Writing Special Provisions for FRP Strengthening Projects

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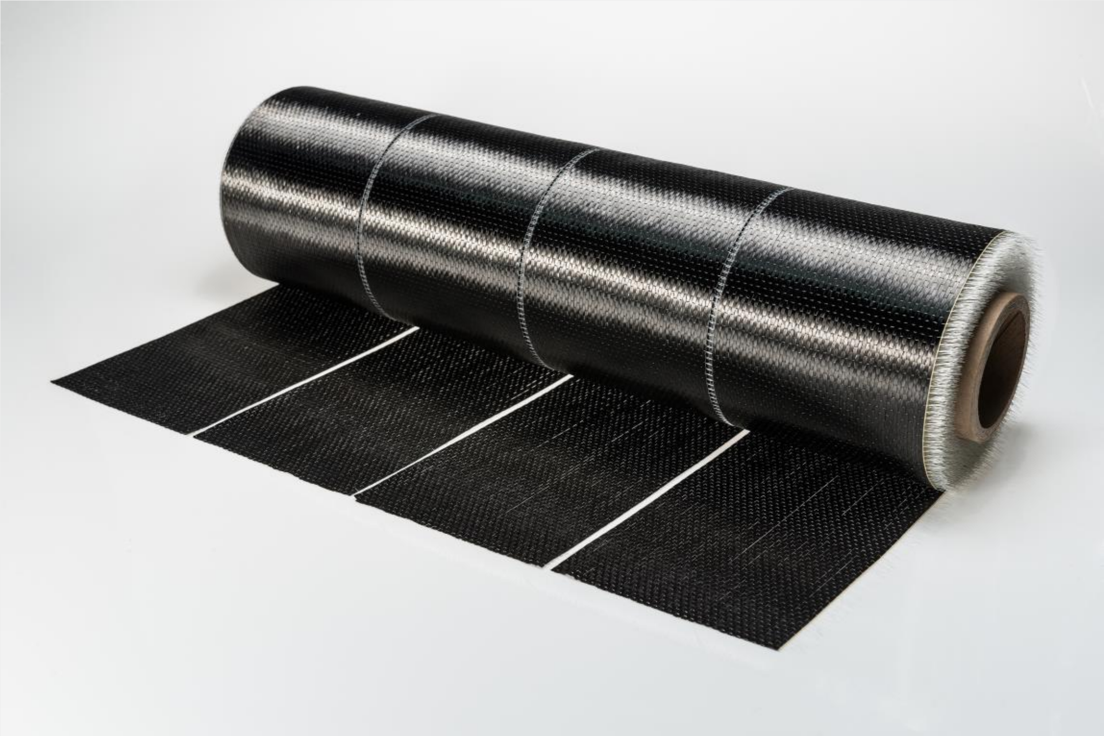
The Basics

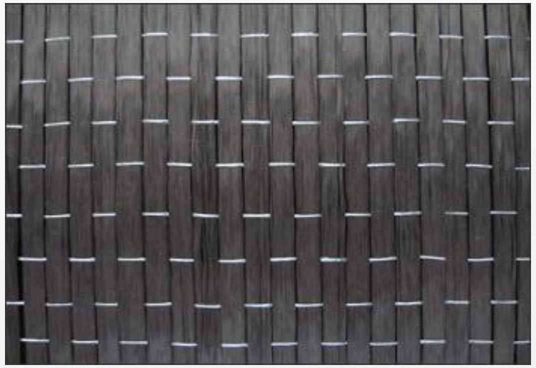
- FRPs are externally bonded to or wrapped around existing concrete or steel members to increase their strength or seismic performance.

- FRPs are used where additional rebar or steel plates are desired.

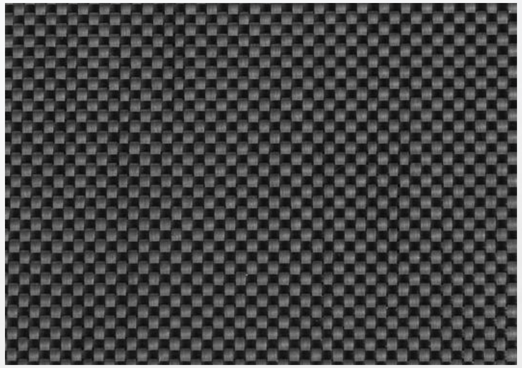
- FRPs compete with many strengthening techniques but are often the most attractive solution.



Common Strengthening Forms



Unidirectional Fabrics



Multi-directional Fabrics

- Bi-directional (0/90)
- Bi-Ax (± 45)

