Marine Composites

Webb Institute
Senior Elective

Reinforcements and Resin Systems

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Reinforcement Fibers

E-glass - Glass fibers account for over 90% of the fibers used in reinforced plastics because they are inexpensive to produce and have relatively good strength to weight characteristics. Continuous glass fibers are formed by extruding molten glass to filament diameters between 5 and 25 micrometers. Individual filaments are coated with a sizing that acts as a coupling agent during resin impregnation.

Polymer Fibers - These range from aramids, such as Kevlar® with very high strength to polyester and nylon thermoplastic fibers, with very high elongation.

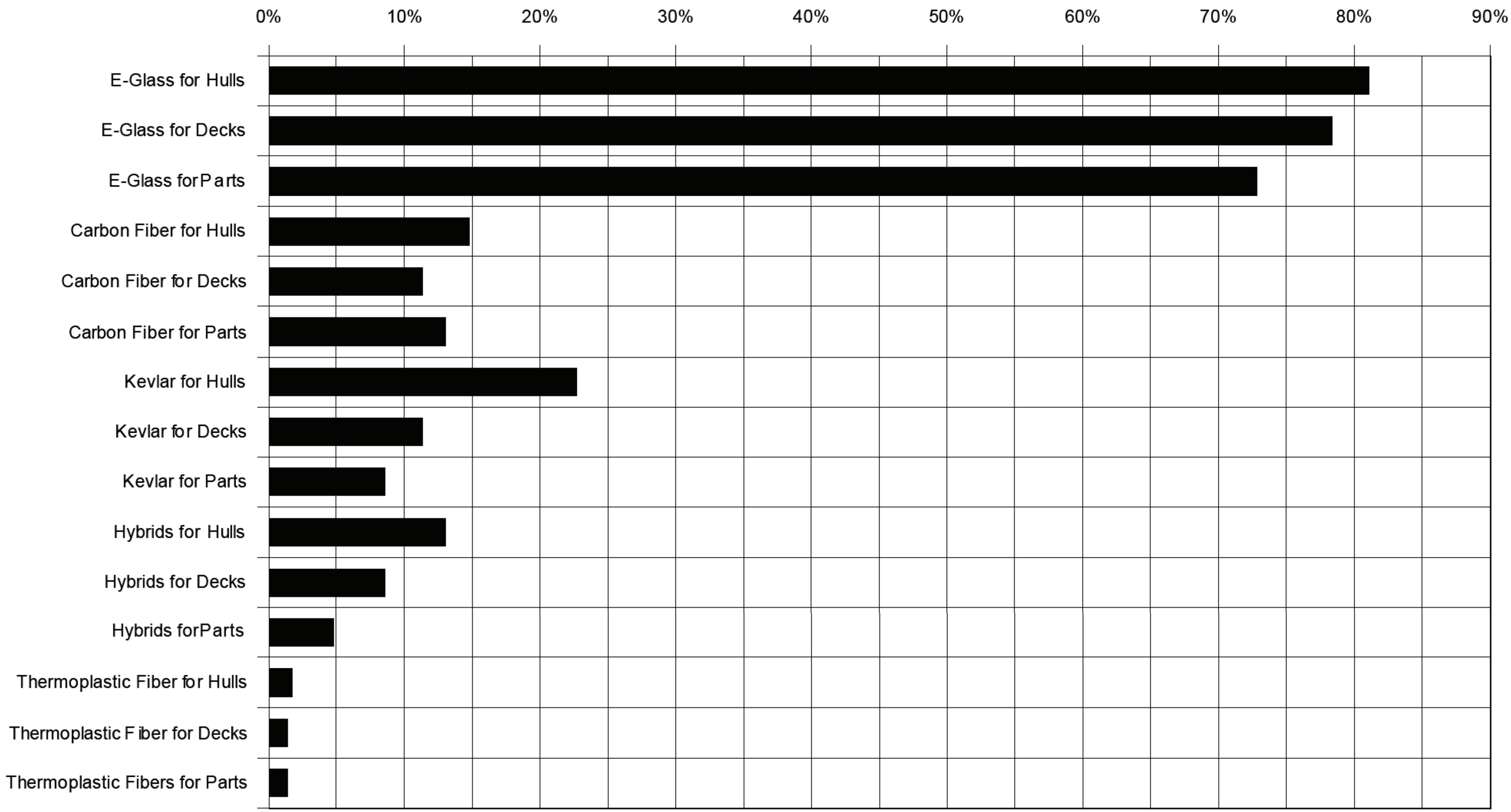
Carbon Fiber -The terms “carbon” and “graphite” fibers are typically used interchangeably. Carbon fibers offer the highest strength and stiffness of all commonly used reinforcement fibers.

Fiber Mechanical Properties

	Density gm/cm^3	Strength MPa	Modulus GPa	Specific Strength MPa*	Specific Modulus GPa*
E-glass	2.60	3450	72	1327	28
S-glass	2.49	4589	87	1843	35
Aramid	1.44	3623	124	2516	86
Carbon (commercial)	1.76	2415	227	1372	129
Carbon (high performance)	1.76	4830	393	2744	223
Polyethylene	0.97	3000	170	3093	175
Basalt	2.66	2950	90	1109	34
HT steel	7.86	750	210	95	27
Aluminum	2.66	310	75	117	28

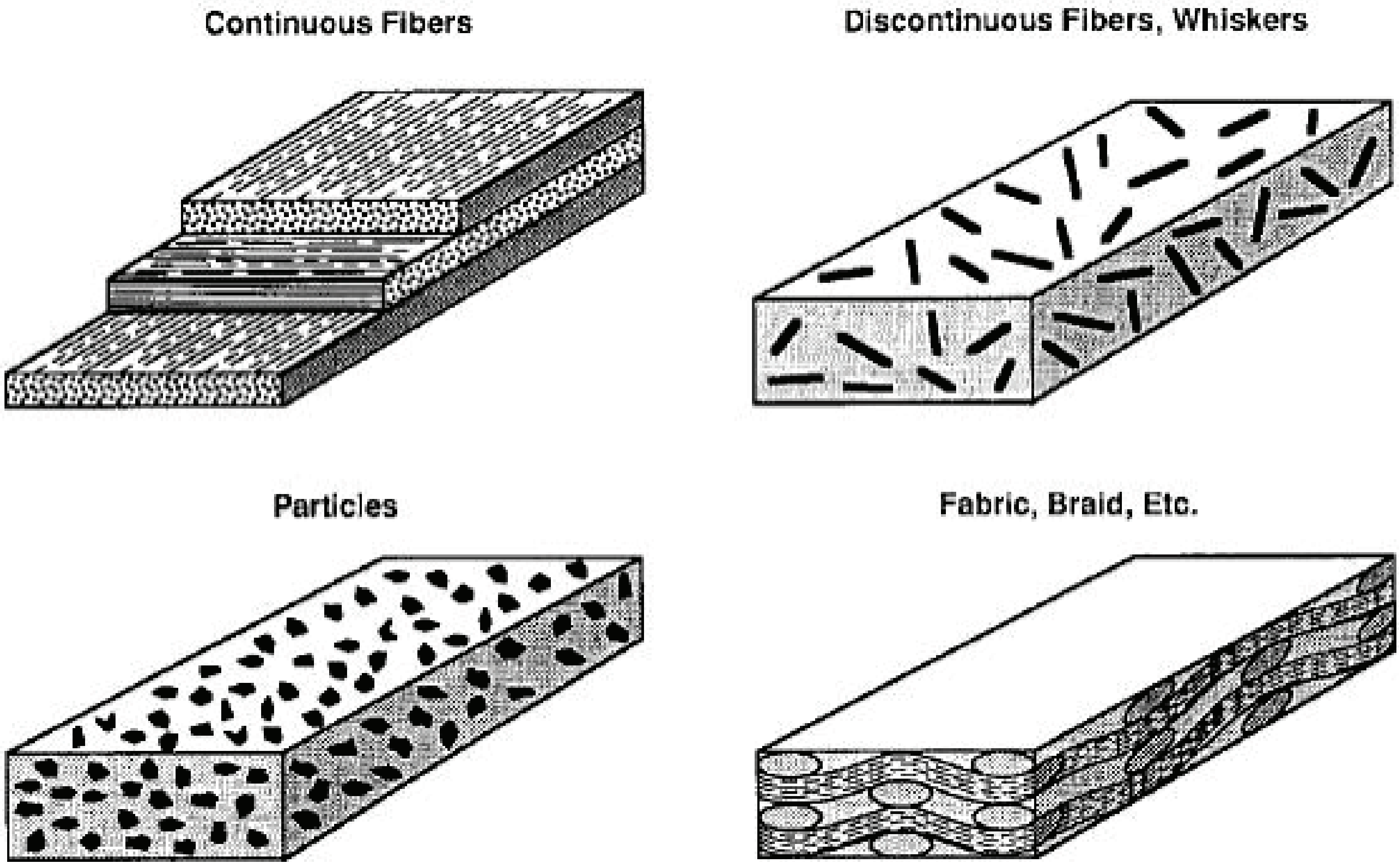
* Strength or stiffness divided by density

Boatbuilder Reinforcement Types



data from Eric Greene Associates 1995 survey

Reinforcement Types



Reinforcement Architectures

Filaments - Fibers as initially drawn

Continuous Strands - Basic filaments bundled together

Yarns - Twisted strands (treated with after-finish)

Chopped Strands - Strands chopped 5 to 50 mm

Rovings - Strands bundled together like rope but not twisted

Milled Fibers - Continuous strands hammermilled into short lengths 0.8 mm to 3 mm long

Reinforcing Mats - Nonwoven random matting consisting of continuous or chopped strands

Woven Fabric - Cloth woven from yarns

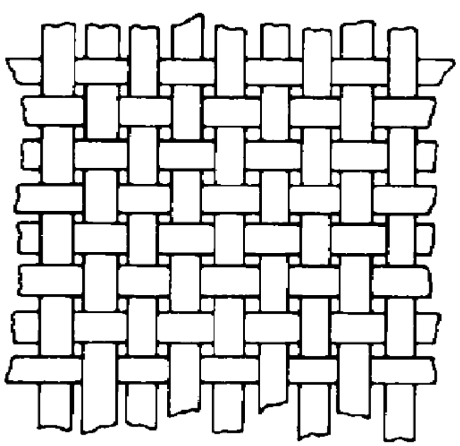
Woven Roving - Strands woven like fabric but coarser and heavier

Spun Roving - Continuous single strand looped on itself many times and held with a twist

