Composite Materials

Materials form an integral part of the way composite structures perform. Because the builder is creating a structural material from diverse constituent compounds, material science concepts are essential to the understanding of how structural composites behave. This chapter encompasses three broad groups of composite materials:

- Reinforcements;
- Resins; and
- Core Materials.

Descriptions and physical property data of representative marine materials will be presented. As with all composite material system design, the reader is cautioned not to optimize materials from each group without regard for how a system will perform as a whole. Material suppliers are often a good source of information regarding compatibility with other materials.

Reinforcements for marine composite structures are primarily E-glass due to its cost for strength and workability characteristics. In contrast, the aerospace industry relies on carbon fiber as it's backbone. In general, carbon, aramid fibers and other specialty reinforcements are used in the marine field where structures are highly engineered for optimum efficiency. Architecture and fabric finishes are also critical elements of correct reinforcement selection.

Resin systems are probably the hardest material group for the designer and builder to understand. Fortunately, chemists have been working on formulations since Bakelite in 1905. Although development of new formulations is ongoing, the marine industry has generally based its structures on polyester resin, with trends to vinyl ester and epoxy for structurally demanding projects and highly engineered products. A particular resin system is effected by formulation, additives, catylization and cure conditions. Characteristics of a cured resin system as a structural matrix of a composite material system is therefore somewhat problematic. However certain quantitative and qualitative data about available resin systems exists and is given with the caveat that this is the most important fabrication variable to be verified by the “build and test” method.

Core materials form the basis for sandwich composite structures, which clearly have advantages in marine construction. A core is any material that can physically separate strong, laminated skins and transmit shearing forces across the sandwich. Core materials range from natural species, such as balsa and plywood, to highly engineered honeycomb or foam structures. The dynamic behavior of a composite structure is integrally related to the characteristics of the core material used.

Reinforcement Materials

Fiberglass

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. Additionally, glass fibers exhibit good chemical resistance and processability. The excellent tensile strength of glass fibers, however, may deteriorate when loads are applied for long periods of time. [2-1] Continuous glass fibers are formed by extruding molten glass to filament diameters between 5 and 25 micrometers. Table 2-1 depicts the designations of fiber diameters commonly used in the FRP industry.

Table 2-1 Glass Fiber Diameter Designations [Shell, *Epon® Resins for Fiberglass Reinforced Plastics*]

Designation	Mils	Micrometers (10^{-6} meters)
C	0.18	4.57
D	0.23	5.84
DE	0.25	6.35
E	0.28	7.11
G	0.38	9.65
H	0.42	10.57
K	0.53	13.46

Individual filaments are coated with a sizing to reduce abrasion and then combined into a strand of either 102 or 204 filaments. The sizing acts as a coupling agent during resin impregnation. Table 2-2 lists the composition by weight for both E- and S-glass. Table 2-3 lists some typical glass finishes and their compatible resin systems. E-glass (lime aluminum borosilicate) is the most common reinforcement used in marine laminates because of its good strength properties and resistance to water degradation. S-glass (silicon dioxide, aluminum and magnesium oxides) exhibits about one third better tensile strength, and in general, demonstrates better fatigue resistance. The cost for this variety of glass fiber is about three to four times that of E-glass. Table 2-4 contains data on raw E-glass and S-glass fibers.

Table 2-2 Glass Composition by Weight for E- and S-Glass [BGF]

	E-Glass	S-Glass
Silicone Dioxide	52 - 56%	64 - 66%
Calcium Oxide	16 - 25%	0 - .3%
Aluminum Oxide	12 - 16%	24 - 26%
Boron Oxide	5 - 10%	—
Sodium & Potassium Oxide	0 - 2%	0 - .3%
Magnesium Oxide	0 - 5%	9 - 11%
Iron Oxide	.05 - .4%	0 - .3%
Titanium Oxide	0 - .8%	—
Fluorides	0 - 1.0%	—

Polymer Fibers

The most common aramid fiber is Kevlar® developed by DuPont. This is the predominant organic reinforcing fiber, whose use dates to the early 1970s as a replacement for steel belting in tires. The outstanding features of aramids are low weight, high tensile strength and modulus, impact and fatigue resistance, and weaveability. Compressive performance of aramids is not as good as glass, as they show nonlinear ductile behavior at low strain values. Water absorption of un-impregnated Kevlar® 49 is greater than other reinforcements, although ultra-high modulus Kevlar® 149 absorbs almost two thirds less than Kevlar® 49. The unique characteristics of aramids can best be exploited if appropriate weave style and handling techniques are used.

Table 2-3 Resin Compatibility of Typical Glass Finishes [BGF, Shell, SP Systems and Wills]

Designation	Type of Finish	Resin System
Volan® A	Methacrylato chromic chloride	Polyester, Vinyl Ester or Epoxy
Garan	Vinyl silane	Epoxy
NOL-24	Halosilane (in xylene)	Epoxy
114	Methacrylato chromic chloride	Epoxy
161	Soft, clear with good wet-out	Polyester or Vinyl Ester
504	Volan® finish with .03%-.06% chrome	Polyester, Vinyl Ester or Epoxy
504A	Volan® finish with .06%-.07% chrome	Polyester, Vinyl Ester or Epoxy
538	A-1100 amino silane plus glycerine	Epoxy
550	Modified Volan®	Polyester or Vinyl Ester
558	Epoxy-functional silane	Epoxy
627	Silane replacement for Volan®	Polyester, Vinyl Ester or Epoxy
630	Methacrylate	Polyester or Vinyl Ester
A-100	Amino silane	Epoxy
A-172	Vinyl	Polyester or Vinyl Ester
A-174	Vinyl	Polyester or Vinyl Ester
A-187	Epoxy silane	Epoxy
A-1100	Amino silane	Epoxy or Phenolic
A-1106	Amino silane	Phenolic
A-1160	Ureido	Phenolic
S-553	Proprietary	Epoxy
S-920	Proprietary	Epoxy
S-735	Proprietary	Epoxy
SP 550	Proprietary	Polyester, Vinyl Ester or Epoxy
Y-2967	Amino silane	Epoxy
Y-4086/7	Epoxy-modified methoxy silane	Epoxy
Z-6030	Methacrylate silane	Polyester or Vinyl Ester
Z-6032	Organo silane	Epoxy
Z-6040	Epoxy-modified methoxy silane	Epoxy

Allied Corporation developed a high strength/modulus extended chain polyethylene fiber called Spectra® that was introduced in 1985. Room temperature specific mechanical properties of Spectra® are slightly better than Kevlar®, although performance at elevated temperatures falls off. Chemical and wear resistance data is superior to the aramids. Data for both Kevlar® and Spectra® fibers is also contained in Table 2-4. The percent of manufacturers using various reinforcement materials is represented in Figure 2-1.

Table 2-4 Mechanical Properties of Reinforcement Fibers

Fiber	Density lb/in^3	Tensile Strength psi x 10^3	Tensile Modulus psi x 10^6	Ultimate Elongation	Cost $/lb
E-Glass	.094	500	10.5	4.8%	.80-1.20
S-Glass	.090	665	12.6	5.7%	4
Aramid-Kevlar® 49	.052	525	18.0	2.9%	16
Spectra® 900	.035	375	17.0	3.5%	22
Polyester-COMPET®	.049	150	1.4	22.0%	1.75
Carbon-PAN	.062-.065	350-700	33-57	0.38-2.0%	17-450

Polyester and nylon thermoplastic fibers have recently been introduced to the marine industry as primary reinforcements and in a hybrid arrangement with fiberglass. Allied Corporation has developed a fiber called COMPET®, which is the product of applying a finish to PET fibers that enhances matrix adhesion properties. Hoechst-Celanese manufactures a product called Treveria®, which is a heat treated polyester fiber fabric designed as a "bulking" material and as a gel coat barrier to reduce "print-through." Although polyester fibers have fairly high strengths, their stiffness is considerably below that of glass. Other attractive features include low density, reasonable cost, good impact and fatigue resistance, and potential for vibration damping and blister resistance.

