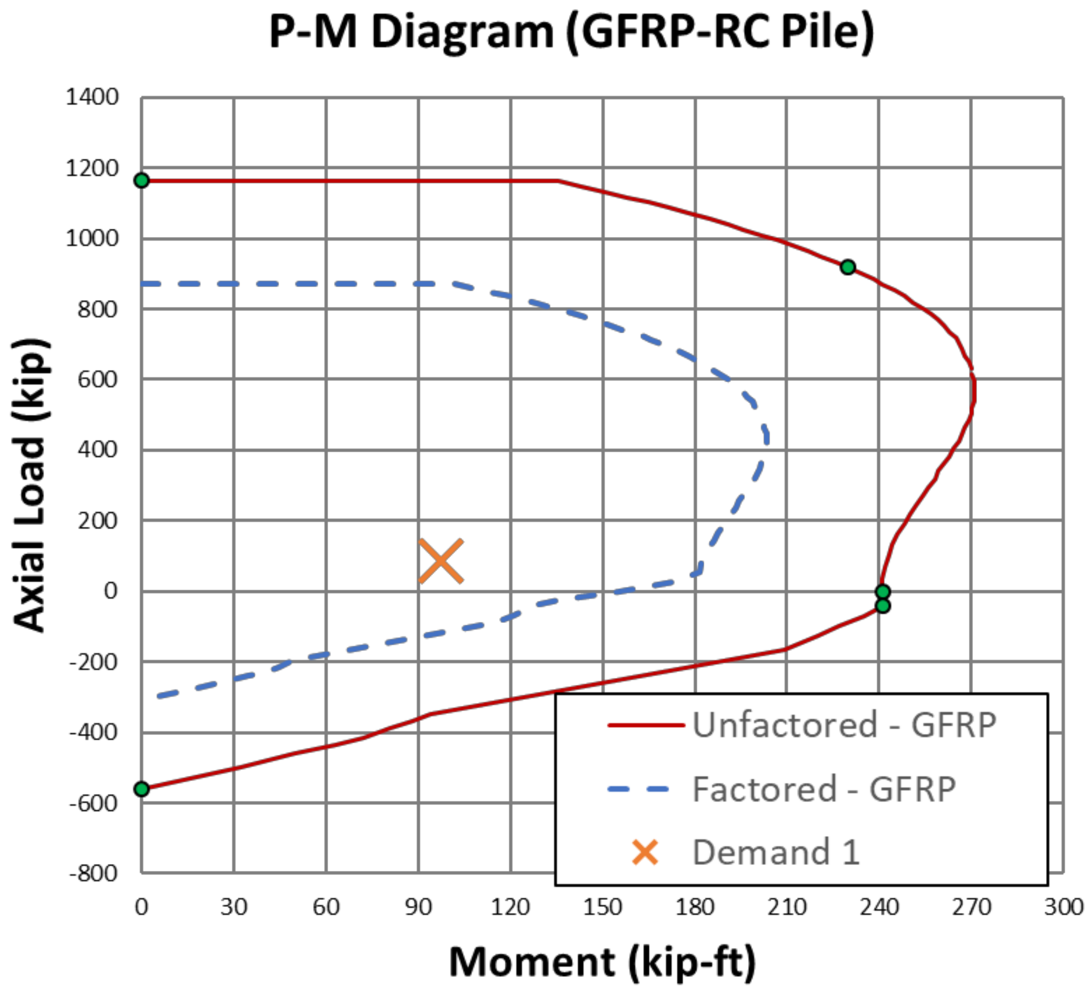
Laterally Loaded Pile Results



	Shear	Moment	Axial	Lateral Deflection
Max:	15.3 kip	97.4 kip-ft	87.7 kip	0.301 in
Min:	-22.9 kip	-33.4 kip-ft	-63.0 kip	-0.037 in

Pile Example

Plotting Demand Point in P-M Diagram



Questions?

AASHTO GFRP-Reinforced Concrete Design Training Course

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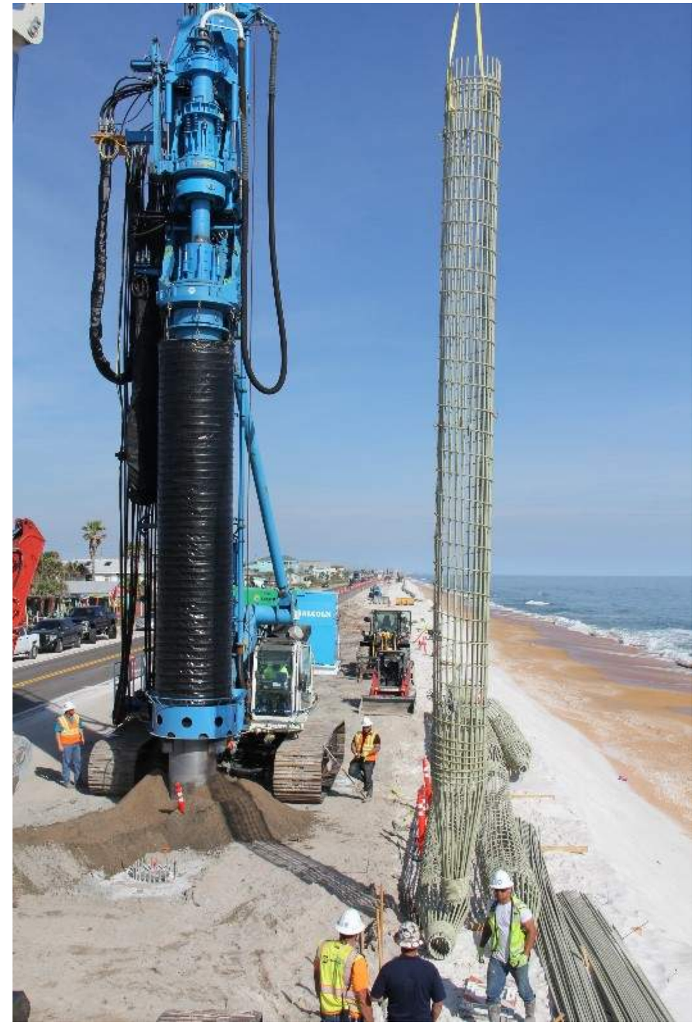
Course Outline

