Marine Composites

Webb Institute
Senior Elective

Composite Material Concepts

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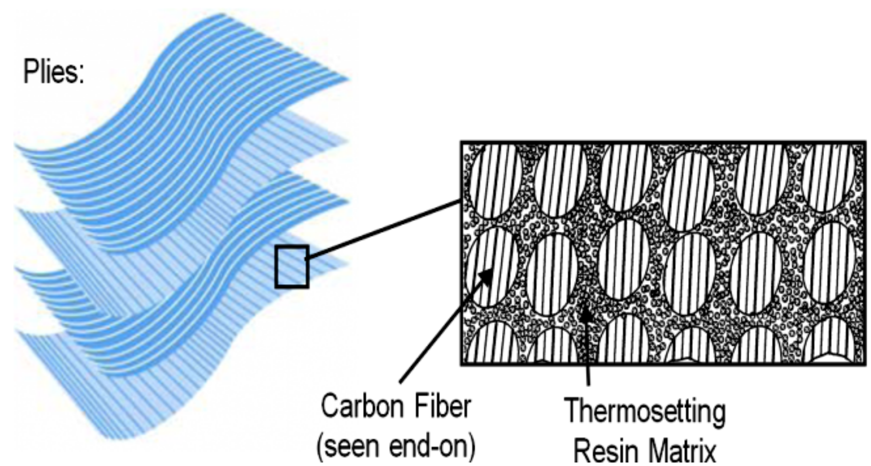
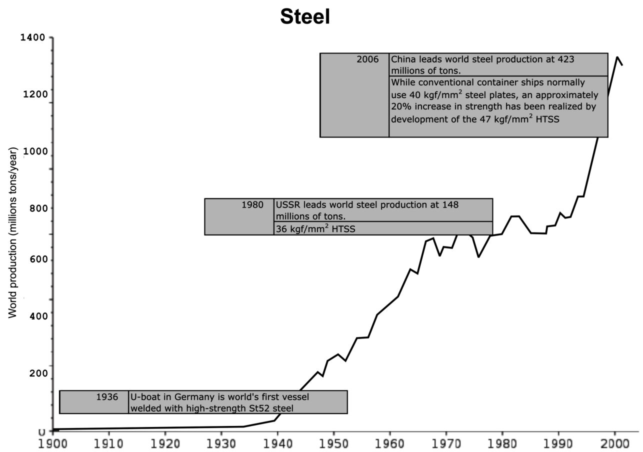
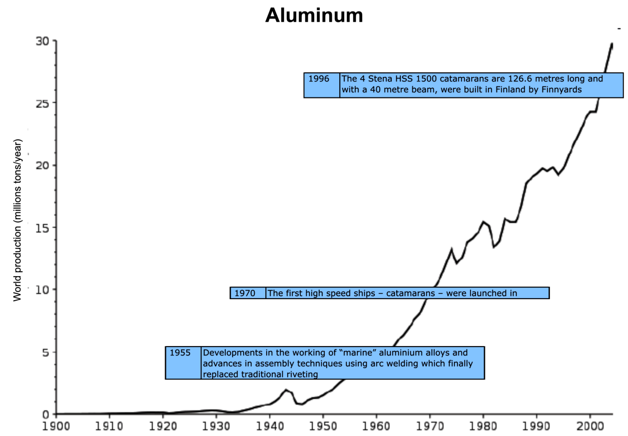
What Are Composite Materials?

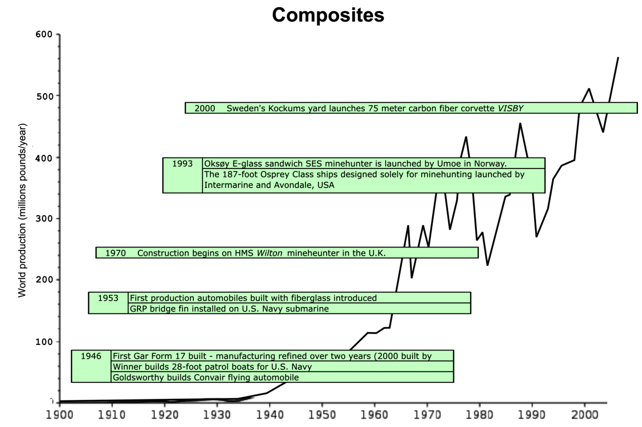
- A composite is the combination of materials that results in a greatly improved structure
- Resin matrices transform from liquid to solid during fabrication to “tie” the structure together
- Fiberglass, Aramid, and carbon laminates with resins are examples of composites, as is plywood and other “engineered” wood products
- Resin matrices are either “thermosets” that cure to solids through a non-reversible chemical process called “crosslinking” or “thermoplastics” that can be reformed when heated

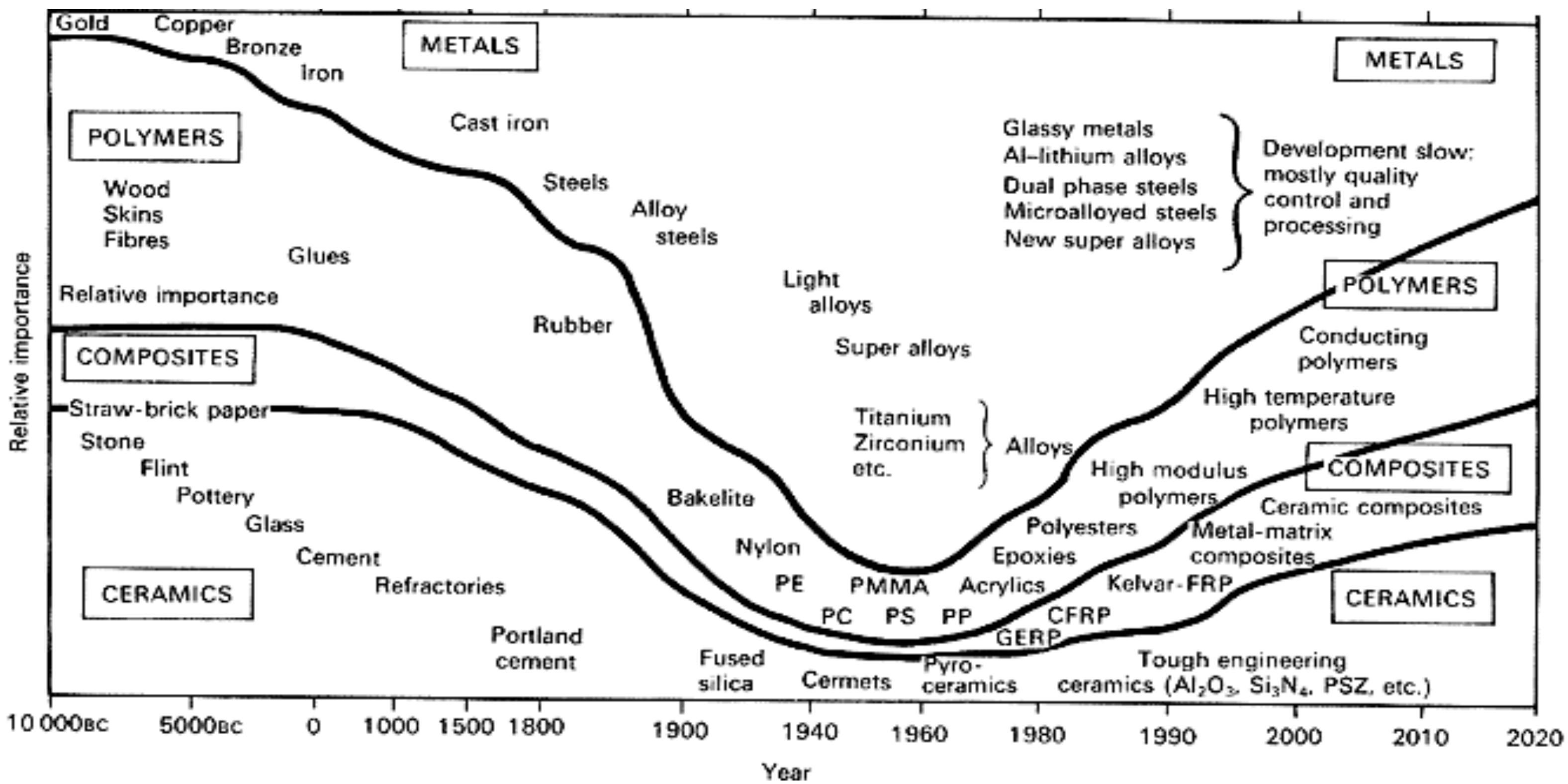


History of Engineered Materials





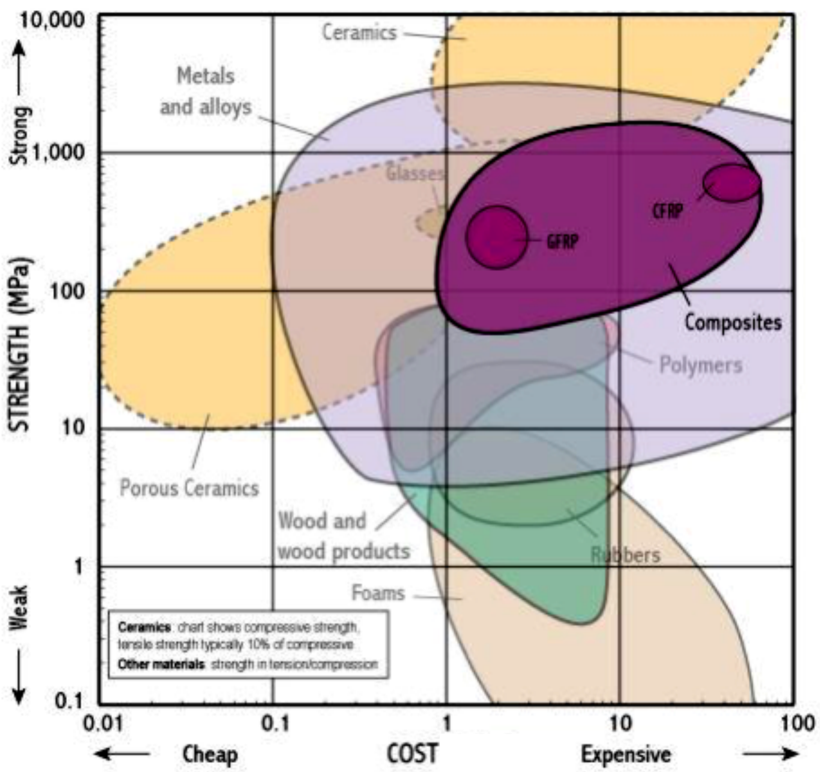


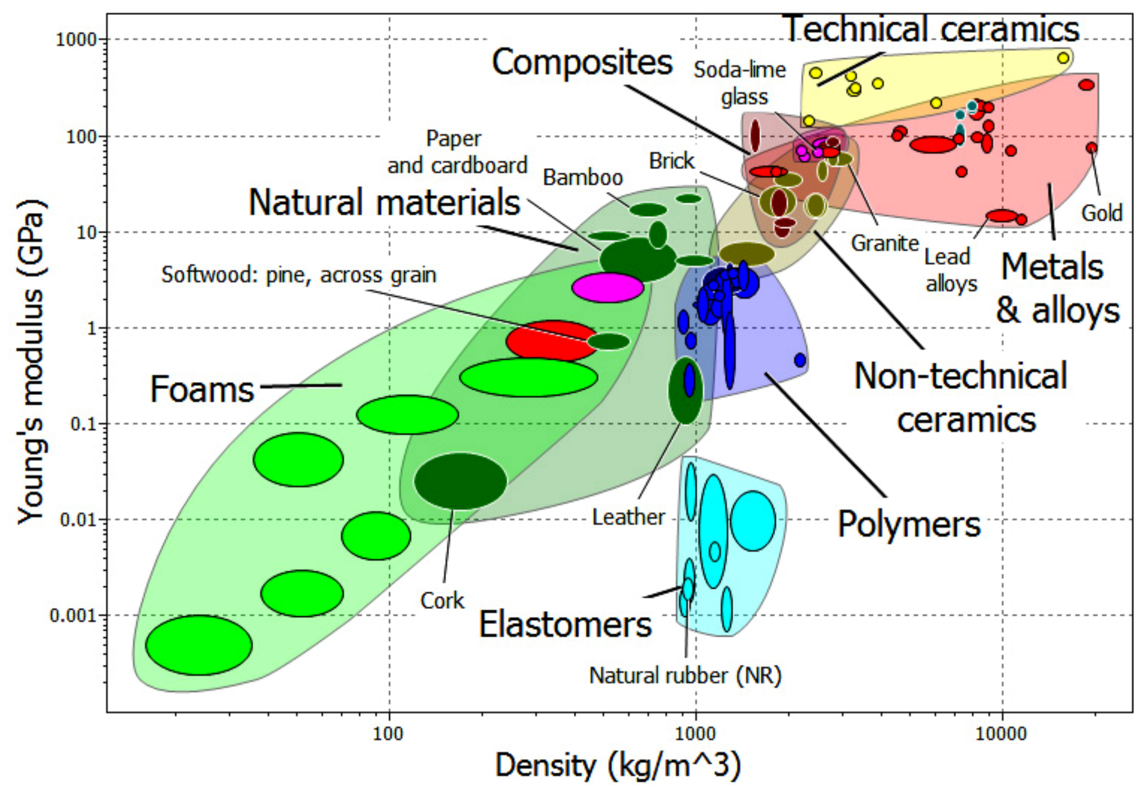


History of Marine Composites

- Modern day composite materials were launched with phenolic resins almost 100 years ago
- Fiberglass boat building began just after World War II when the Navy built a class of 28-foot personnel craft
- During the 1960s, fiberglass boat building proliferated and with it came the rapid increase in boat ownership
- From the 1960s to the present, advances in materials and fabrication techniques used in the pleasure craft industry have helped to reduce production costs and improve product quality
- In 2000 *MARINE COMPOSITES* is published as a free online document

