Fiber Reinforced Polymer (FRP) Education

Engineering Design Series

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1. **Characteristics and Behaviors of Fiber Reinforced Polymers (FRPs) Used for Reinforcement and Strengthening of Structures.**
2. Design of Reinforced Concrete Structures using FRP Reinforcing Bars
3. Flexural and Shear Strengthening of Reinforced Concrete Structures using Exterior Bonded FRPs.
4. Axial, Flexural, and Shear Strengthening of Reinforced Concrete Columns using Exterior Bonded FRPs.
5. Strengthening of Unreinforced Masonry Structures using Exterior Bonded FRPs.
6. Construction Oversight, Inspection, and Documentation of FRP Installations.

Fortec Stabilization FRP Engineering Design Series

Characteristics and Behaviors of Fiber Reinforced Polymers (FRPs) Used for Reinforcement and Strengthening of Structures

Learning Objective

This presentation describes fiber reinforced polymer (FRP) systems used to reinforce and strengthen concrete, masonry, steel and timber structures including aramid (AFRP), basalt (BFRP), carbon (CFRP), and glass (GFRP) fibers. Their use as original reinforcement and as strengthening components will be discussed. The mechanical behavior of FRP reinforcement versus steel reinforcement will be presented. In addition, the different types of FRP systems used for reinforcement will be discussed including nets, tow sheets, fabrics, pultruded bars and plates, prepreg fabrics, and precured systems. Finally, the different resins used in FRP reinforcement systems will be discussed including saturating resins, primers, fillers, putties and adhesives.

Upon completion of the presentation the participant should be able to:

- Understand the behavior and characteristics of FRPs of various fibers and matrices;
- Understand the differences of various FRP systems and their advantages;
- Understand the differences between FRP and steel reinforcement behavior; and,
- Discuss the different types and advantages of FRP reinforcement systems.

Prerequisites

Participants should:

- Have a basic understanding of tensile and compressive strength, modulus of elasticity, stress, and strain as related to mechanics of materials; and,
- Understand the fundamentals of reinforced concrete, masonry, or timber design and construction.

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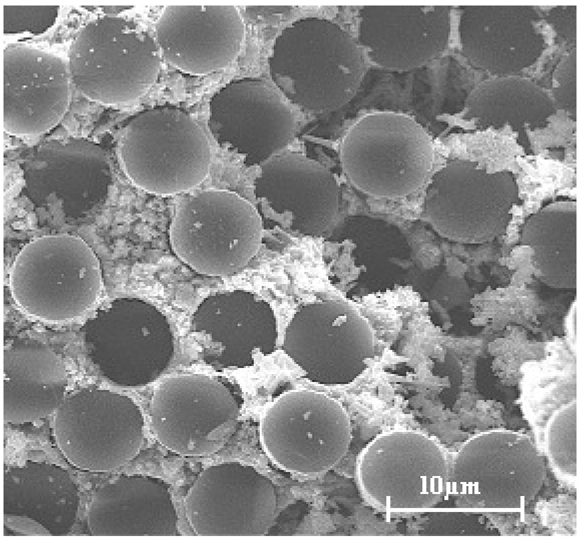
A. Introduction

1. A fiber reinforced polymer (FRP), also known as fiber reinforced plastic, is a composite material that uses natural or synthetic fibers to mechanically enhance the strength and stiffness of a plastic or polymer matrix.

2. FRPs used for the reinforcement and strengthening of structures use long, straight, continuous fibers in a polymer matrix to provide excellent tensile strength in the direction of the fibers.



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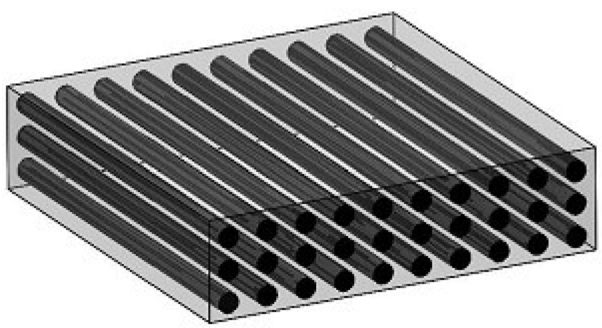

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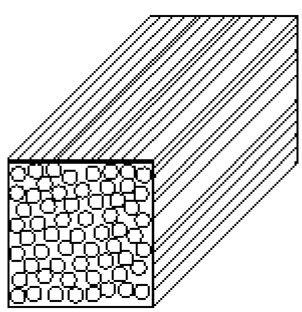
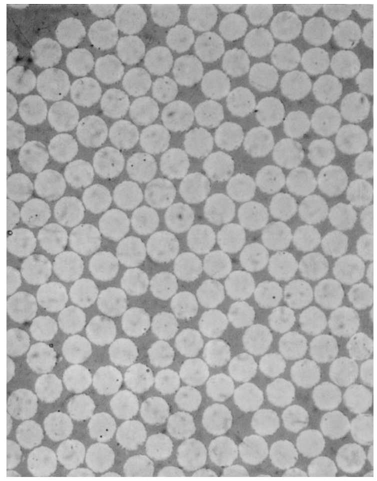


Image from
http://www.efunda.com/formulae/solid_mechanics/composites/comp_intro.cfm



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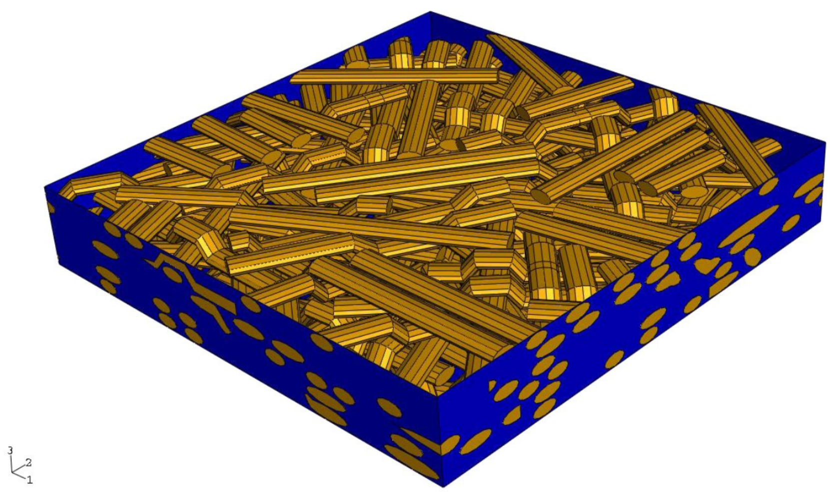


http://rci.rutgers.edu/~yipan/

3. The first significant studies of using FRPs as a reinforcement material began in 1996 during Japan's research of magnetically levitated (maglev) train support structures.
4. The predominant fibers used in FRPs related to structure reinforcement are:
   a. E-glass,
   b. S-glass,
   c. Aramid, also known as the DuPont trade names Kevlar® and Nomex® (AFRP), and,

d. Carbon.

e. Basalt fibers, which have better properties than E-glass at about the same price, may become a common fiber in FRPs used in construction

B. Applications

1. Original reinforcement

a. Reinforcement bars (rebar) and dowels

i. Roads, bridges, slopes, tunnels, marine environments

FRP dowels used for load transfer in concrete pavement

Image from http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/06106/chap5.cfm

