KOMPOZİT SANAYİCİLERİ DERNEĞİ
TURKISH COMPOSITES MANUFACTURERS ASSOCIATION

American Concrete Institute

An ACI Center of Excellence for Nonmetallic Building Materials

Workshop on Composites in Construction

Istanbul, Türkiye

18 November 2025

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

Designing Concrete Structures Reinforced with GFRP Bars Using the New ACI CODE 440.11-22

Learning Objectives:

- Understand GFRP reinforcing bar material properties, production and proper material selection.
- Gain insights into construction principles for reinforced concrete construction using GFRP reinforcement.
- Learn about basic design provisions for reinforced concrete construction using GFRP reinforcement.

Workshop on Composites in Construction

Session 1: Structural Concrete Reinforced with GFRP Bars

- General Introduction to ACI CODE 440.11
- GFRP reinforcement and introduction to ASTM D7957
- General Introduction to ACI SPEC 440.5
- Fire Resistance of GFRP Reinforced Concrete

Refreshment Break

- General Design Provisions for Flexure, Shear, and Axial Strength
- Seismic Limitations
- Structural System Requirements
- Slabs-on-Ground

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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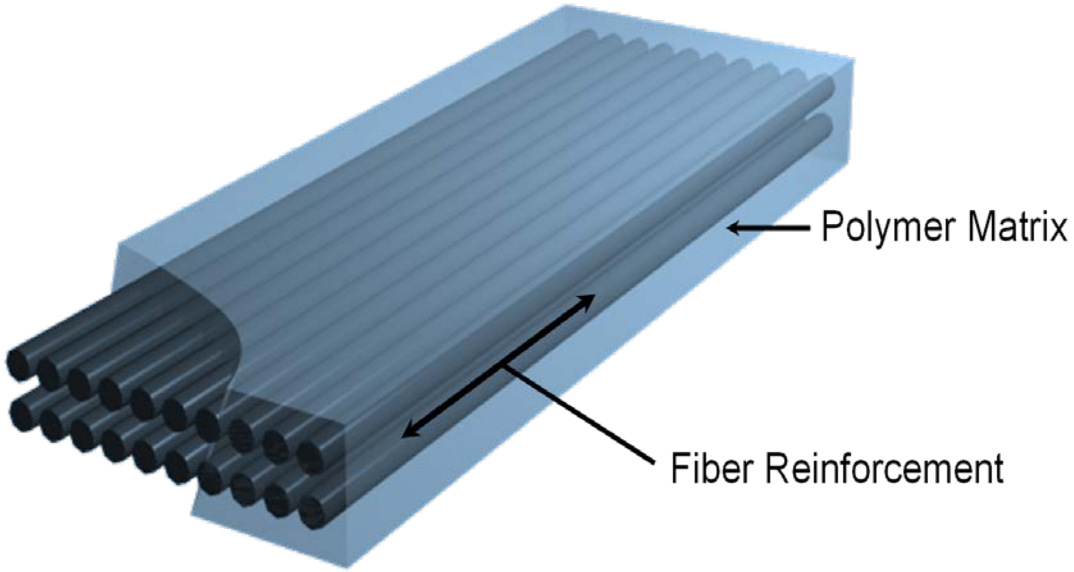
FRP Materials
Fiber Reinforced Polymers

- High strength continuous fibers
- Encapsulated in a polymer matrix
- Commonly used in aircraft, ships, and sporting goods



FRP Materials
Why Use FRP to Reinforce Concrete?

FRP Rebars

FRP Materials
GFRP Rebar

- Glass Fiber Reinforced Polymer (GFRP) bars as alternative reinforcement for concrete





Photos courtesy of MST Rebar, Inc.

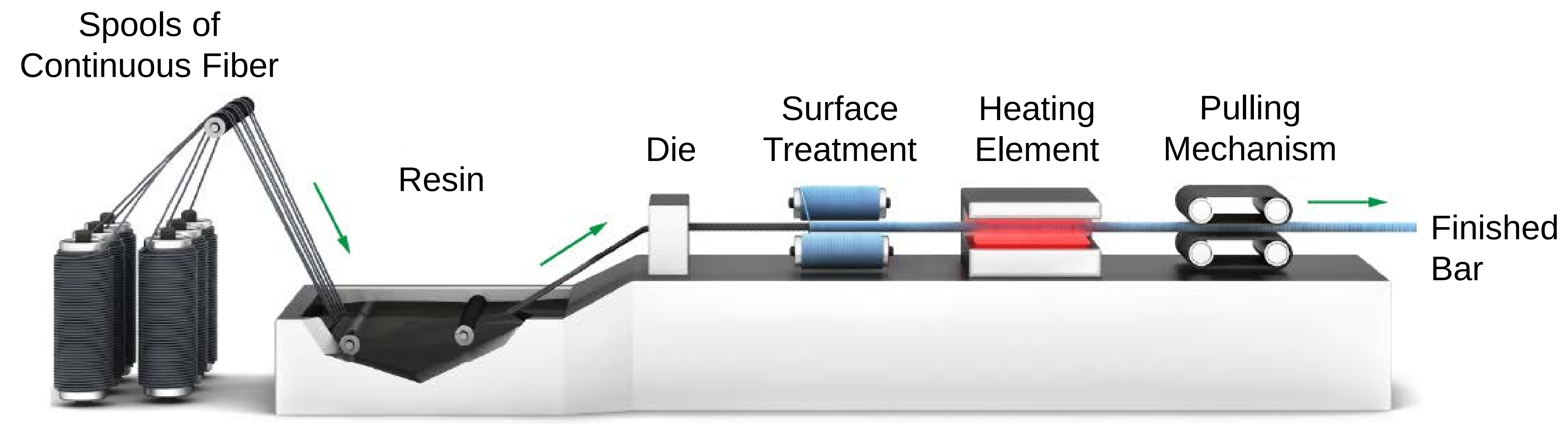
FRP Materials
Steel-free Concrete Structures

- Harker Island Bridge, Outer Banks, NC

Photos courtesy of Owens Corning Infrastructure Solutions

FRP Materials
GFRP Bar Manufacturing

- Typically produced by the pultrusion process



FRP Materials
GFRP Bar Shapes

Straight bars

Bent bars

Spirals

Applications
Concrete Exposed to Marine Chlorides

Photo courtesy of Owens Corning

- Balconies in Coastal Locations
- Seawalls
- Piers, Wharfs, Docks
- Bridges over Coastal Locations
- Seawater Spillways

Applications
Concrete Exposed to Deicing Chemicals

- Bridge decks
- Approach slabs
- Barrier walls
- Salt storage facilities
- Parking Garages
- Walkways

Photo courtesy of Owens Corning

Applications
Sustainability

- Longer Service Life
- Utilization of Natural Resources
  - Seawater concrete
  - Substandard aggregates (Beach sand)

Photo courtesy of the University of Miami

Applications
Electromagnetic Transparency

- MRI rooms in hospitals
- Airport radio & compass calibration pads
- Electrical high voltage transformer vaults
- Concrete near high voltage cables and substations

Applications
Low Thermal Conductivity

Photo courtesy of Owens Corning

- Thermal Breaks in Insulated Panels
- Reinforcement for ICF Walls

Applications
Consumable Reinforcement

- Soft-eyes (tunneling)
- Slab penetrations
- Temporary structures

Photo courtesy of Owens Corning

Applications
Ease of Handling

Photo courtesy of IKK Mateenbar.

- GFRP bars are less than 1/3 the weight of steel bars
  - A 30-ft long, #5 GFRP bar weighs 9-lbs. A 30-ft long, #5 steel bar weighs 30-lbs.

Applications
Ease of Handling

- Bars are easy to transport
- Areas with difficult access
- Reduced transportation costs

Photo courtesy of MST Rebar, Inc.

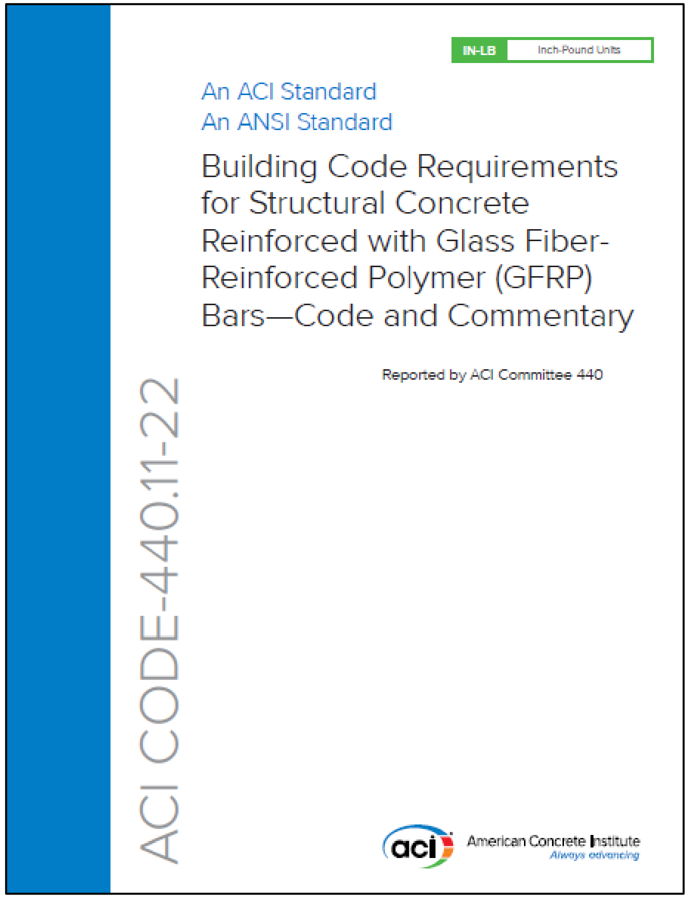
Applications
Ease of Handling

- GFRP bars can be easily cut individually or in bundles
- GFRP bars do not become excessively hot or cold

Photo courtesy of MST Rebar, Inc.

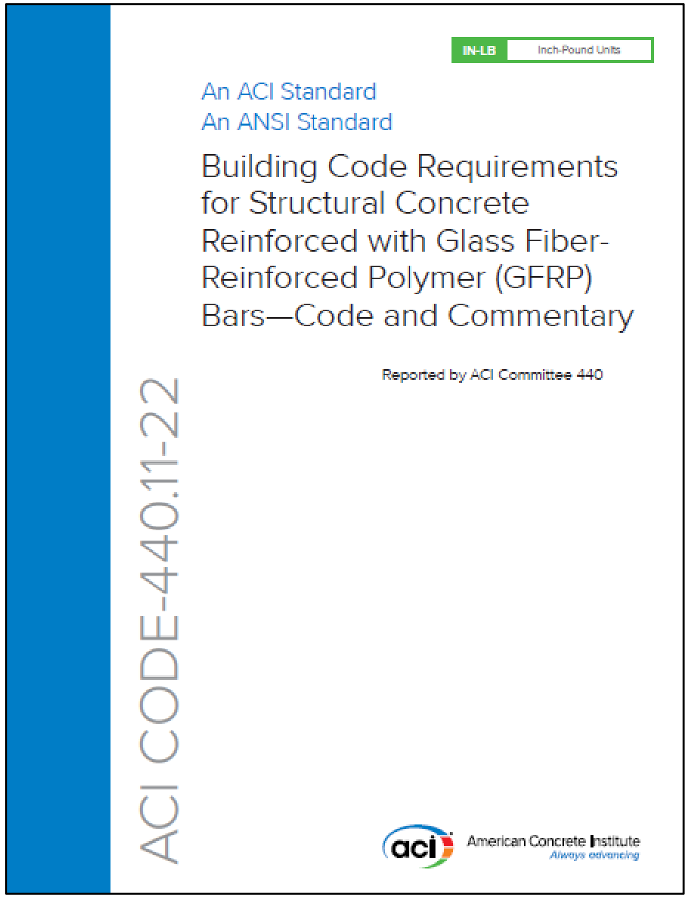
Standards and Guides
Code Requirements

- The new **ACI CODE 440.11-22** Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars
- Dependent on ACI 318-19
  - Same layout and chapters as 318-19
  - Consistent numbering with 318-19 where possible



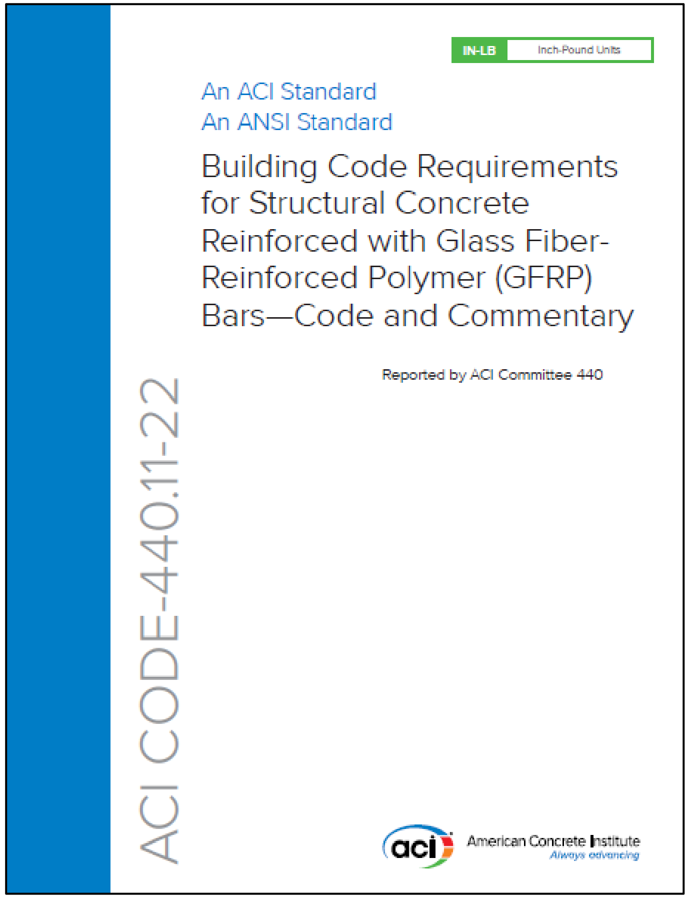
Standards and Guides
The New ACI CODE 440.11-22

- Excluded Chapters either marked
  - “NOT ADDRESSED”
    - Not included in this version, but expected to be included in future versions
    - Chapter 12 – Diaphragms (likely next edition)
    - Chapter 17 – Anchoring to Concrete
    - Chapter 18 – Earthquake-Resistant Structures
    - Chapter 23 – Strut-and-Tie Models
  - Or “NOT APPLICABLE”
    - Chapter 14 – Plain Concrete



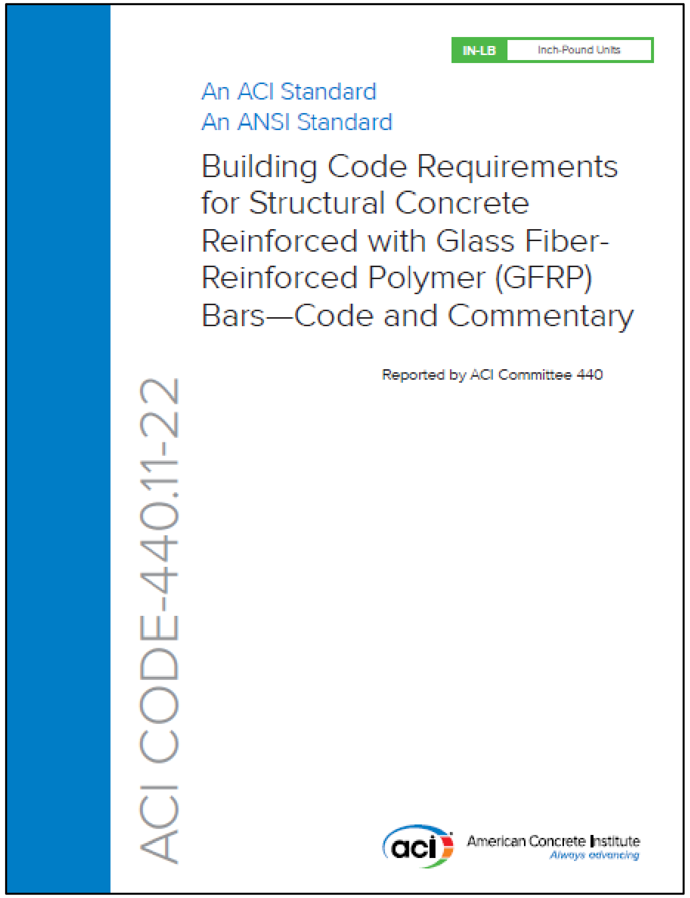
Standards and Guides
The New ACI CODE 440.11-22

- Code also does not currently cover
  - Lightweight concrete
  - Prestressed concrete
  - Deep beams
  - Shotcrete



Standards and Guides
The New ACI CODE 440.11-22

- Code DOES cover
  - Beams
  - One-way and two-way slabs
  - Columns
  - Walls
  - Foundations
  - Joints/Connections between members
  - Strength evaluation of existing structures



Standards and Guides
The New ACI CODE 440.11-22

- Clauses that are identical to ACI 318-19 are marked with a “=” before the start of the clause

=**9.2.1.1** Design properties for concrete shall be selected to be in accordance with Chapter 19.

Standards and Guides
The New ACI CODE 440.11-22

- Some chapters and sections marked “Not Applicable”
  - Not included and not deemed applicable to GFRP reinforced concrete

CHAPTER 14—PLAIN CONCRETE—NOT APPLICABLE

Covered by 318

20.5.2 *Nonprestressed coated reinforcement*—Not applicable

Standards and Guides
The New ACI CODE 440.11-22

– Some numbered sections marked “out of scope”
  - Not included in this version, but likely to be added in the future

> **7.7.4** *Flexural reinforcement in prestressed slabs*—Out of scope

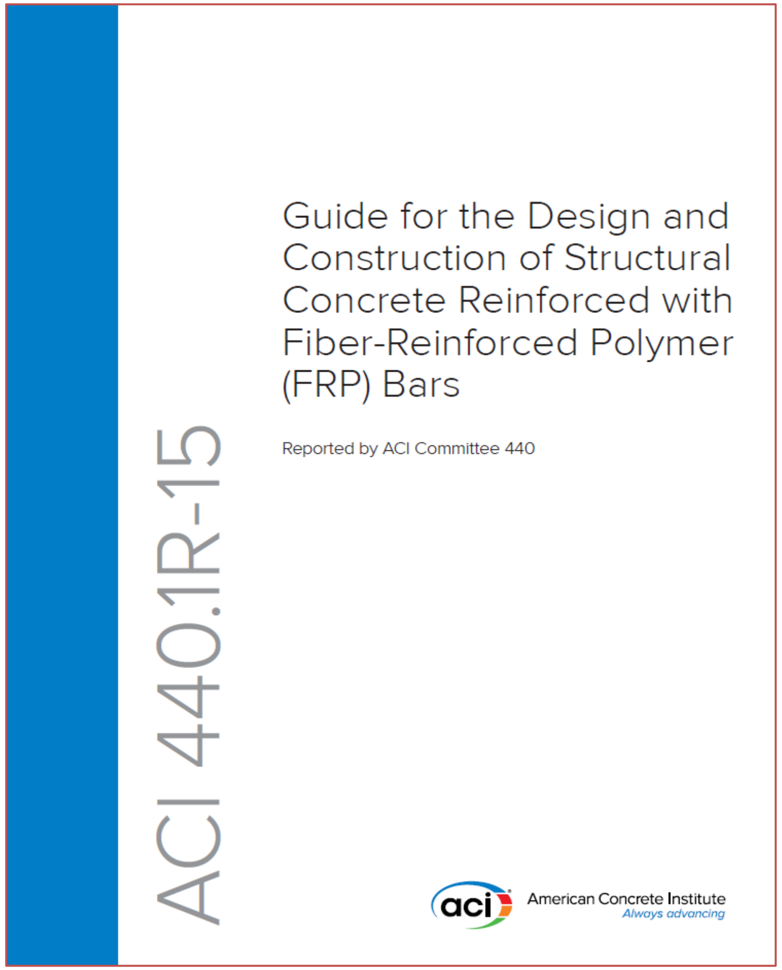
– Some numbered sections marked “intentionally left blank”
  - Numbered section left as a placeholder to keep numbering consistent with 318-19

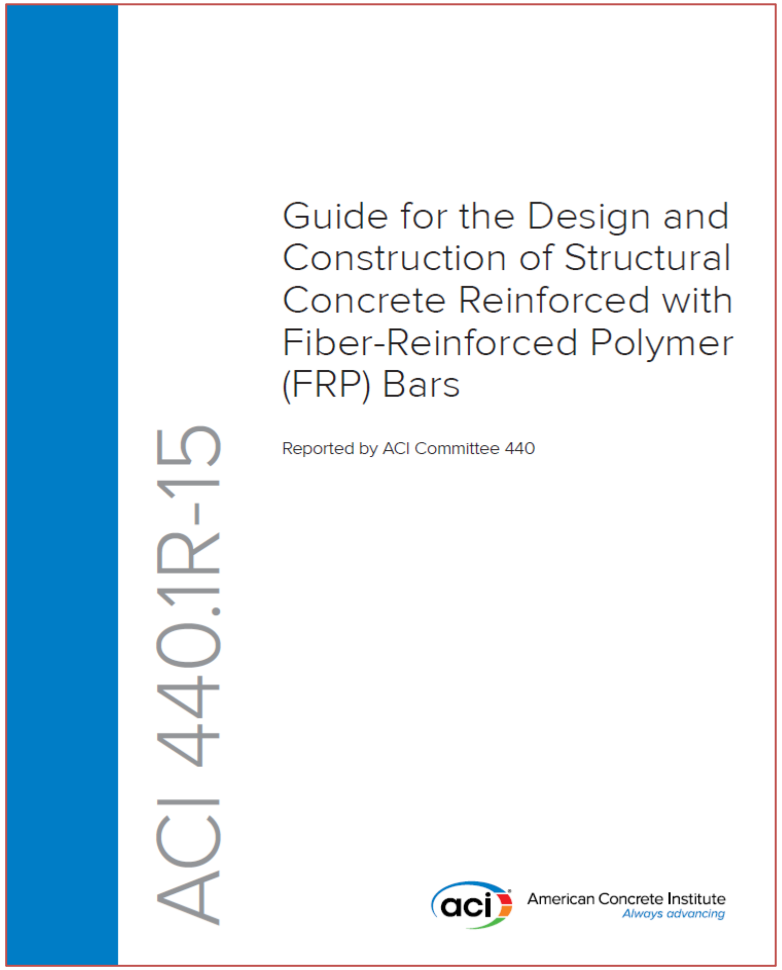
> **1.4.4** Intentionally left blank.

