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Myths and Fallacies Related to the Determination of Design Values for FRP Systems

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Wet Layup FRP: Field-Saturated Fabric

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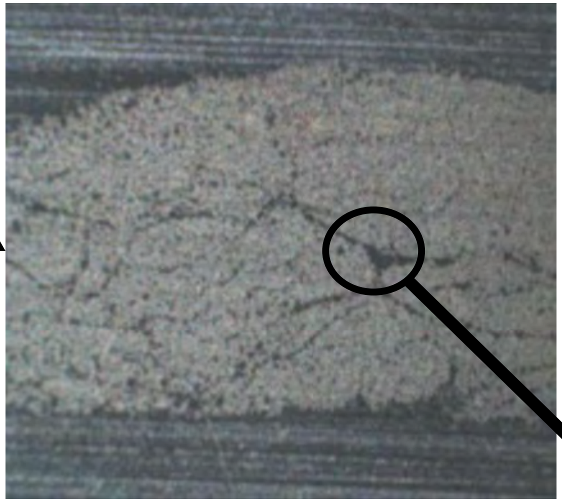
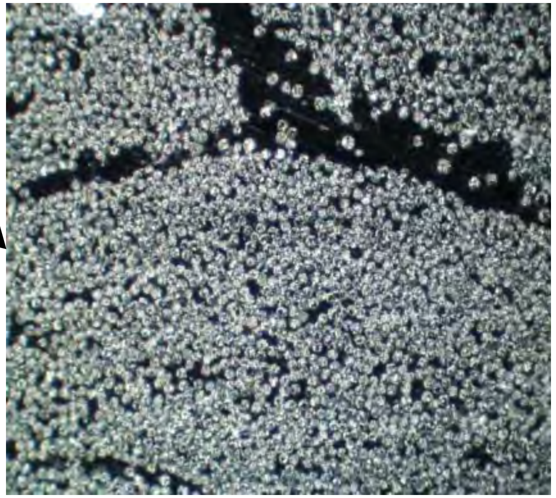
Wet Layup FRP - A Closer Look…





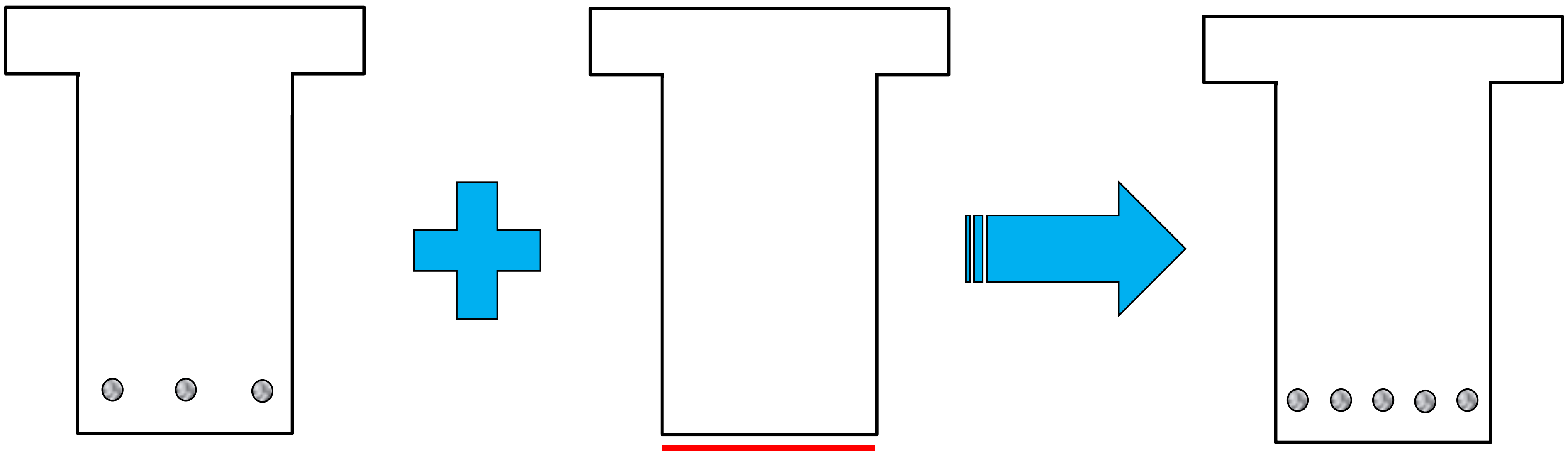
Fiber governs the structural properties and behavior.
Epoxy governs the durability properties of FRP.