Pre-cured FRPs

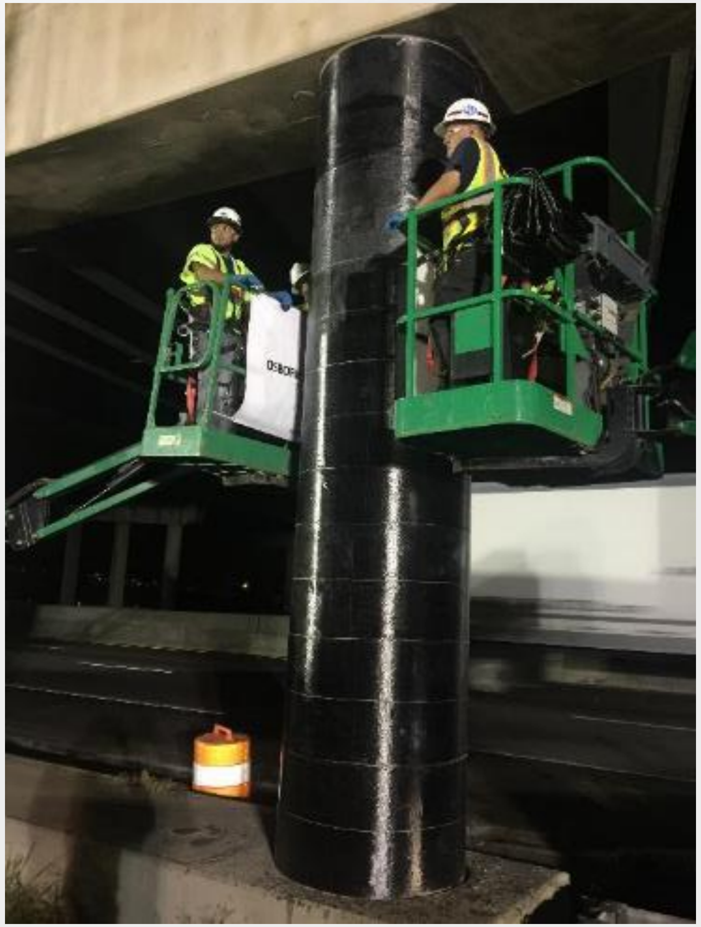
- Strand Sheets
- CFRP Plates

NSM

- CF Bars
- CF Tapes

How DOT's Use FRP Strengthening Systems

Pier Column Strengthening



How DOT’s Use FRP Strengthening Systems

Pier Cap Strengthening

Girder Strengthening

CFRP U-wraps used for shear strengthening of concrete girder

How DOT's Use FRP Strengthening Systems

AASHTO Girder Repairs

How DOT's Use FRP Strengthening Systems

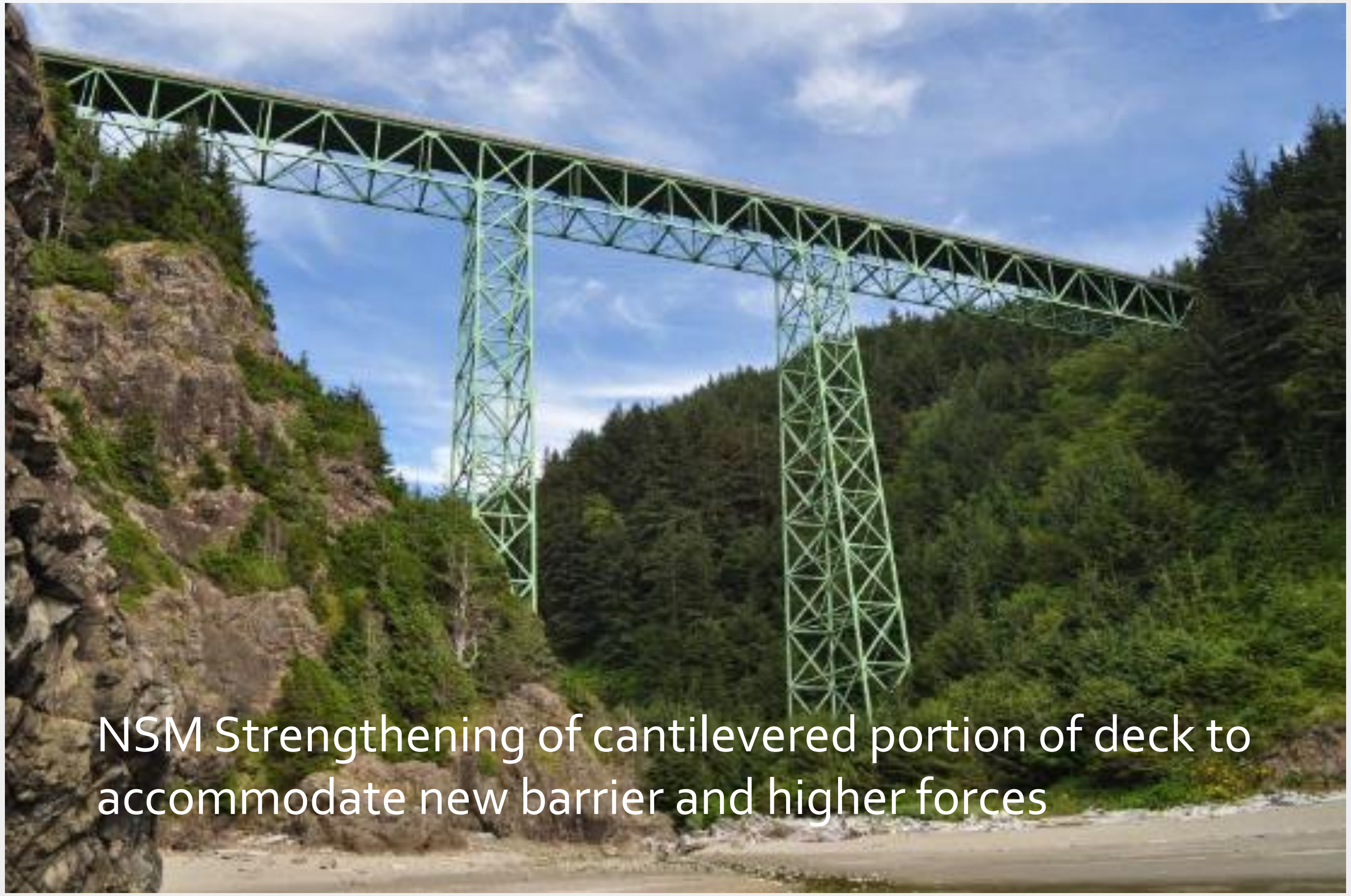
Deck Strengthening



Negative moment strengthening of deck slab using CF Bars installed in NSM slots

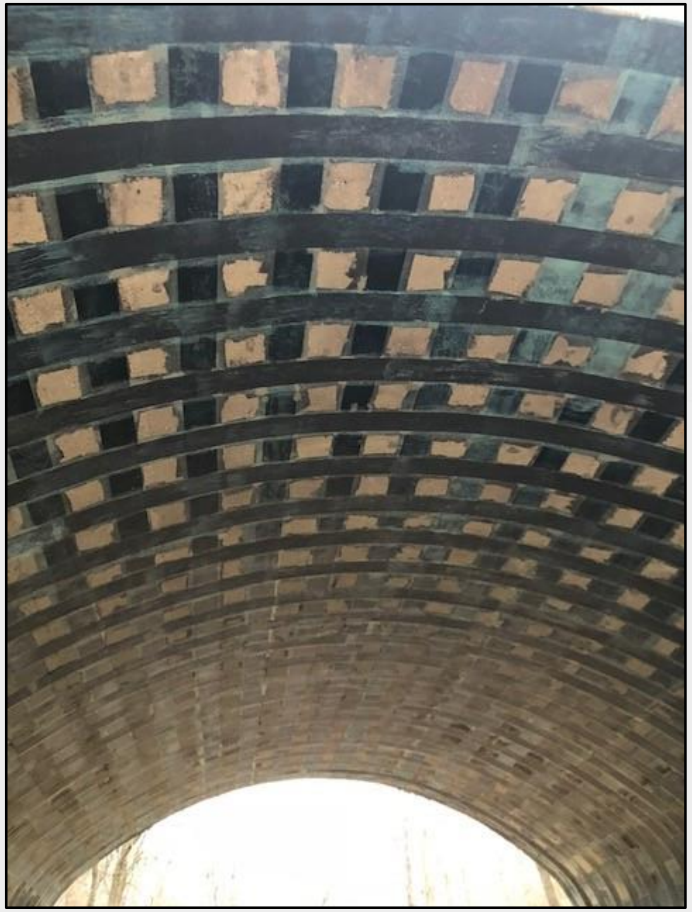
How DOT’s Use FRP Strengthening Systems

Deck Strengthening



NSM Strengthening of cantilevered portion of deck to accommodate new barrier and higher forces

Arch Slab Strengthening



Protection, Spall Repair Confinement

How DOT’s Use FRP Strengthening Systems

Steel Member Strengthening

How DOT’s Use FRP Strengthening Systems

Steel Member Strengthening

UHM CFRP Strand Sheets used to restore lost cross-section

Conclusions

Structural Applications

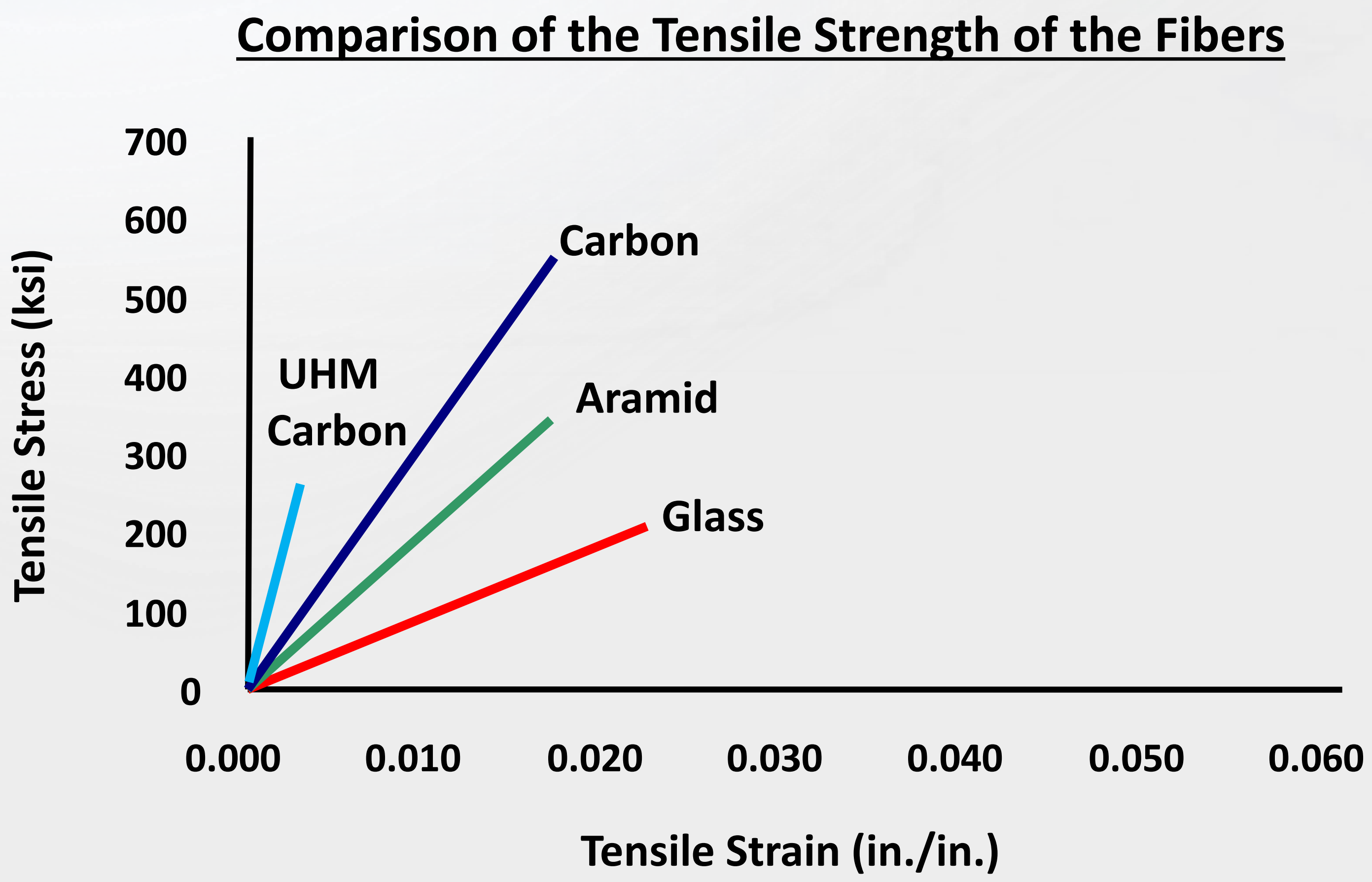
- Pier Caps
- Pier Columns
- Girders
- Decks
- Piling
- Steel Members

