KOMPOZİT SANAYİCİLERİ DERNEĞİ
TURKISH COMPOSITES MANUFACTURERS ASSOCIATION

aci American Concrete Institute

NEX™ An ACI Center of Excellence for Nonmetallic Building Materials

Workshop on Composites in Construction

Istanbul, Türkiye

18 November 2025

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TURKISH COMPOSITES MANUFACTURERS ASSOCIATION
NEX

Workshop on Composites in Construction

	Welcome and Introductions	9:00 to 9:30
Session 1:	Structural Concrete Reinforced with Glass Fiber Reinforced Polymer (GFRP) Bars	9:30 to 12:00
	Lunch	12:00 to 1:00
Session 2:	Strengthening of Structural Concrete with Fiber Reinforced Polymer (FRP) Systems	1:00 to 15:30
	Concluding Remarks and Adjournment	15:30 to 16:00

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Workshop on Composites in Construction

Learning Objectives:

- Understand carbon or glass FRP fabric & composite material properties and proper material selection.
- Learn about the basic design provisions for reinforced concrete member strengthening using FRP composites.
- Gain insights into construction principles and field inspection, testing & evaluation.

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Session 2: Strengthening of Structural Concrete FRP Systems

- General Introduction to ACI CODE 440.13 & ACI PRC 440.2
- FRP Material Specifications per ACI SPEC 440.8
- Concrete Substrate Requirements
- Fire Resistance of FRP Strengthened Members
- Field Inspection, Testing, and Evaluation

Refreshment Break

- General Design Requirements
- FRP System Requirements
- Design for Flexural and Shear Strengthening and Confinement
- Guide for Seismic Strengthening with FRP

First Presenter
Mahmut Ekenel, Ph.D., P.E., FACI

Mahmut Ekenel, Ph.D., P.E., FACI is currently employed as Certification and Conformity Assessment Engineer at American Concrete Institute. He is also the Technical Consultant for NEx, An ACI Center of Excellence for Nonmetallic Building Materials.

He joined ACI in 2023 after working as Senior Staff Engineer at the International Code Council (ICC) Evaluation Service for over 17 years. He received his Ph.D. from Missouri S&T University in 2004, where he also worked as a Postdoctoral Researcher in 2005. He is a licensed professional civil engineer (PE) in the States of California, Ohio, and Michigan. He was named a Fellow of ACI in 2020.

He has expertise in testing, evaluation, and certification of construction materials and building code compliance in the U.S.A.

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Strengthening Concrete Structures

- Strengthening
  - Change of Use
  - New Equipment
  - Seismic retrofit
  - Blast hardening
- Structural Rehabilitation
  - Replace corroded rebar
  - Impact damage
  - Reinforce slab cut-outs

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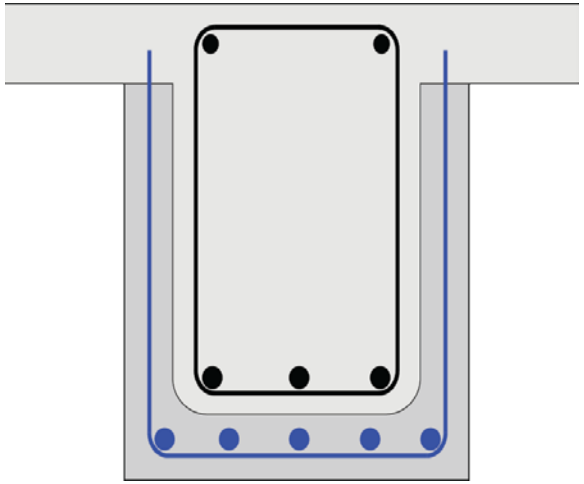
Section Enlargement



External Steel Plates

FRP Strengthening Systems

- Externally Bonded FRP Reinforcement
  - Similar to steel plates
  - Higher strength than steel
  - Much lighter weight
  - Flexible
  - Cost effective
  - No corrosion

External FRP Reinforcement

- Benefits
  - Thin cross section (<1 mm)
  - Can easily reinforce in multiple directions
  - Does not change appearance or impact headroom

External FRP Reinforcement

- Benefits
  - Easy to conceal

External FRP Systems

- Benefits
  - Apply in areas with limited access


Photo courtesy of Structural Technologies Inc

External FRP Systems

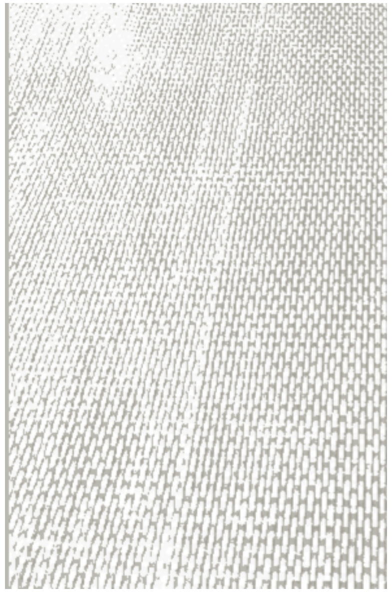
- Benefits
  - No fasteners
  - Conform to existing structural shapes

Components : Fibers

- Four main types

Carbon

Glass

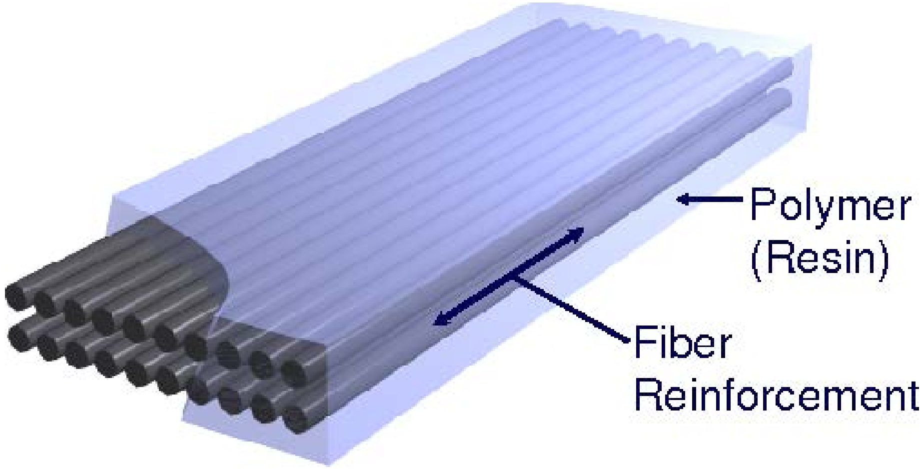


Basalt

Aramid

Components : Resins

- Holds the fibers together
- Transfers the load between fibers and from the substrate to the fibers
- Protect the fibers from mechanical and environmental damage

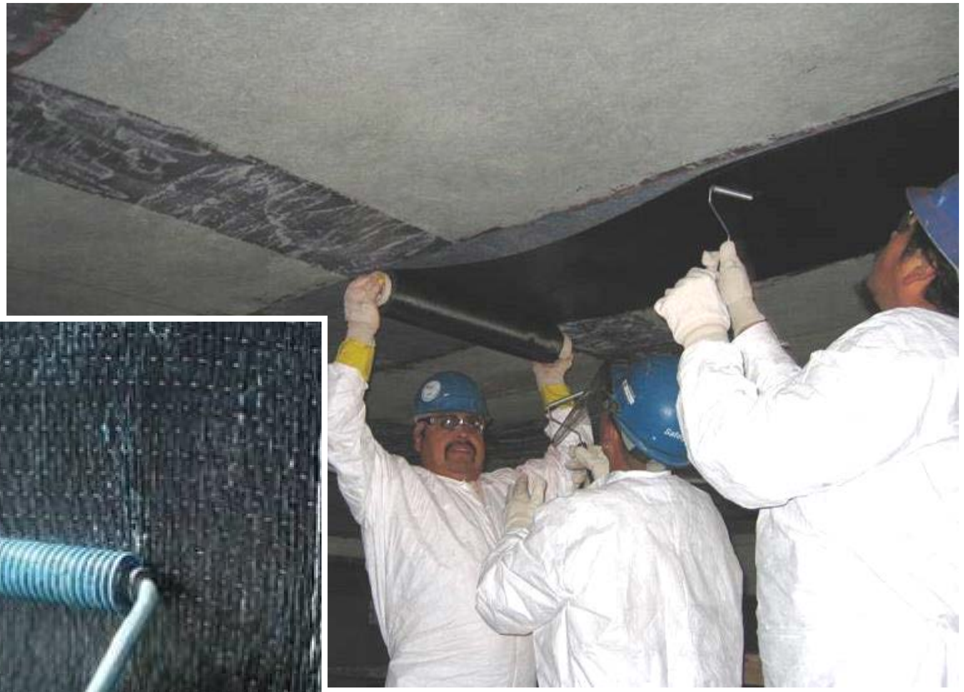


Components : Resins

- Epoxy resins are used in most FRP strengthening systems.
- Vinyl ester resins are used in some precured FRP systems
- Urethane (polyurethane) resins are also found in some FRP strengthening systems.

Components : Resins/Primers, putty, and adhesives

- Primers and putties
  - Used in all systems for surface preparation
  - Composition is compatible with the resin or adhesive
- Adhesives
  - Adhering FRP bars or plates



Systems : Wet Layup FRP System

- Fabric is saturated with epoxy resin mixed in the field
- Can be multiple layers and various fiber orientations
- Fabrics can be applied using a saturating machine that rolls fabric through a resin bath prior to placement

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Systems : Precured FRP System

- CFRP plates are adhered to the substrate using epoxy adhesives
- Plates can be predetermined lengths or cut to length from coils

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Systems : Near-Surface-Mounted FRP System

- FRP bars placed into grooves saw cut into the substrate and backfilled with epoxy adhesive

Applications

- Beams
  - Can strengthen reinforced and prestressed members
  - Increases in bending capacity of up to 50% are possible
  - Does not appreciably reduce deflections

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Applications

- Beams
  – Strengthening shear capacity at bearing locations


Photo courtesy of Sika (www.gbr.sika.com)

Applications

- Slabs
  - One-way and two-way slabs
  - Reinforced and post-tensioned slabs

Applications

- Slabs
  - Negative Moment
  - Topside reinforcement
  - Slabs and beams
  - No change to floor elevation
  - Can directly apply flooring materials on top

Applications

- Reinforcing Slab Cutouts
  - Replace cut reinforcing bars
  - Control cracking around perimeter of opening

Applications

- Walls
  - Below grade masonry walls strengthened for additional soil pressure

Applications

- Walls
  - Reinforce shear walls to resist lateral forces

Applications

- Blast Hardening

Applications

- Bridge Girders
  - Flexible, contour to the shape of the substrate
  - Proper detailing of re-entrant corners
  - Versatile method of adding reinforcement

Applications

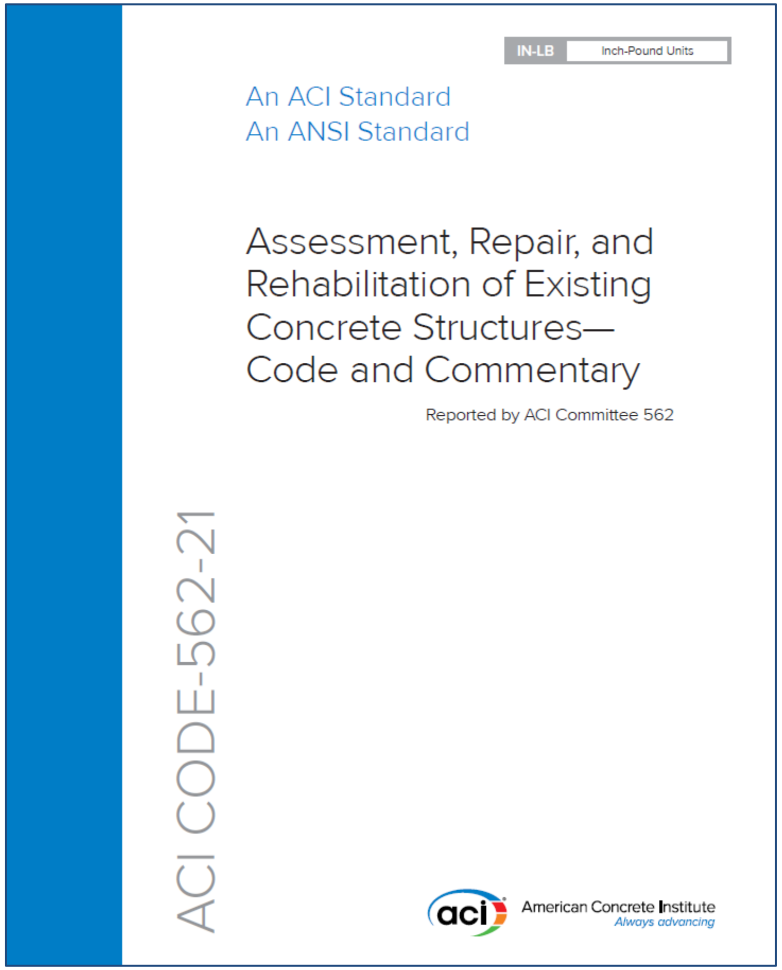
- Columns
  - Column confinement for increased seismic resistance
  - Modest increases in axial capacity

Codes, Standards & Guides

ACI CODE 562-21

– Concrete Repair Code

- Requirements for repairing existing concrete structures
- Referenced by model codes like the International Existing Building Code (IEBC)
- Use it to evaluate whether FRP can be used
- 2025 version references ACI 440.13 for FRP system details



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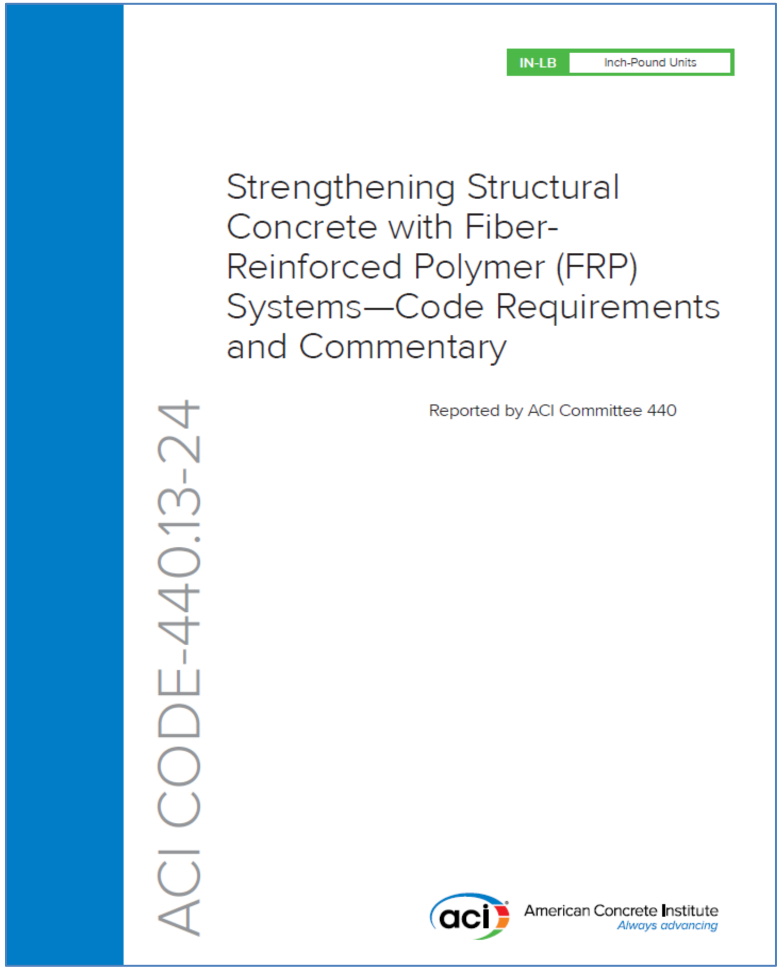
Codes, Standards & Guides

ACI CODE 440.13-24

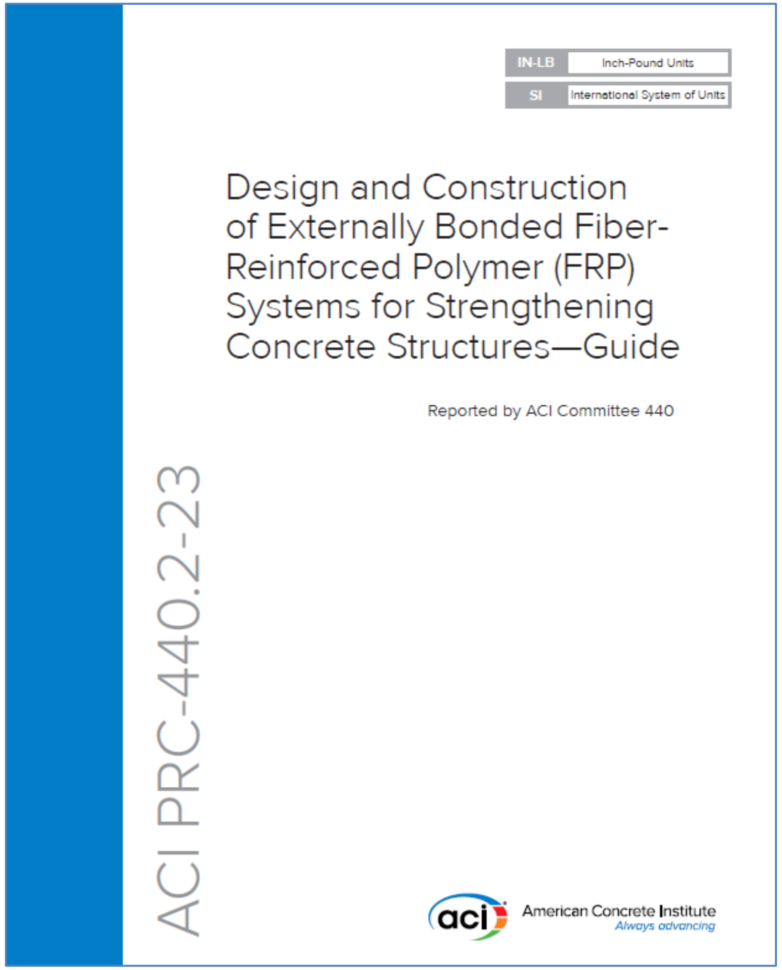
- Code for FRP strengthening of concrete structures
  - Mandatory requirements
  - Design, Construction, and Inspection
  - Based on ACI PRC 440.2 guidelines originally published in 2002
- Referenced by the IEBC (International Existing Building Code) which is adopted by all 50 states.



Codes, Standards & Guides

ACI PRC 440.2-23

– Comprehensive Guide for FRP strengthening of concrete structures
  - Most current knowledge and recommendations on FRP strengthening systems
  - Detailing guidelines
  - Example problems



Codes, Standards & Guides

ACI CODE 440.13-24

- Mandatory requirements
- Carbon and Glass fibers only
- Seismic retrofit not covered
- Code and commentary language only
- Masonry strengthening not covered

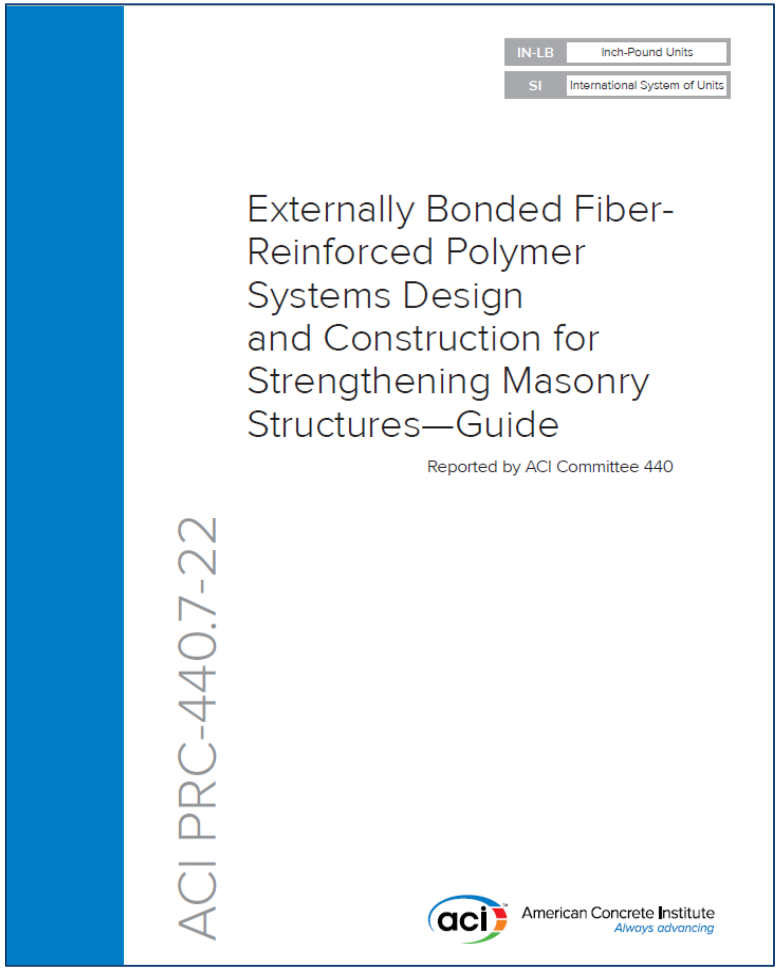
ACI PRC 440.2-23 (Guide)

- Carbon, Glass, Basalt, and Aramid fibers
- Comprehensive **seismic retrofit** chapter
- Background information and example problems
- Masonry strengthening not covered, but…

Codes, Standards & Guides

ACI PRC 440.7-22

- Guidelines for FRP strengthening of masonry structures
  - Similar to ACI PRC 440.2, but with specific guidelines for masonry structures



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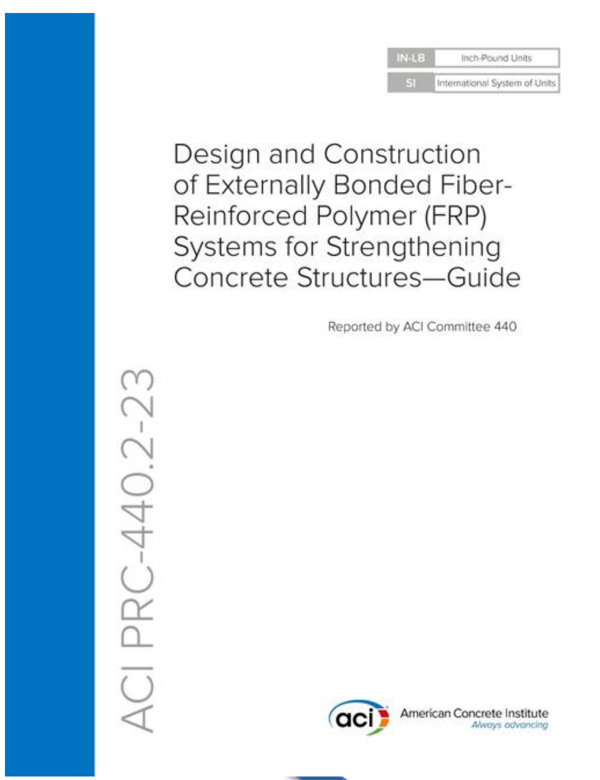
Codes, Standards & Guides


IN-LB Inch-Pound Units
SI International System of Units

Design and Construction of Externally Bonded Fiber-Reinforced Polymer (FRP) Systems for Strengthening Concrete Structures—Guide

Reported by ACI Committee 440

ACI PRC-440.2-23

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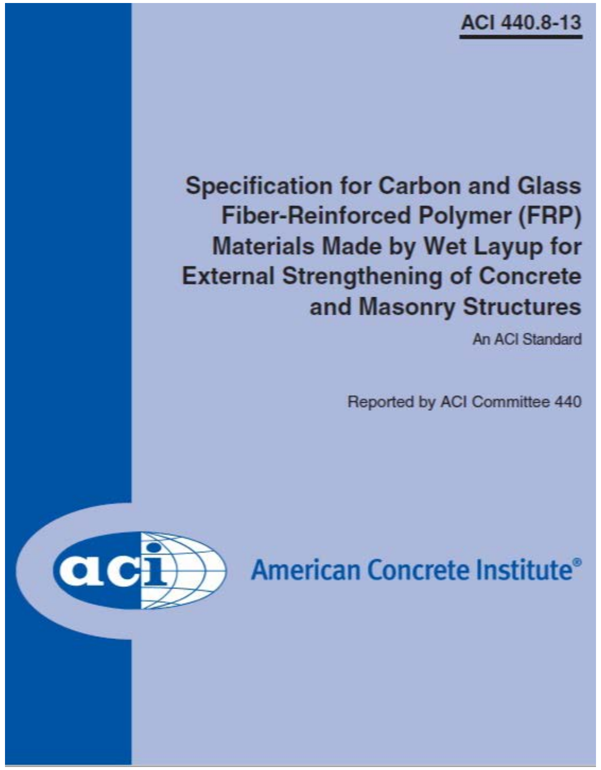
ACI 440.8-13

Specification for Carbon and Glass Fiber-Reinforced Polymer (FRP) Materials Made by Wet Layup for External Strengthening of Concrete and Masonry Structures

An ACI Standard

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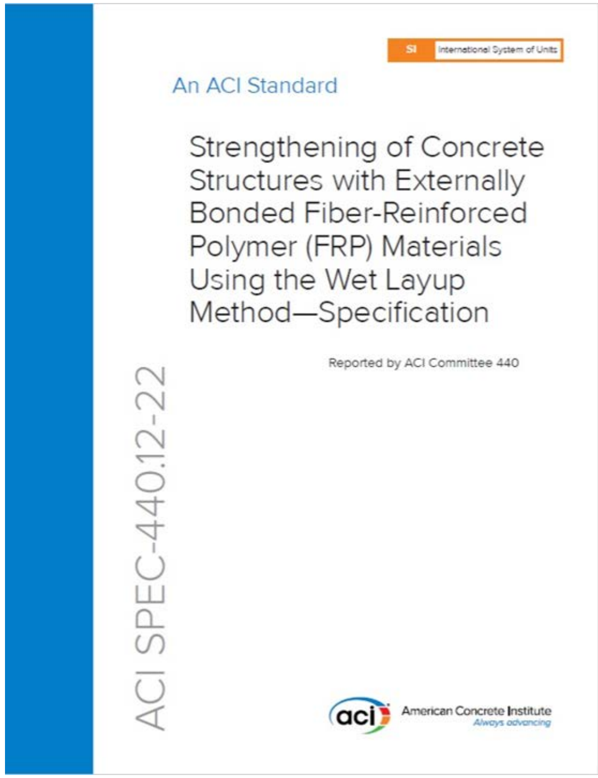
SI International System of Units

An ACI Standard

Strengthening of Concrete Structures with Externally Bonded Fiber-Reinforced Polymer (FRP) Materials Using the Wet Layup Method—Specification

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ACI SPEC-440.12-22

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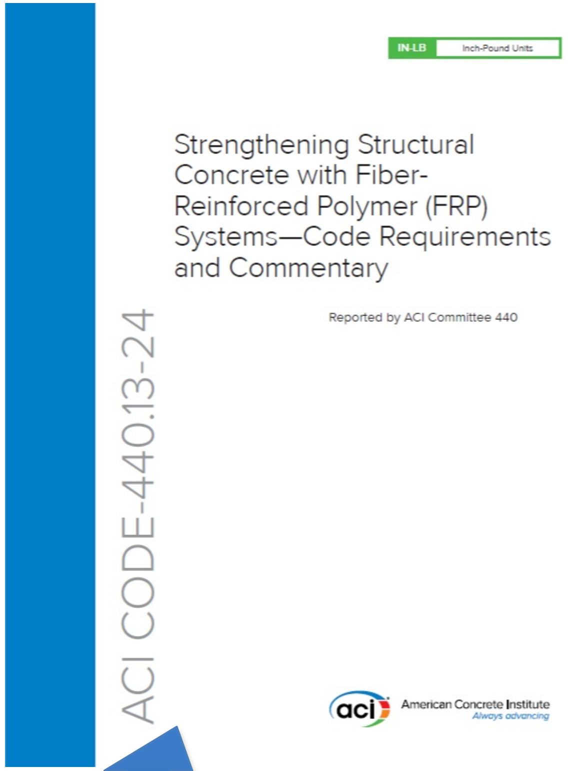
IN-LB Inch-Pound Units

Strengthening Structural Concrete with Fiber-Reinforced Polymer (FRP) Systems—Code Requirements and Commentary

Reported by ACI Committee 440

ACI CODE-440.13-24

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Externally-bonded (EB)

Wet layup CFRP
ACI SPEC 440.12

Wet layup GFRP
ACI SPEC 440.8

Precured CFRP
No Spec- (ICC AC125)

Near-surface mounted (NSM)

Pultruded CFRP bars
ACI SPEC 440.6

Pultruded GFRP bars
ASTM D7957

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Refreshment Break

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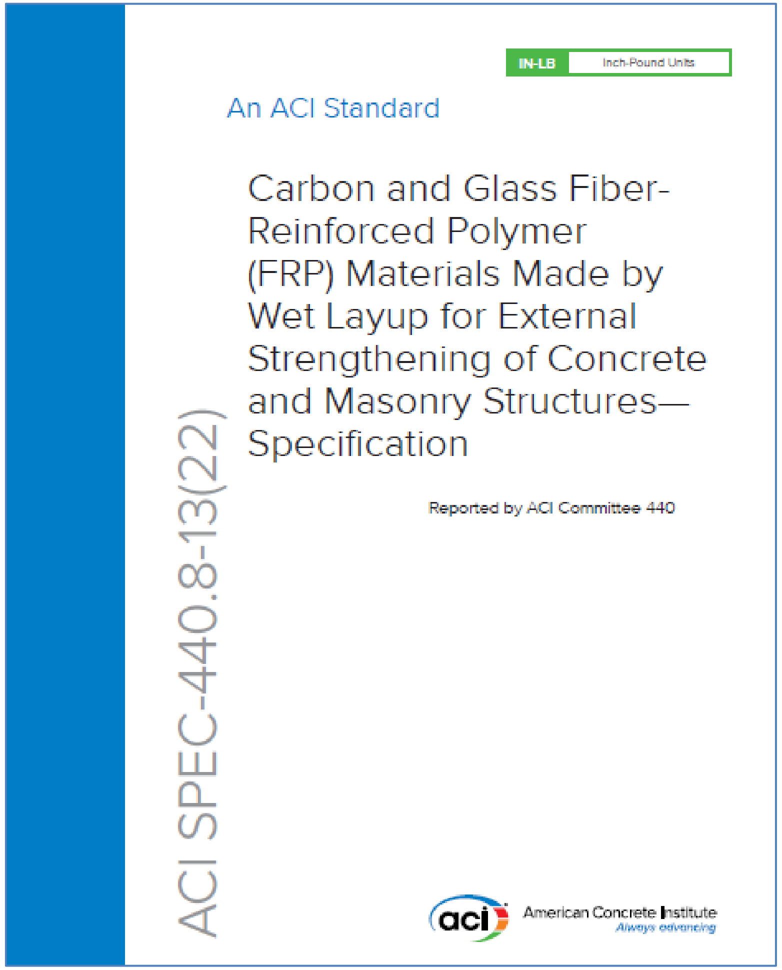
Material Specification

ACI SPEC 440.8-13(22)

– Material Specification
  - Carbon and glass fiber
  - Epoxy resin systems only
  - Data sheet requirements


IN-LB Inch-Pound Units

An ACI Standard

Carbon and Glass Fiber-Reinforced Polymer (FRP) Materials Made by Wet Layup for External Strengthening of Concrete and Masonry Structures—Specification

Reported by ACI Committee 440

ACI SPEC-440.8-13(22)

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Material Specification

- The glass transition temperature of the FRP system shall not be less than 140°F.
- The glass transition temperature shall be measured according to the dynamic mechanical analysis (DMA) method in ASTM E1640.