Glass FRP bars (striped bars) with epoxy coated steel rebar underneath

Image from http://archive.bettendorf.org/publicworks/ibrc/ibrc.html

Placing concrete in a bride slab reinforced with glass FRP bars (top layer) and epoxy coated steel bars (bottom layer)

Image from http://www.virginiadot.org/vtrc/main/online_reports/pdf/05-cr24.pdf

b. Prestressed and post tensioned structural members

c. Tunnel diaphragm walls

d. Supporting structures for magnetically sensitive equipment

 i. Medical scanning equipment, large motors, maglev railways

2. Strengthening

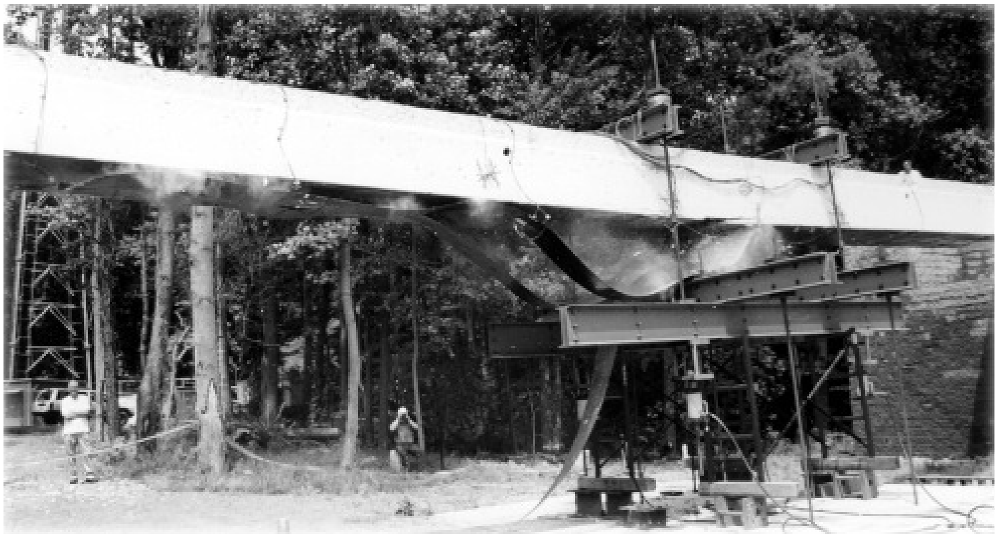
a. Beam and Wall Flexural

Photo of the Strengthening of Steel Girder Bridge Using Post-tensioned FRP Rods/Strands

Image from http://www.iowadot.gov/bridge/ibrc_projects/frp_tension_photos.htm

Images of carbon FRP plate (left) and carbon FRP grid (right) adhered to masonry walls for strength increase to resist bending loads

Images from http://www.fortecstabilization.com/casestudies.php?casestudy=MasUnit and http://www.fortressstabilization.com/casestudies/sheerslide.php



40-year old prestressed box girder strengthened with carbon fiber laminate undergoing testing

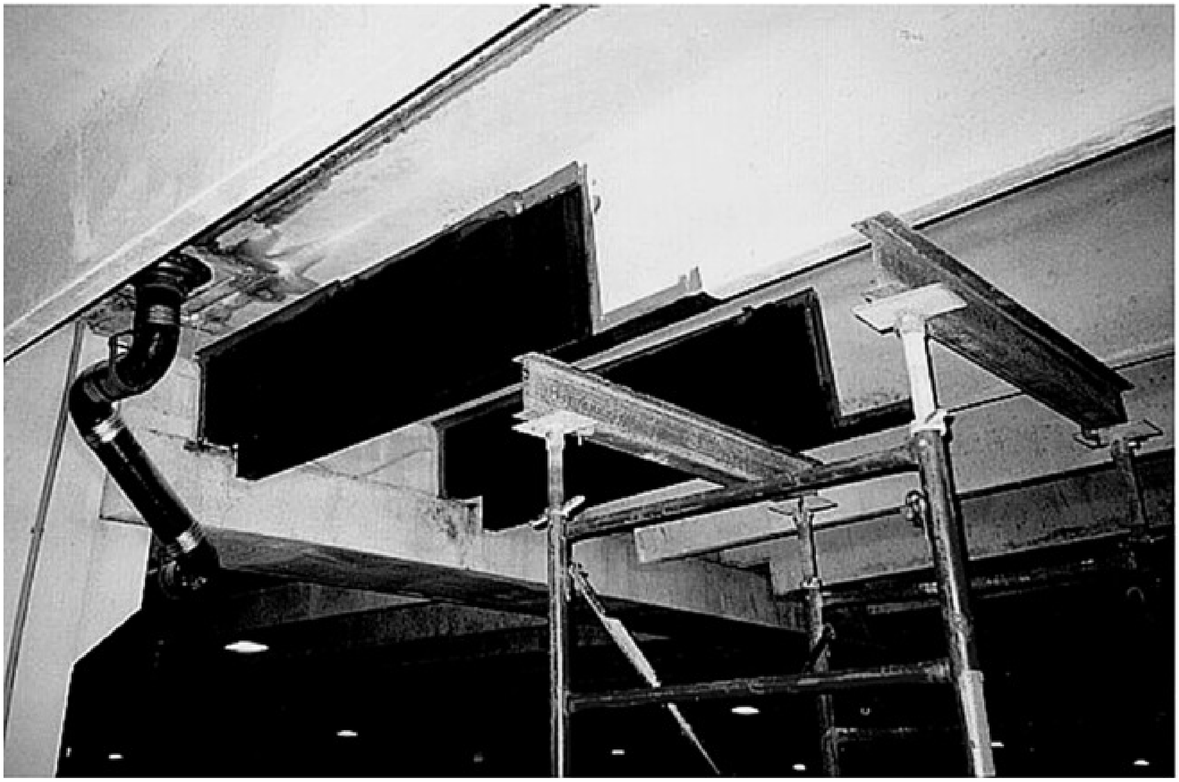
Image from http://bit.ly/VSxhLu

U.S. Dept. of Transportation, “Research & Technology Transporter,” September 2000, FHWA-RD-00-017

b. Beam and Wall Shear

This two story hospital wing in Cauquenes, Chile suffered severe damage to the wall of the first floor as a result of the M 8.8 earthquake on Feb. 27, 2010. All patients survived and were evacuated.