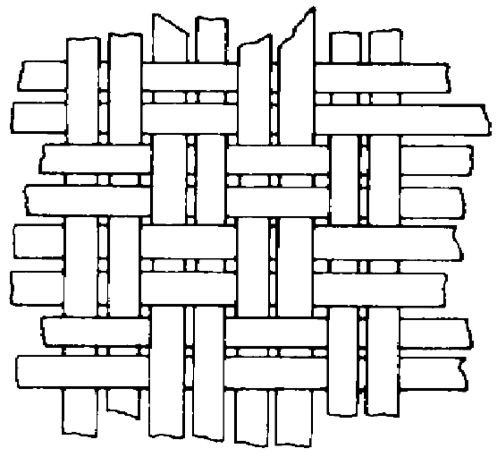
Nonwoven Fabrics - Similar to matting but made with unidirectional rovings in sheet form

Surfacing Mats - Random mat of monofilaments

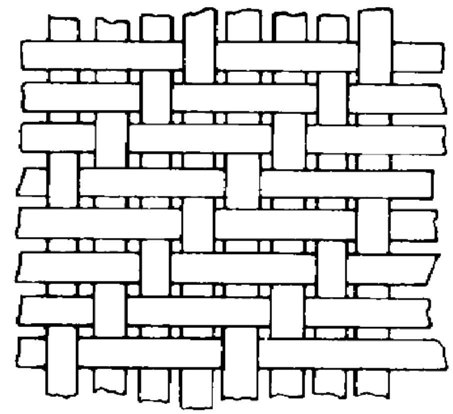
Woven Reinforcement Styles



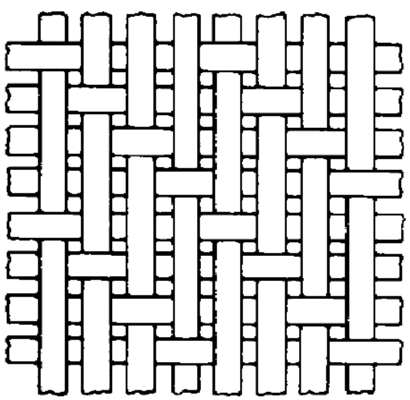
Plain weave



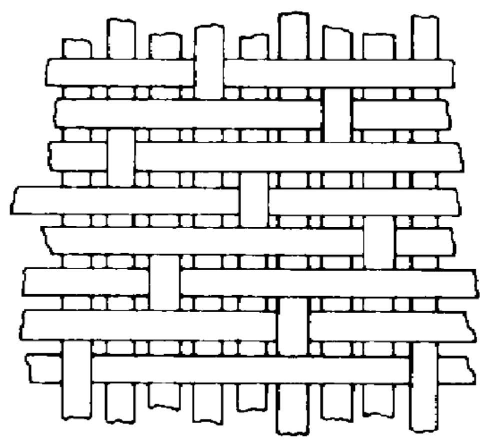
Basket weave



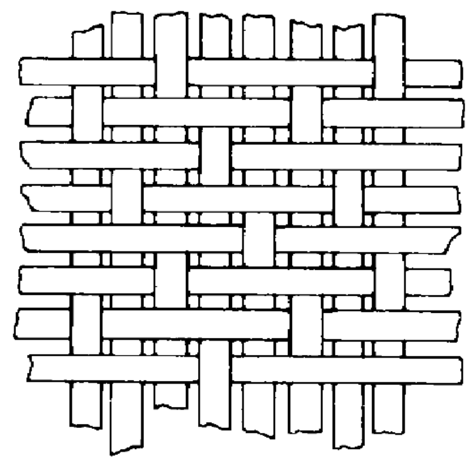
Twill



Crowfoot satin



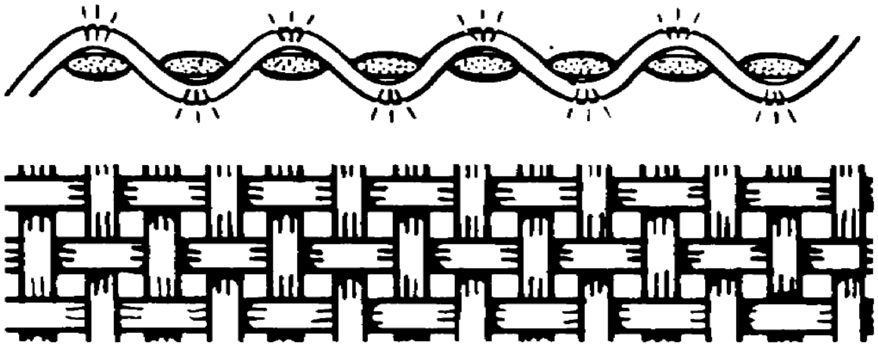
8 harness satin



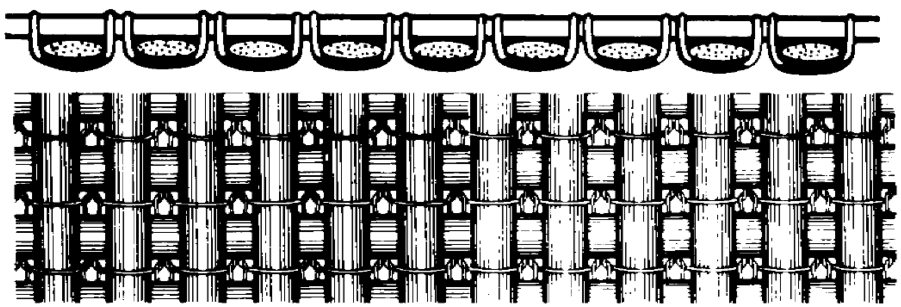
5 harness satin

Woven and Knit Reinforcements

Woven such as Woven Roving or Cloth



Better damage resistance and good for building up single skin thickness

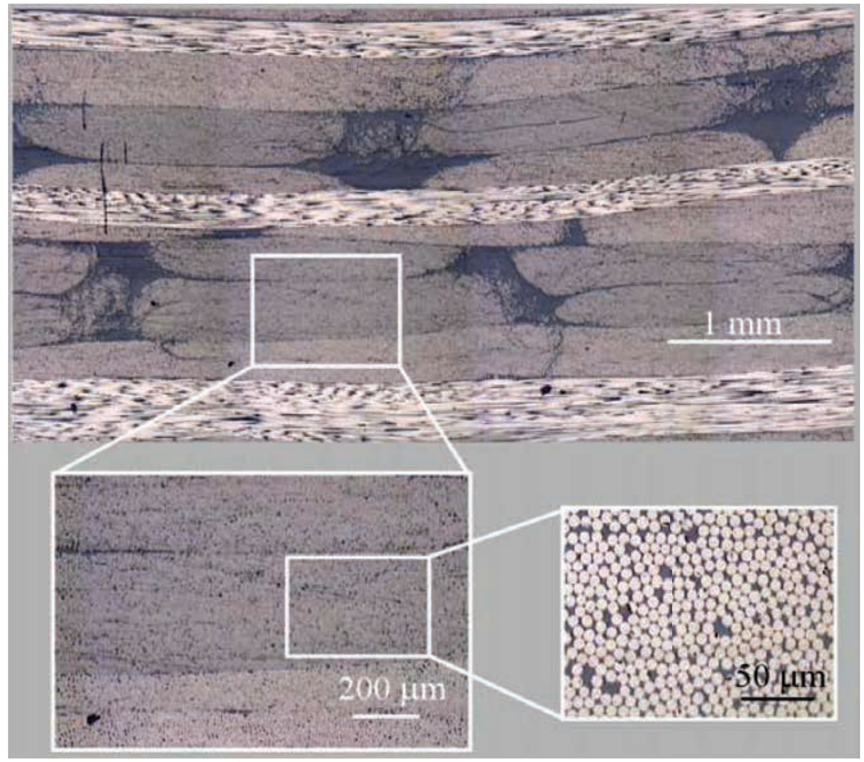


Knit or non-woven fabric

Better in-plane properties - best used with sandwich construction

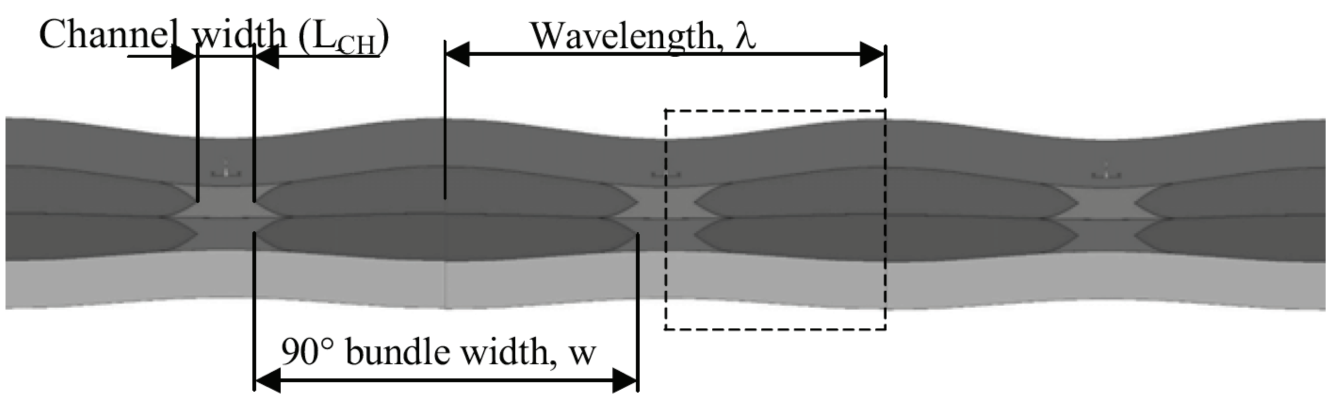
Knit Reinforcement Architecture

Structure of the knit reinforcement composites



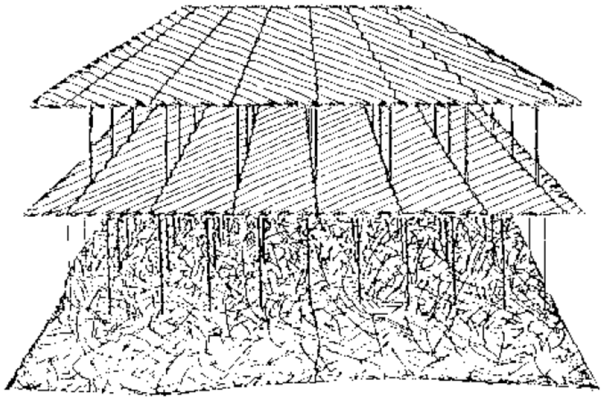
David Mattsson, "Mechanical performance of NCF composites," , Luleå University of Technology, Luleå, Sweden, 2005