Non-Structural Applications

- Spall confinement
- Waterproofing

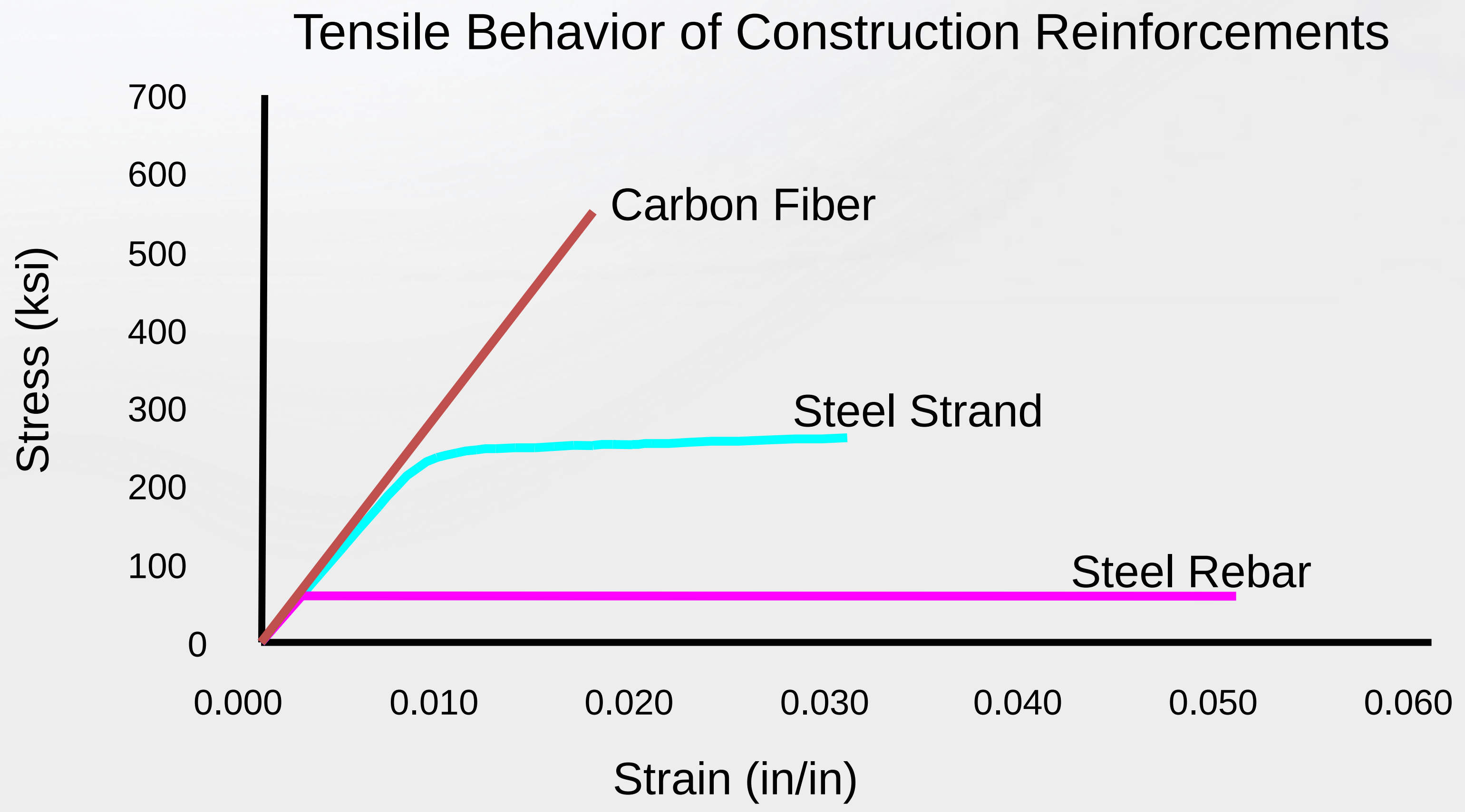
FRP Design Basics

Material Properties



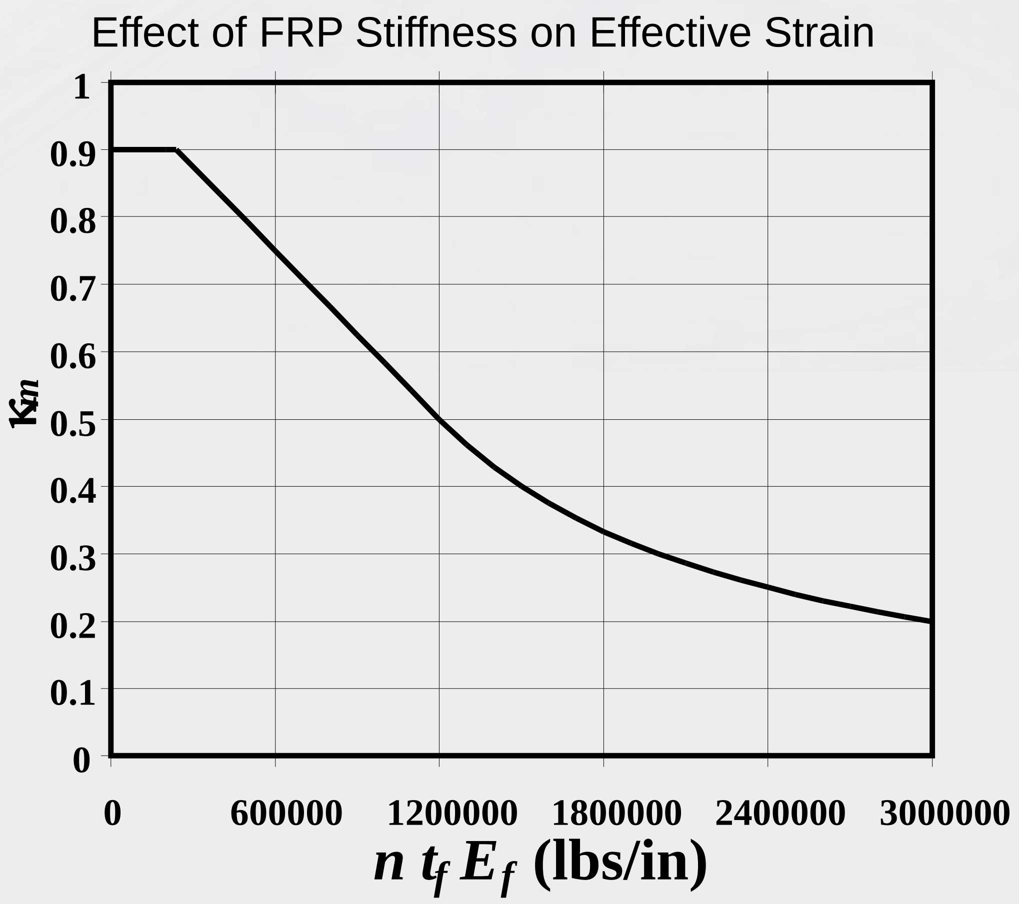
FRP Design Basics

Material Properties

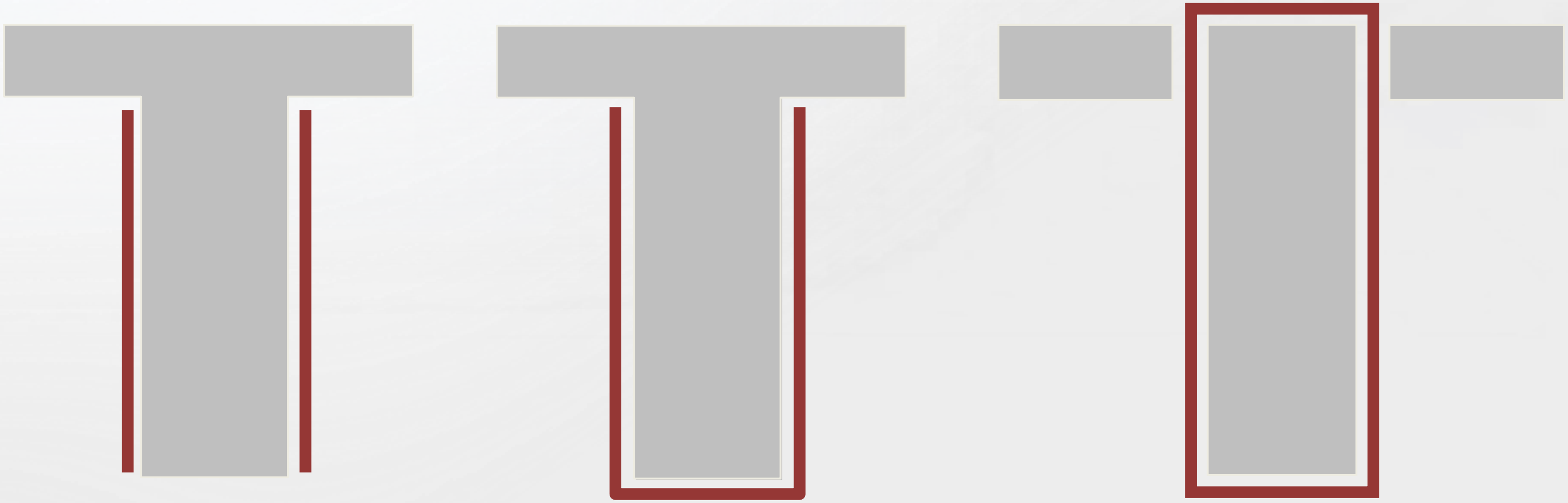


Flexure

- Most bond applications are controlled by…
  - FRP rupture
  - Concrete failure
  - Debonding of FRP
- The more layers of FRP used, the more likely debonding will control
- The more layers of FRP, the less efficient each layer becomes
- Increasing FRP stiffness lowers the effective strain of the FRP



Shear



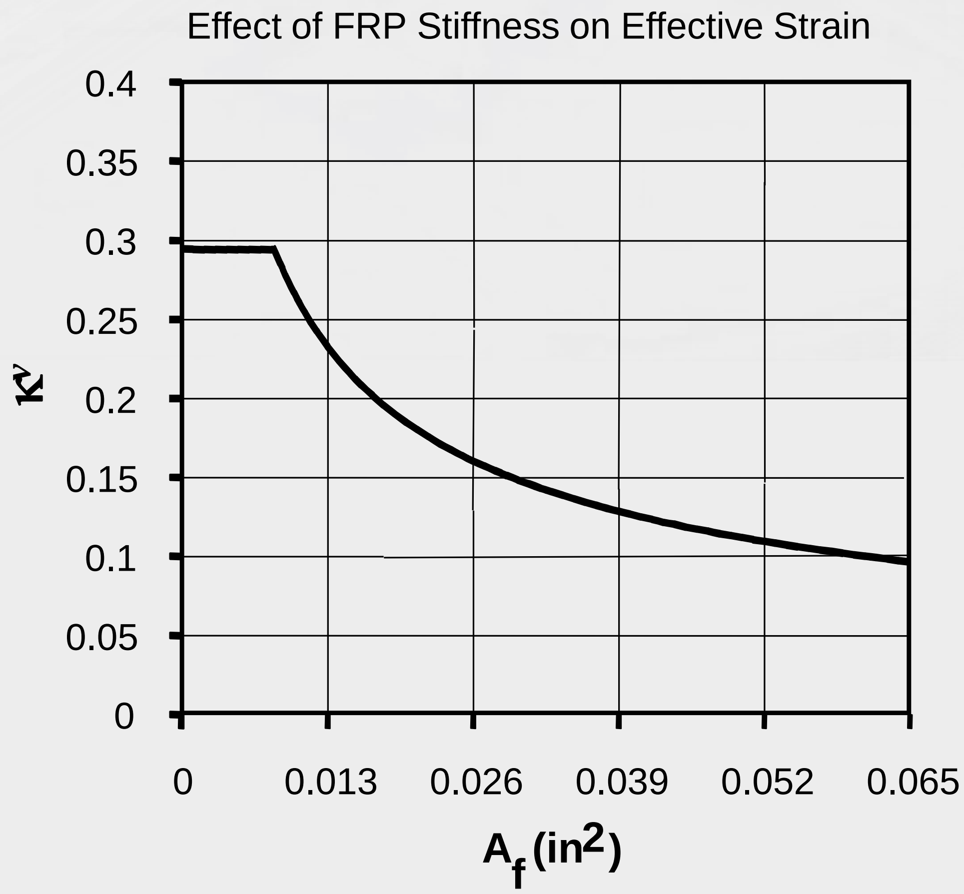
Two-sides | U-wrap | Fully Wrapped

GOOD | **BETTER** | **BEST**

FRP Design Basics

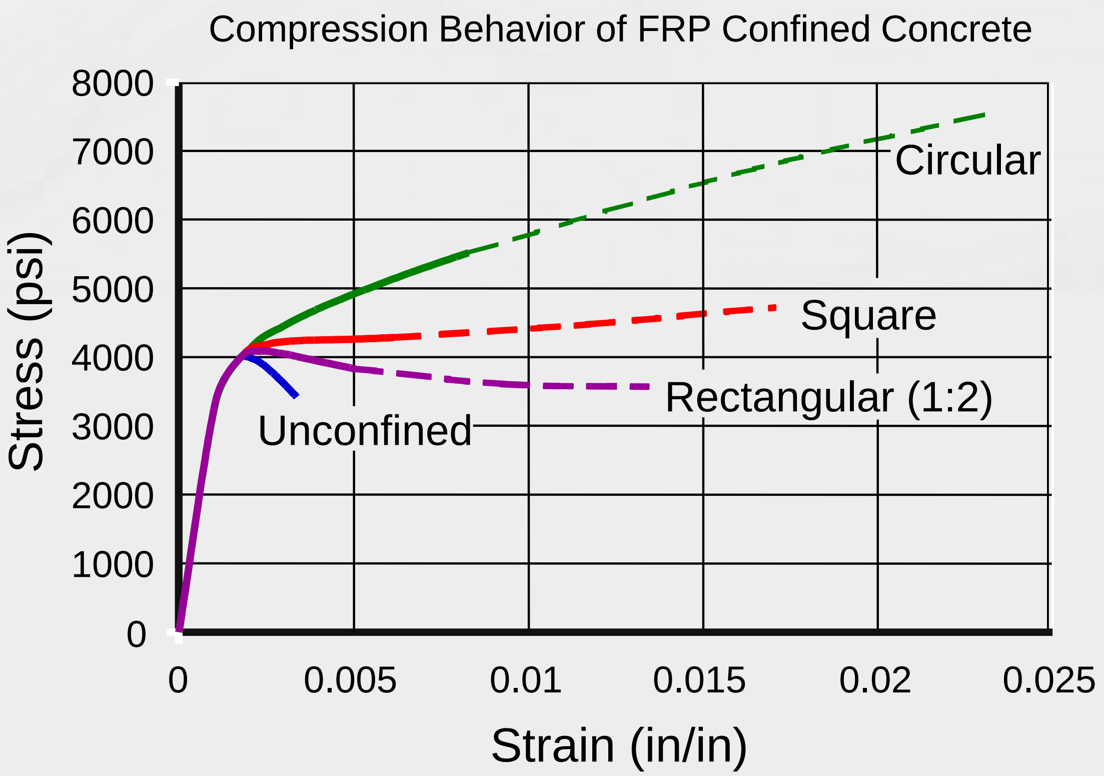
Shear

- Most bond applications are controlled by…
  - Debonding of FRP
  - Concrete shear failure
- Strain in FRP is limited to 0.004 to prevent loss of aggregate interlock
- The more layers of FRP used, the more likely debonding will control
- The more layers of FRP, the less efficient each layer becomes
- Increasing FRP stiffness lowers the effective strain of the FRP



Axial Enhancement

- Fibers oriented <u>transverse</u> to the longitudinal axis of the member
- Results in an increase in the apparent strength of the concrete and in the maximum usable compressive strain in the concrete
- Passive confinement: Intimate contact between FRP system and member is critical
- Improves ductility of column
- Practical limit is based on service stress
- Strain in FRP is limited to 0.004 to guard against shear failure