Standards and Guides
Design Guidelines

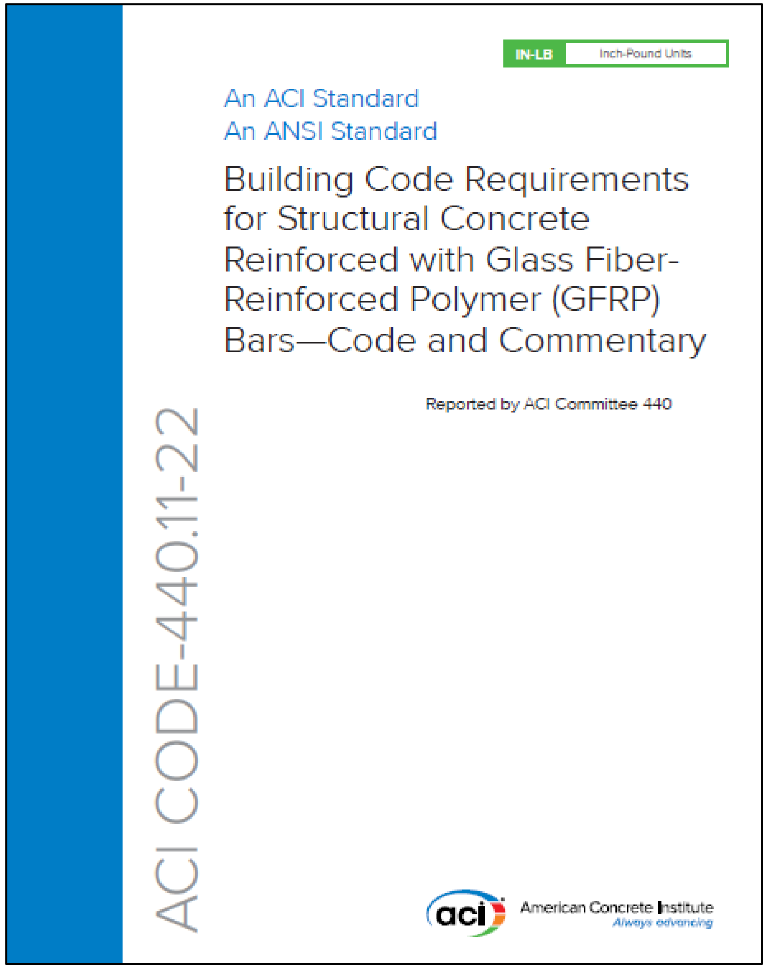
ACI PRC 440.1R-15 Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars

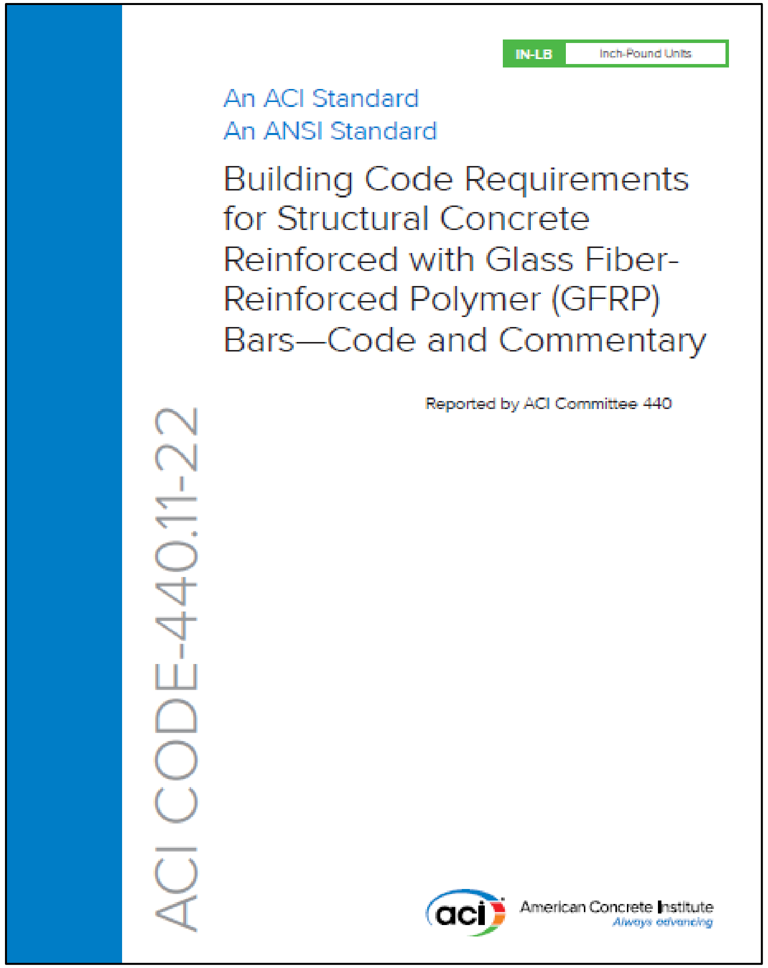
- Additional background on design
- Examples similar to PCA Notes on 318
- Slab-on-grade Recommendations
- Needs to be updated to be consistent with 440.11



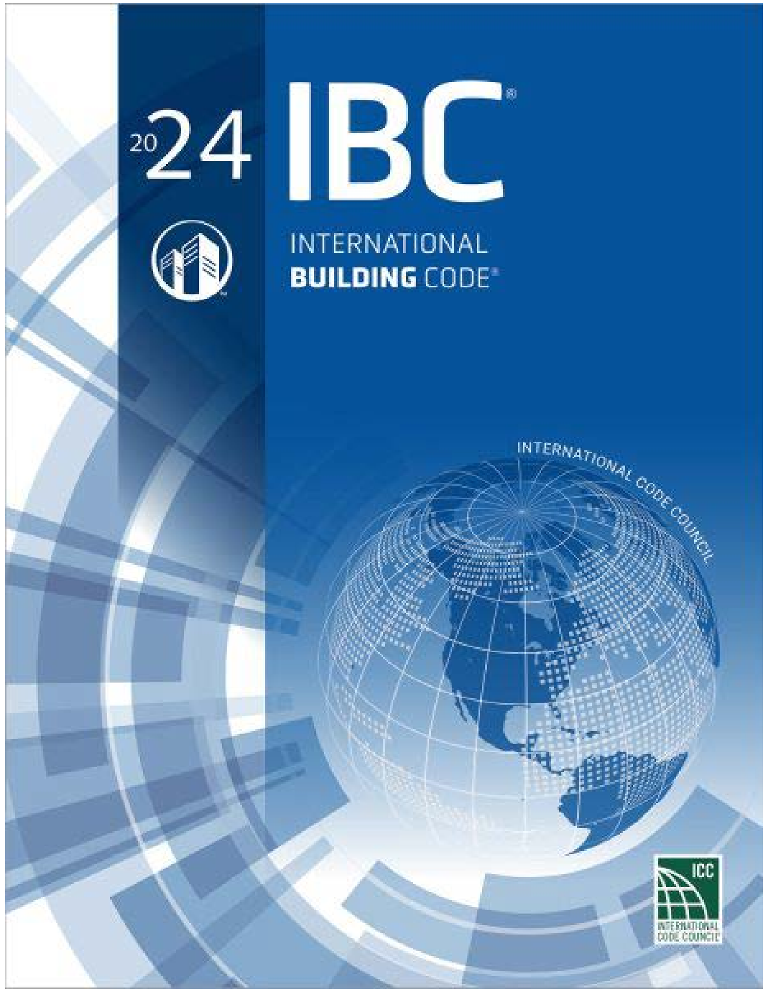


From guide to code





From model code to national code



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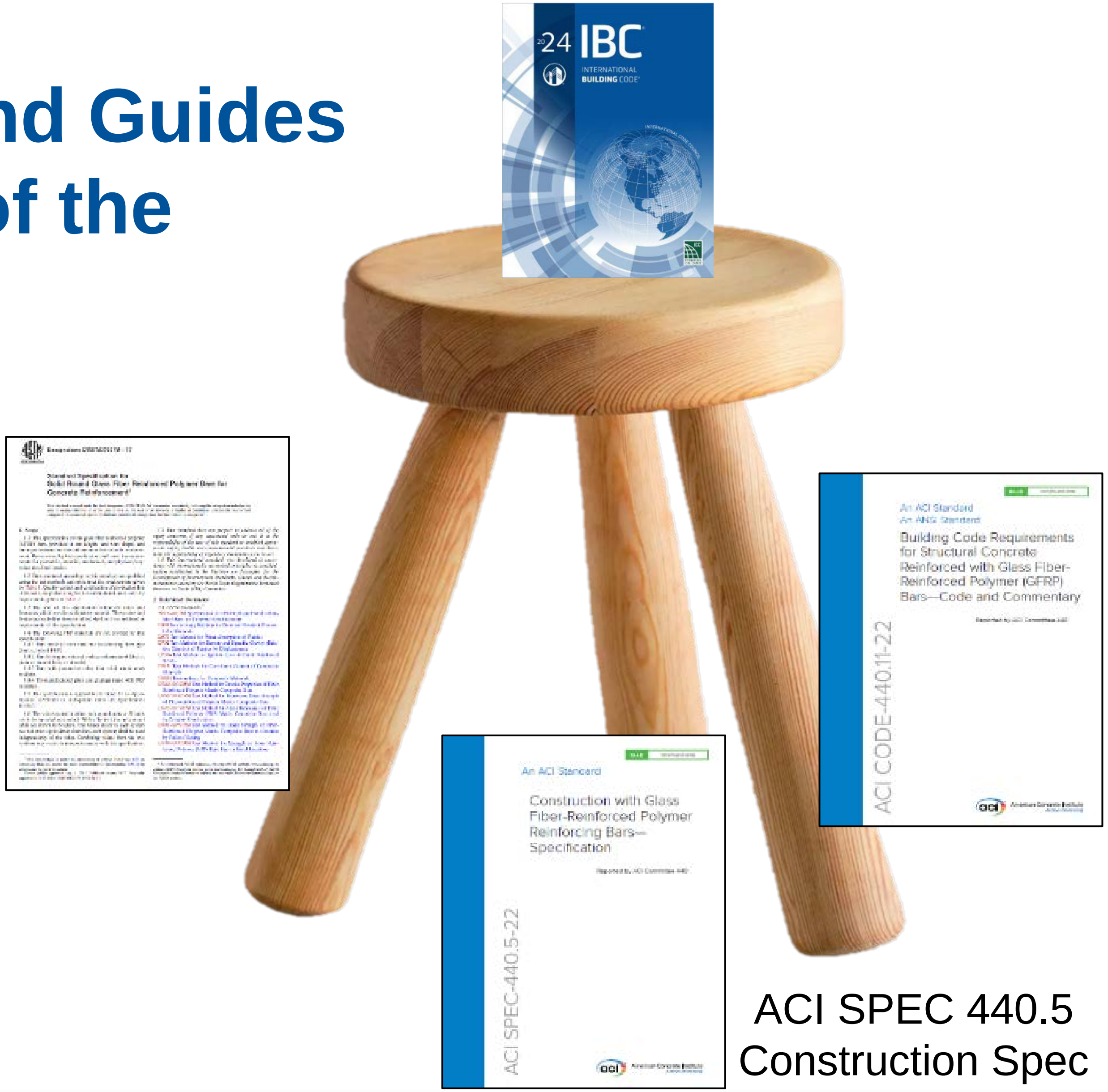
Standards and Guides Three Legs of the Stool



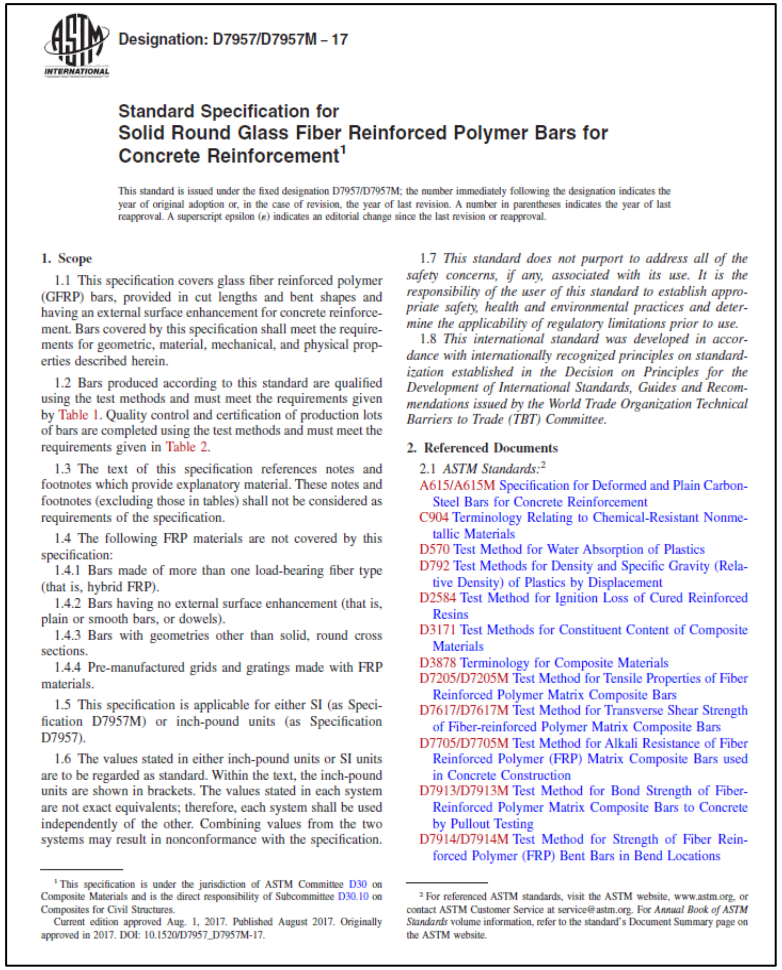
ASTM D7957 Material Spec

ACI CODE 440.11 Design Code

ACI SPEC 440.5 Construction Spec

Standards and Guides
Material Specification

- ASTM D7957 – Standard Specification for Solid Round GFRP Bars for Concrete Reinforcement
  - – Glass fiber, vinyl ester resin bars only
  - – Manufactured by pultrusion
  - – Specified material properties
  - – Specified durability properties
- ASTM D7957 is the code in the USA for GFRP rebars, directly referenced by the International Building Code



Designation: D7957/D7957M – 17

Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement[1]

This standard is issued under the fixed designation D7957/D7957M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers glass fiber reinforced polymer (GFRP) bars, provided in cut lengths and bent shapes and having an external surface enhancement for concrete reinforcement. Bars covered by this specification shall meet the requirements for geometric, material, mechanical, and physical properties described herein.

1.2 Bars produced according to this standard are qualified using the test methods and must meet the requirements given by Table 1. Quality control and certification of production lots of bars are completed using the test methods and must meet the requirements given in Table 2.

1.3 The text of this specification references notes and footnotes which provide explanatory material. These notes and footnotes (excluding those in tables) shall not be considered as requirements of the specification.

1.4 The following FRP materials are not covered by this specification:

1.4.1 Bars made of more than one load-bearing fiber type (that is, hybrid FRP).

1.4.2 Bars having no external surface enhancement (that is, plain or smooth bars, or dowels).

1.4.3 Bars with geometries other than solid, round cross sections.

1.4.4 Pre-manufactured grids and gratings made with FRP materials.

1.5 This specification is applicable for either SI (as Specification D7957M) or inch-pound units (as Specification D7957).

1.6 The values stated in either inch-pound units or SI units are to be regarded as standard. Within the text, the inch-pound units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with the specification.

1.7 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health and environmental practices and determine the applicability of regulatory limitations prior to use.

1.8 This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A615/A615M Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement
C904 Terminology Relating to Chemical-Resistant Nonmetallic Materials
D570 Test Method for Water Absorption of Plastics
D792 Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
D2584 Test Method for Ignition Loss of Cured Reinforced Resins
D3171 Test Methods for Constituent Content of Composite Materials
D3878 Terminology for Composite Materials
D7205/D7205M Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars
D7617/D7617M Test Method for Transverse Shear Strength of Fiber-reinforced Polymer Matrix Composite Bars
D7705/D7705M Test Method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction
D7913/D7913M Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing
D7914/D7914M Test Method for Strength of Fiber Reinforced Polymer (FRP) Bent Bars in Bend Locations

[1] This specification is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.10 on Composites for Civil Structures.

Current edition approved Aug. 1, 2017. Published August 2017. Originally approved in 2017. DOI: 10.1520/D7957_D7957M-17.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

Standards and Guides
Material Specification

- ASTM D8505 – New Specification for Higher Modulus GFRP and BFRP Bars
  - Not currently referenced by any ACI Codes
  - Does represent what manufactures are capable of producing now
  - ASTM D8505 is also not yet been referenced by the national code

Designation: D8505/D8505M – 23

Standard Specification for Basalt and Glass Fiber Reinforced Polymer (FRP) Bars for Concrete Reinforcement[1]

This standard is issued under the fixed designation D8505/D8505M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

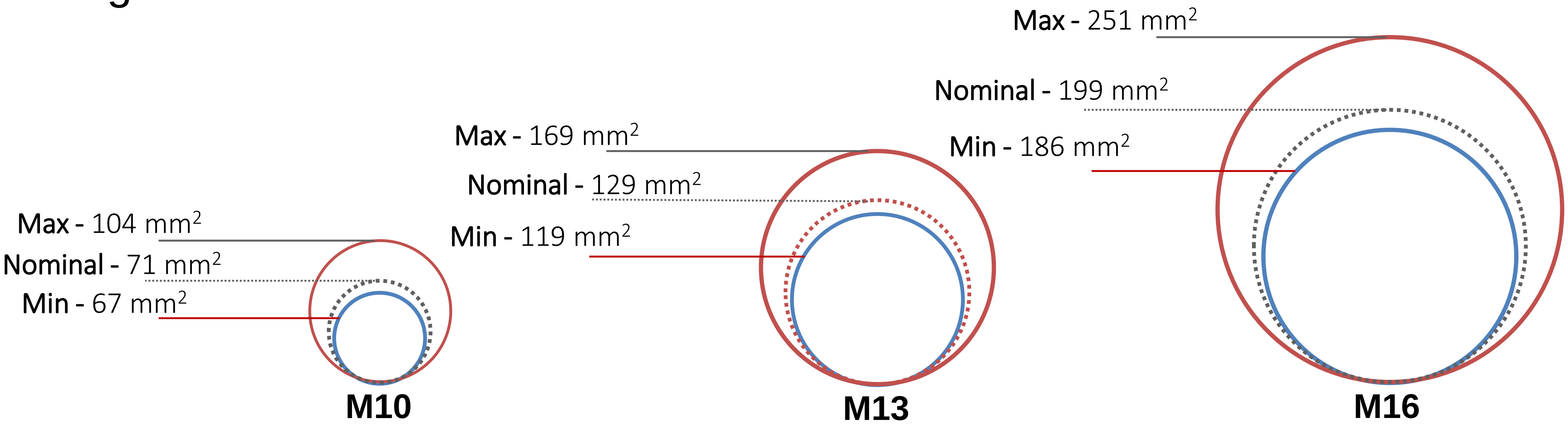
Standards and Guides
ASTM D7957 Bar Sizes

- Standard Bar Sizes are the Same as Steel Bars (No. 2 thru No. 10)
- Bar Areas are the Same as Steel Bars
- But…strength varies by bar size
  - – No. 2 is 125-ksi minimum
  - – No. 10 is 77-ksi minimum

Photo courtesy of Galen-Panamerica/Binevir.