Schematic picture of the out-of-plane misalignment of the 0° bundle

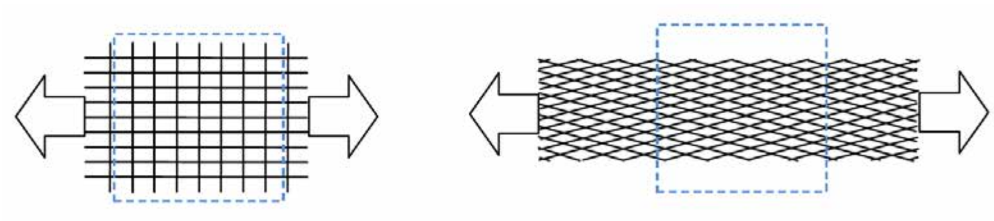


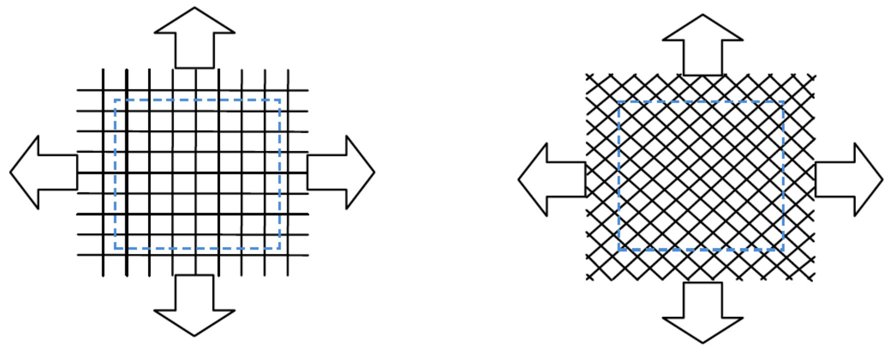
Double Bias (±45°) Reinforcement

Stitched Double Bias and Mat

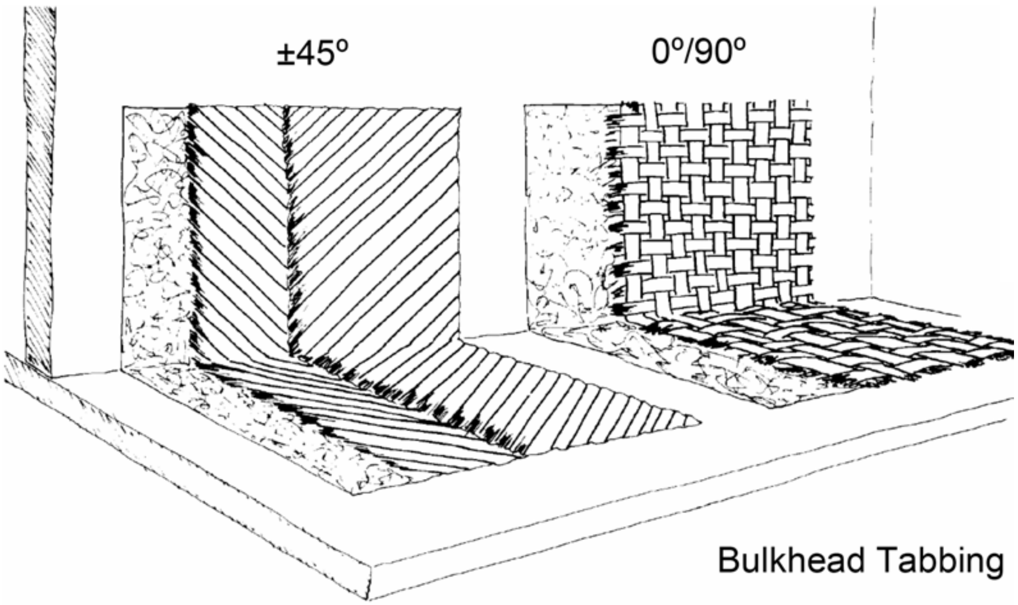


Resists Membrane Tension better than In-Plane Loads



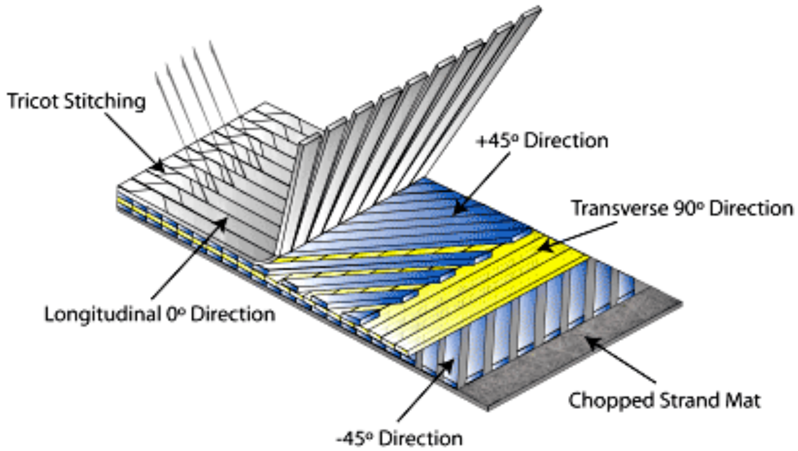


Conformity and Shear Strength



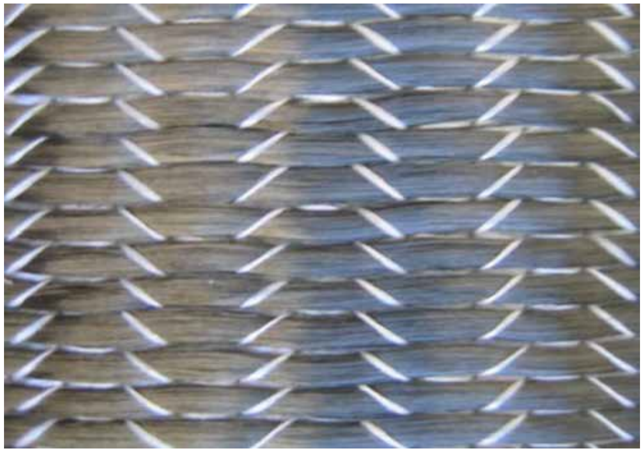
Multi-axial Reinforcements

Multi-Axial Architecture



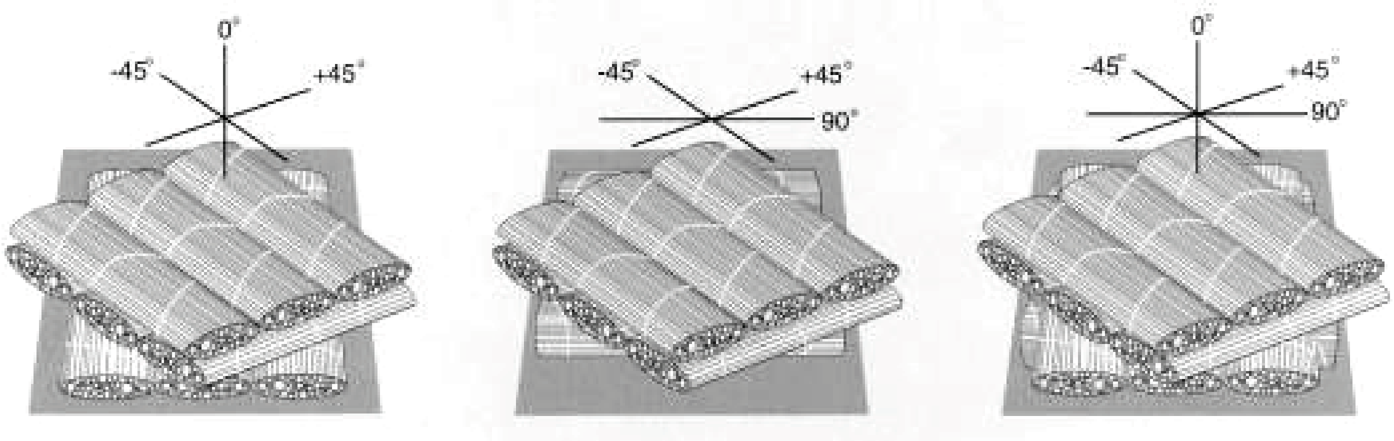
Stitch bonded example-Quadraxial. Typical quadraxial ply stack includes 0°, 90°, ±45° plies. In this case quads are designed with more 90° fiber than the other axis. [Vectorply Corporation]