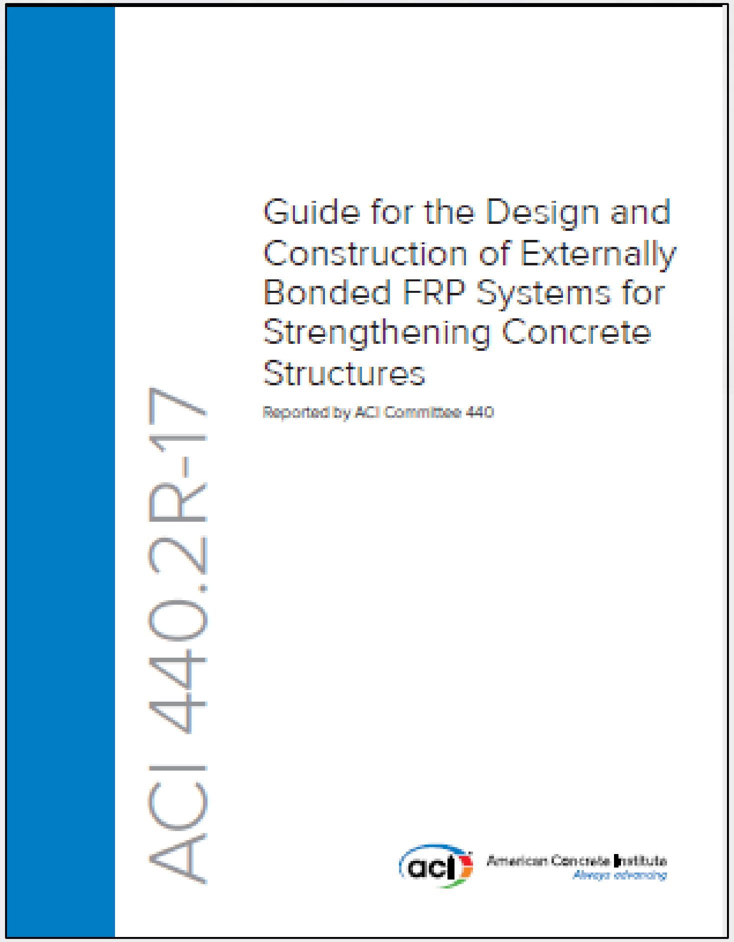


Specifying and Detailing

Sources of Information

ACI 440.2R-17

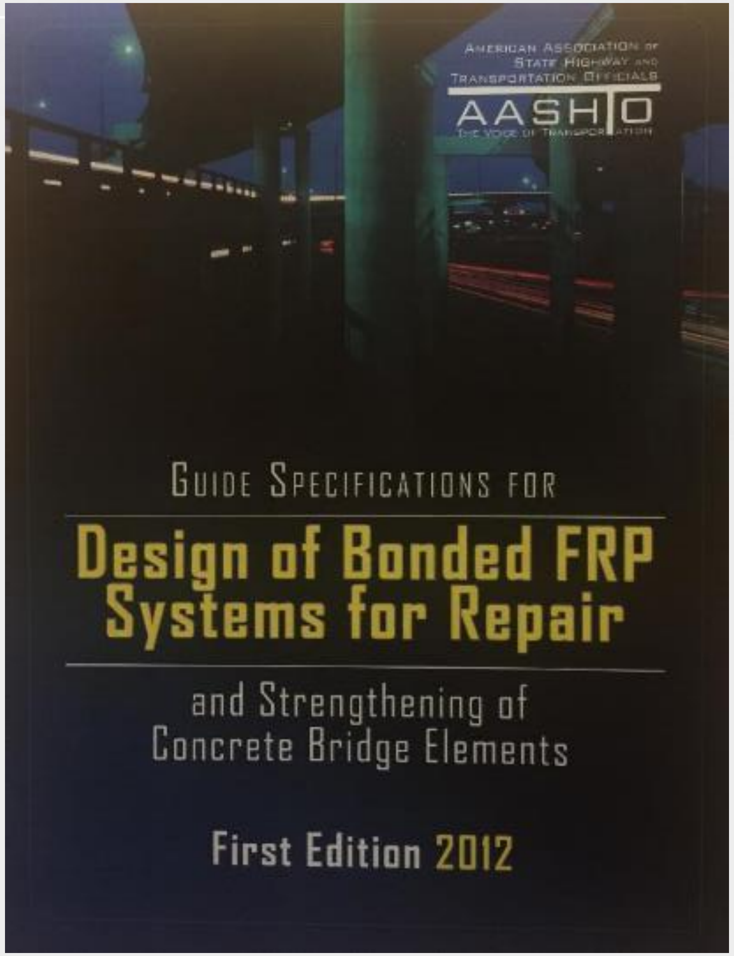
- Design guide for concrete strengthening since 2002
- 2017 edition includes seismic provisions
- Emphasis on buildings
- Includes provisions for NSM strengthening
- Limited info on anchors
- Technote to address confusion surrounding the UL-Listings for fire



Sources of Information

AASHTO Guide Specification

- Similar to ACI 440.2R
- Includes design equations for flexure, shear/torsion, and axial strengthening
- Designs made with AASHTO are different from those made with ACI 440 (BEWARE)
- Never specify both ACI 440 and AASHTO guides on a project!



Sources of Information
AASHTO Guide Spec

- Peeling requirement appears more academic than practical
- Cannot be quantified in practice
- Suppliers do not report shear modulus values of the resin
- Bond line thickness (while important) is not measured or controlled in the field.
- How to QC this?

3.4.3.2—Reinforcement End-Termination Peeling

The peel stress at the point of end-termination of externally bonded reinforcement shall meet the following requirement:

$$f_{peel} \leq 0.065\sqrt{f'_c} \qquad (3.4.3.2\text{-}1)$$

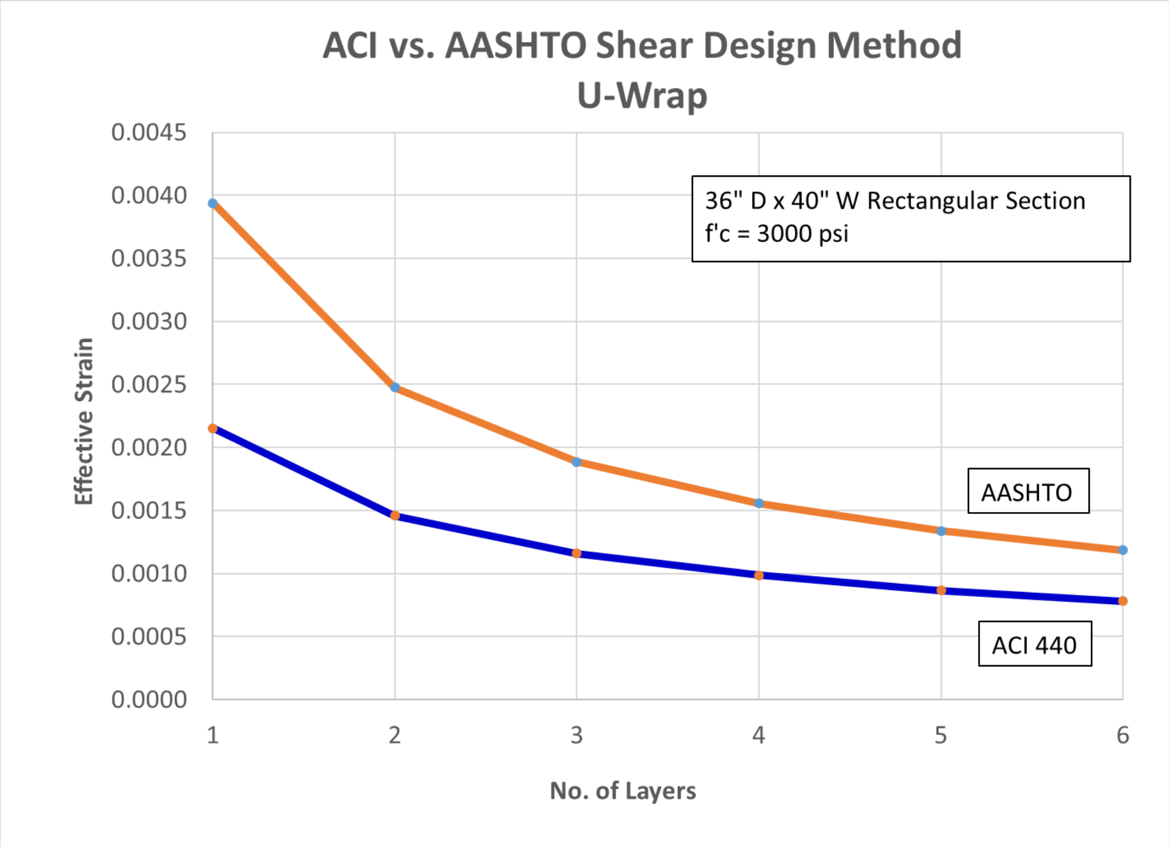
which

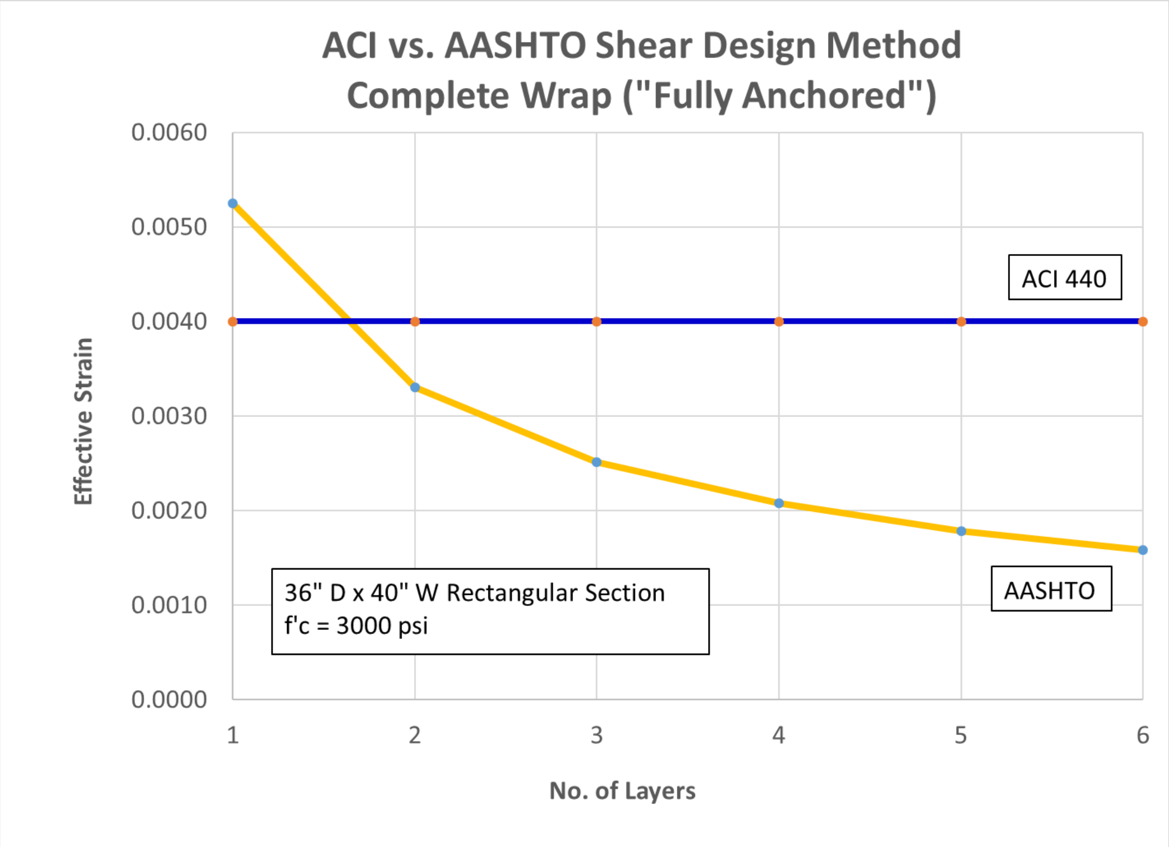
$$f_{peel} = \tau_{av}\left[\left(\frac{3E_a}{E_{frp}}\right)\frac{t_{frp}}{t_a}\right]^{\frac{1}{4}} \qquad (3.4.3.2\text{-}2)$$

$$\tau_{av} = \left[V_u + \left(\frac{G_a}{E_{frp}t_{frp}t_a}\right)^{\frac{1}{2}} M_u\right]\frac{t_{frp}(h-y)}{I_T} \qquad (3.4.3.2\text{-}3)$$

Sources of Information

AASHTO vs. ACI





Sources of Information

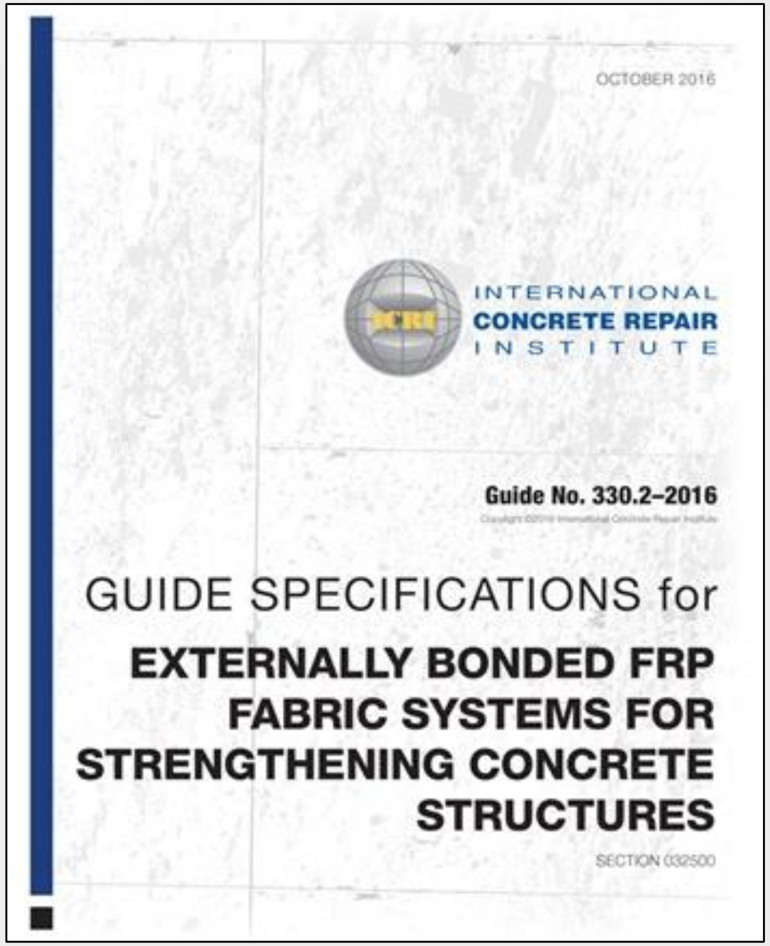
ICRI Guide 330.2-2016

- ICRI 330 Committee composed entirely of engineers, contractors, and material suppliers.

- Based largely on the contents of the ACI 440.2R guide <u>and the collective experience of committee members</u>

- It's a special provision for buildings!

- Covers fabric FRP systems (NSM soon to be released)


OCTOBER 2016

INTERNATIONAL CONCRETE REPAIR INSTITUTE

Guide No. 330.2–2016

GUIDE SPECIFICATIONS for

EXTERNALLY BONDED FRP FABRIC SYSTEMS FOR STRENGTHENING CONCRETE STRUCTURES

SECTION 032500

Phases in a Typical Project

1. Condition survey
2. Analyze structure and determine members/sections that require strengthening
3. Determine if FRP is feasible
4. Design FRP
5. Shop drawings and specifications
6. Review submittals
7. Inspect installation

Structural Analysis Phase – Role of EOR

- EOR will nearly always be responsible for the condition assessment and analysis of the structure
  - Design-build projects are more unique
- Determine location and magnitude of deficiencies
- Verify if FRP can be used
- Determine who will be responsible for FRP design (EOR or Contractor)
- Prescriptive or performance special provision?
  - Most projects combine performance and prescriptive elements
- Where will information be communicated (drawing notes, special provision)

Structural Analysis Phase – Role of EOR

1) Verify if FRP can be used before specifying

Unstrengthened member checks:

- ACI 440.2R: $(\phi R_n)_{existing} \geq (1.1DL + 0.75LL)_{new}$
- AASHTO: $(R_r)_{existing} \geq \eta_i[(DC + DW) + (LL + IM)\ ]_{new}$

(Guards against over-strengthening and collapse if FRP fails)

2) Is application bond-critical or contact-critical?
   - Impacts design, detailing, installation and inspection
   - f'c > 2000 psi for bond-critical

Where to Communicate FRP Requirements?

- FRP special provision is part of a large project manual
  - Project manual includes specifications on concrete repair, crack injection, etc.

- FRP requirements are shown as part of the general notes on the plans

- Drawing notes accompanying the FRP details

Prescriptive Specifications

EOR designs FRP system

- On plans, EOR provide all details of FRP system
  - Number of plies
  - Ply width
  - Ply orientation
  - Anchors
- EOR specifies an acceptable FRP product(s) or minimum properties
- Contractor submits products meeting specification
  - Sealed calculations/shop drawings usually not required

Commonly used for non-structural applications like confinement of spalls or protection where no design calculations are made

Performance Specifications

EOR defines performance requirements and Contractor designs FRP system

- EOR specifies requirements at sections to be strengthened
- EOR provides all necessary information at sections to be strengthened to complete FRP design.
- EOR specifies minimum properties of FRP system
- EOR requires contractor to submit product data, design calculations and shop drawings
- If details are unknown, EOR needs to provide guidance

Used on the majority of all FRP projects, especially structural applications

Specifying the Member Requirements

1) Provide FRP equivalent to calculated additional rebar
   - For example, provide FRP equivalent to #5 @ 12 o.c.
   - Must require FRP design to be based on effective strain per ACI 440 and include FRP reduction factors (C_e, ψ_f)

2) Specify strengths to be provided by FRP ($\psi_f M_f$, $\psi_f V_f$, etc.)
   - Include all information to make a design (dimensions, rebar layout, etc.)