Composites and other Structural Materials

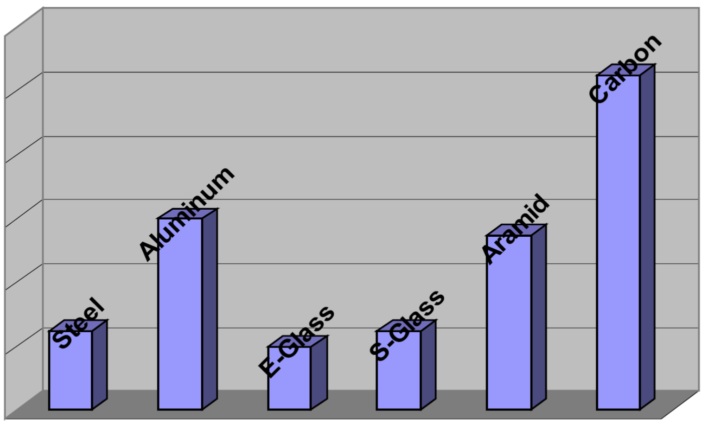




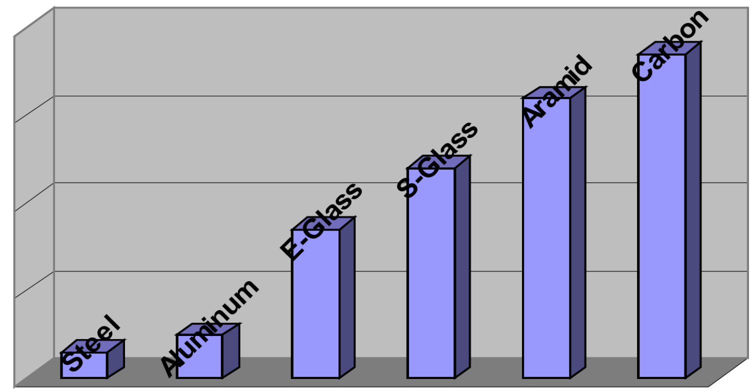
http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/strength-cost/NS6Chart.html