Potential Fiber Waviness

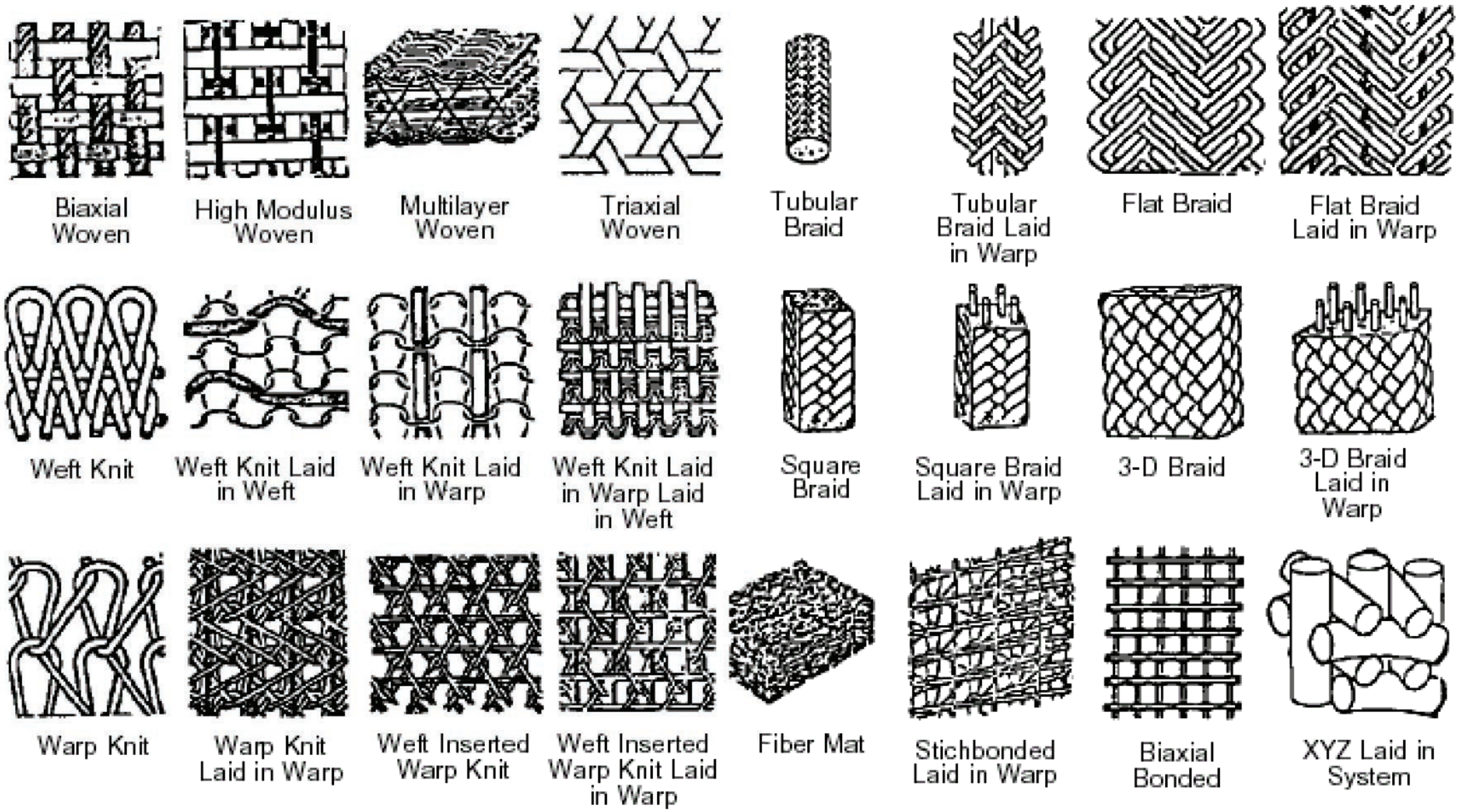


Detail image of stitched reinforcement shows fiber waviness as a potential manufacturing artifact

Diagram of Stitched Triaxial and Quadraxial Fabrics

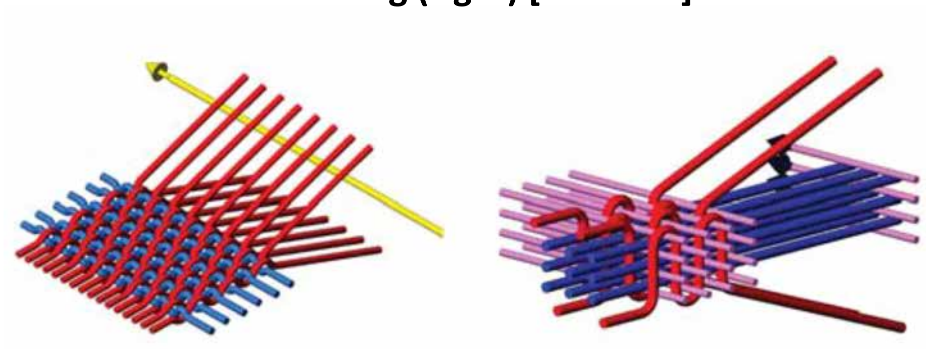


Additional Reinforcement Styles



Braided Reinforcements

Schematic of 2-D weaving (left) and 3-D weaving (right) [3TEX Inc]

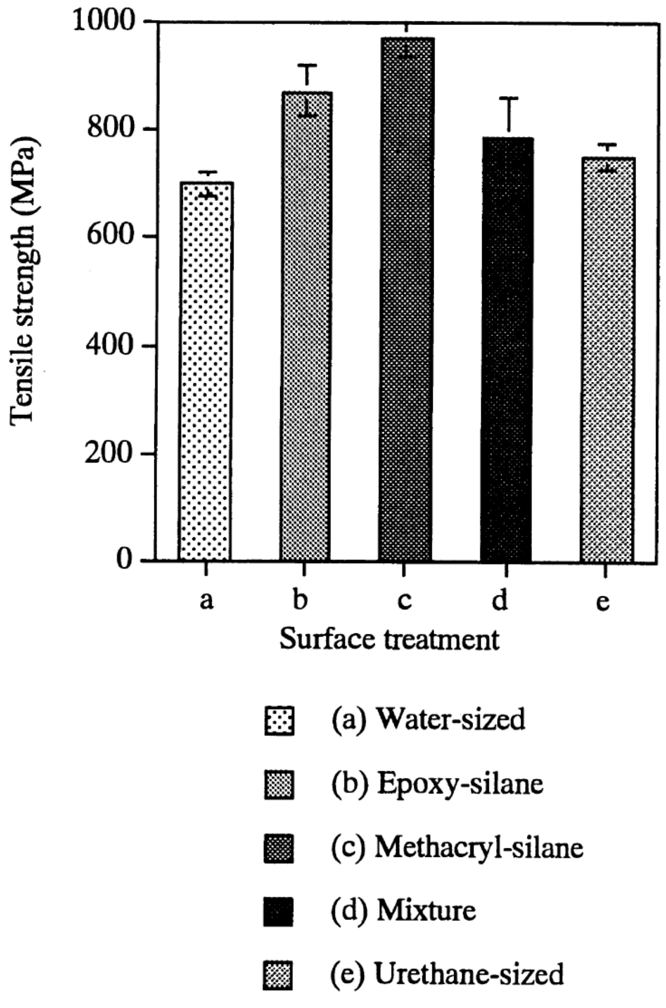


Mat Reinforcements

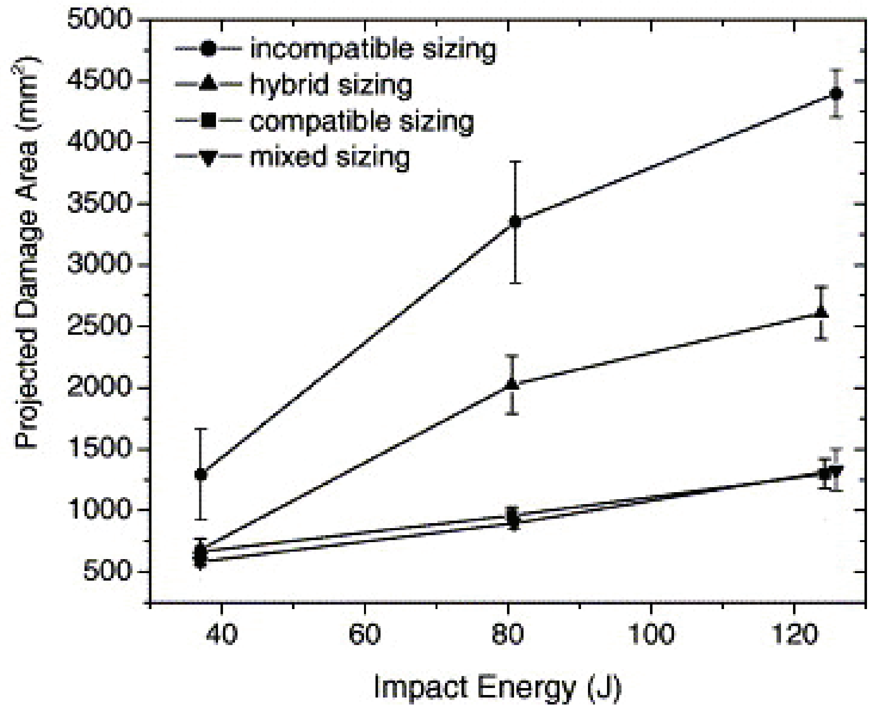
- Mat reinforcements can be applied during hand lay-up as prefabricated mat or via the spray-up process as chopped strand mat.
- Chopped strand mat consists of randomly oriented glass fiber strands that are held together with a soluble resinous binder.
- Both hand lay-up and spray-up methods produce plies with equal properties along the x and y axes and good interlaminar shear strength.
- This is a very economical way to build up thickness, especially with complex molds. This is why most small parts are made with mat.
- Mechanical properties are less than other reinforcements.
- The weight by area of fiberglass mat is expressed as ounces/ft^2 or grams/meter^2.

Fiber Surface Treatment

Strength of Carbon Fiber Laminates based on Surface Treatment



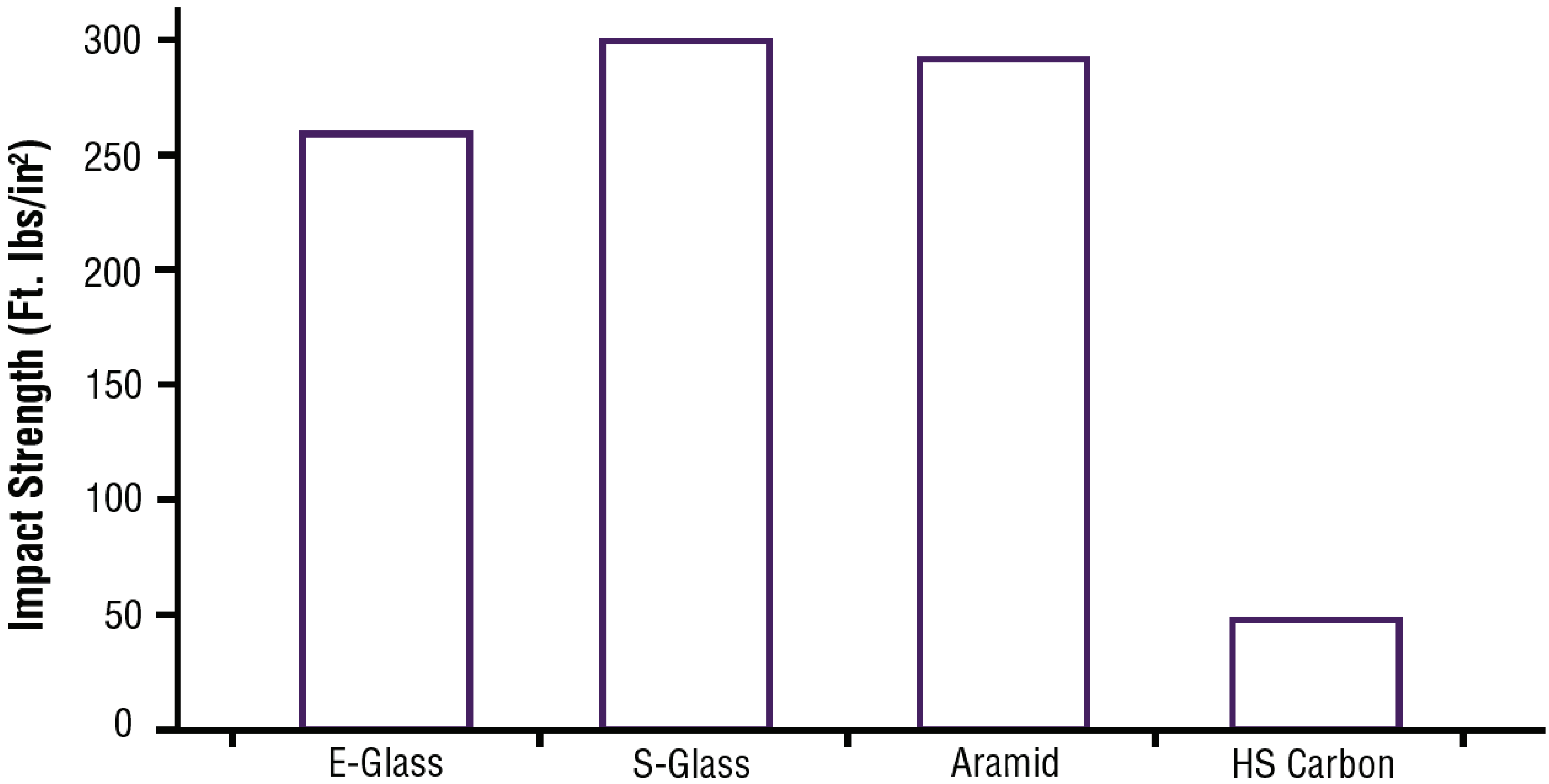
Damage area vs. impact energy plots for composite panels with E-glass fibers treated with hybrid, compatible, mixed, and incompatible fiber sizings