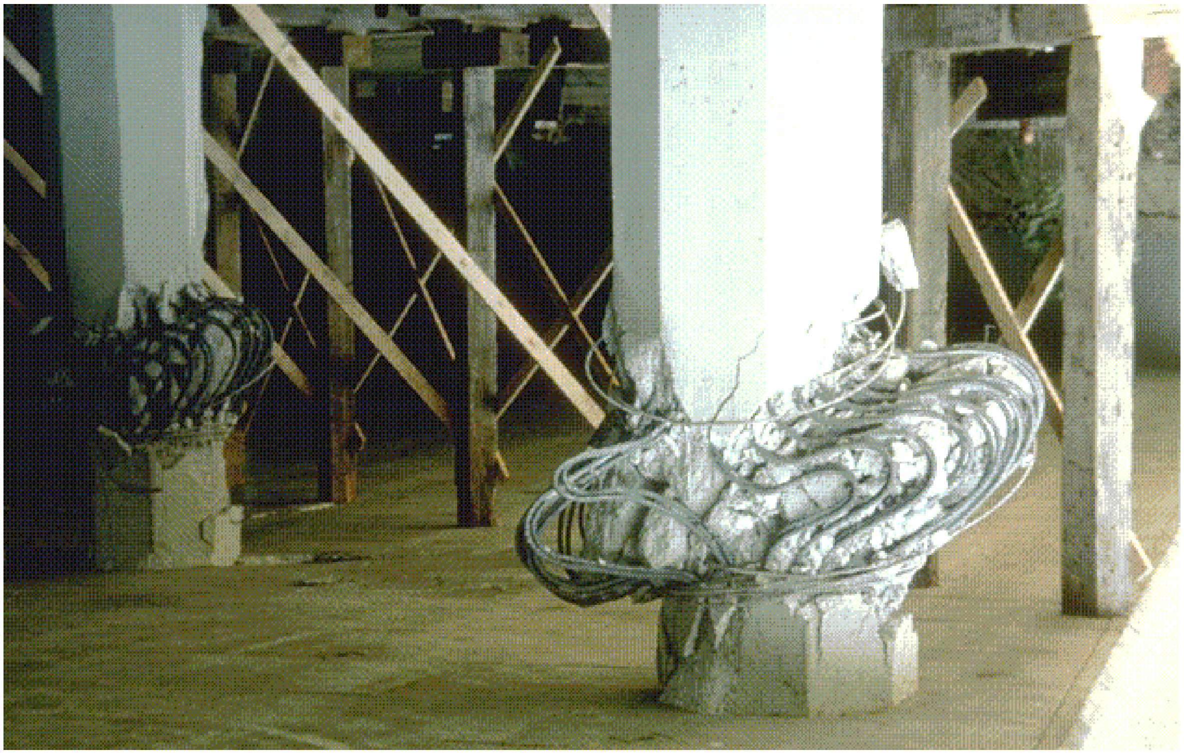
Image from
http://gallery.usgs.gov/images/03_30_2010/q74Xo00Nni_03_30_2010/medium/IMG_6770.jpg



c. Slab Flexural

Image from http://www.fortecstabilization.com/casestudies.php?casestudy=EqBridge

d. Axially & Eccentrically Loaded Columns
e. Seismic Retrofit of Columns



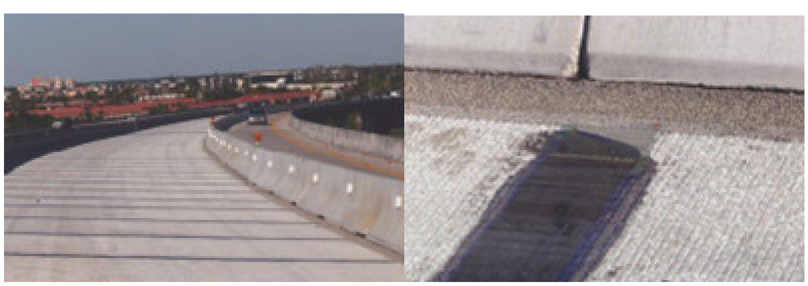
1994 Northridge Earthquake. Buckling of freeway support columns under the Simi Valley Freeway at the north end of the San Fernando Valley. This buckling shows the structural failure produced by high vertical acceleration.

Image from http://www.data.scec.org/chrono_index/slide_north118.html

Image from http://www.fhwa.dot.gov/publications/publicroads/97spring/compos.cfm

f. Repair

Images from http://www.fhwa.dot.gov/publications/focus/08mar/02.cfm



Images from
http://www.fortecstabilization.com/casestudies.php?casestudy=HighwayRep

Images from http://www.fortecstabilization.com/casestudies.php?casestudy=ColumnRep

g. Under Design

Images from http://www.fortressstabilization.com/casestudies/waterpark.php

3. **Corrosion Protection**
   a. Column Wrapping
   b. Structure Jacketing

Image from http://wpbk.substructure.com/marine-services/marine-encapsulation/

Image from http://www.dsbrown.com/Resources/Articles/Masterbuilder.pdf

Image from http://www.forconstructionpros.com/print/Concrete-Contractor/Concrete-Contractor-Online-Features/FRP-Pile-Jacket-Solution-has-no-Pier-in-Timber-Pile-Restoration/7FCP12740

C. Pros and Cons

1. Advantages

a. High strength and light weight
   i. Low weight assists transportation, assembly & installation costs.
b. Corrosion resistant
   i. Resistant to many aggressive chemicals, acids and alkalis
   ii. Enhances durability of reinforced structures
c. Dimensional stability
d. Low thermal conductivity
e. Nonconductive
f. Electromagnetically transparent
g. Impact resistant
h. Low lifecycle costs

2. Disadvantages

a. High initial cost
   i. Of materials
b. Susceptibility to mechanical damage
   i. By a determined attack
c. Fire
   i. Although FRPs can be designed to self-extinguish and resist the spread of fire, there is loss of strength due to high temperatures.
d. Inability to bend onsite
e. Longer load transfer (lap) lengths
f. Poor shear strength
   i. Compared to steel
g. Low strain to failure
   i. Brittle

D. Components of FRPs

1. Matrix

a. The matrix is a resin in which fibers are impregnated. For exterior strengthening applications, resins are also used as substrate primers and protective coatings.

b. Thermosets are used as the predominant polymer matrix in structural reinforcement FRPs.

c. Thermoset polymers feature cross-linked polymer chains that become solid during a chemical reaction or in contact with a catalyst and heat. A thermoset reaction is largely irreversible.[1]

   i. Polyester:

      (a) Low cost, highly resistant to acids, weak alkalies, and organic solvents, and can be formulated for flexible or rigid end products. Easy to process.

   ii. Vinyl ester:

      (a) Excellent resistance to water, organic solvents and alkalies. Stronger than polyesters and more resilient than epoxies.

      (b) Vinyl ester resins may be used in applications up to 338 ˚F (170 ˚C).[15]

   iii. Epoxy:

      (a) Excellent adhesion properties and can be formulated for temperatures as high as 500 ˚F (260 ˚C). Epoxy based FRPs have generally higher fatigue properties than polyesters.[1] For high strength applications.

   iv. Polyurethane

      (a) Very high toughness, high elongation, faster cure times and good adhesion to fibers.

d. Glass transition temperature, T_G, is the temperature where a FRP matrix or resin changes from a rigid state to a flexible state. Most resins in use for FRP systems have a glass transition temperature between 125 to 180 °F (52 to 82 °C) although some resins have a T_G as high as 500 ˚F (260 ˚C).[___] A FRP system's service temperature should never reach the glass transition temperature.

e. Properties of some thermosetting matrices are shown below.

Table 1 Typical properties of thermosetting matrices

	Matrix			
Property	Polyester	Epoxy	Vinyl Ester	Polyurethane
Density, lb/ft^3 (g/cm^3)	75-87 (1.2-1.4)	75-87 (1.2-1.4)	72-84 (1.15-1.35)	64-94 (1.03-1.5)
Tensile Strength, ksi (MPa)	5-15 (34.5-104)	8-19 (55-130)	10-12 (73-81)	0.7-4.5) (5-31)
Elastic Modulus, ksi (GPa)	300-500 (2.1-3.45)	400-600 (2.75-4.1)	435-510 (3.0-3.5)	14.5-100 (0.1-0.7)

Information from *fib*TG9.3 [15], Kachlakev [17], and http://www.efunda.com/materials/polymers/properties/polymer_datasheet.cfm?MajorID=PU&MinorID=1

2. Fibers

a. Glass

i. Glass fibers are the predominant reinforcing fiber in all FRPs.[1]

ii. E-glass is the most commonly used. It has high electrical insulating properties, good heat resistance, and has the lowest cost.

iii. S-Glass has higher heat resistance and about one-third higher tensile strength than E-glass.