3) Specify desired member strengths (ϕM_n, ϕV_n, etc.)
   - Include all information to make a design (dimensions, rebar layout, etc.)
   - Include unfactored dead and live loads to do service checks

Required Information for Performance Specifications

- Location of all sections to be strengthened
- Dimensions of existing sections and framing plan
- Sufficient dimensions to be able to do a take-off
- Existing reinforcement layout and grade
- Existing concrete strengths
- Be careful when including quantities in bill of material
  - Coverage area (1 ply) or area of material

Include all the information used to determine their was a deficiency.

The FRP Engineer will need to design the FRP

Specifying the General Requirements

Submittals

- Only require submittals that will be reviewed
- Product technical data sheets
- Select test reports, installation guides, SDS, etc.
- Shop drawings
  - Needed for performance specifications
- Engineering calculations
  - Make sure they are really required
  - May be needed to show products meet minimum requirements or equivalency
- Avoid requiring sealed drawings/calculations to be submitted with bid.

Payment Basis and Warranty

PAYMENT BASIS

- Lump sum is common and should cover all materials, labor, equipment work to complete the job
- Unit price basis may be used.
  - Normally SF of coverage area, not SF of material area
- Bid Tabulations
  - Be careful about comparing unit prices from job to job – highly dependent on number of layers, surface prep, etc.
- Avoid exotic units

WARRANTY

- Majority of projects require 1 year warranty on materials and installation
  - Manufacturer warrants materials
  - Contractor warrants installation
- Avoid unreasonable warranties which will…
  - Unnecessarily raise project cost
  - Invite "desperate" suppliers and installers to "roll-the-dice"
- Avoid subjective language like…
  - "FRP system shall be designed to last 50 years"

Understanding Technical Data Sheets

Features of a typical TDS

- Typical vs. design properties
- “Fiber” properties
- Laminate/design properties
- Are unit values for strength/modulus reported?
- Where is ply thickness specified?
- AASHTO requires minimum 1% design elongation

September 2017

Milliken Infrastructure

RenewWrap™ ESR CF600

Unidirectional Carbon Fiber Reinforcing Fabric

BRIDGES + ROADWAYS · BUILDINGS + PARKING FACILITIES · OIL, GAS + INDUSTRIAL

RenewWrap™ ESR CF600 is a dry, unidirectional reinforcing fabric made with high-strength, standard modulus carbon fibers. RenewWrap ESR CF600 fabrics, along with RenewWrap™ ESR Saturant are used to strengthen or retrofit existing concrete and masonry structures.

Benefits

- Lightweight, flexible, high-strength fabric can be wrapped around and externally bonded to structural elements
- Easy to impregnate using wet or dry lay-up methods
- EZ-Slit™ system enabling accurate, rapid, and clean slitting

Limitations

- Design calculations shall be made and sealed by a licensed, independent engineer knowledgeable with the design of FRP strengthening systems.
- Avoid completely encapsulating/covering concrete or masonry members subject to freeze/thaw or moisture vapor transmission.
- Ambient temperature cure wet lay-up FRP strengthening systems are not suitable for applications requiring substantial strengthening and a structural fire rating. For these applications, consider using the **FireStrong™ FRP Strengthening System.**

Product Designation

RenewWrap™ ESR CF600 products are available with and without EZ-Slit slitting zones. All products have a total reinforcement width of 24", with the roll width increasing slightly to accommodate the slitting zones. Other roll widths and EZ-Slit configurations are available.

PRODUCT DESIGNATION	NO. OF FABRIC ZONES	ZONE WIDTH
CF600 - 1 x 24	1	24 in. (610 mm)
CF600 - 2 x 12	2	12 in. (305 mm)
CF600 - 4 x 6	4	6 in. (152 mm)
CF600 - 1 x 50	1	50 in. (1270 mm)
CF600 - 2 x 24	2	24 in. (610 mm)

Packaging

The material is available in 150 ft. (45.7 m) long rolls suspended in boxes. Yield equals 300 ft^2/roll (27.8 m^2).

Typical Uses

Recommended for:

- Strengthen for load increases
- Address changes in structural system, like slab openings
- Retrofit for seismic, wind, or blast
- Restore strength to damaged members like fire or vehicle impact
- Restore strength to deteriorated members subject to corrosion
- Strengthen for design/construction errors

Storage & Shelf Life

Store in a cool, dry place at 50-90 °F (10-32 °C) on a roll suspended in a box away from flame or other hazards. Shelf life is 10 years in unopened packaging.

Caution

RenewWrap carbon fabrics are non-reactive. Wear appropriate PPE and use caution when handling since fine carbon dust may be present on surface of fabric. Use caution when cutting or working with carbon fiber around electrical equipment since carbon fibers are electrically conductive. SDS are available and should be consulted for additional information.

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RenewWrap™ ESR CF600

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Typical Fabric and Fiber Properties[1]

PROPERTY	VALUE
Fiber Type	Carbon
Color	Black
Fabric Construction	Unidirectional
Fiber Tensile Strength	700 ksi (4830 MPa)
Fiber Tensile Modulus	33,400 ksi (230 GPa)
Fiber Rupture Strain	2.0%
Fabric Areal Weight[2]	18 oz./yd^2 (600 gsm)

NOTES:

1. Fiber properties are typical values of the fibers used in the manufacture of the reinforcing fabrics. They are based on proprietary test methods employed by the supplier of the carbon fibers. Fiber properties shall not be used for design. They are reported here to provide the designer with a general understanding of the grade of fibers used in the reinforcing fabrics.
2. Reported value represents the minimum fabric areal weight.

Mechanical and Physical Properties

PROPERTY	VALUE	METHOD
Nominal Thickness[1]	0.050 in. (1.3 mm)	
Tensile Strength	123 ksi (850 MPa)	ASTM D3039
Tensile Modulus of Elasticity[2]	9.6 Msi (66 GPa)	ASTM D3039
Elongation at Break	1.16%	ASTM D3039
Tensile Strength/Unit Width	6.1 kip/in./ply (1.07 kN/mm/ply)	ASTM D7565
Tensile Modulus/Unit Width[2]	480 kip/in./ply (84 kN/mm/ply)	ASTM D7565
Glass Transition Temperature	140 °F (60 °C)	ASTM E1640

NOTES:

1. The reported thickness is based on measurements made on panels prepared in the laboratory. Based on experience the typical thickness of a single ply (fibers + saturant), impregnated with **RenewWrap™ ESR Saturant** is approximately 0.06-0.08 inch depending on how the fabric is impregnated in the field. Actual thicknesses measured in the field may vary slightly. As with any FRP strengthening system, the strength/unit width and modulus/unit width should be used for design and for field QC purposes.
2. Modulus of elasticity and unit stiffness are reported as average values in accordance with ACI 440.2R and shall be used for design. They shall not be used for accepting/rejecting results of field QC test results.
3. Based on tests of samples cured at ambient temperature. Tested per ASTM E1640. Higher Tg values may be obtained by post-curing. Contact Milliken Infrastructure for more information.