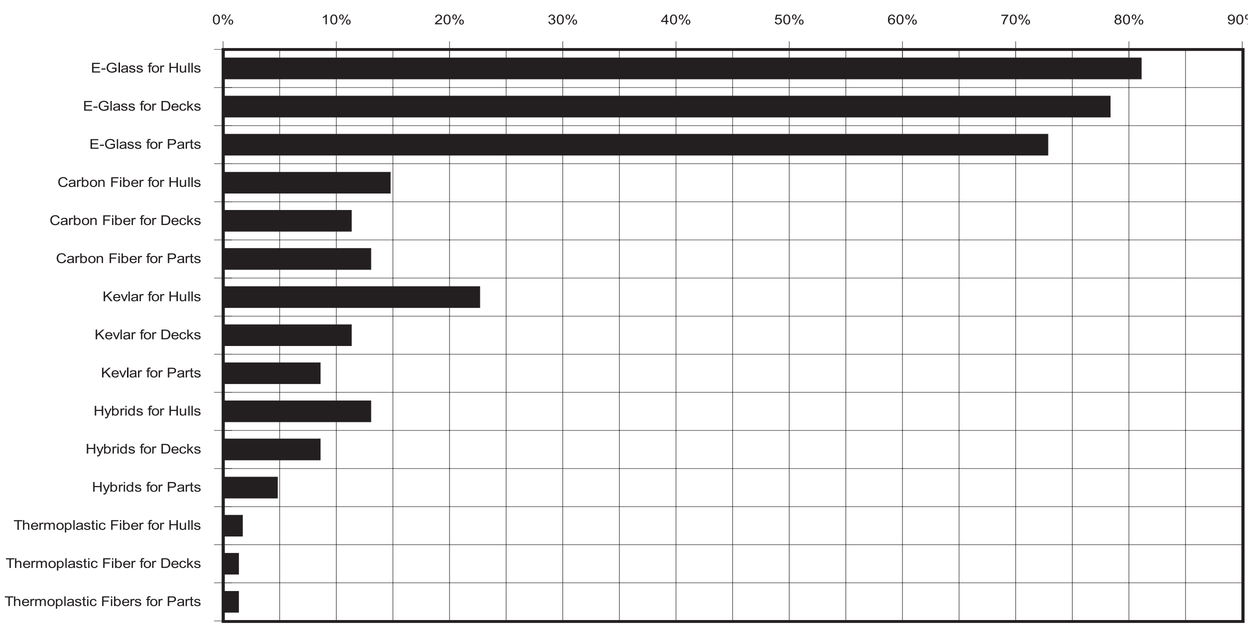


Figure 2-1 Marine Industry Reinforcement Material Use [EGA Survey]

Carbon Fibers

The terms “carbon” and “graphite” fibers are typically used interchangeably, although graphite technically refers to fibers that are greater than 99% carbon composition versus 93 to 95% for PAN-base fibers. All continuous carbon fibers produced to date are made from organic precursors, which in addition to PAN (polyacrylonitrile), include rayon and pitches, with the latter two generally used for low modulus fibers.

Carbon fibers offer the highest strength and stiffness of all commonly used reinforcement fibers. The fibers are not subject to stress rupture or stress corrosion, as with glass and aramids. High temperature performance is particularly outstanding. The major drawback to the PAN-base fibers is their relative cost, which is a function of high precursor costs and an energy intensive manufacturing process. Table 2-4 shows some comparative fiber performance data.

Reinforcement Construction

Reinforcement materials are combined with resin systems in a variety of forms to create structural laminates. The percent of manufacturers using various reinforcement styles is represented in Figure 2-5. Table 2-5 provides definitions for the various forms of reinforcement materials. Some of the lower strength non-continous configurations are limited to fiberglass due to processing and economic considerations.

Table 2-5 Description of Various Forms of Reinforcements
[Shell, *Epon® Resins for Fiberglass Reinforced Plastics*]

Form	Description	Principal Processes
Filaments	Fibers as initially drawn	Processed further before use
Continuous Strands	Basic filaments gathered together in continuous bundles	Processed further before use
Yarns	Twisted strands (treated with after-finish)	Processed further before use
Chopped Strands	Strands chopped 1/4 to 2 inches	Injection molding; matched die
Rovings	Strands bundled together like rope but not twisted	Filament winding; sheet molding; spray-up; pultrusion
Milled Fibers	Continuous strands hammermilled into short lengths 1/32 to 1/8 inches long	Compounding; casting; reinforced reaction injection molding (RRIM)
Reinforcing Mats	Nonwoven random matting consisting of continuous or chopped strands	Hand lay-up; resin transfer molding (RTM); centrifugal casting
Woven Fabric	Cloth woven from yarns	Hand lay-up; prepreg
Woven Roving	Strands woven like fabric but coarser and heavier	Hand or machine lay-up; resin transfer molding (RTM)
Spun Roving	Continuous single strand looped on itself many times and held with a twist	Processed further before use
Nonwoven Fabrics	Similar to matting but made with unidirectional rovings in sheet form	Hand or machine lay-up; resin transfer molding (RTM)
Surfacing Mats	Random mat of monofilaments	Hand lay-up; die molding; pultrusion

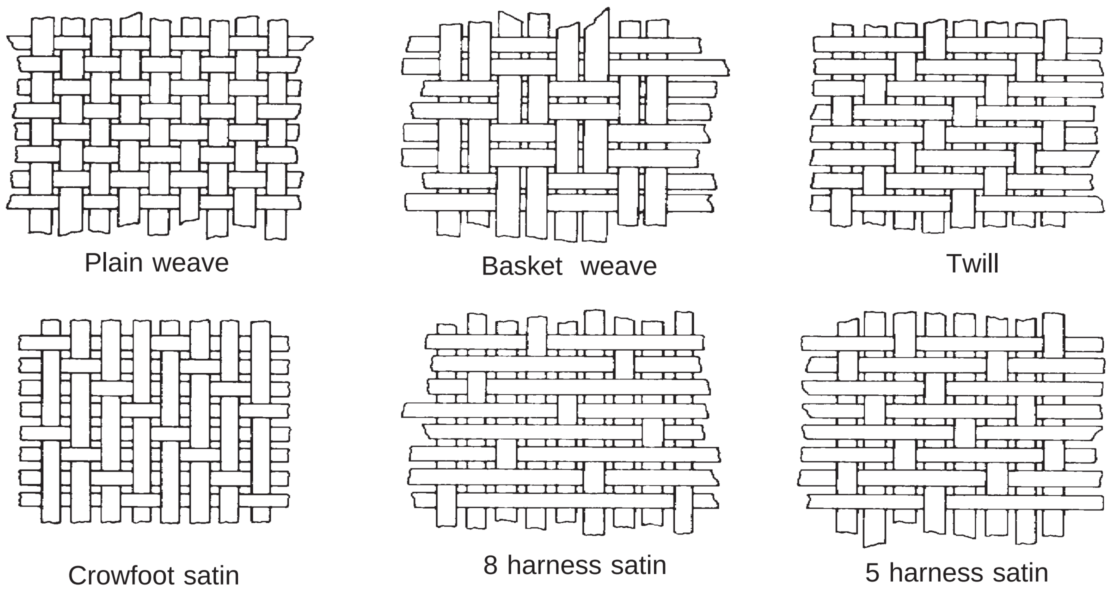


Figure 2-2 Reinforcement Fabric Construction Variations [*ASM Engineered Materials Handbook*]

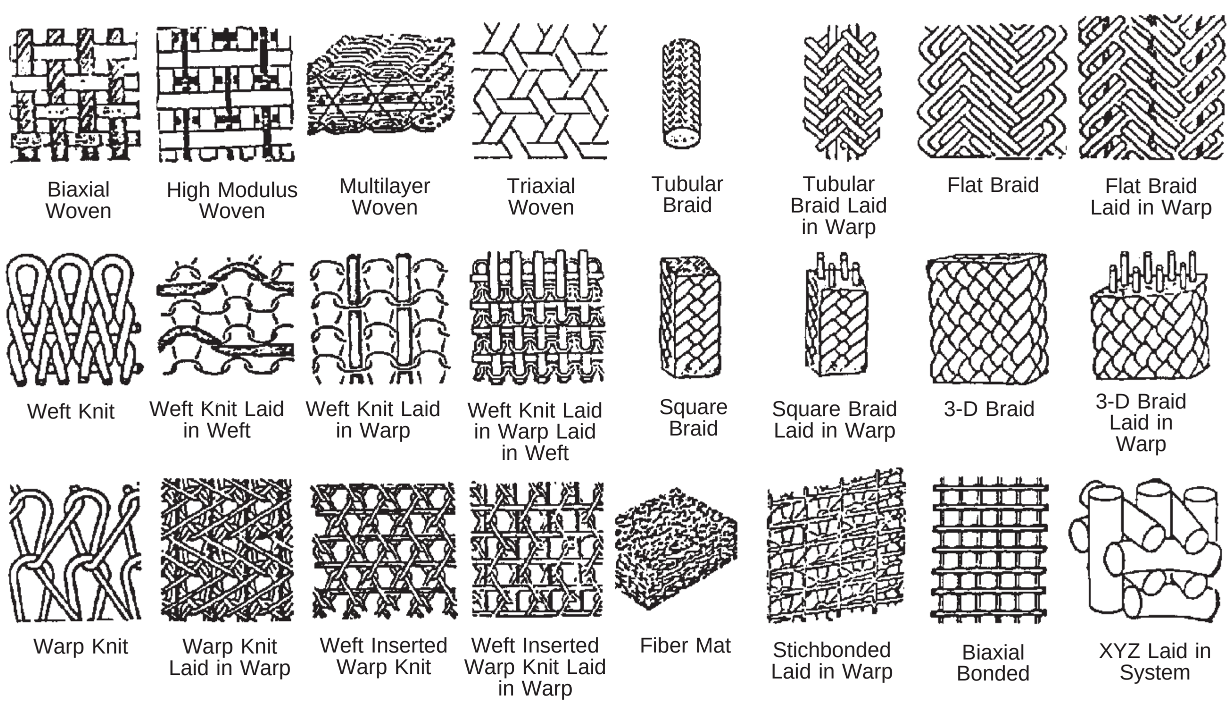


Figure 2-3 Various Forms of Reinforcement Architectures [Frank Ko, Drexel University]