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



5. CASE STUDIES & FIELD OPERATIONS

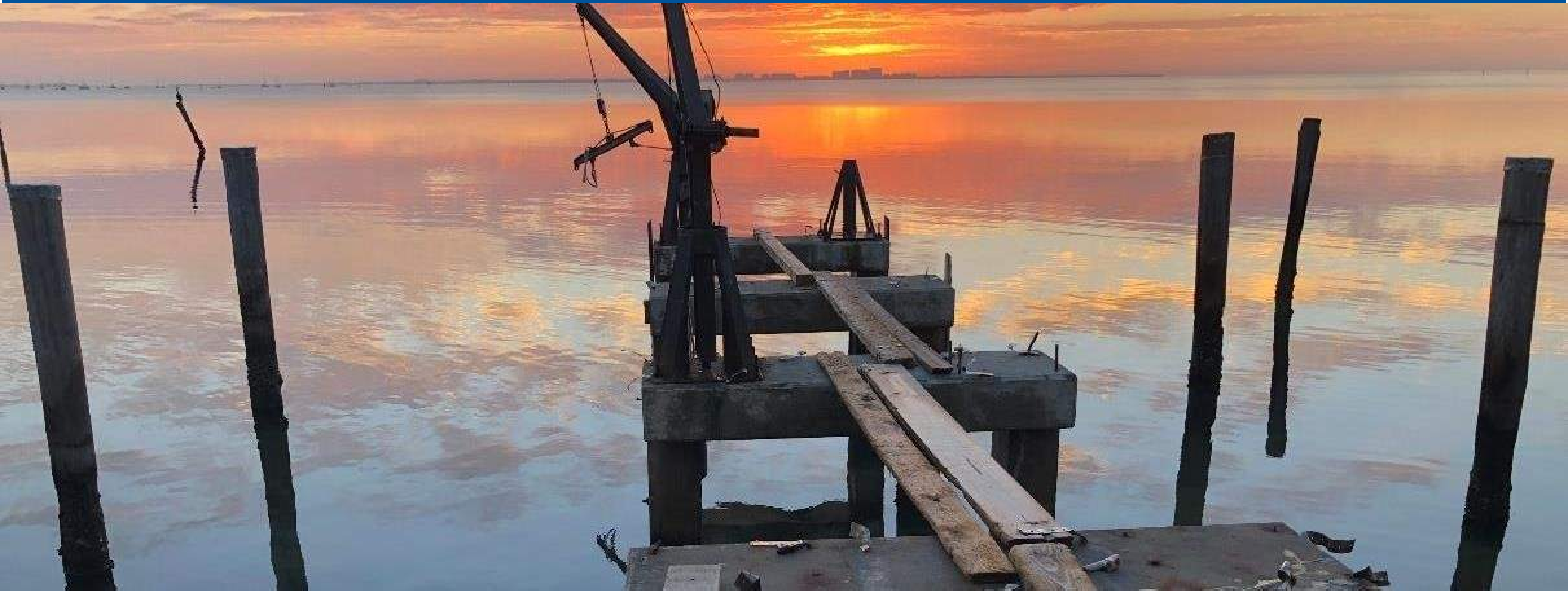


Table of Contents – Case Studies

- **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

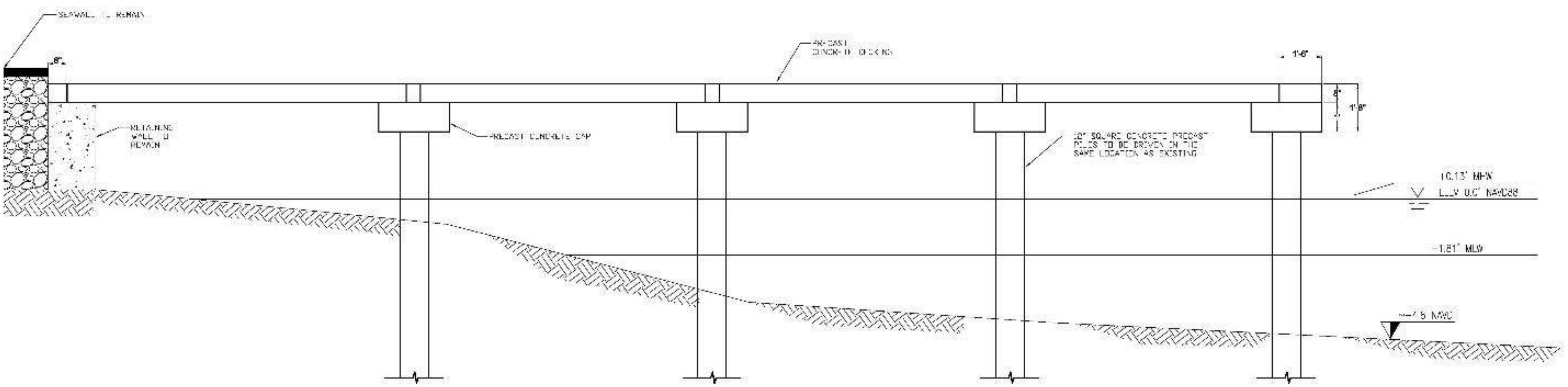
iDock Construction Intent - Miami, Florida