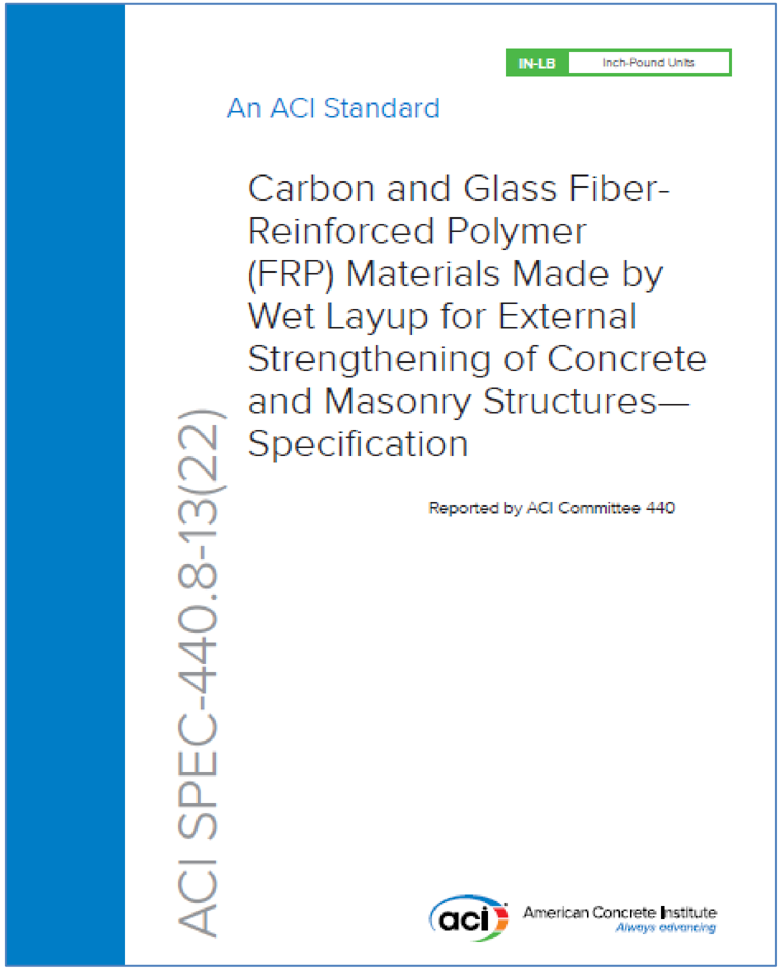

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Table 7.1.2—Minimum properties for saturating resins

Property	ASTM test method	Mean value
Ultimate tensile strength	D638 Type 1	6000 psi
Tensile modulus	D638 Type 1	250,000 psi
Elongation at failure	D638 Type 1	3 percent
Ultimate flexural strength	D790	10,000 psi
Flexural modulus	D790	250,000 psi

Table 7.2.1—Tensile properties for FRP system

System designation	Minimum ultimate* tensile force per areal weight [kip/in./(oz/yd^2)]	Minimum mean chord tensile stiffness per areal weight [kip/in./(oz/yd^2)]
Carbon	0.170	20.0
Glass	0.0625	4.160

*Mean minus three standard deviations.

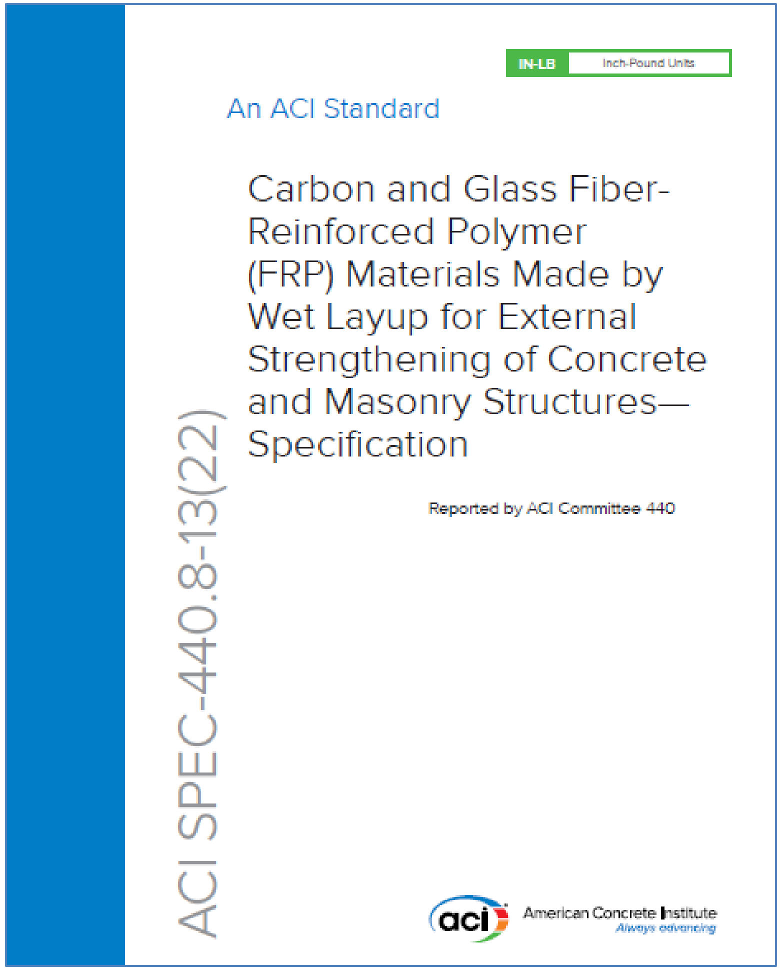
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Table 8.1—Minimum mean retained tensile force per unit width of FRP system after environmental conditioning*

Environmental exposure conditions	ASTM test method	Conditioning	Percent retention		
			1000 hours	2000 hours	3000 hours
Water resistance	D2247	100 percent relative humidity at 100°F ± 2°F	90	NA	85
Salt water resistance	D1141 C581	Immersion at 73°F ± 2°F	90	NA	85
Alkali resistance	C581	Immersion in $Ca(CO_3)$ at pH = 9.5 and 73°F ± 3°F	90	NA	85
Dry heat resistance	D3045	140°F ± 5°F	90	NA	85
Exterior exposure	G153	2000-hour conditioning as follows: Exposed to cycles consisting of 102 min light and 18 min light and water spray. The black-body temperature is 143°F.	NA	90	NA

*Note: Additional durability documentation, such as freezing-and-thawing resistance, is often requested by the purchaser or a governmental regulatory agency. The freezing-and-thawing test method described in ICC Evaluation Service Acceptance Criteria (AC125) may be used for this purpose.

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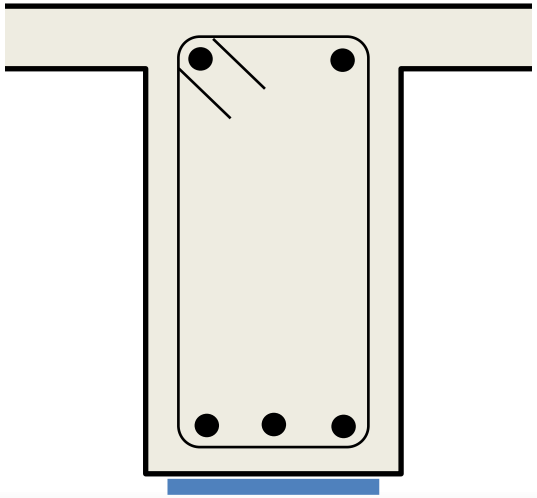
Basis of Design

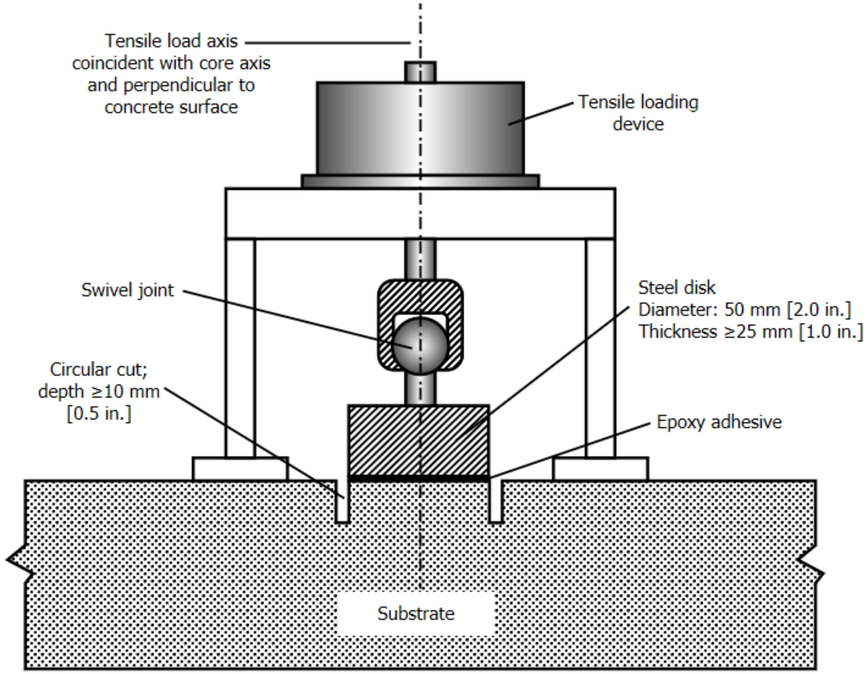
ACI CODE 440.13-24 Section 6.2.1:

Design shall be based on the dimensions, amount, distribution, and locations or internal steel reinforcement, material properties, and condition of the existing concrete member to be strengthened.



Concrete Substrate Requirements

- ACI CODE 440.13-24 Sec 5.1
  - ASTM C1583 test result ≥ 200 psi
  - Minimum compressive strength of 2500 psi



Concrete Substrate Requirements

ACI CODE 440.13-24 Sec 5.1

- Concrete Repair
  - Remove and replace unsound concrete
  - Repair and mitigate corrosion damage
    - (Ref ACI 364.1-19 and TechNotes)

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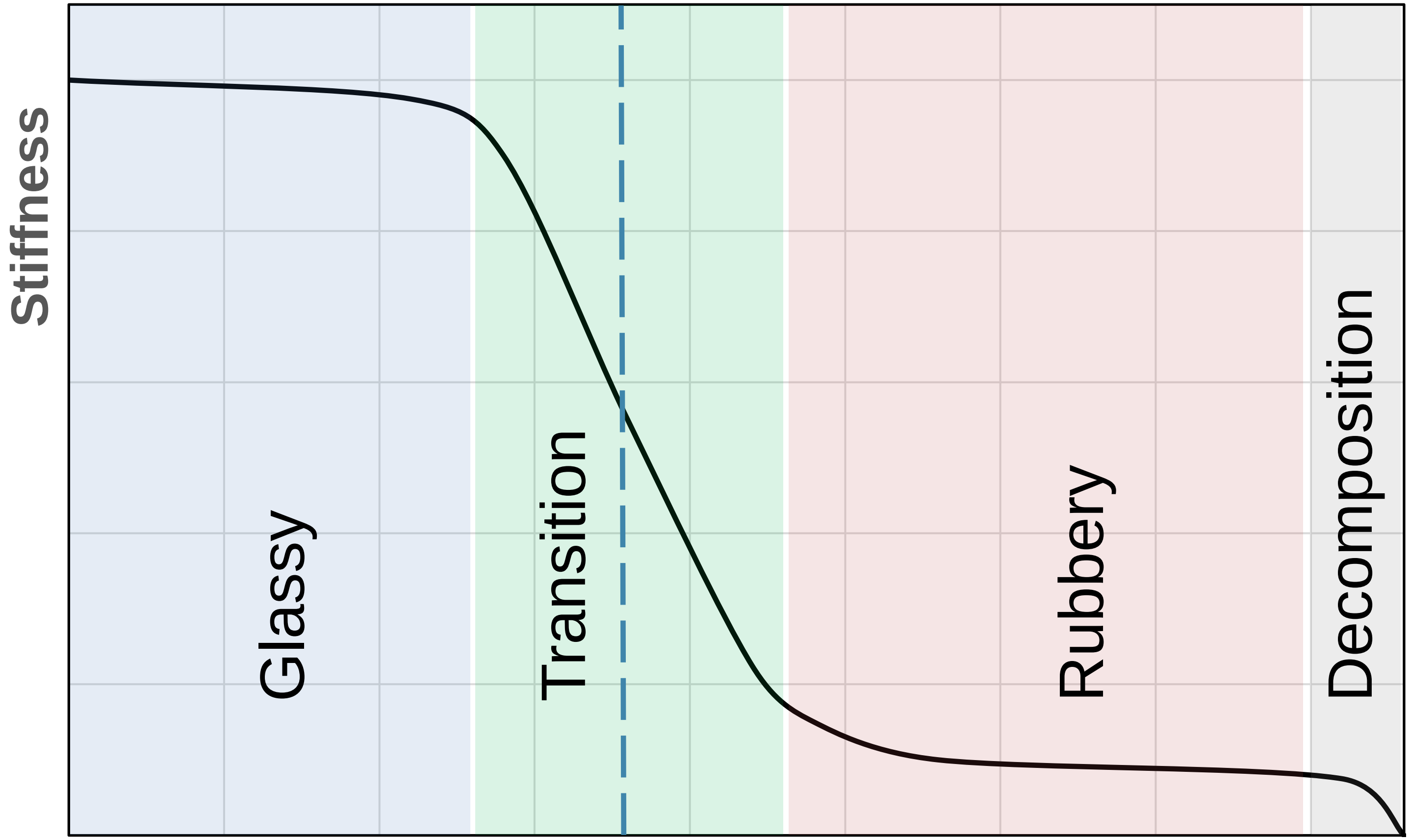
Glass Transition Temperature



T_g = 140 to 180ºF (60 to 82 º C) **Temperature**

Maximum Service Temperature

- ACI CODE 440.13-24 Section 6.6.1
  - FRP systems shall not be used when the in-service substrate temperatures are expected to exceed T_g – 27ºF (T_g – 15ºC)

Fire Resistance

Fire Endurance Requirements

$$\phi_{ex} R_{ex} \geq (0.9 \ or \ 1.2)D + 0.5L + 0.2S$$

ACI CODE 562-21
Eq. (5.5.3)

$\phi_{ex} R_{ex}$ is the strength of the member under fire exposure without the contribution of the FRP and considering reduced concrete and steel material strengths

Calculated using ACI CODE 216.1

Requirements are repeated in ACI CODE 440.13 Appendix A.

Fire Resistance

ACI PRC 440.10-21

–Fire Resistance TechNote

- When is fire protection needed?
- What fire protection options are available?

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PRC-440.10-21
TechNote

Fire Resistance of FRP-Strengthened Concrete Members—TechNote

Keywords: fiber-reinforced polymer; fire; fire protection; fireproofing; repair; strengthening.

Introduction

The use of fiber-reinforced polymer (FRP) materials to strengthen concrete members is an accepted technology. In many applications, performance of FRP-strengthened members during exposure to fire remains a significant concern to design professionals, building officials, and owners. The objective of this TechNote is to provide a brief overview of key concepts, code provisions, and industry guidelines relating to the structural performance of FRP-strengthened members during a fire event.

Research findings regarding the performance of FRP-strengthened members during exposure to fire have been published by Williams et al. (2008). However, design examples and guidance regarding the performance of externally bonded FRP during exposure to fire are not widely available. In addition, differences in the design approaches and load combinations used by the steel and concrete industries, combined with the relatively recent emergence of FRP fire protection systems, have created challenges for practicing engineers tasked with assessing the structural fire resistance of FRP-strengthened members.

Questions

Under what circumstances does an FRP-strengthened member need to be protected from the detrimental effects of fire? If protection is warranted, what fire protection options are available?

Answers

The need for FRP-strengthened members to be protected from fire depends on project-specific factors, including building code requirements, structural parameters, member type, fire risk, fire severity, and method of evaluation. The design professional should evaluate these factors to determine if an unprotected member possesses sufficient strength during (and potentially after) the fire event to resist anticipated demands. Calculations can be performed based on material properties that have been adjusted to account for the detrimental effects of fire while using appropriate load and strength-reduction factors. If the analysis determines that the unprotected member does not possess sufficient strength, then fire protection may be required to enhance performance of the strengthened member. Options include mortars, coatings, boards, or other materials that have been specifically tested for use with the FRP system. As discussed in this TechNote, these insulating materials protect the embedded reinforcing steel and concrete, rather than the FRP system.

Discussion

Building codes establish minimum requirements for structures to resist detrimental effects of a standard fire as defined by test standards such as ASTM E119, UL 263, and ISO 834. In the United States, the code applicable to new construction is typically the International Building Code (IBC). The IBC sets forth required fire-resistance ratings (referred to hereinafter as fire rating) in terms of duration based on occupancy, size, separation, construction materials, and other factors. The required fire rating usually ranges from 1 to 3 hours. Certain low-fire-risk buildings, such as open parking garages sufficiently separated from adjacent occupancies, may not require a fire rating depending on size, construction material, and other factors.

For new construction, the fire rating is typically determined by an architect. Many FRP-strengthening projects do not include an architect on the design team, and even when they do, the architect may have little experience with FRP. In these instances, the building official and architect may require evidence from the structural engineer that the FRP-strengthening complies with fire resistance provisions of the code. If the structural engineer does not possess fundamental knowledge of fire protection concepts or is unfamiliar with interpreting code provisions related to fire, then assistance from an experienced fire protection design professional should be obtained.

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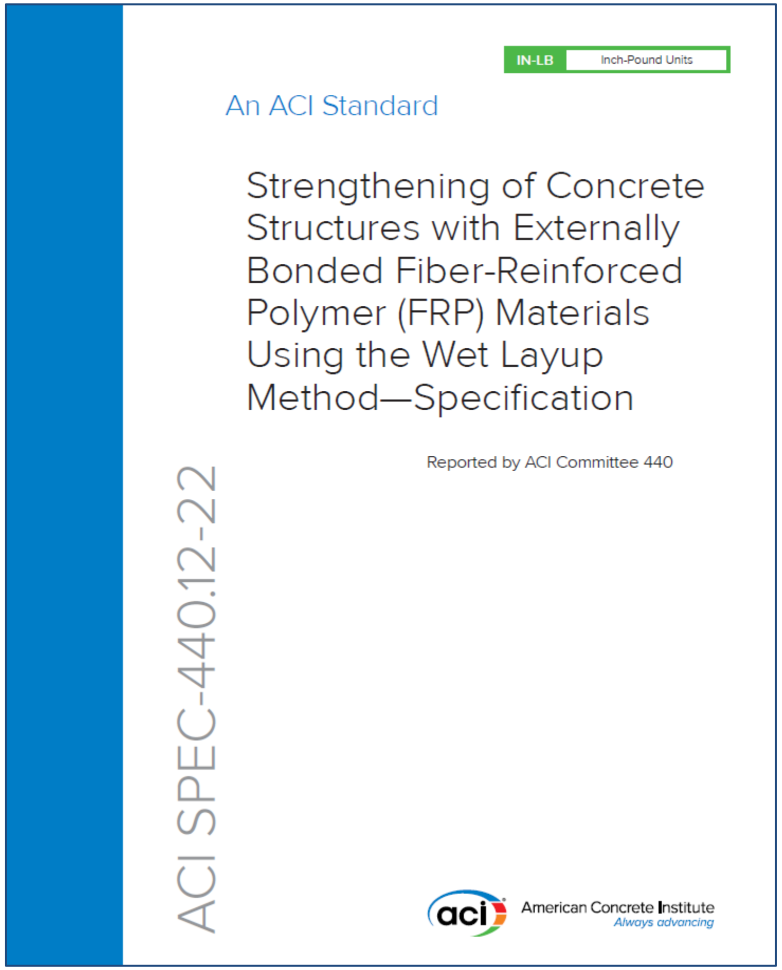
Construction Specification

ACI SPEC 440.12-22

- Construction Specification
  - Applies to wet layup systems
  - All application requirements
    - Surface prep
    - Mixing and applying resins
    - Applying fabrics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Strengthening of Concrete Structures with Externally Bonded Fiber-Reinforced Polymer (FRP) Materials Using the Wet Layup Method—Specification

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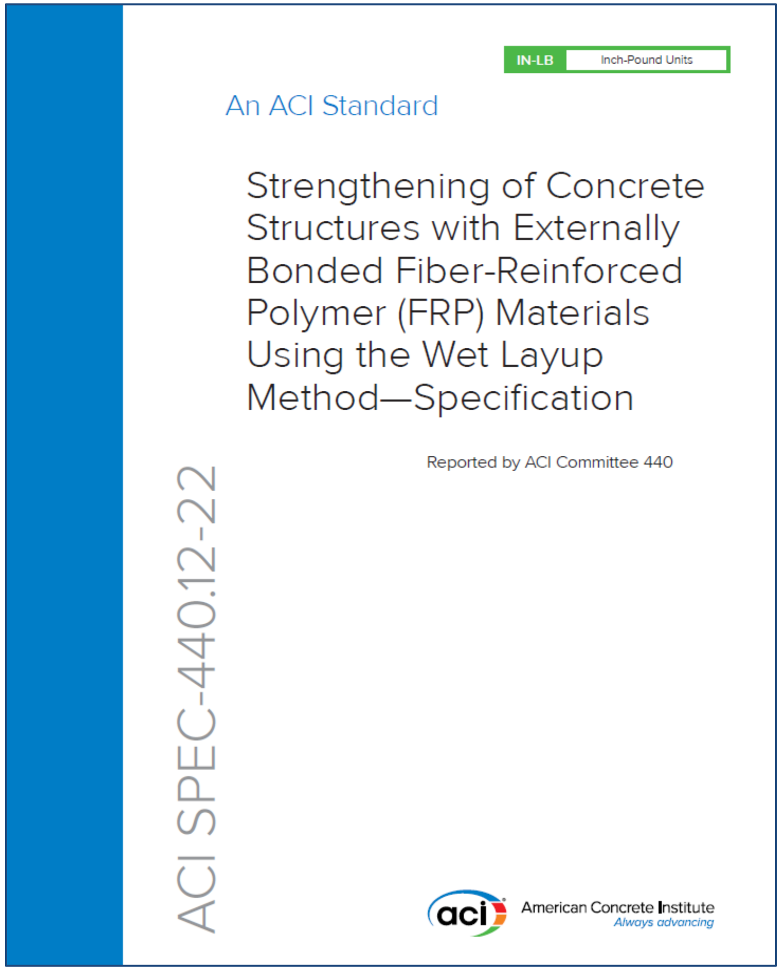
Construction Specification

ACI SPEC 440.12-22

– Construction Specification
  - Material selection
  - Basis of design
  - Surface preparation
  - Installation & Curing
  - Quality control requirements
  - Acceptance of work
  - Mandatory requirements checklist

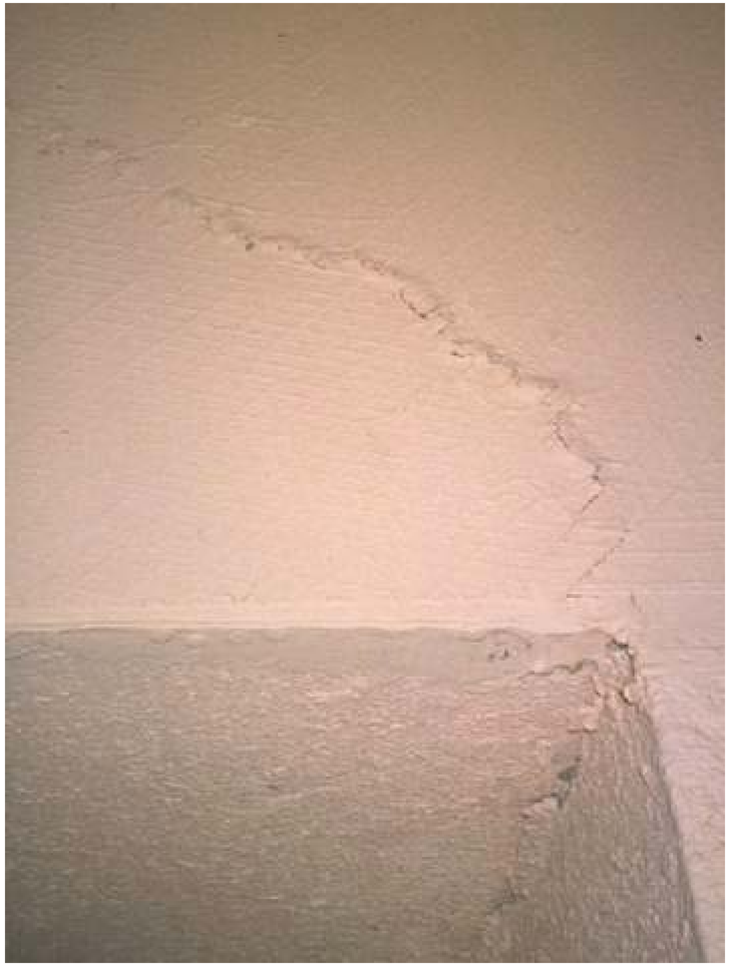


Installation Requirements

- Surface Prep
  - CSP 3 surface profile per ASTM D7682 Method A
  - ICRI 310.2R chips

Installation Requirements

- Repair Existing Cracks
  - Epoxy inject cracks >0.010-in.