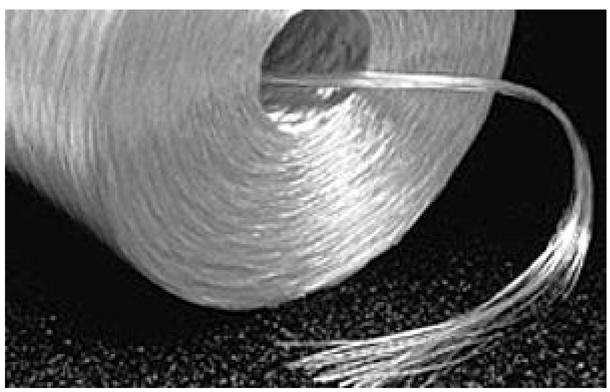


Figure 1 Glass roving (group of untwisted fibers).

Image from http://www.directindustry.com/prod/owens-corning/multi-end-e-glass-rovings-37816-259793.html

b. Aramid

i. Aramid, also known as aromatic polyamide, fibers have high strength, a high elastic modulus, and 40% lower density than glass fibers.

ii. Aramid fibers have a low compressive strength and absorb and dissipate energy perpendicular to the fiber direction very well making them the preferred fiber used in bullet-proof vests and other ballistic resistant, personnel armor.

iii. Aramid fibers are known by different trade names including Kevlar®, Nomex®, and Twaron®. Kevlar® and Nomex® are registered trademarks of E.I. du Pont de Nemours and Company. Twaron® is a registered trademark of Teijin Twaron, BV.

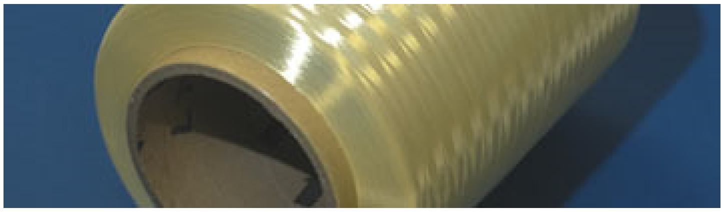


Figure 2 Spool of DuPont™ Kevlar® fibers

Image from http://www2.dupont.com/Kevlar/en_US/products/fibers/fiber.html

c. Carbon

i. Carbon fibers have a very high tensile strength and elastic modulus. The elastic modulus of "high modulus" carbon fiber is similar to steel.

ii. CFRP is popular in the aerospace industry because its strength to weight ratio is among the highest of all FRPs.

iii. Carbon fibers are very small, about 0.24 mils (6 μm) in diameter. Below is a photograph comparing a carbon fiber to a human hair.

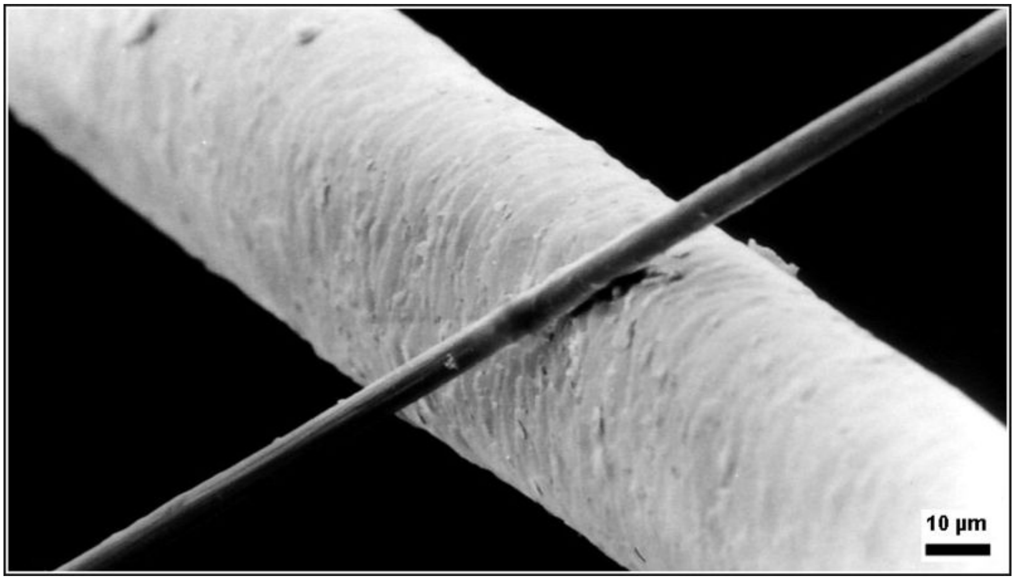
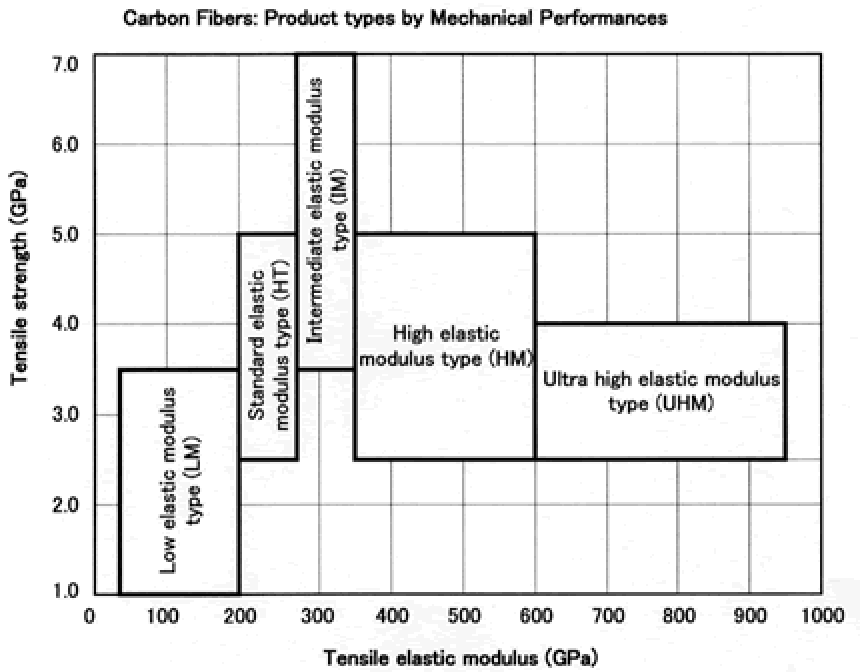


Figure 3 Comparison of a carbon fiber filament (dark strand) versus a human hair.