- 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

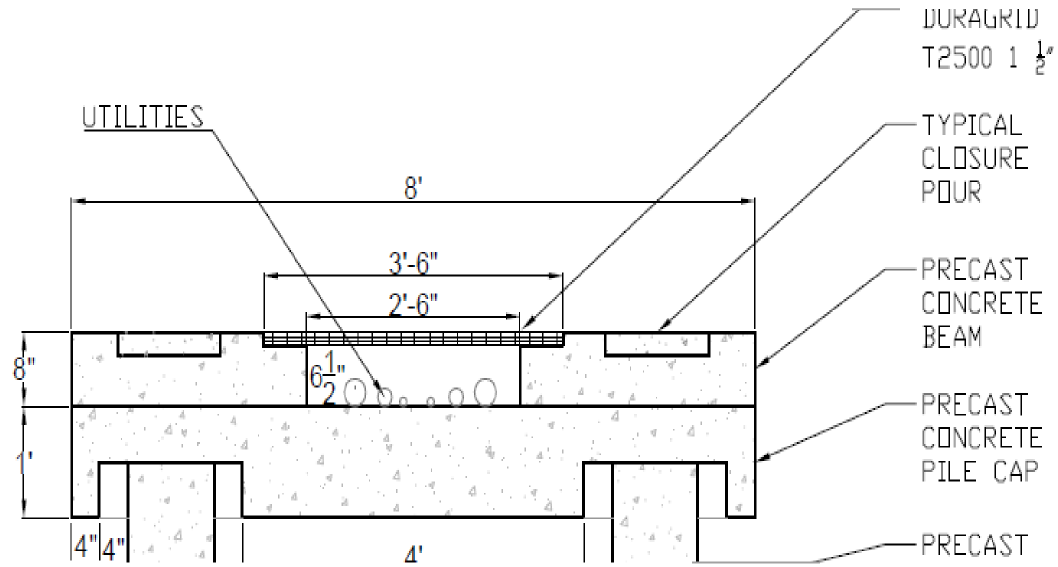
Traditional vs. Innovative Approach

- **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

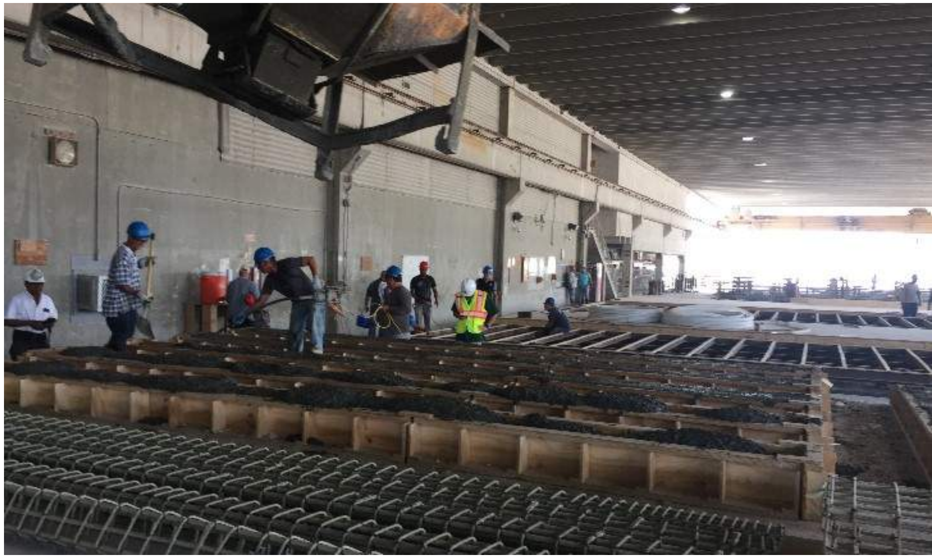
iDock Design



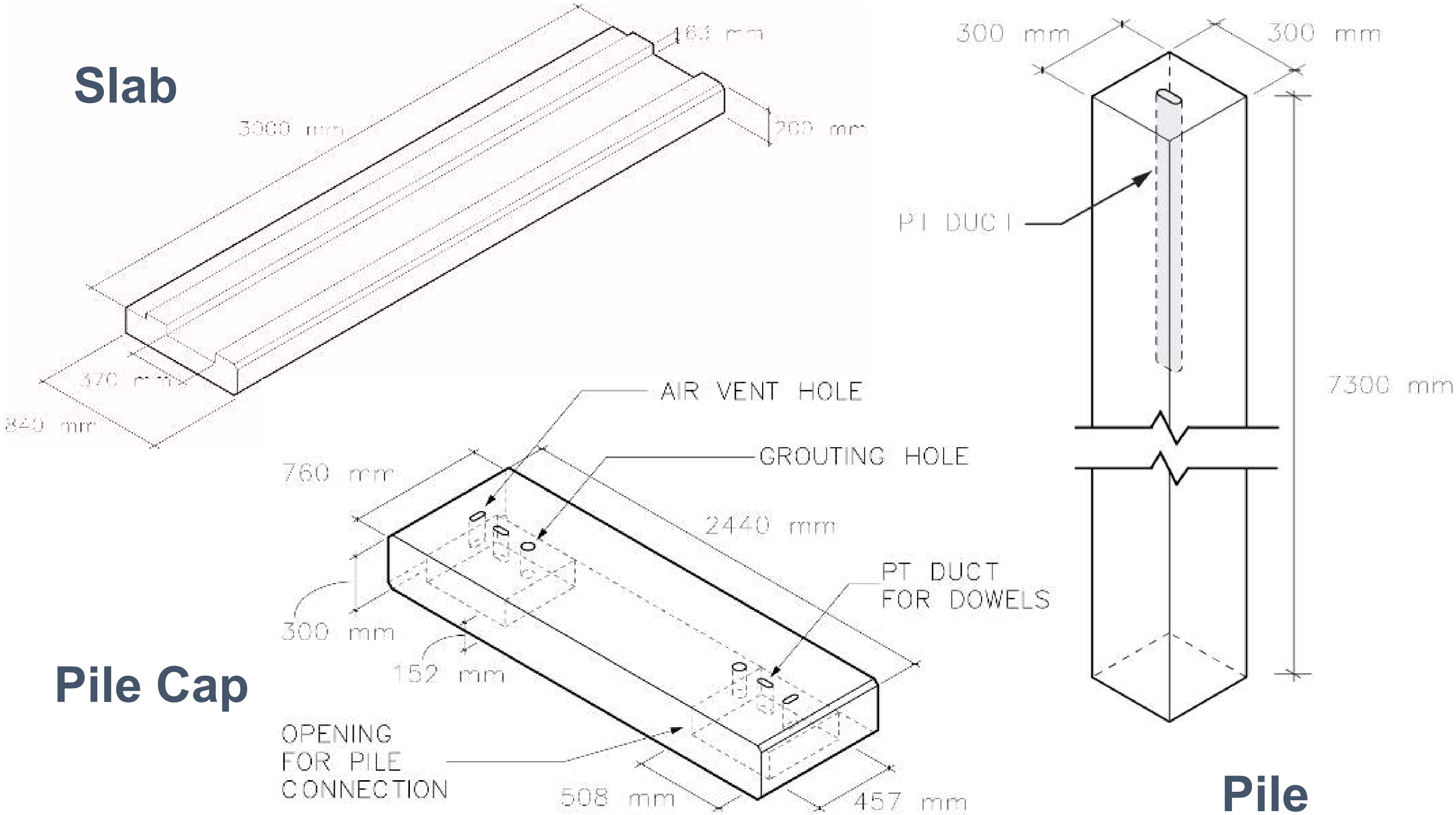
Four-span bridge-type dock with precast GFRP-RC driven piles, GFRP-RC pile-bent caps and slab-beams. Continuity CIP pour with BFRP bars and mesh