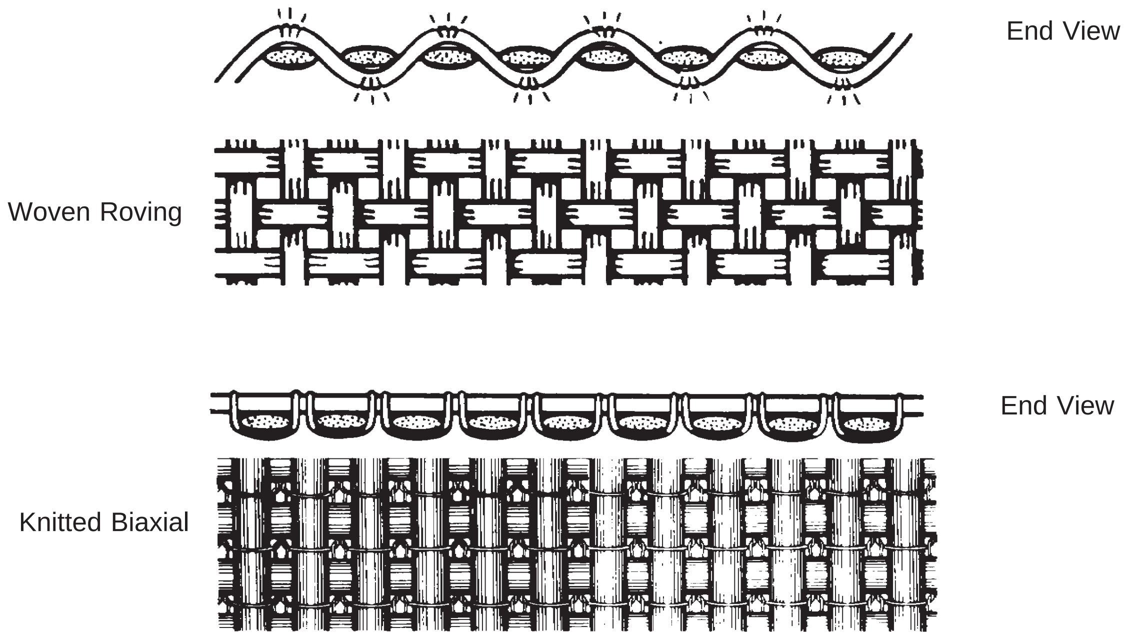


Figure 2-4 Comparison of Conventional Woven Roving and a Knitted Biaxial Fabric Showing Theoretical Kink Stress in Woven Roving [Composites Reinforcements, Inc.]

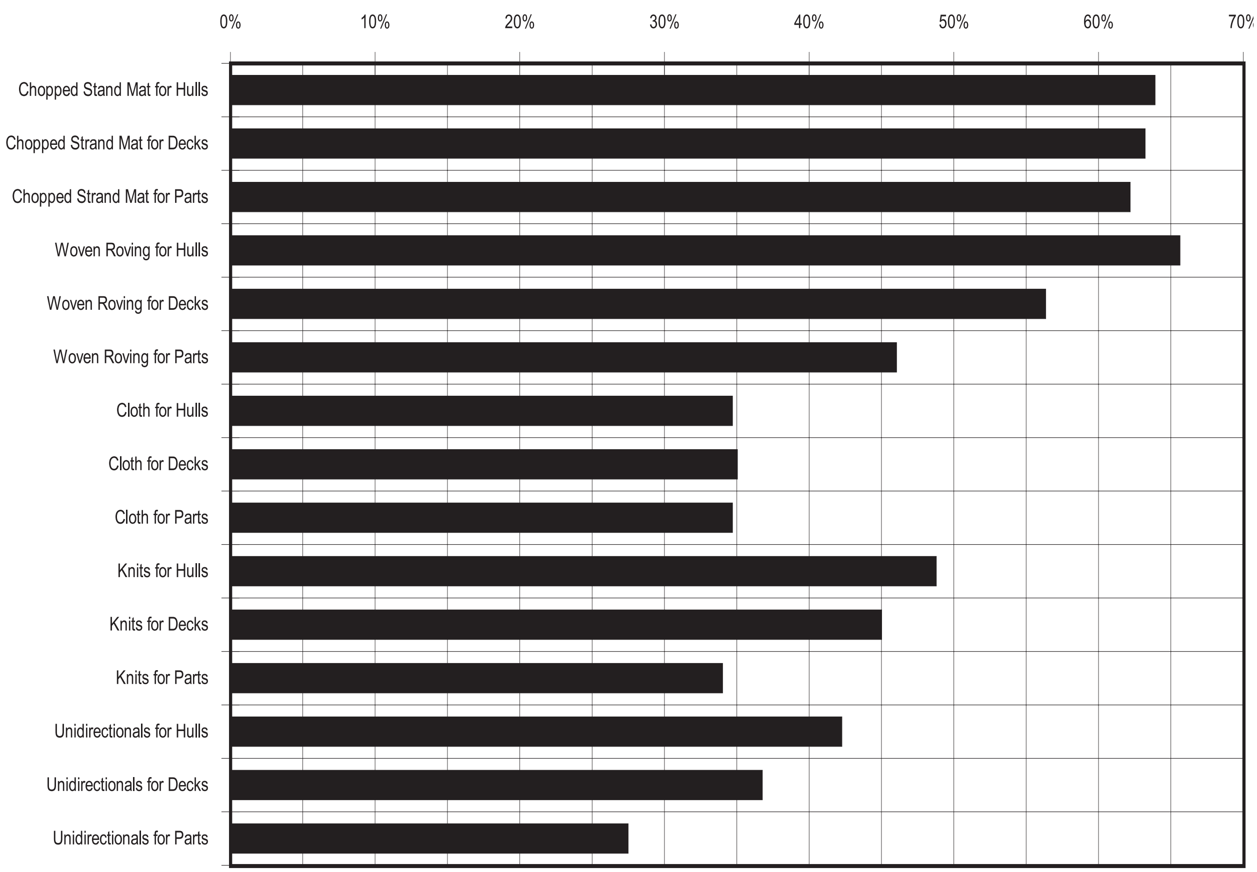


Figure 2-5 Marine Industry Reinforcement Style Use [EGA Survey]

Wovens

Woven composite reinforcements generally fall into the category of cloth or woven roving. The cloths are lighter in weight, typically from 6 to 10 ounces per square yard and require about 40 to 50 plies to achieve a one inch thickness. Their use in marine construction is limited to small parts and repairs. Particular weave patterns include plain weave, which is the most highly interlaced; basket weave, which has warp and fill yarns that are paired up; and satin weaves, which exhibit a minimum of interlacing. The satin weaves are produced in standard four-, five- or eight-harness configurations, which exhibit a corresponding increase in resistance to shear distortion (easily draped). Figure 2-2 shows some commercially available weave patterns.

Woven roving reinforcements consist of flattened bundles of continuous strands in a plain weave pattern with slightly more material in the warp direction. This is the most common type of reinforcement used for large marine structures because it is available in fairly heavy weights (24 ounces per square yard is the most common), which enables a rapid build up of thickness. Also, directional strength characteristics are possible with a material that is still fairly drapable. Impact resistance is enhanced because the fibers are continuously woven.