ASTM D7957 Bar Sizes

- Large tolerance on bar size



Standards and Guides
GFRP 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

Major Differences in Design
Guaranteed Tensile Properties

ASTM D7957 requires properties obtained from the bar manufacturer be based on ASTM D7205 and ASTM D7914 tests

- Straight bar guaranteed tensile strength, $f_{fu}{}^*$

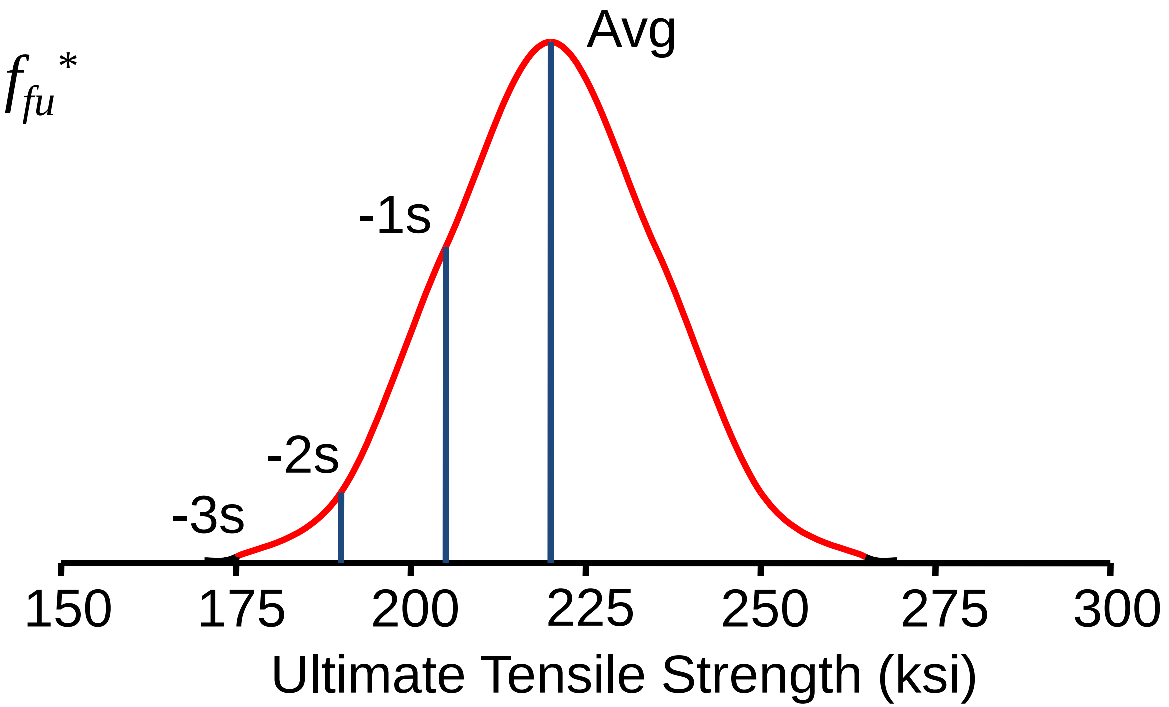
$$f_{fu}^* = f_{fu,ave} - 3\sigma$$

- Mean tensile modulus, E_f

$$E_f = E_{f,ave}$$

- Guaranteed tensile strength at bend, $f_{fb}{}^*$

$$f_{fb}^* = f_{fb,ave} - 3\sigma$$



ASTM D7205 Testing

Video courtesy of Binevir Composites

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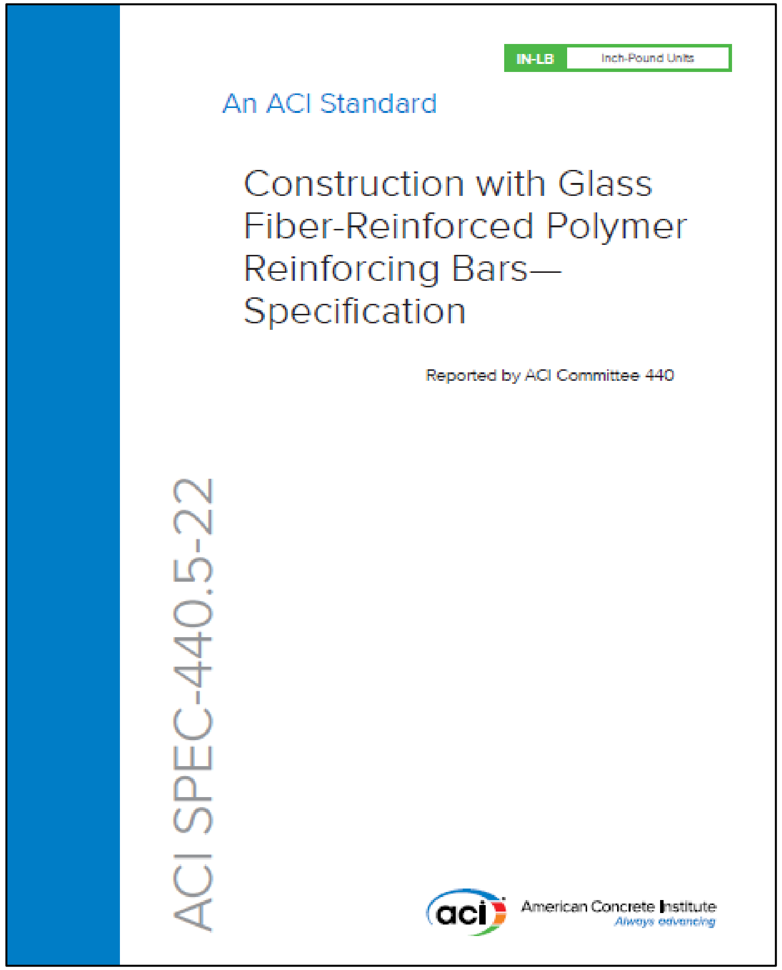
Standards and Guides
Construction Specification

- ACI SPEC 440.5-22 Construction with Glass Fiber-Reinforced Polymer Reinforcing Bars


IN-LB Inch-Pound Units

An ACI Standard

Construction with Glass Fiber-Reinforced Polymer Reinforcing Bars—Specification

Reported by ACI Committee 440

ACI SPEC-440.5-22

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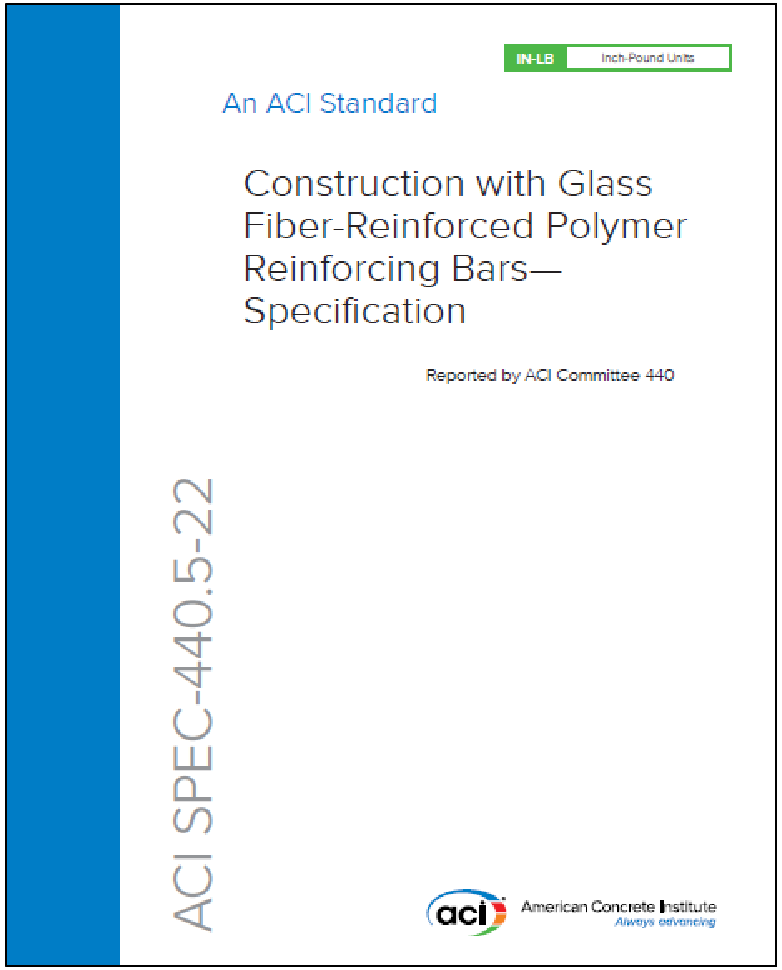
Standards and Guides
Construction Specification

ACI SPEC 440.5-22 Construction with Glass Fiber-Reinforced Polymer Reinforcing Bars − Specification:

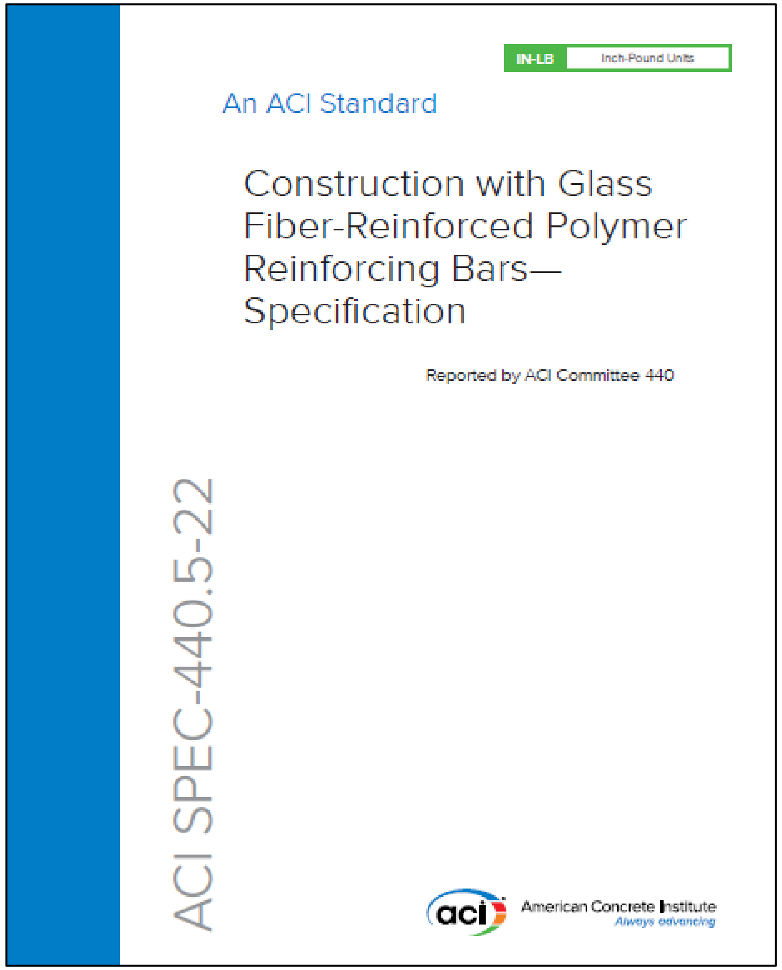
- Covers GFRP bars,
- Storage, handling, cutting, bar supports, ties,
- Cover requirements,
- Bar bends, etc.



Standards and Guides
Construction Specification

GFRP reinforcing bar — GFRP bar manufacturer’s certified test reports in conformance with ASTM D7957 shall be provided.

Mat reinforcement — Mat reinforcement made of preassembled GFRP reinforcing bars is covered by this Specification.


IN-LB Inch-Pound Units

An ACI Standard

Construction with Glass Fiber-Reinforced Polymer Reinforcing Bars—Specification

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ACI SPEC-440.5-22

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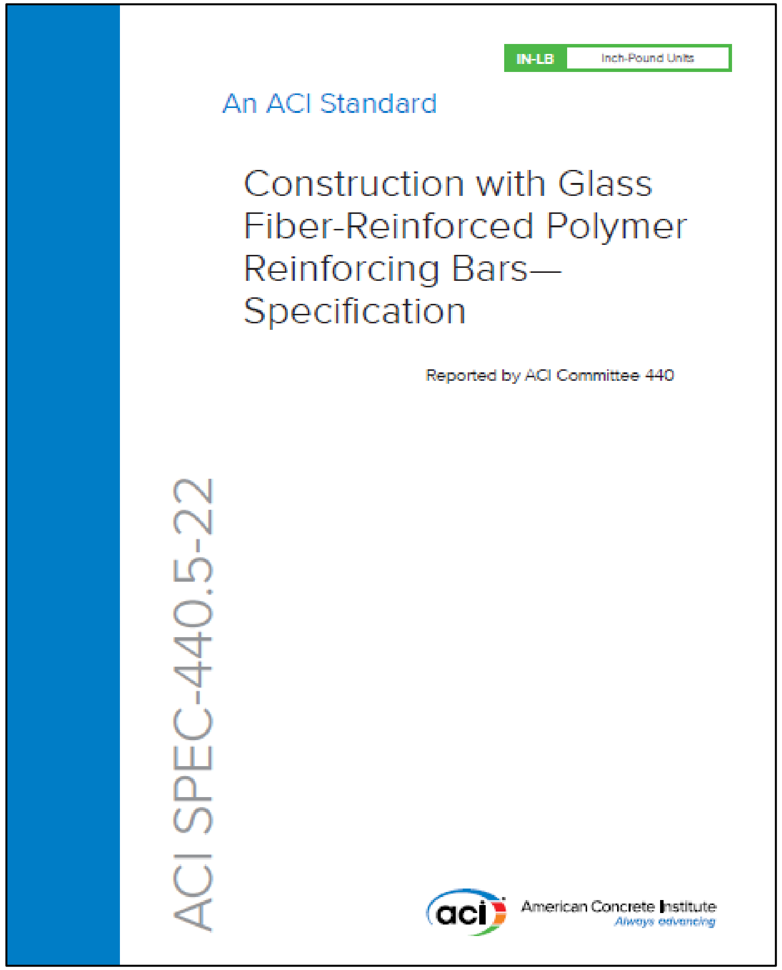
Standards and Guides
Construction Specification

Information about:

- prevention of bending; dragging; gouging; crushing…
- handling GFRP reinforcement
- Prevent exposure of GFRP reinforcing bars to ambient temperatures
- maximum total unrepaired visible damage permitted
- reinforcement bar supports
- Factory bar bending
- Placement tolerances, relation
- Concrete cover
- Other construction considerations


IN-LB Inch-Pound Units

An ACI Standard

Construction with Glass Fiber-Reinforced Polymer Reinforcing Bars—Specification

Reported by ACI Committee 440

ACI SPEC-440.5-22

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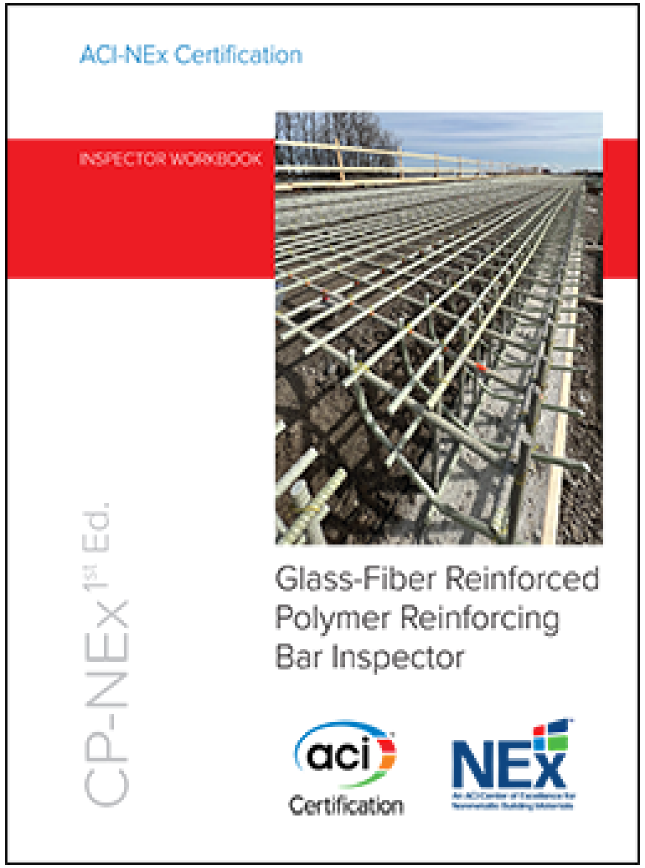
Additional Resources

ACI GFRP Reinforcing Bar Inspector Program:

A certified Glass Fiber-Reinforced Polymer (GFRP) Reinforcing Bar Inspector is an individual who has demonstrated the knowledge required to properly perform jobsite inspection of GFRP Reinforcing Bars used in concrete construction projects.



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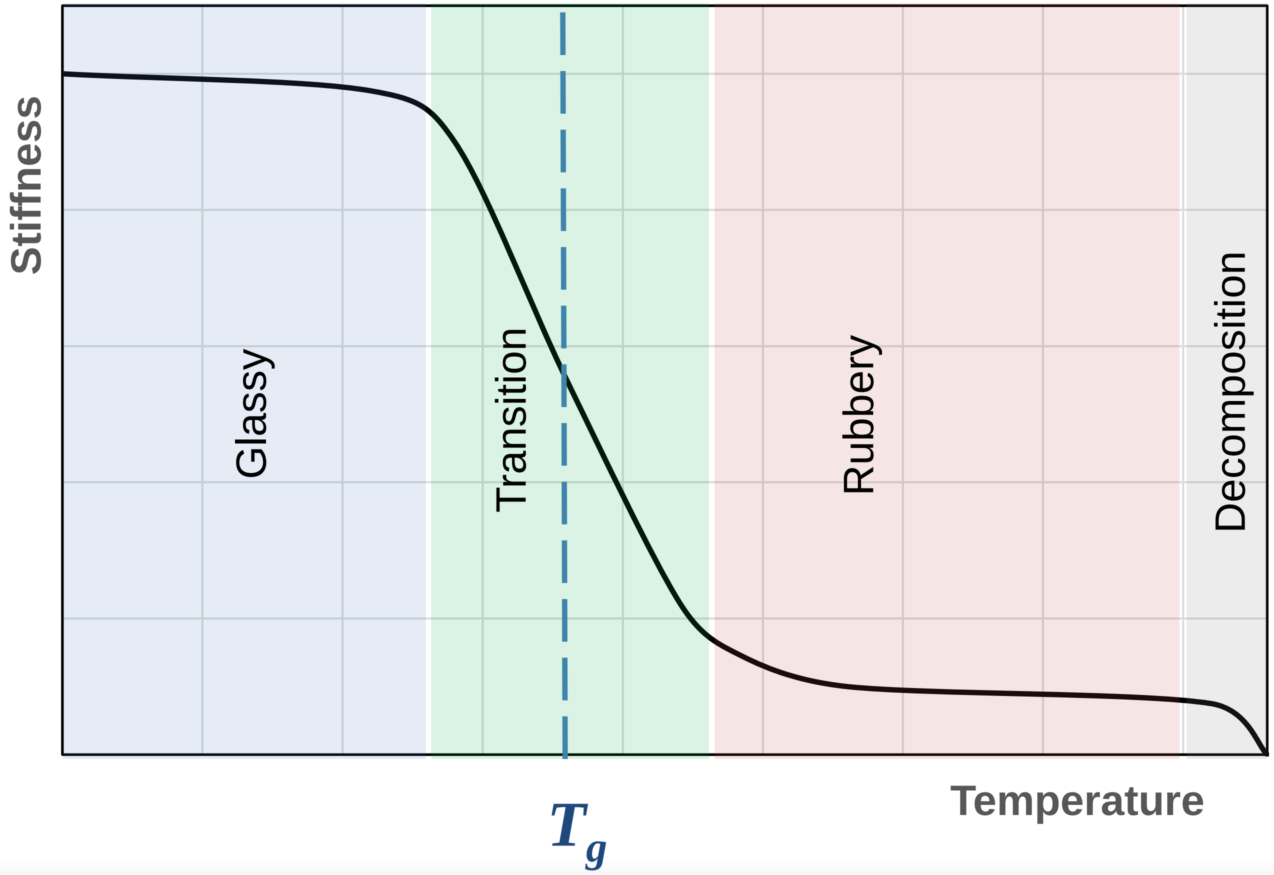
Major Design Limitations
Glass Transition Temperature



For GFRP Bars:

$$T_g = 212 \text{ to } 250°\text{F}$$
$$T_g = 100 \text{ to } 121 \text{ C}$$

Major Design Limitations
Elevated Service Temperature 4.11.3

- Service Temperature Limitations
  - GFRP bars shall not be used in environments with a service temperature higher than 27°F (14 C) below the glass transition temperature.

$$T_g - 27°\mathrm{F}$$

  - ASTM D7957 requires a minimum glass transition temperature of 212°F (100 C).