R.E. Jensen and S.H. McKnight, "Inorganic–organic fiber sizings for enhanced energy absorption in glass fiber-reinforced composites intended for structural applications," Composites Science and Technology, March 2006

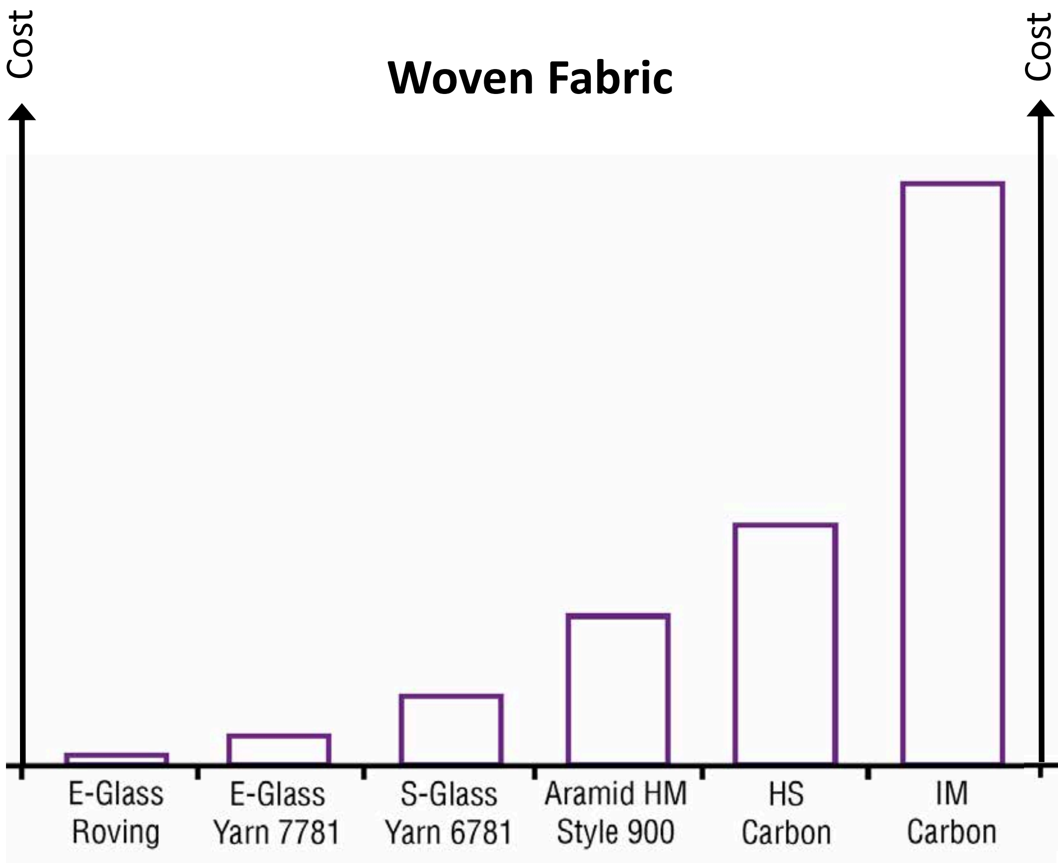
Impact Strength

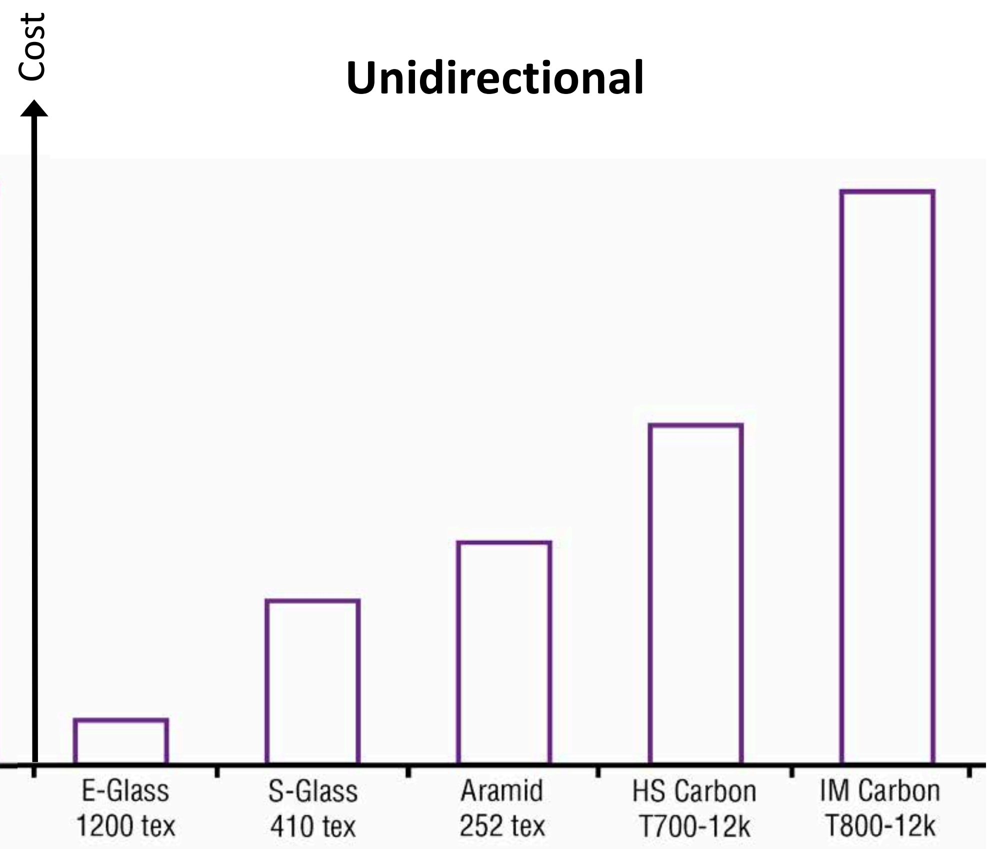
Comparison of Laminate Impact Strength



SP Systems, Guide to Composites," GTC-1-1098

Comparative Fiber Costs





SP Systems, Guide to Composites," GTC-1-1098

Carbon Fiber Data

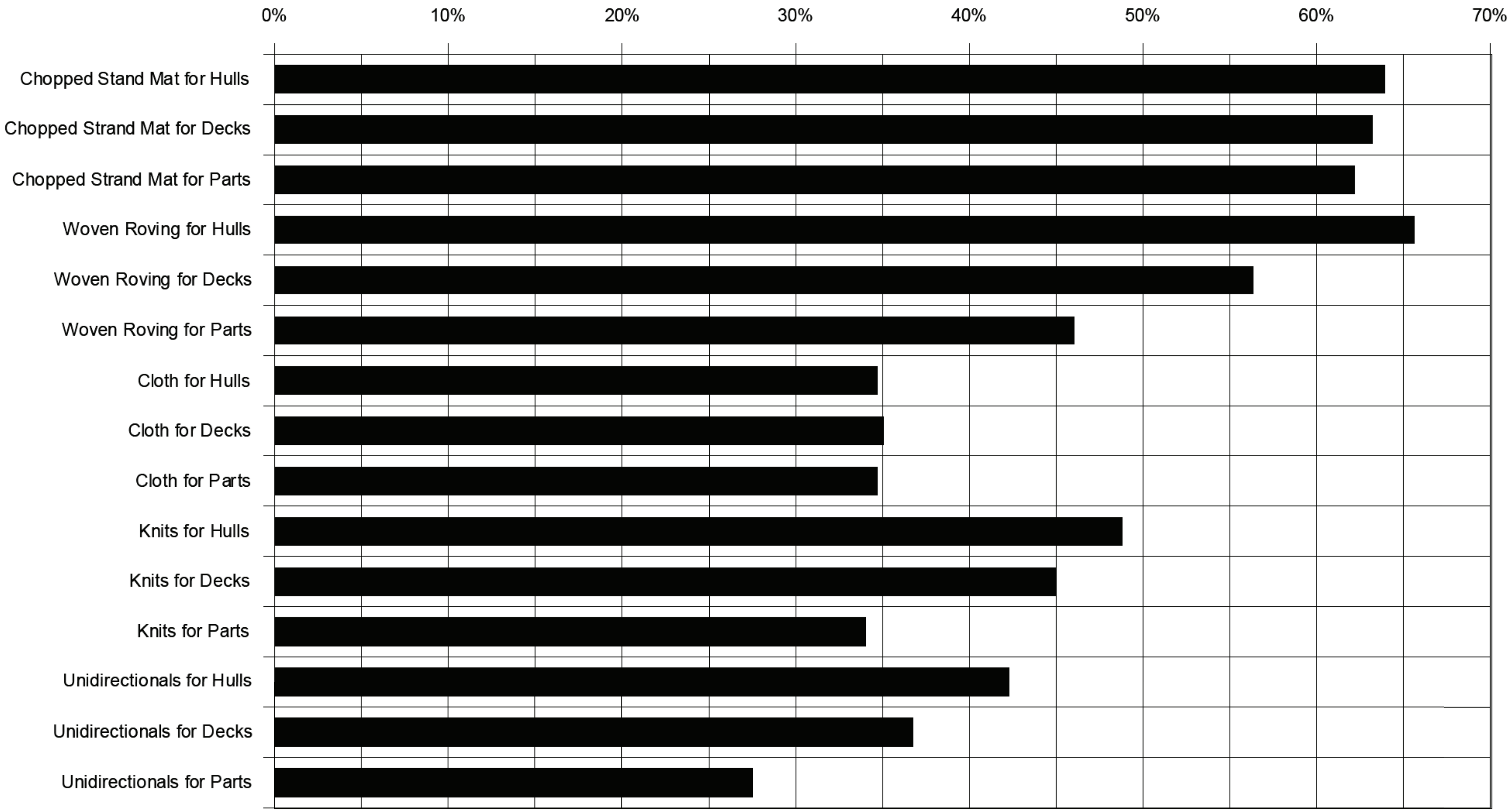
Strength and Modulus Figures for Commercial PAN-based Carbon Fibers