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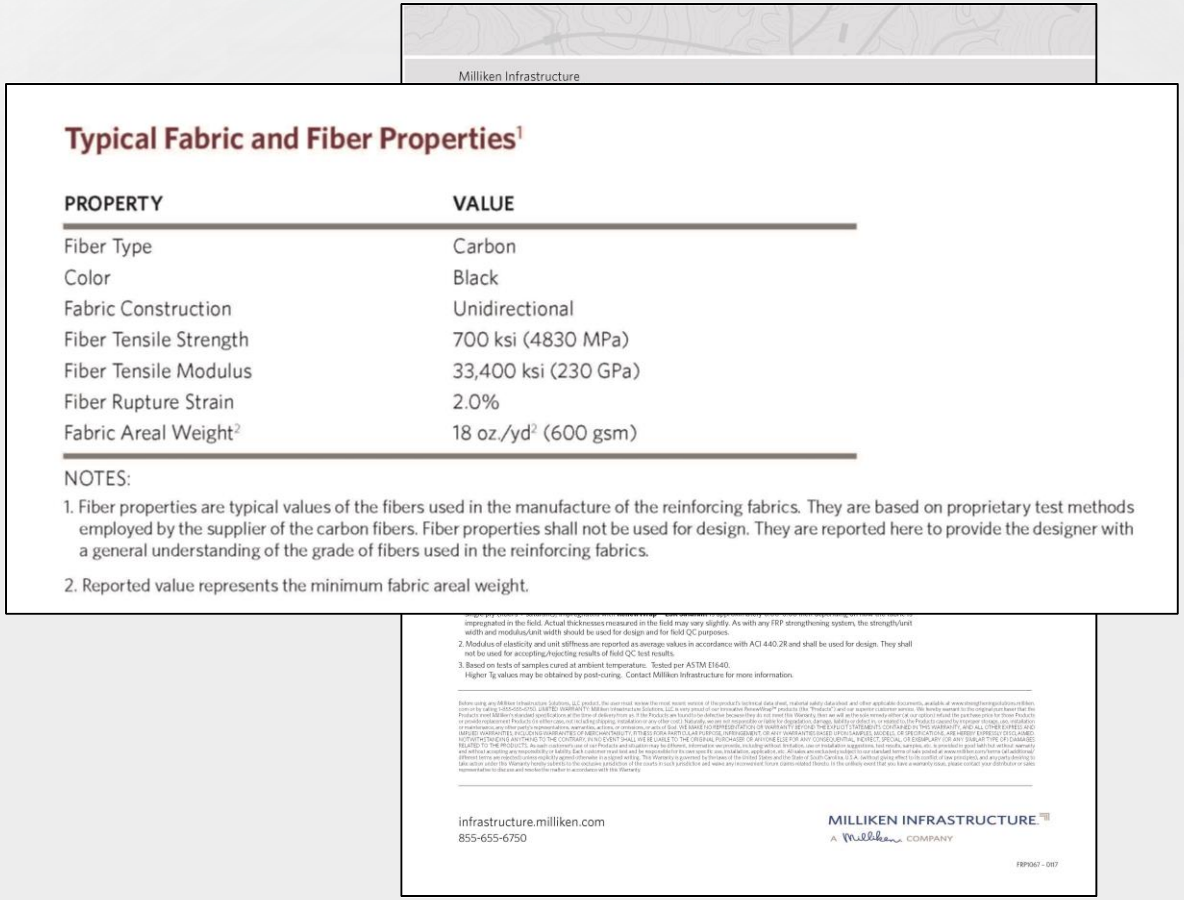
Understanding Technical Data Sheets

Typical Fabric and Fiber Properties

- NEVER USE FOR DESIGN!
- Intended to convey the grade of fiber used in fabric and fabric weight
- ACI 440 recognizes FRP systems that report properties using the “Net Fiber Area” method where the ply thickness is calculated based on the area of the fibers.



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Specifying the Materials

Understanding Technical Data Sheets

Mechanical and Physical Properties

- Make sure they are “design” properties.
- Modulus is reported as an average value.
- Avoid FRP systems that require you to call to get the design properties
- Typical values may be reported for Tg and other physical properties

Milliken Infrastructure

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Unidirectional Carbon Fiber Reinforcing Fabric

BRIDGES + ROADWAYS

BUILDINGS + PARKING FACILITIES

OIL, GAS + INDUSTRIAL

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Specifying the Materials

Unit Tensile Properties

- Normalized tensile strength/stiffness in terms of kips/inch/ply.
- Allows properties of any FRP system to be compared or accepted/rejected as equivalent.
- Calculated as follows:
  - $Unit\ Strength = t_f \times f_{fu}^{*}$ (kips/inch/ply)
  - $Unit\ Stiffness = t_f \times E_f$ (kips/inch/ply)
- All manufacturers should report unit tensile values on their TDS
- Most important design property is unit stiffness (Et) since all applications limit the strain in the FRP

Always specify the following:

- Min. unit tensile strength (kips/inch/ply)
- Min. unit tensile modulus (kips/inch/ply)
- Min. rupture strain (%)

OR

- Min. tensile strength (ksi)
- Min. tensile modulus (ksi)
- Min. rupture strain (%)
- Ply thickness (inch)

Specify Resin Properties?

- **DO NOT** specify minimum mechanical properties of the resin
  - The resin properties are not used in design equations

- **DO** require the FRP system and all it’s constituent materials be tested together as a system.

- **BE CAREFUL** about allowing field thickening of resins
  - Thickening epoxy using Cab-o-Sil is fairly common practice
  - Adding filler to epoxy weakens and makes it brittle.
  - Better to specify lighter weight fabrics than allowing field thickening

- **DO NOT** over specify properties – you could end up with no product meeting spec!

Additional Requirements

- Include minimum Tg of 140 F. Most FRP systems can meet this temperature requirement.
- Durability testing
  - CALTRANS requires 10,000-hr exposure tests
- Require ICC-ES Reports?
  - ICC-ES evaluates products for “compliance” with an acceptance criteria and the building code.
  - Maybe. Almost universally required on the West Coast.
  - At a minimum, require the durability testing outline in AC 125

FRP Installation Techniques

- Wet Lay-up Method
  - Used for fabric FRP systems
  - Roller application "Dry Lay-up"
  - Pre-Saturation
  - Impregnating machine

- Secondarily Bonded
  - Used for pre-cured FRP systems (NSM)

Specifying the Installation

General Installation Procedure

1) Repair substrate (Inject cracks, repair spalls, fill voids, etc.)
2) Prepare substrate surface (sand-blast, grind, water-blast, round corners, etc.)
   – Is application bond-critical or contact-critical?
3) Install FRP system (wet or dry lay-up)
4) Remove air voids
5) Allow FRP system to cure
6) Inspect cured system
7) Paint/coat FRP

- Substrate repairs are not included in the FRP special provision
- Many of the installation methods are "in accordance with manufacturer's recommendations"

Installation Considerations

- Temperature/Humidity
  - Resin working time
  - Resin cure time
  - Moisture vapor transmission (MVT)
  - Storage of materials
- May need to ice resins or heat tented area using clean heat source
- In case of MVT, may need to install at night as temperature is falling
- Wet surfaces
- Age/cure of patching materials

Specify the following:

- Temperature range FRP may be installed
- Minimum age/strength of patching materials (Avoid 28 days)

Surface Preparation

- Bond-Critical
  - Make repairs first
  - Grit-blasting or other means to achieve ICRI CSP-3 or higher
  - Surface needs to be flat
  - Round corners (for U-wraps)
  - Clean surface

- Contact-Critical
  - Round corners to ½" radius
  - Surface profile needs to promote continuous contact
  - Remove paint or other coatings?
  - Clean surface

Application of the FRP

- Wet lay-up or "dry lay-up"
  - Refers to whether a machine is used to wet out the fabric
  - Heavier weight fabrics will usually require a machine to wet them out
  - Specify that fabrics should be wet out in accordance with manufacturer's instructions

Specifying the QC Inspections

General Requirements

- Material certificates of conformance
- Daily reports (what was installed, where, temperature, etc.)
- Tensile tests (witness panels)
- Fabric alignment (< 1"/foot deviation)
- Delaminations
- Cure of resins
- Adhesion strength (for bond-critical)

For any inspection tests, minimum acceptance criteria need to be provided.

Specifying the QC Inspections

Inspection Requirements

Inspection	Bond-Critical		Contact-Critical	
	Structural	Protection	Structural	Protection
Visual	X	X	X	X
Sounding	X	X	X	X
Adhesion Testing	X	X		
Witness Panels	X		X	

Specifying the QC Inspections

Witness Panels

- Witness panels are fabricated and cured in the field from the same materials (fabrics and resin) used on the project
- Analogous to concrete cylinders
- Panel quality varies widely and is challenging to get good test results
- Usually one per day per crew or 5,000 SF of material installed
- Test per ASTM D7565 and report unit tensile values
- Proposed acceptance criteria:
  - Individual tensile strength > reported design value
  - Average modulus > 90% reported value

Delaminations/Voids

- Not uncommon
- Found visually or by acoustic sounding (tap testing)
- Suggested frequency of 1 tap per 0.5 SF
- Outline of delaminations should be marked
- Acceptance Criteria:
  - Small delaminations (<2 in^2) are OK provided they…
    - do not exceed 5% of total area
    - there are not more than 10 per 10 SF area
  - Large delaminations (>25 in^2) need to be cut out
  - Mid-size delaminations (>2 in^2 and <2 in^2) may be repaired by epoxy injection

Specifying the QC Inspections

Adhesion Strength

- Only for bond-critical Applications
- ASTM D7522
- Suggested frequency of one per day per crew or one per 1,000 SF of contact area
- Acceptance criteria:
  - Strength > 200 psi
  - Ideally, failure in the substrate
  - Failures not in substrate are reported to engineer

Concluding Remarks

- **DO** analyze structure
- **DO** determine if FRPs are an appropriate method
- **DECIDE** on prescriptive or performance
- **ALWAYS** specify unit tensile values (or tensile properties + ply thickness)
- **INCLUDE** all section details for performance specifications
- **INCLUDE** detailed FRP design values for prescriptive specifications
- **DO NOT** over specify properties
- **CONTINUE** to use FRPs with confidence!

THANK YOU!

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