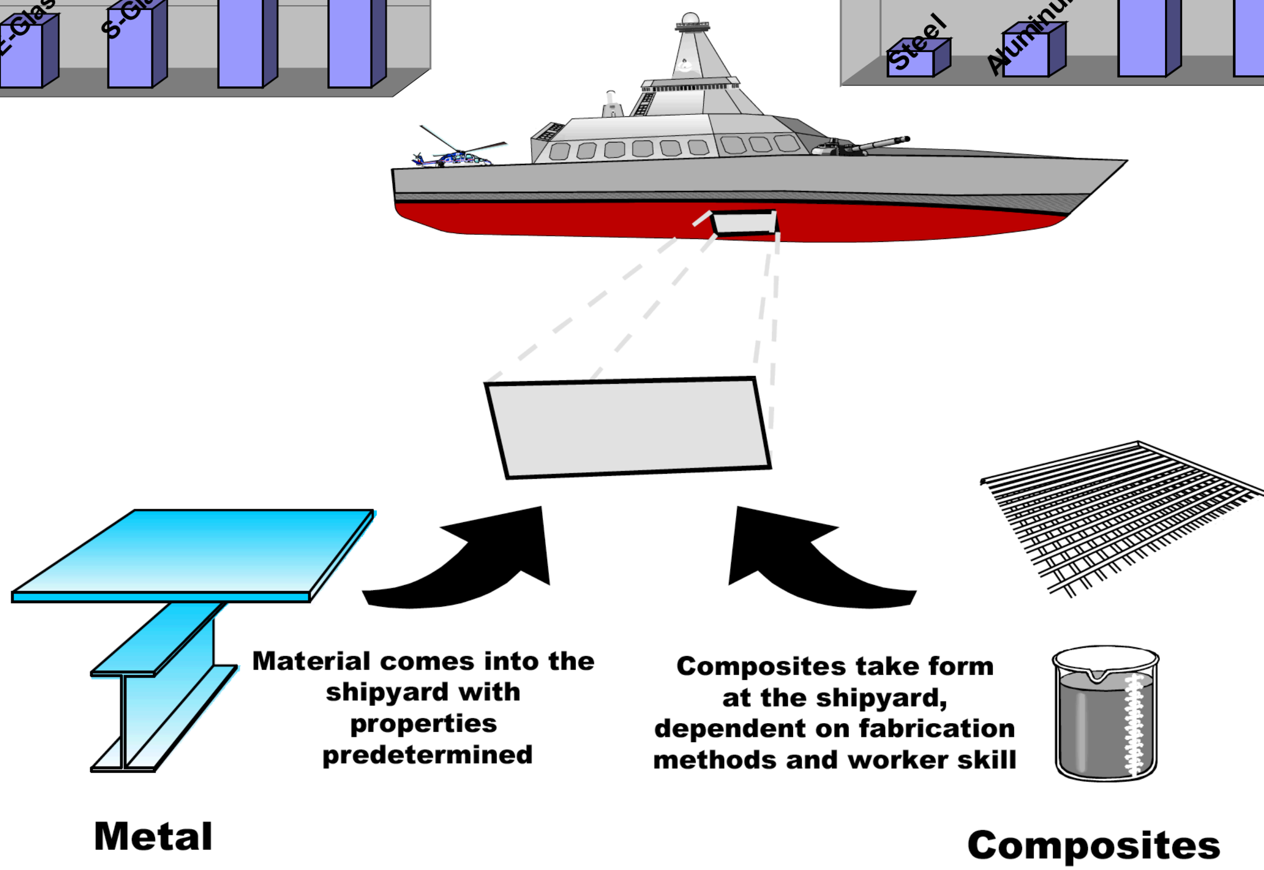
Composites vs. Metals

Specific Stiffness

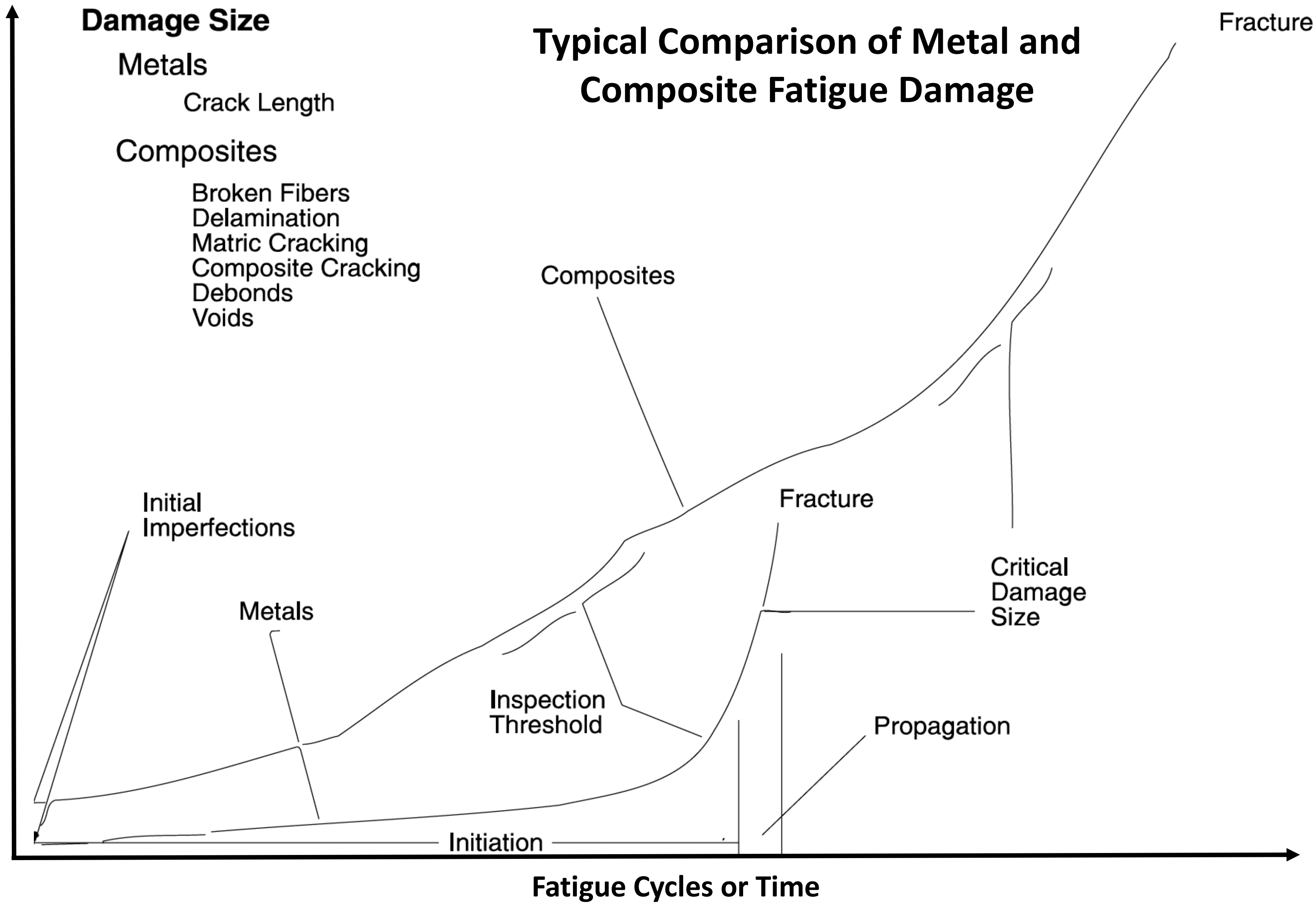


Specific Strength



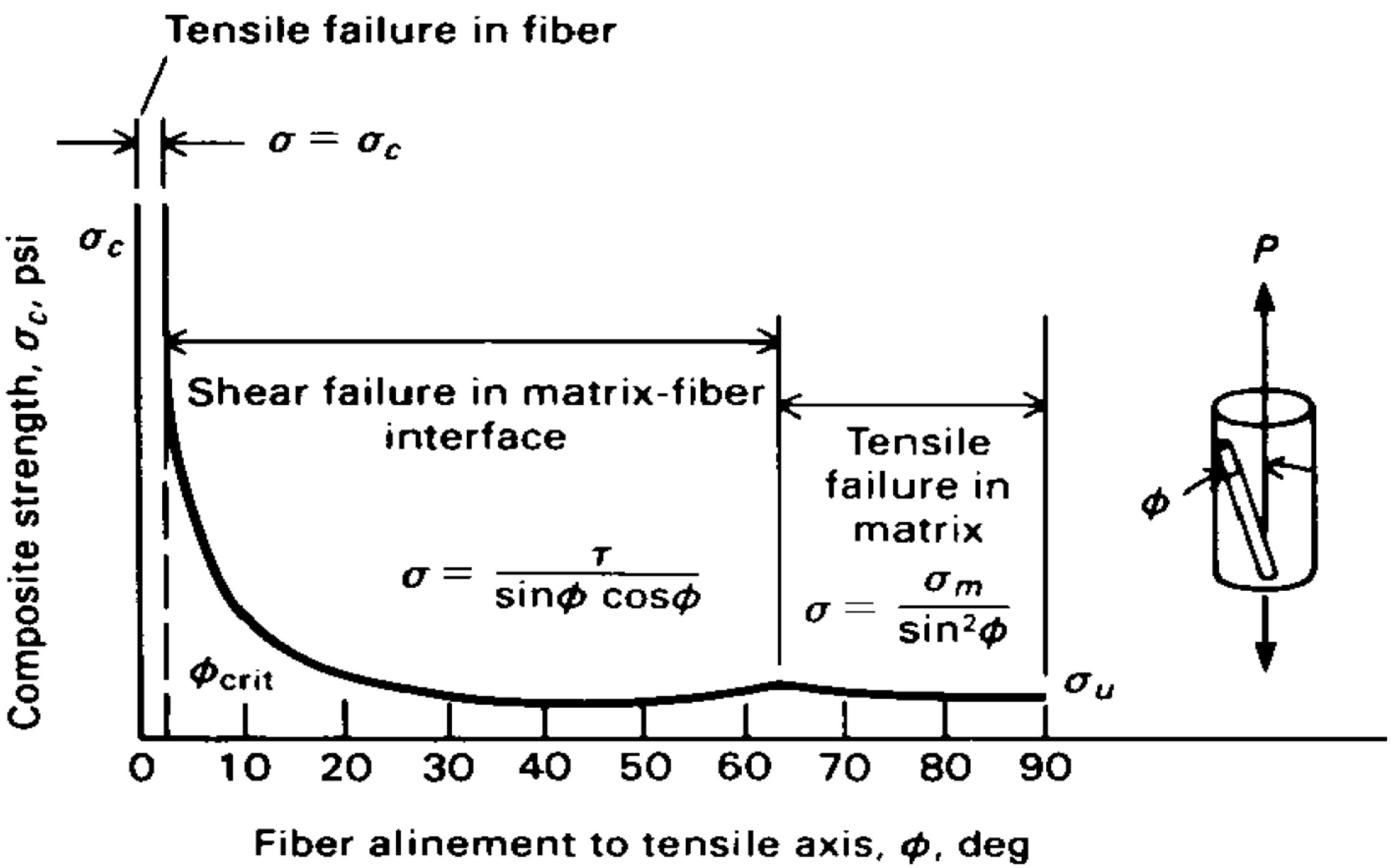


Composites vs. Metals



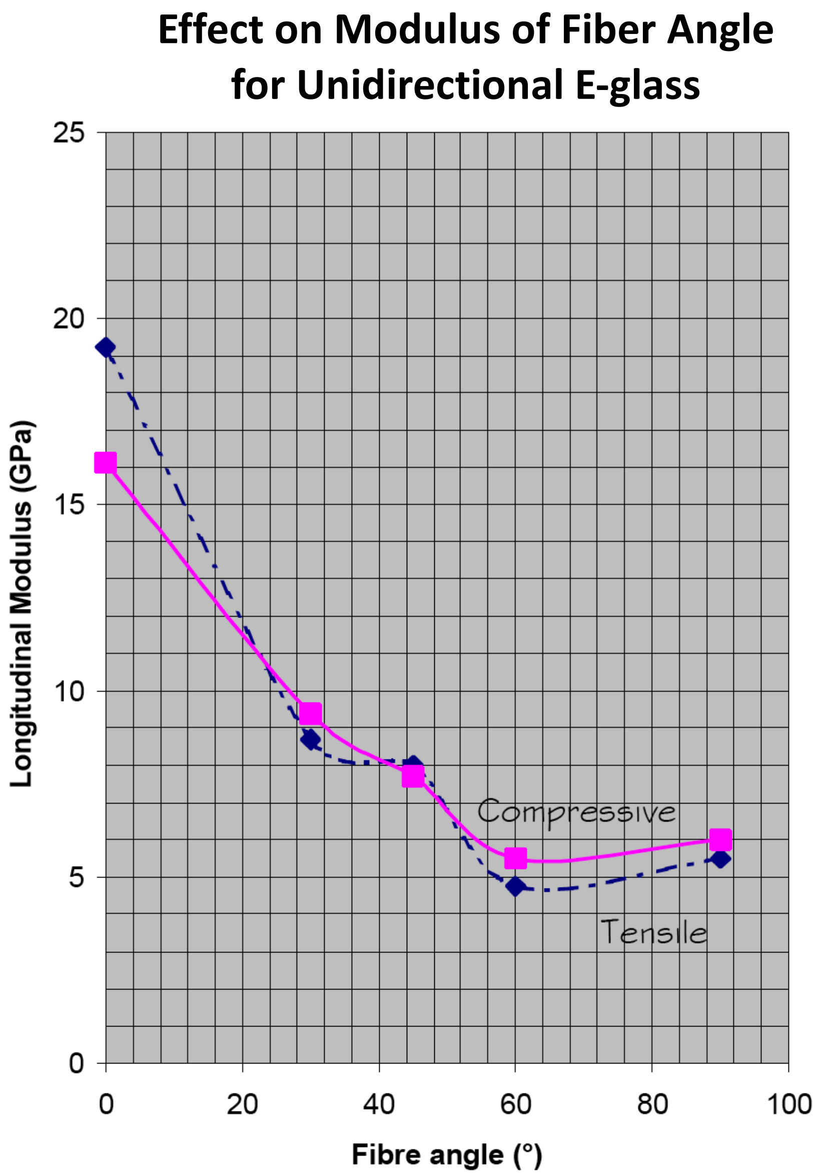
Salkind, M.J., "Fatigue of Composites," Composite Materials: Testing and Design, ASTM STP 497, 1972.

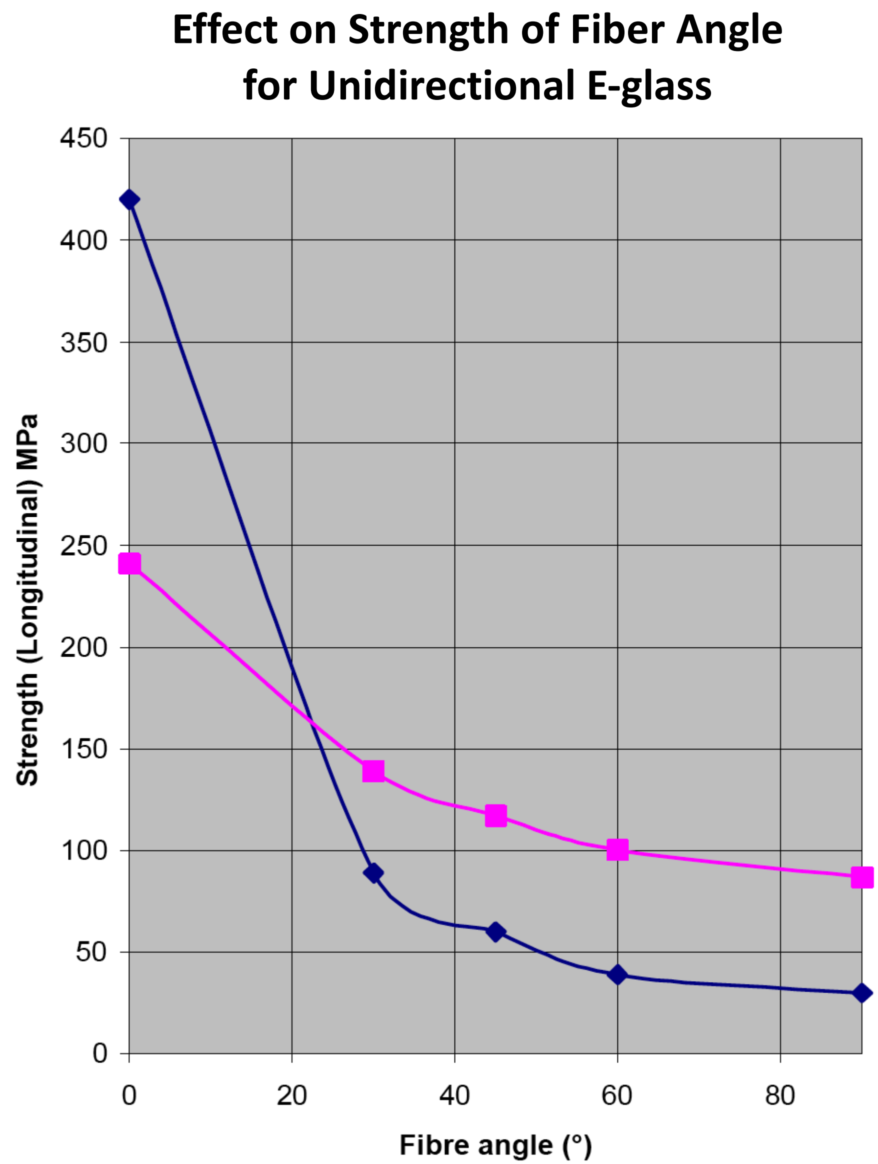
Directional Properties of Composites



The strength of composite fibers are dramatically reduced as the angle to the applied load is increased