Image from http://commons.wikimedia.org/wiki/File:Cfaser_haarrp.jpg



d. Basalt

i. Basalt is a type of igneous rock formed by the rapid cooling of lava at the surface of a planet. It is the most common rock in the Earth's crust.[2]

ii. The production of basalt fiber is very similar to glass fiber. Basalt fiber is a continuous fiber produced through igneous basalt rock melt drawing at about 2,700 ˚F (1,500 ˚C).[3]

iii. Basalt fiber requires less energy to produce than glass fibers and unlike glass fibers has a high resistance to acids and alkalis.[7]

iv. Compared to carbon and aramid fiber, it has the features of wider application temperature range -452 ˚F to 1,200 ˚F (-269 ˚C to +650 ˚C), higher oxidation resistance, higher radiation resistance, higher compression strength, and higher shear strength.[3] Its price is less than bulk carbon fiber.[4]

(a) It should be noted that application temperature of FRPs are limited by the glass transition temperature of the matrix which is lower than the application temperature of the fibers.

Figure 4 Spool of basalt roving

Image from http://basalt-alf.narod.ru/

e. Other fibers

i. Natural fibers from animal (wool, silk), vegetable (bamboo, cotton, hemp), cellulose (acetate, rayon) and other synthetic (acrylic, nylon, polyethylene), sources are not used in FRPs for structural reinforcement due to low strengths, temperature related fluctuation or other poor physical characteristics.

ii. This presentation will review the three common fibers, E-glass, aramid, and standard modulus carbon, used in FRP reinforced structures, and basalt, the upcoming fiber.

3. Fiber arrangement

a. Unidirectional

i. Predominant structure reinforcement arrangement

ii. Tow Sheets

(a) A tow sheet is a fabric in which fibers in groups called tows are arranged in the long (0˚) direction of the fabric. The tows are held together by weaving a cheap, low strength fiber such as cotton or polypropylene in the cross (90˚) direction.

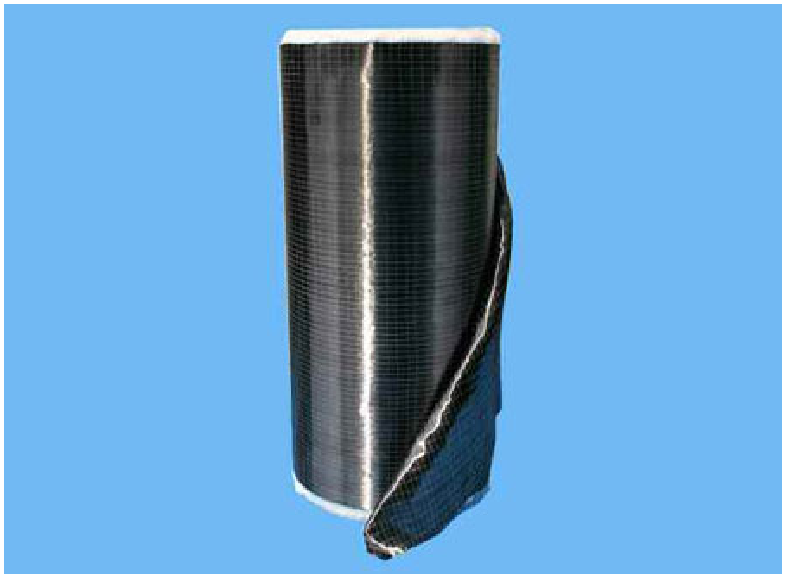


Figure 5 Carbon fiber unidirectional tow sheet

Image from http://www.fortecstabilization.com/products.php

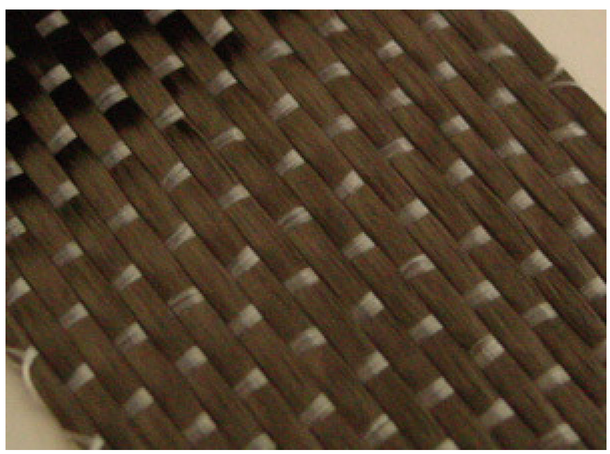


Image from http://compositeenvisions.com/raw-fabric-cloth-2/carbon-fiber-97/carbon-fiber-fabric-uni-directional-12k-11oz-tape-611.html

(b) A tow (or roving) is a large numbers of filaments gathered together without twisting. A tow is named for carbon fiber and a roving for glass and aramid fibers. The number of filaments in a tow can vary from a few thousand to 50,000.

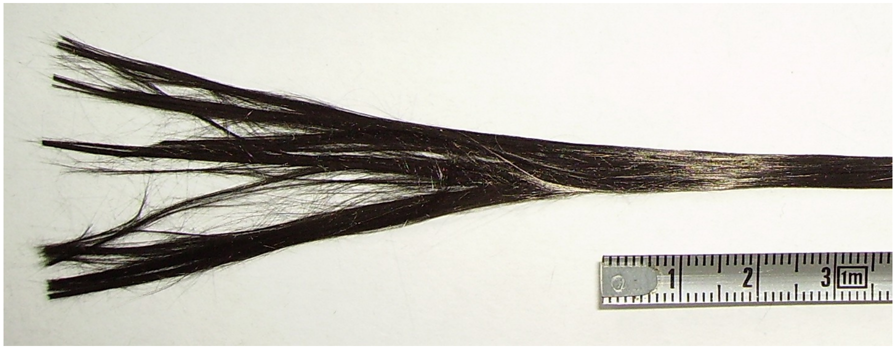


Figure 6 Carbon fiber tow

Image from http://commons.wikimedia.org/wiki/File:Carbon_fiber-2.jpg

(c) Tow sheets are used as externally applied reinforcement for flexural and shear strengthening.

iii. Pultruded Shapes

(a) Pultrusion is the process where (usually) tows or fabrics are "pulled through a resin bath to wet-out the fibers, then drawn through a forming block that sets the shape of the composite and removes excess resin, and through a heated steel die to cure the resin."[1] A cutoff saw is used to cut the solid FRP to length. See Figure 1.