We Are Not Talking About These…

Pultruded FRP Structural Shapes

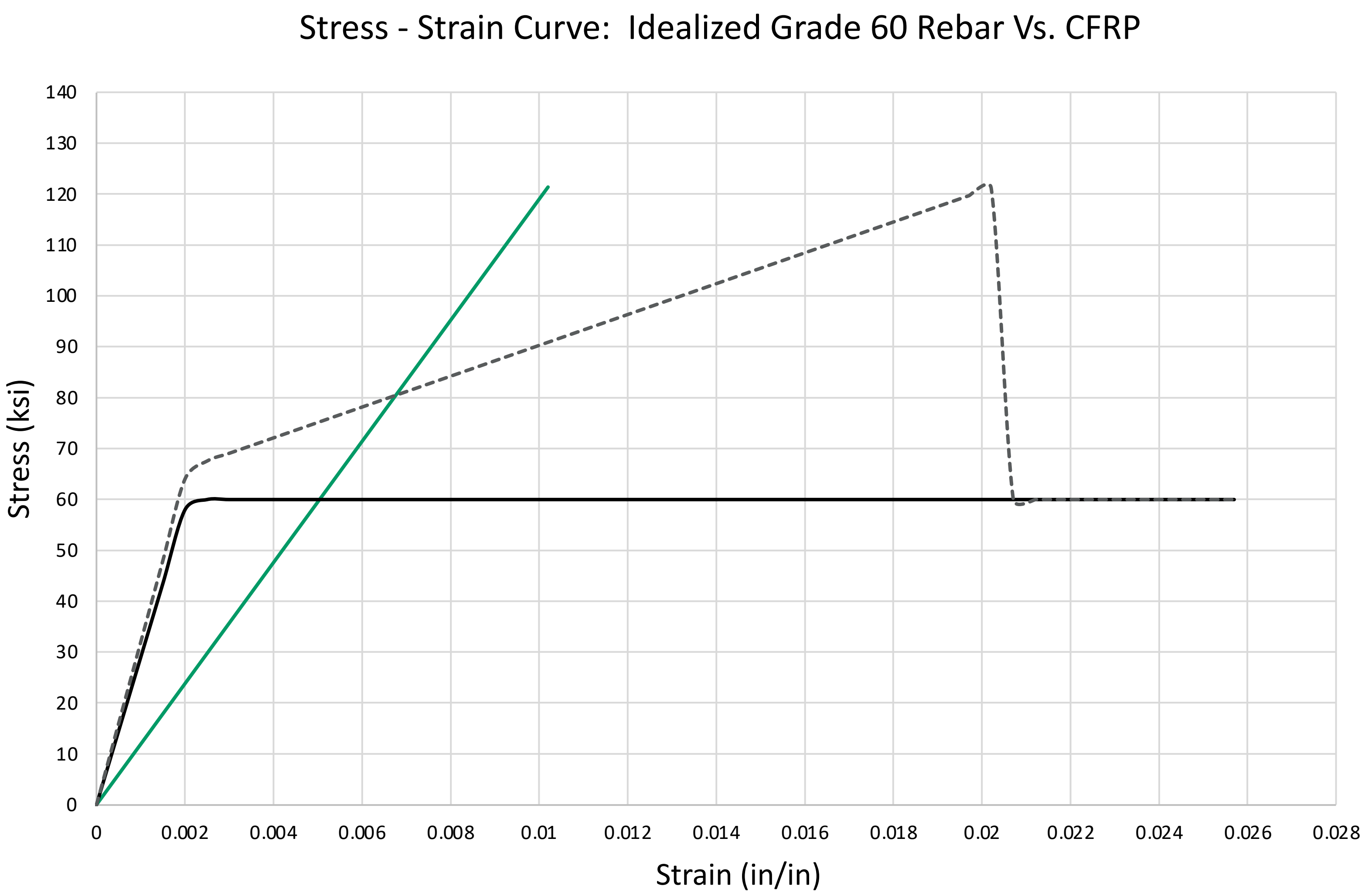
Pultruded FRP Laminates

Simplified Visualization of FRP Strengthening (Positive Flexural Reinforcement Shown)



Supplemental externally bonded reinforcement.

Design Basics – Tensile Modulus is Key!



FRP Strengthening Examples

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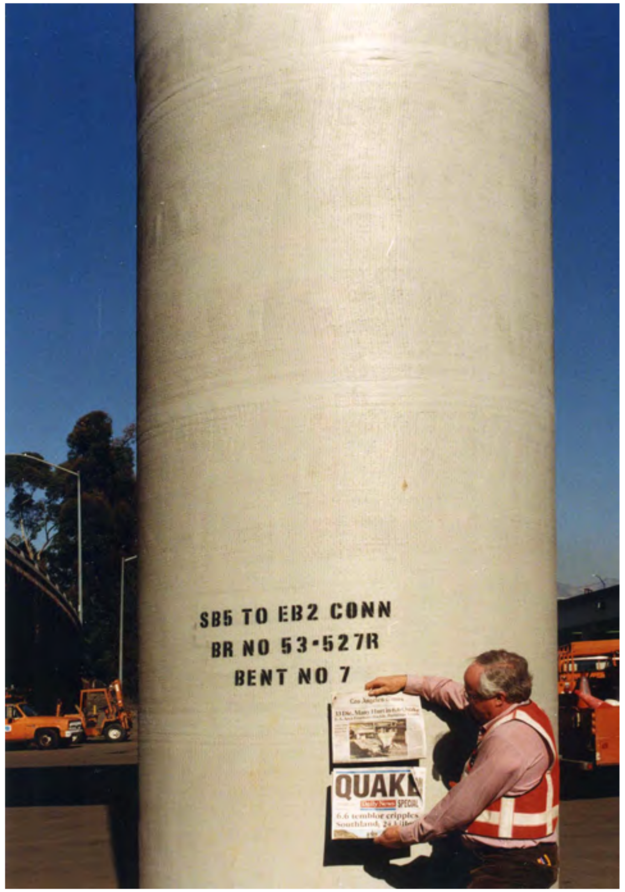
Myths and Fallacies…

- **FRP System properties are determined from the same test.**
- **The data from the tests is evaluated in the same way.**
- **All properties are conservatively reduced…especially the most important one, the tensile modulus.**
- **The engineering community understands how design values are determined.**
- **All manufacturers report their properties in the same way.**



Note: The goal of this discussion is to provide a more complete understanding of these materials for practicing civil/structural engineers. I hope to point out some inconsistencies and confusion commonly experienced by designers, and to suggest a rational approach.

Purpose of This Presentation

- Show how tensile data is evaluated/tested
- Show how the test data is reduced for design/characteristic properties
- Show how manufacturers report different values based on different interpretations of ACI
- Suggest a more rational and conservative approach for the industry

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The Solution

Engineers of Record: Require material properties to be computed in accordance with ASTM D7290 in your FRP specifications!!

ASTM D7290 – Standard Practice for Evaluating Material Property Characteristic Values for Polymeric Composites for Civil Engineering Structural Applications

ASTM D3039 = Test Method

ASTM D7290 = Statistical Analysis of Test Results

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Three Ways to Define FRP Material Properties

Gross Laminate – Based on directly measured thickness/area

Net-Fiber – Based on a theoretical fabric thickness

Dry Fiber Method – Based on feed fiber properties and the “rule of mixtures”

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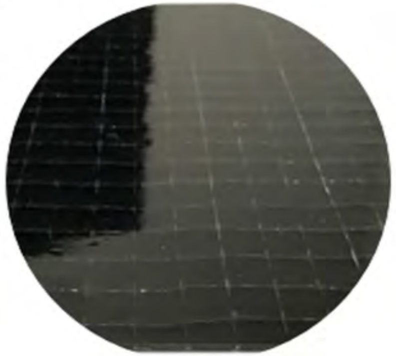
Three Ways to Define FRP Material Properties

	Tensile Properties of CFRP System		
	Dry Fiber Properties	**Net-Fiber Area Method**	**Gross Laminate Area Method**
Layer Thickness	N/A	0.031	0.080
Tensile Strength, ksi	650+	400+	150+
Tensile Modulus, Msi	36+	36+	14+