Grade	Tensile Modulus (GPa)	Tensile Strength (GPa)	Country of Manufacture
Standard Modulus (<265GPa) (also known as 'High Strength')			
T300	230	3.53	France/Japan
T700	235	5.3	Japan
HTA	238	3.95	Germany
UTS	240	4.8	Japan
34-700	234	4.5	Japan/USA
AS4	241	4.0	USA
T650-35	241	4.55	USA
Panex 33	228	3.6	USA/Hungary
F3C	228	3.8	USA
TR50S	235	4.83	Japan
TR30S	234	4.41	Japan
Intermediate Modulus (265-320GPa)			
T800	294	5.94	France/Japan
M30S	294	5.49	France
IMS	295	4.12/5.5	Japan
MR40/MR50	289	4.4/5.1	Japan
IM6/IM7	303	5.1/5.3	USA
IM9	310	5.3	USA
T650-42	290	4.82	USA
T40	290	5.65	USA

Grade	Tensile Modulus (GPa)	Tensile Strength (GPa)	Country of Manufacture
High Modulus (320-440GPa)			
M40	392	2.74	Japan
M40J	377	4.41	France/Japan
HMA	358	3.0	Japan
UMS2526	395	4.56	Japan
MS40	340	4.8	Japan
HR40	381	4.8	Japan
Ultra High Modulus (~440GPa)			
M46J	436	4.21	Japan
UMS3536	435	4.5	Japan
HS40	441	4.4	Japan
UHMS	441	3.45	USA

SP Systems, Guide to Composites," GTC-1-1098

Boatbuilder Reinforcement Architectures



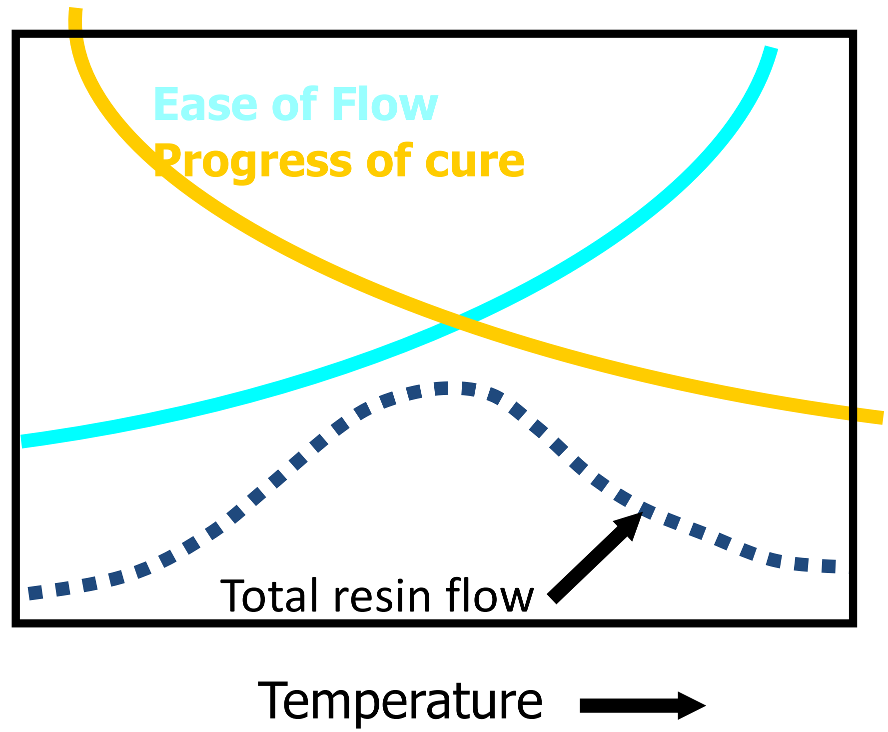
data from Eric Greene Associates 1995 survey

Resin Chemistry

- *Thermoset* resins are characterized by a non-reversible, chemical reaction (cross-linking) during cure that gives off heat (exothermic)
- *Catalysts*, such as MEKP, are mixed in quantities of 1% to 2.5% with the resin just prior to use
- *Inhibitors* are use to slow the rate of cross-linking, which increases the working time of the resin
- *Accelerators*, such as Cobalt, are used to help speed the crosslinking but only work in the presence of initiator. Accelerator and initiator should never come in direct contact or stored together (explosive hazard).
- If a resin is draining down a vertical surface, the “*thixotropic* index” can be increased with an additive, such as silicon dioxide
- The typical shelf life of un-catalyzed polyester resin is 90 days when stored in a controlled temperature environment protected from fire

Thermoset Resins

- Generally supplied as a liquid
- Cross-linked (cured) by chemicals (and heat)
  - heat reduces the instantaneous viscosity
  - heat increases the rate of cure
  - cure decreases the viscosity over time
- Product is a 3D molecular network whereas a thermoplastic is usually a 2D chain



Stages of Cure

A-stage: soluble and fusible

B-stage: may be swollen but not dissolved by a variety of solvents

C-stage: rigid, hard, insoluble, infusible

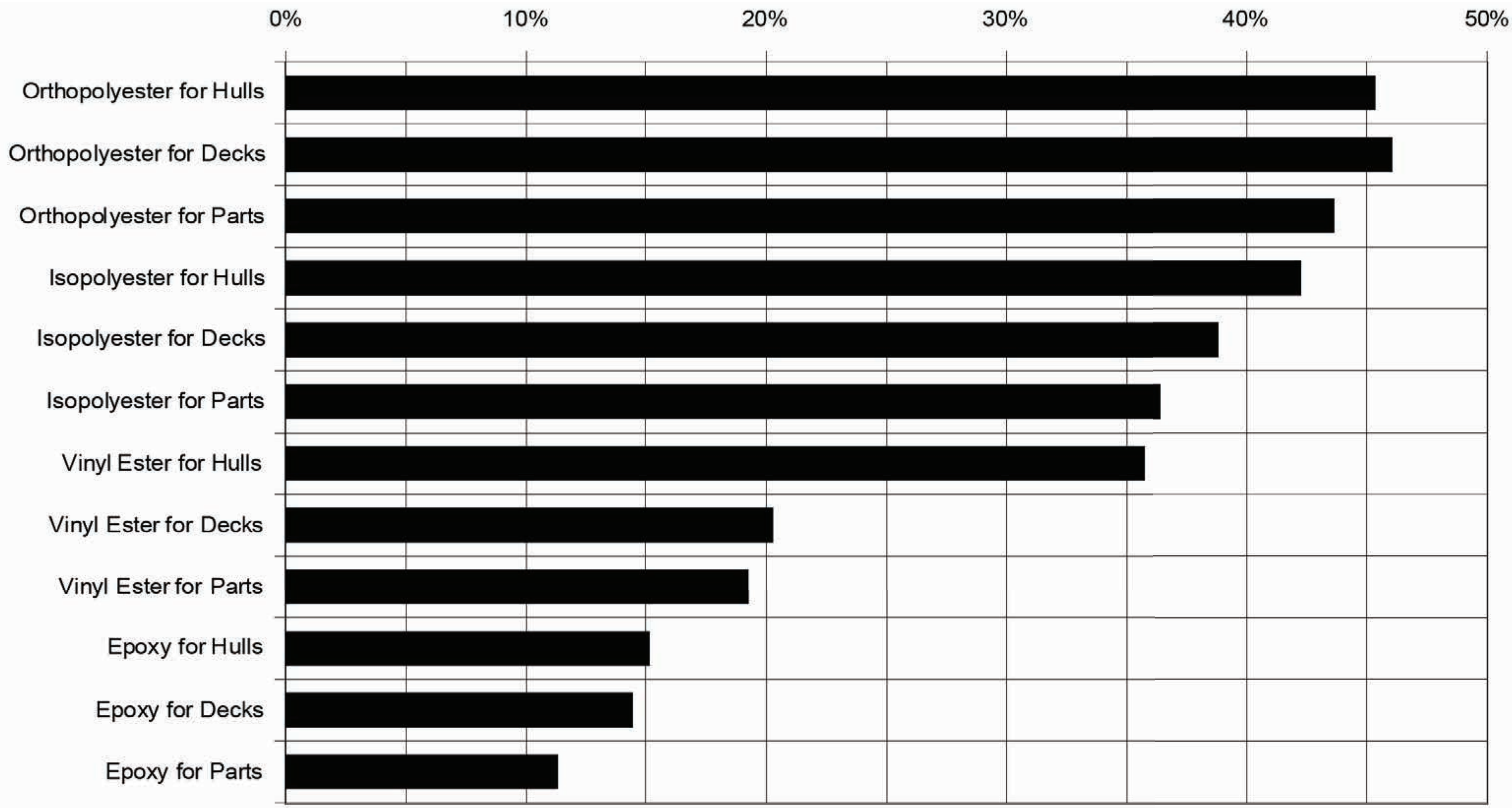
John Summerscales, University of Plymouth, Jan., 2013

Resin System Mechanical Properties

Property	Ortho Polyester	Iso Polyester	Vinylester	Laminating Epoxy	Multi-Purpose Epoxy
Tensile Strength (Mpa)	41	61	79	83	50
Tensile Modulus (Mpa)	3480	3380	3380	3650	3170
Tensile Elongation	1.2%	1.6%	5.0%	9.0%	10.0%
Heat Distortion Temperature (°C)	65	97*	105-120*	110*	54
Shrinkage	9.00%	8.20%	7.80%	0.75%	0.80%

* Post-cured property [ATL Composites Pty Ltd]

Boatbuilder Resin Use



data from Eric Greene Associates 1995 survey

Resin System Comparison

Polyester

Polyester resins are the simplest, most economical resin systems that are easiest to use and show good chemical resistance.