Precast Construction



Precast Construction



Precast Construction

Pile-Driving and Slab Installation

Pile-Driving at iDock

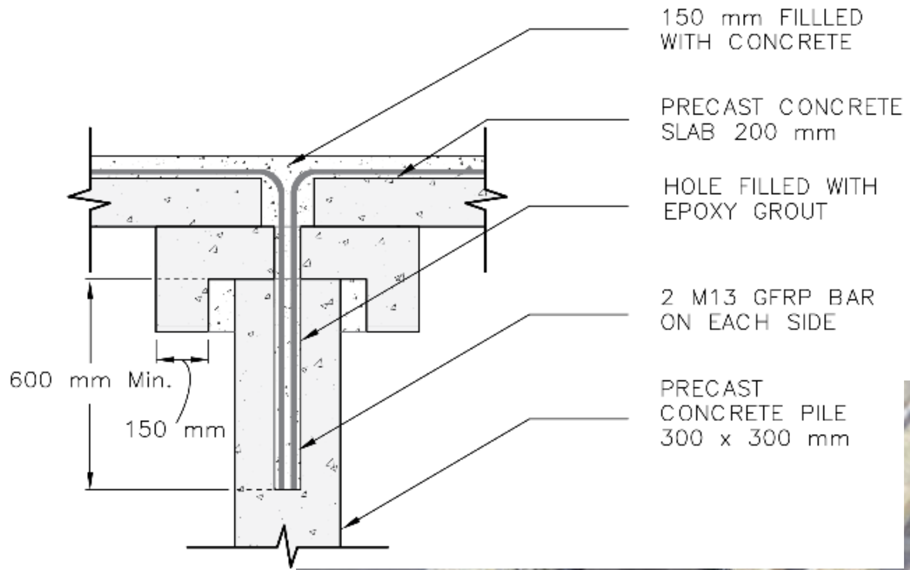
Piles installed in original steel-PC pile locations

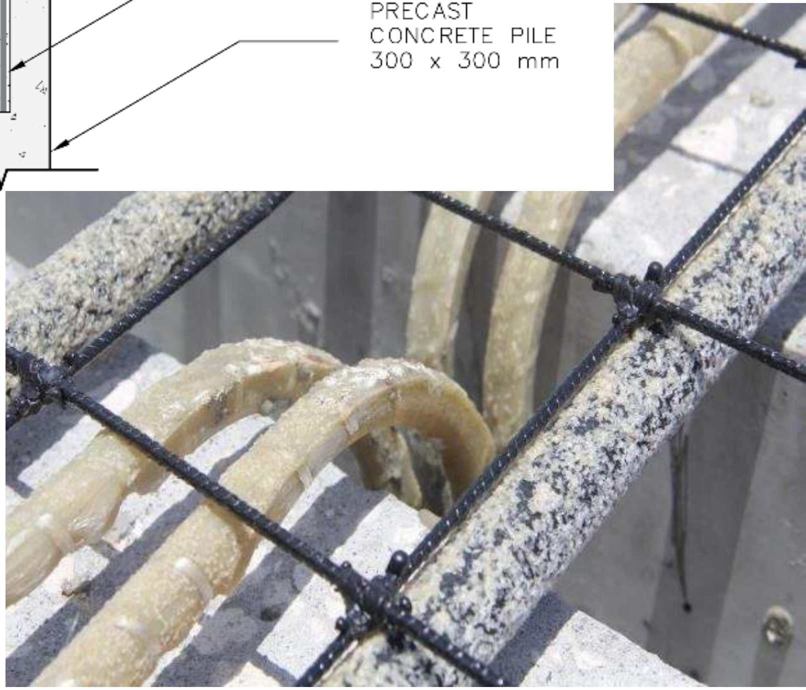
Precast Slab-Beam installed in sections after cap placement

iDock Precast Element Installation

iDock Connections (Cap-Slab)