$185°\mathrm{F}$
85 C

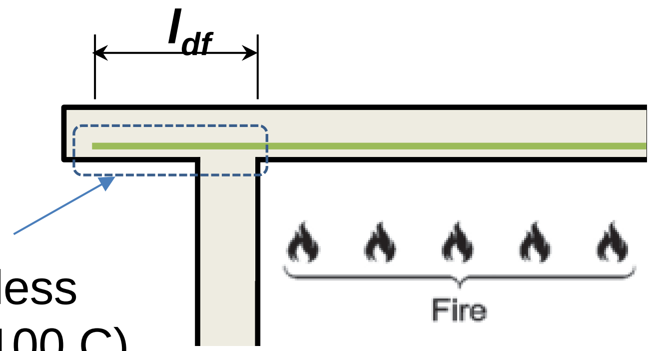
Maximum service temperature based on ASTM D 7957 minimum T_g

Major Design Limitations
Fire Resistance 4.11.1

- Fire Resistance – Code requirement
  - Structural concrete reinforced with GFRP bars shall not be permitted where fire-resistance ratings are required except where the fire resistance has been shown to be adequate by calculations or tests and approved by the building official.

Major Design Limitations
Fire Resistance R4.11.1

- Commentary to Code on Fire Resistance
  - Fire endurance relies on maintaining bond between the GFRP bars and concrete
  - Specific detailing in the way of “cool anchorage” is needed to reasonably achieve fire ratings
  - Service level stress in the bars should be limited to 0.30ffu

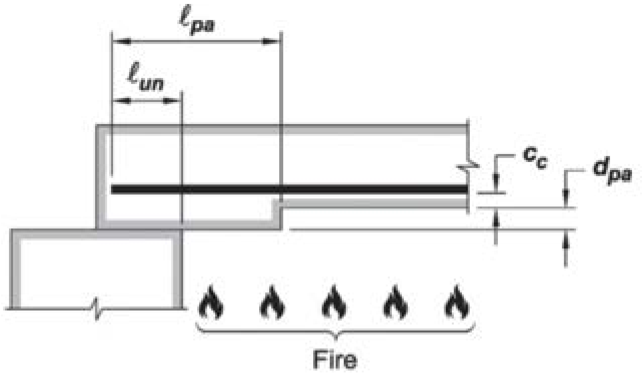


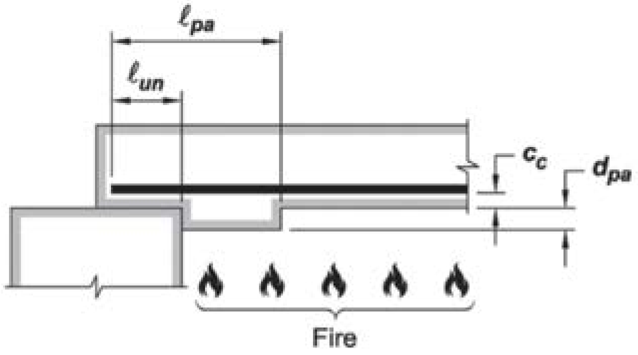
Average bar temperature less than 210°F (100 C)

l_{df} is the bond development length corresponding to 1.3 times the maximum bar stress due to full service loads (1.0D + 1.0L)

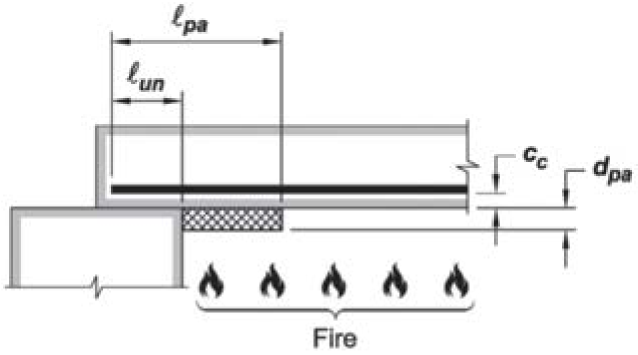
Major Design Limitations
Fire Resistance R4.11.1

- Commentary to Code on Fire Resistance
  - Various potential fireproofing options





Increase concrete cover by using a haunch or drop panel at the anchorage location



Insulate anchorage

Major Design Limitations
Fire Resistance R4.11.1

- <u>Commentary</u> to Code on Fire Resistance
  - Insulation should be at least 2 in. (51 mm) thick, and the insulation material should be tested for application on concrete in accordance with ASTM E119 to verify that the insulated concrete surface temperature does not exceed 300°F (150 C) for the duration of the required fire-resistance rating

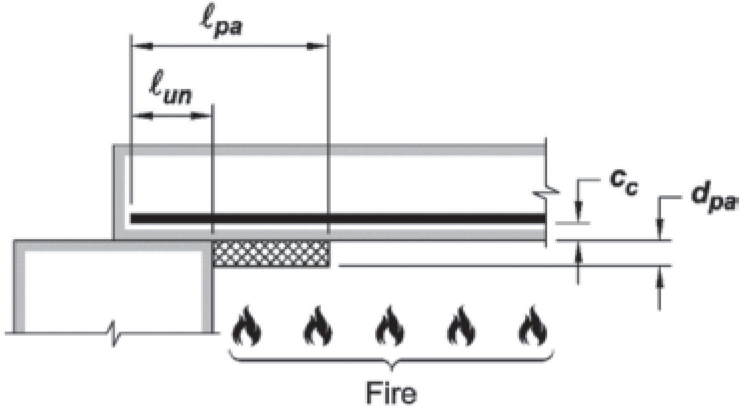


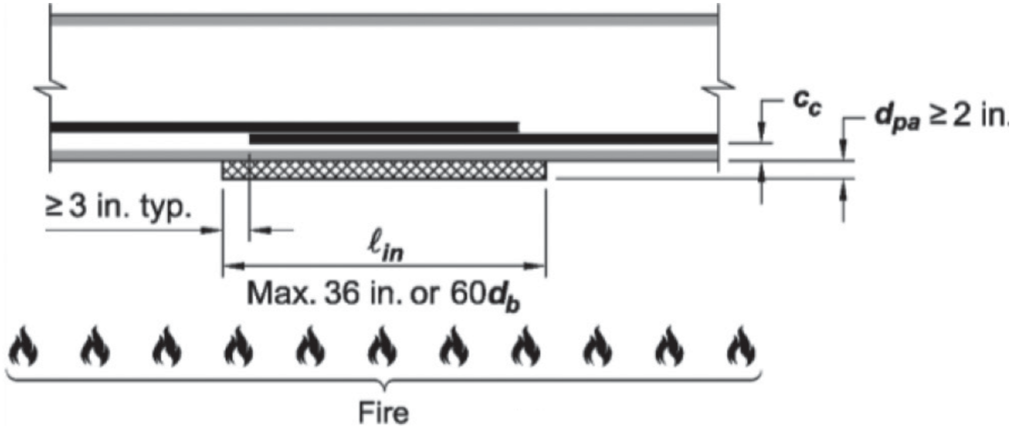
Table R4.11.1—Haunch, drop panel, or insulation for protection of GFRP reinforcement near supports

ℓ_{un}, in.	ℓ_{pa}, in.	d_{pa}, in.
4	Max(22or 30d_b)	2
6	Max(20 or 28d_b)	2
8	Max(16 or 25d_b)	2
10	Max(14 or 22d_b)	2
Max(12 or 20d_b)	—	—

*For 2-hour fire exposer. Assumes clear cover ≥ 1.5 in., $f_c' \geq 4000$ psi, and maximum bar stress due to $1.0D + 1.0L < 35$ ksi.

Major Design Limitations
Fire Resistance R4.11.1

- Commentary to Code on Fire Resistance
  – Splices need protection too!



Workshop on Competites in Construction

Session 1: Structural Concrete Reinforced with GFRP Bars

- General Introduction to ACI CODE 440.11
- GFRP reinforcement and introduction to ASTM D7957
- General Introduction to ACI SPEC 440.5
- Fire Resistance of GFRP Reinforced Concrete

Refreshment Break

- General Design Provisions for Flexure, Shear, and Axial Strength
- Seismic Limitations
- Structural System Requirements
- Slabs-on-Ground

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.

Workshop on Composites in Construction

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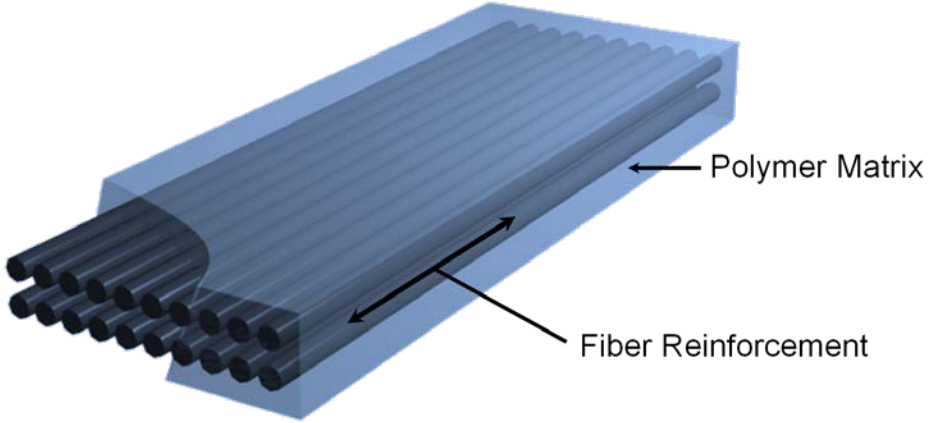
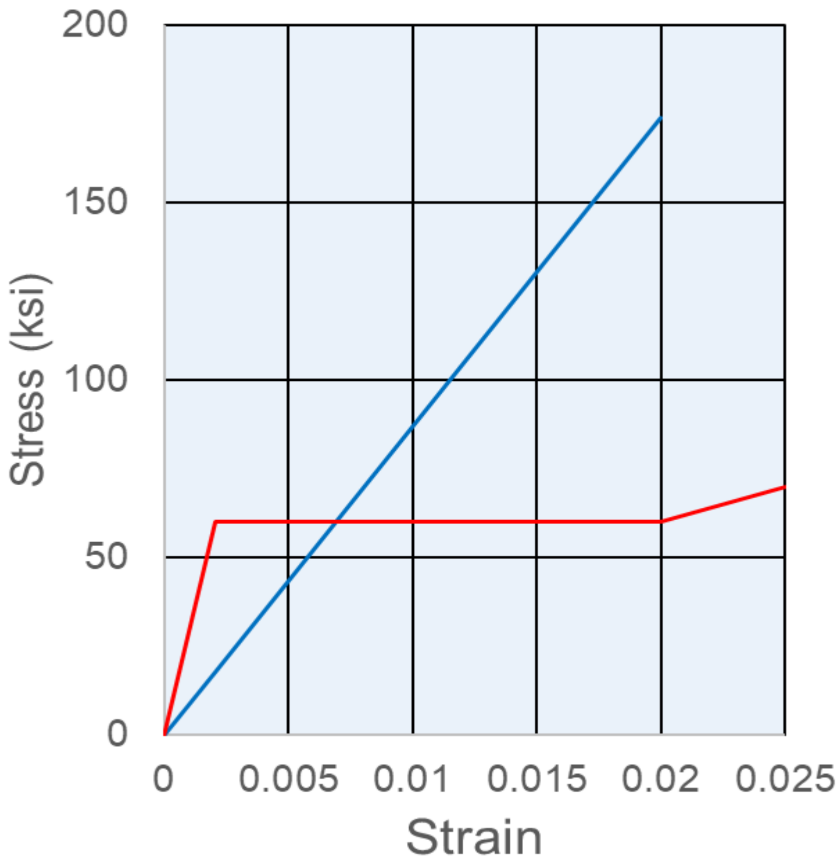
Refreshment Break

- **General Design Provisions for Flexure, Shear, and Axial Strength**
- Seismic Limitations
- Structural System Requirements
- Slabs-on-Ground

GFRP Mechanical Properties and Behavior
Points to Understand

- Higher tensile strength, but less stiff than steel
- Elastic up to failure - no ductility
- Anisotropic behavior
- Resins soften at high temps





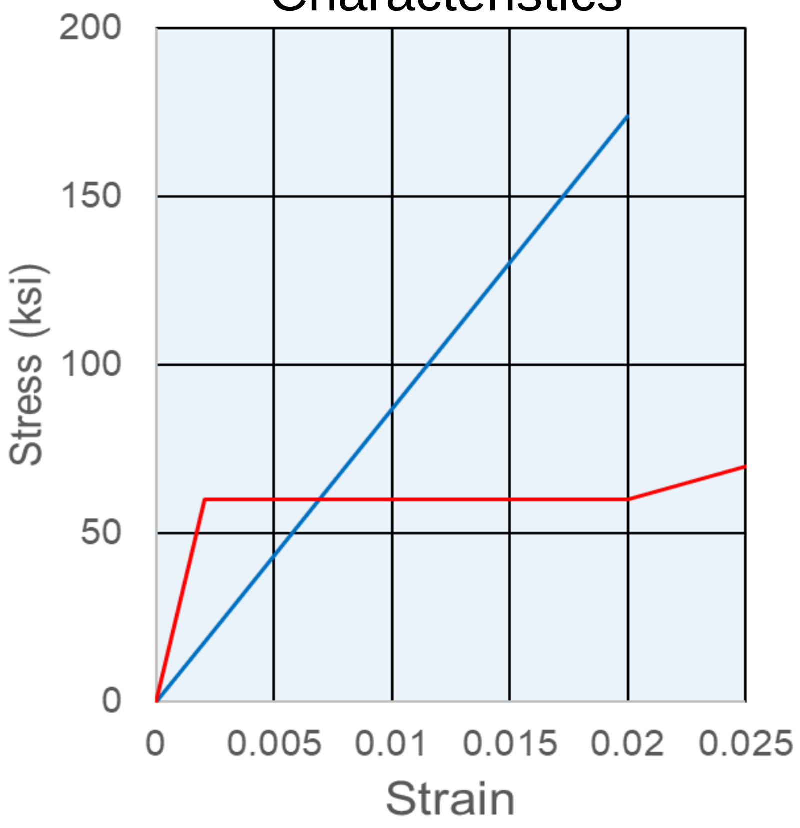
GFRP Mechanical Properties and Behavior

Video courtesy of Escuela Colombiana de Ingenieria, Bogota

GFRP Mechanical Properties and Behavior
Mechanical Behavior

- 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



GFRP Mechanical Properties and Behavior
Tensile Stress-Strain Characteristics

Tensile Properties

	Yield Stress (ksi)	Tensile Strength (ksi)	Elastic Modulus ($\times 10^3$ ksi)	Yield Strain (%)
Steel	40 to 75	70 to 100	29	0.14 to 0.25
GFRP	N/A	77 to 175*	6.5 to 8.7	N/A

* Strength varies by bar size

GFRP Mechanical Properties and Behavior
Other Mechanical Properties

- Strength of FRP at bends
  - FRP bars can be fabricated with bends, however the tensile strength at bends 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 load
  - FRP bars can undergo creep-rupture under sustained loading

GFRP Mechanical Properties and Behavior Differences from Steel Reinforcement

- High longitudinal strength to weight ratio
- Corrosion resistant
- Electro-magnetic neutrality
- High fatigue endurance
- Low thermal and electrical conductivity
- Lightweight
- Easily cut onsite

- No yielding before failure
- Low transverse strength
- Relatively low modulus
- Susceptible to fire and smoke production
- High coefficient of thermal expansion perpendicular to fibers
- Can not be field bent

GFRP Mechanical Properties and Behavior
Density and CTE

Density (lb/ft^3)

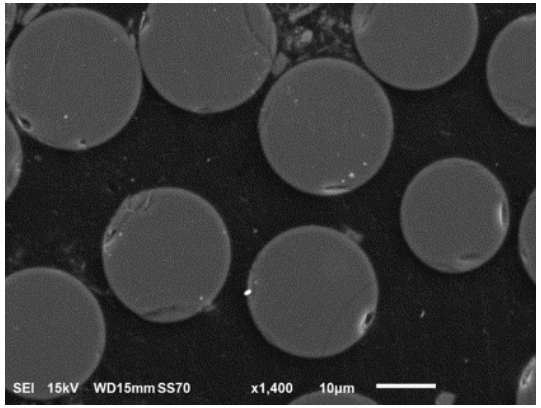
Concrete (normal weight)	135 to 160
Steel	493
GFRP	150

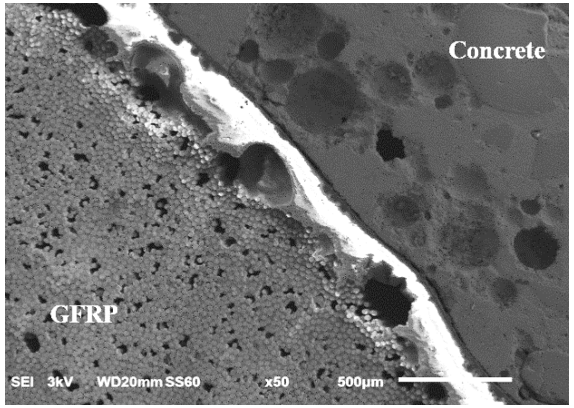
Coefficient of Thermal Expansion ($10^{-6}/^{o}F$)

	Longitudinal Direction	Transverse Direction
Concrete	4 to 6	4 to 6
Steel	6.5	6.5
GFRP	3.5 to 5.6	12

Major Differences in Design
Durability

- FRP bars will not corrode, but glass fibers have potential for degradation under high pH
  - 2% reduction in tensile strength seen after 17 years of in-field service
- ASTM requires minimum durability properties that ensure protection from alkaline degradation