Knits

Knitted reinforcement fabrics were first introduced by Knytex® in 1975 to provide greater strength and stiffness per unit thickness as compared to woven rovings. A knitted reinforcement is constructed using a combination of unidirectional reinforcements that are stitched together with a nonstructural synthetic such as polyester. A layer of mat may also be incorporated into the construction. The process provides the advantage of having the reinforcing fiber lying flat versus the crimped orientation of woven roving fiber. Additionally, reinforcements can be oriented along any combination of axes. Superior glass to resin ratios are also achieved, which makes overall laminate costs competitive with traditional materials. Figure 2-4 shows a comparison of woven roving and knitted construction.

Omnidirectional

Omnidirectional 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. Continuous strand mat is similar to chopped strand mat, except that the fiber is continuous and laid down in a swirl pattern. 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. Mechanical properties are less than other reinforcements.

Unidirectional

Pure unidirectional construction implies no structural reinforcement in the fill direction. Ultra high strength/modulus material, such as carbon fiber, is sometimes used in this form due to its high cost and specificity of application. Material widths are generally limited due to the difficulty of handling and wet-out. Anchor Reinforcements has recently introduced a line of unidirectionals that are held together with a thermoplastic web binder that is compatible with thermoset resin systems. The company claims that the material is easier to handle and cut than traditional pure unidirectional material. Typical applications for unidirectionals include stem and centerline stiffening as well as the tops of stiffeners. Entire hulls are fabricated from unidirectional reinforcements when an ultra high performance laminate is desired.

Resins

Polyester

The percent of manufacturers using various resin systems is represented in Figure 2-6. Polyester resins are the simplest, most economical resin systems that are easiest to use and show good chemical resistance. Almost one half million tons of this material is used annually in the United States. Unsaturated polyesters consist of unsaturated material, such as maleic anhydride or fumaric acid, that is dissolved in a reactive monomer, such as styrene. Polyester resins have long been considered the least toxic thermoset to personnel, although recent scrutiny of styrene emissions in the workplace has led to the development of alternate formulations (see Chapter Five). Most polyesters are air inhibited and will not cure when exposed to air. Typically, paraffin is added to the resin formulation, which has the effect of sealing the surface during the cure process. However, the wax film on the surface presents a problem for secondary bonding or finishing and must be physically removed. Non-air inhibited resins do not present this problem and are therefore, more widely accepted in the marine industry.

The two basic polyester resins used in the marine industry are orthophthalic and isophthalic. The 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. The iso resins generally have better mechanical properties and show better chemical resistance. Their increased resistance to water permeation has prompted many builders to use this resin as a gel coat or barrier coat in marine laminates.

The rigidity of polyester resins can be lessened by increasing the ratio of saturated to unsaturated acids. Flexible resins may be advantageous for increased impact resistance, however, this comes at the expense of overall hull girder stiffness. Nonstructural laminate plies, such as gel coats and barrier veils, are sometimes formulated with more flexible resins to resist local cracking. On the other end of the spectrum are the low-profile resins that are designed to minimize reinforcement print-through. Typically, ultimate elongation values are reduced for these types of resins, which are represented by DCPD in Table 2-7.

Curing of polyester without the addition of heat is accomplished by adding accelerator along with the catalyst. Gel times can be carefully controlled by modifying formulations to match ambient temperature conditions and laminate thickness. The following combinations of curing additives are most common for use with polyesters:

Table 2-6 Polyester Resin Catalyst and Accelerator Combinations [Scott, *Fiberglass Boat Construction*]

Catalyst	Accelerator
Methyl Ethyl Keytone Peroxide (MEKP)	Cobalt Napthanate
Cuemene Hydroperoxide	Manganese Napthanate

Other resin additives can modify the viscosity of the resin if vertical or overhead surfaces are being laminated. This effect is achieved through the addition of silicon dioxide, in which case the resin is called thixotropic. Various other fillers are used to reduce resin shrinkage upon cure, a useful feature for gel coats.

Vinyl Ester

Vinyl ester resins are unsaturated resins prepared by the reaction of a monofunctional unsaturated acid, such as methacrylic or acrylic, with a bisphenol diepoxide. The resulting polymer is mixed with an unsaturated monomer, such as styrene. 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, and excellent physical properties, such as impact and fatigue resistance. It has been shown that a 20 to 60 mil layer with a vinyl ester resin matrix can provide an excellent permeation barrier to resist blistering in marine laminates.

Epoxy

Epoxy resins are a broad family of materials that contain a reactive functional group in their molecular structure. 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. Table 2-7 shows some comparative data for various thermoset resin systems.

Table 2-7 Comparative Data for Some Thermoset Resin Systems (castings)

Resin	Barcol Hardness	Tensile Strength psi x 10^3	Tensile Modulus psi x 10^5	Ultimate Elongation	1990 Bulk Cost $/lb
Orthophthalic Atlas P 2020	42	7.0	5.9	.91%	.66
Dicyclopentadiene (DCPD) Atlas 80-6044	54	11.2	9.1	.86%	.67
Isophthalic CoRezyn 9595	46	10.3	5.65	2.0%	.85
Vinyl Ester Derakane 411-45	35	11-12	4.9	5-6%	1.44
Epoxy Gouegon Pro Set 125/226	86D*	7.96	5.3	7.7%	4.39
*Hardness values for epoxies are traditionally given on the “Shore D” scale					+

Thermoplastics

Thermoplastics have one- or two-dimensional molecular structures, as opposed to three-dimensional structures for thermosets. The thermoplastics generally come in the form of molding compounds that soften at high temperatures. Polyethylene, polystyrene, polypropylene, polyamides and nylon are examples of thermoplastics. Their use in the marine industry has generally been limited to small boats and recreational items. Reinforced thermoplastic materials have recently been investigated for the large scale production of structural components. Some attractive features include no exotherm upon cure, which has plagued filament winding of extremely thick sections with thermosets, and enhanced damage tolerance. Processability and strengths compatible with reinforcement material are key areas currently under development.

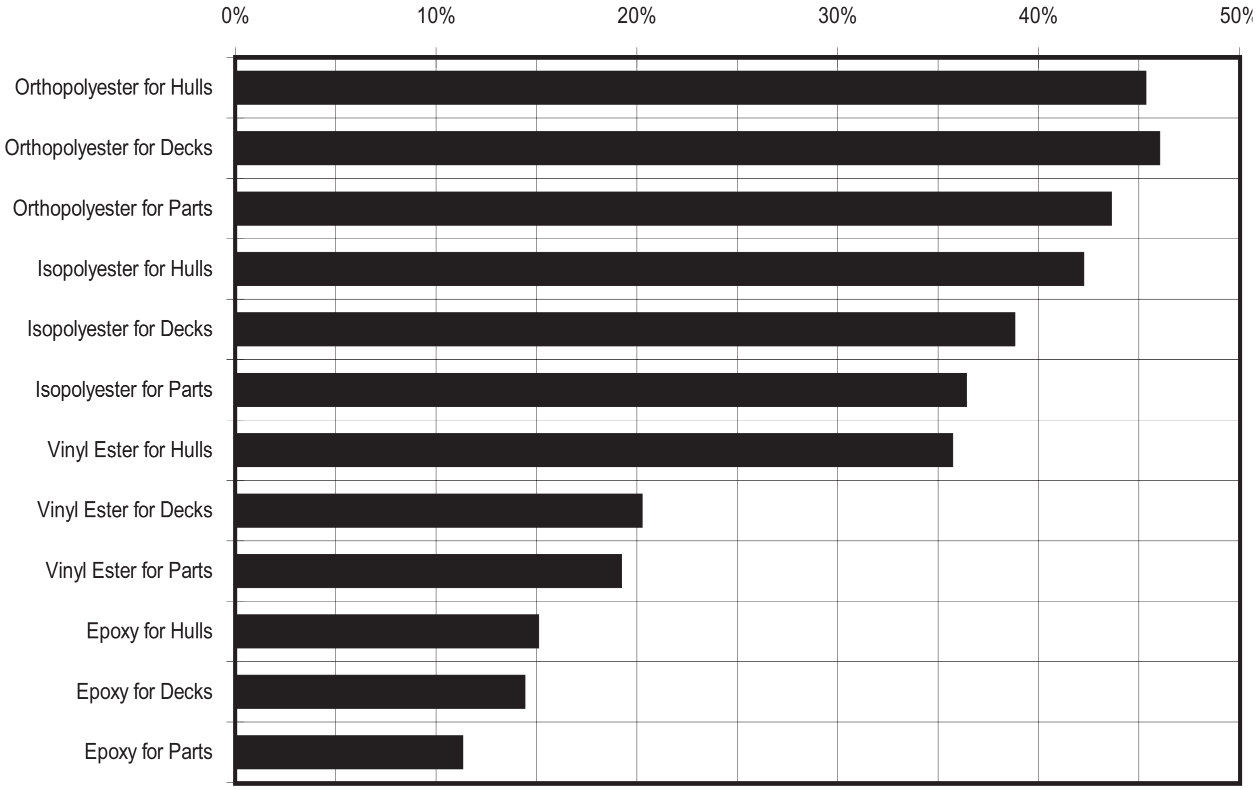


Figure 2-6 Marine Industry Resin System Use [EGA Survey]

Core Materials

Balsa

End grain balsa's closed-cell structure consists of elongated, prismatic cells with a length (grain direction) that is approximately sixteen times the diameter (see Figure 2-7). In densities between 6 and 16 pounds ft^3 (0.1 and 0.25 gms/cm^3), the material exhibits excellent stiffness and bond strength. Stiffness and strength characteristics are much like aerospace honeycomb cores Although the static strength of balsa panels will generally be higher than the PVC foams, impact energy absorption is lower. Local impact resistance is very good because stress is efficiently transmitted between sandwich skins. End-grain balsa is available in sheet form for flat panel construction or in a scrim-backed block arrangement that conforms to complex curves.