- *Orthophthalic (ortho)* resins were the original group of polyesters developed and are still in widespread use. They have somewhat limited thermal stability, chemical resistance, and processability characteristics.
- *Isophthalic (iso)* resins generally have better mechanical properties and show better chemical resistance.
- *Low-profile resins (DCPD)* are blends designed to minimize reinforcement print-through. Typically, ultimate elongation values are reduced for these types of resins.

Vinyl Ester

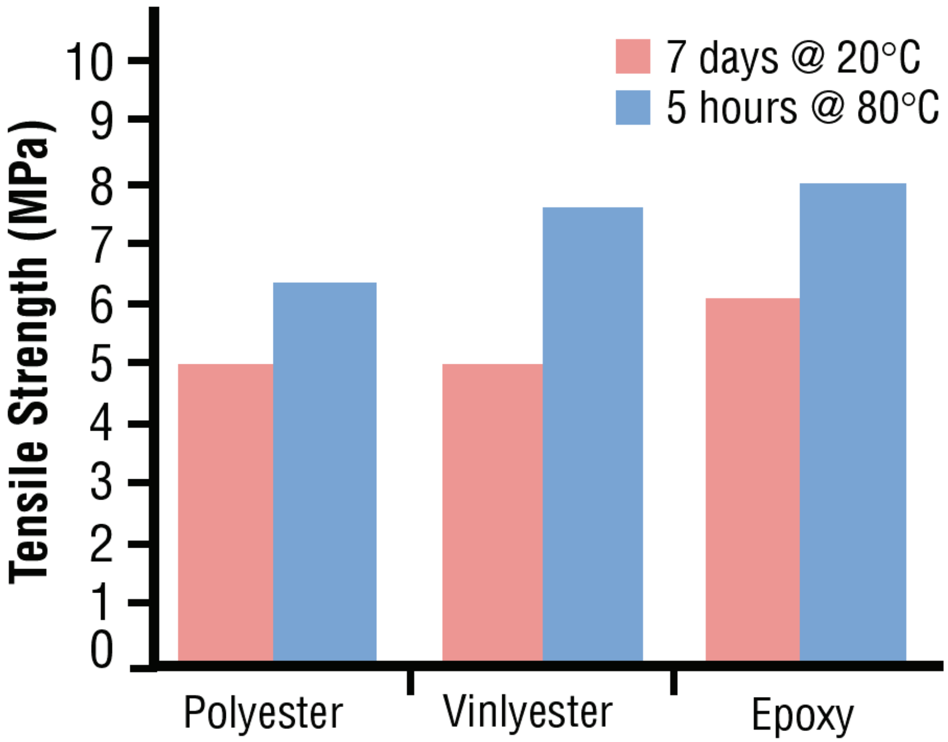
The handling and performance characteristics of vinyl esters are similar to polyesters. Some advantages of the vinyl esters, which may justify their higher cost, include:

- Superior corrosion resistance
- Hydrolytic stability (blister resistance)
- Better secondary bonding properties
- Excellent physical properties, such as impact and fatigue resistance.

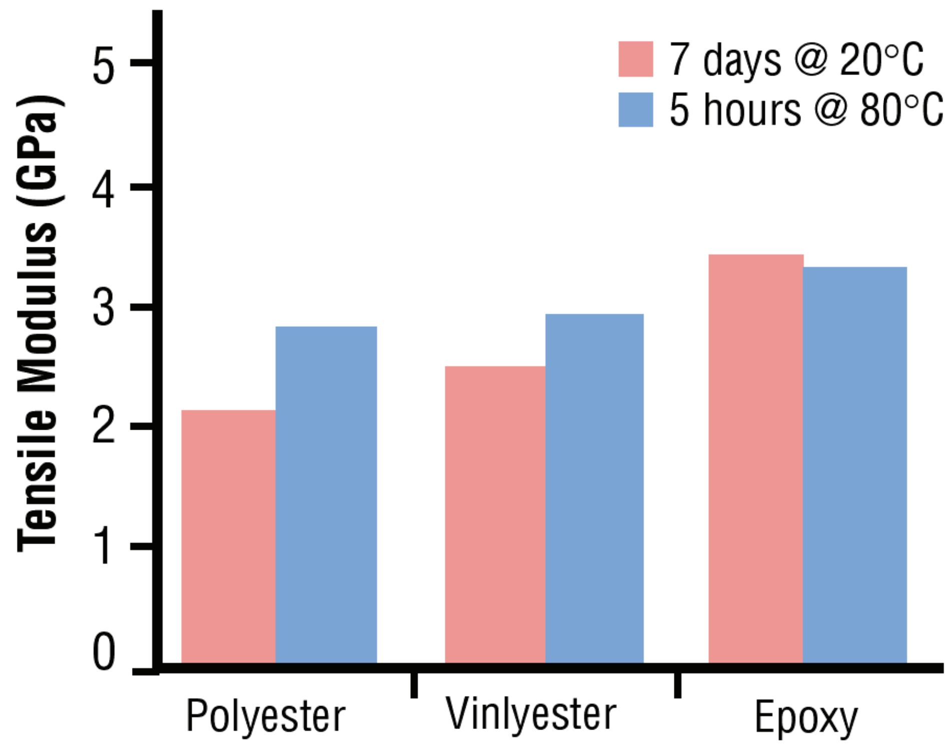
Epoxy

- Epoxy resins show the best performance characteristics of all the resins used in the marine industry.
- Aerospace applications use epoxy almost exclusively, except when high temperature performance is critical.
- The high cost of epoxies and handling difficulties have limited their use for large marine structures to date.
- Epoxies are considered environmentally-friendly because styrene isn't released into the atmosphere during fabrication.