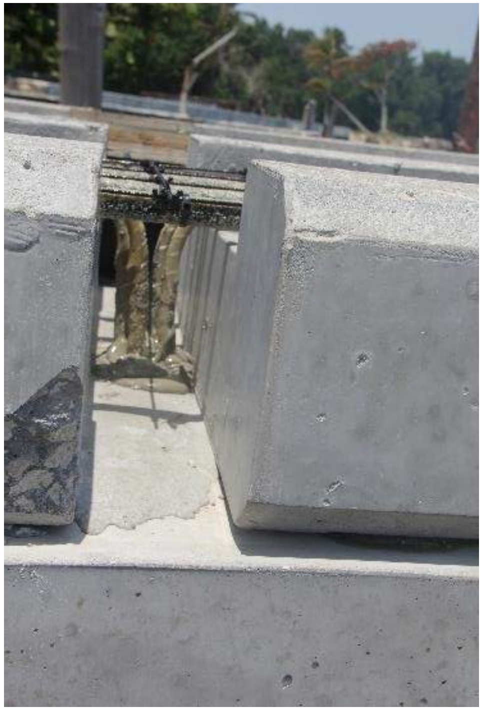
- GFRP dowel bars (greenish) connecting horizontal to vertical components
- BFRP (darker color) bars for flexural continuity
- Connection cast in place to interlock precast components and create continuity over the four spans





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.]

Conclusions and Remarks

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)
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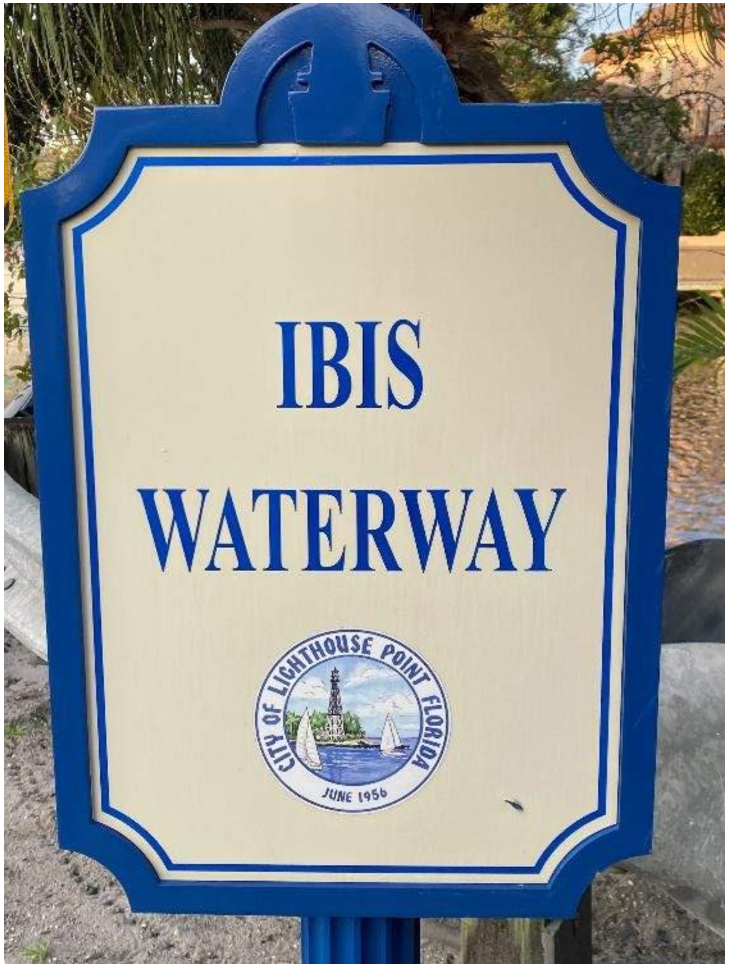
- SR-A1A Flagler Beach (Segment 3), (FPN 440557-7-52-01)
- FDOT Fast Facts

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

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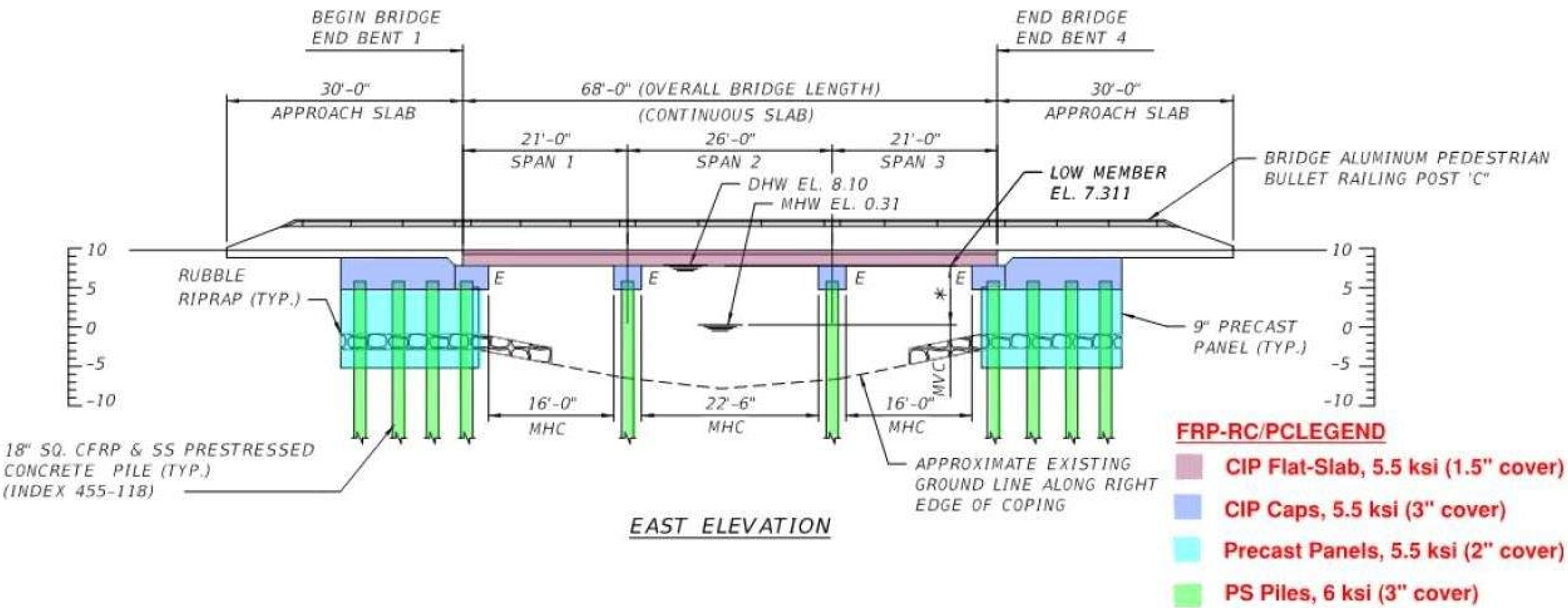
IBIS Waterway Bridge Layout