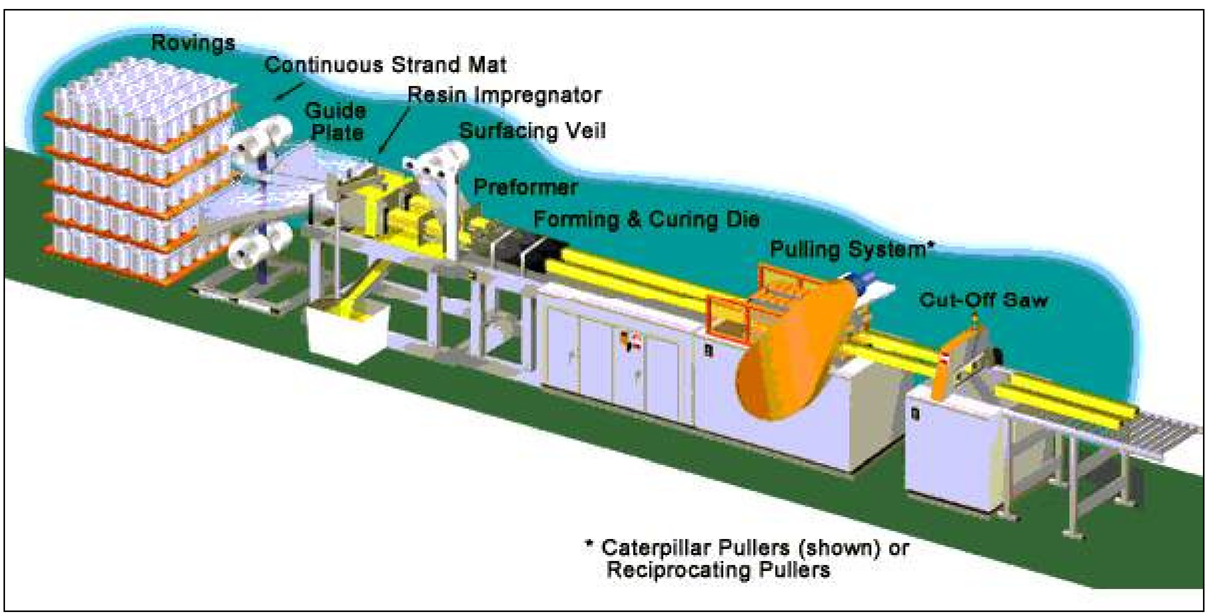


Figure 7 Pultrusion Process

Image from http://www.strongwell.com/pultrusion/

(b) Bars

(i) Pultruded shapes, by their manufacturing process, have a very smooth surface. In order for concrete or mortar to adhere to FRP reinforcement bars (and dowels), they are available with matrix deformed shapes (as with steel rebar), wrapped, or sand coated.

(ii) FRP bars are used as internal reinforcement in concrete and masonry structures and also used as "externally" applied reinforcement using the near-surface mounted (NSM) technique. The NSM method has been used to strengthen concrete, masonry and timber structures.

Figure 8 Various FRP reinforcing bar (rebar) finishes

Image from http://www.tradekool.com/common/image.php?file=1309165&x=0&y=0&jpg

(c) Plates

(i) FRP plates (also known as straps) are pultruded shapes. They are available in various widths and usually between 1 mm and 2 mm thick.

(ii) Carbon is the predominant fiber used in FRP plates.

(iii) FRP plates are used as externally applied reinforcement to strengthen concrete, masonry, timber and steel structures.

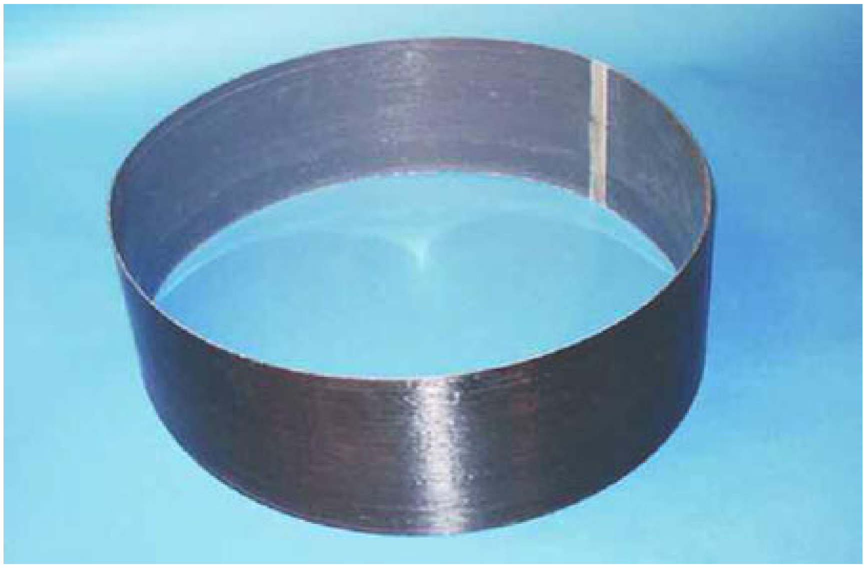


Figure 9 Carbon fiber plate lapped in a circular orientation

Image from http://www.fortressstabilization.com/strap.php

Figure 10 CFRP Plates bonded with epoxy to a concrete beam

Image from http://www-civ.eng.cam.ac.uk/cjb/cjbresearch1.html

Figure 11 CFRP Plate bonded to a masonry wall

Image from http://alljackedupconcretelifters.com/WALLSTRAIGHTENING.aspx

(d) Tapes and Strips

(i) Tapes and strips are simply pultruded plate but with thinner sections. They are used as externally bonded and as NSM reinforcement.

Figure 12 Carbon fiber tape

Image from http://www.petenplanes.com.au/hardware-items/dave-brown-carbon-fiber-strip-5-5-39-/prod_173.html

iv. Prepreg

(a) "Prepreg" is a term in the FRP industry meaning resin pre-impregnated fibers. Structure reinforcement prepregs come in various shapes for different purposes.

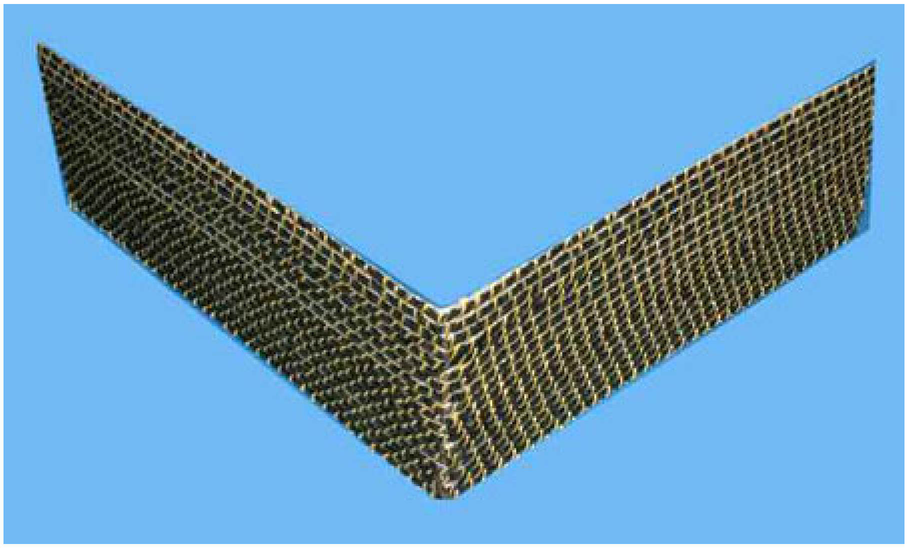


Figure 13 Carbon fiber prepreg corner strap

Carbon tows make up the fibers in the long direction. The cross fibers in this product are aramid.