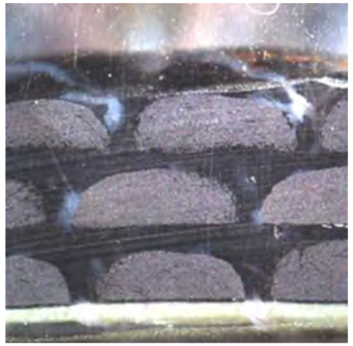
ACI 440.2R-17 Fiber Area Definition

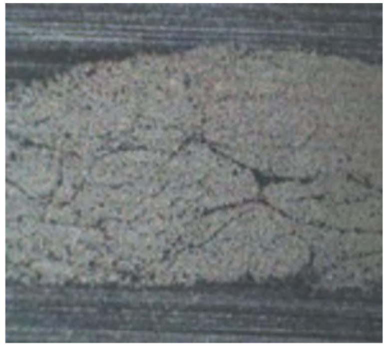
- Per ACI 440.2R-17 section 4.3.1, net-fiber area is suggested for wet layup applications.
  - *Note that it is more common in the industry to use the reported gross laminate thickness/area.*

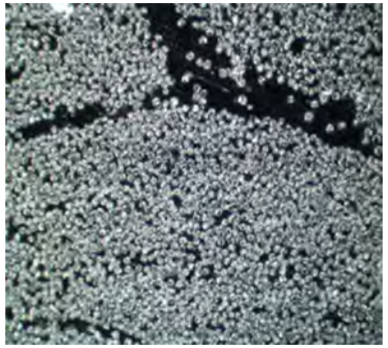
- However, the method needed to calculate both the gross-laminate area and the net-fiber area is not apparent and "dry fiber" area (including the rule of mixtures) is not mentioned.

The gross-laminate area of an FRP system is calculated using the total cross-sectional area of the cured FRP system, including all fibers and resin. The gross-laminate area is typically used for reporting precured laminate properties where the cured thickness is constant and the relative proportion of fiber and resin is controlled.

The net-fiber area of an FRP system is calculated using the known area of fiber, neglecting the total width and thickness of the cured system; thus, resin is excluded. The net-fiber area is typically used for reporting properties of wet layup systems that use manufactured fiber sheets and field-installed resins. The wet layup installation process leads to controlled fiber content and variable resin content. A method similar to net-fiber area reporting is to report the tensile force or stiffness per unit width of the FRP system as required by ASTM D7565/D7565M.







Dry Fiber Tensile Properties

- Refers to the input fiber properties used to construct the FRP sheet or fabric.
- Why use these properties for design purposes?

- Dry fiber properties have...
- ~ 4X higher strength (550 – 700 ksi compared to 120 - 170 ksi)
- ~ 2.5x higher modulus (33 – 37 Msi compared to 11 – 16 Msi)
- ...than Gross Laminate FRP properties

- The “Rule of Mixtures” is considered unconservative.
- Reduction factors should be applied to account for efficiency of fiber-resin system and for fabric and sheet architecture.

$$E_f = E_{fib} \cdot V_{fib} + E_m \cdot V_m$$

$$f_f \approx f_{fib} \cdot V_{fib} + f_m \cdot V_m$$

FIB Bulletin 90 – Technical Report

- **Rule of Mixtures** , though unconservative, is an approximation. A more accurate prediction of stress-strain behavior should be obtained through tensile testing of FRP
- If dry properties are used to calculate properties, a reduction factor should be applied to account for efficiency of fiber-resin system and for fabric and sheet architecture.

$$r_e \cdot E_{fib} \cdot t_{fib} = E_f \cdot t_f$$

- FRP properties shall be obtained and tested via the **ISO 10406-2:2015 - Fiber-Reinforced Polymer (FRP) Reinforcement Of Concrete - Test Methods - Part 2: FRP Sheets**
- **Modulus of elasticity** is defined as the mean value from stress-strain slope. Characteristic values (5% fractile) are applied to tensile strength and strain to designate tensile strength class of FRP
- For the tensile strength and the elastic modulus it should be **clearly stated which value for the nominal laminate thickness has been taken into consideration.**
- Alternatively, **EN 2561 - Tensile Properties Parallel to the Fiber Direction of Unidirectional Carbon Fiber-Reinforced Plastics** provides additional provisions for determination of the FRP tensile properties

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Other Standards

- EN 2561: Carbon fibre reinforced plastics – Unidirectional laminates – Tensile test parallel to the fibre direction
  - Includes equations for both Gross Laminate Area and Net Fiber Area Tensile Properties

Gross Laminate Area Method

8.1 Ultimate tensile strength σ_{T11} (MPa)

$$\sigma_{T11} = \frac{P_R}{b\ h}$$

where:

P_R is the load at failure, in newtons ;
b is the width, in millimeters ;
h is the thickness, in millimeters.

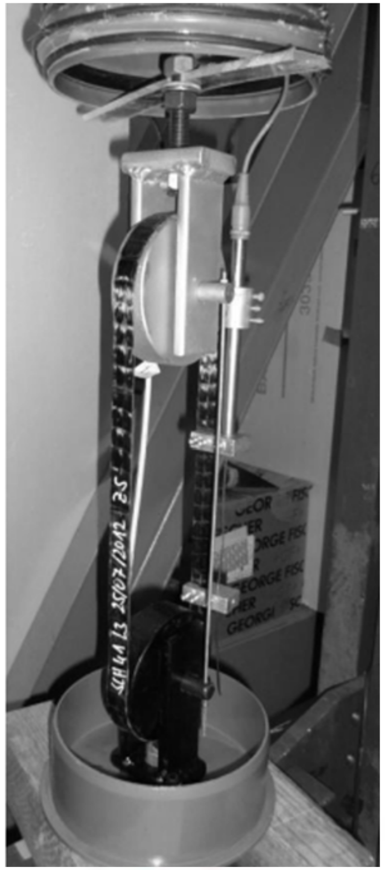
Net Fiber Area Method

8.2 Ultimate tensile strength related to the fibre σ_f (MPa)

$$\sigma_f = \frac{P_R\ \rho_f}{n\ b\ M_{sf}}$$

where:

n is the number of plies ;
M_{sf} is the mass per unit area of fibre, in grams per square meter, per ply ;
ρ_f is the density of fibre, in kilograms per cubic meter ;
P_R is the load at failure, in newtons;
b is the width, in millimeters.



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Net-Fiber Area Tensile Properties

- Calculated using the known area of fiber, neglecting resin of cured system.
- Net fiber thickness is determined by dividing areal weight of the fabric by the density of the fiber… i.e. the thickness is calculated, not measured.
- The definition above is NOT defined in ACI440.2R (see European Standards).
- Net-Fiber Area Properties ~ 2.5X higher than Gross Laminate Properties.