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

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Production of Experimental GFRP Piles

#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

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- **Halls River Bridge (HRB) (FPN 430021-1-52-01)**
- SR-A1A Flagler Beach (Segment 3) (FPN 440557-7-52-01)
- FDOT Fast Facts

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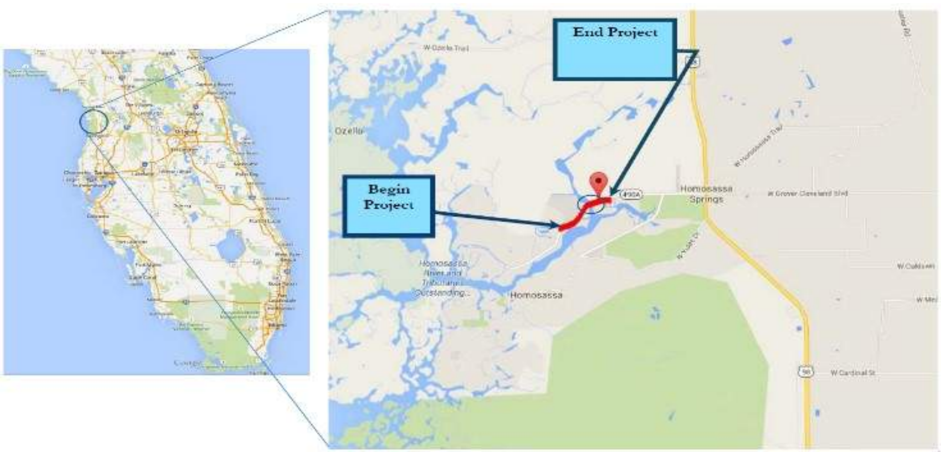
First of a Kind 5-span Bridge

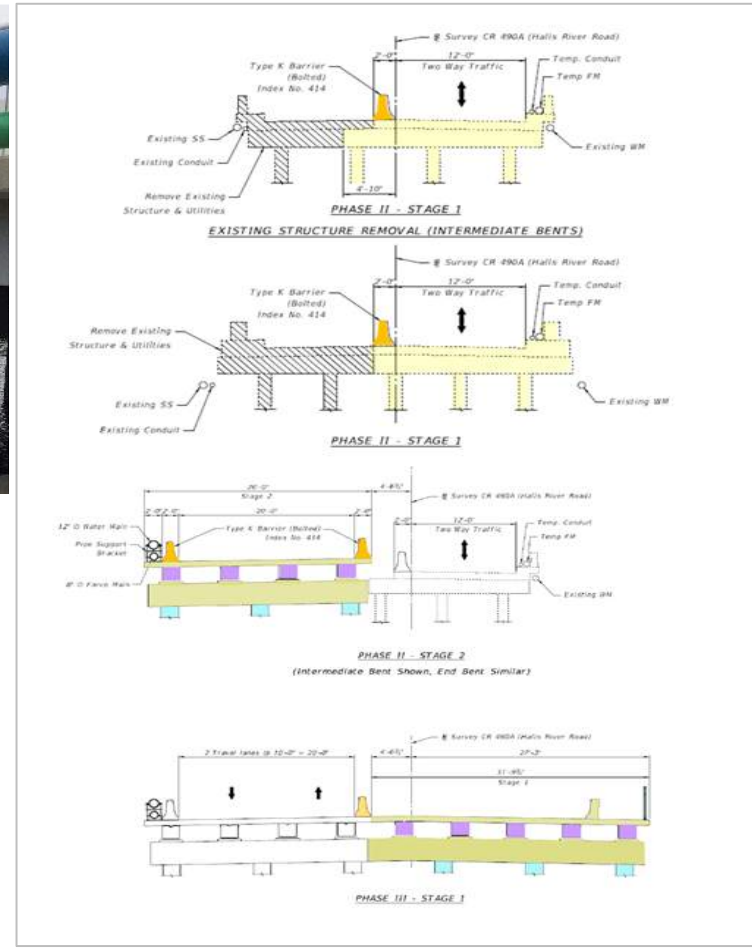
FRP PC/RC Structure

- 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

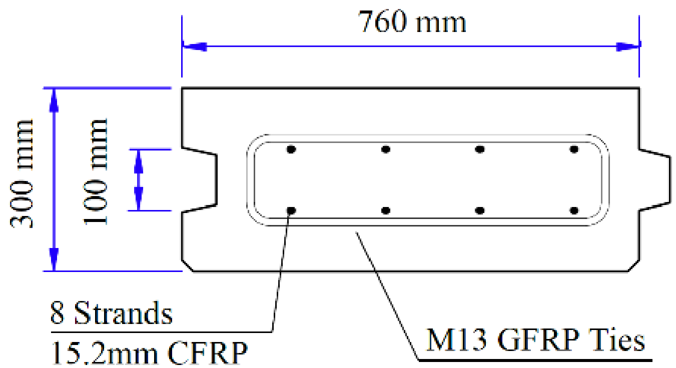
Prototype for Future FRP Bridge-Projects