Effect of Fiber Angle

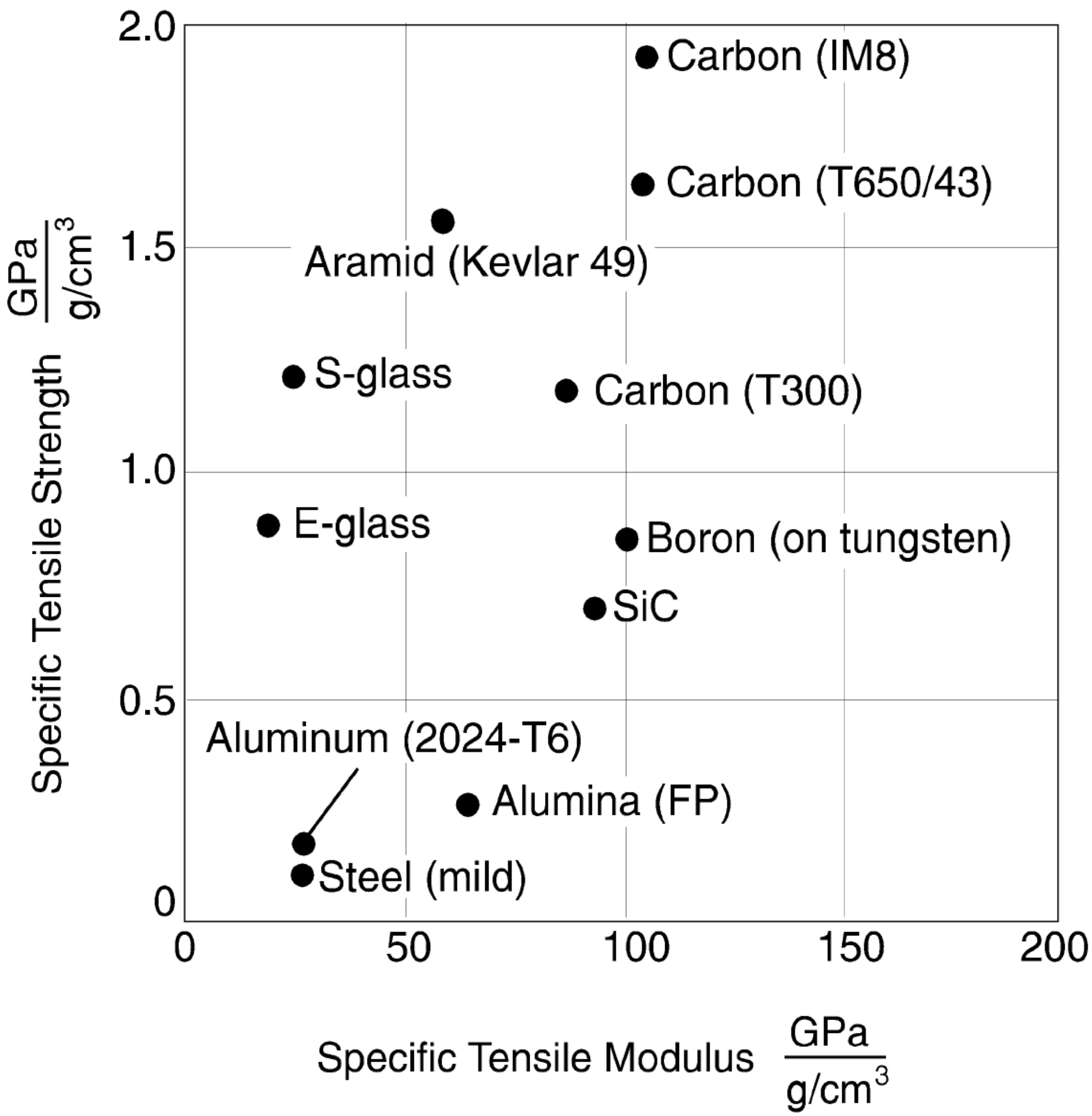




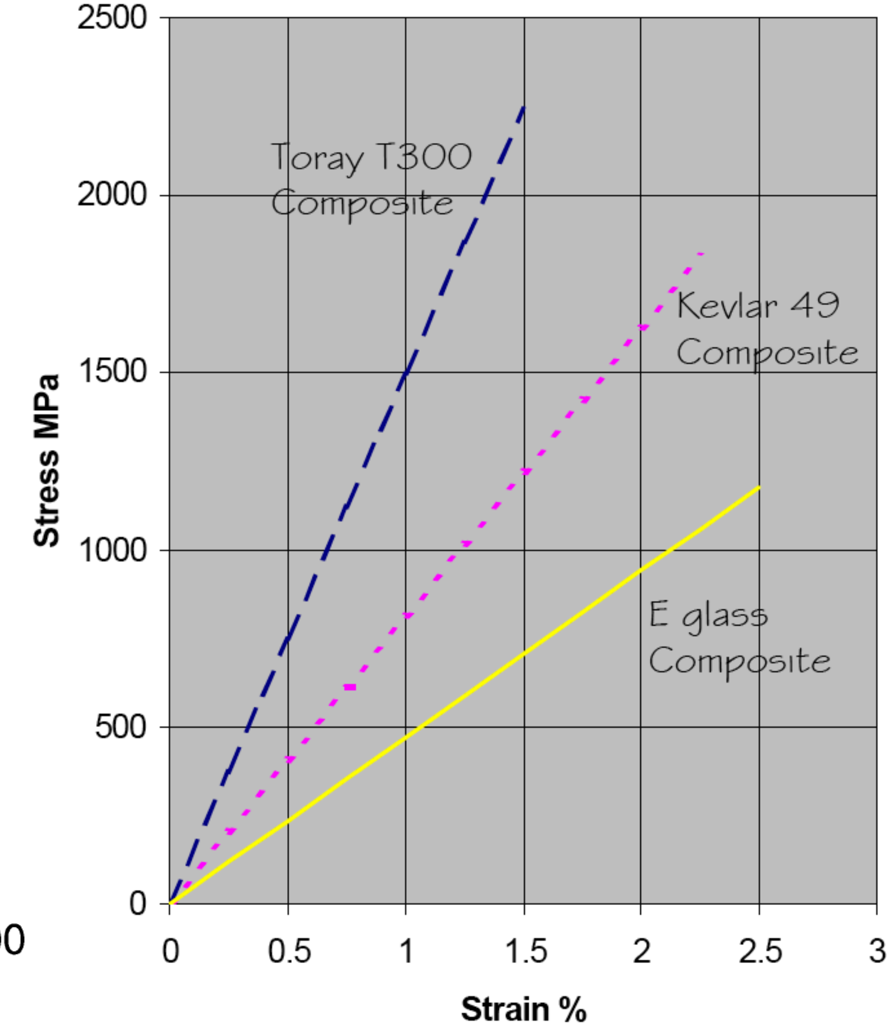
Holmes M Al-Khatat Q, "Structural Properties of GRP," Composites July 1975

Strength and Stiffness Characteristics

Specific Strength and Stiffness



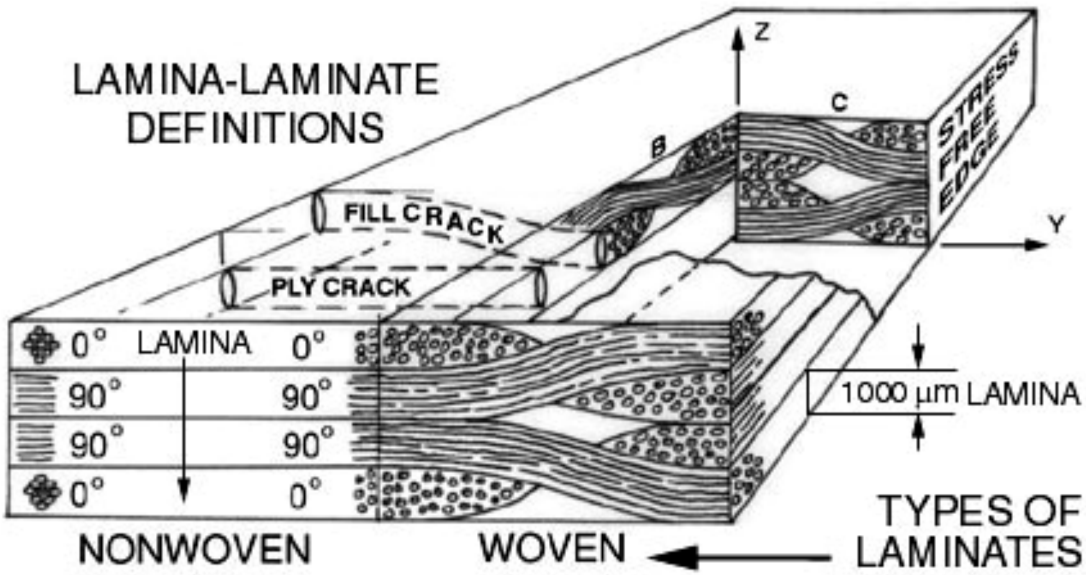
Stress/Strain Behavior



Lamina-Laminate Definitions

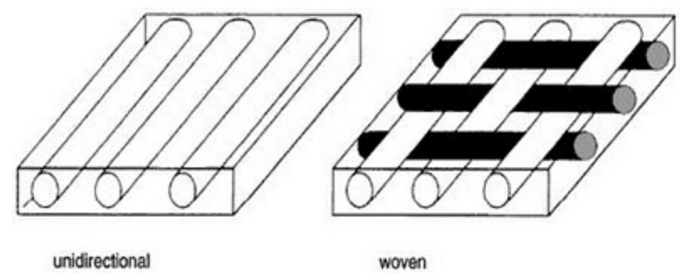
A lamina is a flat (or sometimes curved) arrangement of unidirectional (or woven) fibers suspended in a matrix material. A lamina is generally assumed to be orthotropic, and its thickness depends on the material from which it is made.

A laminate is a stack of lamina oriented in a specific manner to achieve a desired result. The laminate's mechanical properties depend on the properties of each lamina, as well as the order in which the lamina are stacked.

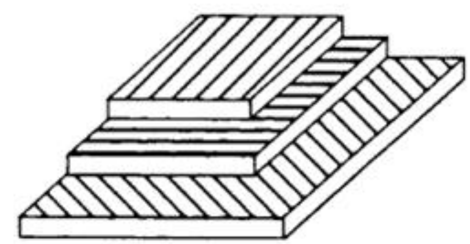


Ronald D. Kriz, "Microstructure Lectures," Virginia Polytechnic Institute and State University

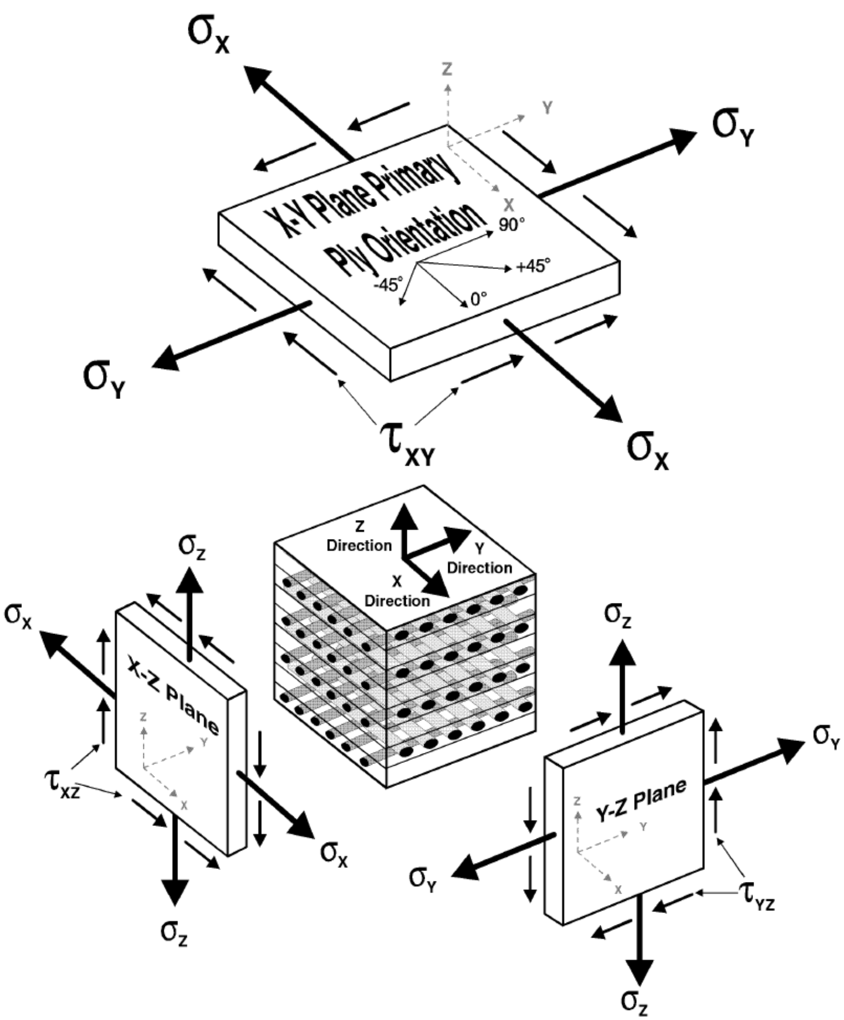
Lamina



Laminate



Laminate Mechanical Properties



Stiffness	X	Longitudinal	Tensile Modulus	E_x^t	Compressive Modulus	E_x^c
	Y	Transverse	Tensile Modulus	E_y^t	Compressive Modulus	E_y^c
	Z	Thickness	Tensile Modulus	E_z^t	Compressive Modulus	E_z^c
	XY	Longitudinal/ Transverse	Shear Modulus	G_{xy}		
	XZ	Longitudinal/ Thickness	Shear Modulus	G_{xz}		
	YZ	Transverse/ Thickness	Shear Modulus	G_{yz}		
Strength	X	Longitudinal	Tensile Strength	$\sigma_x^{t\,ult}$	Compressive Strength	$\sigma_x^{c\,ult}$
	Y	Transverse	Tensile Strength	$\sigma_y^{t\,ult}$	Compressive Strength	$\sigma_y^{c\,ult}$
	Z	Thickness	Tensile Strength	$\sigma_z^{t\,ult}$	Compressive Strength	$\sigma_z^{c\,ult}$
	XY	Longitudinal/ Transverse	Shear Strength	τ_{xy}^{ult}		
	XZ	Longitudinal/ Thickness	Shear Strength	τ_{xz}^{ult}		
	YZ	Transverse/ Thickness	Shear Strength	τ_{yz}^{ult}		

Poisson's Ratio

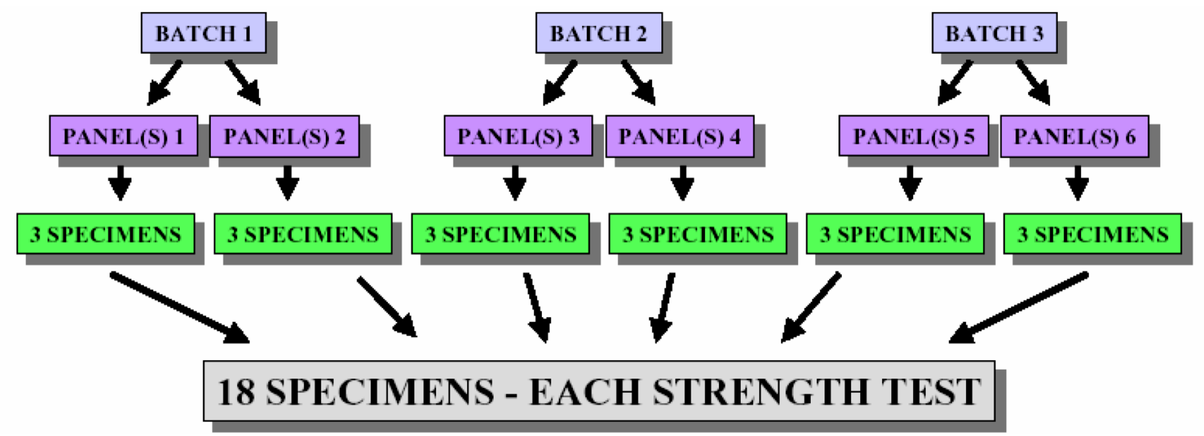
Direction:	XY (Major)	YX (Minor)	ZX	YZ
Notation:	ν_{xy}^t, ν_{xy}^c	ν_{yx}^t, ν_{yx}^c	ν_{zx}^t, ν_{zx}^c	ν_{yz}^t, ν_{yz}^c

Material Allowables

The method for determining material allowables is to conduct a formal testing program to determine the behavior of the material in its anticipated in-service operating environment.