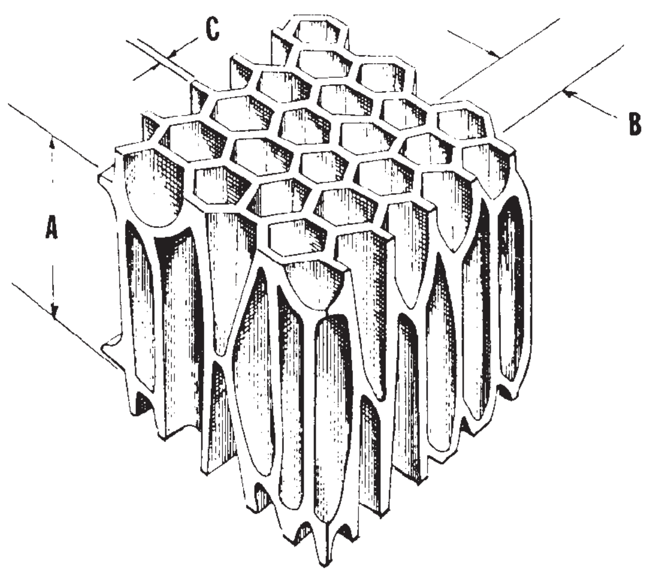


Figure 2-7 Balsa Cell Geometry with **A** = Average Cell Length = .025"; **B** = Average Cell Diameter = .00126"; **C** = Average Cell Wall Thickness = .00006" [Baltek Corporation]

Thermoset Foams

Foamed plastics such as cellular cellulose acetate (CCA), polystyrene, and polyurethane are very light (about 2 lbs/ft^3) and resist water, fungi and decay. These materials have very low mechanical properties and polystyrene will be attacked by polyester resin. These foams will not conform to complex curves. Use is generally limited to buoyancy rather than structural applications. Polyurethane is often foamed in-place when used as a buoyancy material.

Syntactic Foams

Syntactic foams are made by mixing hollow microspheres of glass, epoxy and phenolic into fluid resin with additives and curing agents to form a moldable, curable, lightweight fluid mass. Omega Chemical has introduced a sprayable syntactic core material called SprayCore™. The company claims that thicknesses of 3⁄8" can be achieved at densities between 30 and 43 lbs/ft^3. The system is being marketed as a replacement for core fabrics with superior physical properties. Material cost for a square foot of 3⁄8" material is approximately $2.20.

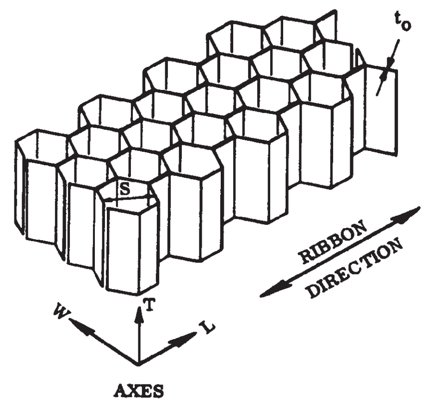


Figure 2-8 Hexagonal Honeycomb Geometry [MIL-STD-401B]

Cross Linked PVC Foams

Polyvinyl foam cores are manufactured by combining a polyvinyl copolymer with stabilizers, plasticizers, cross-linking compounds and blowing agents. The mixture is heated under pressure to initiate the cross-linking reaction and then submerged in hot water tanks to expand to the desired density. Cell diameters range from .0100 to .100 inches (as compared to .0013 inches for balsa). [2-2] The resulting material is thermoplastic, enabling the material to conform to compound curves of a hull. PVC foams have almost exclusively replaced urethane foams as a structural core material, except in configurations where the foam is "blown" in place. A number of manufacturers market cross-linked PVC products to the marine industry in sheet form with densities ranging from 2 to 12 pounds per ft^3. As with the balsa products, solid sheets or scrim backed block construction configurations are available.

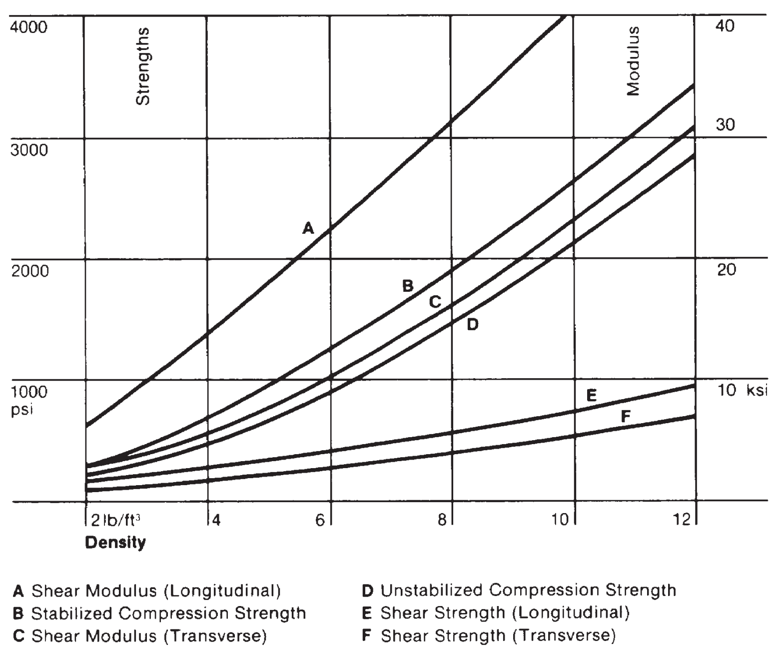


Figure 2-9 Core Strengths and Moduli for Various Core Densities of Aramid Honeycomb [Ciba-Geigy]