Image from http://www.fortressstabilization.com/cornerstrap.php

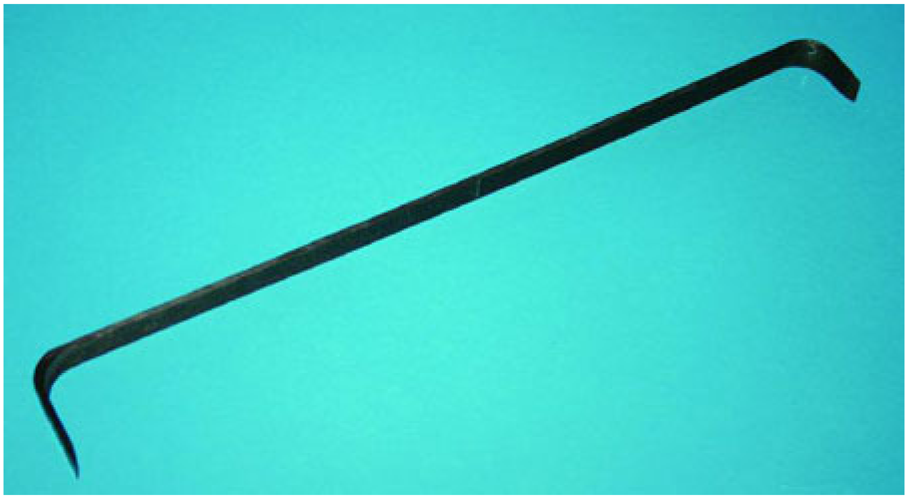


Figure 14 Carbon fiber prepreg and precured "staple"

Used for crack arrest.

Image from http://www.fortressstabilization.com/countersunk.php

b. Bidirectional

i. Woven Fabrics

(a) Fabrics are woven with fibers in the 0˚ and 90˚ directions. They can be useful in some strengthening circumstances but have less tensile strength than unidirectional (tow) sheets due to less fibers per unit width in a given direction and due to crimping of fibers in the weave pattern.

(b) Bidirectional strengthening can be accomplished by using two layers of unidirectional (tow) sheets laid in the 0˚ and 90˚ directions.

c. Multidirectional

i. Mats

(a) Multidirectional fiber mats use either short, randomly oriented fibers or continuous fibers in random, swirling patterns.

(b) A nonwoven geotextile is an example of a multidirectional mat that uses polypropylene or polyethylene fibers.

(c) Generally not used as structure reinforcement

Figure 15 Basalt fiber mat

Image from
http://bspmat.com.previewyoursite.com/documents/Techtextil+2002+Basalt+paper1.pdf

4. Fiber Properties

a. The primary physical properties considered for fibers in composite materials are:

i. Ultimate tensile strength, f_{fu}*, a material's resistance to stretching;

ii. Tensile Modulus of Elasticity, E_f, measure of a material's stiffness; and,

iii. Ultimate Rupture Strain, or Elongation at Break, ε_{fu}*, the strain of a material at the point of rupture.

(a) ACI nomenclature is used here.

iv. Fibers and FRPs exhibit linear-elastic behavior, therefore these three properties are interrelated as defined by Hooke's law:

$$E_f = \frac{f_{fu}^*}{\varepsilon_{fu}^*}$$

b. The material properties of the various fibers are shown below.

Table 2 Comparison between various fiber properties

	E-Glass	S-Glass	Aramid	Carbon[1]	Basalt[2]
Tensile strength, ksi (MPa)	490 (3,400)	710 (4,900)	420-435 (2,900-3,000)	500-710 (3,500-4,900)	406-580 (2,800-4,000)
Elastic Modulus, ksi (GPa)	10,500 (72.3)	12,600 (86.9)	10,300-16,240 (71-112)	33,350 (230)	12,500-12,900 (86-89)
Elongation at break, %	4.8	5.7	2.4-3.6	1.5-2.1	3.15

[1] "Standard" modulus carbon

[2] Some manufacturers report higher strengths but cannot be substantiated at the time of this writing.

Information from http://www.basfiber.com/src/bridges.pdf

E. FRP Physical and Mechanical Properties

1. Density

a. An advantage of FRP reinforcement products is their high specific strength, that is, they have a high strength to weight ratio compared to steel. This is especially advantageous when strengthening existing structures.

b. The following table lists the typical densities of various reinforcing FRPs.

Table 3 Typical densities of reinforcing materials in lb/ft^3 (gm/cm^3)

Steel	GFRP	CFRP	AFRP	BFRP
493.0 (7.90)	77.8 to 131.0 (1.25 to 2.10)	93.3 to 100.0 (1.50 to 1.60)	77.8 to 88.1 (1.25 to 1.40)	112.3 to 131.0 (1.80 to 2.10)

(Information is from ACI [8] and author's research.)

2. Tensile Strength

a. Strength Behavior. Unlike steel reinforcement, FRP reinforcement products have anisotropic strength properties, that is, strength is different in tension and compression, and in different directions.

   i. Tension resistance is measured parallel to the fiber (longitudinal) direction.

   ii. Compression resistance in the longitudinal direction is generally ignored in ACI design methodology. There are no standardized test methods to characterize the compressive behavior of FRP bars.[8]

   iii. There is little reporting of compressive resistance perpendicular to the fiber (transverse) direction for FRP reinforcement products.

   iv. Read and understand an FRP manufacturer's strength report for bars and other products. In general, the tensile strength per unit area of pultruded FRP bars tends to decrease as the cross-sectional area increases.[8] FRP bars fabricated using twisted or braided strands does not have as severe a phenomenon.

b. Tensile behavior of FRP reinforcement is generally characterized by a linear-elastic stress-strain relationship until failure.[8] In other words, a typical FRP reinforcement system does not yield like steel does; it loads up until it breaks.

Table 4 Typical tensile properties of FRP bars, plates, and laminated tow sheets[1] as compared to steel

	Steel	GFRP	BFRP	AFRP	CFRP
Yield strength, ksi (MPa)	40-75 (276-517)	N/A	N/A	N/A	N/A
Tensile strength, ksi (MPa)	70-100 (483-690)	70-230 (483-1,600)	150-240 (1,035-1,650)	250-368 (1,720-2,540)	87-585 (600-3,690)
Elastic modulus, ksi (GPa)	29.0 (200.0)	5,100-7,400[2] (35.0-51.0)	6,500-8,500 (45.0-59.0)	6,000-18,200 (41.0-125.0)	15,900-84,000[3] (120.0-580.0)
Yield strain, %	1.4-2.5	N/A	N/A	N/A	N/A
Rupture strain, %	6.0-12.0	1.2-3.1	1.6-3.0	1.9-4.4	0.5-1.7

[1] typical values for fiber volume fractions ranging from 0.5 to 0.7

[2] ACI 440.6-08 specifies that the tensile elastic modulus be at least 5,700 ksi (39.3 GPa) for rebar

[3] ACI 440.6-08 specifies that the tensile elastic modulus be at least 18,000 ksi (124 GPa) for rebar

Information from ACI [8], [13], and author's research

3. **Thermal Expansion**
   a. Anisotropic behavior
      i. The coefficient of thermal expansion in FRP systems is different between the long and transverse direction and varies with the type of fiber, matrix, and volume fraction of fibers within the matrix.[8] A table of coefficients of thermal expansion is shown below.

Table 5 Typical coefficients of thermal expansion (CTE) for concrete and reinforcing bars

	CTE, $x10^{-6}/^{\circ}F$ ($x10^{-6}/^{\circ}C$)					
Direction	Concrete	Steel	GFRP	AFRP	CFRP	BFRP
Longitudinal, α_L	4 to 6 (7.2 to 10.8)	6.5 (11.7)	3.3 to 5.6 (6 to 10)	-3.3 to -1.1 (-6 to -2)	-4 to 0 (-9 to 0)	4.4 (8)
Transverse, α_T	4 to 6 (7.2 to 10.8)	6.5 (11.7)	11.7 to 12.8 (21 to 23)	33.3 to 44.4 (60 to 80)	41 to 58 (74 to 104)	N/A

[1] typical values for fiber volume fractions ranging from 0.5 to 0.7

Information from ACI [8], fib [15], and Saravanan [16].