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

Major Differences in Design
Design Tensile Properties

- Design tensile strength and rupture strain for straight bars

$$f_{fu} = C_E f_{fu}^*$$ **20.2.2.3.**

$$\varepsilon_{fu} = \frac{\varepsilon_{fu}^*}{E_f}$$ **20.2.2.5.**

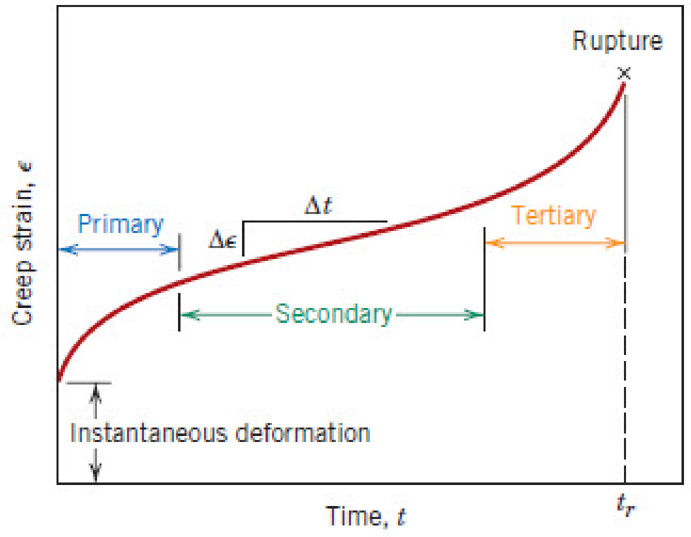
- Design tensile strength for transverse reinforcement

$$f_{ft} = C_E f_{fb}^* \leq 0.005E_f$$ **20.2.2.4 and 20.2.2.6**

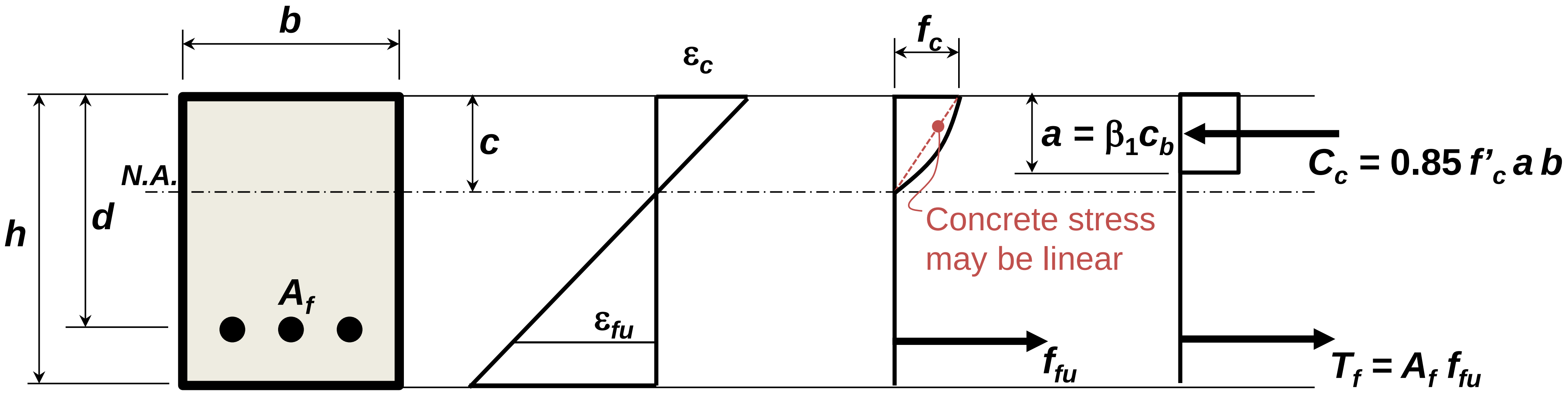
- C_E is an environmental reduction factor = 0.85

Major Differences in Design
Time-Dependent Behavior

- GFRP reinforcing bars subjected to a constant load over time can suddenly fail
- This phenomenon is known as creep rupture (or static fatigue)
- Keep stress due to unfactored sustained loads less than 0.3 f_{fu} (24.6.2)



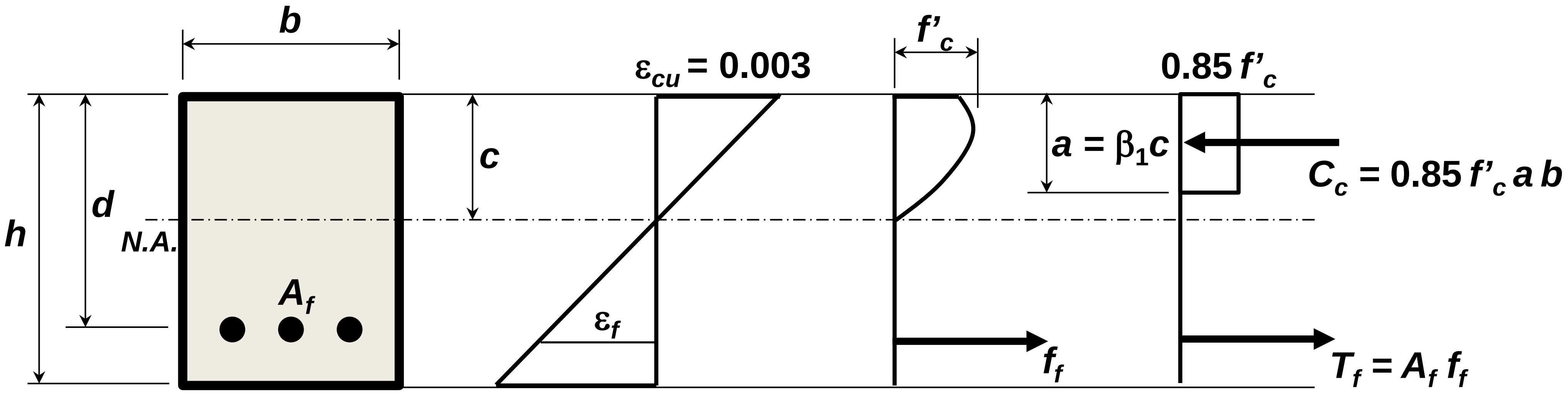
Major Differences in Design
Failure Governed by FRP Rupture



Stress in bar is f_{fu} → know T_f and C_c

But the full non-linear stress distribution in the concrete is not achieved…and Whitney's stress block does not apply.

Major Differences in Design
Failure Governed by Concrete Crushing



Whitney's stress block applies

But stress in the FRP is not known. Must simultaneously solve force equilibrium and strain compatibility.

Flexural Strength (22.2 and 22.3)
Philosophy

- **GFRP bars DO NOT YIELD**
- Tension-controlled sections fail by rupture of GFRP in the tension zone, while compression-controlled sections fail by crushing of concrete in the compression zone
- **No advantage** to tension-controlled sections over compression-controlled sections as in steel RC members where tension-controlled failures are more gradual due to yielding of steel
- Tensile-controlled sections require less GFRP reinforcement than compression-controlled sections, but the higher bar stresses impact design for crack control and creep rupture
- **Both** failure modes are acceptable provided that strength and serviceability criteria are satisfied
- Design assumptions in 440.11 Section 22.2 are consistent with those in 318
- Flexural resistance factors have been calibrated based on failure mode to maintain a minimum reliability index of 3.5

Flexural Strength
Strength Reduction Factor (21.2)

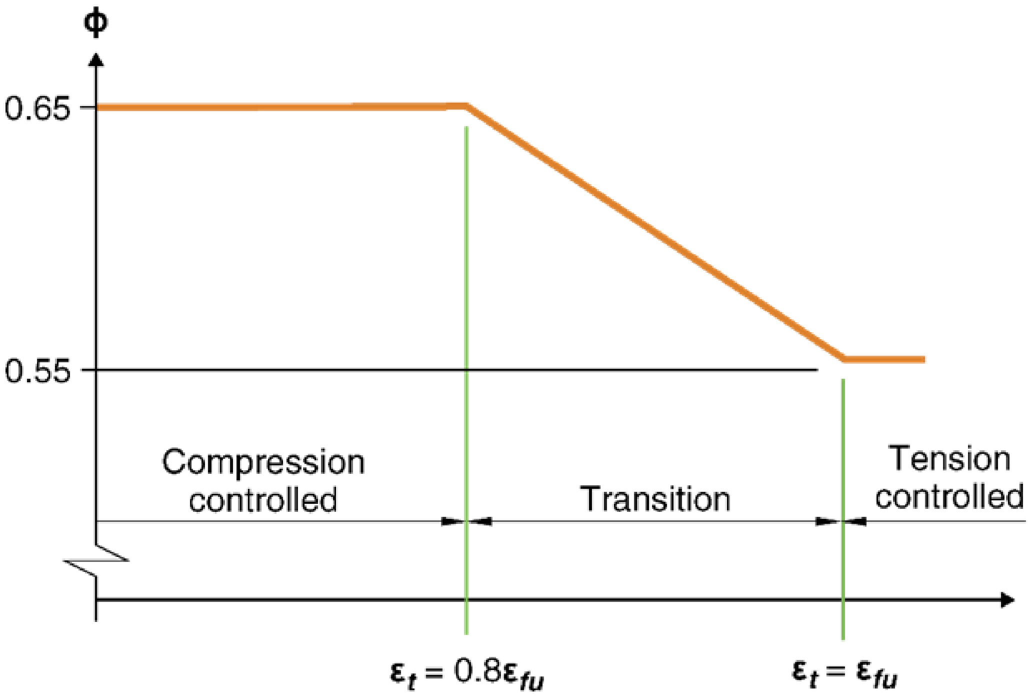
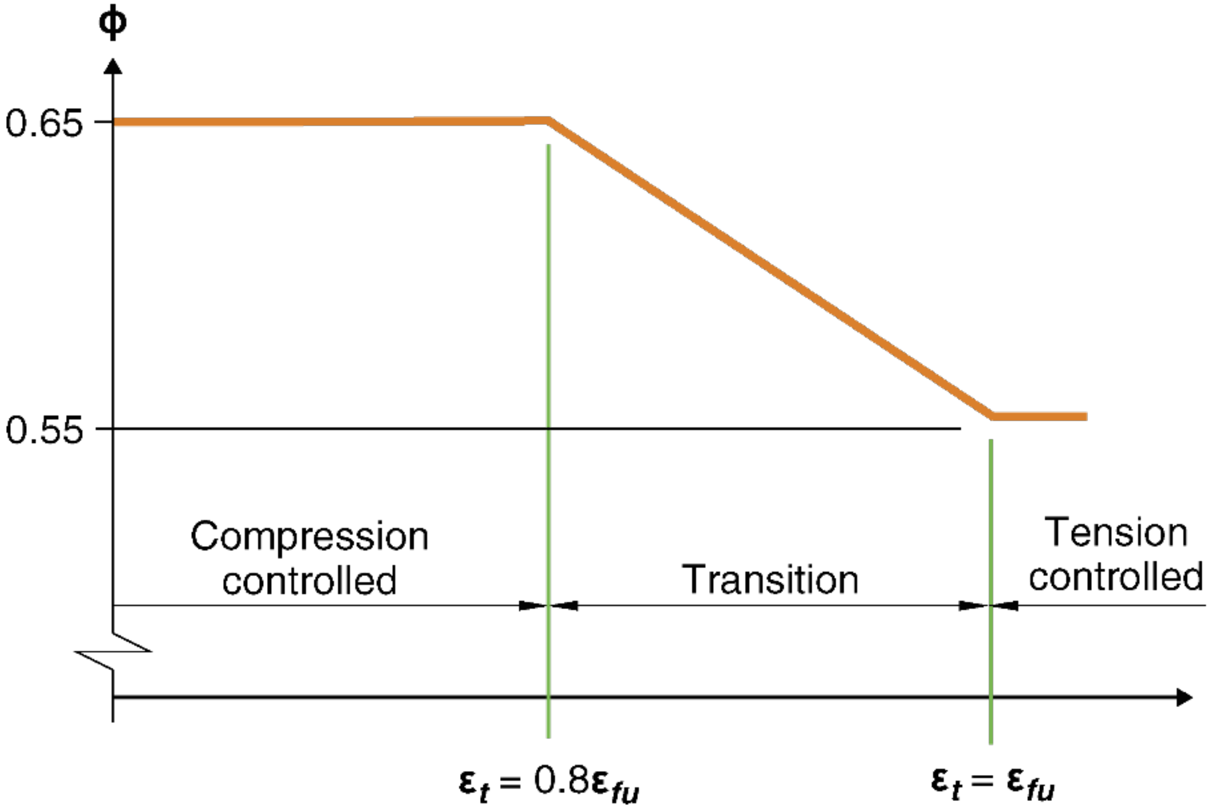


Table 21.2.2

Net tensile strain at failure, ε_{ft}	Strength reduction factor, Φ
$\varepsilon_{ft} = \varepsilon_{fu}$	0.55 (tension-controlled)
$\varepsilon_{fu} > \varepsilon_{ft} > 0.8\varepsilon_{fu}$	$1.05 - 0.5\varepsilon_{ft} / \varepsilon_{fu}$ (transition)
$\varepsilon_{ft} \leq 0.8\varepsilon_{fu}$	0.65 (compression-controlled)

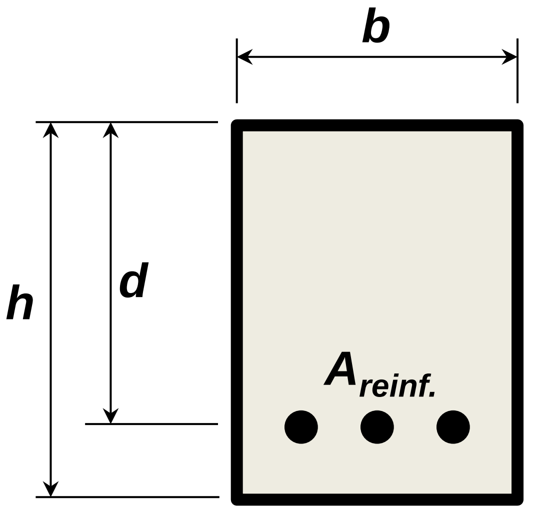
Major Differences in Design
Strength Reduction Factors 21.2.2.

Flexure

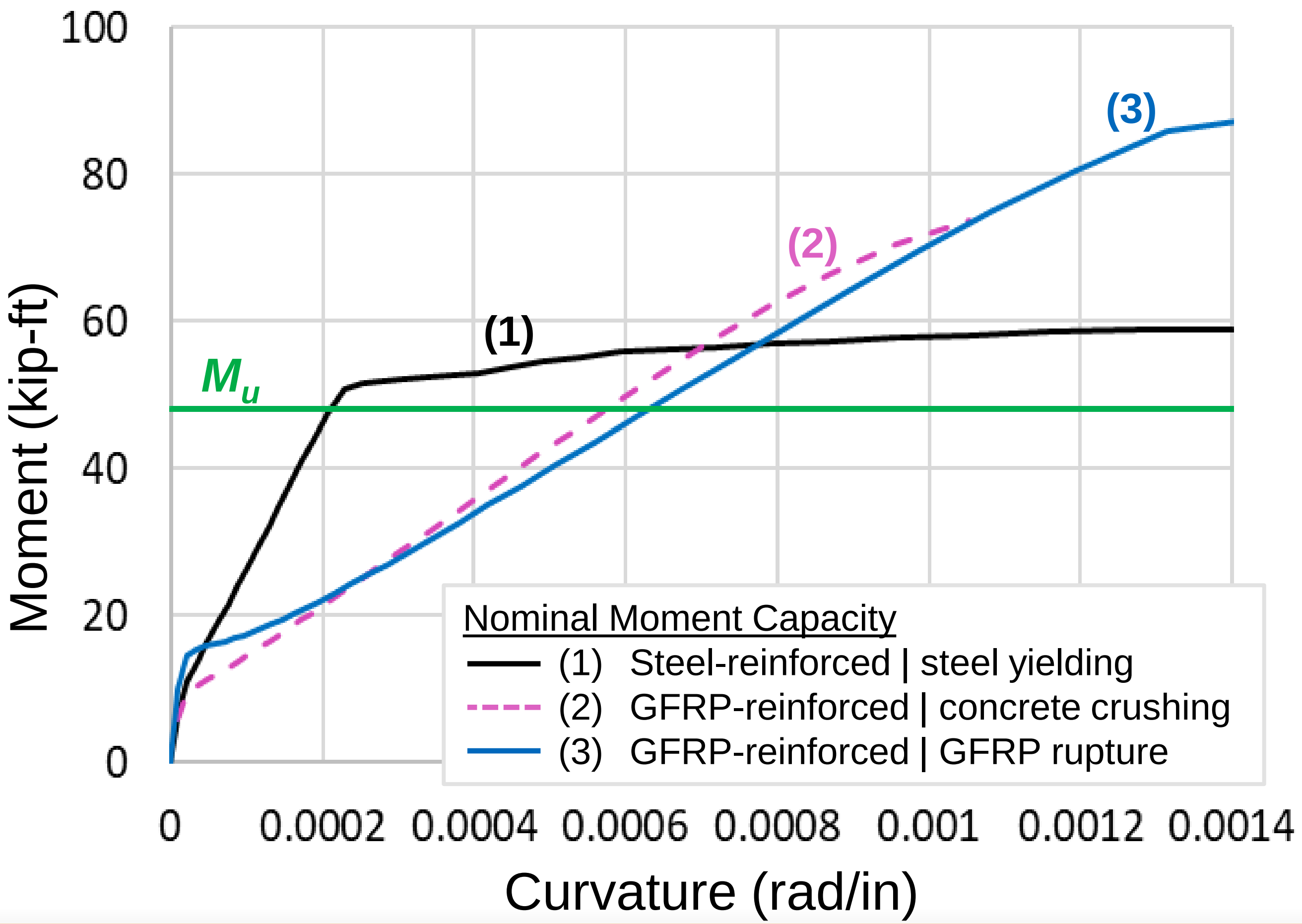


Shear → $\phi = 0.75$
Torsion → $\phi = 0.75$
Bearing → $\phi = 0.65$

Major Differences in Design
Moment-Curvature Relationship



	b (in)	*h* (in)	*d* (in)	$A_{reinf.}$ (in^2)
(1)	8	15	12.5	0.93
(2)	8	15	12.5	0.93
(3)	12	16	13.5	0.62



Major Differences in Design Serviceability

- Serviceablity considerations typically control design (not strength)
  - Cracking – Excessive crack width is undesirable for aesthetic and other reasons that can damage or deteriorate the structural concrete
  - Deflection – Deflections should be within acceptable limits imposed by the use of the structure
- Substitution of GFRP for steel on an equal area basis → larger deflections and wider crack widths
  - Not the philosophy of the code

Serviceability
Effective Moment of Inertia (24.2.3.5)

- The overall flexural stiffness, $E_c I$, of a flexural member that has experienced cracking at service varies between $E_c I_g$ and $E_c I_{cr}$
  - Note: I_{cr} is calculated with the modular ratio between GFRP reinforcement and concrete ($n_f = E_f / E_c$), considerably smaller than the modular ratio between steel and concrete.
- Equations for Effective Moment of Inertia, I_e :
  - If applied moment is less than 80% of the cracking moment ($M_a < 0.80\ M_{cr}$), section is assumed to be uncracked with $I_e = I_g$
  - If applied moment exceeds 80% of the cracking moment ($M_a > 0.80\ M_{cr}$), I_e is reduced according to a weighted average of flexibility:

$$I_e = \frac{I_{cr}}{1 - \gamma \left(\frac{0.8\ M_{cr}}{M_a}\right)^2 \left(1 - \frac{I_{cr}}{I_g}\right)} \leq I_g$$

Table 24.2.3.5

Where, $$\gamma = 1.72 - 0.72 \frac{0.8\ M_{cr}}{M_a}$$

Eq. 24.2.3.5b

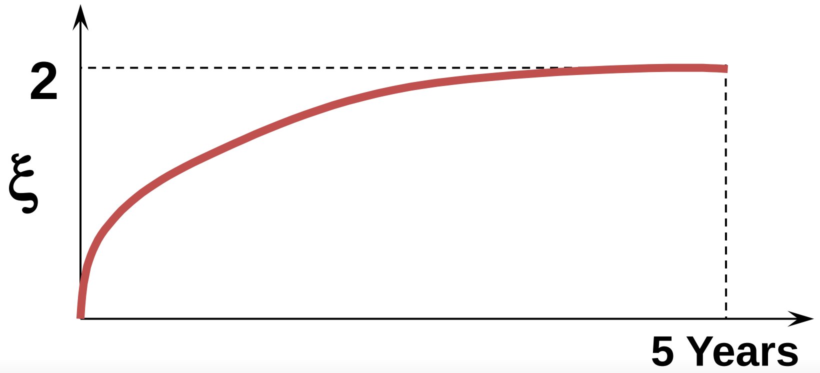
Serviceability
Calculation of Time-dependent Deflections

- Time-dependent deflection increase for GFRP RC members is typically smaller than that for steel RC members with similarly-sized immediate deflections.
- Long-term deflection multiplier does **not** account for presence of GFRP compression reinforcement.
- The long-term deflection can be calculated from:

$$\Delta_{(cp+sh)} = 0.6\ \xi\ (\Delta_i)_{sus}$$ **Eq. 24.2.4.1.1**

$(\Delta_i)_{sus}$ = short term deflection due to sustained load

ξ = time dependent factor for sustained load (ξ = 2 for more than 5 years)
Table 24.2.4.1.3