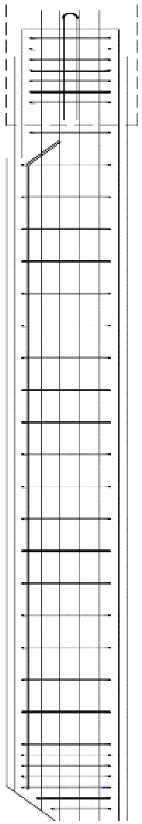




Sheet Piles: CFRP-PC/GFRP-RC (FDOT Index D22440)

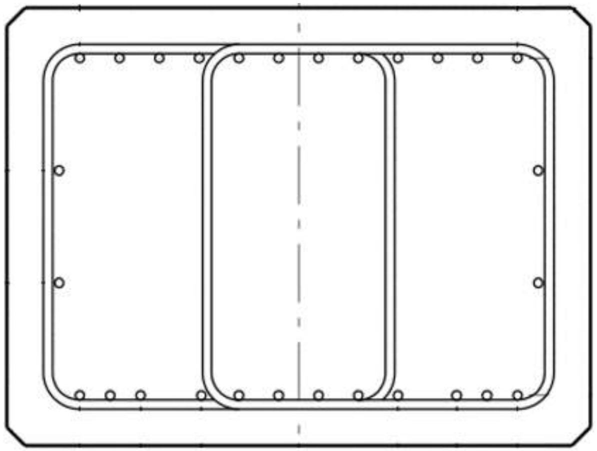
- CFRP Strands (8 ø 0.6 in.)
- GFRP Ties (#4 @ 4 in.
- C40/45 (12 x 30 in.)
- 13 to 26 ft. depth
- Cantilever or tied-back





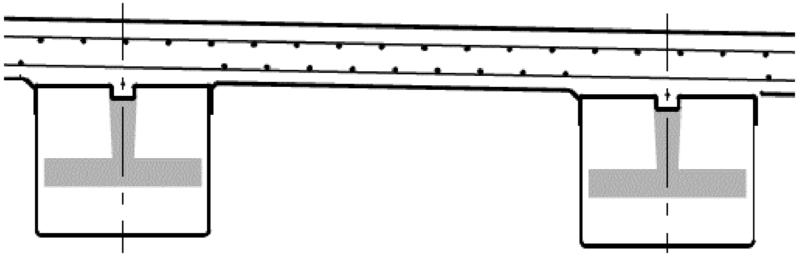
Bent Caps: GFRP-RC (FDOT Software Bent Cap v1.0)

- 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 2nd 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

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- NE 23rd Avenue Bridge over Ibis Waterway (FPN 434359-1-52-01)
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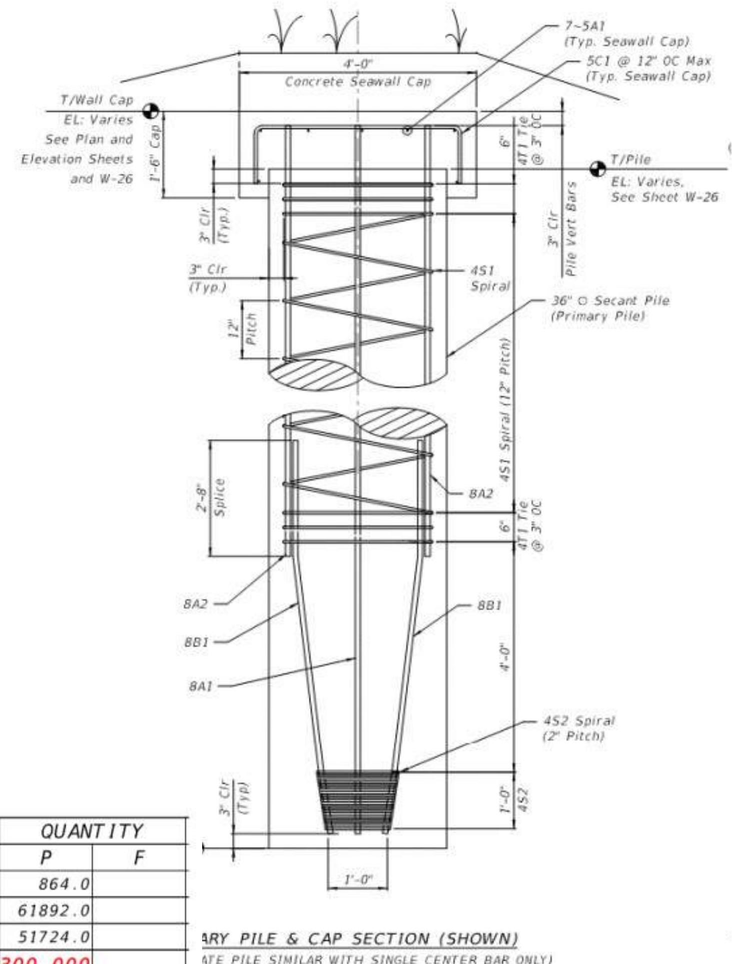
- **SR-A1A Flagler Beach (Segment 3) (FPN 440557-7-52-01)**
- FDOT Fast Facts

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



WALL NO.	PAY ITEM NO.	PAY ITEM DESCRIPTION	LOCATION STA. TO STA.	SIDE	UNIT	QUANTITY P	QUANTITY F
W1 Thru W11	0400-4-11	Class IV Concrete (Retaining Wall Cap)		Rt	CY	864.0	
	415-10-5	Fiber Reinforced Polymor Bars, #5			LF	61892.0	
	455-112-6	Pile Auger Grouted, 36" Diameter			LF	51724.0	
		#5 GFRP Reinforcing Bars	approx.		FT	300,000	
		#8 GFRP Reinforcing Bars	approx.		FT	960,000	

GFRP bar site delivery and storage

- Straight bars, bent bars, hoops and toe bent bars
- Site storage and protective measures from elements