4. **Stiffness**

   a. Elastic Modulus. With the exception of high strength and high modulus carbon FRPs, generally all FRP reinforcement products have a lower modulus of elasticity than that of steel. The following figure shows the relative stress-strain relationship of various reinforcing materials.

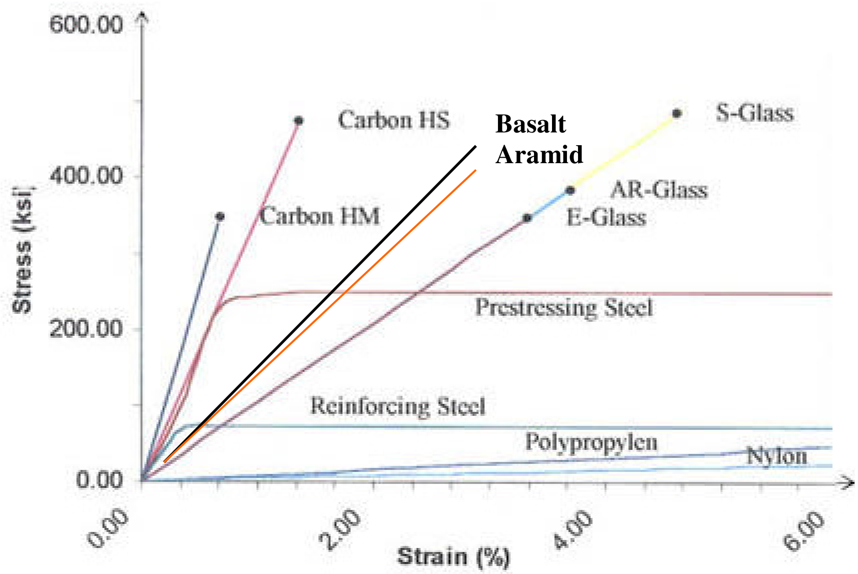


Figure 16 Tensile stress-strain relationship of reinforcement fibers as compared to steel

Image from Xi and Cusson.[10]

5. **Shear Strength**

   a. The minimum transverse shear strength (perpendicular to the fiber direction) specified by ACI [13] is 18 ksi (124.1 MPa)

6. **Creep-Rupture and Fatigue**

   a. Carbon based FRPs exhibit higher resistance to sustained and cyclic loading compared to glass, aramid and (likely) basalt based FRPs.

   b. The behavior of basalt bars under sustained load is not yet fully understood. Based on the similarities in composition of basalt and glass fibers, it may be probable that basalt and glass fibers have similar creep rupture behavior.[14] Preliminary testing suggests a coefficient 20% to 35% higher than glass fibers. Prior to applying a creep-rupture and fatigue load stress limit to basalt FRPs, additional research and testing is needed.

   c. To avoid creep-rupture and fatigue failure under sustained and cyclic loads, ACI recommends a reduction factor. Values for safe sustained plus cyclic stress levels are shown below.

Table 6 FRP reinforcement creep-rupture and fatigue load stress limits

	GFRP	AFRP	CFRP	BFRP[1]
Stress limit, $F_{f,s}$	$0.20 \cdot f_{fu}$	$0.30 \cdot f_{fu}$	$0.55 \cdot f_{fu}$	$0.15 \cdot f_{fu}$ to $0.27 \cdot f_{fu}$

Source: ACI. [9]

[1] Author's estimate based on two research papers. More testing is required to establish a limit factor.

F. References

1. Molded Fiber Glass Companies, “Designing with Fiber Reinforced Plastics / Composites, Techniques and Technologies for Cost Effectiveness,” 2003

2. PAUL HANCOCK and BRIAN J. SKINNER. "basalt." The Oxford Companion to the Earth. 2000. *Encyclopedia.com.* http://www.encyclopedia.com/doc/1O112-basalt.html

3. “Continuous basalt fiber sector in shaping. (Statistics)” China Chemical Reporter. July 6, 2010. *highbeam.com*. http://www.highbeam.com/doc/1G1-231544702.html

4. Jackson, Todd., Technical Director, Fortress Stabilization Systems. Personal communications 2009-2018.

5. Specialty Materials, Inc. “Boron Fiber.” *specmaterials.com*. http://specmaterials.com/boronfiber.htm

6. “Silicon Carbide Fibers.” CRC Press, LLC. 1989. *About.com.* http://composite.about.com/library/glossary/s/bldef-s4905.htm

7. Palmieri, A., Matthys, S., and Tierens, M. “Basalt fibres: Mechanical properties and applications for concrete structures.” Taylor and Francis Group. 2009. *crcnetbase.com.* http://www.crcnetbase.com/doi/abs/10.1201/9780203864005.ch29

8. American Concrete Institute. “Guide for the Design and Construction of Concrete Reinforced with FRP Bars.” ACI 440.1R-01. May 2001.

9. American Concrete Institute. “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures.” ACI 440.2R-08. July 2008.

10. Xi, Y. and Cusson, R. “The Behavior of Fiber-Reinforced Polymer Reinforcement in Low Temperature Environmental Climates.” Report No. CDOT-DTD-R-2003-4. December 2002. http://cospl.coalliance.org/fez/eserv/co:5270/tra210034internet.pdf

11. American Concrete Institute. “Prestressing Concrete Structures with FRP Tendons.” ACI 440.4R-04. December 2004.

12. Patanaik, Anil. “Applications of Basalt Fiber Reinforced Polymer (BFRP) Reinforcement for Transportation Infrastructure.” TRB. November 2009.

13. American Concrete Institute. “Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement.” ACI 440.6-08. July 2008.

14. Darby, A., Ibell, T., Evernden, M. “Innovative use and characterization of polymers for timber-related construction.” February 10, 2010. Materials, 3 (2), pp. 1104-1124. *opus.bath.ac.uk* http://opus.bath.ac.uk/17899/1/darby-a-2010.pdf

15. International Federation for Structural Concrete (*fib* - fédération internationale du béton) Task Group 9.3. “FRP reinforcement in RC structures.” September 2007.

16. Saravanan, D. “Spinning the Rocks – Basalt Fibres.” February 2006. IE(I) Journal-TX Vol. 86. *www.ieindia.org*. http://www.ieindia.org/pdf/86/ext4f6a3.pdf

17. Kachlakev, Damian I. “Strengthening Structures Using FRP Composite Materials.” California Polytechnic State University. ceenve3.civeng.calpoly.edu/kachlakev/FRP%20Materials.ppt

18. GangaRao, Hota V.S. Reinforced concrete design with FRP composites. CRC Press. 2007.

G. Associations

- ACI – American Concrete Institute www.concrete.org
- *fib* - Fédération Internationale du Béton (International Federation for Structural Concrete) www.fib-international.org.
- CSA – Canadian Standards Association www.shopcsa.com
- ISIS Canada – Intelligent Sensing for Innovative Structures Canada www.isiscanada.com
- IIFC – International Institute for FRP in Construction www.iifc-hq.org
- JSCE – Japan Society of Civil Engineers www.jsce-int.org