Installation Requirements

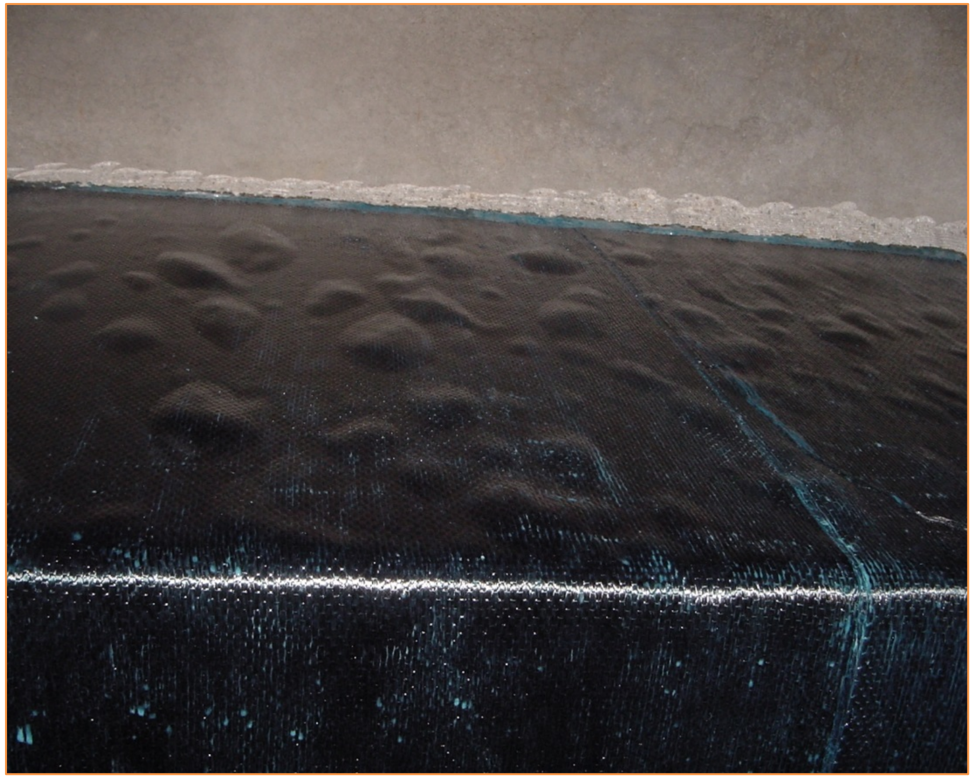
- Surface Treatment
  - Epoxy mix ratio and method
  - Coverage rates
  - Primer and putty/filler
  - Curing

Installation Requirements

- Fiber Reinforcement
  - Proper dimensions
  - Fiber alignment
  - Flat
  - Good saturation

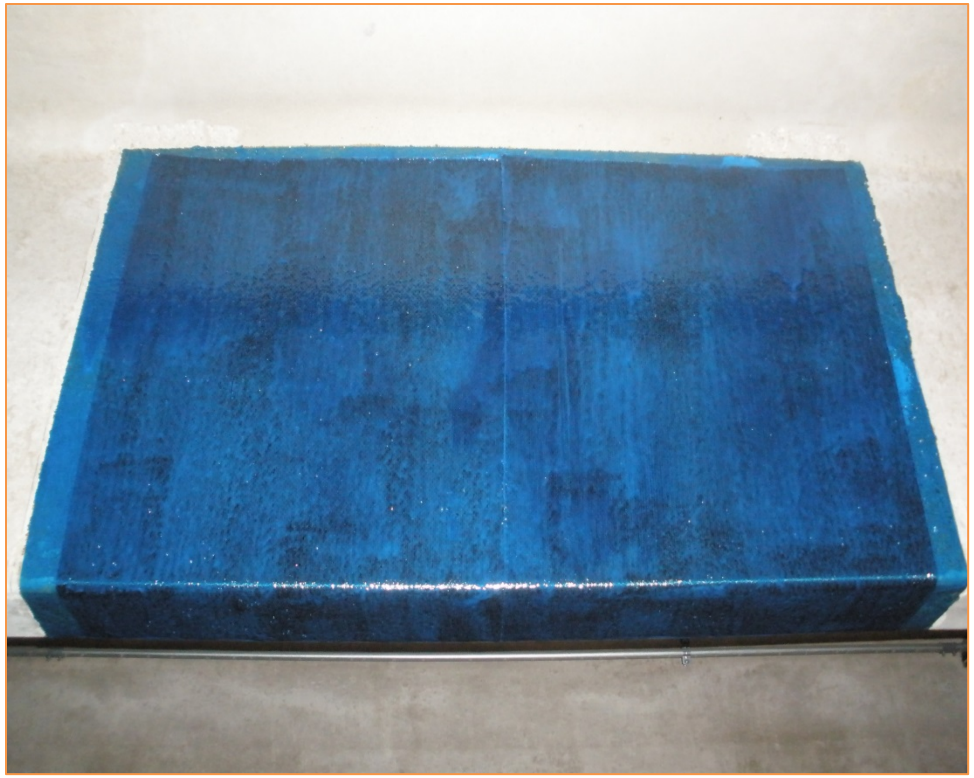
Installation Steps

- Moisture Transmission
  - Delaminations caused by moisture vapor transmission during installation



Installation Steps

- Proper Installation
  - Same application.
  - Applied as ambient temperatures were falling



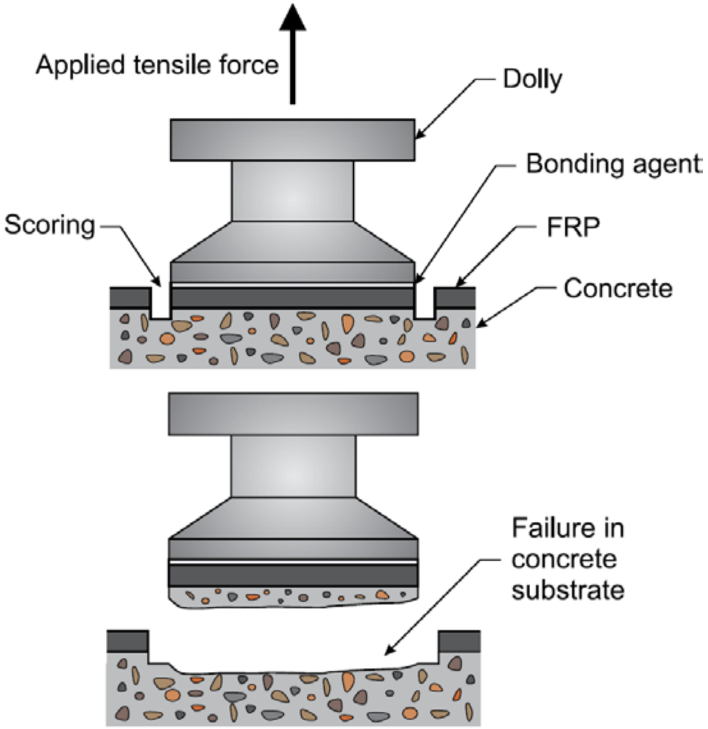
Coating Prep and Application

- Protective coatings
  - Aesthetics
  - Chemical resistance
  - Potable water
- Surface preparation
  - Varies based on FRP and coating
  - Application window

Application of topcoat for aesthetics and improved durability

Quality Control Testing

- Adhesion Strength (ASTM D7522)

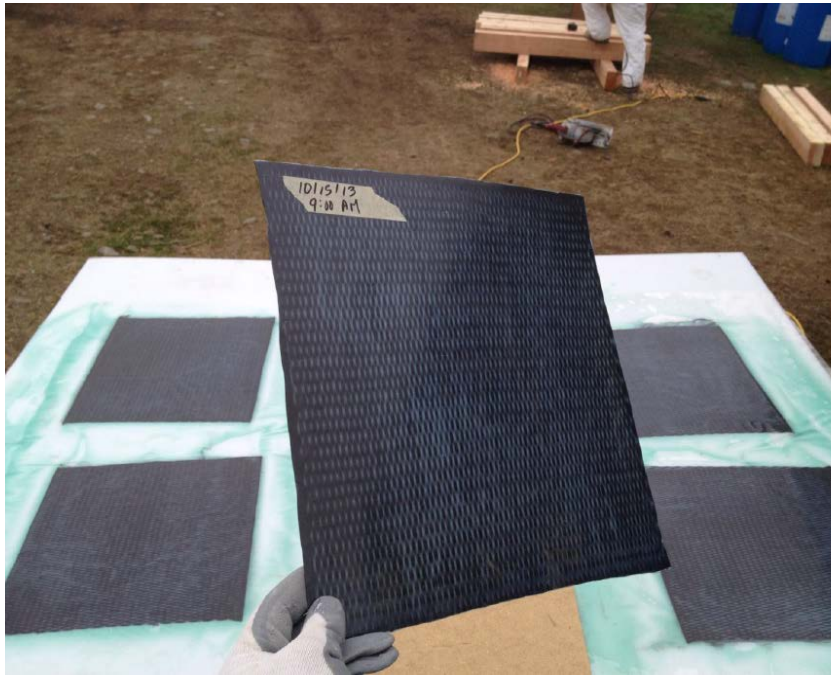


Quality Control Testing

- Adhesion Strength (ASTM D7522)
  - Conducted by a 3rd party testing agency
  - Acceptance Criteria (ACI SPEC 440.12-22)
    - Minimum adhesion strength of 1.5 MPa and
    - Failure in the substrate (Mode G)
  - Frequency (ACI SPEC 440.12-22)
    - At least 3 tests per 100 m^2 of surface area or 3 tests per day
    - Each substrate type and surface prep method

Quality Control Testing

- Witness Panel Testing (ASTM D7565)
  - Field constructed / field cured sample panels of materials applied
  - Strips cut and tested for tensile strength and modulus



Quality Control Testing

- Follow ACI SPEC 440.12 requirements along with manufacturer recommendations

Workshop on Composites in Construction

Session 2: Strengthening of Structural Concrete FRP Systems

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- Fire Resistance of FRP Strengthened Members
- Field Inspection, Testing, and Evaluation

Refreshment Break

- General Design Requirements
- FRP System Requirements
- Design for Flexural and Shear Strengthening and Confinement
- Guide for Seismic Strengthening with FRP

Second Presenter
William J. Gold, P.E., FACI

William J. Gold, P.E., FACI is a Senior Engineer at the American Concrete Institute. He has over 25 years of experience with the use of composite materials in construction. As a former Engineering Manager for BASF Corporation and Master Builders Solutions, he was actively involved in numerous construction applications of FRP materials, development of FRP systems, and evaluations of FRP materials.

He has given talks on FRP in construction to a wide range of audiences. Mr. Gold served as Chairman of ACI Committee 440 during the development of ACI CODE 440.11. He is currently Secretary of ACI Committee 440S on code requirements for FRP strengthening systems. In addition to his work at ACI, he is active in ASTM and the Canadian Standards Association. He is a registered Professional Engineer in the State of Ohio.

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Supplemental vs Primary Reinforcement (6.3.2)

$$(\phi R_n)_{existing} \geq (1.1D + 0.75L)_{new}$$

ACI CODE 562-21
Eq. (5.5.2b)

Requirements are repeated in ACI CODE 440.13 Appendix A.

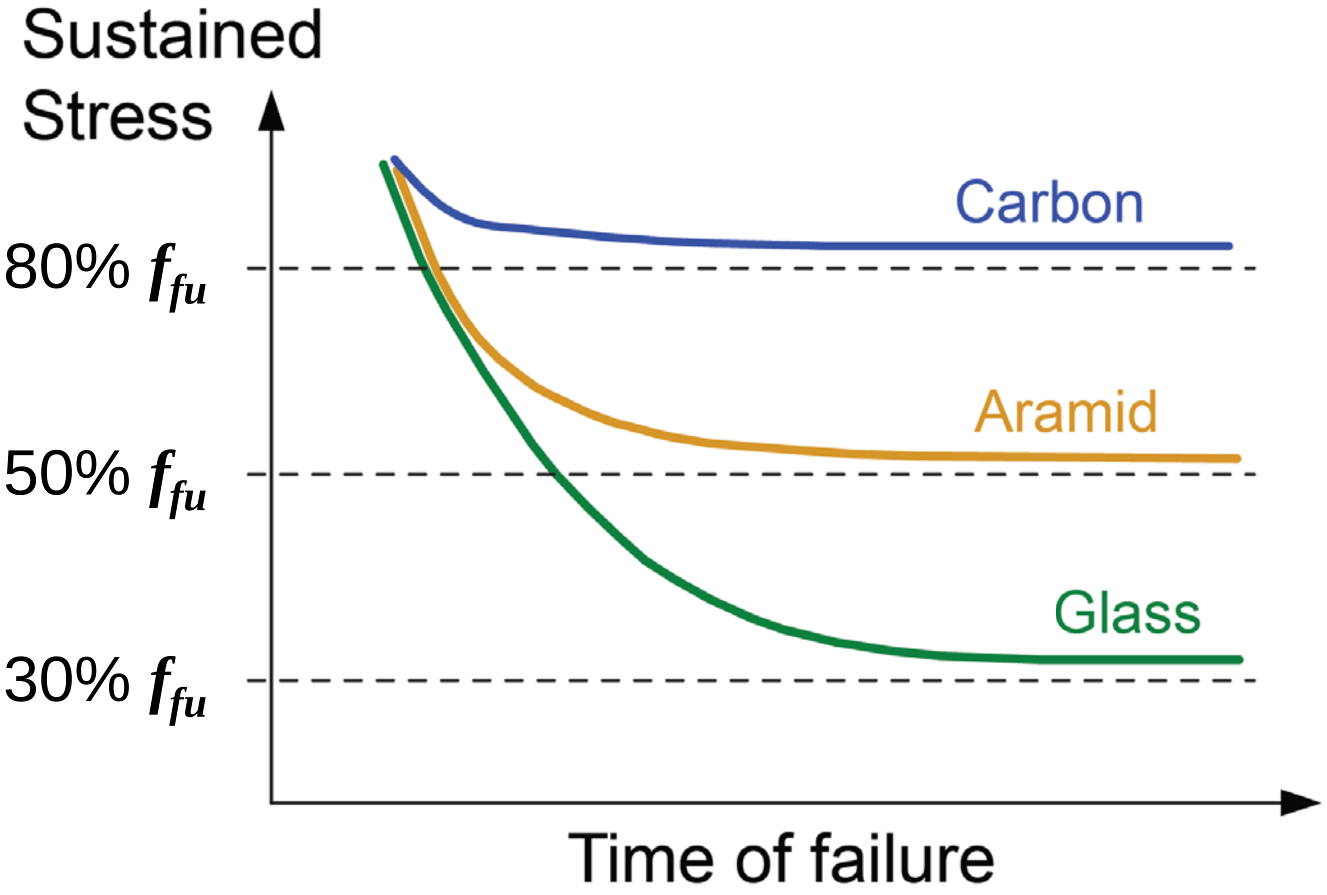
Strengthen to get to…

$$(\phi R_n)_{new} \geq (1.2D + 1.6L)_{new}$$

Material Selection – Fiber Types

Property	Carbon	Glass	Aramid
Cost	High	Low	Very high
Strength	High	High	High
Stiffness	High	Low	Moderate
Coeff. Thermal Exp.	Very Low	Moderate	Low
Impact resistance	Low	←Between→	Very High
Moisture resistance	Yes	Sensitive	Swells
Chemical resistance	Yes	Low	Yes
Galvanic action	Sensitive	None	None
Conductivity	High	Low	Low
Sustained load resistance	High	Low	Moderate
Alkalinity resistance	Yes	Low	
UV sensitivity			Sensitive

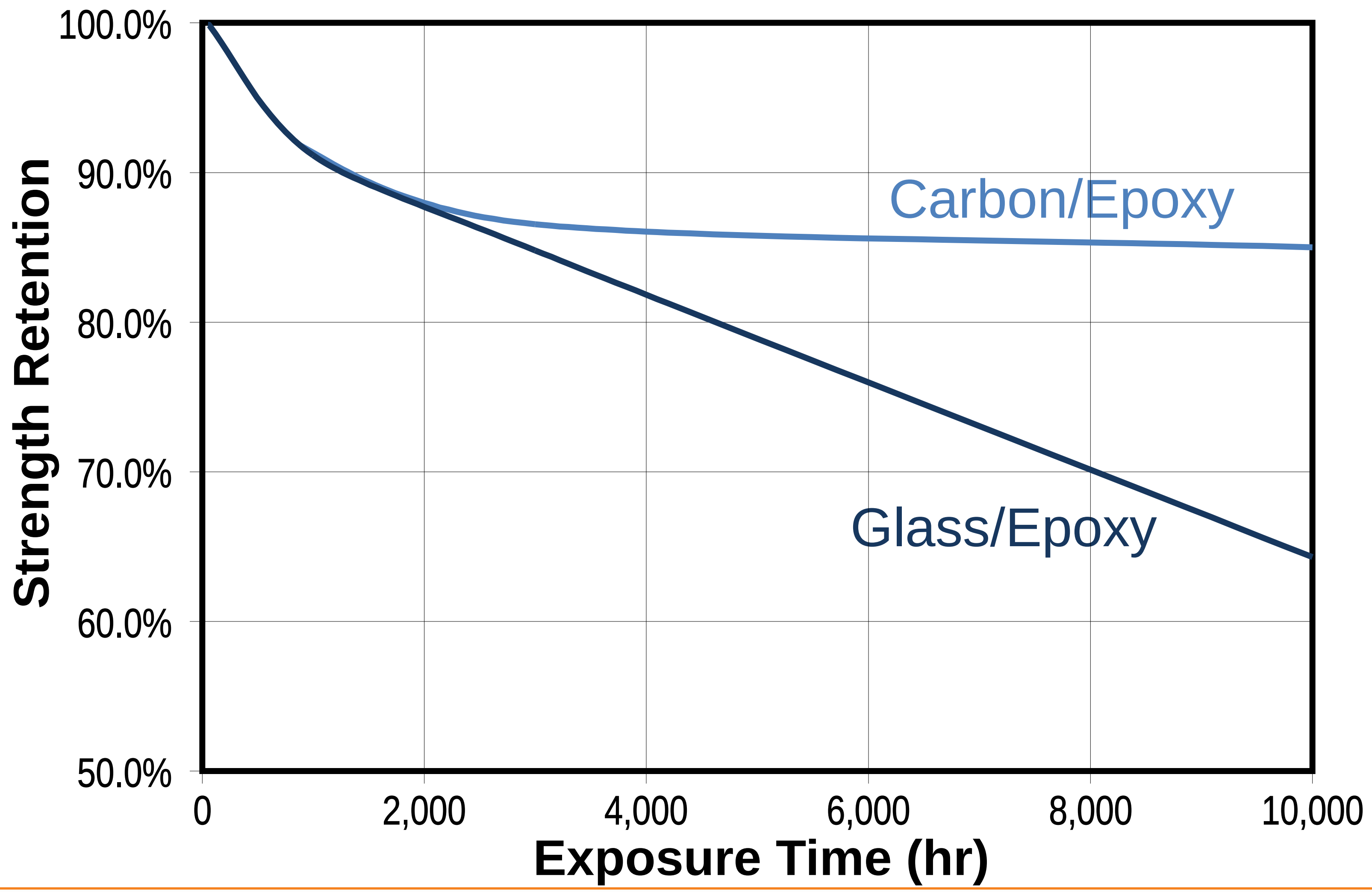
Sustained Load Resistance – Creep Rupture



Maximum Sustained Loads (6.5)

- ACI CODE 440.13-24 Section 6.5.1
  - Sustained plus cyclic stress limits:
  - 0.55 f_{fu} for carbon FRP systems
  - 0.20 f_{fu} for glass FRP systems

Exposure to 100%RH / 40ºC



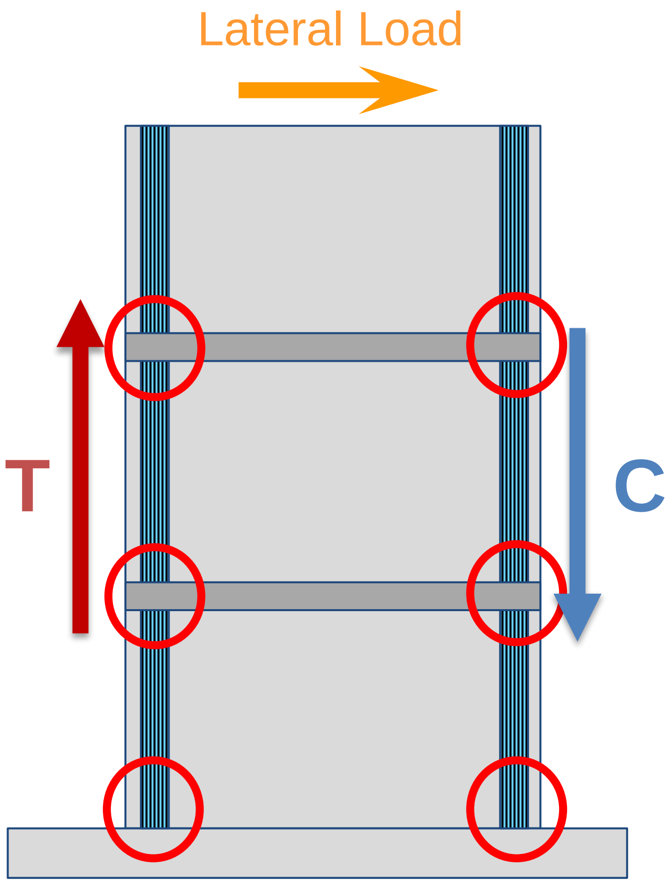
Environmental Reduction Factor (6.4)

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

ACI CODE 440.13
Eq. (6.4.1a)

Exposure Condition	Fiber Type	Environmental Reduction Factor, C_E
Interior Exposure	Carbon	0.95
	Glass	0.75
Exterior Exposure	Carbon	0.85
	Glass	0.65
Aggressive Environment	Carbon	0.85
	Glass	0.50

Global Structural Behavior (6.2)



- ACI CODE 440.13-24 Section 6.2.6
  - FRP systems shall not be used resist compression
- ACI CODE 440.13-24 Section 6.2.3
  - Structural elements and connections supporting FRP-strengthened members must be capable of supporting loads from those members

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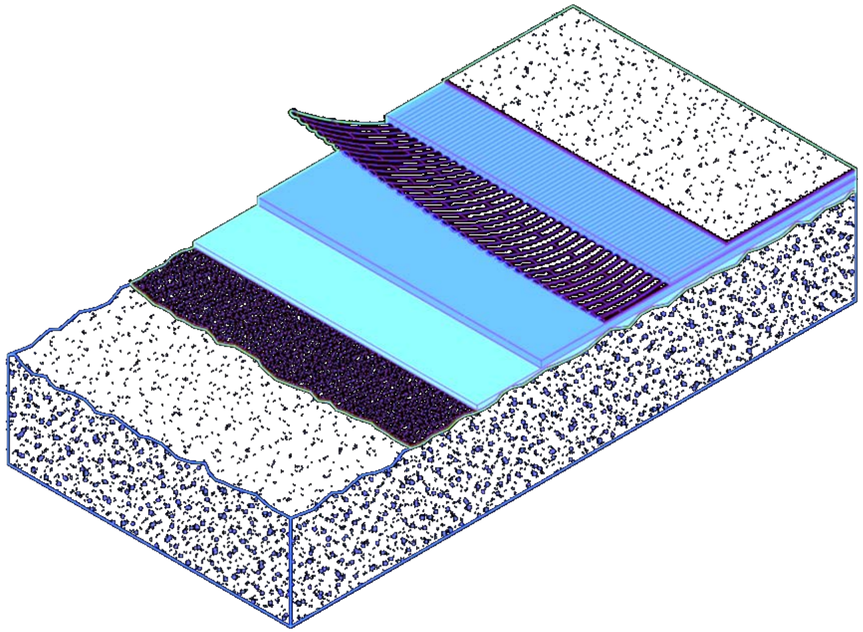
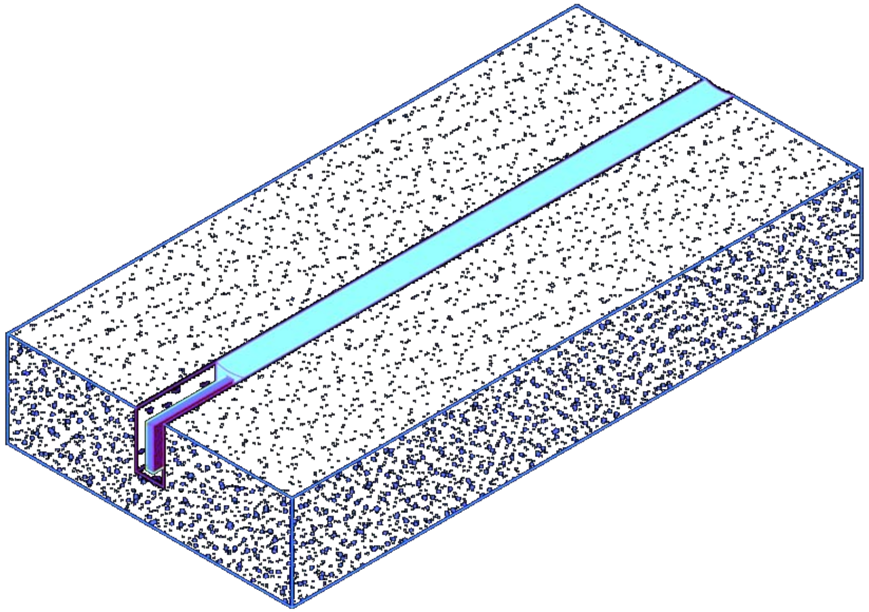
FRP Strengthening Systems



Wet Layup Systems



Precured and NSM Systems

FRP Systems

- All FRP materials used for strengthening concrete should be *systems*
  - Chemically matched fibers and resins
  - Known properties and durability
  - Proven field performance
  - Tested in accordance with appropriate material standards

Wet Layup FRP Systems

ACI SPEC 440.8-13(22)

- Minimum material properties
- Physical properties (T_g)
- Durability Properties

Table 7.1.2—Minimum properties for saturating resins

Property	ASTM test method	Mean value
Ultimate tensile strength	D638 Type 1	6000 psi
Tensile modulus	D638 Type 1	250,000 psi
Elongation at failure	D638 Type 1	3 percent
Ultimate flexural strength	D790	10,000 psi
Flexural modulus	D790	250,000 psi

Table 7.2.1—Tensile properties for FRP system

System designation	Minimum ultimate* tensile force per areal weight [kip/in./(oz/yd^2)]	Minimum mean chord tensile stiffness per areal weight [kip/in./(oz/yd^2)]
Carbon	0.170	20.0
Glass	0.0625	4.160

*Mean minus three standard deviations.

Wet Layup FRP Systems

ACI SPEC 440.8-13(22)

- Minimum material properties
- Physical properties (T_g)
- Durability Properties

Table 8.1—Minimum mean retained tensile force per unit width of FRP system after environmental conditioning*

Environmental exposure conditions	ASTM test method	Conditioning	Percent retention		
			1000 hours	2000 hours	3000 hours
Water resistance	D2247	100 percent relative humidity at 100°F ± 2°F	90	NA	85
Salt water resistance	D1141 C581	Immersion at 73°F ± 2°F	90	NA	85
Alkali resistance	C581	Immersion in $Ca(CO_3)$ at pH = 9.5 and 73°F ± 3°F	90	NA	85
Dry heat resistance	D3045	140°F ± 5°F	90	NA	85
Exterior exposure	G153	2000-hour conditioning as follows: Exposed to cycles consisting of 102 min light and 18 min light and water spray. The black-body temperature is 143°F.	NA	90	NA

*Note: Additional durability documentation, such as freezing-and-thawing resistance, is often requested by the purchaser or a governmental regulatory agency. The freezing-and-thawing test method described in ICC Evaluation Service Acceptance Criteria (AC125) may be used for this purpose.

Precured and NSM Systems

ACI CODE 440.13-24
Section 4.3 and 4.4

- Requirements are written directly into the code
- Adhesive requirements
- Laminate requirements

Property	ASTM standard	required value
minimum bond strength, 14 days	C882	1000 psi (7 MPa)
maximum absorption, 24 hours	D570	1%
minimum glass transition temperature	D3418	140ºF (60ºC)
minimum compressive yield strength, 7 days	D695	8,000 psi (55 MPa)
minimum compressive modulus	D695	150,000 psi (1000 MPa)
minimum tensile strength, 7 days	D638	3600 psi (25 MPa)
minimum elongation at break	D638	1%

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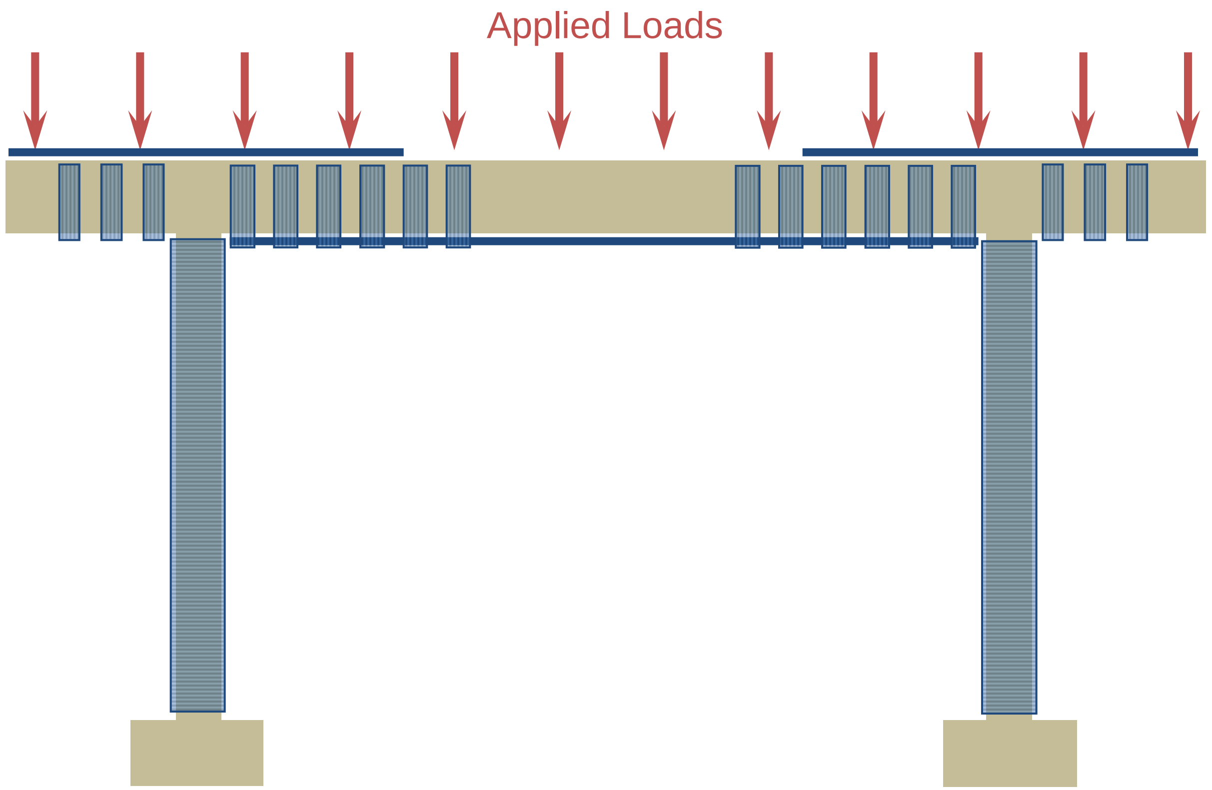
Applications

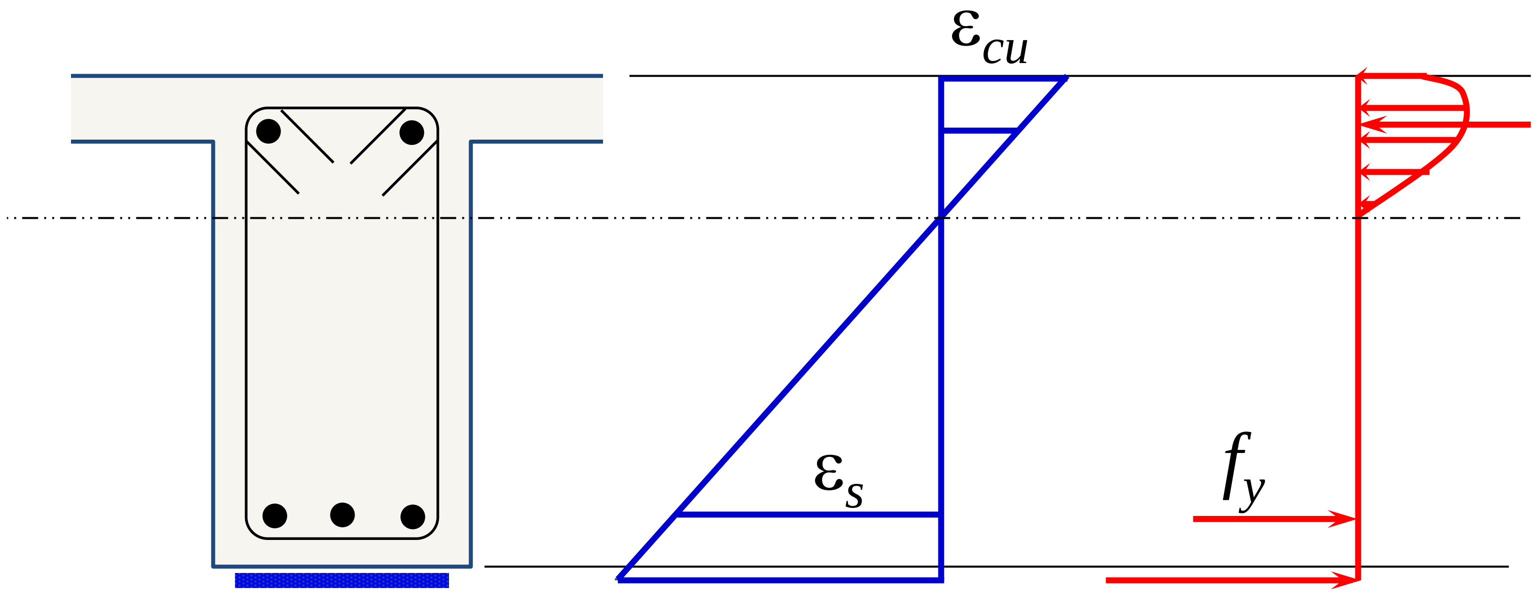
- Supplemental Reinforcement
  - Flexural Strengthening
  - Shear Strengthening
  - Confinement