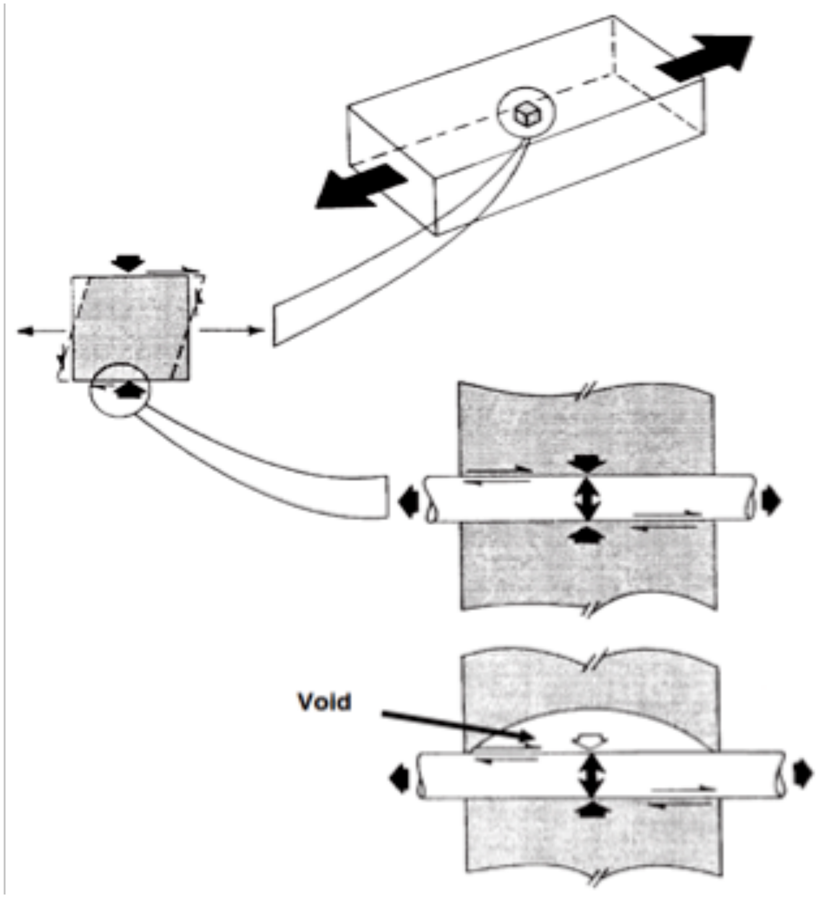
- All material specimens for the testing program should be fabricated under identical conditions and processes as those anticipated for the production of the final structure.
- The material testing program is also to account for the statistical variability in actual composite material properties, both as manufactured and at the end of service life.
- The test program shall be defined to develop B-Basis values, which are the values at which 90 percent of the population of the data is expected to fall, with a 95 percent confidence.

Minimum requirement for the material test program (For panels to be considered from a separate batch, they must be shot separately with separately measured and mixed resin. Each panel from each batch is to be layed-up at different times)



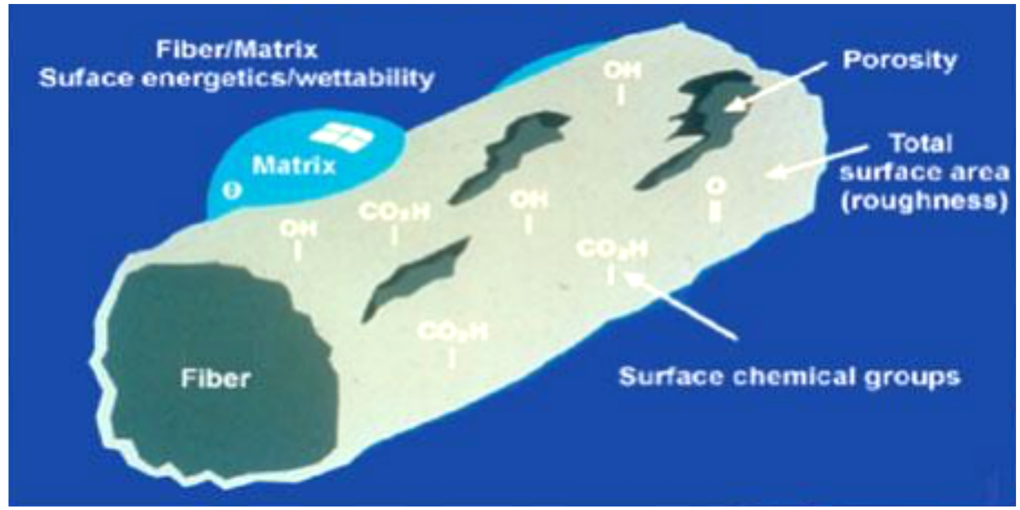
Resin/Fiber Interface

Fiber Resin Interaction

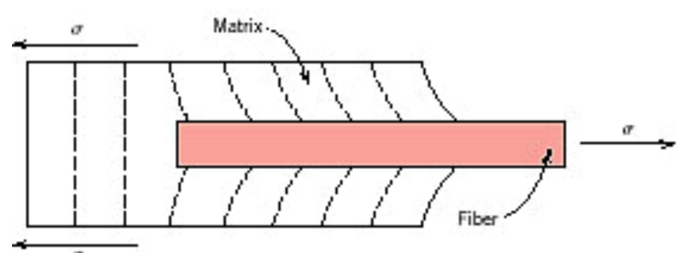


Material Engineering, May, 1978 p. 29

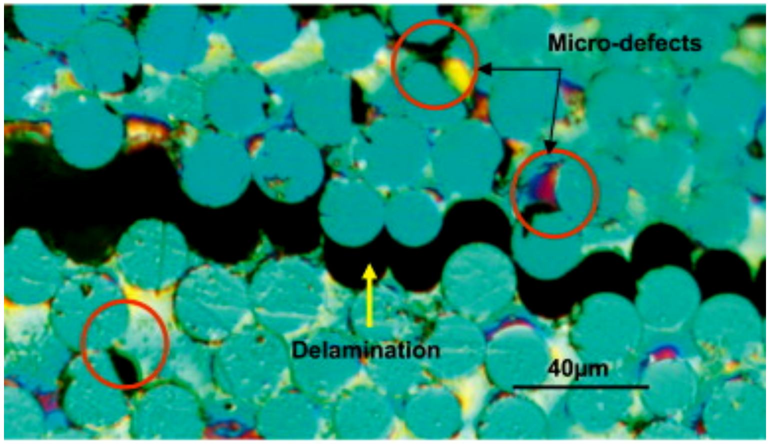
Surface Characteristics

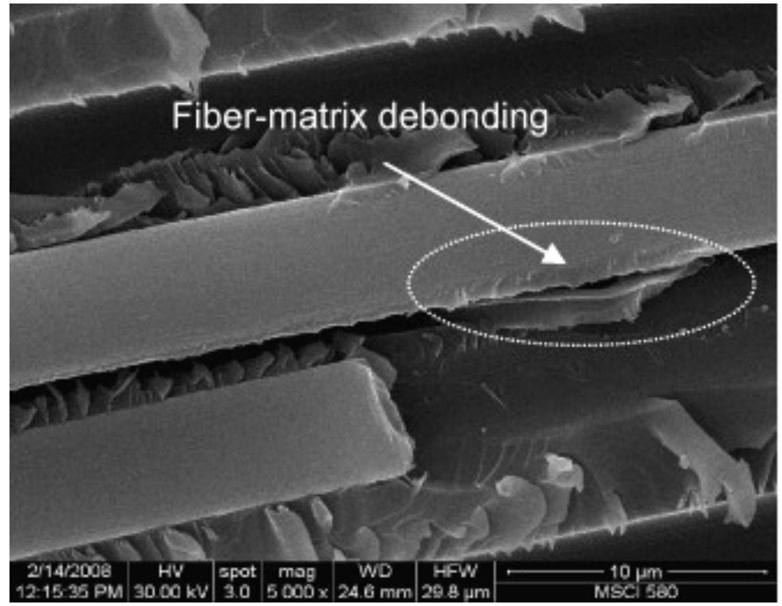


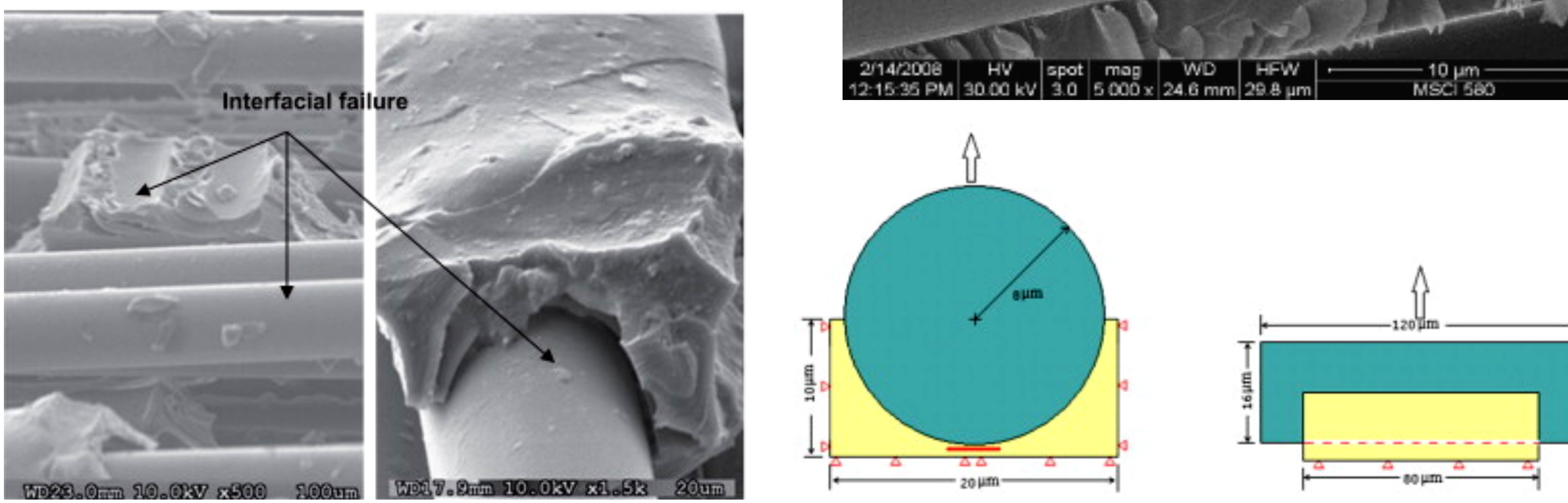
Surface treatment and sizing increase the fiber’s total surface area and porosity and alter its surface energy to improve adhesion between the fiber and the resin matrix in a composite. [Grafil Inc.]



Micro-scale Fiber/Resin Interface



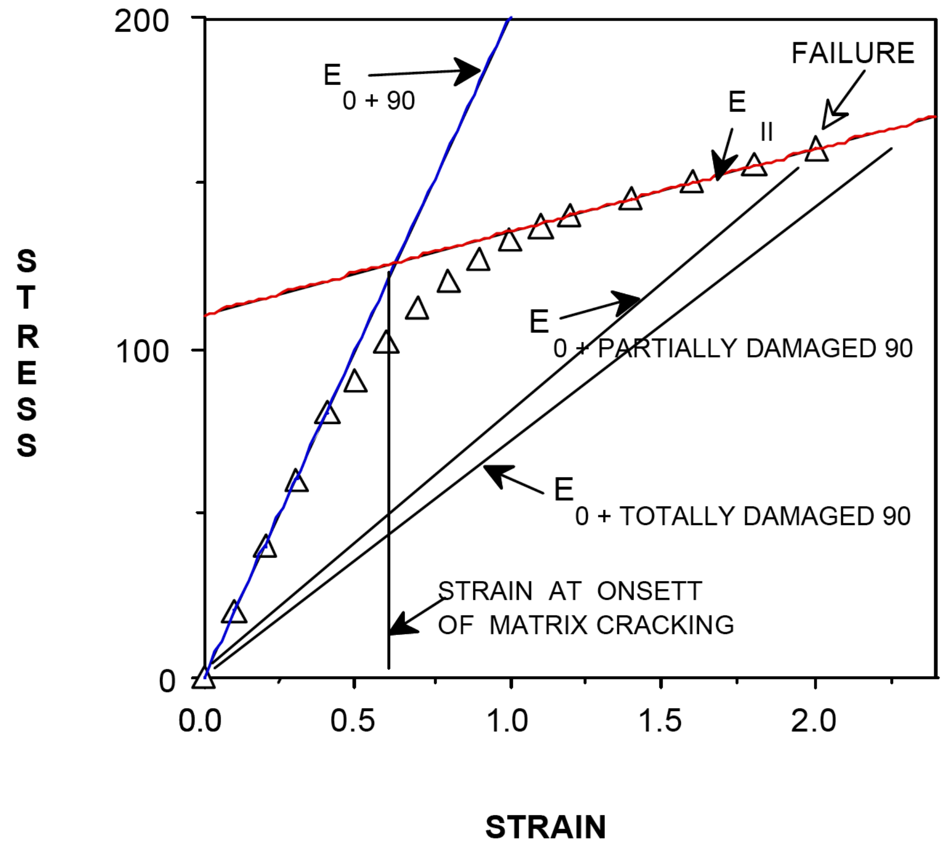




S.A. Hashim, J.A. Nisar, "An investigation into failure and behaviour of GFRP pultrusion joints," International Journal of Adhesion and Adhesives, Jan. 2013

Laminate Failure

- The key criterion for composite failure is the local strain to failure: ε' a.k.a. elongation at break and not stress (note that ε' for the fiber/matrix interface i.e. transverse fibers ≅ 0.25 %)
- Matrix cracking:
  - polyester resin ε' = 0.9-4.0 %
  - vinyl ester ε' = 1.0-4.0 %
  - epoxy resin ε' = 1.0-3.5 %
  - phenolic resin ε' = 0.5-1.0 %
- Fiber fracture:
  - S/R-glass ε' = 4.6-5.2 %
  - E-glass ε' = 3.37 %
  - Kevlar 49 ε' = 2.5 %
  - HS-carbon ε' = 1.12 %
  - UHM-carbon ε' = 0.38