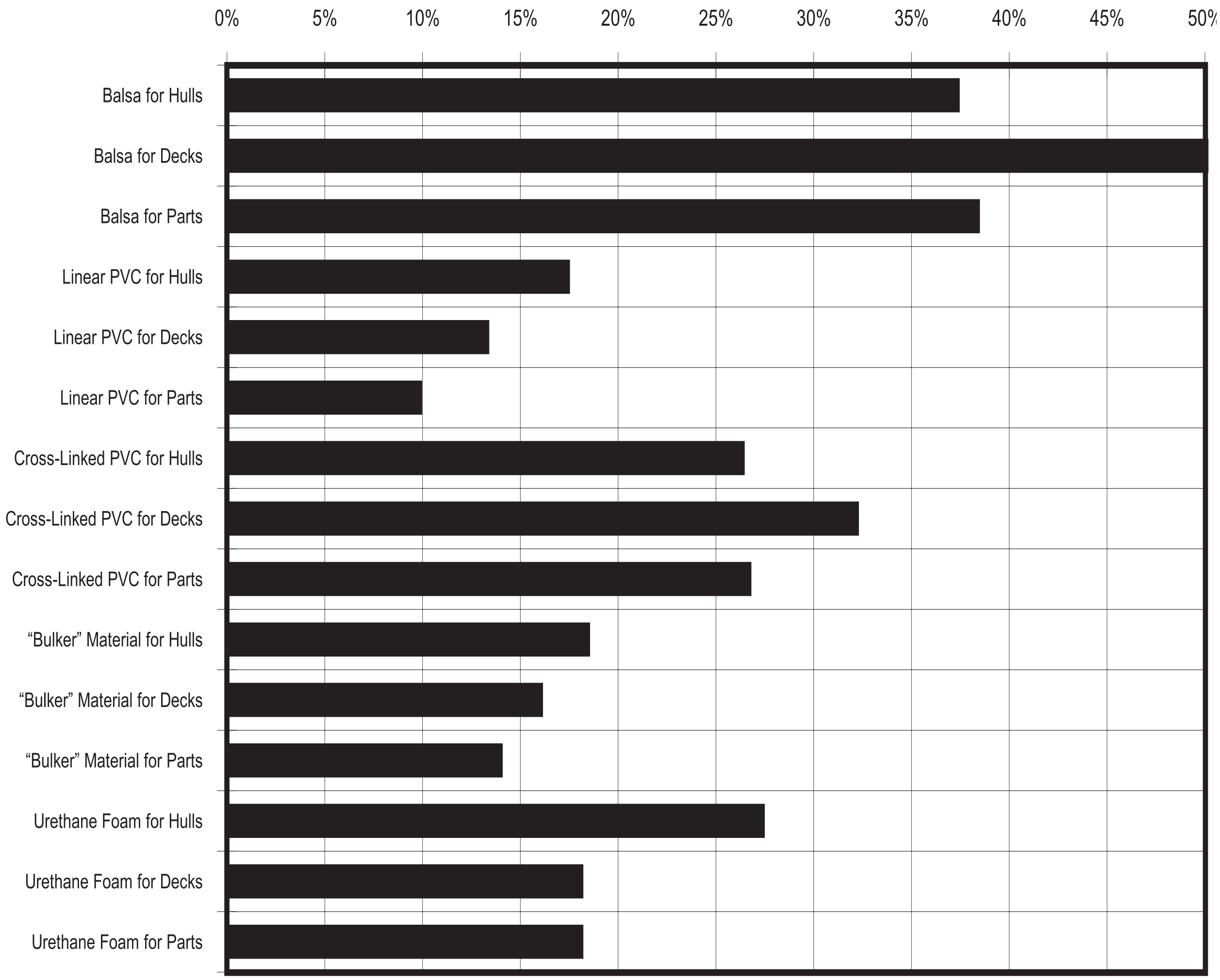


Figure 2-10 Marine Industry Core Material Use [EGA Survey]

Linear PVC Foam

Airex® and Core-Cell® are examples of linear PVC foam core produced for the marine industry. Unique mechanical properties are a result of a non-connected molecular structure, which allows significant displacements before failure. In comparison to the cross linked (non-linear) PVCs, static properties will be less favorable and impact will be better. For Airex,® individual cell diameters range from .020 to .080 inches. [2-3] Table 2-8 shows some of the physical properties of the core materials presented here.

Honeycomb

Various types of manufactured honeycomb cores are used extensively in the aerospace industry. Constituent materials include aluminum, phenolic resin impregnated fiberglass, polypropylene and aramid fiber phenolic treated paper. Densities range from 1 to 6 lbs/ft^3 and cell sizes vary from ⅛ to ⅜ inches. [2-4] Physical properties vary in a near linear fashion with density, as illustrated in Figure 2-9. Although the fabrication of extremely lightweight panels is possible with honeycomb cores, applications in a marine environment are limited due to the difficulty of bonding to complex face geometries and the potential for significant water absorption. The Navy has had some corrosion problems when an aluminum honeycomb core was used for ASROC housings. Data on a Nomex® phenolic resin honeycomb product is presented in Table 2-8.

PMI Foam

Rohm Tech, Inc. markets a polymrthacrylimide (PMI) foam for composite construction called Rohacell®. The material requires minimum laminating pressures to develop good peel strength. The most attractive feature of this material is its ability to withstand curing temperatures in excess of 350°F, which makes it attractive for use with prepreg reinforcements. Table 2-8 summarizes the physical properties of a common grade of Rohacell®.

Table 2-8 Comparative Data for Some Sandwich Core Materials

Core Material		Density		Tensile Strength		Compressive Strength		Shear Strength		Shear Modulus	
		lbs/ft^3	g/cm^3	psi	Mpa	psi	Mpa	psi	Mpa	psi x 10^3	Mpa
End Grain Balsa		7	112	1320	9.12	1190	8.19	314	2.17	17.4	120
		9	145	1790	12.3	1720	11.9	418	2.81	21.8	151
Cross-Linked PVC Foam	Termanto, C70.75	4.7	75	320	2.21	204	1.41	161	1.11	1.61	11
	Klegecell II	4.7	75	175	1.21	160	1.10			1.64	11
	Divinycell H-80	5.0	80	260	1.79	170	1.17	145	1.00	4.35	30
	Termanto C70.90	5.7	91	320	2.21	258	1.78	168	1.16	2.01	13
	Divinycell H-100	6.0	96	360	2.48	260	1.79	217	1.50	6.52	45
Linear Structural Foam	Core-Cell	3-4	55	118	0.81	58	0.40	81	0.56	1.81	12
		5-5.5	80	201	1.39	115	0.79	142	0.98	2.83	20
		8-9	210	329	2.27	210	1.45	253	1.75	5.10	35
Airex Linear PVC Foam		5-6	80-96	200	1.38	125	0.86	170	1.17	2.9	29
PMI Foam	Rohacell 71	4.7	75	398	2.74	213	1.47	185	1.28	4.3	30
	Rohacell 100	6.9	111	493	3.40	427	2.94	341	2.35	7.1	49
Phenolic Resin Honeycomb		6	96	n/a	n/a	1125	7.76	200	1.38	6.0	41
Polypropylene Honeycomb		4.8	77	n/a	n/a	218	1.50	160	1.10	n/a	n/a

FRP Planking

Seemann Fiberglass, Inc. developed a product called C-Flex® in 1973 to help amateurs build a cost effective one-off hull. The planking consists of rigid fiberglass rods held together with unsaturated strands of continuous fiberglass rovings and a light fiberglass cloth. The self-supporting material will conform to compound curves. Typical application involves a set of male frames as a form. The planking has more rigidity than PVC foam sheets, which eliminates the need for extensive longitudinal stringers on the male mold. A ⅛ inch variety of C-Flex® weighs about ½ pound dry and costs about $2.00 per square foot.

Core Fabrics

Various natural and synthetic materials are used to manufacture products to build up laminate thickness economically. One such product that is popular in the marine industry is Firet Coremat, a spun-bound polyester produced by Lantor. Hoechst Celanese has recently introduced a product called Trevira®, which is a continuous filament polyester. The continuous fibers seem to produce a fabric with superior mechanical properties. Ozite produces a core fabric called Compozitex™ from inorganic vitreous fibers. The manufacturer claims that a unique manufacturing process creates a mechanical fiber lock within the fabric. Although many manufacturers have had much success with such materials in the center of the laminate, the use of a Nonstructural thick ply near the laminate surface to eliminate print-through requires engineering forethought. The high modulus, low strength ply can produce premature cosmetic failures. Other manufacturers have started to produce "bulking" products that are primarily used to build up laminate thickness. Physical properties of core fabric materials are presented in Table 2-9.

Table 2-9 Comparative Data for Some "Bulking" Materials (impregnated with polyester resin to manufacturers' recommendation)

Material	Type	Dry Thickness inches	Cured Density lb/ft²	Tensile Strength psi	Compressive Strength psi	Shear Strength psi	Flexural Modulus psi x 10³	Cost $/ft²
Coremat®	4mm	.157	37-41	551	3191	580	130	.44
Trevira®	Core 100	.100	75	2700	17700	1800	443	.28
Baltek®Mat	T-2000	.098	40-50	1364	—	1364	—	.31
Tigercore®	TY-3	.142	35	710	3000	1200	110	.44
Compozitex™	3mm	.118			Not tested			.35

Plywood

Plywood should also be mentioned as a structural core material, although fiberglass is generally viewed as merely a sheathing when used in conjunction with plywood. Exceptions to this characterization include local reinforcements in way of hardware installations where plywood replaces a lighter density core to improve compression properties of the laminate. Plywood is also sometimes used as a form for longitudinals, especially in way of engine mounts. Concern over the continued propensity for wood to absorb moisture in a maritime environment, which can cause swelling and subsequent delamination, has precipitated a decline in the use of wood in conjunction with FRP. Better process control in the manufacture of newer marine grade plywood should diminish this problem. The uneven surface of plywood can make it a poor bonding surface. Also, the low strength and low strain characteristics of plywood can lead to premature failures when used as a core with thin skins.

The technique of laminating numerous thin plies of wood developed by the Gougeon Brothers and known as wood epoxy saturation technique (WEST® System) eliminates many of the shortcomings involved with using wood in composite structures.