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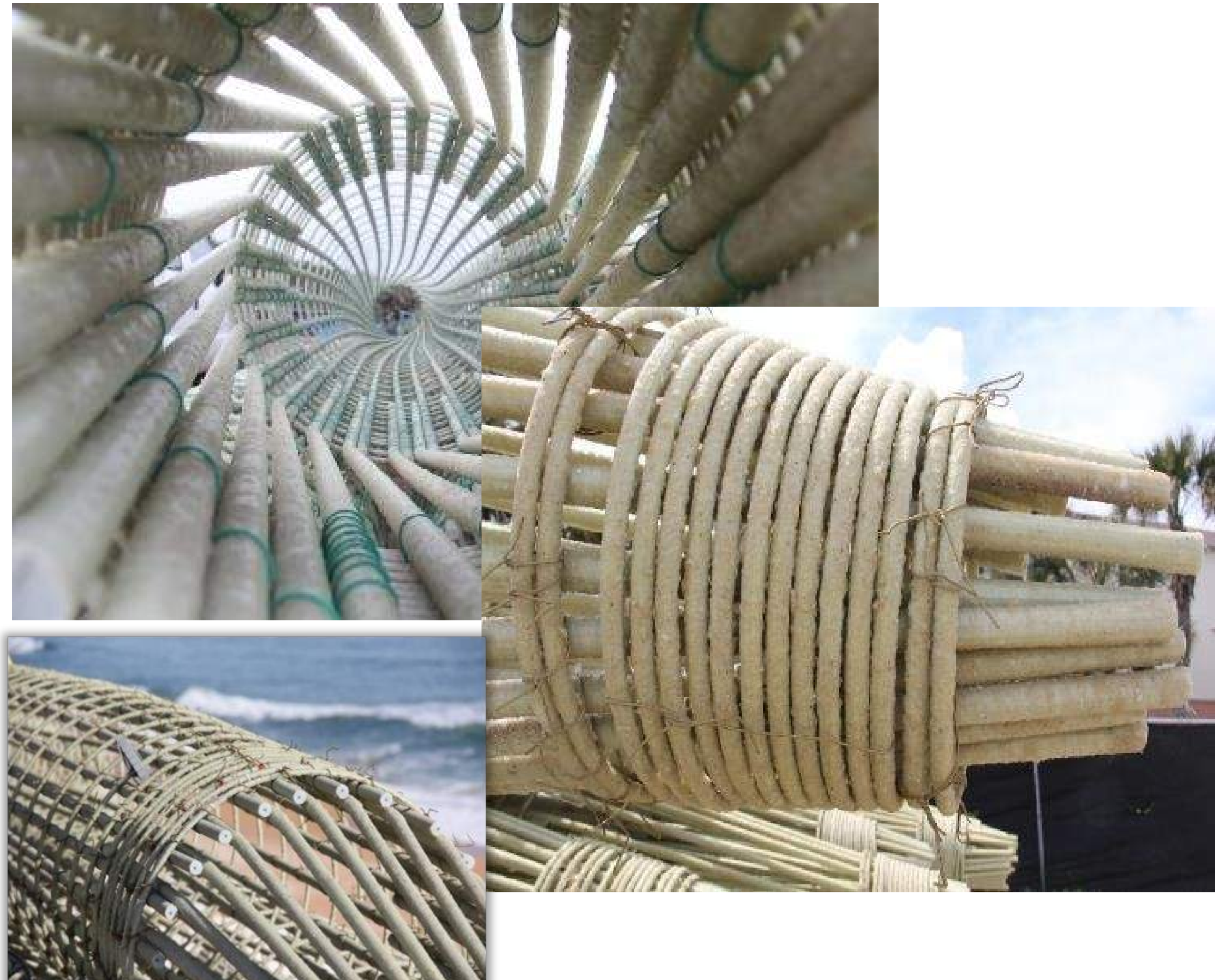
GFRP Bars - Cage Assembly

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 piles18 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

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www.fdot.gov/structures/innovation

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Structures Design

Structures Design / Design Innovation

Fiber Reinforced Polymer Reinforcing

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

www.fdot.gov/structures/innovation

Multiple online resources available

- Overview
- Usage Restrictions / Parameters
- Design Criteria
- Specifications
- Standards
- Producer Quality Control Program
- Projects
- Technology Transfer (T^2)
- FDOT Research
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www.fdot.gov/structures/innovation

Fast-Fact sheets for selected FDOT and affiliated projects in Florida (completed and under construction)

- 40th Ave NE over Placido Bayou
- Arthur Drive over Lynn Haven Bayou
- Bakers Haulover Cut Bulkhead Replacement
- Cedar Key Bulkhead Rehab
- Halls River Bridge
- Key West Bight Ferry Terminal Extension
- NE 23rd Ave over Ibis Waterway
- PortMiami Tunnel Retaining Walls
- South Maydell Dr over Palm River
- SR-A1A Flagler Beach Seawall (Segment 3)
- SR-A1A over Myrtle Creek and Simpson Creek
- SR-5 (US-17) over Trout River
- SR-5 (US 41) over Morning Star and Sunset Waterways
- SR-5 (US 41) over North Creek
- SR-30 over St Joe Inlet
- SR-312 over Matanzas River
- SR-520 over Indian River Bulkhead Rehab
- Sunshine Skyway Seawall Rehabilitation
- UM Innovation Bridge
- UM Fate Bridge
- UM I-Dock
- US-1 over Cow Key Channel

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.shtm
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.

FDOT

Fast Facts:

Glass Fiber Reinforced Polymer

FDOT

Project Location: FDOT District Two
Levy County
Cedar Key, Florida

Agency: Florida Department of Transportation

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

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 lampposts, 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.

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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: 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.

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Questions?

Thank U

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AASHTO GFRP-Reinforced Concrete Design Training Course



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