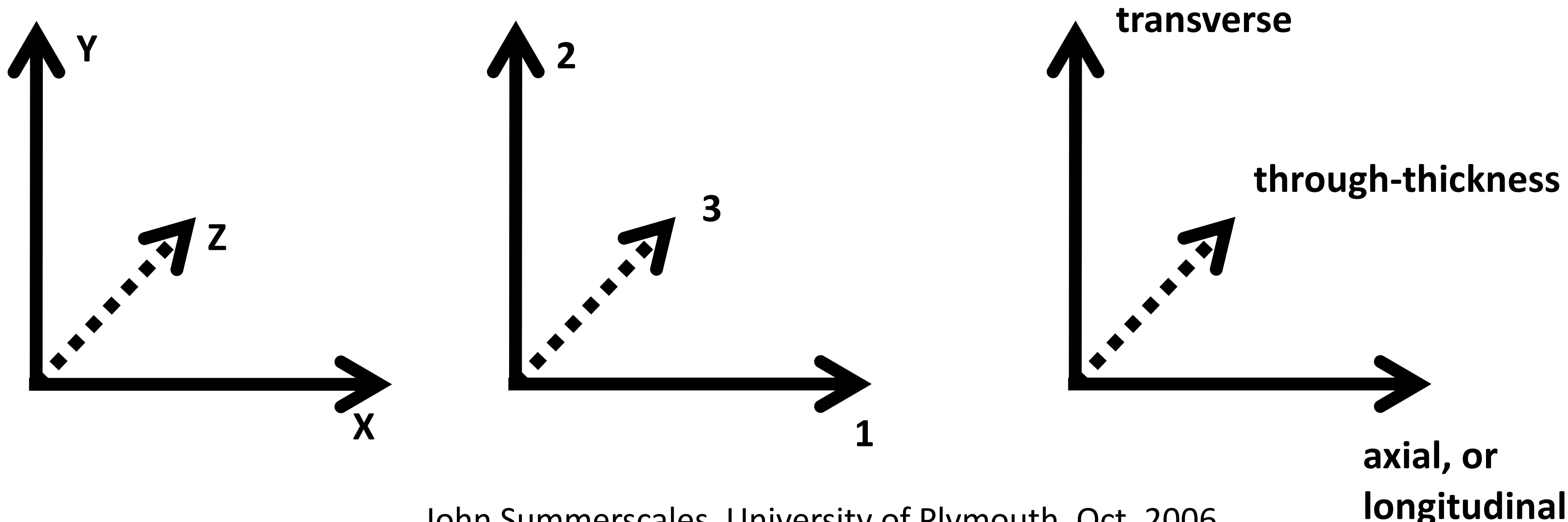


John Summerscales, University of Plymouth, Oct. 2006

Elastic Properties

- Young's moduli - uniaxial stress/unixaial strain
- Poisson's ratio - transverse strain/strain parallel to the load
- Shear moduli - biaxial stress/biaxial strain
- Bulk modulus - triaxial stress (pressure)/triaxial strain

Subscript nomenclature



John Summerscales, University of Plymouth, Oct. 2006

Poisson's Ratio

Isotropic

$$\nu = -\frac{\text{(strain normal to the applied stress)}}{\text{(strain parallel to the applied stress)}}$$

$-1 < \nu < \frac{1}{2}$

Orthotropic: ν_{ij}

Maxwell's reciprocal theorem

$\nu_{12}E_2 = \nu_{21}E_1$

Lemprière constraint

$\nu_{ij} \leq (E_i/E_j)^{1/2}$ and $\nu_{21}\nu_{23}\nu_{13} < \frac{1}{2}$

Poisson's ratios for GRP

high values
low values

	UD C1	UD C1	WR A2	WR A2
	ν_{ij}	$\sqrt{E_i/E_j}$	ν_{ij}	$\sqrt{E_i/E_j}$
ν_{12}	0.308	1.606	0.140	0.942
ν_{21}	0.123	0.623	0.109	1.061
ν_{13}	0.354	1.687	0.408	1.285
ν_{31}	0.124	0.593	0.247	0.778
ν_{23}	0.417	1.051	0.380	1.364
ν_{32}	0.414	0.952	0.297	0.733

John Summerscales, University of Plymouth, Oct. 2006

Shear and Bulk Modulus

	Shear Modulus	Bulk Modulus
Isotropic	$G = \dfrac{E}{2(1+\nu)}$	$K = \dfrac{E}{3(1-2\nu)}$
Orthotropic	$G_{12} = \dfrac{\sqrt{E_x E_y}}{2\left(1+\sqrt{\nu_{xy}\nu_{yx}}\right)}$	$K = \dfrac{\sqrt[3]{E_x E_y E_z}}{3\left(1-2.\sqrt[3]{\nu_{xy}\nu_{zx}\nu_{yz}}\right)}$

John Summerscales, University of Plymouth, Oct. 2006

Isotropy

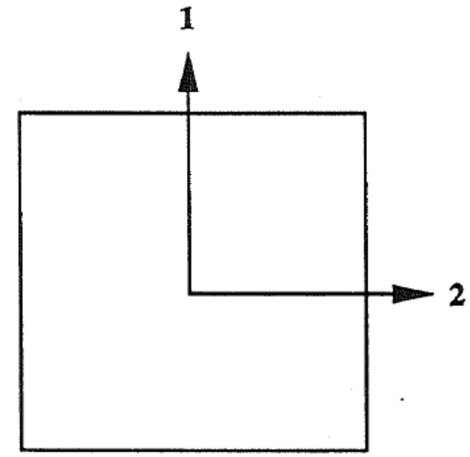
In the study of mechanical properties of materials, isotropic means having identical values of a property in all directions.

An orthotropic material has two or three mutually orthogonal twofold axes of rotational symmetry so that its mechanical properties are, in general, different along each axis.

Anisotropy can be defined as a difference, when measured along different axes, in a material's physical or mechanical properties.

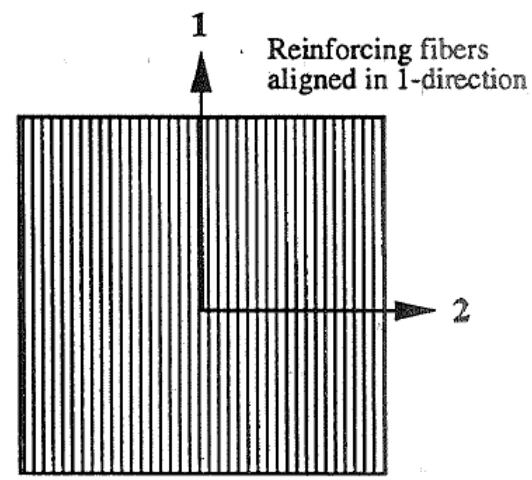
Quasi-isotropic laminates exhibit isotropic (that is, independent of direction) in-plane response but are not restricted to isotropic out-of-plane (bending) response.

Isotropic Plate



Stiffness in 1-direction = stiffness in 2-direction = stiffness in *any* direction

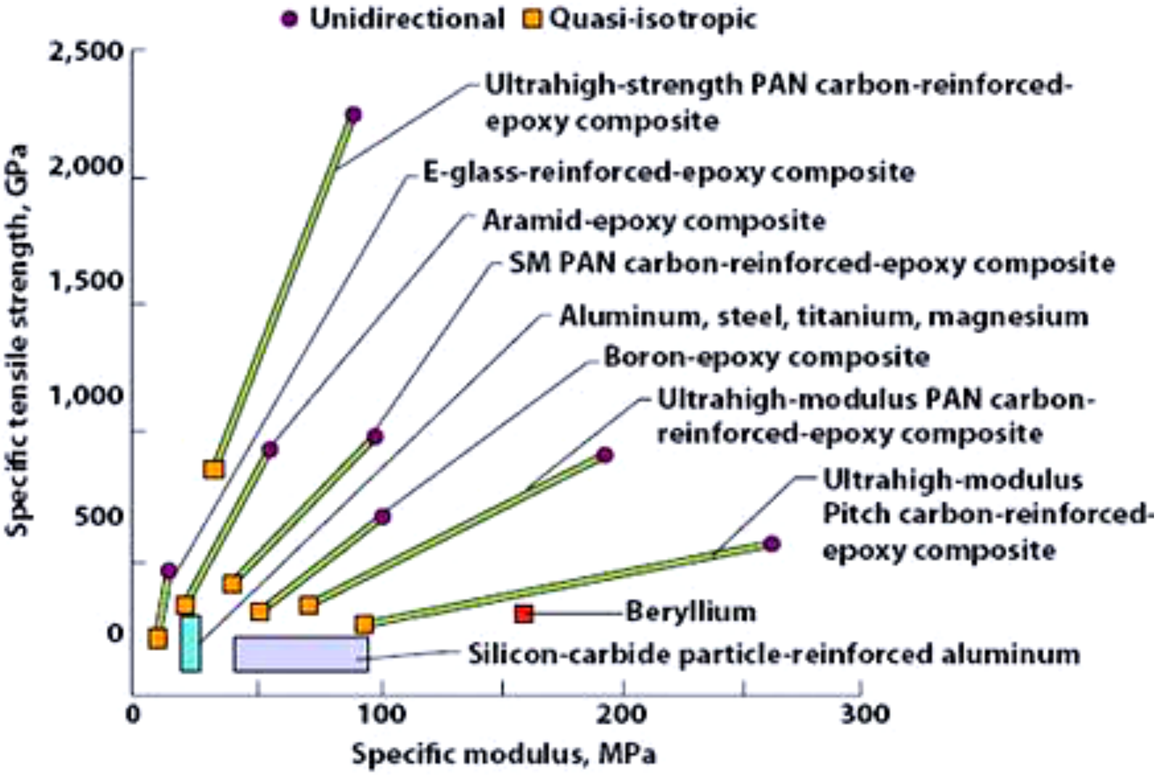
Orthotropic Plate

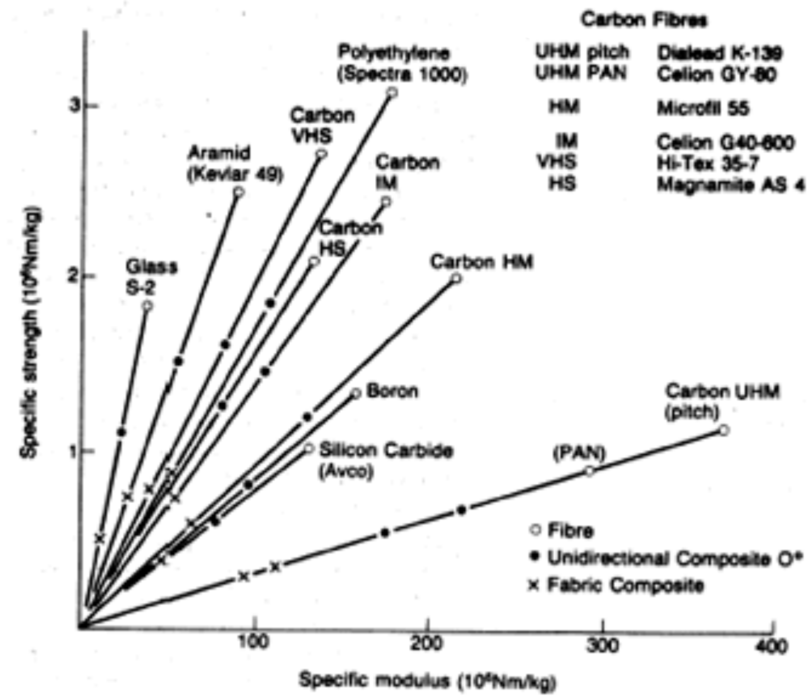


Stiffness in 1-direction >> stiffness in 2-direction ≠ stiffness in other directions

Isotropy Property Influence

Specific Strength versus Specific Modulus

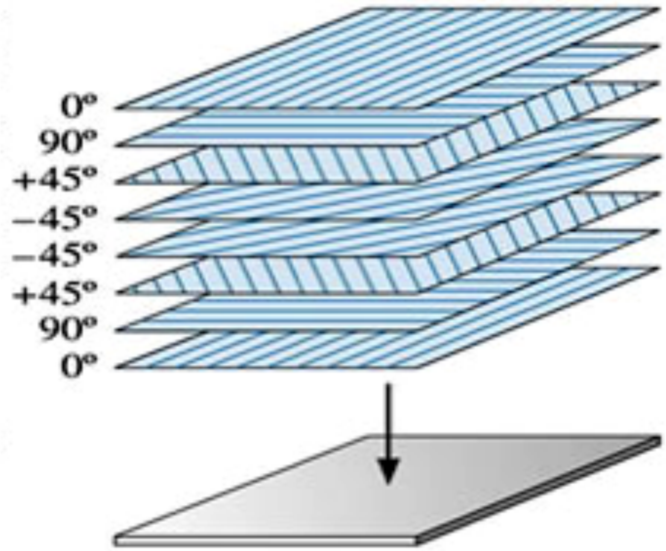




Carl Zweben and Jean M. Hoffman, “Stronger and Lighter — Composites Make Their Mark,” MachineDesign.com Mar., 2008

http://hsc.csu.edu.au/engineering_studies/focus/aero/2579/polymer_composites.html