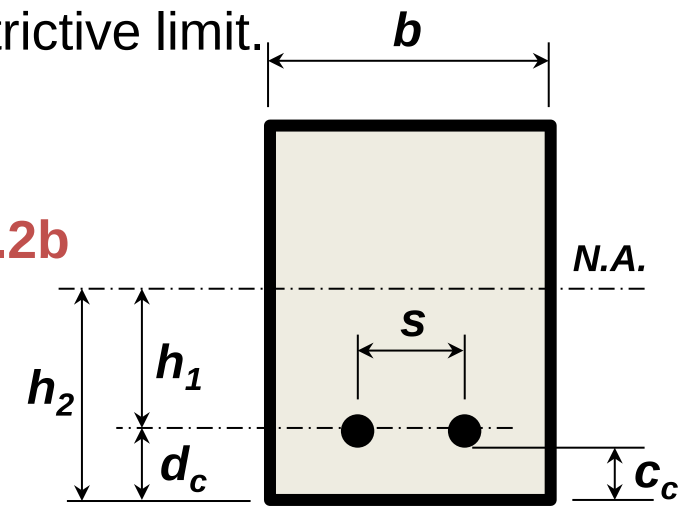


Serviceability
GFRP Bar Spacing for Crack Control

- From a practical perspective, GFRP RC crack widths may have to be larger than the 0.018 in. crack width limit in ACI 318.
- GFRP bar spacing limits in 24.3.2 based on a 0.028 in. maximum crack width; coefficients in the crack width equations may be linearly adjusted to impose a more restrictive limit.
- Spacing of reinforcement closest to the tension face must satisfy:

$$s \leq \frac{0.032\, E_f}{f_{fs} k_b} - 2.5 c_c$$ **Eq. 24.3.2a** **and** $$s \leq \frac{0.026\, E_f}{f_{fs} k_b}$$ **Eq. 24.3.2b**

Where, f_{fs} = service-load GFRP bar stress
c_c = least distance from surface of GFRP to tension face
k_b = 1.2 bond dependent coefficient (24.3.2.3)



- GFRP bar stress, f_{fs}, must also satisfy: $$f_{fs} \leq \frac{0.014\, E_f}{d_c \beta_{cr} k_b}$$ **Eq. 24.3.2.2** $$\beta_{cr} = \frac{h_2}{h_1}$$

Major Differences in Design
Shear Strength 22.5

- Shear strength provided by concrete reinforced with GFRP is lower than shear strength provided by concrete reinforced with steel reinforcement
  - Increased crack width → Less aggregate interlocking
  - Small compressive zone depth → Less concrete resistance in the compressive zone

$$V_n = V_c + V_f$$

V_n = nominal shear strength at section
V_c = nominal shear strength provided by concrete
V_f = shear resistance provided by FRP Stirrups

Shear and Torsion Design
One-Way Shear Strength (22.5)

- Nominal one-way shear strength: $V_n = V_c + V_f$ **22.5.1.1**
- $\boldsymbol{V_f}$ is the contribution of GFRP stirrups *(discussed later)*
- Limiting dimensions: $V_u \leq \phi 0.2 f_c' b_w d$ **22.5.1.2**
- Shear strength provided by concrete (same used regardless if shear reinforcement provided): **22.5.5.1**

Net Axial Load	$\boldsymbol{V_c}$		
Compressive or No Axial Load	Greater of	$5\lambda_s k_{cr}\sqrt{f_c'}b_w d$	(a)
		$0.8\lambda_s\sqrt{f_c'}b_w d$	(b)
Tensile Axial Load	$5\lambda_s k_{cr}\sqrt{f_c'}\, b_w d$		(c)

  – $\boldsymbol{V_c}$ differs from steel-RC and accounts for axial stiffness, $\boldsymbol{E_f A_f}$, of GFRP flexural bars and effects of axial load in the calculation of $\boldsymbol{k_{cr}}$.
  – (b) accounts for observations in lightly reinforced members like slabs that (a) is unreasonably low. (b) is based on reliability analysis

Major Differences in Design
Shear Strength 22.5

- GFRP has a relatively low modulus of elasticity and is linearly elastic
  - Strain limitation of 0.005 to limit crack width and maintain aggregate interlock
- Tensile strength of a bend is lower than the straight portion

Shear and Torsion Design
One-Way Shear Strength (22.5)

- Transverse reinforcement needed when $\boldsymbol{V_u > \phi\, V_c}$ **22.5.8.1**
- Amount needed: $V_f \geq \frac{V_u}{\phi} - V_c$
- The $\boldsymbol{V_f}$ for shear reinforcement is given as:

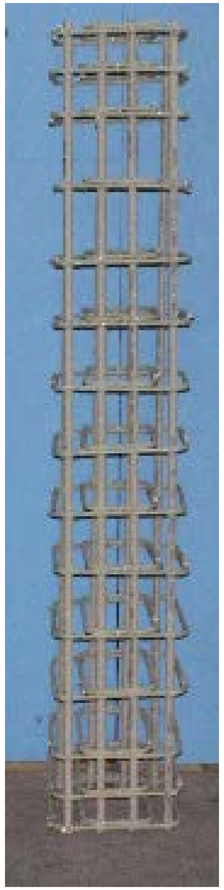
$$V_f = A_{fv} f_{ft} \frac{d}{s}$$ **22.5.8.5.3**

- $\boldsymbol{f_{ft}}$ is the design strength of the transverse reinforcement and is the smaller of $\boldsymbol{f_{fb}}$ and $\boldsymbol{0.005E_f}$
  - $\boldsymbol{f_{fb}}$ reflects the reduced strengths in bent portions of bars and based on the minimum from **ASTM D7957** or from manufacturer preselection **20.2.2.4**
  - $\boldsymbol{0.005E_f}$ reflects a strain limit of 0.005 in the GFRP bars to ensure that shear capacities can be attained without losing aggregate interlock **20.2.2.6**

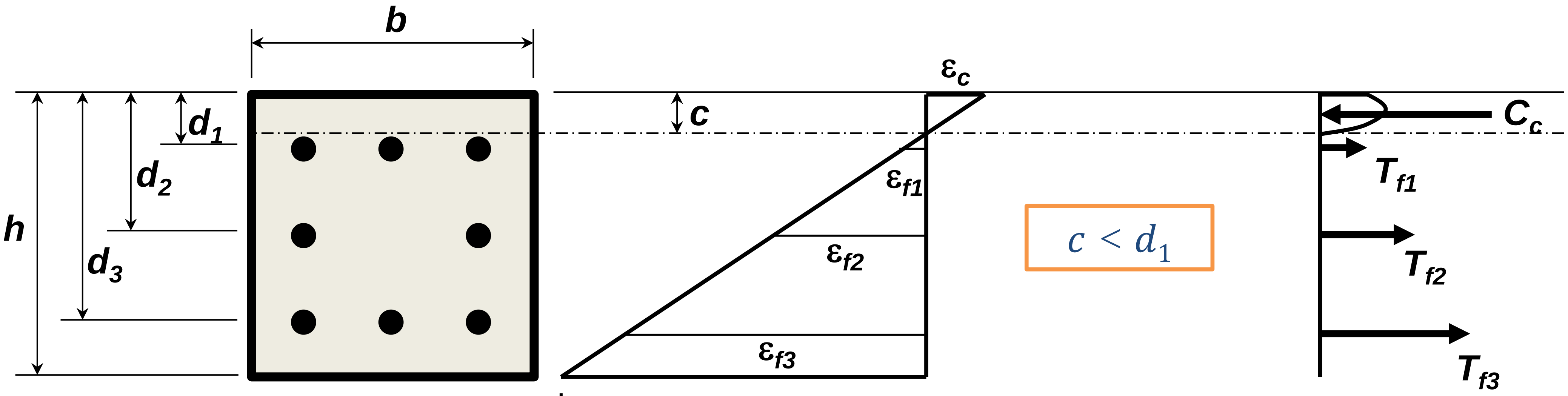
Column Design Philosophy
Axial Compression

GFRP Bars in Compression

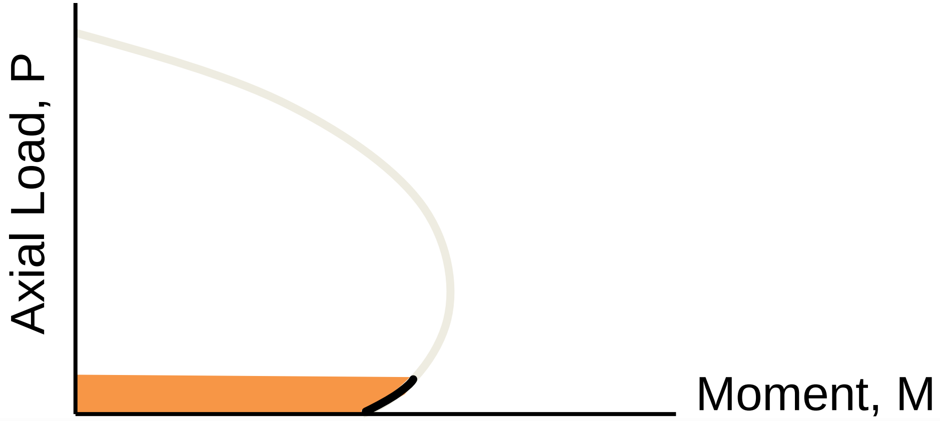
- We know that GFRP Bars have compressive strength
- ASTM D7957 has no requirements for compressive strength
- Reliability of compressive strength is not as well established as tensile strength
- **22.2.3.3** The area of GFRP in compression shall be treated as having the same strength and stiffness as the concrete in the surrounding compression zone.



Column Design Philosophy
Section Analysis and P-M Diagram



At low axial load, all bars in tension



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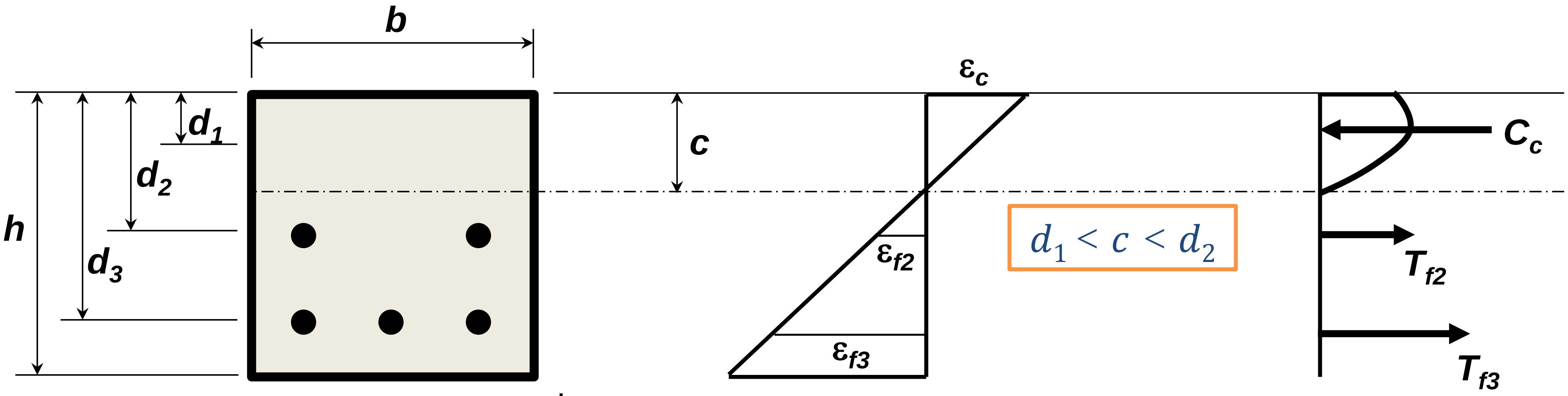
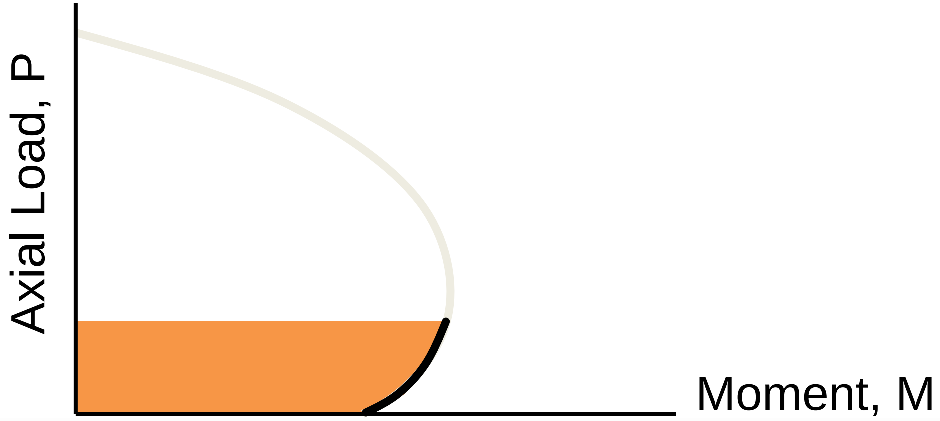
Section Analysis and P-M Diagram



As axial load increases, bars in compression are treated as concrete



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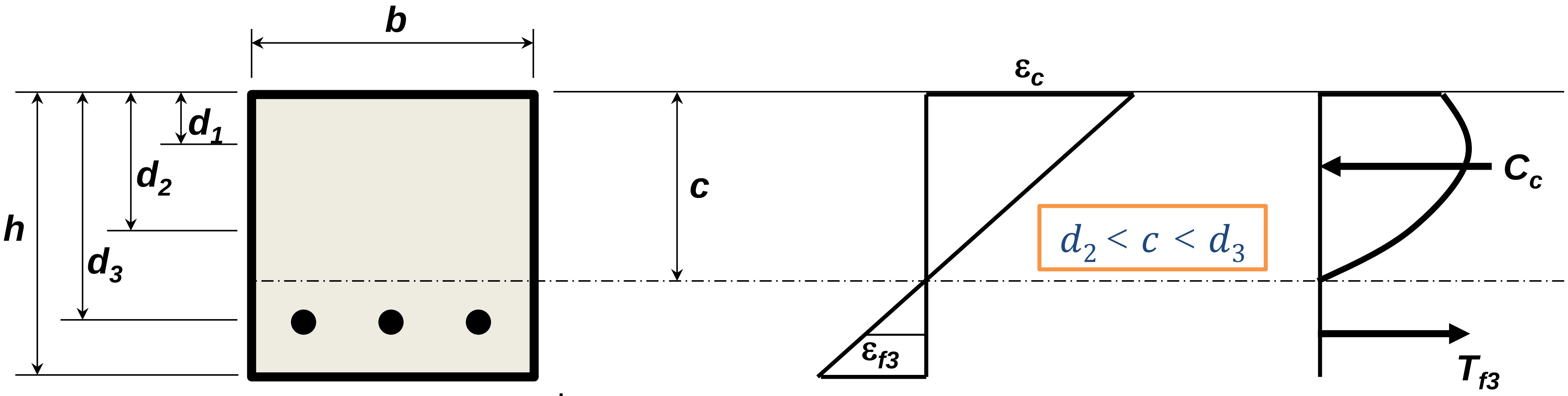

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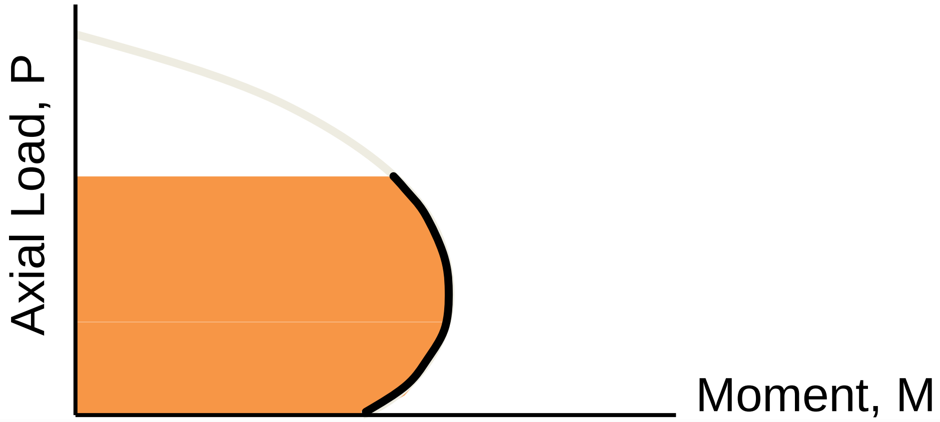
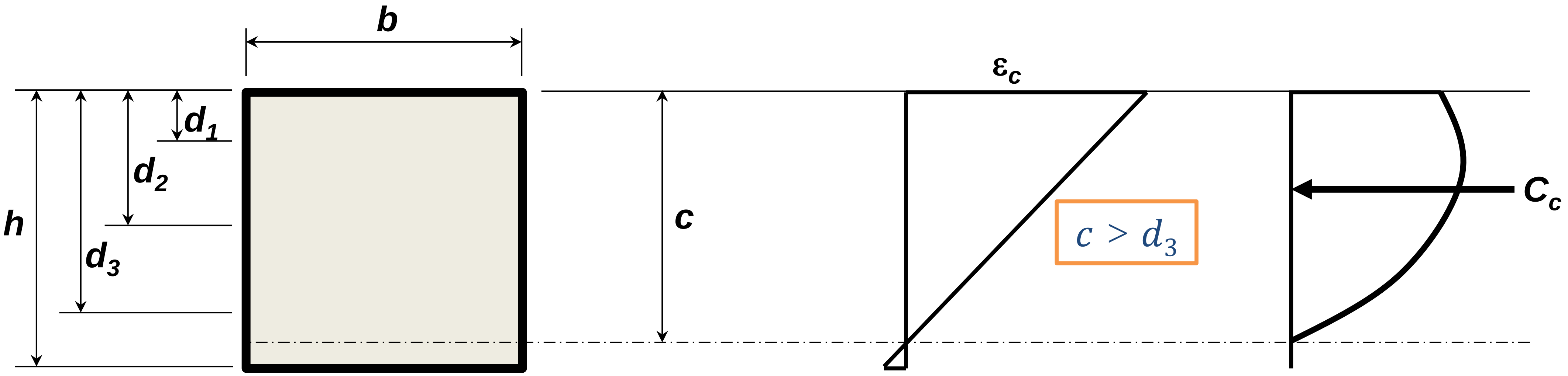
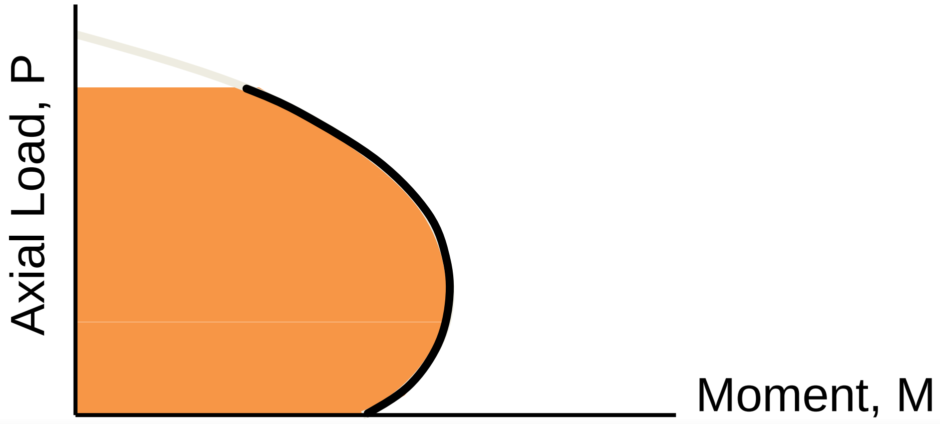