Composite Material Concepts

The marine industry has been saturated with the concept that we can build stronger and lighter vehicles through the use of composite materials. This may be true, but only if the designer fully understands how these materials behave. Without this understanding, material systems cannot be optimized and indeed can lead to premature failures. Wood construction requires an understanding of timber properties and joining techniques. Metal construction also involves an understanding of material specific properties and a knowledge of weld geometry and techniques. Composite construction introduces a myriad of new material choices and process variables. This gives the designer more design latitude and avenues for optimization. With this opportunity comes the greater potential for improper design.

Early fiberglass boats featured single-skin construction with laminates that contained a high percentage of resin. Because these laminates were not as strong as those built today and because builders' experience base was limited, laminates tended to be very thick, made from numerous plies of fiberglass reinforcement. These structures were nearly isotropic (properties similar in all directions parallel to the skin) and were very forgiving. In most cases, boats were overbuilt from a strength perspective to minimize deflections. With the emergence of sandwich laminates featuring thinner skins, the need to understand the structural response of laminates and failure mechanisms has increased.

Reinforcement and Matrix Behavior

The broadest definition of a composite material involves filamentary reinforcements supported in a matrix that starts as a liquid and ends up a solid via a chemical reaction. The reinforcement is designed to resist the primary loads that act on the laminate and the resin serves to transmit loads between the plies, primarily via shear. In compression loading scenarios, the resin can serve to "stabilize" the fibers for in-plane loads and transmit loads via direct compression for out-of-plane loads.

Mechanical properties for dry reinforcements and resin systems differ greatly. As an example, E-glass typically has a tensile strength of 500×10^3 psi (3.45 Gpa) and an ultimate elongation of 4.8%. An iso polyester resin typically has a tensile strength of 10×10^3 psi (69 Mpa) and an ultimate elongation of 2%. As laminates are stressed near their ultimate limits, resin systems generally fail first. The designer is thus required the ensure that a sufficient amount of reinforcement is in place to limit overall laminate stress. Contrast this to a steel structure, which may have a tensile yield strength of 70×10^3 psi (0.48 Gpa), an ultimate elongation of 20% and stiffnesses that are an order of magnitude greater than "conventional" composite laminates.

Critical to laminate performance is the bond between fibers and resin, as this is the primary shear stress transfer mechanism. Mechanical and chemical bonds transmit these loads. Resin formulation, reinforcement sizing, processing techniques and laminate void content influence the strength of this bond.

Directional Properties

With the exception of chopped strand mat, reinforcements used in marine composite construction utilize bundles of fibers oriented in distinct directions. Whether the reinforcements are aligned in a single direction or a combination thereof, the strength of the laminate will vary depending on the direction of the applied force. When forces do not align directly with reinforcement fibers, it is necessary for the resin system to transmit a portion of the load.

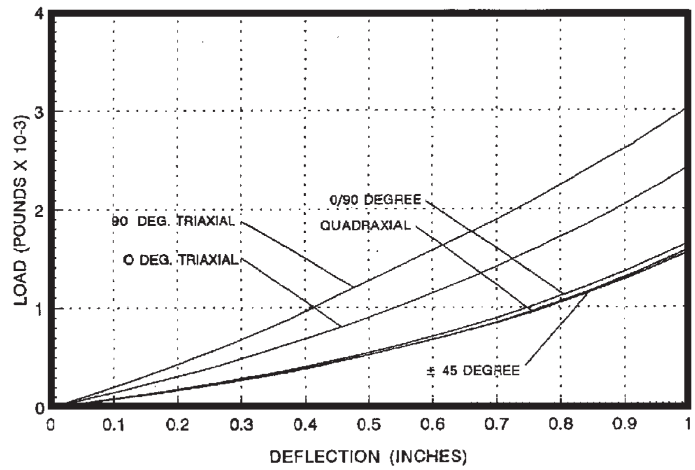


Figure 2-11 Comparison of Various Fiber Architectures Using the Hydromat Panel Tester on 3:1 Aspect Ratio Panels [Knytex]

“Balanced” laminates have a proportion of fibers in 0° and 90° directions. Some newer reinforcement products include ±45° fibers. Triaxial knits have ±45° fibers, plus either 0° or 90° fibers. Quadraxial knits have fibers in all four directions. Figure 2-11 illustrates the response of panels made with various knit fabrics subjected to out-of-plane loading.

Design and Performance Comparison with Metallic Structures

A marine designer with experience using steel or aluminum for hull structure will immediately notice that most composite materials have lower strength and stiffness values than the metal alloys used in shipbuilding. Values for strength are typically reported as a function of cross sectional area (ksi or Gpa). Because composite materials are much lighter than metals, thicker plating can be used. Figure 2-12 illustrates a comparison of specific strengths and stiffnesses (normalized for density) for selected structural materials. Because thicker panels are used for composite construction, panel stiffness can match or exceed that of metal hulls. Indeed, frame spacing for composite vessels is often much greater. For a given strength, composite panels may be quite a bit more flexible, which can lead to in-service deflections that are larger than for metal hulls. Figure 2-13 shows the effect of utilizing sandwich construction.

The above discussion pertains to panel behavior when resisting hydrostatic and wave slamming loads. If the structure of a large ship in examined, then consideration must be given to the overall hull girder bending stiffness. Because structural material cannot be located farther from the neutral axis (as is the case with thicker panels), the overall stiffness of large ships is limited when quasi-isotropic laminates are used. This has led to concern about main propulsion machinery alignment when considering construction of FRP ships over 300 feet (91 meters) in length. With smaller, high performance vessels, such as racing sailboats, longitudinal stiffness is obtained through the use of longitudinal stringers, 0° unidirectional reinforcements, or high modulus materials, such as carbon fiber.

Damage and failure modes for composites also differ from metals. Whereas a metal grillage will transition from elastic to plastic behavior and collapse in its entirety, composite panels will fail one ply at a time, causing a change in strength and stiffness, leading ultimately to catastrophic failure. This would be preceded by warning cracks at ply failure points. Crack propagation associated with metals typically does not occur with composites. Interlaminar failure between successive plies is much more common. This scenario has a much better chance of preserving watertight integrity.

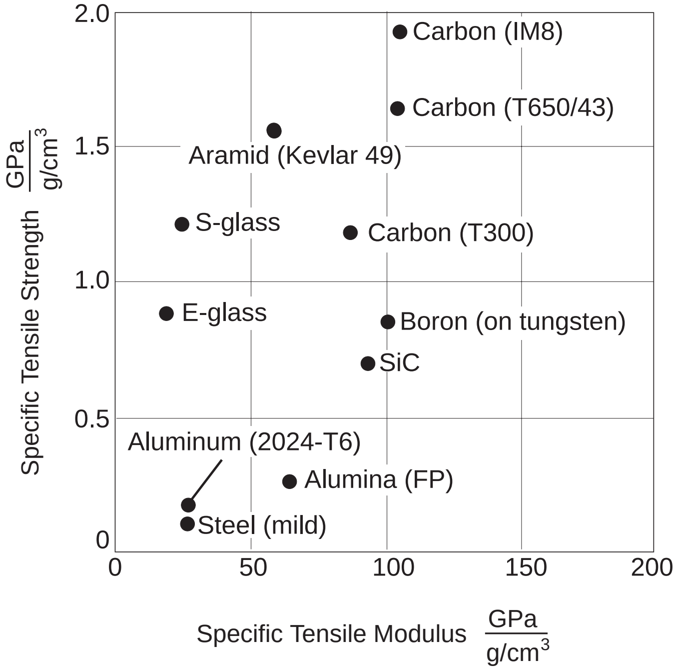


Figure 2-12 Specific Strength and Stiffness of Various Construction Materials [DuPont]

Because composite laminates do not exhibit the classic elastic to plastic stress-strain behavior that metals do, safety factors based on ultimate strength are generally higher, especially for compressive failure modes. Properly designed composite structures see very low stress levels in service, which in turn should provide a good safety margin for extreme loading cases.

Many design and performance factors make direct comparison between composites and metals difficult. However, it is instructive to compare some physical properties of common shipbuilding materials. Table 2-10 provides a summary of some constituent material characteristics.