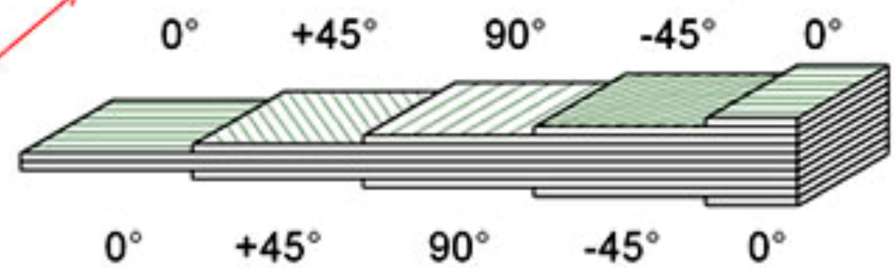
Quasi-isotropic Laminates



Cross-plied quasi-isotropic

- Laminates are often described by an orientation code
- Example: [0/-45/90/+45/0/0/+45/90/-45/0]

1st ply is, by definition, laid-up on the tool



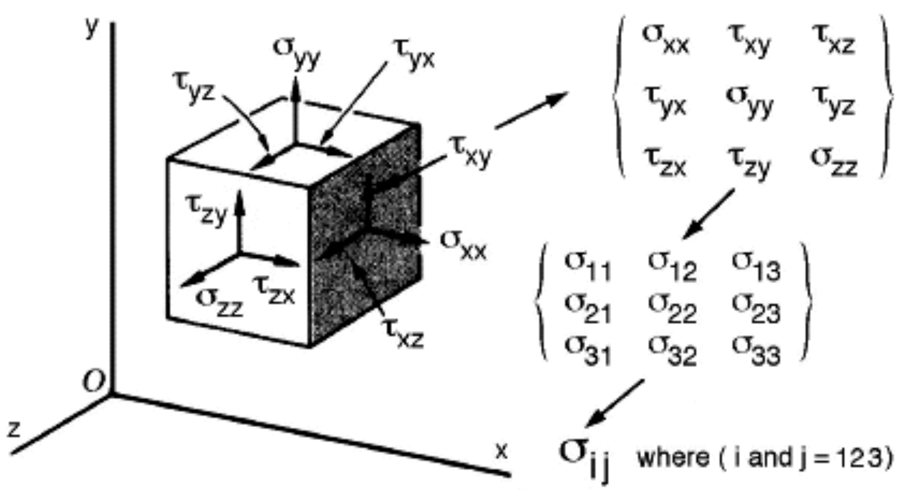
- Short hand: $[0/-45/90/+45]_S$ — *symmetric*
- Short hand: $[0/-45/90/+45]_N$ — *Repeat N times*
- Other Examples: $[0/+45/-45/90]_{2S}$ — *16 total plies*
  $[0_2/+45/-45/90_2]_S$ — *12 total plies*
  $[0_U/+45_{CL}]$ — *2 total plies (1 uni @ 0° and 1 cloth @ ±45°)*

http://www.quartus.com/resources/white-papers/composites-101/

Mechanical Behavior of Orthotropic Materials

Three Young's moduli E_1, E_2, E_3, Poisson's ratios ν_{12}, ν_{13}, ν_{23}, and shear moduli G_{12}, G_{13}, and G_{23}, shown as in the figure below. These moduli enter the elastic compliance matrix as

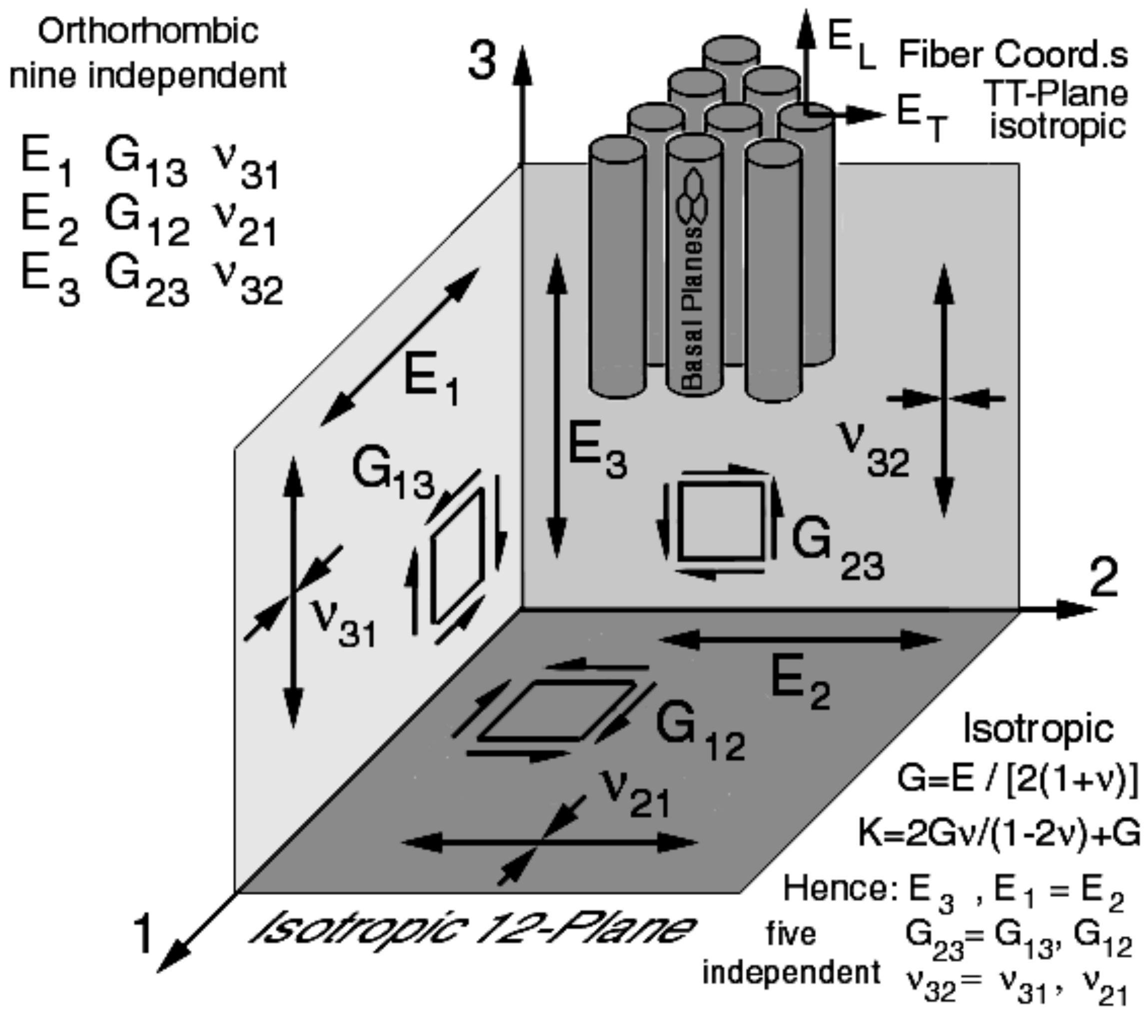
$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_2 & -\nu_{31}/E_3 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & -\nu_{32}/E_3 & 0 & 0 & 0 \\ -\nu_{13}/E_1 & -\nu_{23}/E_2 & 1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix}$$



Possible components of stress acting as forces on a small differential element can be organized into a matrix format

Ronald D. Kriz, "Microstructure Lectures," Virginia Polytechnic Institute and State University

Orthotropic Elastic Properties



Young's Modulus, E, shear modulus, G, and Poisson's Ratio, η, in each orthogonal plane can be used to classify the nine independent orthorhombic elastic constants in terms of engineering properties.

Ronald D. Kriz, “Microstructure Lectures,” Virginia Polytechnic Institute and State University

Rule of Mixtures

Volume fraction of the fiber component V_f is defined as:

$$V_f = \frac{v_f}{v_c}$$

where v_f is the volume of the fiber and v_c is the volume of the composite.

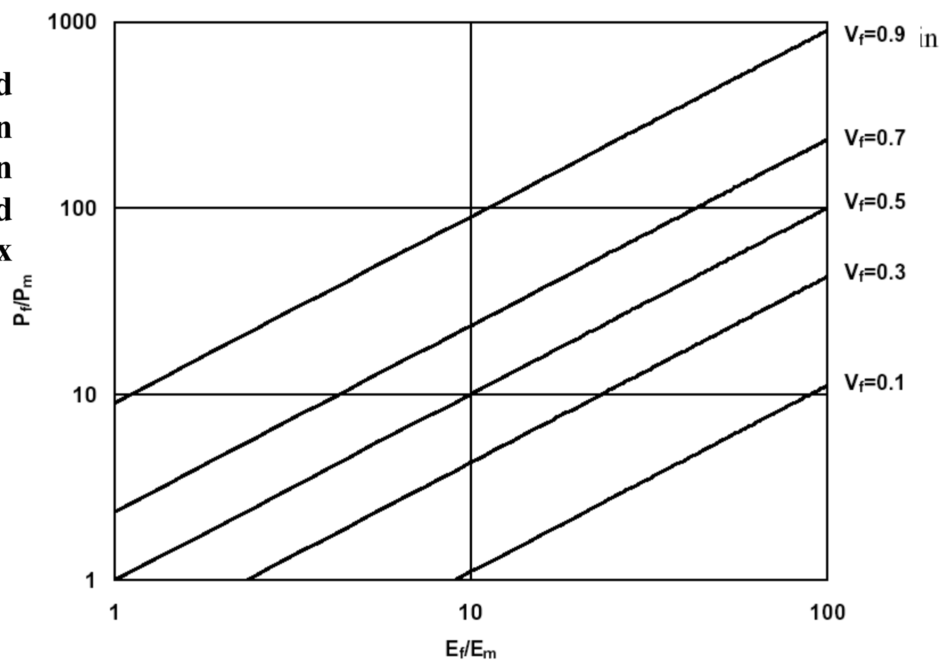
Volume fraction of the matrix component V_m is defined as:

$$V_m = \frac{v_m}{v_c}$$

where v_m is the volume of the matrix.

The sum of the volume fractions of all constituents in a composite must equal 1. In a two-component system consisting of one fiber and one matrix, then, the total volume of the composite is $v_c = v_f + v_m$, hence $V_m = (1 - V_f)$.