Composite System	Net-Fiber Thickness	Gross Laminate Thickness
CFRP System A	0.015 in	0.040 in
CFRP System B	0.031 in	0.080 in

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Gross Laminate Tensile Properties

- Calculated using the composite thickness of the cured system.
- For wet layup systems, nominal thickness is the approximate cured thickness with guidance from measured textile thickness per ASTM D1777.
- Field panel thickness varies & may be required to report per D7565 which removes thickness from calculations.

Composite System	Net-Fiber Thickness	Gross Laminate Thickness
CFRP System A	0.015 in	0.040 in
CFRP System B	0.031 in	0.080 in

ACI 440.2R-17 Tensile Property Definitions

- ACI 440.2R-17 Section 4.3.1 Mechanical Properties:
  - Manufacturers should report an ultimate tensile strength, which is defined as the mean tensile strength of a sample of test specimens minus three times the standard deviation ($f_{fu}^* = f_{fu} - 3\sigma$) and, similarly, report an ultimate rupture strain ($\varepsilon_{fu}^* = \varepsilon_{fu} - 3\sigma$).
  - …the elastic modulus should be calculated in accordance with ASTM D3039/D3039M or D7565/D7565M. A minimum number of 20 replicate test specimens should be used to determine the ultimate tensile properties.
- Per ASTM D3039, $E^{chord} = \Delta\sigma/\Delta\varepsilon$.
- Ultimate strain and stress calculated per ACI 440.2R-17 section 4.3.1 is not used in basic design.
- *NO REDUCTION TO ELASTIC MODULUS. USES MEAN MEASURED VALUE.*
  - *What is the probability that the actual modulus in field prepared samples will exceed this?*

The tensile properties of some commercially available FRP strengthening systems are given in Appendix A. The tensile properties of a particular FRP system, however, should be obtained from the FRP system manufacturer or using the appropriate test method described in ASTM D3039/D3039M, D7205/D7205M, or D7565/D7565M. Manufacturers should report an ultimate tensile strength, which is defined as the mean tensile strength of a sample of test specimens minus three times the standard deviation ($f_{fu}^* = f_{fu} - 3\sigma$) and, similarly, report an ultimate rupture strain ($\varepsilon_{fu}^* = \varepsilon_{fu} - 3\sigma$). This approach provides a 99.87 percent probability that the actual ultimate tensile properties will exceed these statistically-based design values for a standard sample distribution (Mutsuyoshi et al. 1990). The elastic modulus should be calculated in accordance with ASTM D3039/D3039M, D7205/D7205M, or D7565/D7565M. A minimum number of 20 replicate test specimens should be used to determine the ultimate tensile properties. The manufacturer should provide a description of the method used to obtain the reported tensile properties, including the number of tests, mean values, and standard deviations.

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ACI 440.2R-17 Ch. 16 Design Examples

Table 16.2a—Material properties and description of two types of FRP systems

System A (excerpts from data sheet)	System B (excerpts from data sheet)
System type: dry, unidirectional sheet Fiber type: high-strength carbon Polymer resin: epoxy System A is installed using a wet layup procedure where the dry carbon-fiber sheets are impregnated and adhered with an epoxy resin on-site.	System type: precured, unidirectional laminate Fiber type: high-strength carbon Polymer resin: epoxy System B's precured laminates are bonded to the concrete substrate using System B's epoxy paste adhesive.
Mechanical properties*†‡	Mechanical properties*†
t_f = 0.013 in. (0.33 mm)	t_f = 0.050 in. (1.27 mm)
f_{fu}^* = 550 ksi (3792 N/mm²)	f_{fu}^* = 380 ksi (2620 N/mm²)
ε_{fu}^* = 1.6%	ε_{fu}^* = 1.5%
E_f = 33,000 ksi (227,527 N/mm²)	E_f = 22,000 ksi (151,724 N/mm²)

*Reported properties are based on a population of 20 or more coupons tested in accordance with ASTM D3039/D3039M.
†Reported properties have been statistically adjusted by subtracting three standard deviations from the mean tensile stress and strain.
‡Thickness is based on the net-fiber area for one ply of the FRP system. Resin is excluded. Actual installed thickness of cured FRP is 0.04 to 0.07 in. (1.0 to 1.8 mm) per ply.

Table 16.2b—Procedure comparing two types of FRP systems

Procedure	Calculation in in.-lb units
Step 1A—Calculate the tensile strength per unit width of System A $p_{fu}^* = f_{fu}^* t_f$	p_{fu}^* = (550 ksi)(0.013 in.) = 7.15 kip/in.
Step 1B—Calculate the tensile strength per unit width of System B $p_{fu}^* = f_{fu}^* t_f$	p_{fu}^*= (380 ksi)(0.050 in.) = 19 kip/in.
Step 2A—Calculate the tensile modulus per unit width of System A $k_f = E_f t_f$	k_f = (33,000 ksi)(0.013 in.) = 429 kip/in.
Step 2B—Calculate the tensile modulus per unit width of System B $k_f = E_f t_f$	k_f = (22,000 ksi)(0.050 in.) = 1100 kip/in.

- Although net fiber area is used, it's noted that the installed laminate thickness is significantly higher
- The gross laminate thickness can be directly measured in the field.

ACI 440.2R-17 Ch. 16 Design Examples

Table 16.3b—Manufacturer's reported FRP system properties

Thickness per ply t_f	0.040 in.	1.02 mm
Ultimate tensile strength f_{fu}^*	90 ksi	621 N/mm^2
Rupture strain ε_{fu}^*	0.015 in./in.	0.015 mm/mm
Modulus of elasticity of FRP laminates E_f	5360 ksi	37,000 N/mm^2

Table 16.6b—Manufacturer's reported FRP system properties

Thickness per ply t_f	0.0065 in.	0.165 mm
Ultimate tensile strength f_{fu}^*	550,000 psi	3790 N/mm^2
Rupture strain ε_{fu}^*	0.017 in./in.	0.017 mm/mm
Modulus of elasticity E_f	33,000,000 psi	227,530 N/mm^2

- Other examples appear to use gross laminate thicknesses/areas instead of the suggested net-fiber area.

- Inconsistencies between the design examples themselves has led to confusion.

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How are some properties reported?

NOTES:
(1) The nominal fabric thickness is based on the total area of fibers (only) in a unit width. From experience, the actual cured thickness of a single ply laminate (fibers plus saturating resins) is 0.040-in to 0.060-in (1.0-mm to 1.5-mm).
(2) The tensile properties given are those to be used for design. These values are derived by testing cured laminates (per ASTM D3039) and dividing the resulting strength and modulus per unit width by the nominal fabric thickness.
(3) The 0° direction denotes the direction along the length of the fabric.
(4) The 90° direction denotes the direction along the width of the fabric.