Flexural Strengthening

- ACI CODE 440.13 Chapter 7

Flexural Strengthening

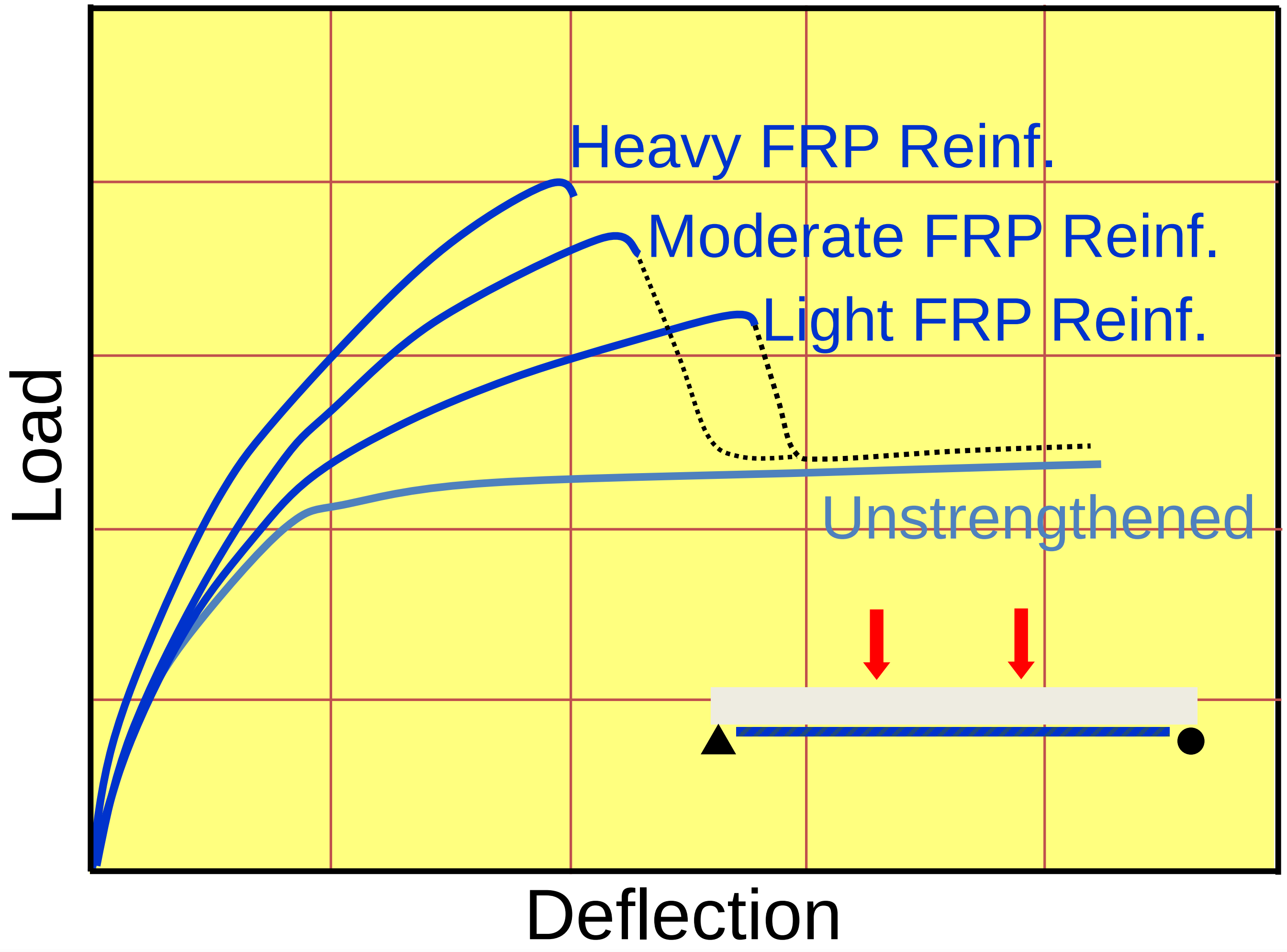


$$A_f = n\, t_f\, w_f$$

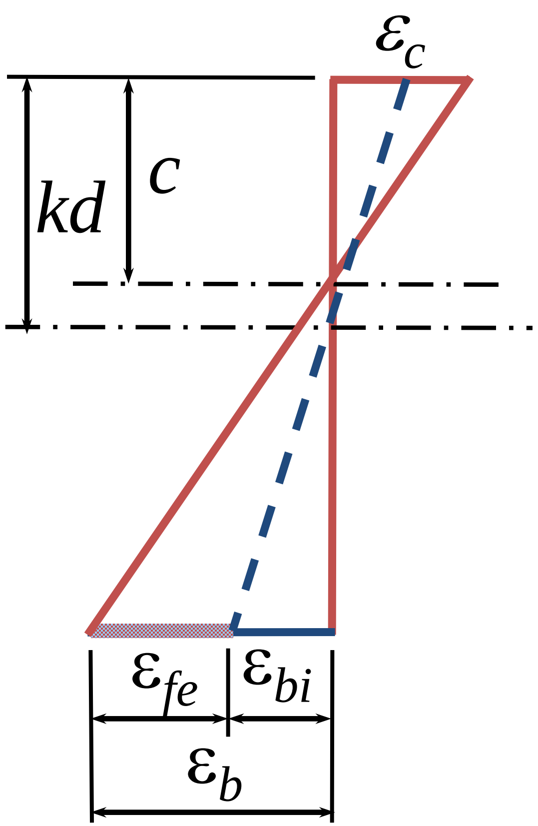
$$f_{fe} = E_f\, \varepsilon_{fe}$$

$$M_n = A_s f_s\left(d - \frac{\beta_1 c}{2}\right) + A_f\, f_{fe}\left(h - \frac{\beta_1 c}{2}\right)$$

Flexural Strengthening



Initial Substrate Strain (6.2.5)

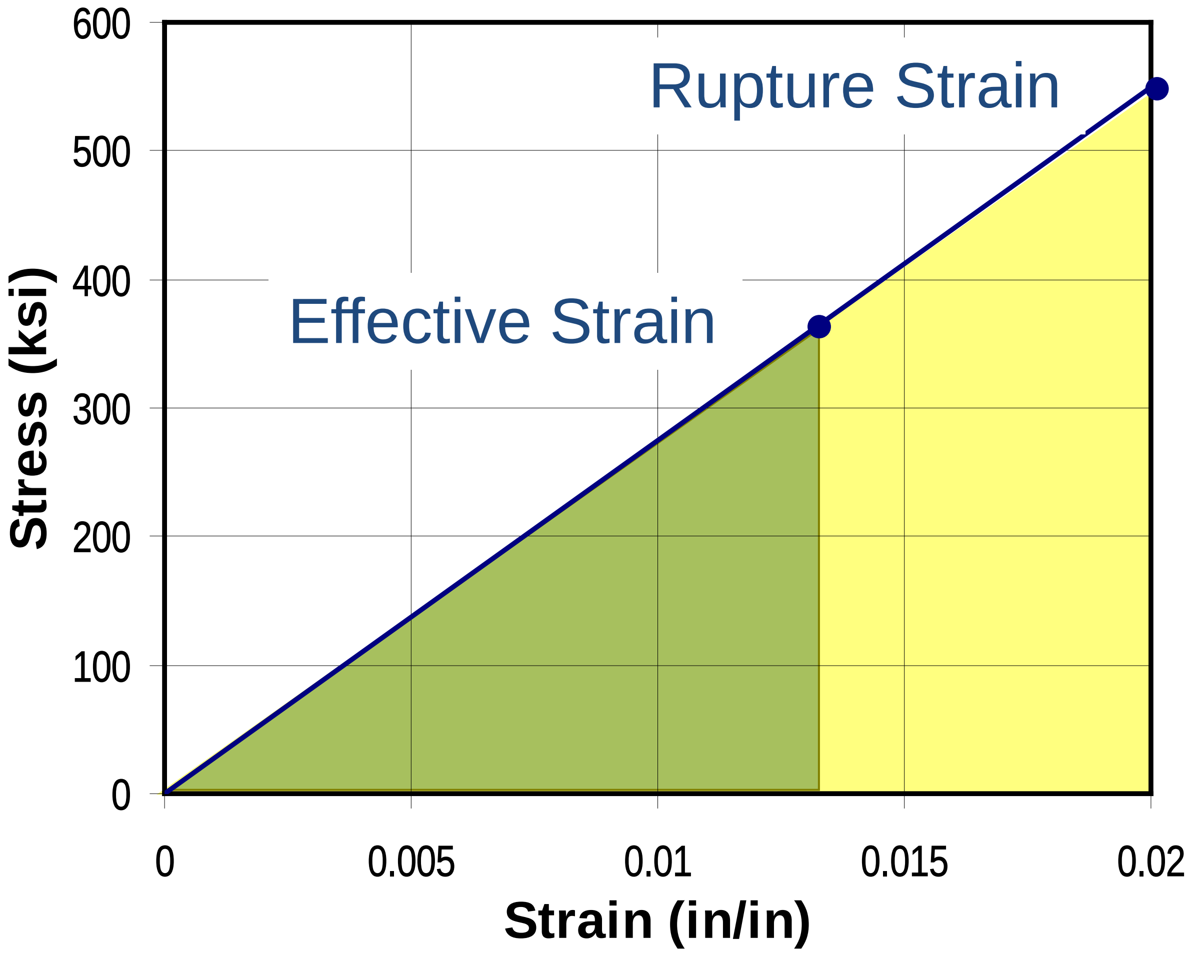


Strain Distribution

- FRP is passive reinforcement
  - Only stressed by loads imposed after the FRP system is installed and cured

$$\varepsilon_{bi} = \frac{M_{ip}(h - kd)}{I_{cr}E_c}$$

Flexural Strengthening



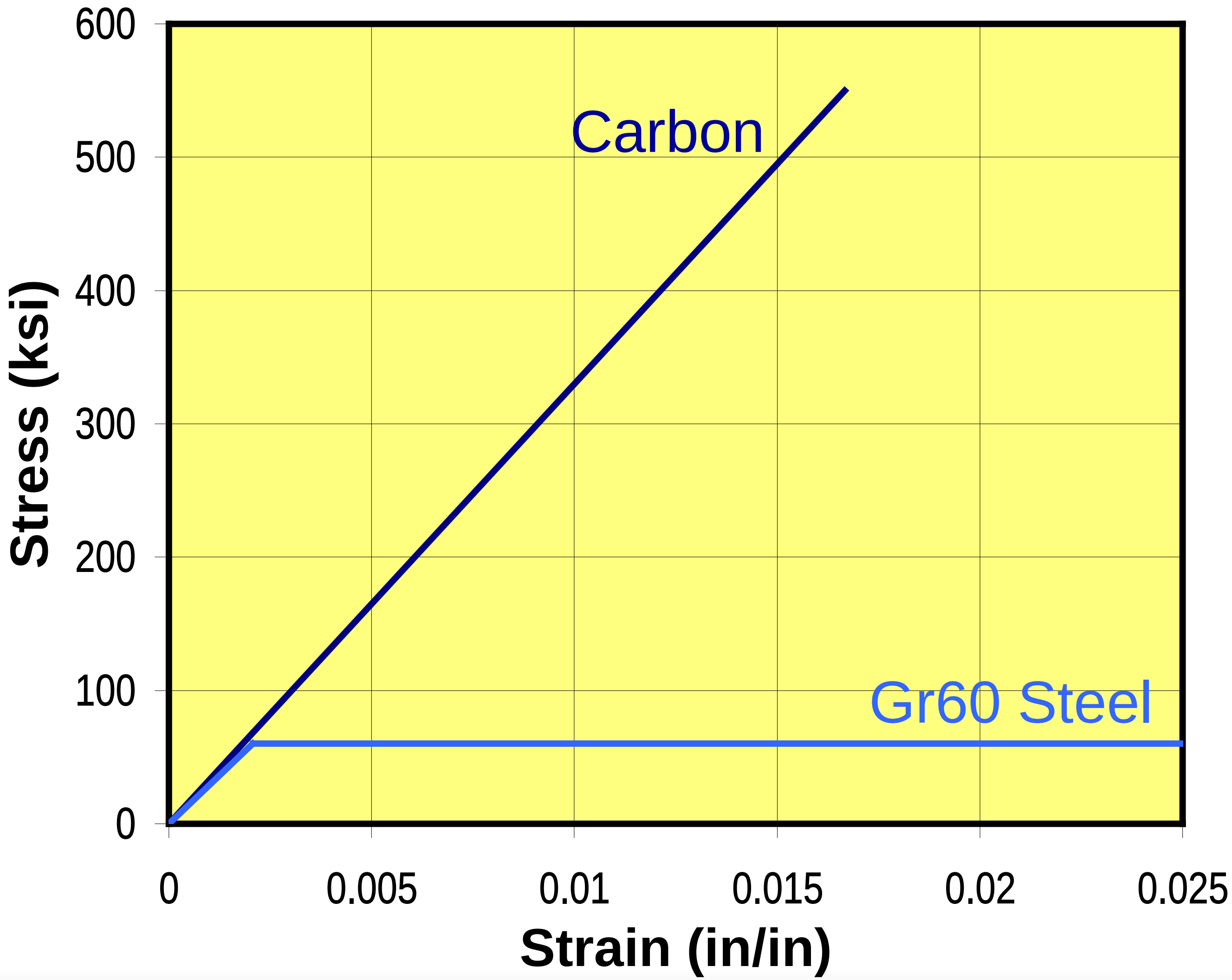
Flexural Strengthening

- <u>Debonding Strain</u> (ε_{fd})
  - The strain level that can be achieved is often controlled by debonding
  - The stiffer the FRP laminate the more prone to debonding it will be
  - The lower the concrete strength, the more prone to debonding it will be

ACI CODE 440.13
Eq. (7.3.8.2)

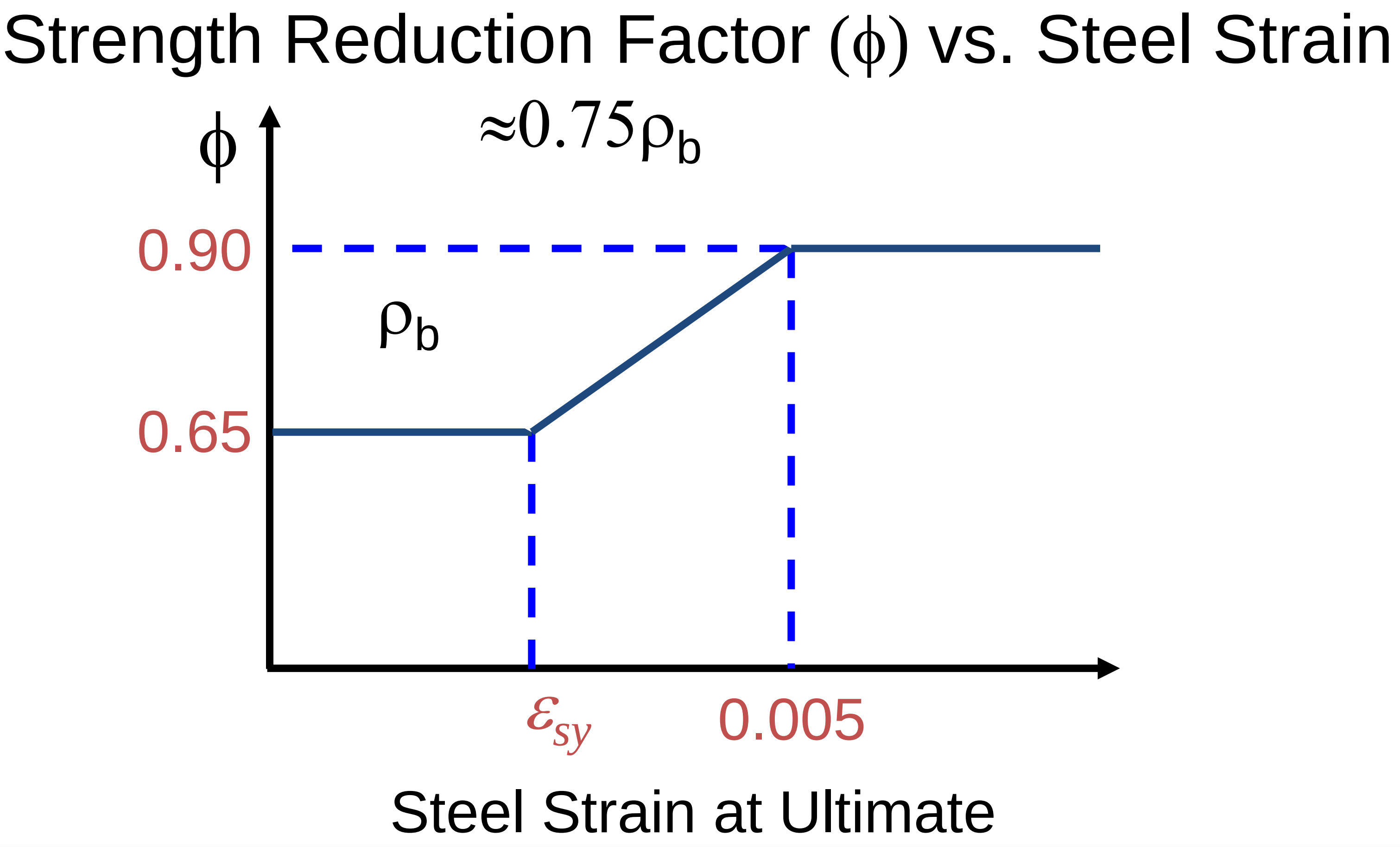
$$\varepsilon_{fd} = 0.41\sqrt{\frac{f_c'}{nE_f t_f}} \leq 0.9\,\varepsilon_{fu}$$

Ductility

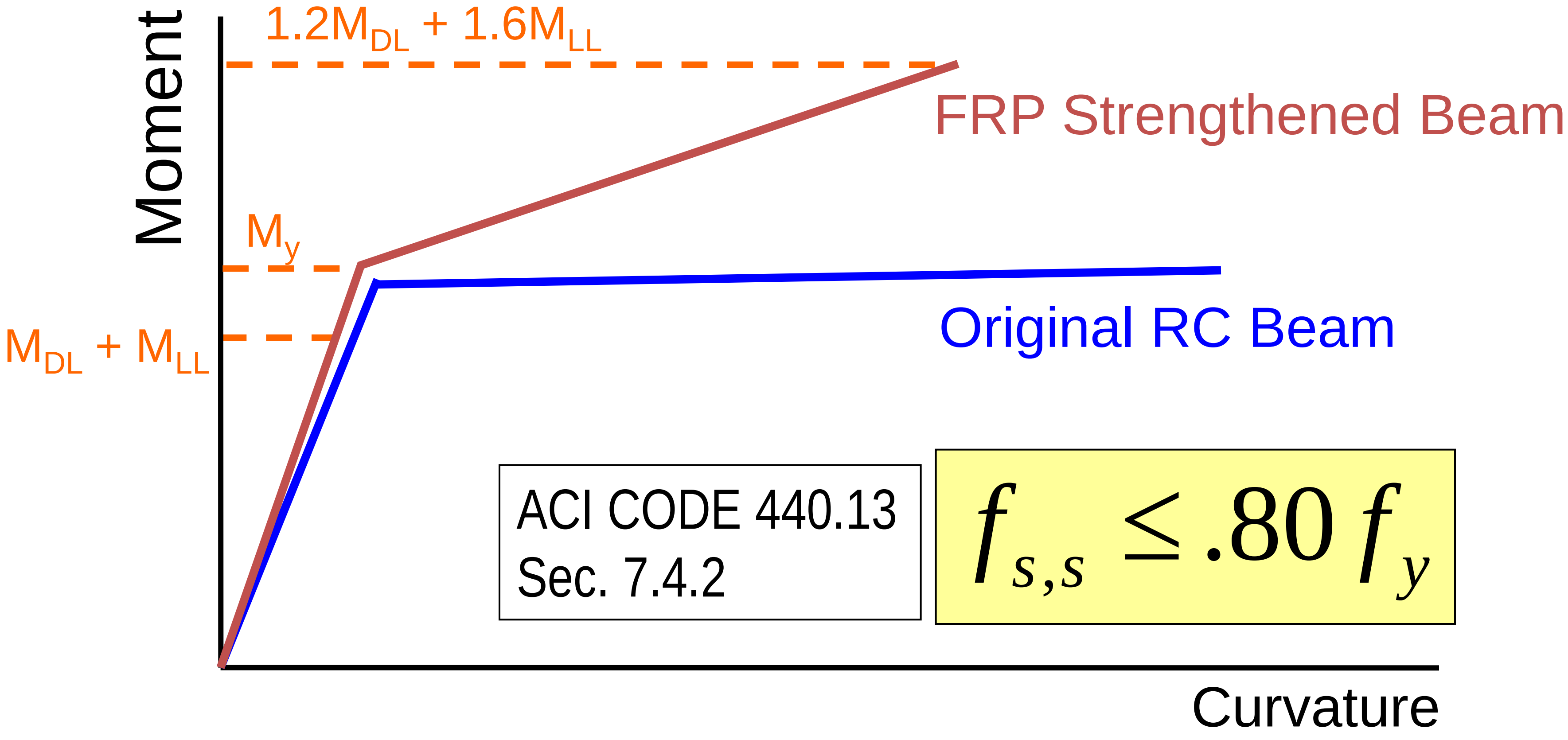


Stress (ksi)
600
500
400
300
200
100
0
Carbon
Gr60 Steel
0
0.005
0.01
0.015
0.02
0.025
Strain (in/in)

Ductility Based Strength Reduction Factor



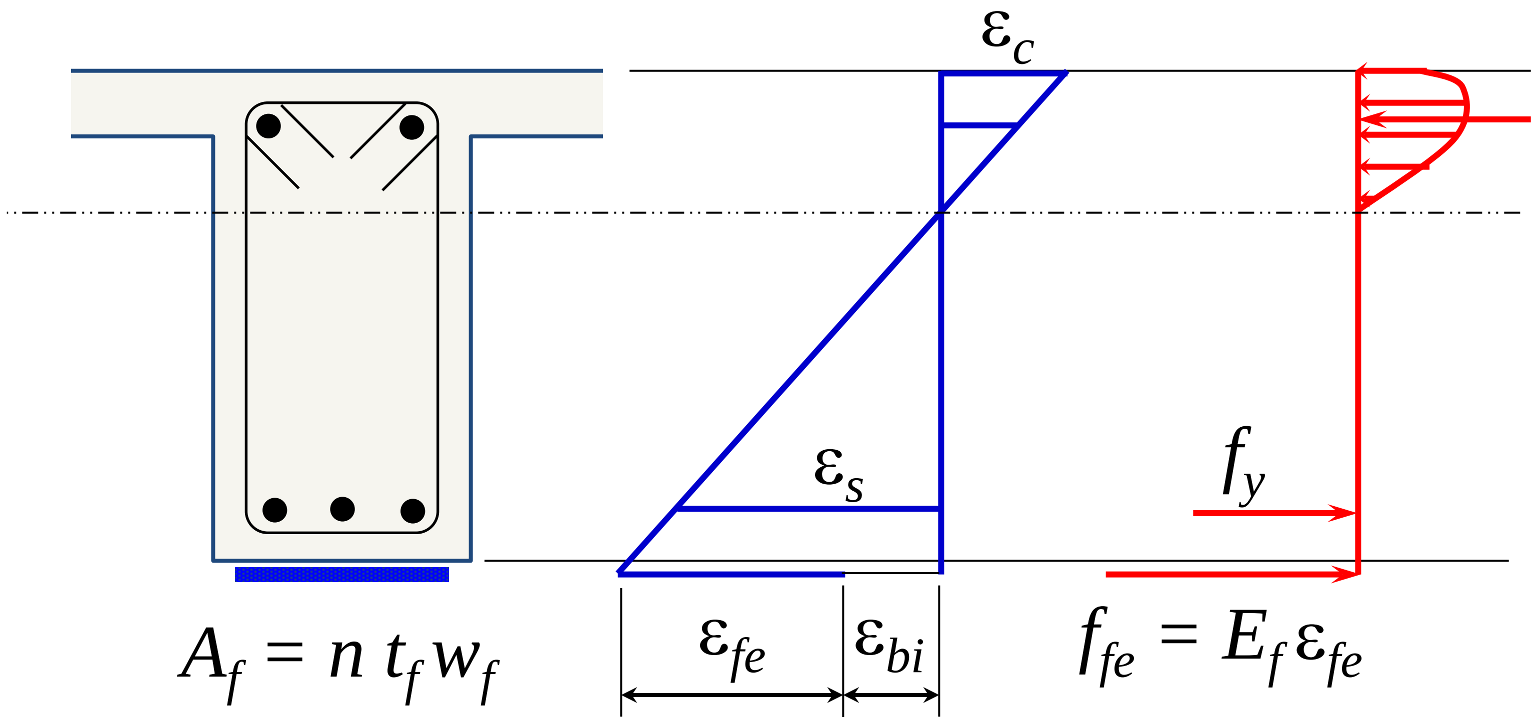
Service Stress Check



ACI CODE 440.13
Sec. 7.4.2

$$f_{s,s} \leq .80\, f_y$$

Flexural Strengthening



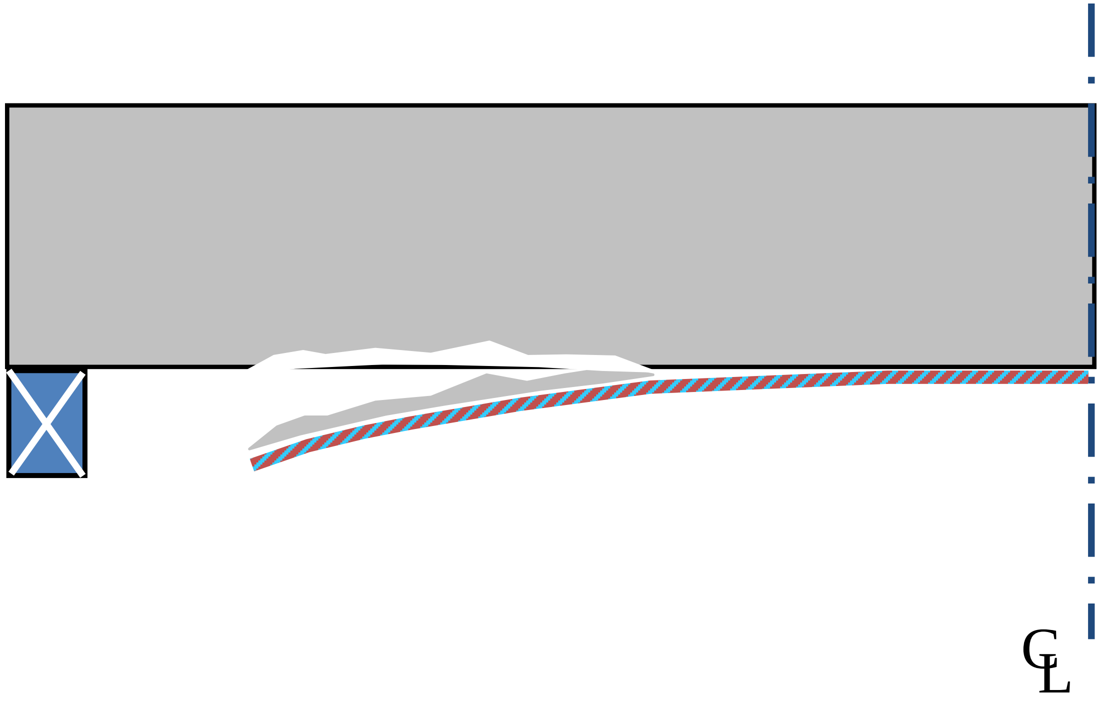
ACI CODE 440.13
Eq. (R7.4.9)

$$\phi M_n = \phi\left[A_s f_s\left(d - \frac{\beta_1 c}{2}\right) + \psi_f A_f f_{fe}\left(h - \frac{\beta_1 c}{2}\right)\right]$$