Compare Resin Properties



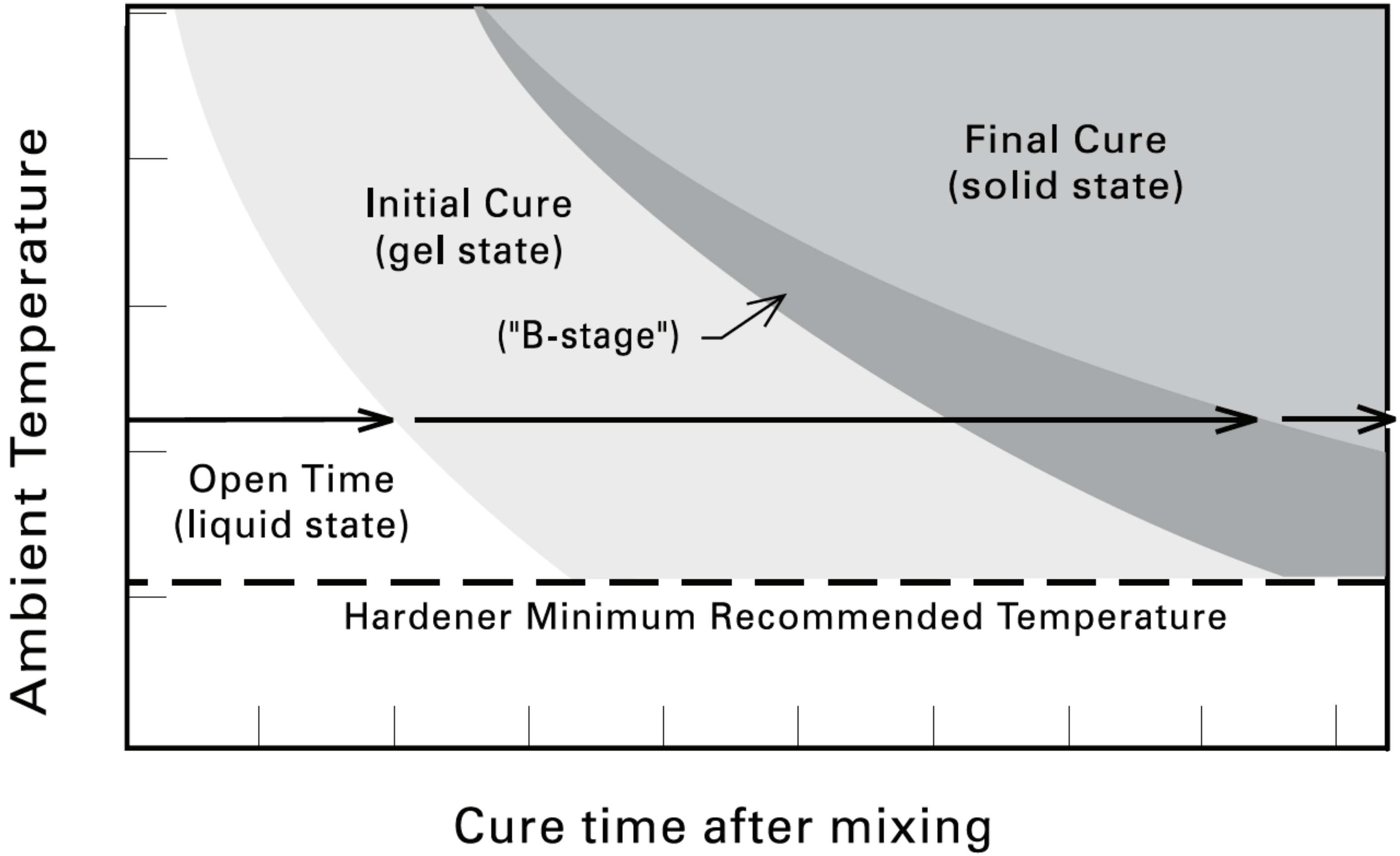
Comparative Tensile Strength of Resins



Comparative Stiffness of Resins

SP Systems, Guide to Composites," GTC-1-1098

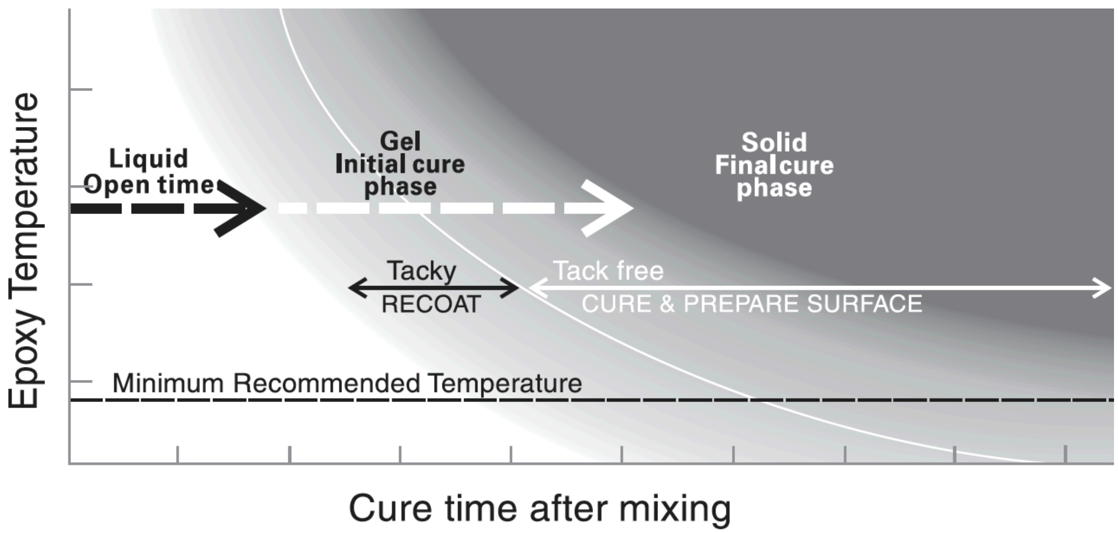
Epoxy Curing Stages



Pro-Set Epoxy Handling Guide, Pro-Set, Inc., Aug 2005

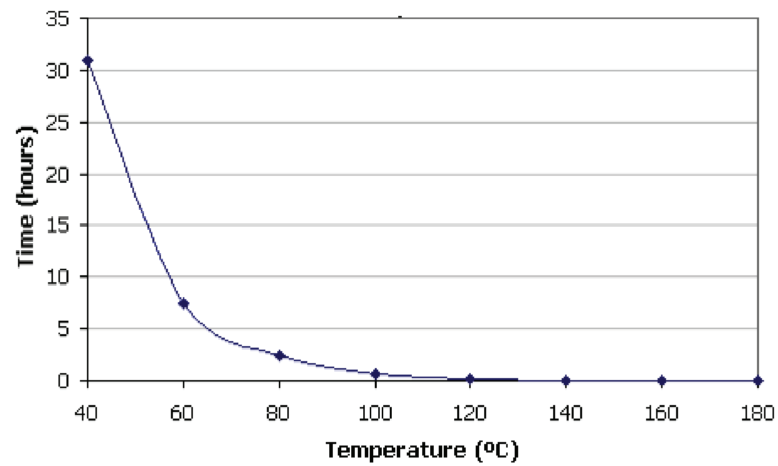
Epoxy Cure Profile

Typical cure characteristics of epoxy resin systems



Gougeon Brothers Inc., "WEST System Fiberglass Boat Repair & Maintenance," 15th Edition, April 2011

Typical gel time of epoxy resin systems



John Summerscales, University of Plymouth, Jan., 2013

Epoxy Cure Temperatures

- Low temperature - ambient to 60°C (140°F)
- Medium temperature - up to 120°C (250°F)
- High temperature - up to 180°C (360F°)

Phenolic Resin

- Generally brittle due to moisture released during curing
- Exceptional Fire, Smoke & Toxicity (FST) properties when burning:
    - Low flame spread
    - Low smoke production
    - Low smoke toxicity - only CO_2 and H_2O released
- Key markets:
    - underground railways
    - mining
    - Submarines
- First truly synthetic resins to be exploited - Baekeland (1907) controlled and modified the reaction to produce useful products (Bakelite)

John Summerscales, University of Plymouth, Jan., 2013

Gel Coat

- Gel coat is a specially formulated resin system designed to be on the surface of the laminate and cure as a thin layer. In the U.S., it is typically applied using an atomized spray gun
- Gel coat typically consists of an unsaturated polyester resin (polyester) base, pigment, and various other additives. Styrene added to gel coat increases its workability but can lead to cracking and yellowing problems.
- Gelcoat is used to enhance cosmetic appearance, reduce water absorption, and protect laminate from the environment. Additives help fine-tune a gelcoats properties. Pigment develops the quality and color of gelcoat. Fillers change viscosity, adhesiveness, and/or cured properties.

Volatile Organic Compounds

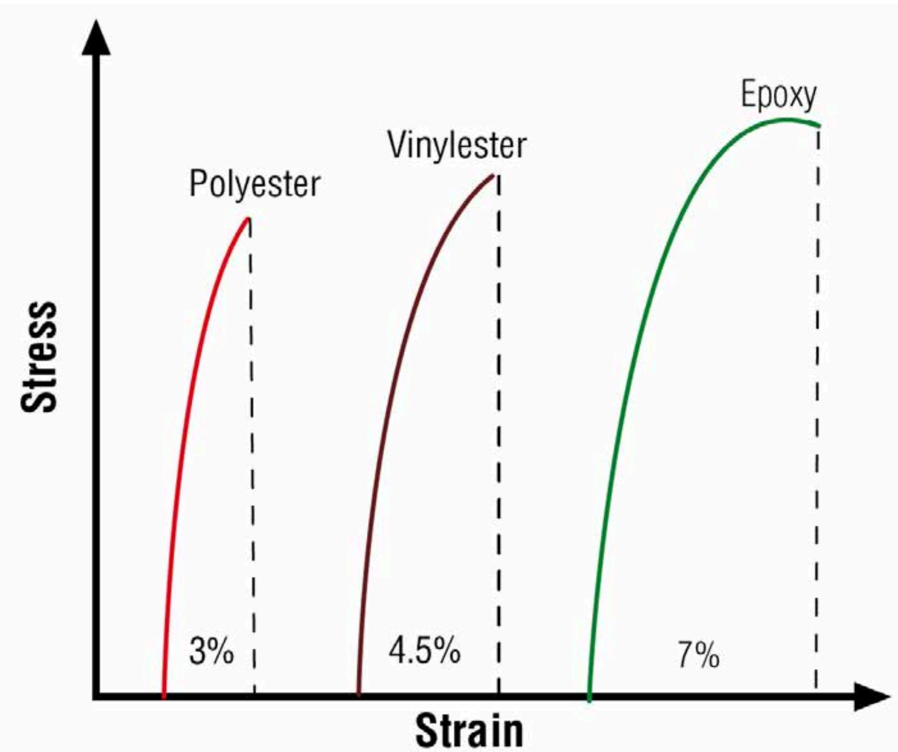
Resin System	Volatile % (by weight)	VOC Content (g/L)	VOC Emissions (g/m^2)
Multi-purpose epoxy resin (A)	1.5	17.7	11.2
Multi-purpose epoxy resin (B)	2.1	25.0	15.9
Multi-purpose epoxy resin (C)	1.6	18.2	11.6
Multi-purpose epoxy resin (D)	1.6	18.0	11.5
High perf. laminating epoxy (A)	0.5	5.9	3.8
High perf. laminating epoxy (B)	0.5	6.0	3.9
High perf. laminating epoxy (C)	0.5	5.3	3.3
High perf. laminating epoxy (D)	0.6	6.9	4.4
iso-NPG Gelcoat	5.6	196.0	124.5
Gelcoat Patch additive	19.0	196.0	124.1
Vinylester Resin	35.0	367.0	233.2
Polyester Laminating Resin	15.7	174.0	110.7

ATL Composites, Australia

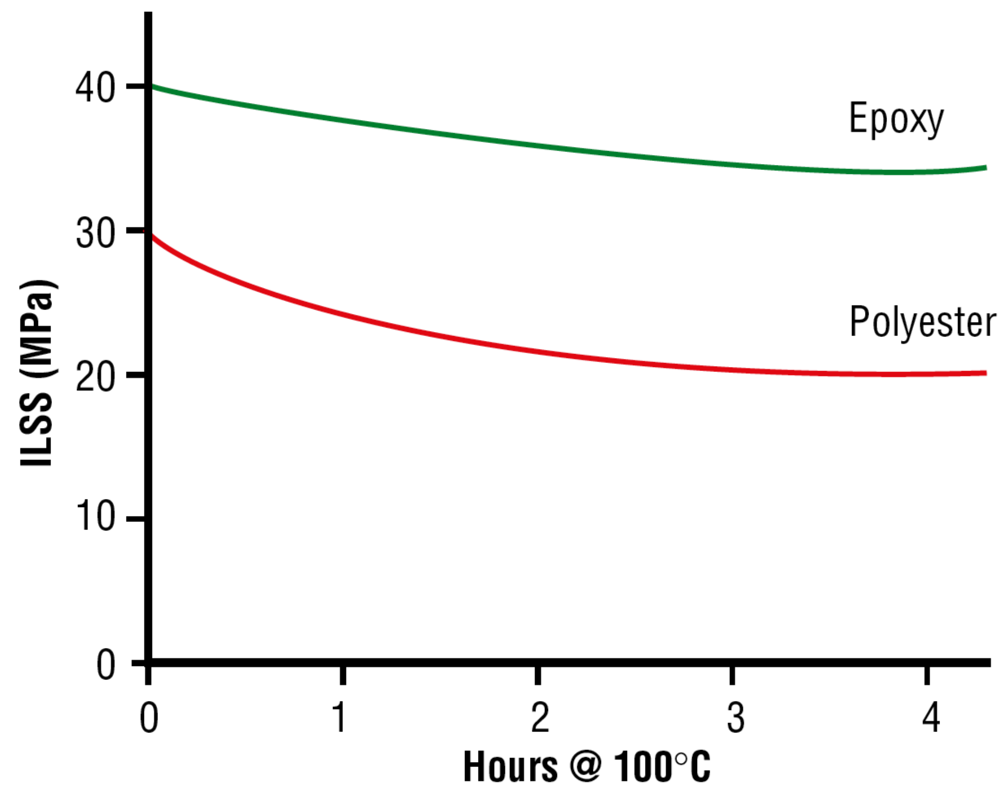
According to the EPA, "volatile organic compounds (VOCs) are emitted as gases from certain solids or liquids. VOCs include a variety of chemicals, some of which may have short- and long-term adverse health effects."

Compare Strain and Moisture Effects

Typical Resin Stress/Strain Curves (Post-Cured for 5 hrs @ 80°C)



Effect of Periods of Water Soak at 100°C on Resin Inter-Laminar Shear Strength



SP Systems, Guide to Composites," GTC-1-1098