PHYSICAL PROPERTIES

PROPERTY	VALUE
Fiber Material	High Strength Carbon
Fiber Tensile Strength	720 ksi [4950 MPa]
Areal Weight	0.124 lb/ft^2 [600 g/m^2]
Fabric Width	20 in 500 mm
Nominal Thickness, t_f (1)	0.013 in/ply [0.33 mm/ply]

0° TENSILE PROPERTIES (2) (3)

PROPERTY	VALUE
Ultimate Tensile Strength, f^*_{fu}	550 ksi [3800 MPa]
Tensile Modulus, E_f	33000 ksi [227 GPa]
Ultimate Tensile Strength per Unit Width, $f^*_{fu}\ t_f$	7.14 kips/in/ply [1.25 kN/mm/ply]
Tensile Modulus per Unit Width, $E_f\ t_f$	430 kips/in/ply [76 kN/mm/ply]
Ultimate Rupture Strain, ε^*_{fu}	1.67%

How are some properties reported?

MATERIAL PROPERTIES

Dry Fiber Properties

Tensile Strength	670,000 psi (4,600 MPa)
Tensile Modulus	37,000 ksi (260 GPa)
Elongation at Break	1.9%
Weight	22.0 oz./yd.^{2} (740 g/m^2)
Color	Black
Density	0.065 lb./in.^{3} (0.0018 g/mm^3)
Dry Fabric Thickness	0.0162 in. (0.42 mm)

Cured Composite Properties[1]

Property	Design Value[2]
Tensile Strength	128,000 psi (880 MPa)
Tensile Modulus	14,200 ksi (98 GPa)
Elongation at Break	0.9%
Thickness per Layer	0.04 in. (1.0 mm)
Stiffness/width	568 k/in. (98,000 N/mm)

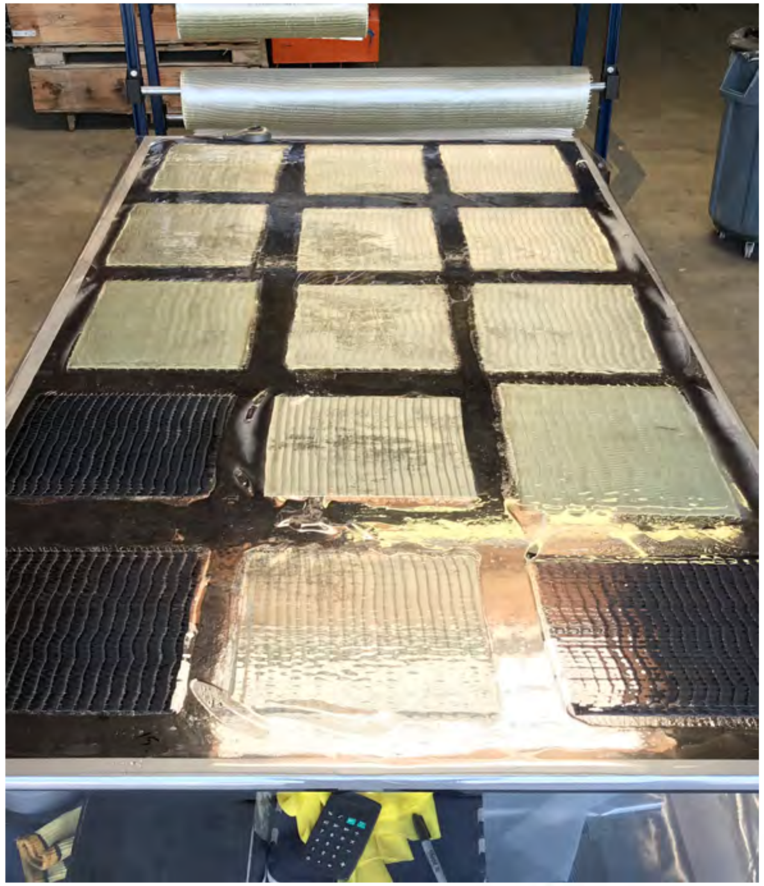
1. When laminated with CSS-ES saturating resin, post cured for 48 hours at 140°F (60°C) and tested per ASTM D3039.
2. Tensile properties based on five percent fractile approach per ACI.

Cured Laminate Properties	Average Values	Design Values*
Tensile Strength:	180,000 psi (1,241 MPa)	155,000 psi (1,068 MPa)
Modulus of Elasticity:	14.24 x 10^6 psi (98,181 MPa)	14.0 x 10^6 psi (96,527 MPa)
Elongation at Break:	1.27%	1.1%
Thickness:	0.04 in. (1.02 mm)	0.04 in. (1.02 mm)
Strength per Unit Width:	7,200 lbs/in. (1.26 kN/mm)	6,200 lbs/in. (1.09 kN/mm)

*Design properties are based on ACI 440.2R using average minus three standard deviations.

How are Tensile Properties Determined?

- FRP System properties are determined per:
  - ASTM D3039: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
  - ASTM D7565: Standard Test Method for Determining Tensile Properties of Fiber Reinforced Polymer Matrix Composites Used for Strengthening of Civil Structures

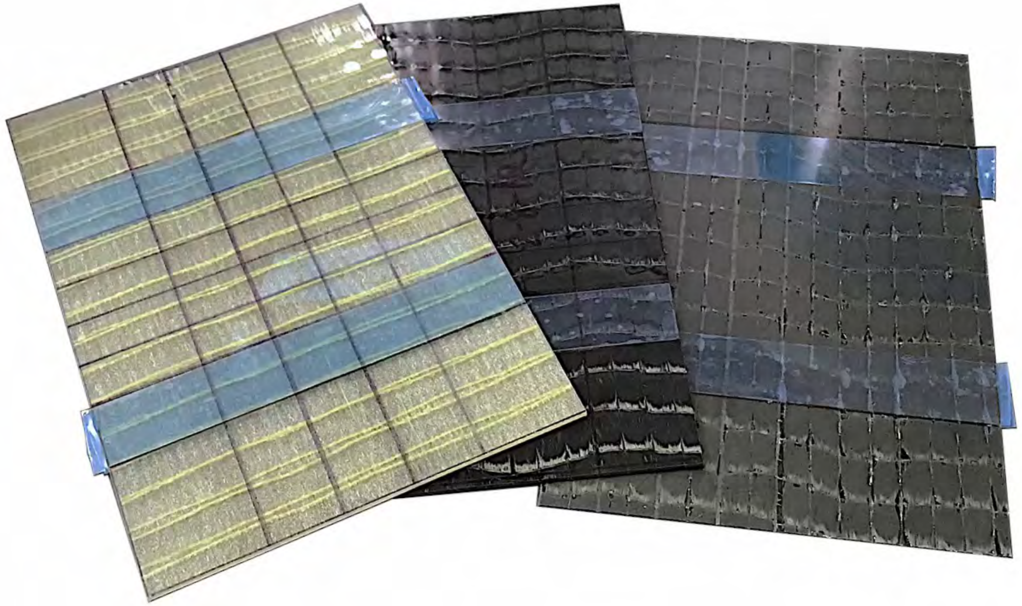


How are Tensile Properties Determined?