Detailing FRP Flexural Reinforcement

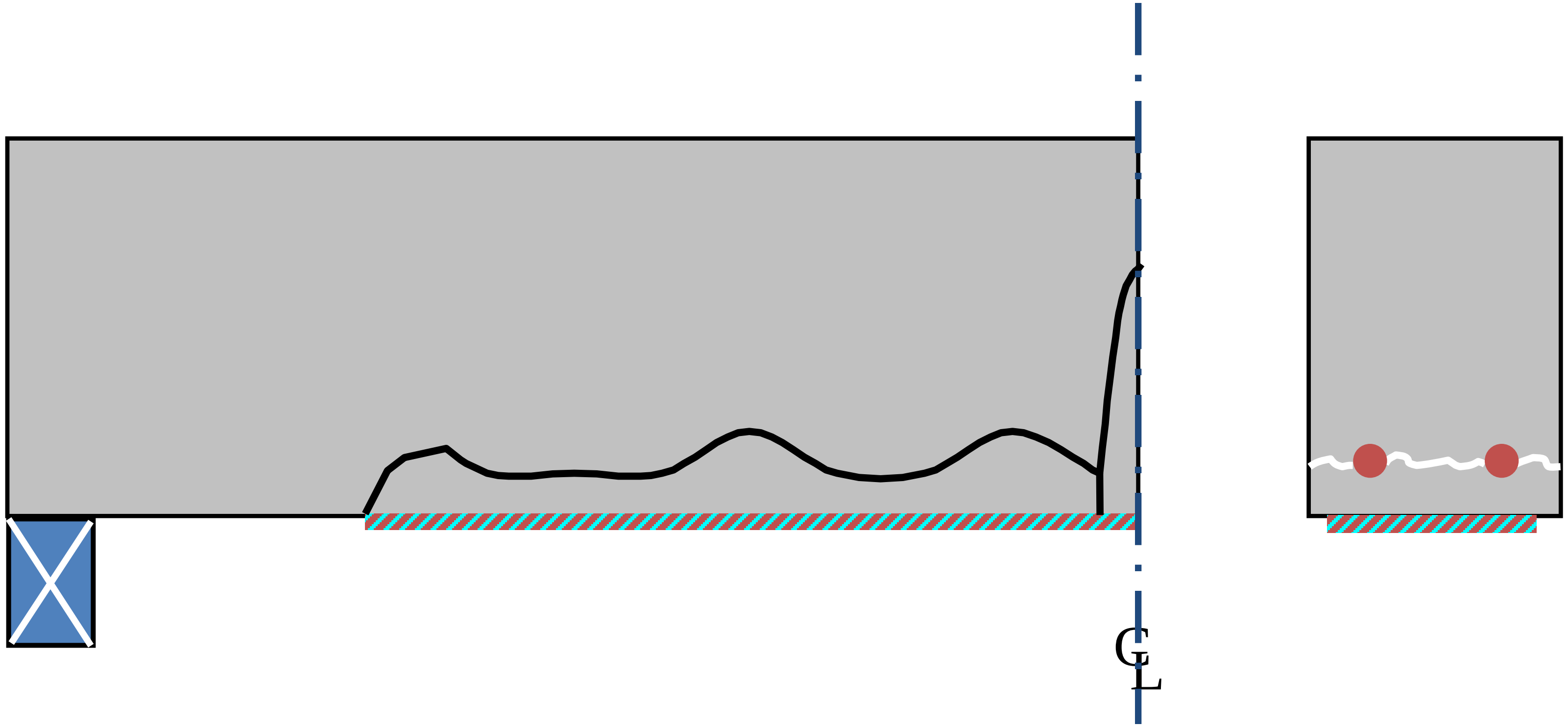
- Development Length
- Cutoff Points

Interfacial Shear (Peeling) Failure



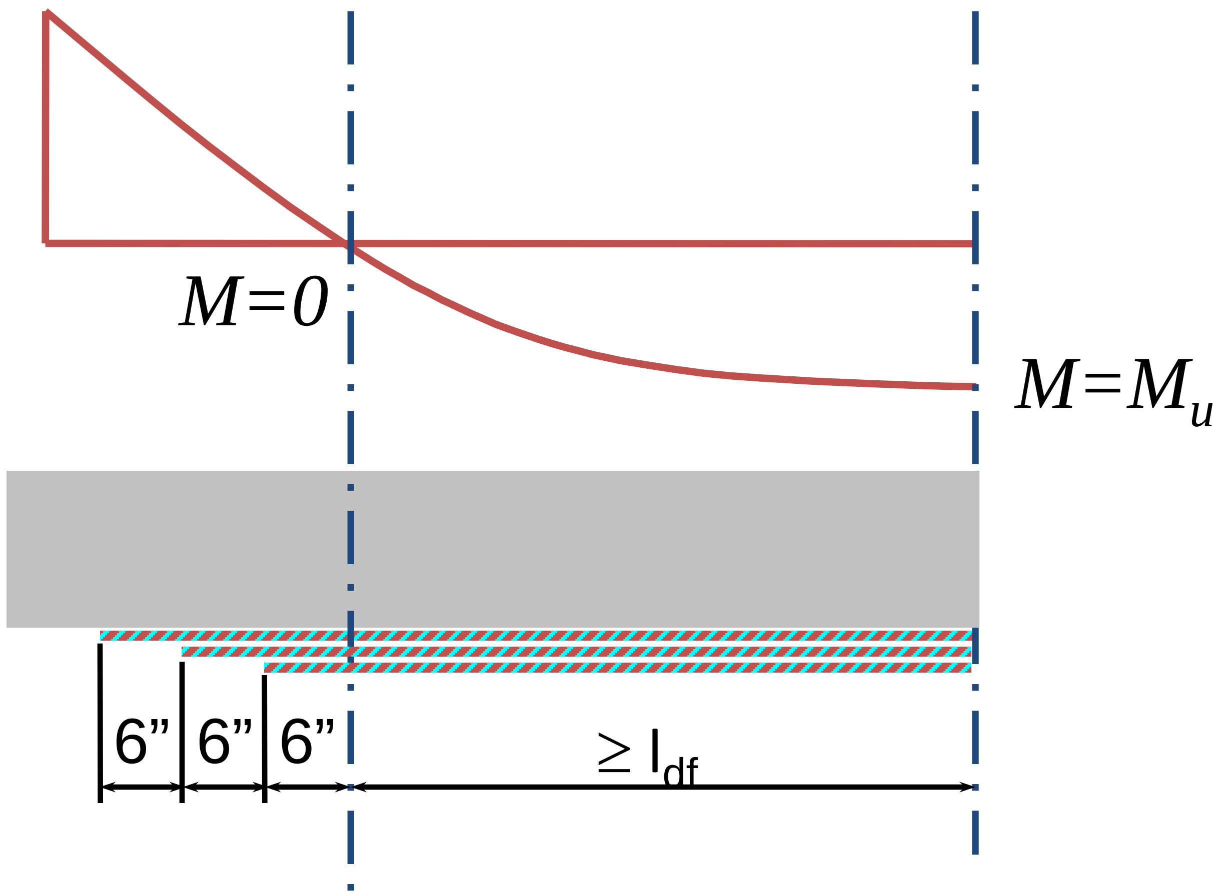
Interfacial Shear (Peeling) Failure

Cover Tension Failure

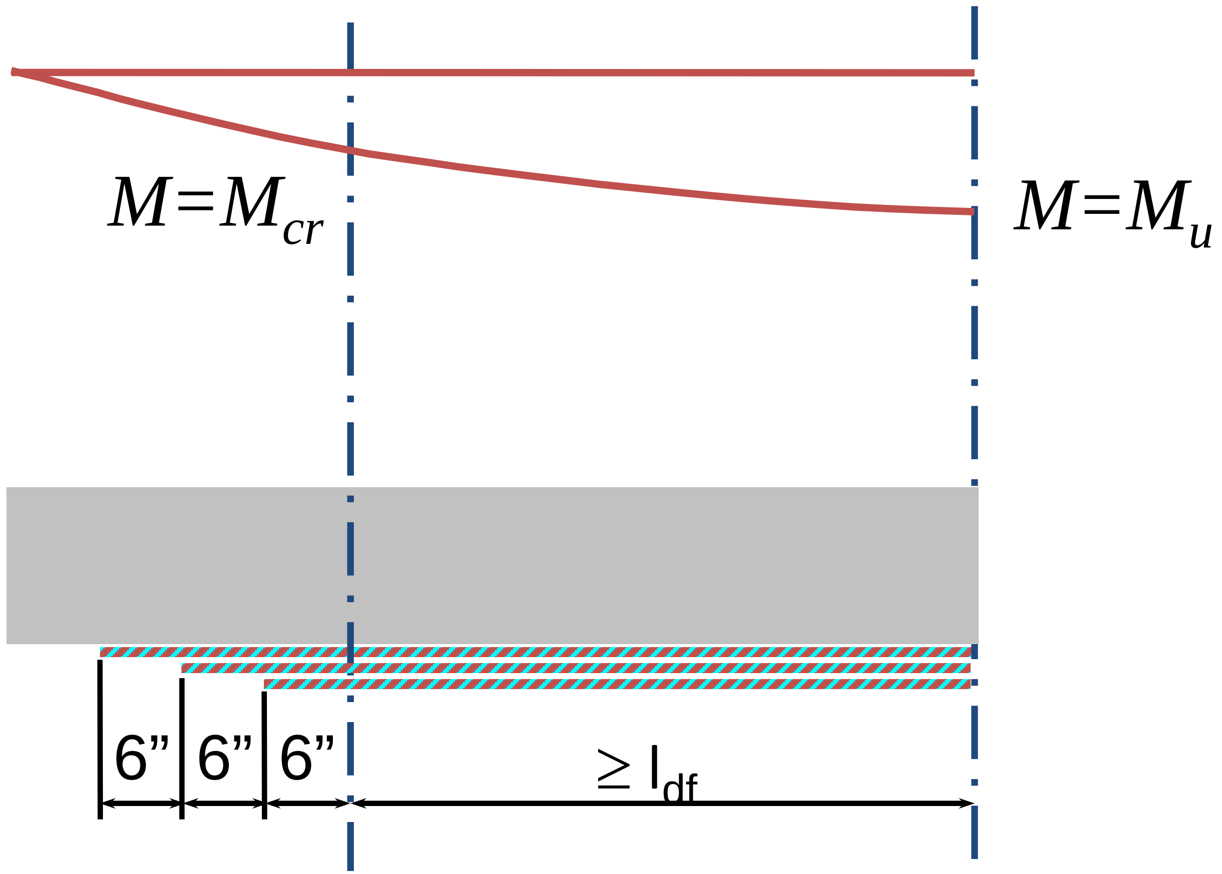


Cover Tension Failure

Cutoff Points – Continuous Span



Cutoff Points – Simple Span



Detailing Guidelines

“U-wrap” Anchorage of Flexural Plies

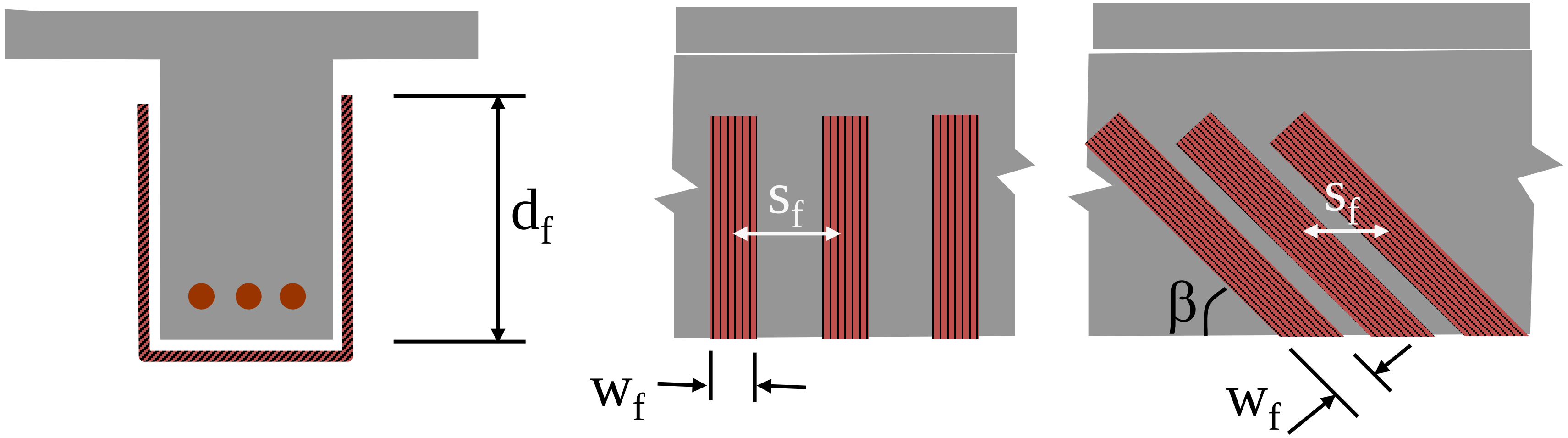
Detailing Guidelines

“Step” plies

Shear Strengthening

- **ACI CODE 440.13 Chapter 8**

Shear Strengthening



ACI CODE 440.13
Eq. (8.6.1)

$$V_f = \frac{A_{fv} f_{fe} (\sin\alpha + \cos\alpha) d_f}{s_f}$$

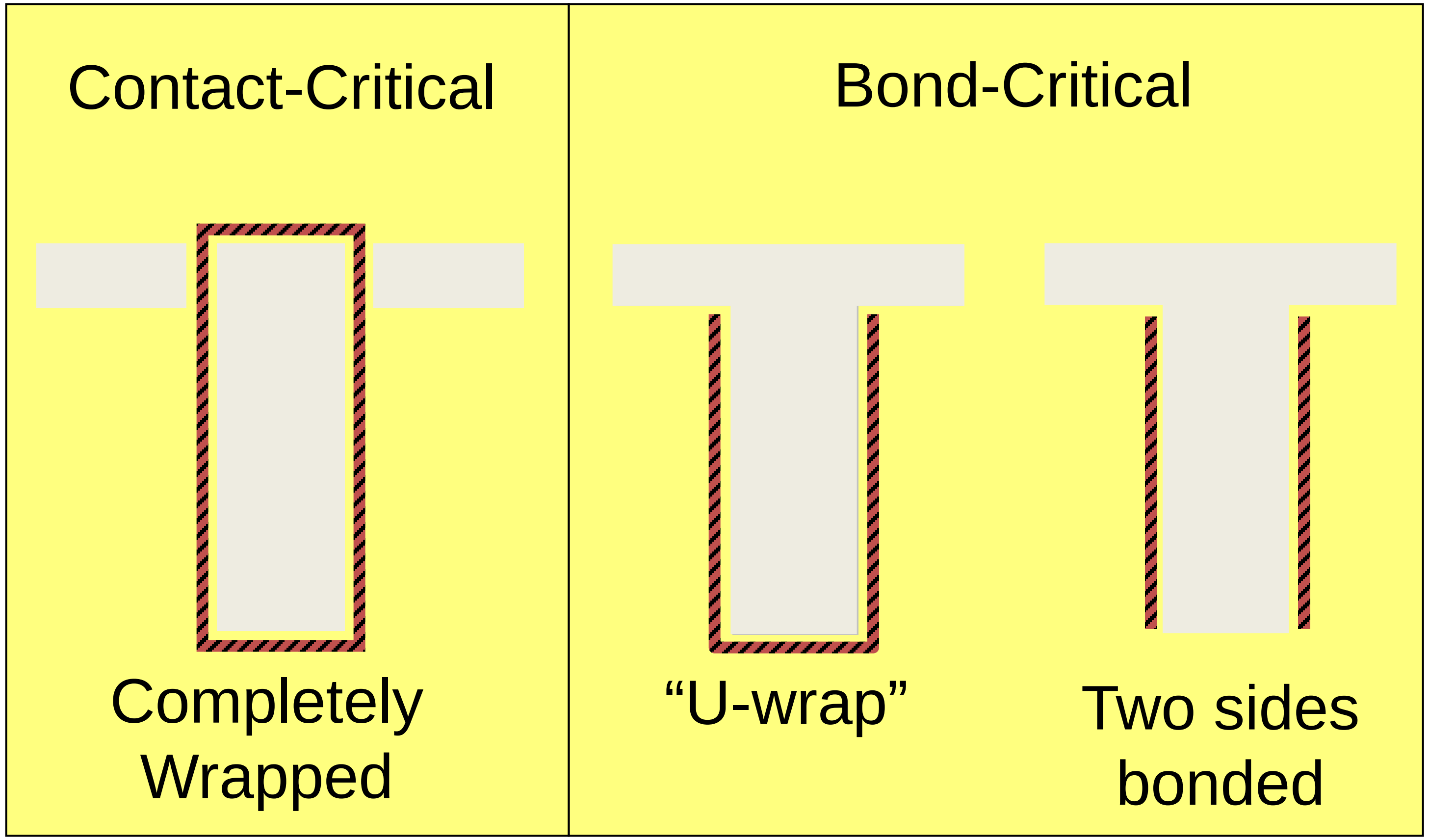
Partial Reduction Factor (8.3.2 and 8.5.3)

- Bond Critical Applications:

$$\psi_f = 0.85$$

- Contact Critical Applications:

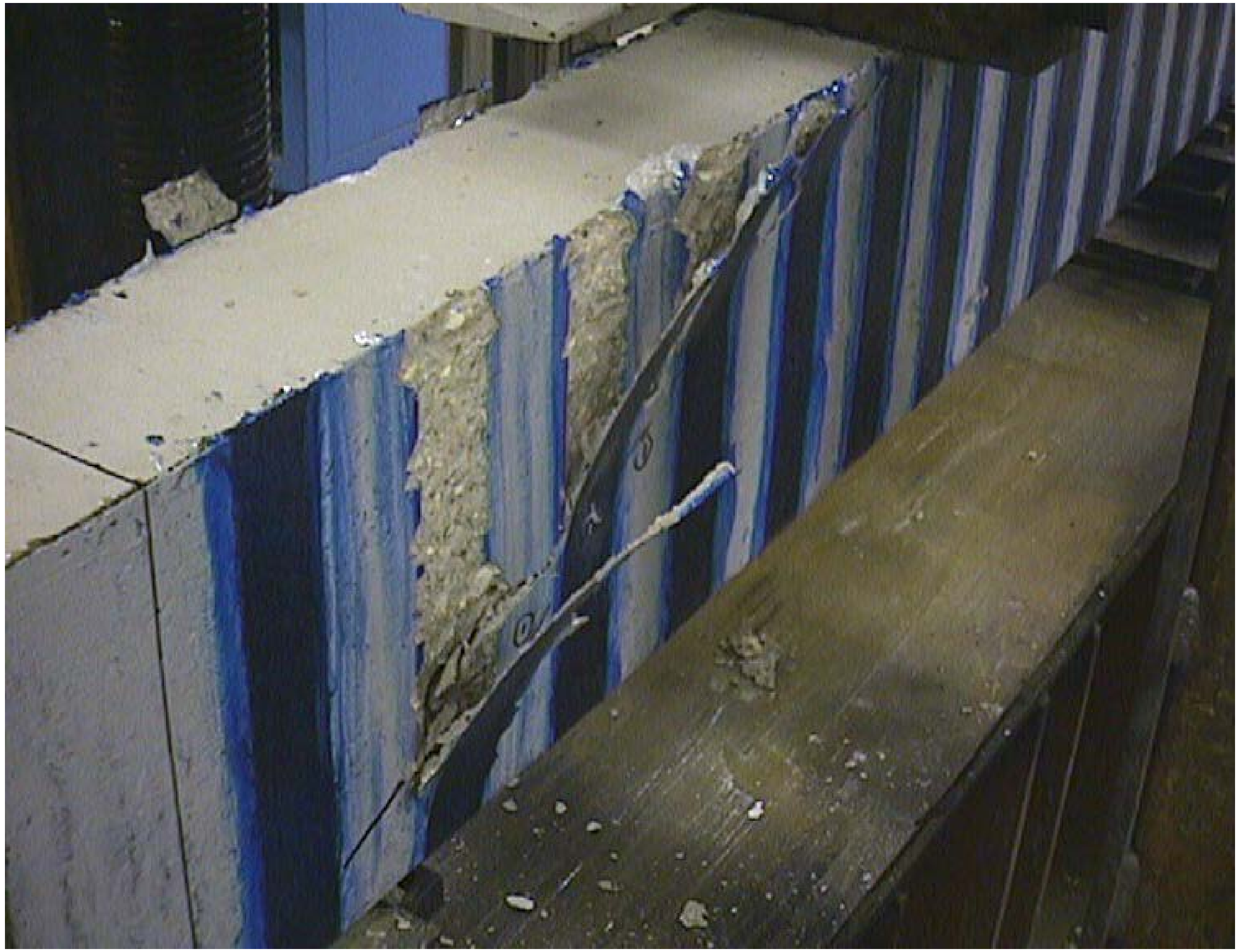
$$\psi_f = 0.95$$



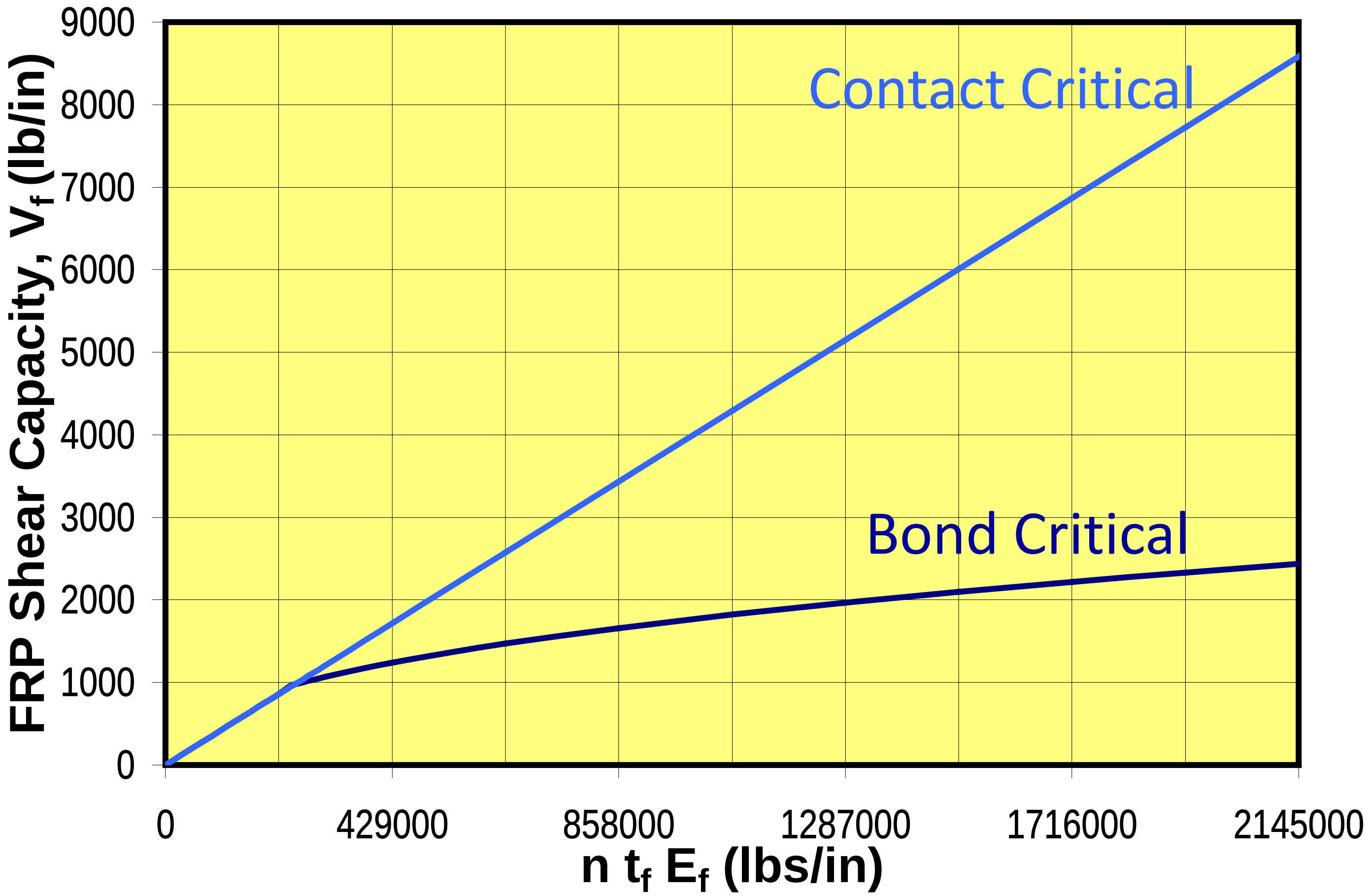
ACI CODE 440.13
Fig. (8.3.2)

Shear Failure Modes

- Debonding of FRP from substrate
- Loss of aggregate interlock (i.e., loss of Vc)
- FRP rupture due to stress concentrations



Shear Strengthening



Shear Strengthening

- <u>Effective Strain – Contact Critical</u>
- Failure of FRP stirrups fully wrapped around the cross section is governed by loss of aggregate interlock

ACI CODE 440.13
Eq. (8.6.5.1)

$$\varepsilon_{fe} = 0.004 \leq 0.75\varepsilon_{fu}$$

Shear Strengthening

- <u>Effective Strain – Bond Critical</u>
- Failure of U-wraps & side bonded FRP stirrups is governed by bond

ACI CODE 440.13 Eq. (8.6.5.2)	$\varepsilon_{fe} = \kappa_v \varepsilon_{fu} \leq 0.004$
ACI CODE 440.13 Eq. (8.6.5.3)	$\kappa_v = \dfrac{k_1 k_2 L_e}{468 \varepsilon_{fu}} \leq 0.75$

Bond Reduction Factor

$$k_1 = \left(\frac{f_c'}{4000}\right)^{2/3}$$

Accounts for concrete strength

$$k_2 = \frac{d_{fe}}{d_f}$$

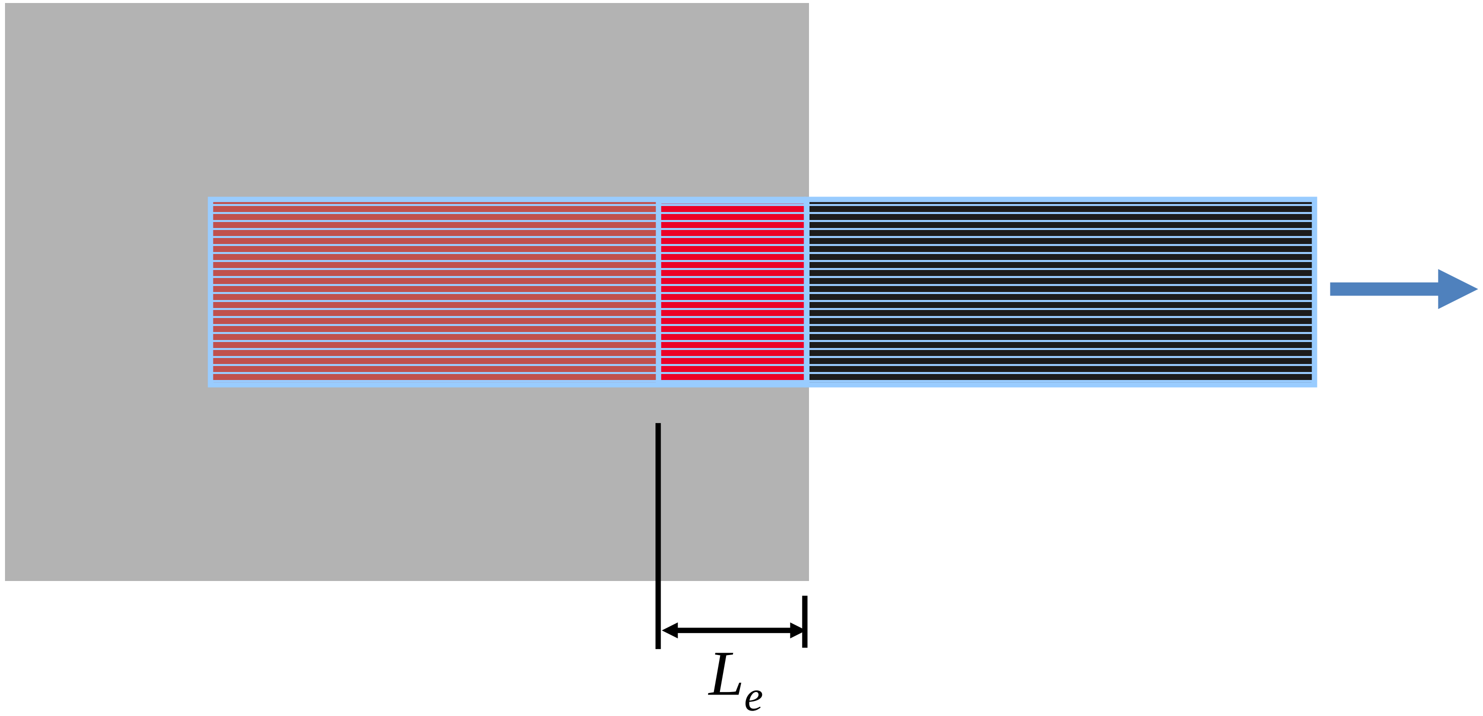
Accounts for wrapping scheme

$$L_e = \frac{1}{\sqrt{n}} L_o$$

Active Bond Length

$$\kappa_v = \frac{k_1 k_2 L_e}{468\,\varepsilon_{fu}}$$

Active Bond Length

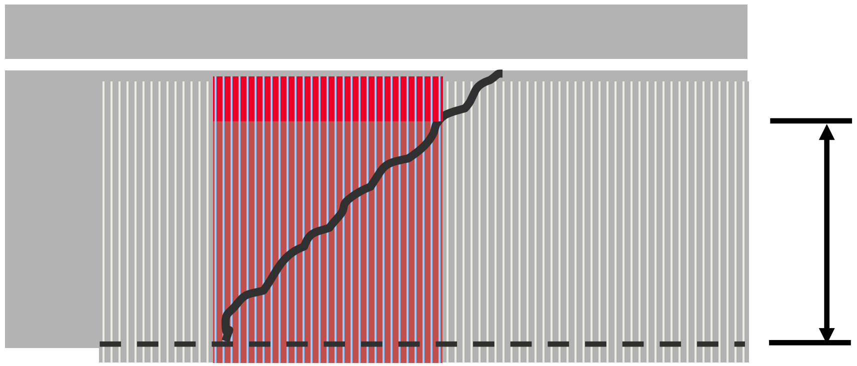


ACI CODE 440.13
Eq. (8.6.5.3.1)

$$L_e = \frac{23{,}300}{\left(n\ t_f E_f\right)^{0.58}}$$

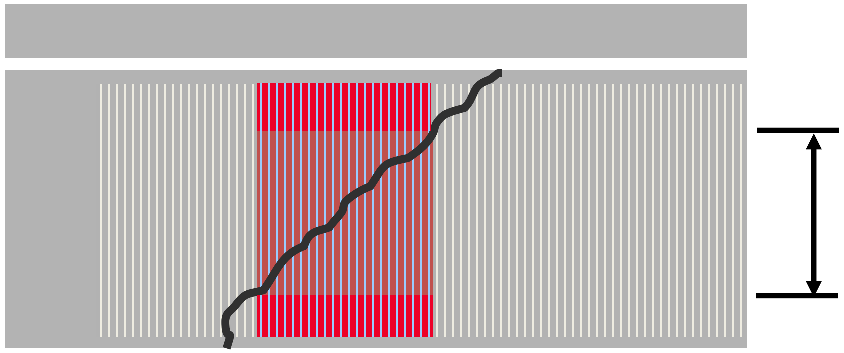
Effective Depth

U-Wrap



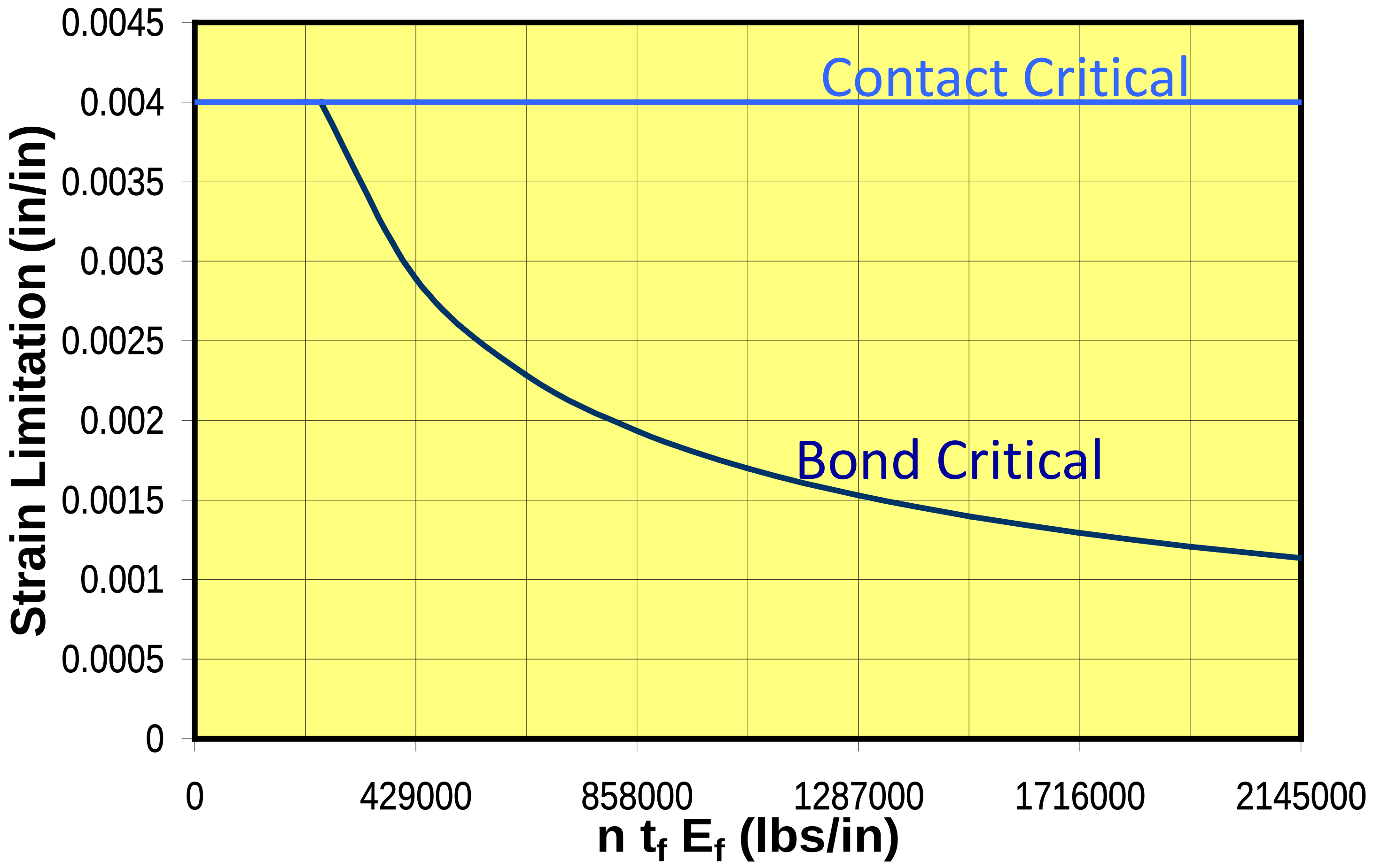
$$d_{fe} = d_f - L_e$$

Sides only



$$d_{fe} = d_f - 2L_e$$

Shear Strengthening



Material Reduction Factors

- <u>Strength Reduction Factors</u>
- Use ϕ factors prescribed by ACI 318
- *Additional Strength Reduction Factor* (ψ_f) applied to the FRP Reinf.