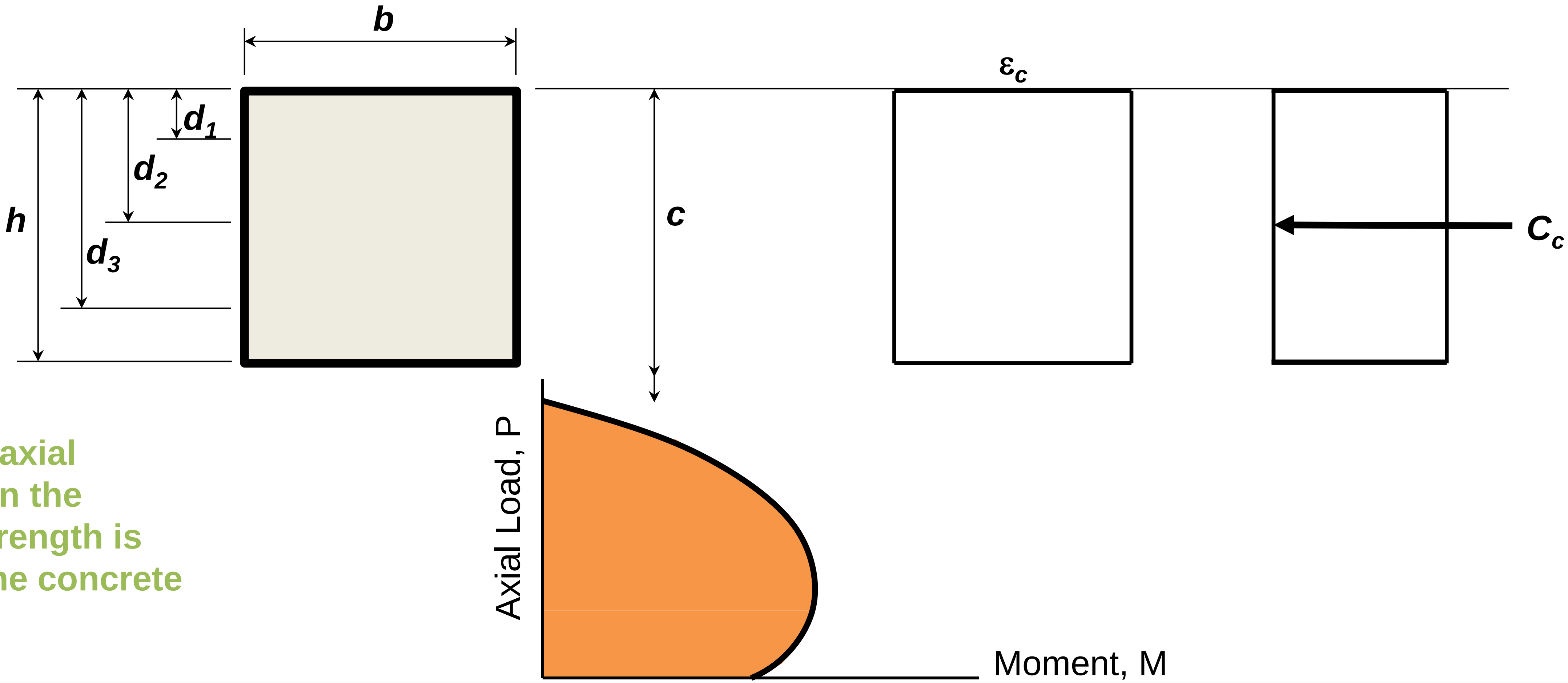
Column Design Philosophy
Section Analysis and P-M Diagram



At high levels of axial load, the GFRP bars are all in compression and are all treated as concrete

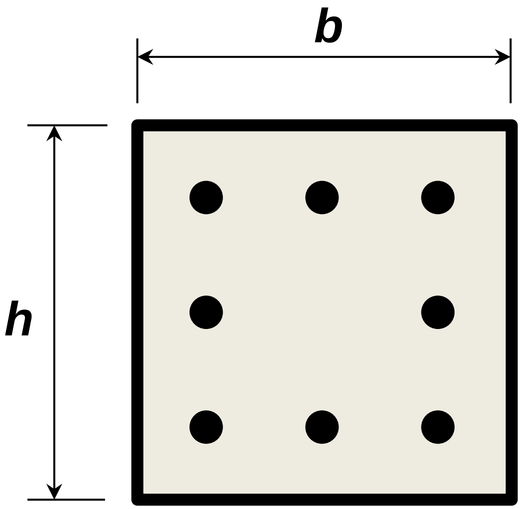


Column Design Philosophy
Section Analysis and P-M Diagram



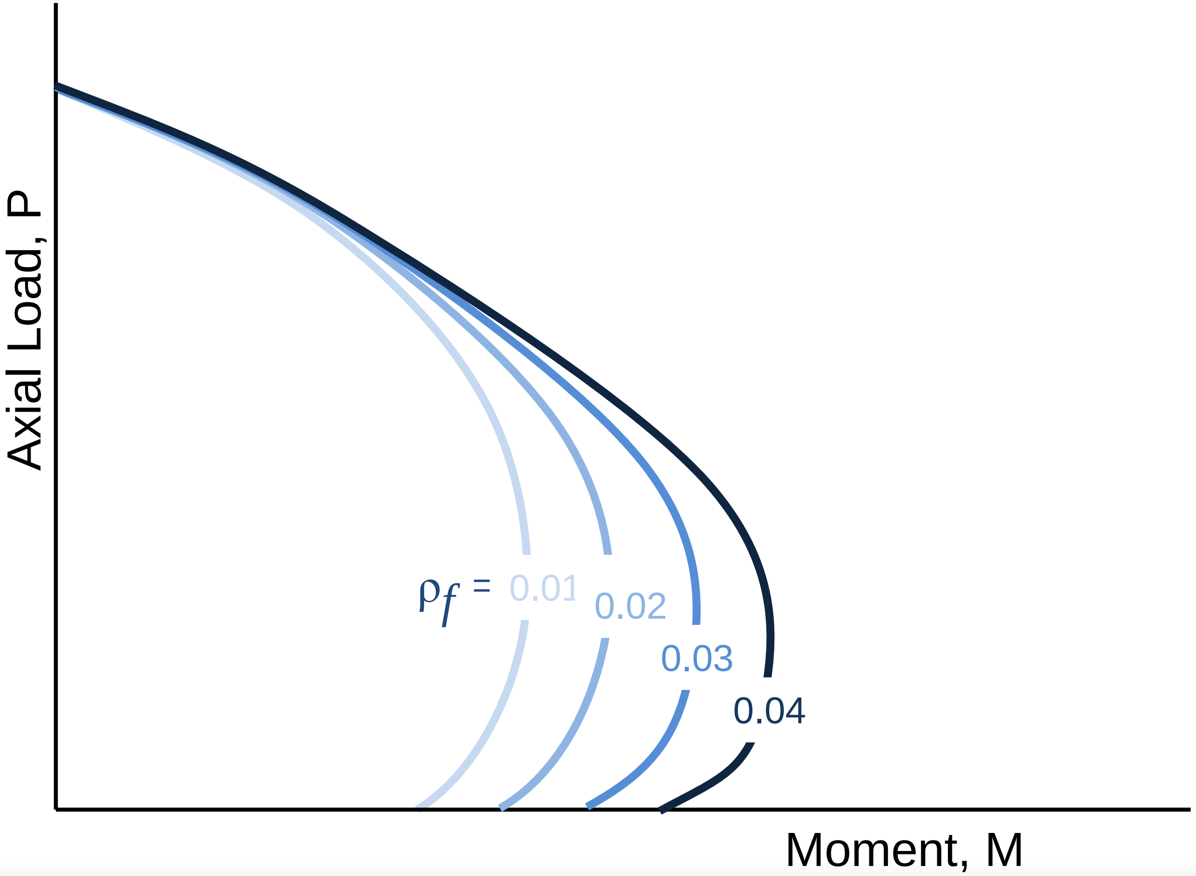
Under pure axial compression the sectional strength is limited by the concrete alone

Column Design Philosophy
Section Analysis and P-M Diagram



A_f = Total area of GFRP bars

$$\rho_f = \frac{A_f}{b\,h}$$



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Refreshment Break

- General Design Provisions for Flexure, Shear, and Axial Strength
- **Seismic Limitations**
- Structural System Requirements
- Slabs-on-Ground

Major Design Limitations
Seismic Design Categories

Seismic Design

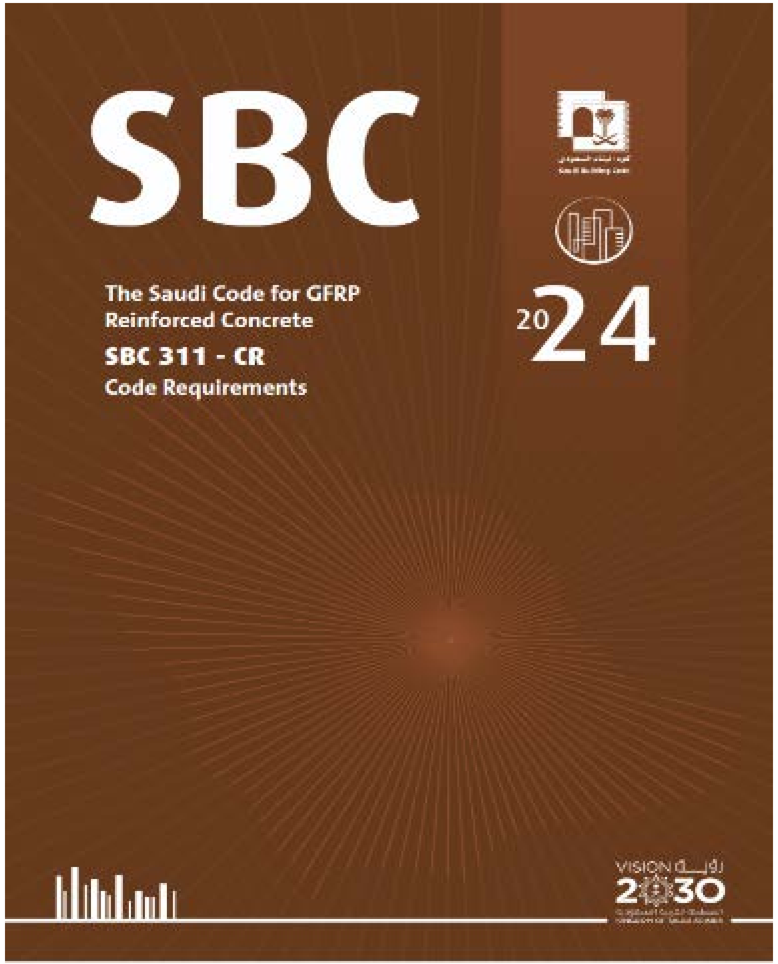
- SDC A – GFRP allowed for any structural elements
- SDC B-C – GFRP allowed only if the structural element is not part of the seismic force resisting system
- SDC D-F – GFRP not permitted in structural elements

(Note IBC language will only allow SDC A)

Major Design Considerations

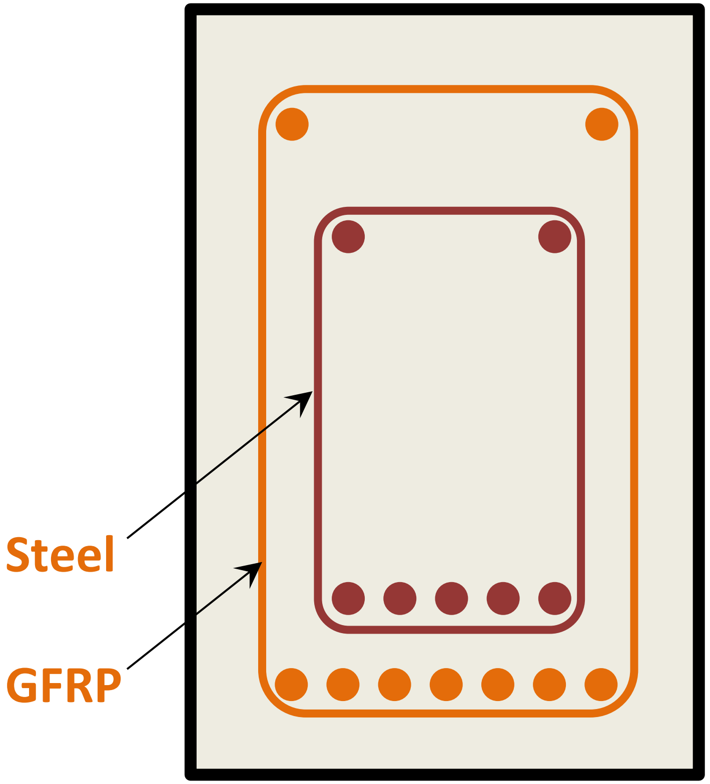
Saudi Code: SBC 311 – CR

- Detailed framework with explicit seismic requirements for GFRP
  - Capacity-limited approach for GFRP elements in seismic force resisting systems
  - Explicit requirements for GFRP in non-seismic force resisting elements
  - Additional requirements for hybrid steel/GFRP reinforced ductile elements



Hybrid Elements

- GFRP and Steel Reinforcement
  - GFRP outer cage provides durability, corrosion resistance, crack control
  - Steel inner cage provides additional strength, ductility, and fire endurance



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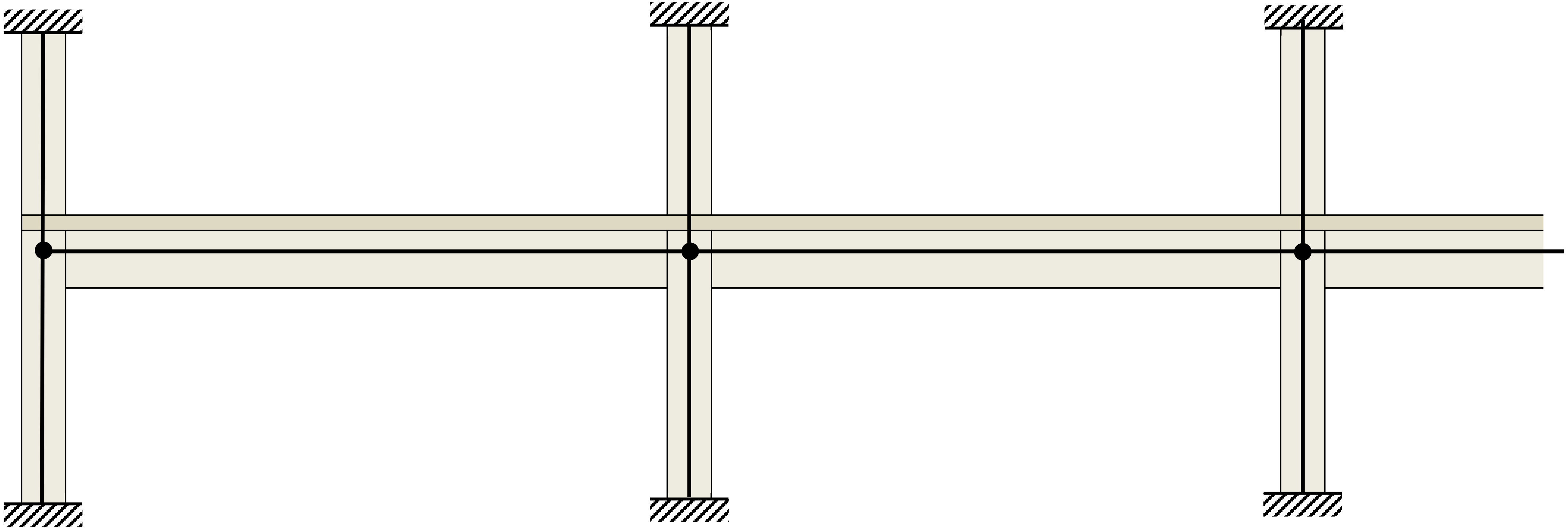
Major Differences in Design
Factored Load Analysis 6.6.3.1.

- Elastic Analysis at Factored Load Level



Major Differences in Design
Factored Load Analysis 6.6.3.1.

- Elastic Analysis at Factored Load Level

Table 6.6.3.1.1—Moment of inertia and cross-sectional area permitted for elastic analysis at factored load level

Member and condition		Moment of inertia	Cross-sectional area for axial deformations	Cross-sectional area for shear deformations
Columns		$0.4I_g$	$1.0A_g$	$b_w h$
Walls	Uncracked	$0.4I_g$		
	Cracked	$0.15I_g$		
Beams		$0.15I_g$		
Flat plates and flat slabs		$0.15I_g$		

The moments of inertia for elastic analysis are reduced from steel reinforced concrete sections due to the lower modulus of GFRP bars

Major Differences in Design
Moment Redistribution

- Moment redistribution is smaller in GFRP flexural members
  - Mainly comes from cracking of concrete
  - No yielding of the bars
- Allowed use of Direct Design Method (DDM) and Equivalent Frame Methods (EFM) relies on observed moment redistribution
- Moment redistribution is not allowed beyond that required for DDM/EFM

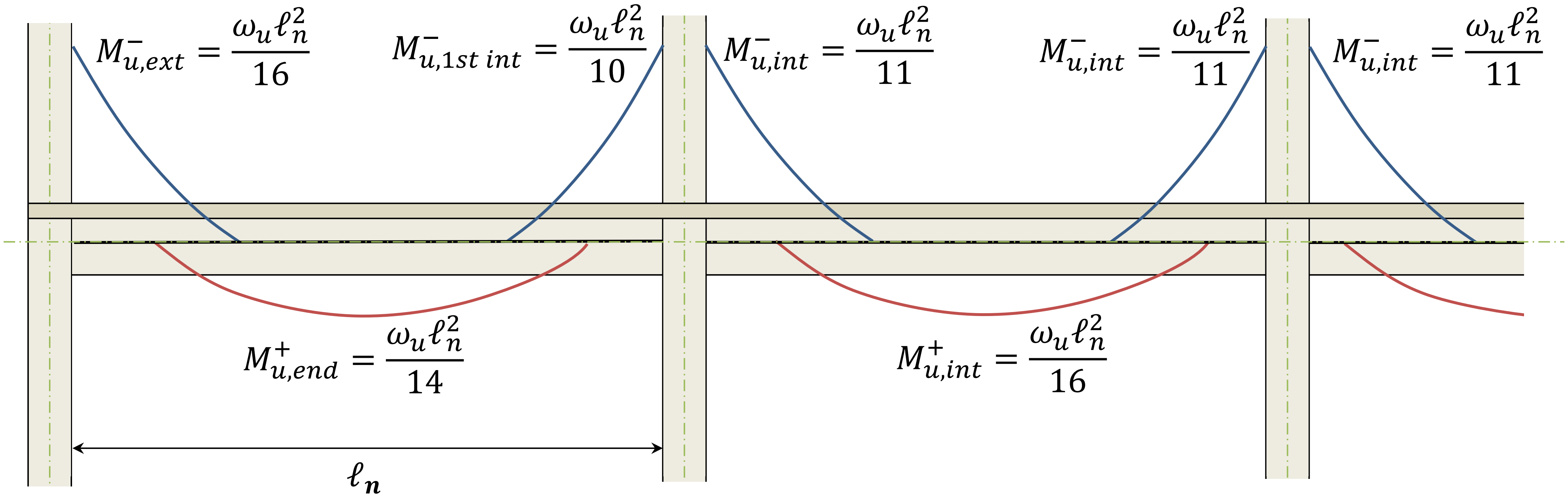
Major Differences in Design
Redistribution of Moments 6.6.5

- Redistribution of moments in continuous flexural members
  - There is some evidence of moment redistribution in GFRP RC continuous beams due to deformation/curvature
  - However, this is "Out of Scope" for ACI 440.11
  - Moment Redistribution provisions are not provided in 6.6.5

- Inelastic analysis (6.8) is also "Out of Scope"

Major Differences in Design
Simplified Method of Analysis 6.5

- Moment Coefficients – Beams Built Integrally with Columns



Workshop on Composites in Construction

Session 1: Structural Concrete Reinforced with GFRP Bars

- General Introduction to ACI CODE 440.11
- GFRP reinforcement and introduction to ASTM D7957
- General Introduction to ACI SPEC 440.5
- Fire Resistance of GFRP Reinforced Concrete

Refreshment Break

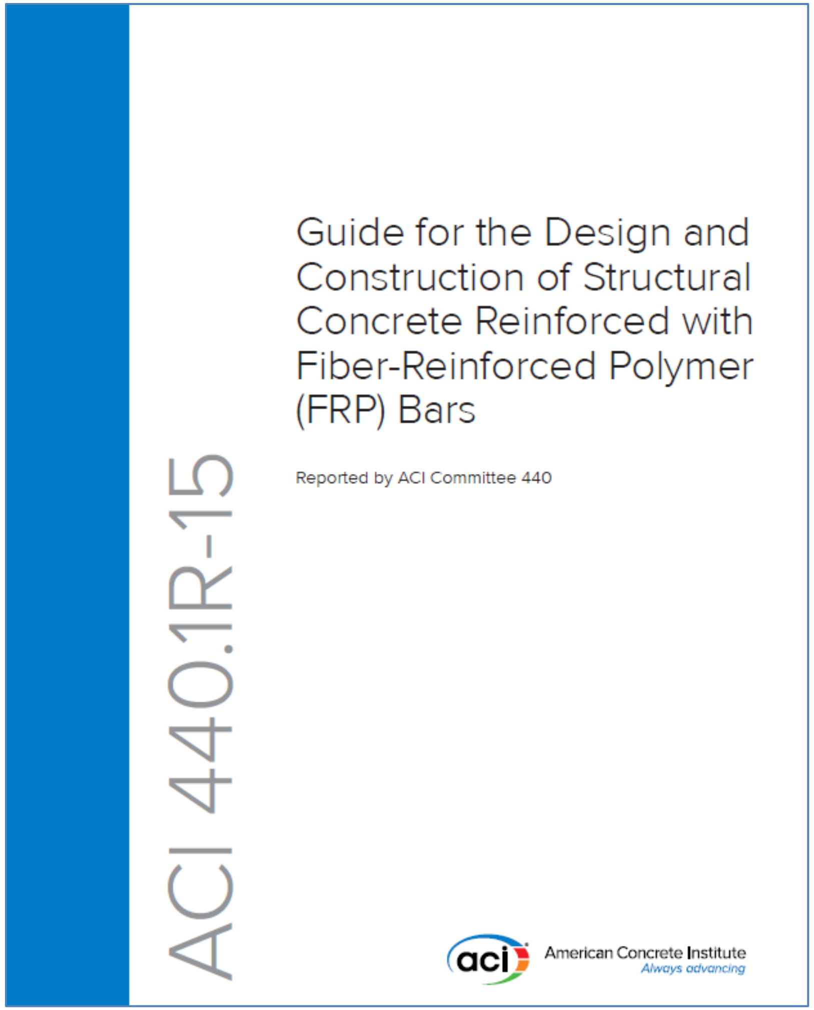
- General Design Provisions for Flexure, Shear, and Axial Strength
- Seismic Limitations
- Structural System Requirements
- **Slabs-on-Ground**