- How do we use both standards?
  - Engineering Design to be based on D3039
  - Field verification and product comparisons can be based on D7565

	Tensile Properties of CFRP System B. Nominal thickness = 0.08 in.	
	ASTM D3039	**ASTM D7565**
Tensile Strength vs Force per inch	131 ksi	10.5 kips/in
Tensile Modulus vs Stiffness per inch	14.6 Msi	1,170 kips/in

ASTM D3039 and ASTM D7565



How are Tensile Properties Determined?

- ASTM D3039: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
  - Tensile Strength, $F = P/A$
  - A = average measured cross-sectional area
  - Tensile Chord Modulus of Elasticity, $E^{chord} = \Delta\sigma/\Delta\varepsilon$

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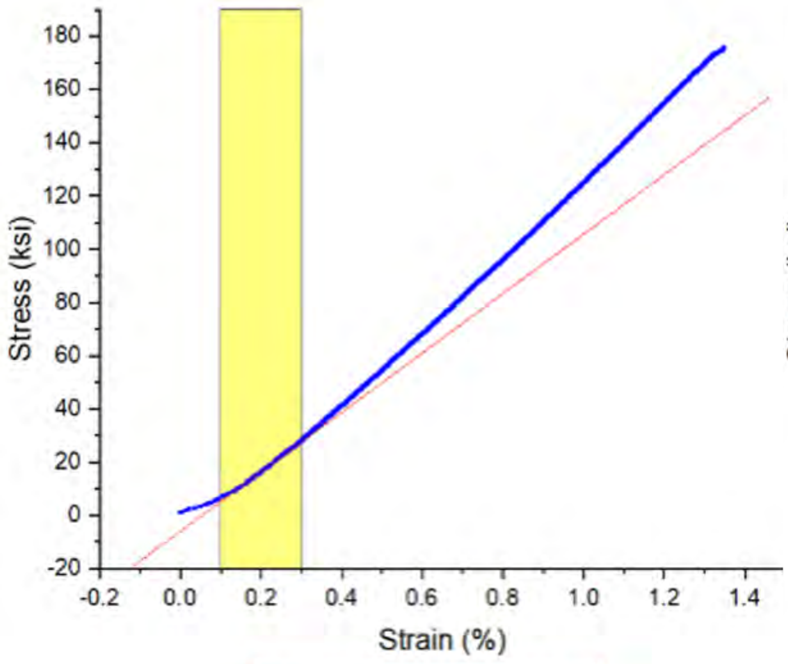
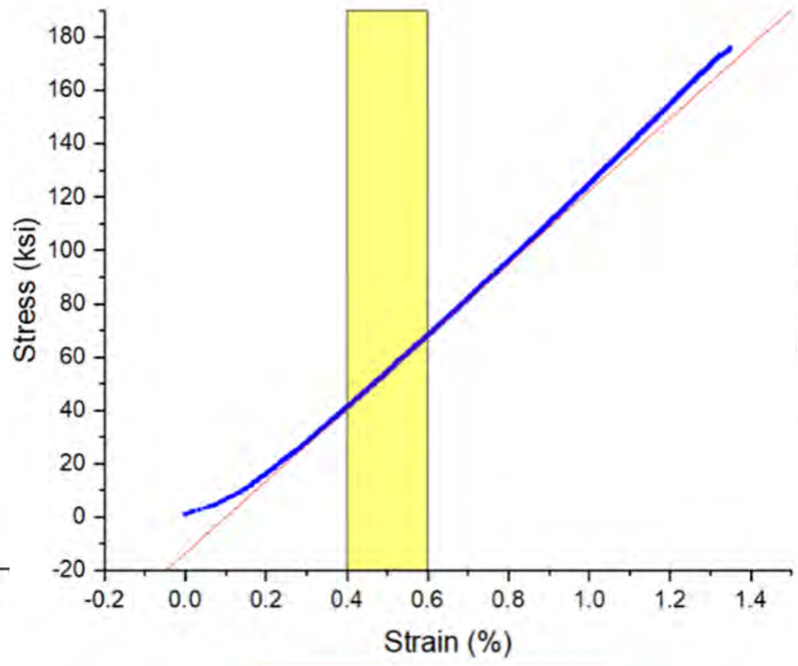
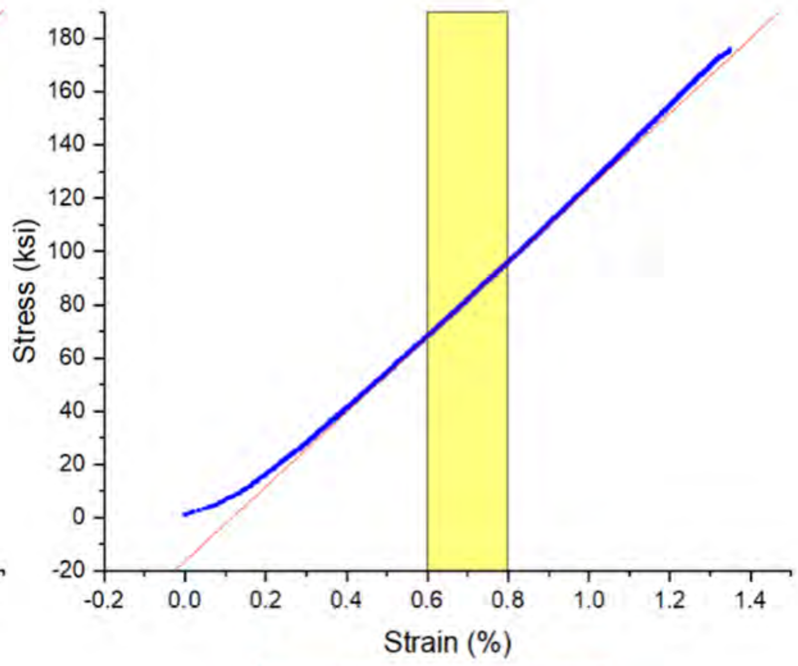
How are Tensile Properties Determined?