ACI CODE 440.13
Eq. (8.5.1)

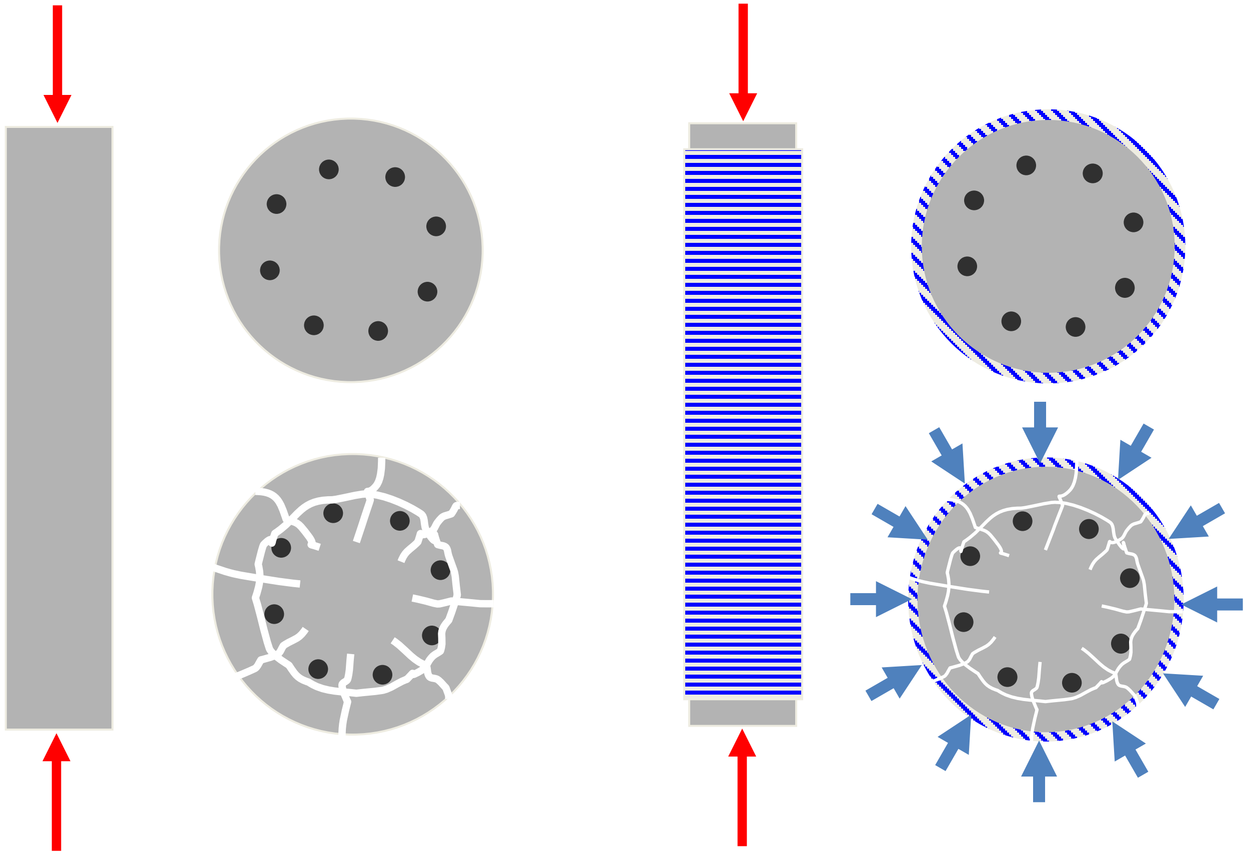
$$\phi V_n = \phi\left(V_c + V_s + \psi_f V_f\right)$$

- ψ_f = 0.95 for Contact-critical apps.
- ψ_f = 0.85 for Bond-critical apps.

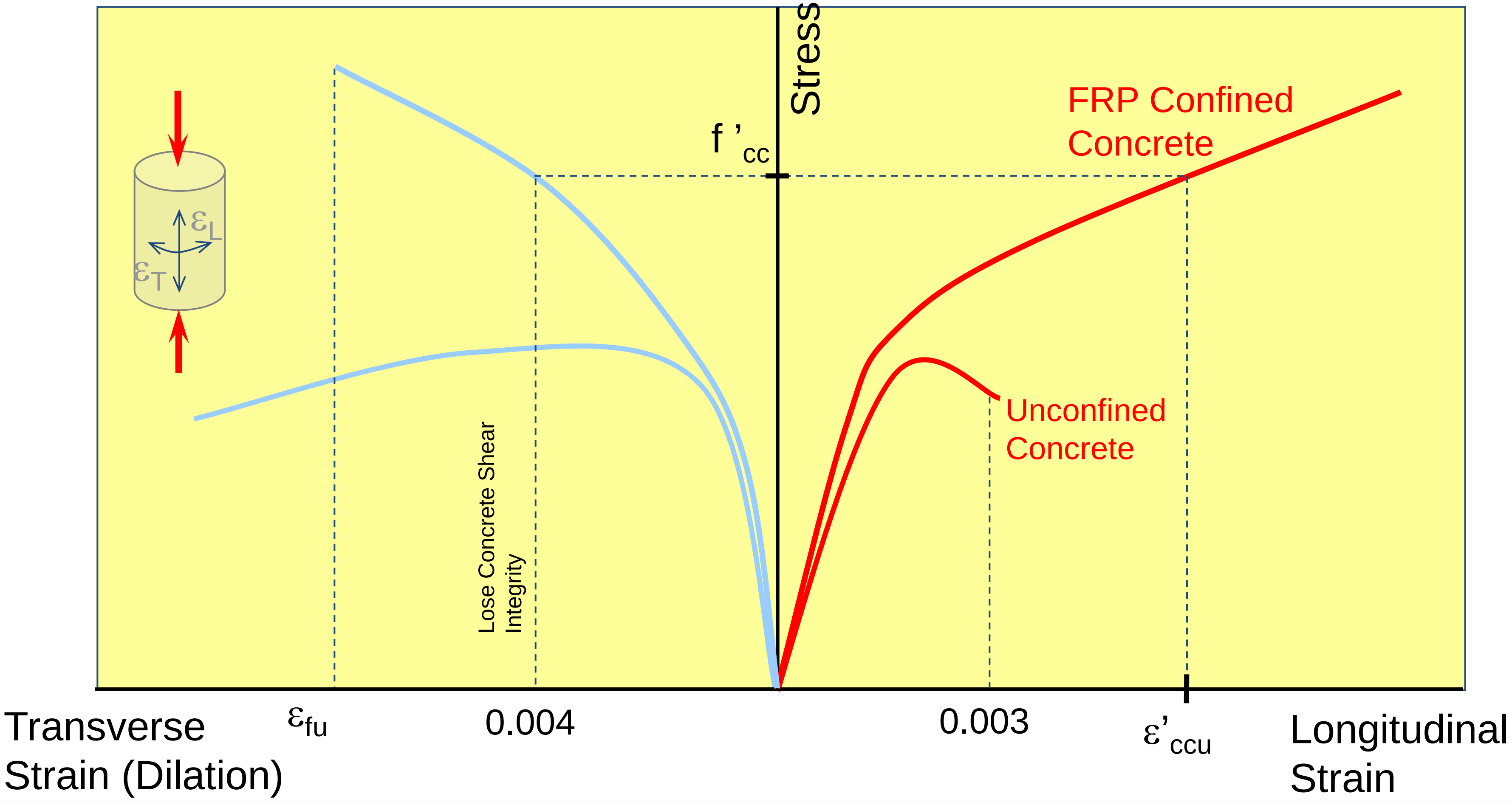
Confinement

- **ACI CODE 440.13 Chapter 9**

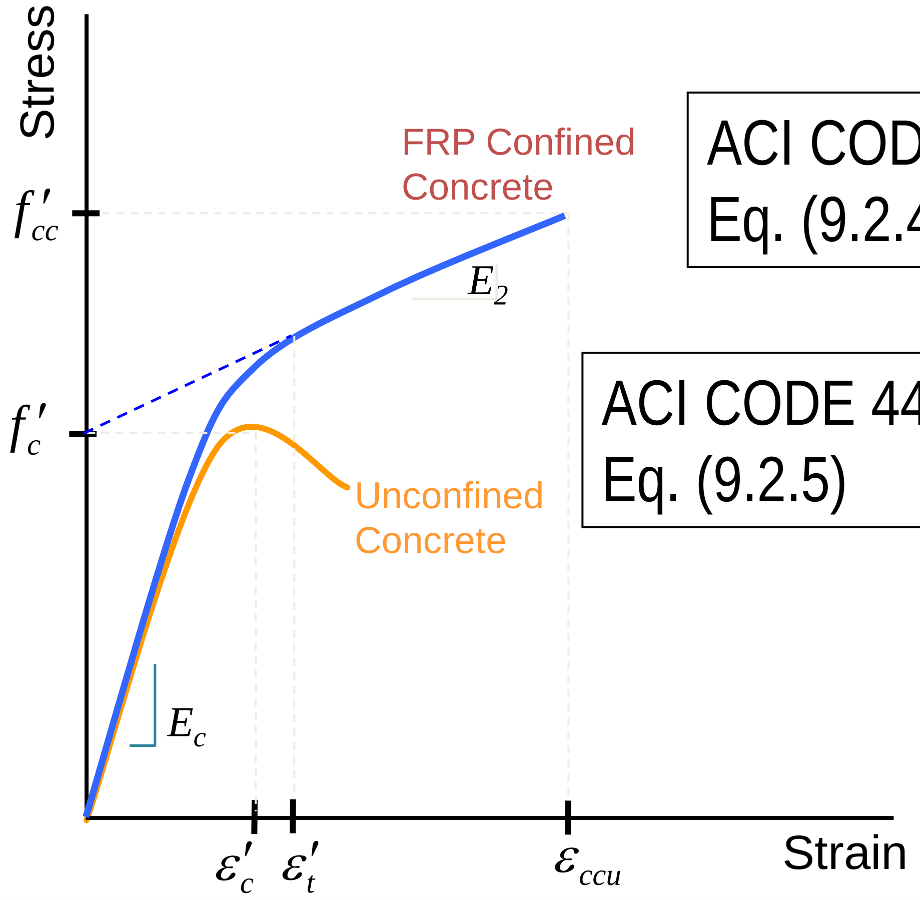
Confinement



FRP Confinement Model



FRP Confinement Model



ACI CODE 440.13
Eq. (9.2.4)

$$f'_{cc} = f'_c + \psi_f 3.3\kappa_a f_l$$

ACI CODE 440.13
Eq. (9.2.5)

$$\varepsilon_{ccu} = \varepsilon'_c \left(1.50 + 12\kappa_b \frac{f_l}{f'_c}\left(\frac{\varepsilon_{fe}}{\varepsilon'_c}\right)^{0.45}\right)$$

Where,

f_l is the confining pressure exerted by the FRP jacket

κ_a and κ_b are shape factors

Axial-Moment Interaction

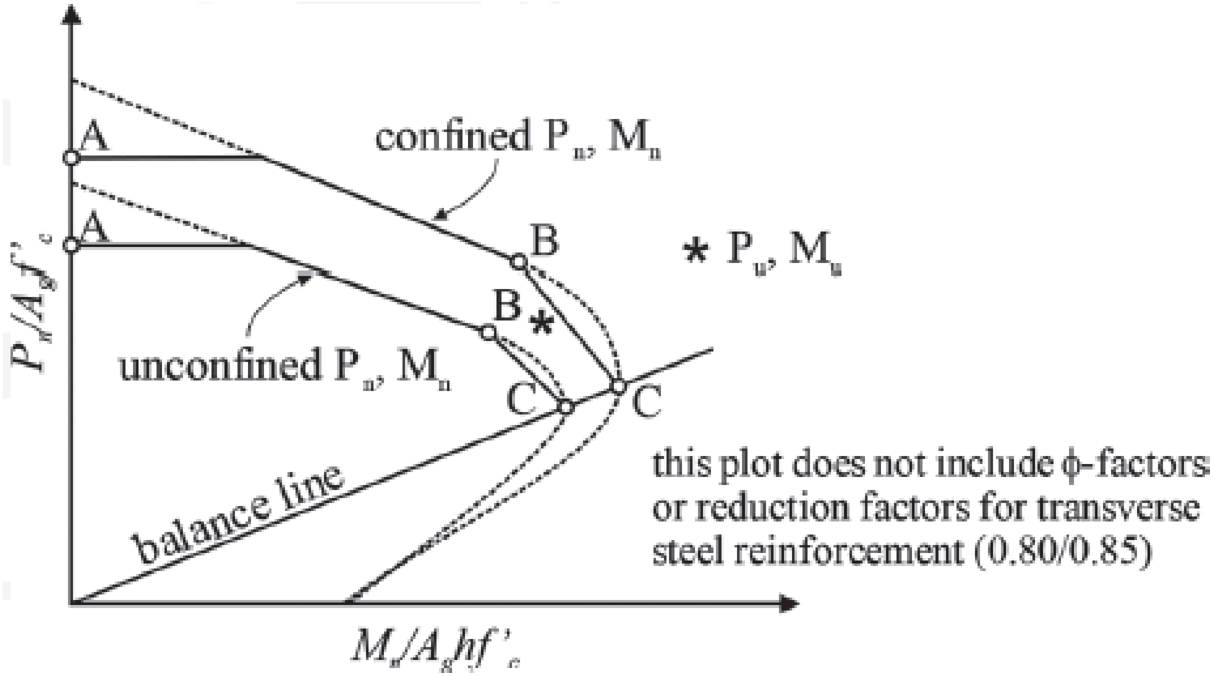


Fig. R9.3.3—Representative P-M *interaction diagram.*

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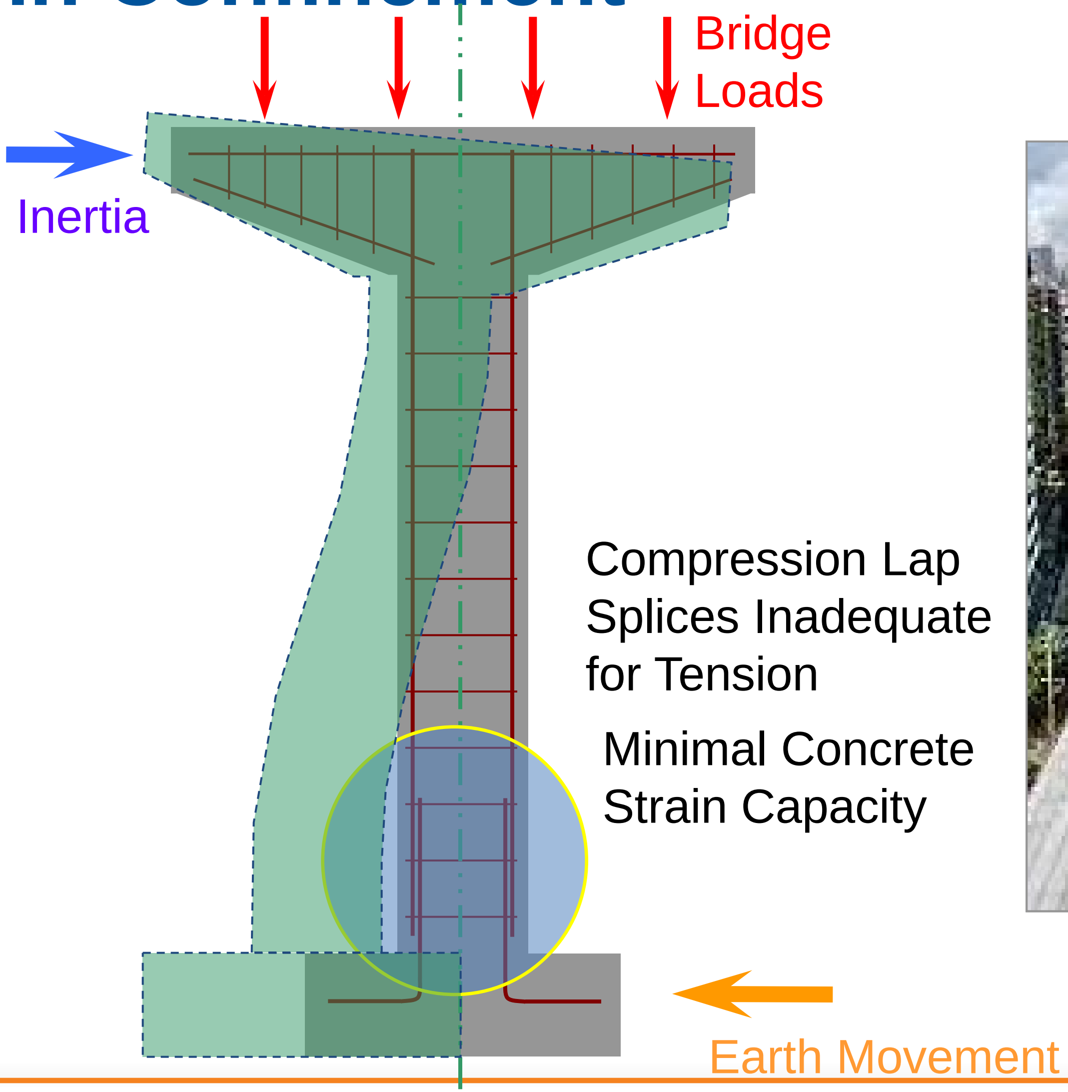
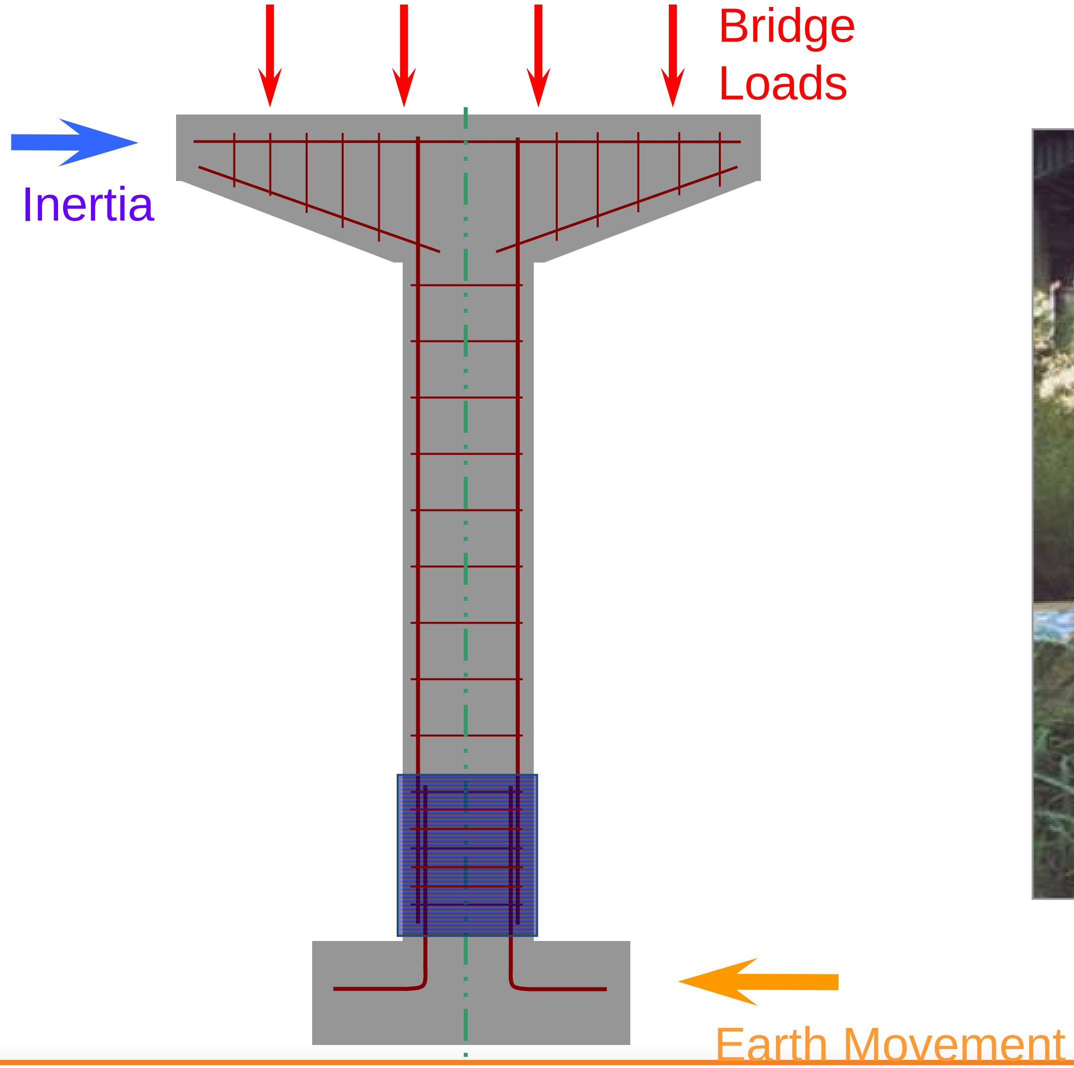
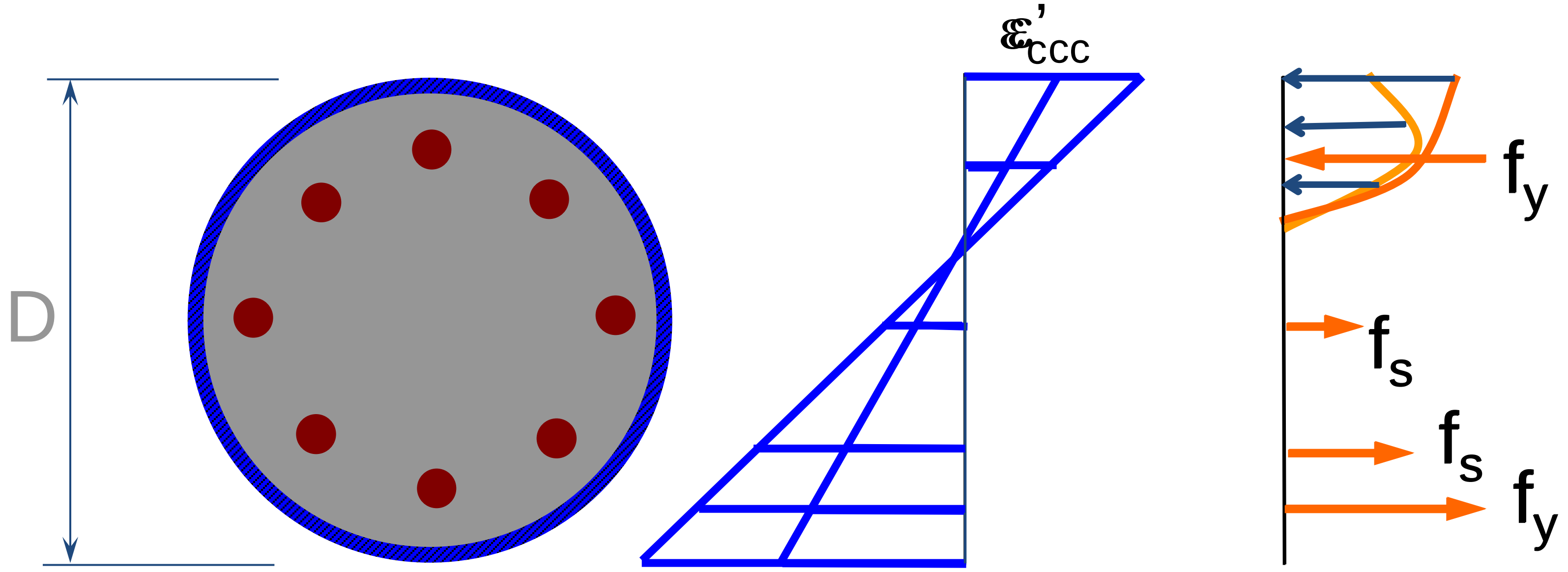
Column Confinement



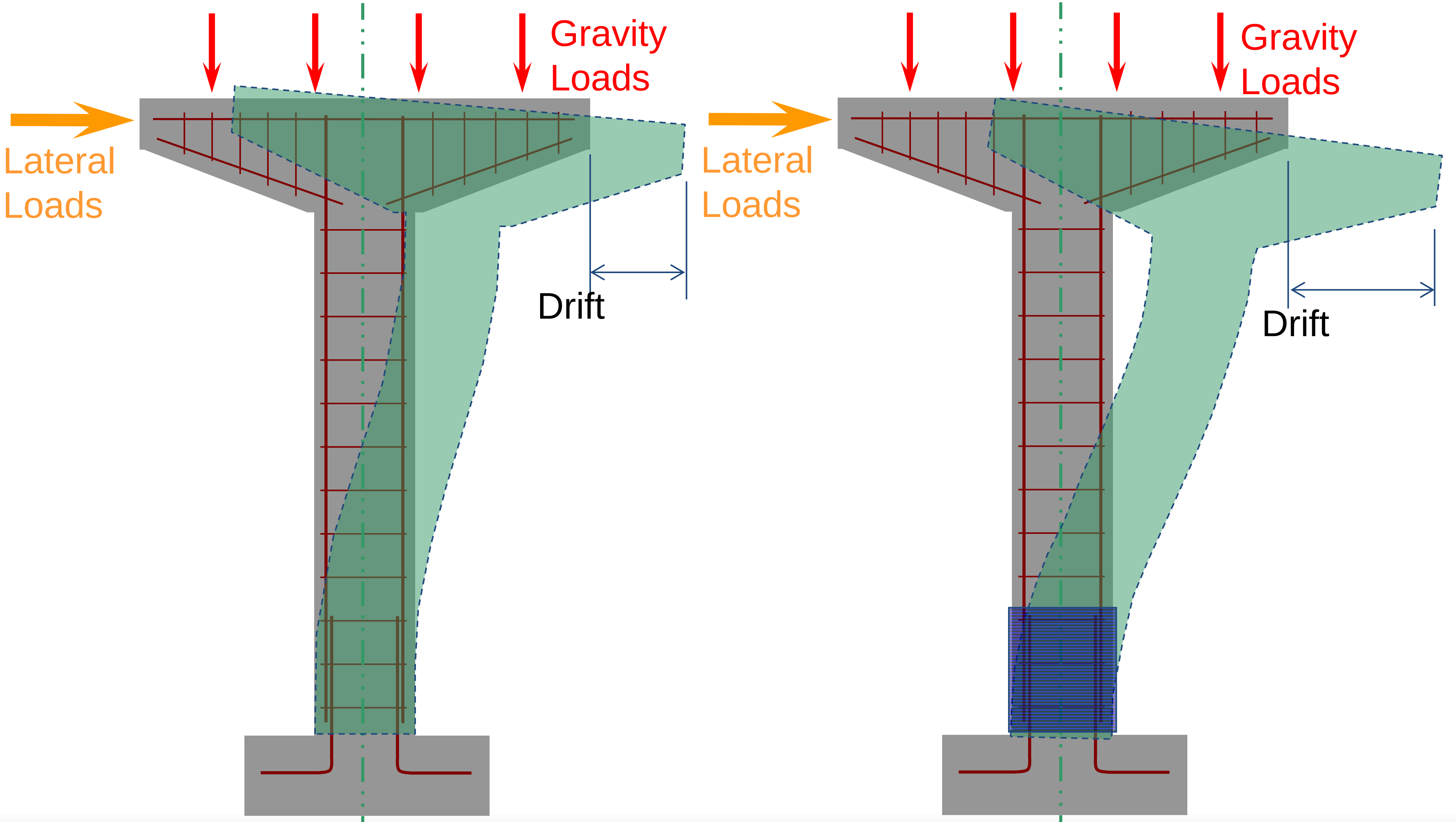
Column Confinement



Moment-Axial Interaction



Seismic Retrofit



FRP Confined Concrete

- Strain Limitation

For pure axial loading:

ACI 440.2R-17
Eq. (12.1i)

$$\varepsilon_{fe} = \kappa_{\varepsilon}\varepsilon_{fu}$$

$$\kappa_{\varepsilon} = 0.55$$

Recommended value *(accounts for variation in FRP strain vs concrete transverse strain)*

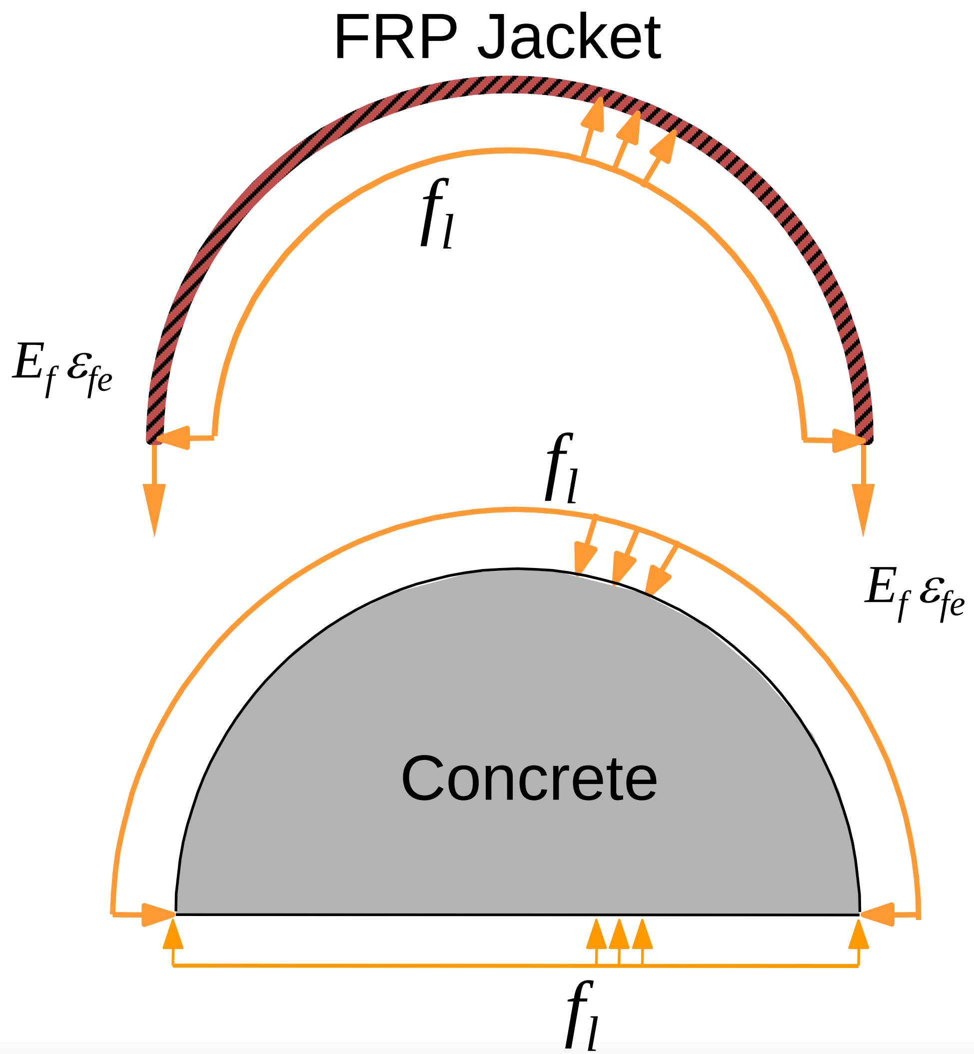
For combined axial + bending:

ACI 440.2R-17
Eq. (12.2)

$$\varepsilon_{fe} = 0.004 \leq \kappa_{\varepsilon}\varepsilon_{fu}$$

Limit to maintain shear integrity of concrete

Circular Sections



Confining pressure:

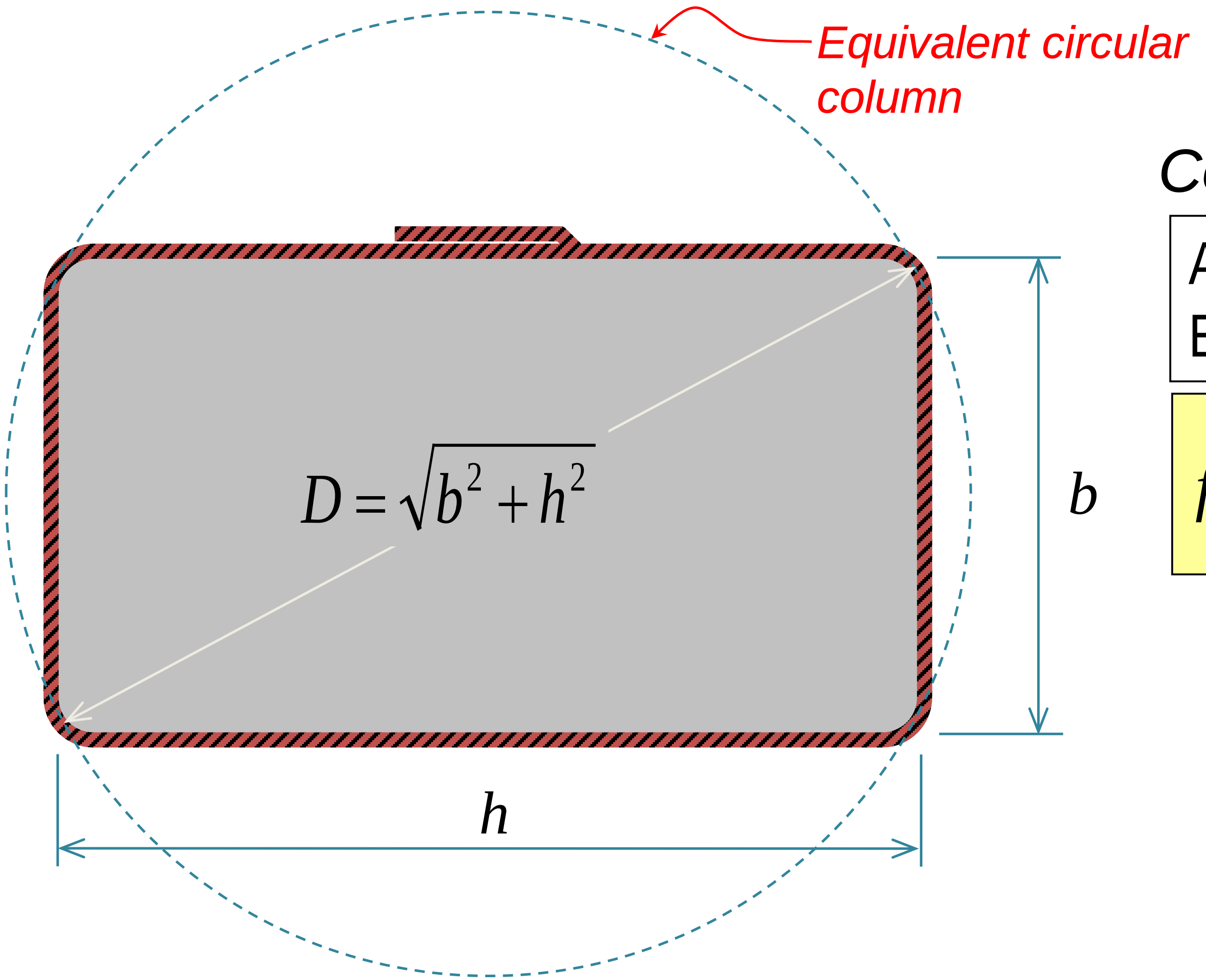
ACI 440.2R-17
Eq. (12.1h)

$$f_l = \frac{2E_f n t_f \varepsilon_{fe}}{D}$$

Shape factors:

$$\kappa_a = \kappa_b = 1.0$$

Rectangular Sections

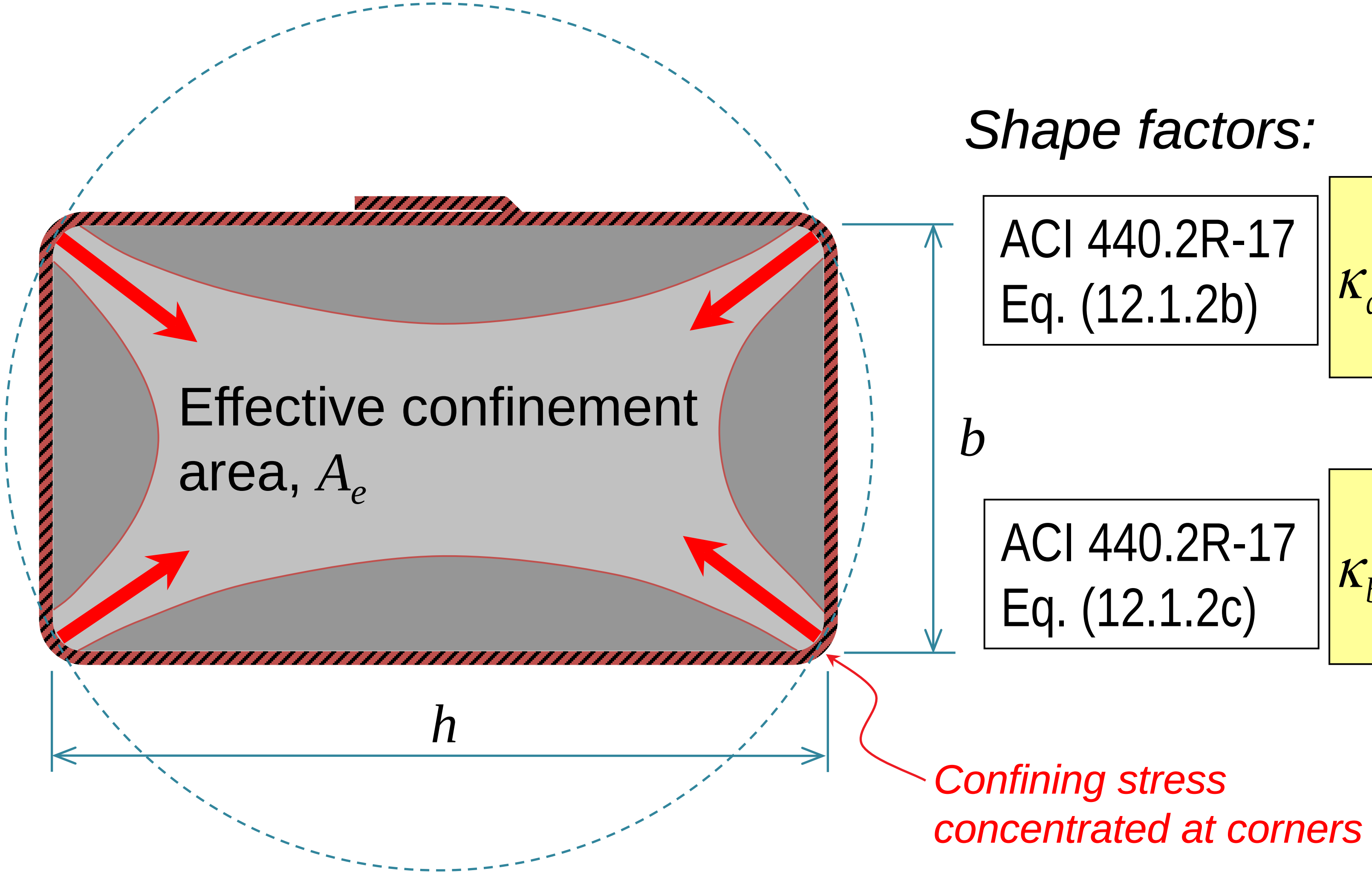


Confining pressure:

ACI 440.2R-17
Eq. (12.1h)

$$f_l = \frac{2E_f n t_f \varepsilon_{fe}}{D}$$

Rectangular Sections



Shape factors:

ACI 440.2R-17 Eq. (12.1.2b)	$\kappa_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2$
ACI 440.2R-17 Eq. (12.1.2c)	$\kappa_b = \frac{A_e}{A_c}\left(\frac{h}{b}\right)^{0.5}$

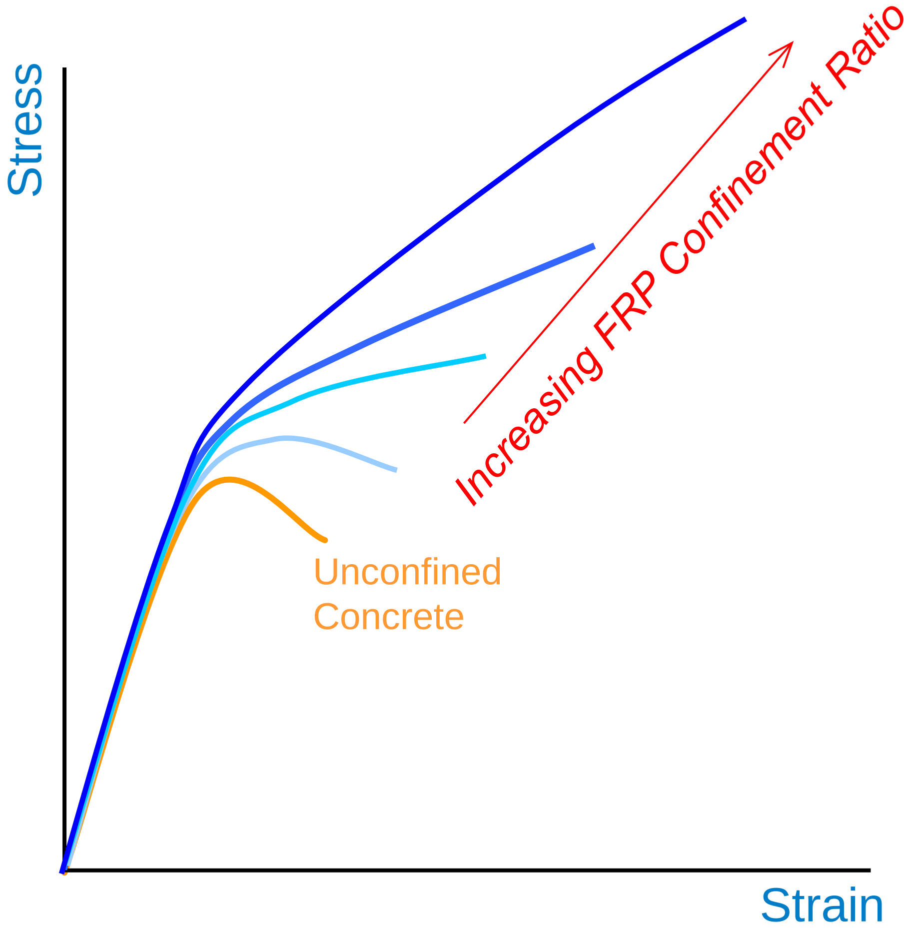
Rectangular Sections

- Effective Confined Area

ACI 440.2R-17
Eq. (12.1.2d)
similar

$$A_e = A_c - \left[\frac{b}{3h}\left(h-2r\right)^2 + \frac{h}{3b}\left(b-2r\right)^2 \right]$$

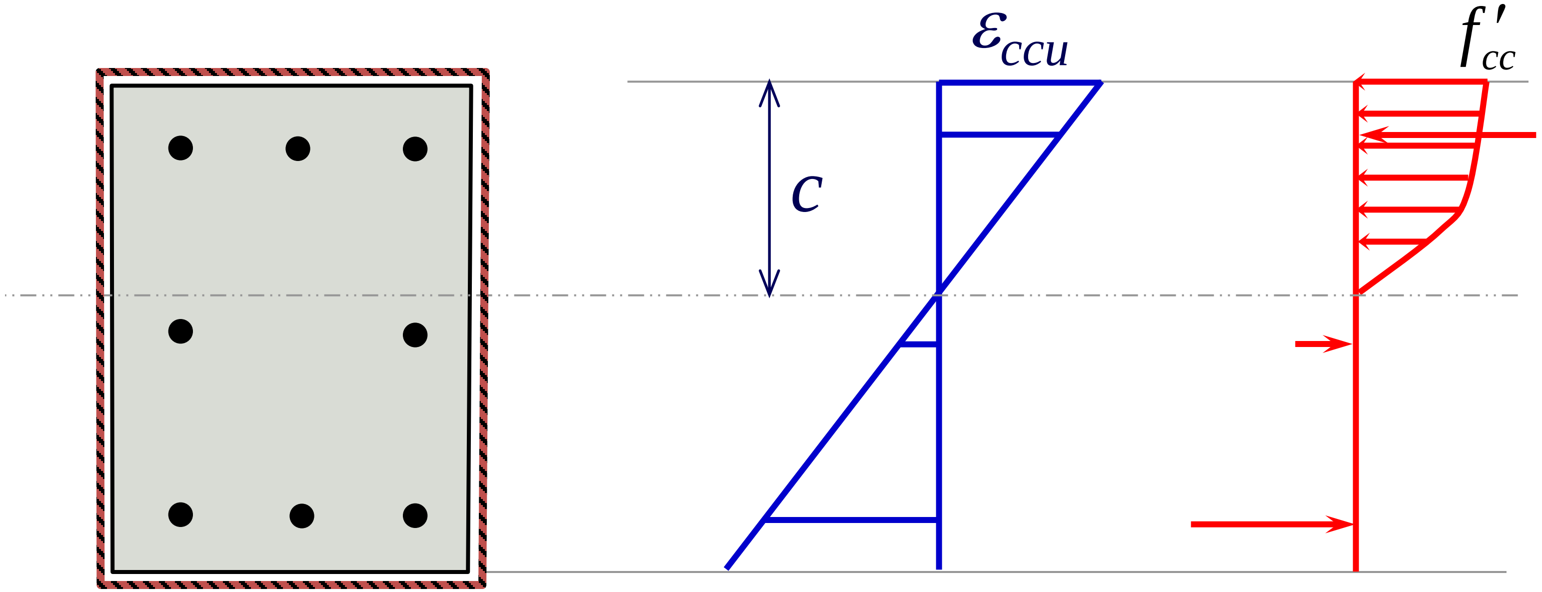
Effect of FRP Confinement Ratio



Light FRP confinement will exhibit “descending branch” and should be avoided.

$$\frac{f_l}{f_c'} > 0.08$$

Using the Confinement Model



Increases Ductility

Increases Strength

Using the Confinement Model

Compressive Strength:

with existing steel spiral reinforcing:

ACI 440.2R-17 Eq. (12.1a)

$$\phi P_n = 0.85\phi\left[0.85 f'_{cc}\left(A_g - A_{st}\right) + f_y A_{st}\right]$$

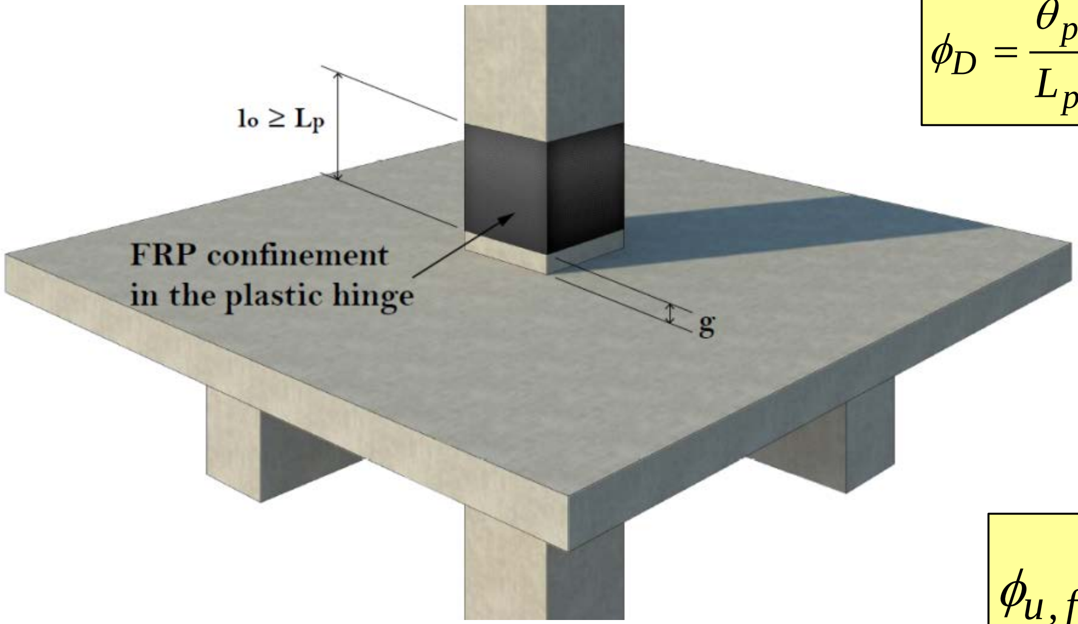
with existing steel-tie reinforcing:

ACI 440.2R-17 Eq. (12.1b)

$$\phi P_n = 0.80\phi\left[0.85 f'_{cc}\left(A_g - A_{st}\right) + f_y A_{st}\right]$$

Use the confined concrete compressive strength in ACI 318 equations

Using the Confinement Model
Seismic Implications



$$\phi_D = \frac{\theta_p}{L_p} + \phi_{y,frp} \le \phi_{u,frp}$$

ACI 440.2R-17
Eq. (13.3.2a)

θ_p is the plastic rotational demand determined from ASCE/SEI 41

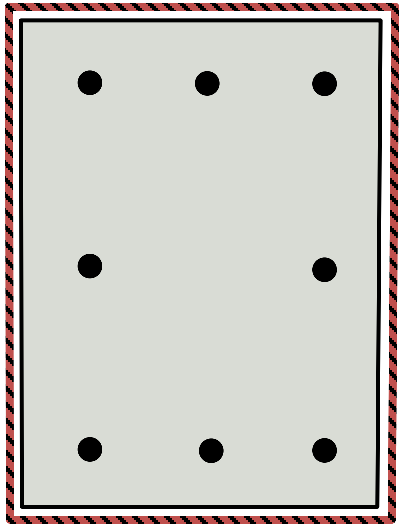
$$\phi_{u,frp} = \frac{\varepsilon_{ccu}}{c_{u,frp}}$$

ACI 440.2R-17
Eq. (13.3.2c)

$$L_p = g + 0.0003 f_y d_{bl}$$

ACI 440.2R-17
Eq. (13.3.2d)

Clamping Lap Splices



Circular Sections:

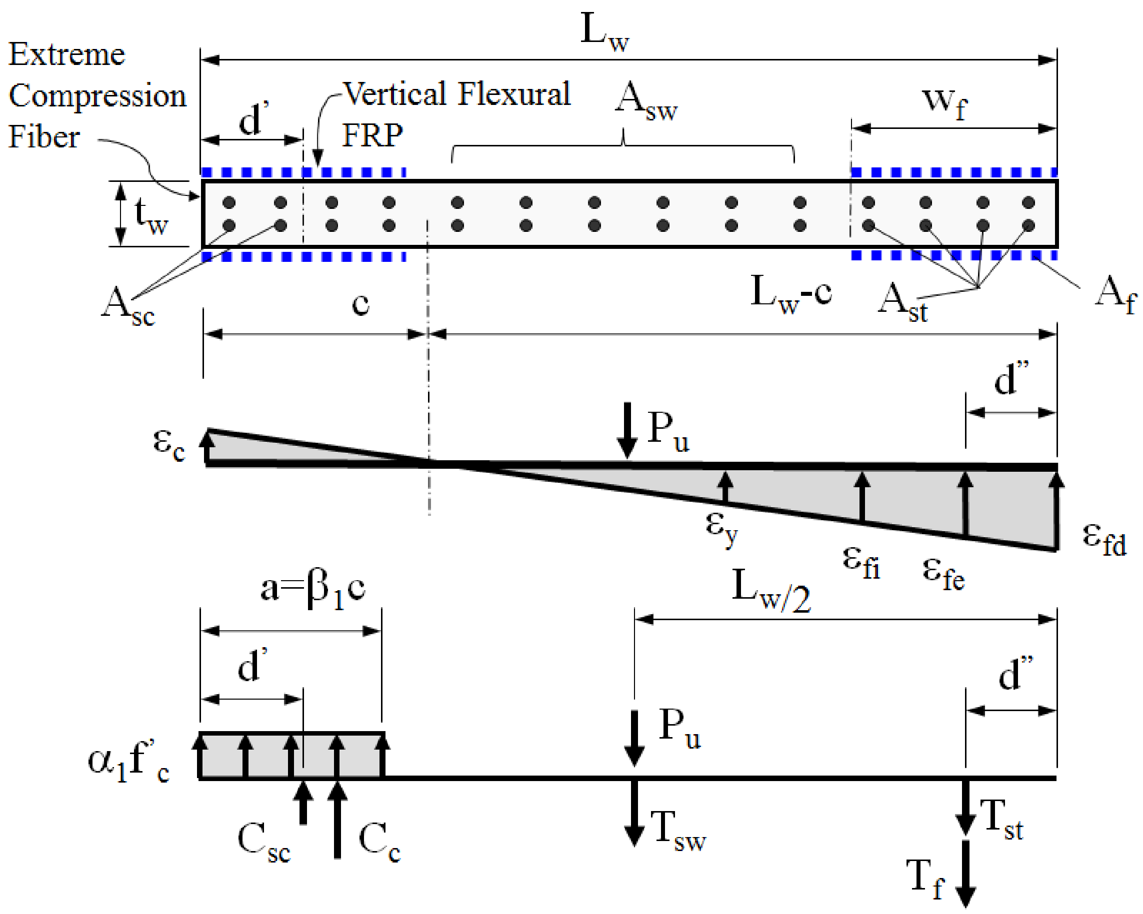
$$nt_f = 145\left(\frac{D}{E_f}\right)$$

Rectangular Sections:

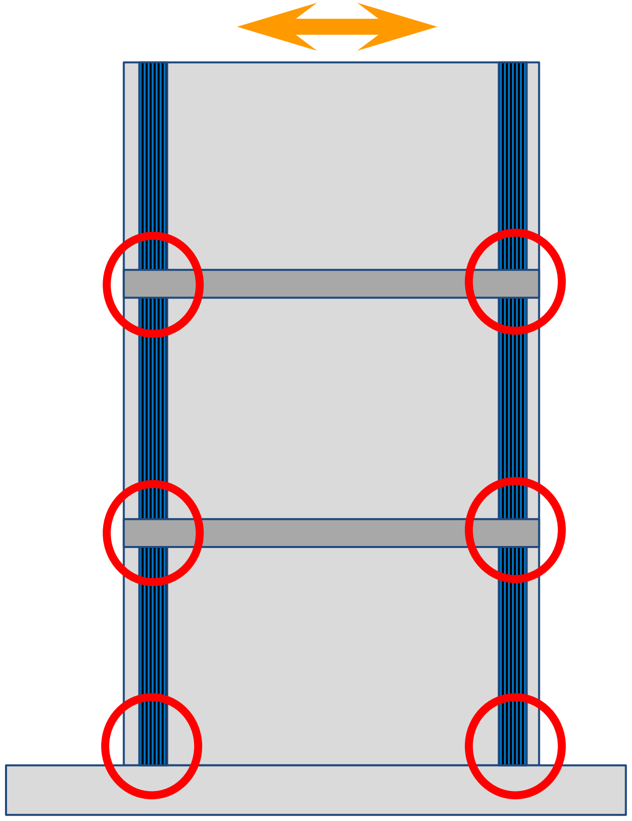
$$nt_f = 218\left(\frac{D}{E_f}\right)$$

ACI 440.2R-17
Eq. (13.3.3a)

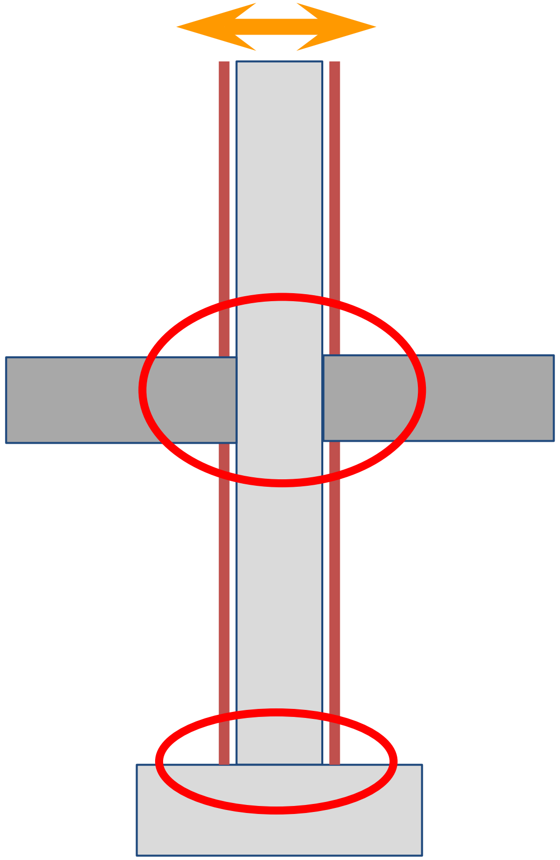
Flexural Strengthening: Shear Walls and Columns