ACI/NEx MNL-6: Pre-Engineered Manual

- Pre-engineered solutions for below grade walls and slabs-on-ground
- Approach is to provide similar performance to properly designed steel-reinforced concrete slabs-on-ground

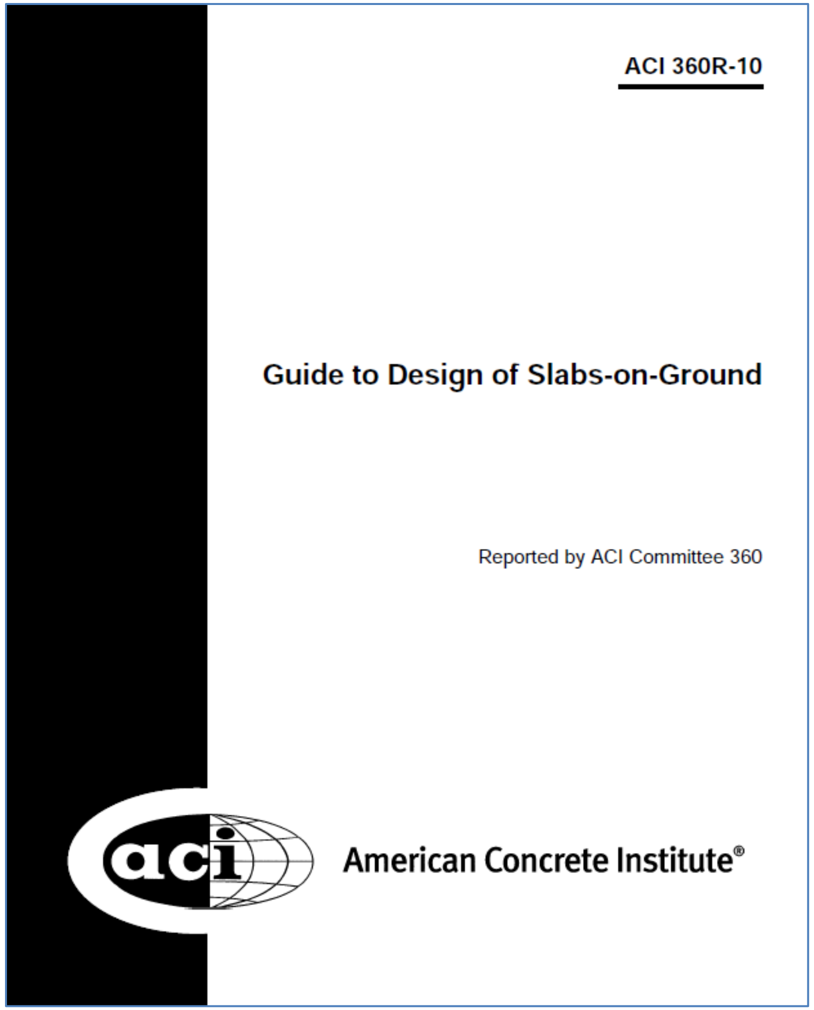
Subgrade Drag

- ACI 440.1R Appendix A uses an approach involving the subgrade drag equation.
- However, ACI 360R eliminated the use of the subgrade drag approach in 2006 due to many problematic designs.
- These were mainly due to curling stresses far outweighing subgrade drag stresses.



Enhanced Aggregate Interlock

- Current ACI 360 guidelines include an "enhanced aggregate interlock" approach.
- Here a small percentage of reinforcement is used along with contraction joints
- The reinforcement helps maintain aggregate interlock across cracked joints but does not provide so much reinforcement that the joints are not activated.



ACI 360R-10

Guide to Design of Slabs-on-Ground

Reported by ACI Committee 360

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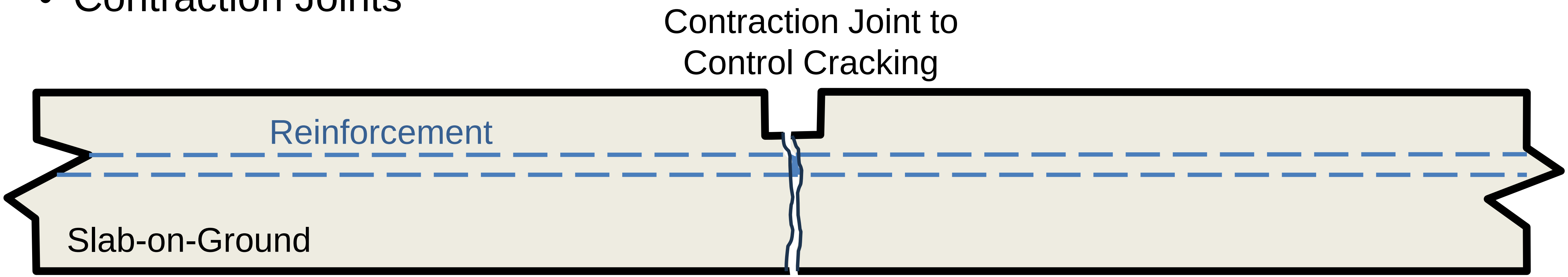
Enhanced Aggregate Interlock

- Contraction Joints



Enhanced Aggregate Interlock

- Steel ratio of 0.1% is recommended to keep the reduction in unrestrained shrinkage strain to below 3%

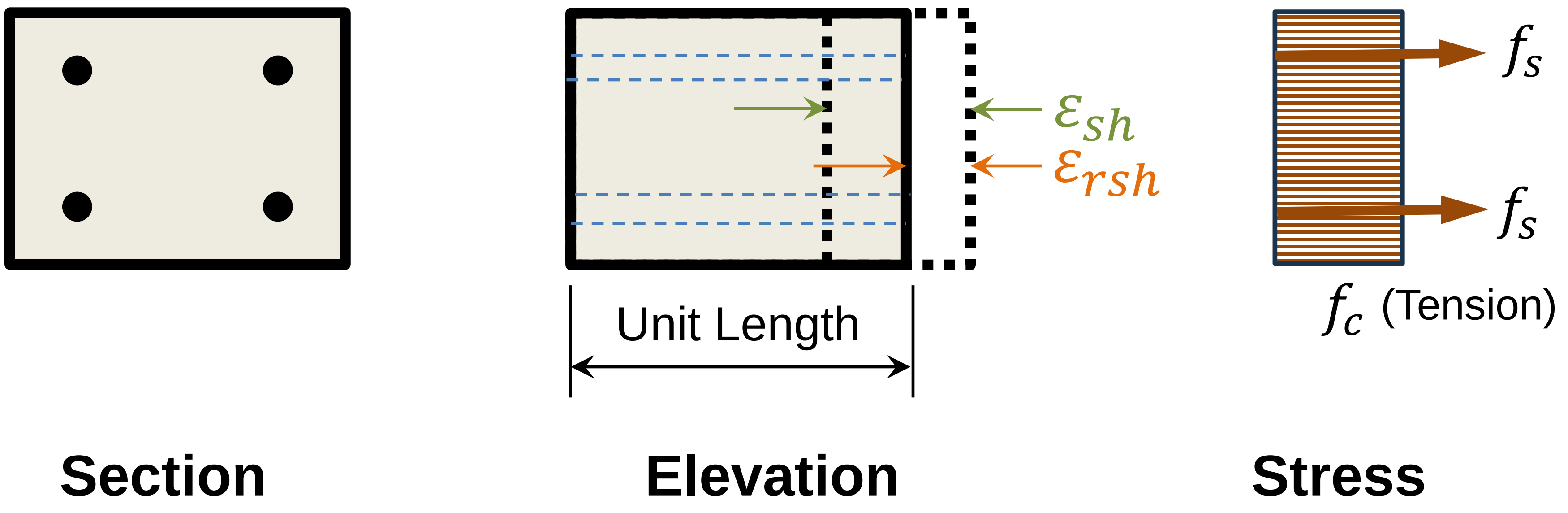
Table 6.2—Reduction in strain due to reinforcing concrete

Steel ratio, %	Concrete stress, psi (tension)	Steel stress, psi (compression)	Restrained shrinkage strain	Reduction in unrestrained shrinkage strain, %
0.1	14	14,078	0.000485	2.91
0.2	27	13,679	0.000472	5.66
0.3	40	13,303	0.000459	8.26
0.4	52	12,946	0.000446	10.71
0.5	63	12,609	0.000435	13.04
0.6	74	12,288	0.000424	15.25
0.7	84	11,983	0.000413	17.36
0.8	94	11,694	0.000403	19.35
0.9	103	11,417	0.000394	21.26
1.0	112	11,154	0.000385	23.08
3.0	229	7632	0.000263	47.37

Note: 1 psi = 0.00690 MPa.

Enhanced Aggregate Interlock

- Park and Pauley (1975)



ε_{sh} = Unrestrained shrinkage

ε_{rsh} = Shrinkage restrained by reinforcement

Enhanced Aggregate Interlock

$$f_c = \frac{\varepsilon_{sh}}{\frac{1 + C_t}{E_c} + \frac{1}{\rho_s E_s}}$$

Concrete stress

$$f_s = \frac{f_c}{\rho_s}$$

Steel stress

$$\varepsilon_{rsh} = \frac{f_s}{E_s}$$

Restrained shrinkage strain

$\varepsilon_{sh} = 0.0005$	Concrete shrinkage strain
$C_t = 2.0$	Creep coefficient
$E_c = 2900$	Concrete modulus
$E_s = 29000$	Steel modulus

ACI 360R Steel Reinforcement Ratio

Reproduction of ACI 360R-10 Table 6.2				
Steel reinf. ratio	Concrete stress (psi)	Steel stress (psi)	Restrained shrinkage strain	Reduction in unrestrained shrinkage strain
0.001	14	14078	0.000485	2.91%
0.002	27	13679	0.000472	5.66%
0.003	40	13303	0.000459	8.26%
0.004	52	12946	0.000446	10.71%
0.005	63	12609	0.000435	13.04%
0.006	74	12288	0.000424	15.25%
0.007	84	11983	0.000413	17.36%
0.008	94	11694	0.000403	19.35%
0.009	103	11417	0.000394	21.26%
0.01	112	11154	0.000385	23.08%
0.03	229	7632	0.000263	47.37%

Maximum reinforcement ratio to maintain joint activation

GFRP Equivalent

$$f_c = \frac{\varepsilon_{sh}}{\frac{1 + C_t}{E_c} + \frac{1}{\rho_f E_f}}$$

Concrete stress

$$f_f = \frac{f_c}{\rho_f}$$

GFRP stress

$$\varepsilon_{rsh} = \frac{f_f}{E_f}$$

Restrained shrinkage strain

$\varepsilon_{sh} = 0.0005$	Concrete shrinkage strain
$C_t = 2.0$	Creep coefficient
$E_c = 2900$	Concrete modulus
$E_f = 6500$	GFRP modulus

Equivalent GFRP Reinforcement Ratio

GFRP Equivalent of ACI 360R-10 Table 6.2				
GFRP reinf. ratio	Concrete stress (psi)	GFRP stress (psi)	Restrained shrinkage strain	Reduction in unrestrained shrinkage strain
0.001	3	3228	0.000497	0.67%
0.002	6	3207	0.000493	1.33%
0.003	10	3186	0.000490	1.98%
0.004	13	3165	0.000487	2.62%
0.00445	14	3156	0.000485	2.91%
0.006	19	3124	0.000481	3.88%
0.007	22	3104	0.000478	4.50%
0.008	25	3084	0.000474	5.10%
0.009	28	3065	0.000471	5.71%
0.01	30	3045	0.000468	6.30%
0.03	81	2704	0.000416	16.79%

ASTM D7957 Bars
E_f = 6,500 ksi

Maximum reinforcement ratio to maintain joint activation

Equivalent GFRP Reinforcement Ratio

GFRP Equivalent of ACI 360R-10 Table 6.2				
GFRP reinf. ratio	Concrete stress (psi)	GFRP stress (psi)	Restrained shrinkage strain	Reduction in unrestrained shrinkage strain
0.001	4	4311	0.000496	0.89%
0.002	9	4273	0.000491	1.77%
0.003	13	4236	0.000487	2.63%
0.00333	14	4223	0.000485	2.91%
0.005	21	4163	0.000478	4.31%
0.006	25	4127	0.000474	5.12%
0.007	29	4092	0.000470	5.93%
0.008	32	4058	0.000466	6.72%
0.009	36	4024	0.000463	7.49%
0.01	40	3991	0.000459	8.26%
0.03	103	3425	0.000394	21.26%

ASTM D8508 Bars
E_f = 8,700 ksi

Maximum reinforcement ratio to maintain joint activation

ACI/NEx MNL-6: Pre-Engineered Manual

Spacing Each Way of GFRP Bars in Slabs-on-Ground			
Slab Thickness	No. 3 Bars	No. 4 Bars	No. 5 Bars
3.5 in.	10 in.	18 in.	NR
4 in.	8 in.	16 in.	25 in.
4.5 in.	7 in.	14 in.	22 in.
5 in.	7 in.	13 in.	20 in.
5.5 in.	6 in.	11 in.	18 in.

Note: NR indicates not recommended. No. 5 bars in a 3.5 in. thick slab do not allow for adequate cover and placement in the upper one-half of the slab depth.

MNL-6 GFRP Reinforcement Ratios

Associated Reinforcement Ratios			
Slab Thickness	No. 3 Bars	No. 4 Bars	No. 5 Bars
3.5 in.	0.00314	0.00317	
4 in.	0.00344	0.00313	0.00310
4.5 in.	0.00349	0.00317	0.00313
5 in.	0.00314	0.00308	0.00310
5.5 in.	0.00333	0.00331	0.00313

Note: NR indicates not recommended. No. 5 bars in a 3.5 in. thick slab do not allow for adequate cover and placement in the upper one-half of the slab depth.

MNL-6 GFRP Cover

- ACI 440.11 recommends 1-1/2 in. or $2d_b$ as minimum cover in exterior environments to allow sufficient cover to restrain volumetric changes under thermal cycles
- Also need adequate cover to allow for sawcut contraction joints to be installed without damaging the bars
- MNL-6 stipulates 1-1/2 in. minimum cover

- Be aware that GFRP bars float!

ACI/NEx MNL-6: Pre-Engineered Manual

- GFRP reinforced slabs-on-ground
- Similar performance to properly designed steel- -ground
- Based on enhanced aggregate interlock
- Adequate cover
- Non-corrosive and durable

Workshop on Composites in Construction

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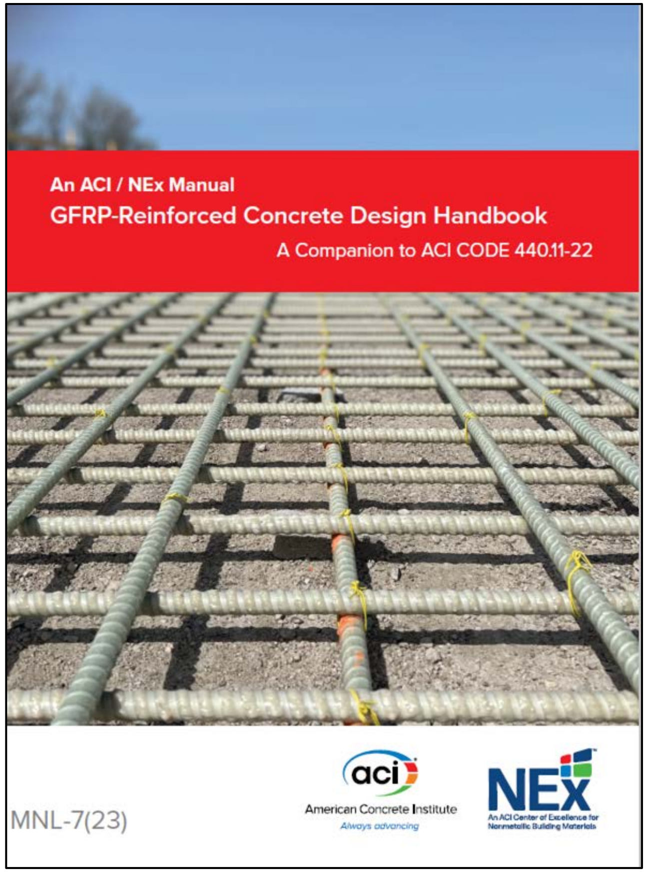
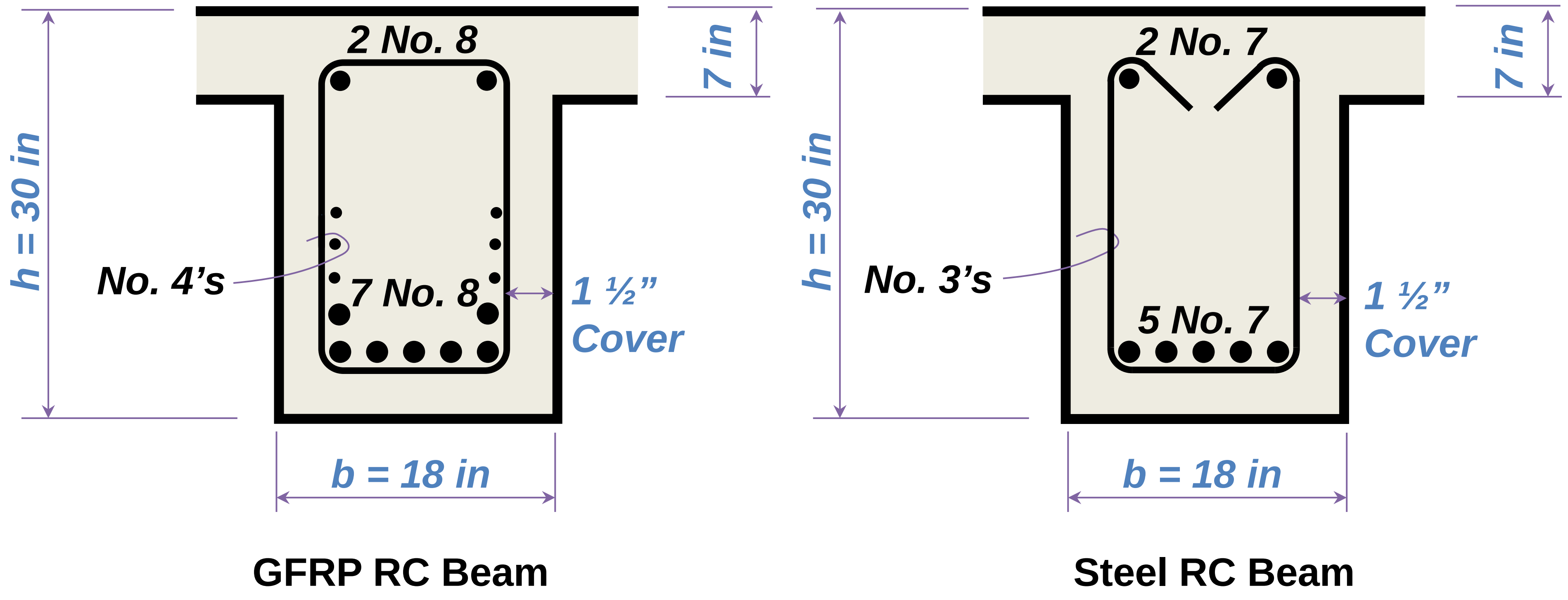
Additional Resources
ACI/NEx MNL-7



- Design Handbook to Accompany 440.11
  – T Beam examples
  – Shear and Torsion examples
  – Two-way slab example
  – Column examples
  – Wall example
  – Foundation and retaining wall examples
- Comparative Examples to MNL-17

GFRP Reinforced Concrete Design Handbook Comparison

- Continuous Interior T Beam Example



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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