Strain Range: 0.1 - 0.3 %
Tensile Modulus: 11.2 Msi



Strain Range: 0.4 - 0.6 %
Tensile Modulus: 13.6 Msi



Strain Range: 0.6 - 0.8 %
Tensile Modulus: 14.0 Msi

- Table 3 Recommended Strain Range for Modulus determination: **0.1 – 0.3 % strain**
- 13.3.1.1 If a transition region occurs within the recommended strain range, then a more suitable strain range shall be used and reported.

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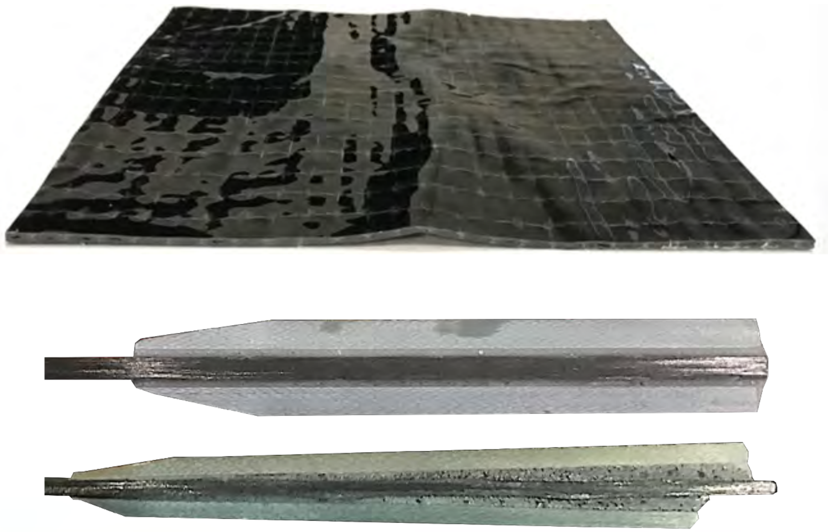
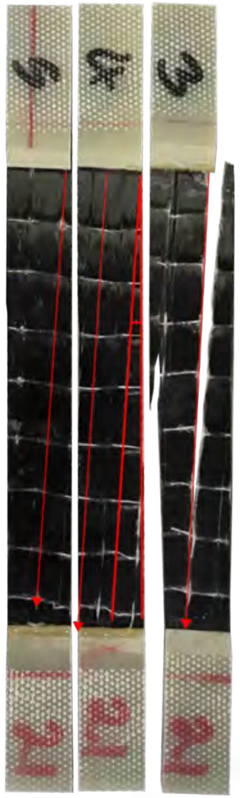
Experienced Labs and Contractors are Important

- Sample Preparation and Analysis are critical!
- Common issues: Area/thickness, Field quality, Misalignment, Tab vs No Tabs, Slippage, Orientation in the wrong direction (bidirectional products)





ASTM D7290 – Standard Practice for Evaluating Material Property Characteristic Values for Polymeric Composites for Civil Engineering Structural Applications.

- Provides procedures for computing the characteristic values of material properties of FRP used in civil applications. Equation accounts for the sample size and coefficient of variance.

- ASTM D7290 Section 3.2.1 Characteristic value:
  - *a statistically-based material property representing the 80% lower confidence bound on the 5th-percentile value of a specified population. The characteristic value accounts for statistical uncertainty due to a finite sample size.*

- *3.2.1.1 Discussion—The 80 % confidence bound and 5th-percentile levels were selected so that composite material characteristic values will produce resistance factors for Load and Resistance Factor Design similar to those for other civil engineering materials.*

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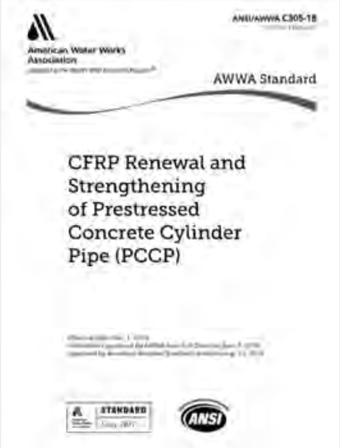
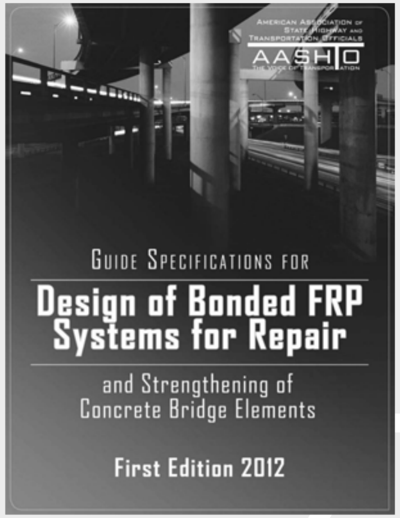
Comparison of Reported Design Properties

- ASTM D7290 Accepted Method used in…
  - AASHTO FRP Guide Specification for the Design of Bonded FRP Systems for Repair and Strengthening of Bridge Elements (2012)
  - DOD Composite Materials Handbook, MIL-HDBK-17
  - AWWA C305-18 CFRP Renewal and Strengthening of PCCP
- Weibull Reduction is applied **to all** design properties.
- Recommends minimum of 30 replicates. Confidence factor improves with higher number of replicates.