Load distribution between fiber and matrix



$$V_v = \frac{\rho_{theroetical} - \rho_{actual}}{\rho_{theoretical}}$$

$$\sigma_c = \sigma_m V_m + \sigma_f V_f$$

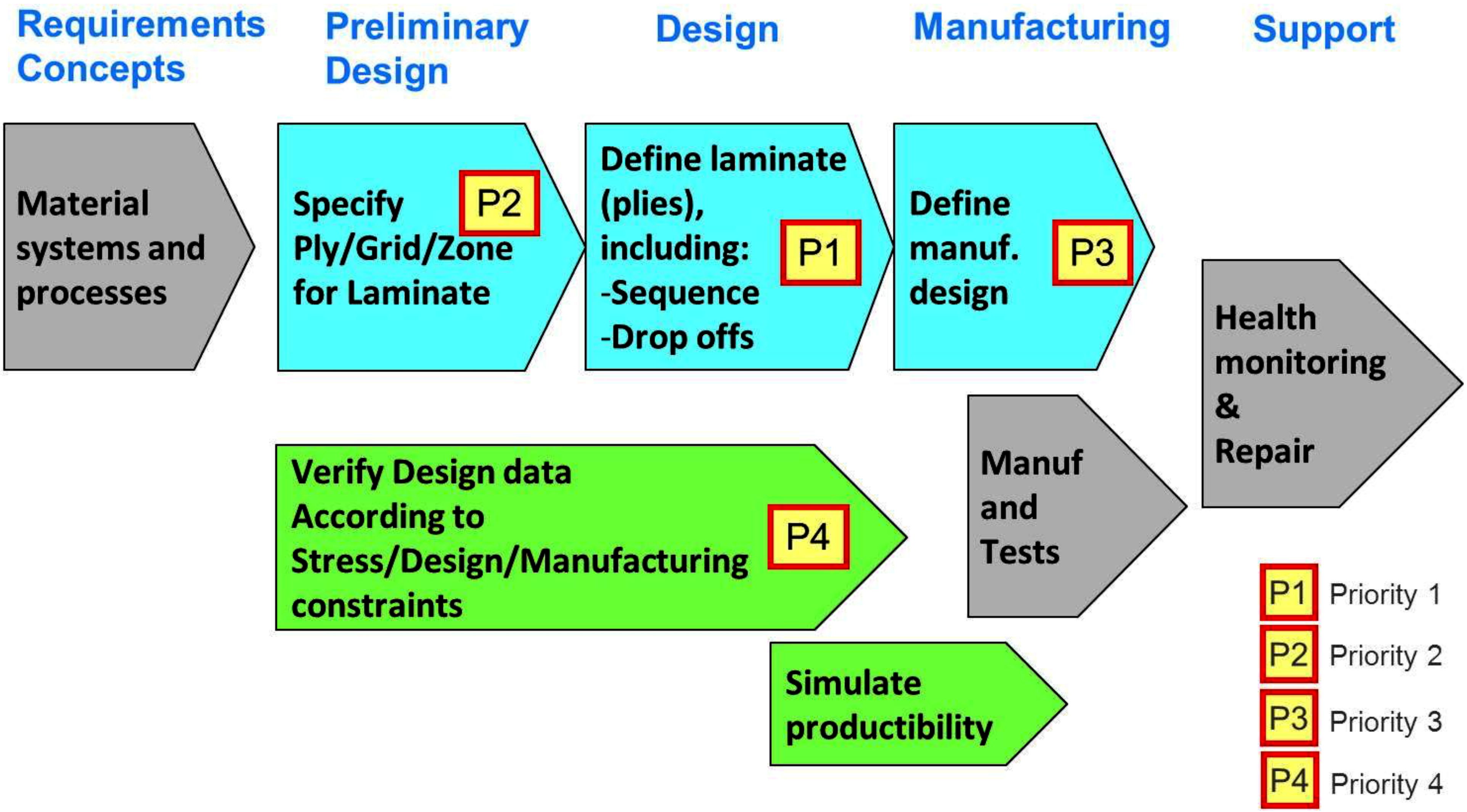
$$E_c = E_m V_m + E_f V_f$$

$$\frac{E_f}{E_m} = \frac{\sigma_f}{\sigma_m}$$

$$\sigma_f = \frac{\sigma_c E_f}{E_f V_f + E_m V_m}$$

Composite Part Development

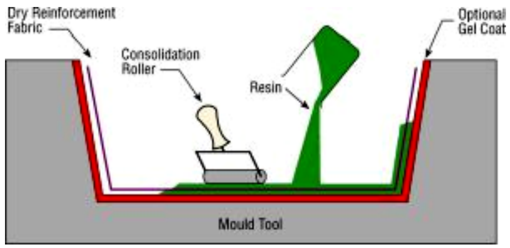
Composite part design, manufacture and support



http://www.lotar-international.org/lotar-workgroups/composites.html

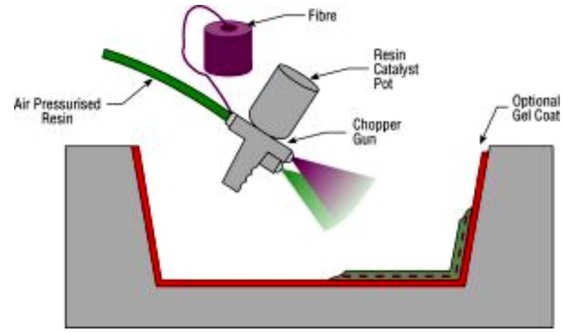
Manufacturing Methods

Hand Layup



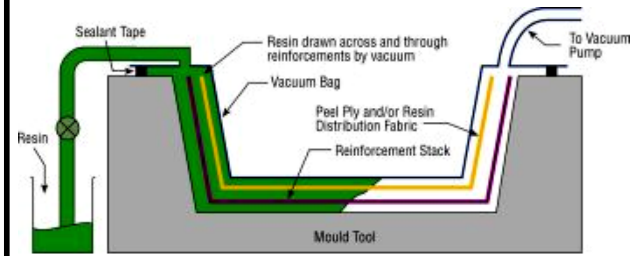
Resins are impregnated by hand into fibers which are in the form of woven, knitted, stitched or bonded fabrics. This is usually accomplished by rollers or brushes, with an increasing use of nip-roller type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. Laminates are left to cure under standard atmospheric conditions.

Spray-up



Fiber is chopped in a hand-held gun and fed into a spray of catalyzed resin directed at the mold. The deposited materials are left to cure under standard atmospheric conditions.

Resin Infusion

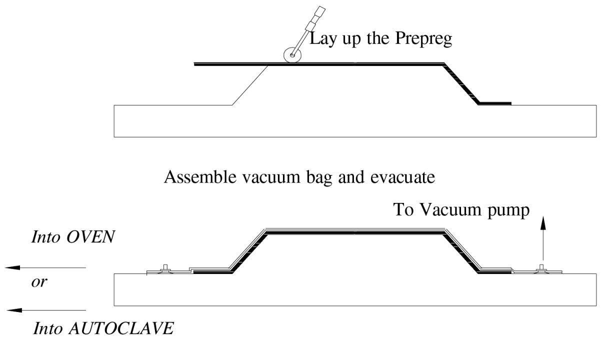


In resin infusion fabrics are laid up as a dry stack of materials. The fiber stack is then covered with peel ply and a knitted type of non-structural fabric. The whole dry stack is then vacuum bagged and resin is allowed to flow into the laminate. The resin distribution over the whole laminate is aided by resin flowing easily through the non-structural fabric, and wetting the fabric out from above.

www.netcomposites.com

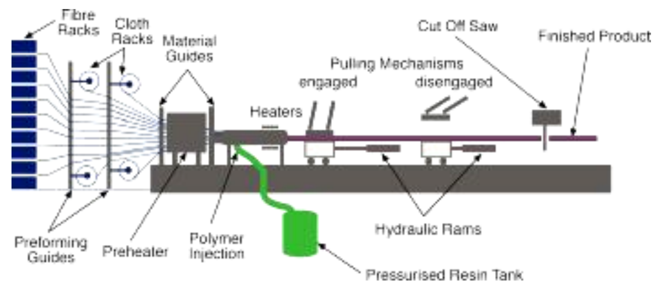
Manufacturing Methods

Prepregs



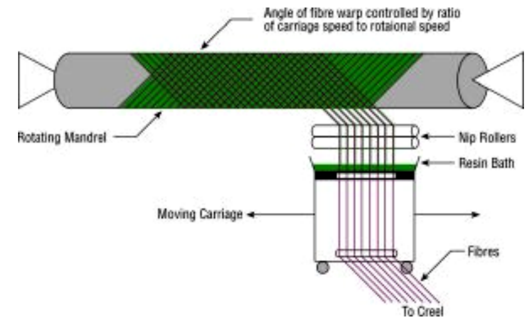
Reinforcements are pre-impregnated with a pre-catalyzed resin. The catalyst is largely latent at ambient temperatures giving the materials several weeks, or sometimes months, of useful life when stored frozen. The prepregs are laid up by hand or machine onto a mold surface, vacuum bagged and then heated to typically 120-180°C. Additional pressure can be provided by an autoclave.

Pultrusion



Fibers are pulled from a creel through a resin bath and then on through a heated die. The die completes the impregnation of the fiber, controls the resin content and cures the material into its final shape as it passes through the die. This cured profile is then automatically cut to length. Fabrics may also be introduced into the die to provide fiber direction other than at 0°.

Filament Winding



This process is primarily used for hollow, generally circular or oval sectioned components, such as pipes and tanks. Fiber tows are passed through a resin bath before being wound onto a mandrel in a variety of orientations, controlled by the fiber feeding mechanism, and rate of rotation of the mandrel.

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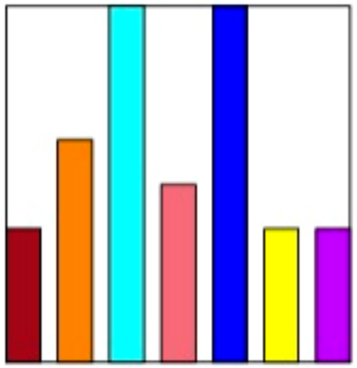
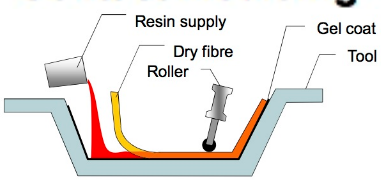
Manufacturing Metrics

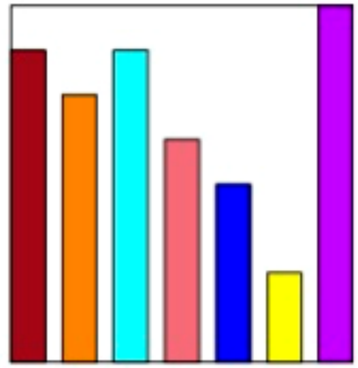
Manufacturing Process	Labor Content	Cycle Time, minutes	Production Quantity Potential	Product Surface Area, m^2	Typical Mold Cost	Typical Equipment Cost
Hand Layup	very high	100-1500	1-400	.1-1,000	$2,000	$100
Spray-up	high	60-500	5-1500	.1-100	$2,000	$15,000
Resin Infusion	high	80-800	1-200	.1-1,000	$2,000	$2,000
Prepregs (autoclave)	very high	100-1500	1-200	.2-100	$5,000	$400,000
Pultrusion	low	n/a	10,000-1,000,000 meters	n/a	$10,000	$250,000
Filament Winding	moderate	40-650	1-100	.1-50	$2,000	$50,000

Manufacturing Method Trade-Offs

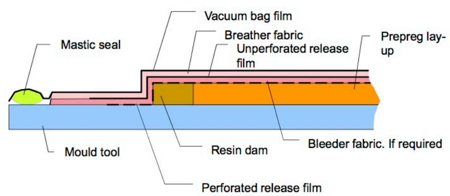


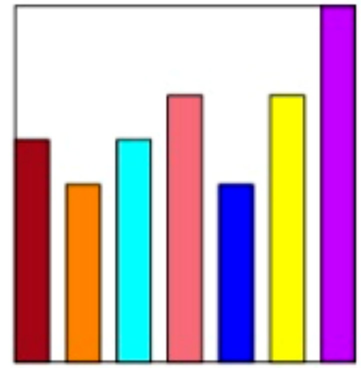
Contact moulding



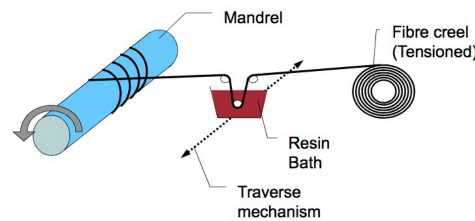


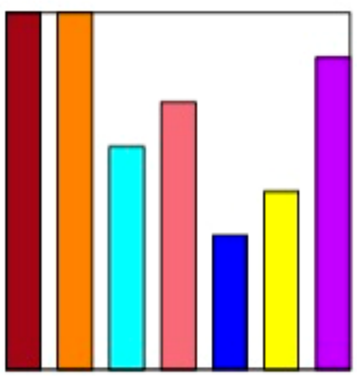
Vac bag/autoclave



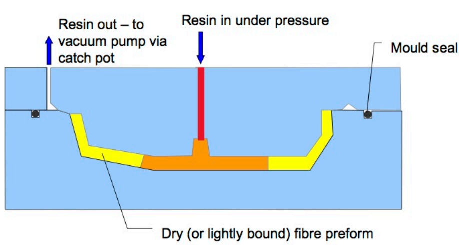


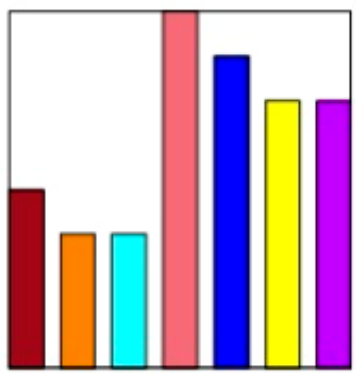
Filament winding



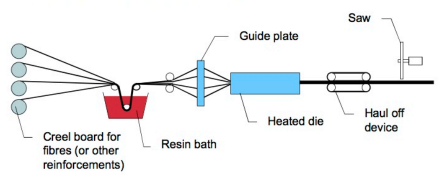


RTM





Pultrusion



- Flexibility of properties
- Flexibility of geometry
- Size potential
- Productivity
- Tooling costs
- Labour skills
- "Quality"

http://aerospaceengineeringblog.com/composite-manufacturing/

Composite Material Concepts Takeaway Summary

- Composite materials are the combination of reinforcement and thermoset resins that form a structure with physical properties superior to the constituent elements
- The physical properties of a laminate are a function of constituent materials and manufacturing variables
- The fiber/resin interface is critical for transmitting loads between laminate plies
- Laminate physical properties are very dependent upon fiber alignment
- Unlike metals, composites are orthotropic, with varying mechanical properties along three primary axis.
- Nine values for strength and stiffness (tension, compression and shear along three axes) and eight values for Poisson's ratio are required to completely characterize the mechanical properties of a composite laminate