Flexural Strengthening: Shear Walls and Columns

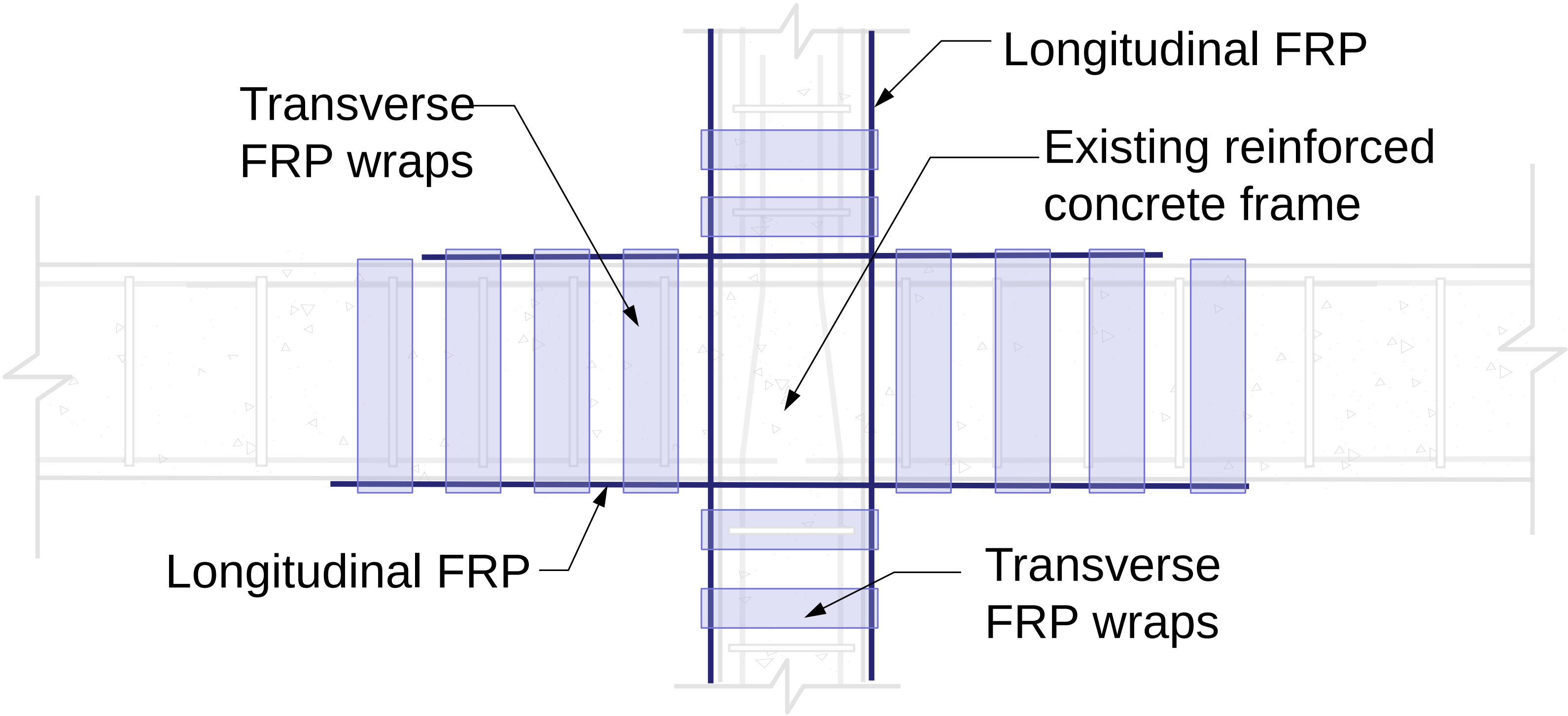


Shear Wall

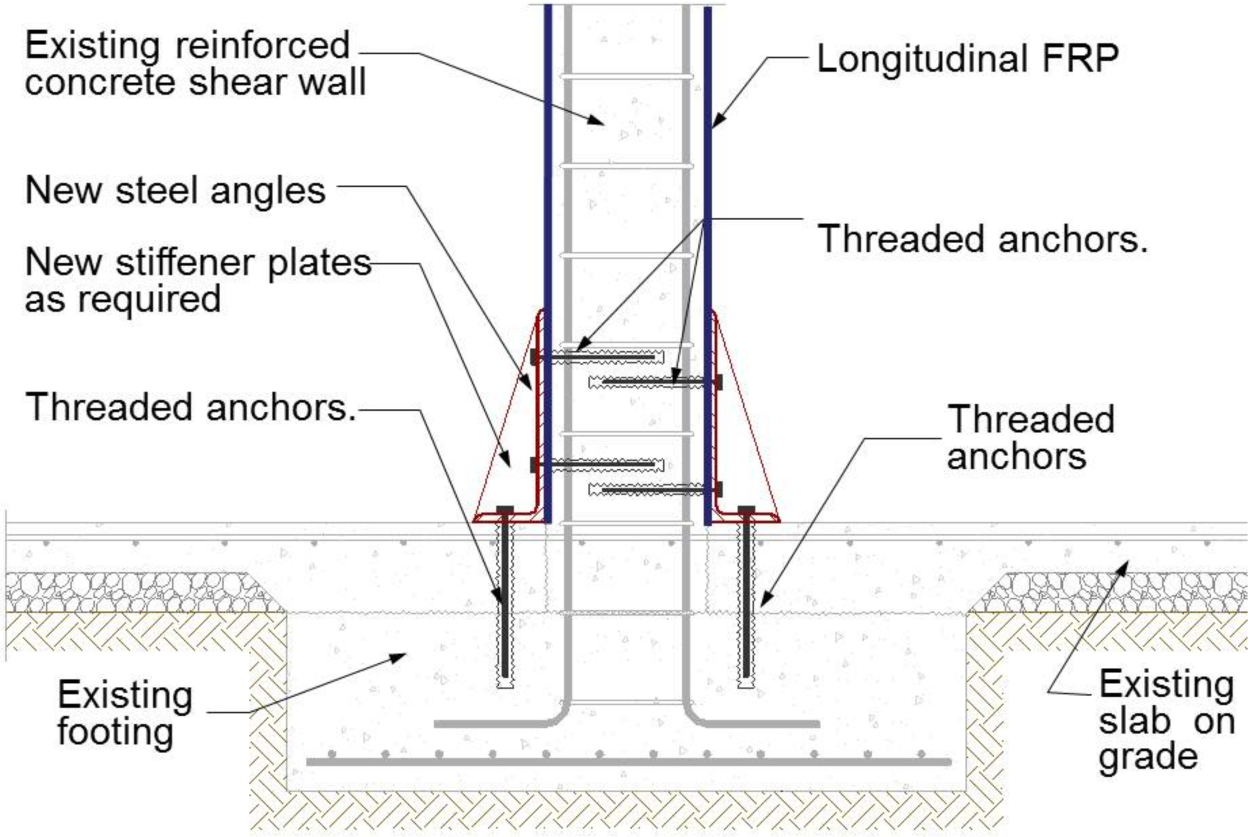


Column

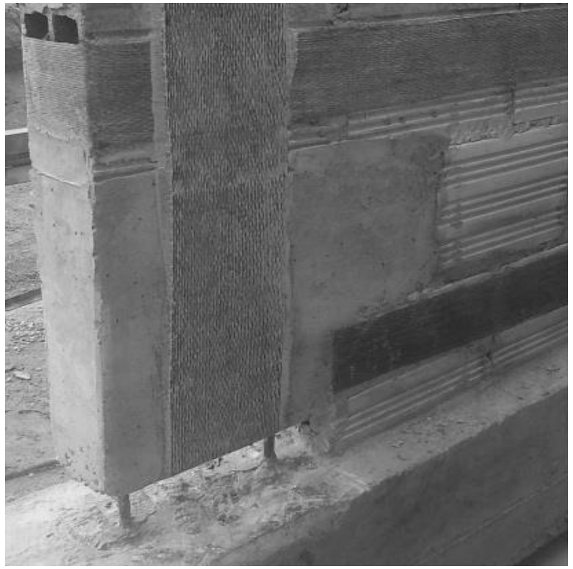
Anchorage: Shear Walls and Columns

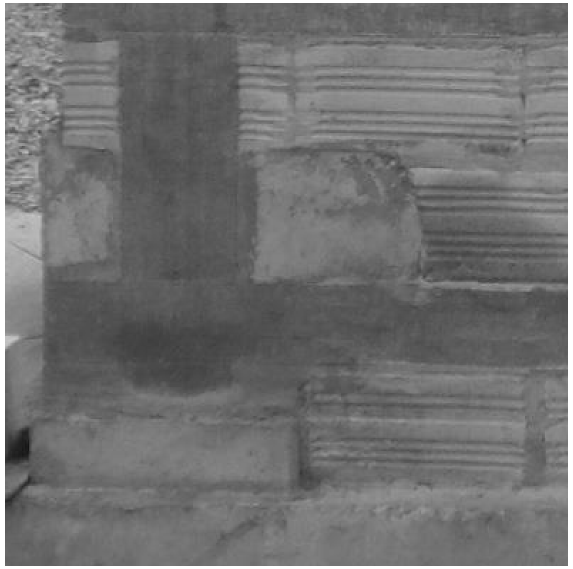


Anchorage: Shear Walls and Columns

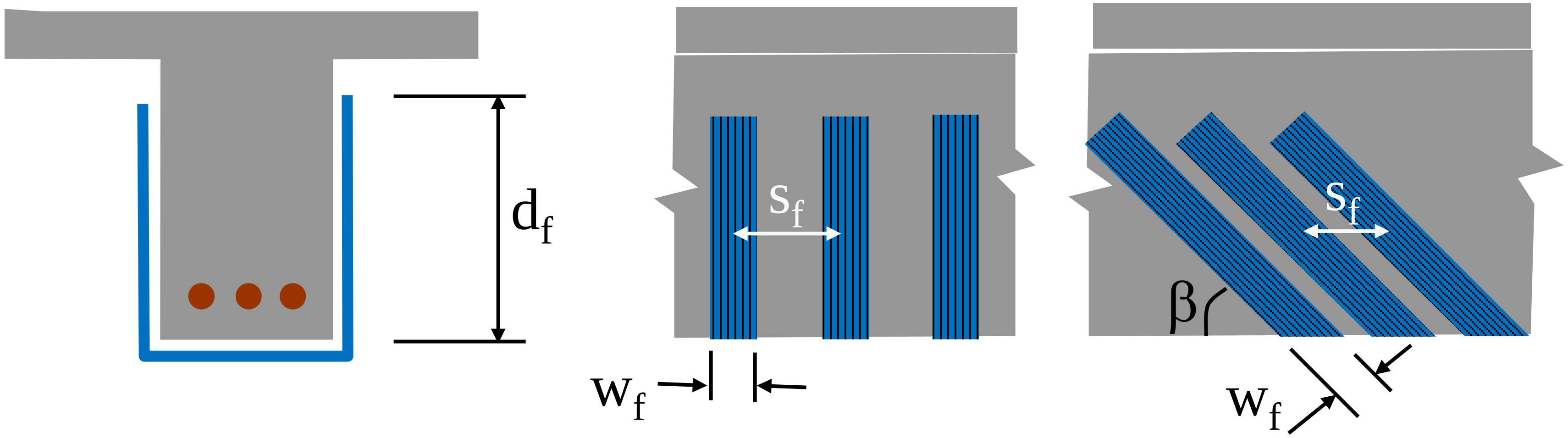


Anchorage: Shear Walls and Columns



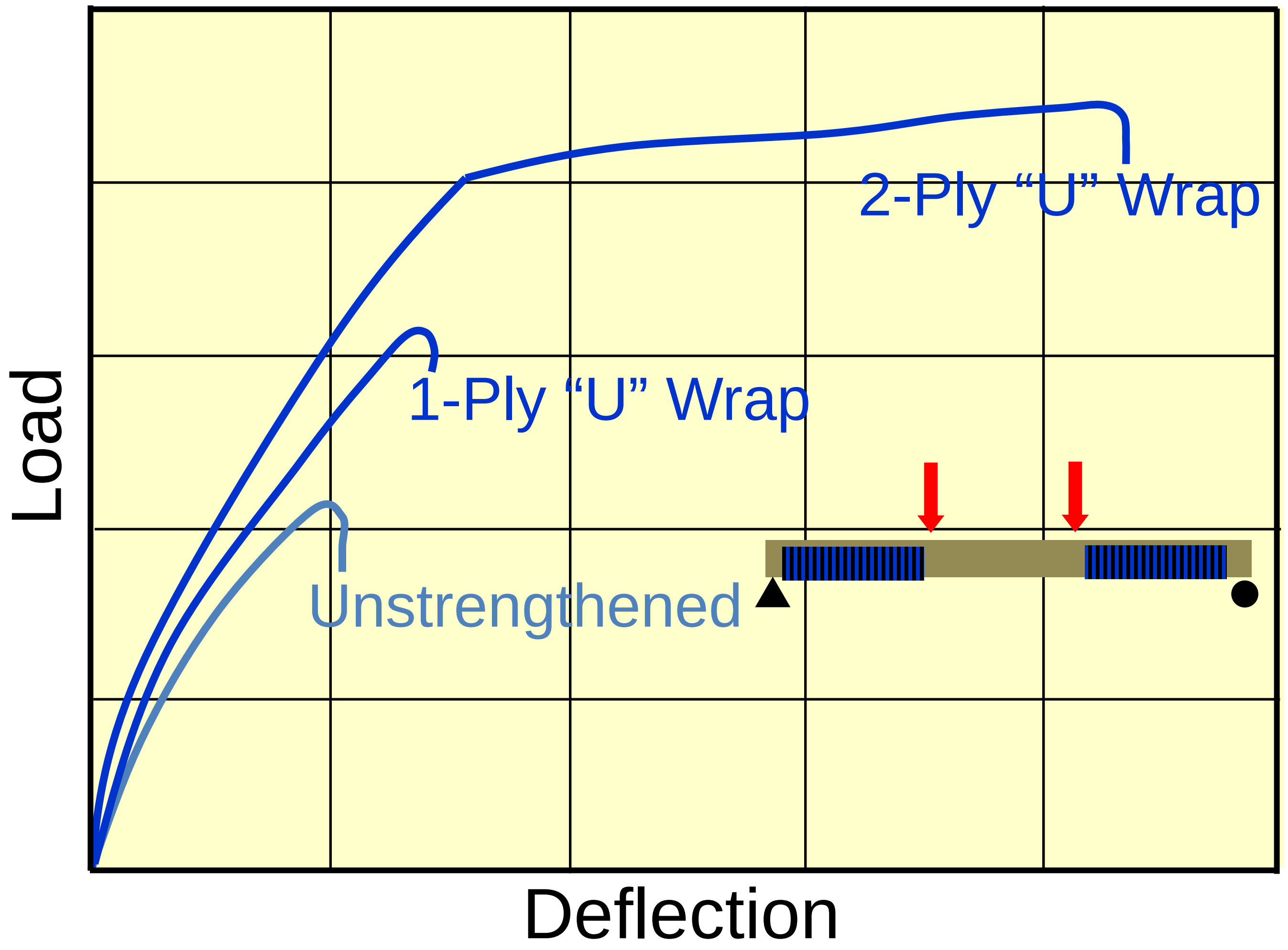


Shear Strengthening

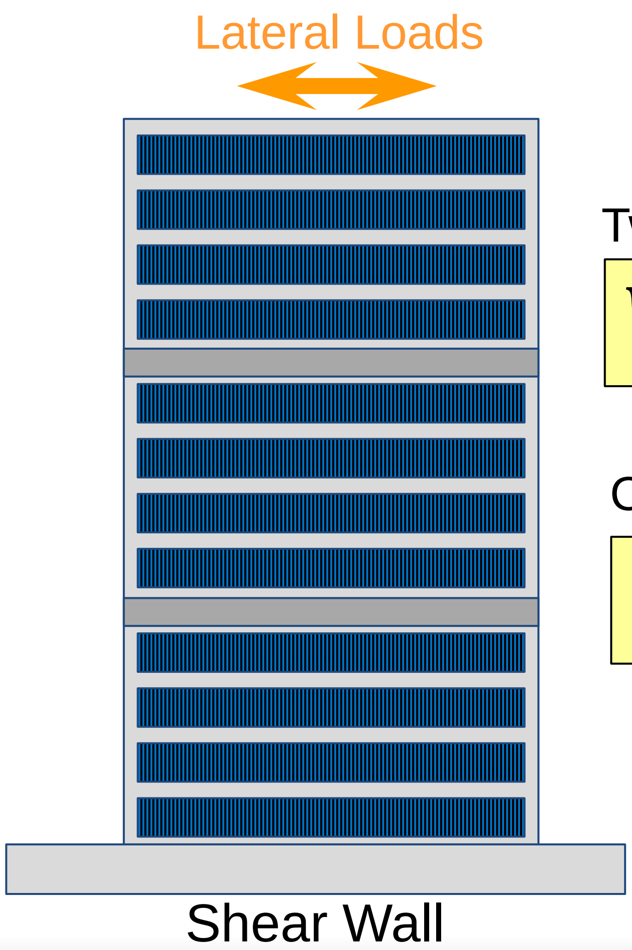


$$V_f = \frac{A_{fv} f_{fe} (\sin\alpha + \cos\alpha) d_f}{s_f}$$

Shear Strengthening



Shear Strengthening: Walls and Diaphragms



Two sides of wall reinforced:

$$V_f = 2 t_f \varepsilon_{fe} E_f d_{f_v}$$

One side of wall reinforced:

$$V_f = 0.75 t_f \varepsilon_{fe} E_f d_{f_v}$$

ACI 440.2R-17
Eq. (13.7.2.2c)

Shear Strengthening: Columns

Circular Sections:

$$A_{f_v} = \left(\frac{\pi}{2}\right) n t_f w_f$$

ACI 440.2R-17
Eq. (11.4c)

Rectangular Sections:

$$A_{fv} = 2 n t_f w_f$$

ACI 440.2R-17
Eq. (11.4b)

Shear Strengthening: Short Columns

Circular Sections:

$$A_{f_v} = \left(\frac{\pi}{2}\right) n t_f w_f$$

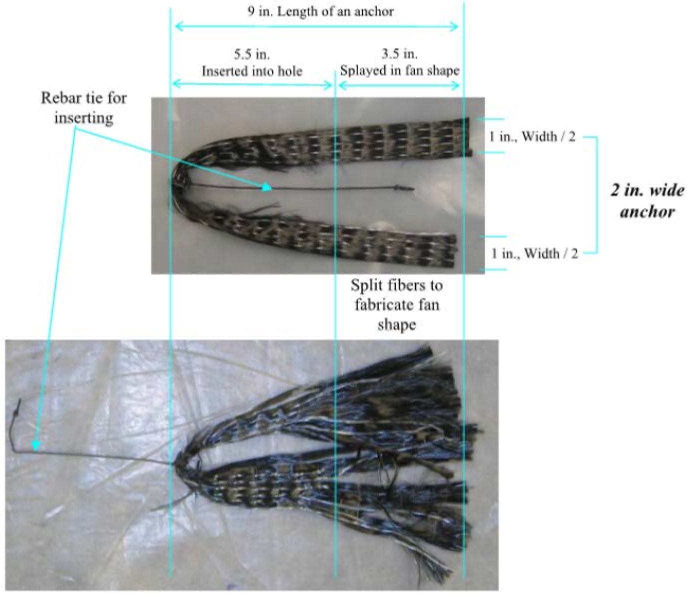
ACI 440.2R-17
Eq. (11.4c)

Rectangular Sections:

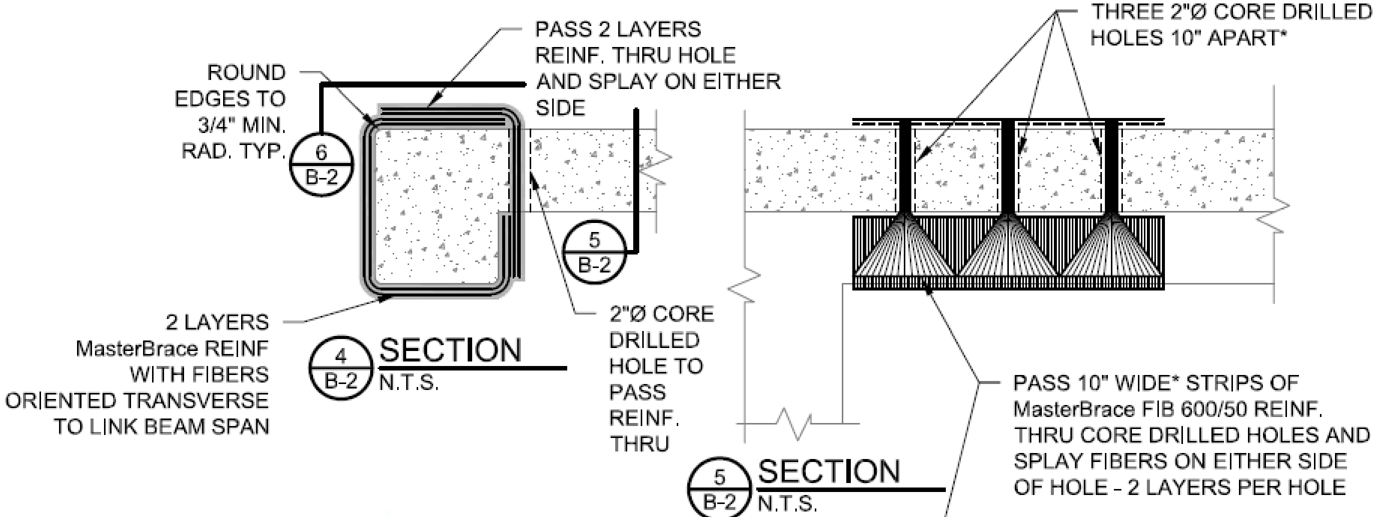
$$A_{fv} = 2 n t_f w_f$$

ACI 440.2R-17
Eq. (11.4b)

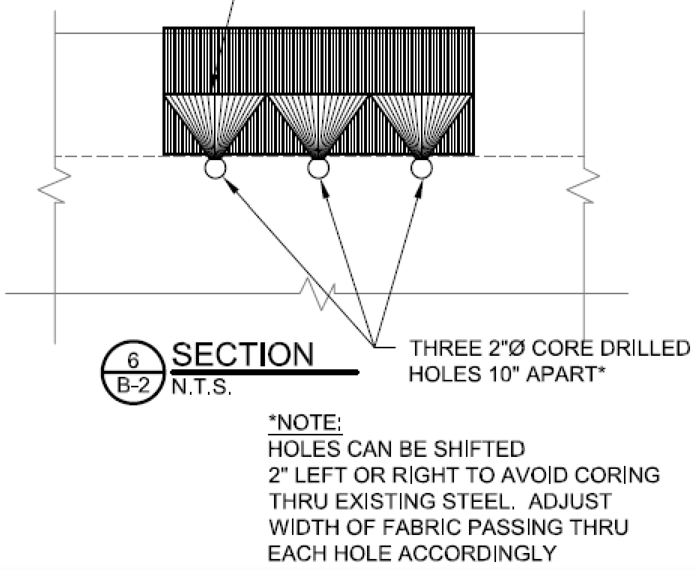
Anchorage



9 in. Length of an anchor
5.5 in.
Inserted into hole
3.5 in.
Splayed in fan shape
Rebar tie for inserting
1 in., Width / 2
2 in. wide anchor
1 in., Width / 2
Split fibers to fabricate fan shape

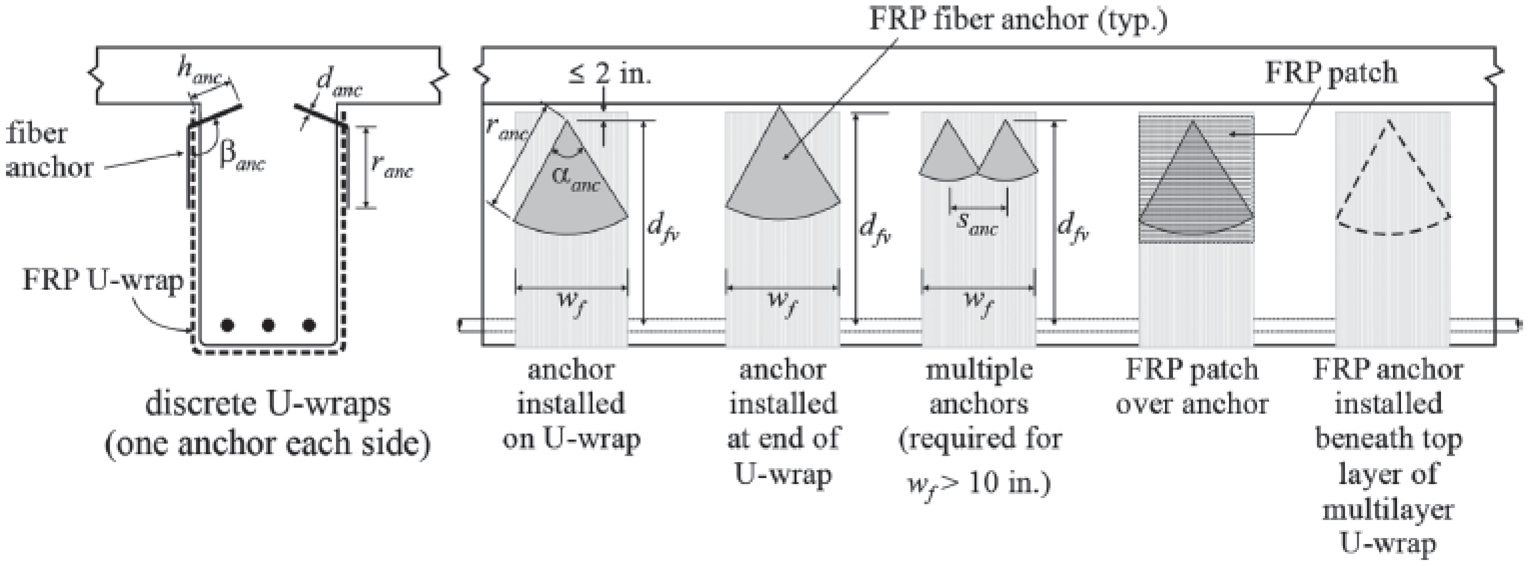


ROUND EDGES TO 3/4" MIN. RAD. TYP.
PASS 2 LAYERS REINF. THRU HOLE AND SPLAY ON EITHER SIDE
6 B-2
5 B-2
2 LAYERS MasterBrace REINF WITH FIBERS ORIENTED TRANSVERSE TO LINK BEAM SPAN
4 B-2 SECTION N.T.S.
2"Ø CORE DRILLED HOLE TO PASS REINF. THRU
THREE 2"Ø CORE DRILLED HOLES 10" APART*
PASS 10" WIDE* STRIPS OF MasterBrace FIB 600/50 REINF. THRU CORE DRILLED HOLES AND SPLAY FIBERS ON EITHER SIDE OF HOLE - 2 LAYERS PER HOLE
5 B-2 SECTION N.T.S.



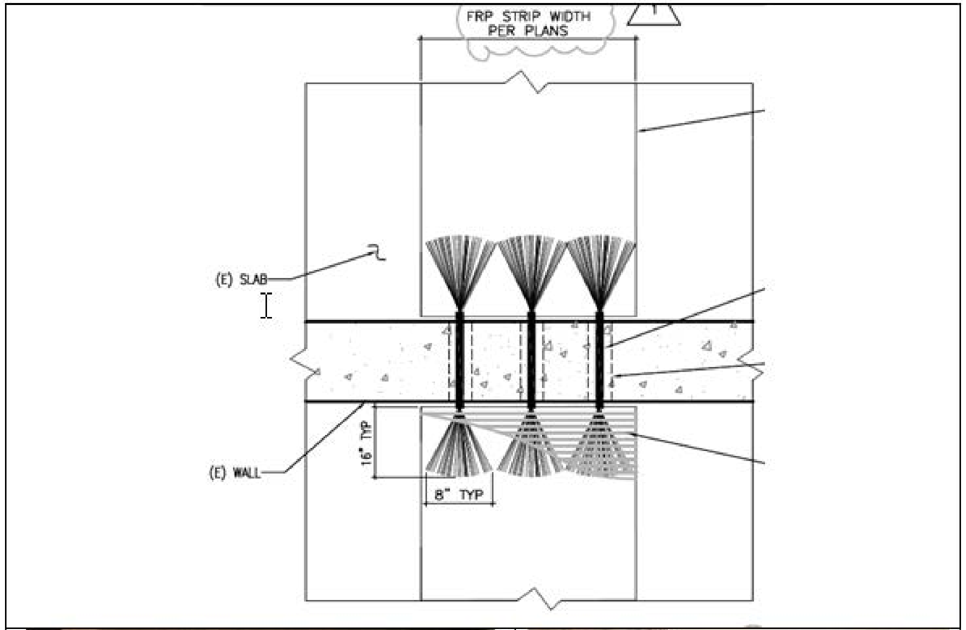
6 B-2 SECTION N.T.S.
THREE 2"Ø CORE DRILLED HOLES 10" APART*
*NOTE:
HOLES CAN BE SHIFTED 2" LEFT OR RIGHT TO AVOID CORING THRU EXISTING STEEL. ADJUST WIDTH OF FABRIC PASSING THRU EACH HOLE ACCORDINGLY

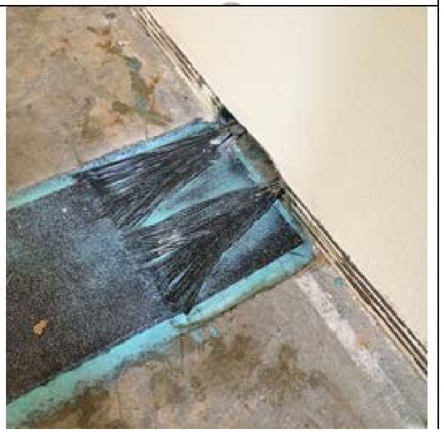
Anchorage


FRP fiber anchor (typ.)
FRP patch
≤ 2 in.
fiber anchor
FRP U-wrap
discrete U-wraps (one anchor each side)
anchor installed on U-wrap
anchor installed at end of U-wrap
multiple anchors (required for w_f > 10 in.)
FRP patch over anchor
FRP anchor installed beneath top layer of multilayer U-wrap

Anchorage

Anchorage





Workshop on Composites in Construction

Session 2: Strengthening of Structural Concrete FRP Systems

- General Introduction to ACI CODE 440.13 & ACI PRC 440.2
- FRP Material Specifications per ACI SPEC 440.8
- Concrete Substrate Requirements
- Fire Resistance of FRP Strengthened Members
- Field Inspection, Testing, and Evaluation

Refreshment Break

- General Design Requirements
- FRP System Requirements
- Design for Flexural and Shear Strengthening and Confinement
- Guide for Seismic Strengthening with FRP

Workshop on Composites in Construction

	Welcome and Introductions	9:00 to 9:30
Session 1:	Structural Concrete Reinforced with Glass Fiber Reinforced Polymer (GFRP) Bars	9:30 to 12:00
	Lunch	12:00 to 1:00
Session 2:	Strengthening of Structural Concrete with Fiber Reinforced Polymer (FRP) Systems	1:00 to 15:30
	Concluding Remarks and Adjournment	15:30 to 16:00