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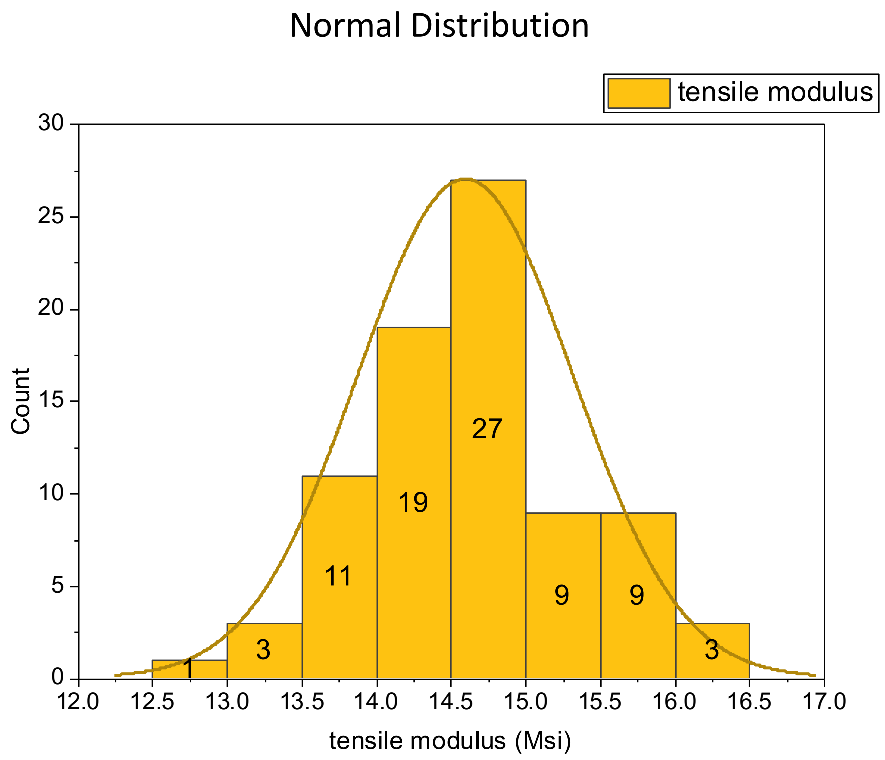
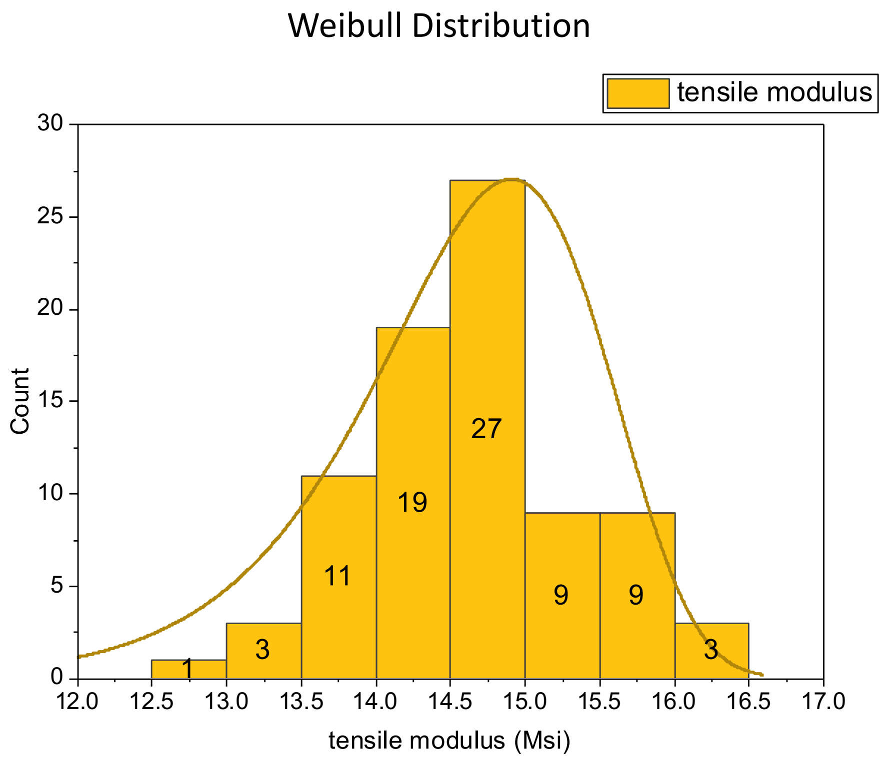
How are some properties reported?





Properties Comparison for One Specific CFRP Material

	Design Values from ASTM D3039 Testing of 80 Specimens of one specific CFRP system		
	Ultimate Tensile Strength, ksi	**Tensile Modulus, Msi**	**Ultimate Strain, %**
Mean (n=80)	**171**	**14.60**	**1.13**
*Previously Reported**	121	11.90	0.8 to 1.7
ACI 440.2R	131	14.60	0.90
ASTM D7290	141	12.66	0.91

*Based on a reduction factor applied to all values from field prepared samples

= Conservative design/characteristic values chosen to report on product data sheets

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ACI 318 Five Percent Fractile Approach Comparison

- ACI 318 uses a normal/Gaussian distribution (not Weibull)
- ACI 440.2R does not state that this ACI 318 method should be used.
- The 5% reduction is only used on the stress and strain, then the modulus (most important design value) is calculated using Hooke's Law.
- The reported modulus is HIGHER than the mean measured value.
- The values shown in the table are reduced from the same data set.

	Suggested design values	Mean Values	5% Fractile (ACI 318)
Tensile Strength, ksi	131	171	145
Elastic Modulus, Msi	12.66	14.6	15.26
Tensile Strain, %	0.90	1.13	0.95

So, What Does This All Mean?

- Our industry has not defined the material properties in a clear and consistent way. Neither ACI nor ICC are consistent.
- The basis of design for externally applied FRP is the tensile modulus.
- The tensile modulus is calculated by the best fit to the slope of the line provided by the ASTM D3039 testing.
- The modulus for wet layup systems is typically based on the Gross Laminate Thickness as measured and reported by the manufacturer (considering ASTM D1777). Note that this is essentially the same thickness that can be measured in the field.
- The design value/characteristic value should be obtained by conservatively reducing the modulus as per ASTM D7290 (with a suggested minimum of 20 test specimens).
- Field prepared samples and particular project parameters may justify an additional reduction factor on the modulus.
- Specification wording should be clear on this topic... and others.

Suggested Design Approach

- Specifications should require all FRP Systems to report their values in the same way.
  - Specify that all systems report their characteristic tensile modulus values based on ASTM D7290 using at least twenty (20), ASTM D3039 test specimens
- Designers should take the time to understand the design and required detailing… don't punt this to manufacturers.
- Designers should clearly specify the required field quality control testing and the acceptable values.
- Designers should understand that although FRP materials are attractive and quite useful, there is still room for scrutiny.

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What Other “Myths and Fallacies” Could Designers Consider?

- Should the application of these linear-elastic materials to RC and masonry be considered force-controlled or displacement-controlled?
- Should fiber anchors (“spike anchors”) have their properties validated in the same way as other, conventional adhesive anchors?
- Should shear strengthening of columns be considered “bond-critical” as per ACI 440.2R?
- Can externally bonded reinforcement be protected/insulated from a fire event?

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Questions? Want the Paper?

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