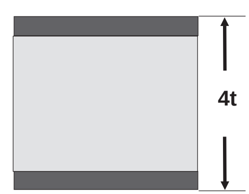
	 t	 2t	 4t
Relative Stiffness	100	700	3700
Relative Strength	100	350	925
Relative Weight	100	103	106

Figure 2-13 Strength and Stiffness for Cored and Solid Construction [Hexcel, The Basics on Sandwich Construction]

Table 2-10 Overview of Shipbuilding Construction Materials

	Material	Density		Tensile Strength		Tensile Modulus		Ultimate Elongation	1995 Cost
		lbs/ft^3	gm/cm^3	psi x 10^3	Mpa	psi x 10^6	Gpa	%	$/lb
Resins	Orthophthalic Polyester	76.7	1.23	7	48.3	.59	4.07	1	1.05
	Isophthalic Polyester	75.5	1.21	10.3	71.1	.57	3.90	2	1.19
	Vinyl Ester	69.9	1.12	11-12	76-83	.49	3.38	4-5	1.74
	Epoxy (Gougeon Proset)	74.9	1.20	7-11	48-76	.53	3.66	5-6	3.90
	Phenolic	71.8	1.15	5.1	35.2	.53	3.66	2	1.10
Fibers	E-Glass (24 oz WR)	162.4	2.60	500	3450	10.5	72.45	4.8	1.14
	S- Glass	155.5	2.49	665	4589	12.6	86.94	5.7	5.00
	Kevlar® 49	90	1.44	525	3623	18	124.2	2.9	20.00
	Carbon-PAN	109.7	1.76	350-700	2415-4830	33-57	227-393	0.38-2.0	12.00
Cores	End Grain Balsa	7	0.11	1.320	9.11	.370	2.55	n/a	3.70
	Linear PVC (Airex R62.80)	5-6	.08-0.1	0.200	1.38	0.0092	0.06	30	5.20
	Cross-Linked PVC (Diab H-100)	6	0.10	0.450	3.11	0.0174	0.12	n/a	5.95
	Honeycomb (Nomex® HRH-78)	6	0.10	n/a	n/a	0.0600	0.41	n/a	13.25
	Honeycomb (Nidaplast H8PP)	4.8	0.08	n/a	n/a	n/a	n/a	n/a	.80
Laminates	Solid Glass/Polyester *hand lay-up*	96	1.54	20	138	1.4	9.66	n/a	2.50
	Glass/Polyester Balsa Sandwich *vacuum assist*	24	0.38	6	41	0.4	2.76	n/a	4.00
	Glass/Vinyl Ester PVC Sandwich *SCRIMP*®	18	0.29	6	41	0.4	2.76	n/a	5.00
	Solid Carbon/Epoxy *filament wound*	97	1.55	88	607	8.7	60	n/a	10.00
	Carbon/Epoxy Nomex Sandwich *prepreg*	9	0.14	9	62	0.5	3.45	n/a	20.00
Metals	ABS Grd A (ASTM 131)	490.7	7.86	58	400	29.6	204	21	0.29
	ABS Grd AH (ASTM A242)	490.7	7.86	71	490	29.6	204	19	0.34
	Aluminum (6061-T6)	169.3	2.71	45	310	10.0	69	10	2.86
	Aluminum (5086-H34)	165.9	2.66	44	304	10.0	69	9	1.65
Wood	Douglas Fir	24.4	0.39	13.1	90	1.95	13.46	n/a	1.97
	White Oak	39.3	0.63	14.7	101	1.78	12.28	n/a	1.07
	Western Red Cedar	21.2	0.34	7.5	52	1.11	7.66	n/a	2.26
	Sitka Spruce	21.2	0.34	13.0	90	1.57	10.83	n/a	4.48

Note: The values used in this table are for illustration only and should not be used for design purposes. In general, strength is defined as yield strength and modulus will refer to the material's initial modulus. A core thickness of 1" with appropriate skins was assumed for the sandwich laminates listed.

Material Properties and Design Allowables

Although it is often difficult to predict the loads that will act on a structure in the marine environment, it is equally difficult to establish material property data and design allowables that will lead to a well engineered structure. It is first important to note that "attractive" property data for a reinforcement as presented in Figure 2-12, may apply only to fibers. Designers always need to use data on laminates, which include fibers and resin manufactured in a fashion similar to the final product.

The aerospace design community typically has material property data for unidirectional reinforcements according to the notation in Figure 2-14, while the marine industry uses the notation of Figure 2-15. Because of extreme safety and weight considerations, the aerospace industry has made considerable investment to characterize relevant composite materials for analytical evaluation. Unfortunately, these materials are typically carbon/epoxy prepregs, which are seldom used in marine construction. The best that a marine designer can expect is primary plane (1-2) data. Most available test data is in the primary or "1" axis direction. The type of data that exists, in decreasing order of availability/reliability is: Tensile, Flexural, Compressive, Shear, Poisson's Ratio.

Test data is difficult to get for compression and shear properties because of problems with test fixtures and laminate geometries. Data that is generated usually shows quite a bit of scatter. This must be kept in mind when applying safety factors or when developing design allowable physical property data.

It should be noted that stiffness data or modulus of elasticity values are more repeatable than strength values. As many composite material design problems are governed by deflection rather than stress limits, strength criteria and published material properties should be used with caution.

The type of loading and anticipated type of failure generally determines which safety factors are applied to data derived from laboratory testing of prototype laminates. If the loading and part geometry are such that long term static or fatigue loads can produce a dynamic failure in the structure, a safety factor of 4.0 is generally applied. If loading is transient, such as with slamming, or the geometry is such that gradual failure would occur, then a safety factor of 2.0 is applied. With once-in-a-lifetime occurrences, such as underwater explosions for military vessels, a safety factor of 1.5 is generally applied. Other laminate performance factors, such as moisture, fatigue, impact and the effect of holes influence decisions on design allowables.

Appendix A contains test data on a variety of common marine reinforcements tested with ASTM methods by Art Wolfe at Structural Composites, Inc.; Dave Jones at Sigma Labs; Tom Juska from the Navy's NSWC; and Rick Strand at Comtrex. In limited cases, data was supplied by material suppliers. Laminates were fabricated using a variety of resin systems and fabrication methods, although most were made using hand lay-up techniques. In general, test panels made on flat tables exhibit properties superior to as-built marine structures. Note that higher fiber content laminates will be thinner for the same amount of reinforcement used. This will result in higher mechanical values, which are reported as a function of cross sectional area. However, if the same amount of reinforcement is present in high- and low-fiber content laminates, they may both have the same "strength" in service. Indeed, the low-fiber content may have superior flexural strength as a result of increased thickness. Care must always be exercised in interpreting test data. Additionally, samples should be fabricated by the shop that will produce the final part and tested to verify minimum properties. As can be seen in Appendix A, complete data sets are not available for most materials. Where available, data is presented for properties measured in 0°, 90° and ±45° directions. Shear data is not presented due to the wide variety in test methods used. Values for Poission's ratio are seldom reported.

Cost and Fabrication

Material and production costs for composite marine construction are closely related. Typically, the higher cost materials will require higher-skilled labor and more sophisticated production facilities. The cost of materials will of course vary with market factors.

Material Costs

Table 2-10 provides an overview of material costs associated with marine composite construction. It is difficult to compare composite material cost with conventional homogeneous shipbuilding materials, such as wood or metals, on a pound-for-pound basis. Typically, an optimized structure made with composites will weigh less than a metallic structure, especially if sandwich techniques are used. Data in Table 2-10 is provided to show designers the relative costs for “common” versus “exotic” composite shipbuilding materials.

Production Costs

Production costs will vary greatly with the type of vessel constructed, production quantities and shipyard efficiency. Table 2-11 is compiled from several sources to provide designers with some data for performing preliminary labor cost estimates.

Table 2-11 Marine Composite Construction Productivity Rates

Source	Type of Construction	Application	Lbs/Hour*	Ft^2/Hour†	Hours/Ft^2‡
Scott *Fiberglass Boat Construction*	Single Skin with Frames	Recreational	20*	33†	.03‡
		Military	12*	20†	.05‡
	Sandwich Construction	Recreational	10*	17†	.06‡
		Military	6*	10†	.10‡
BLA *Combatant Feasibility Study*	Single Skin with Frames	Flat panel (Hull)	13**	22**	.05**
		Stiffeners & Frames	5**	9**	.12**
	Core Preparation for Sandwich Construction	Flat panel (Hull)	26**	43**	.02**
		Stiffeners	26**	43**	.02**
	Vacuum Assisted Resin Transfer Molding (VARTM)	Flat panel (Hull)	10§	43§	.02§
		Stiffeners	7§	14§	.07§

* Based on mat/woven roving laminate
** Based on one WR or UD layer
† Single ply of mat/woven roving laminate
‡ Time to laminate one ply of mat/woven roving (reciprocal of Ft^2/hr)
§ Finished single ply based on weight of moderately thick single-skin laminate

Design Optimization Through Material Selection

Composite materials afford the opportunity for optimization through combinations of reinforcements, resins, and cores. Engineering optimization always involves tradeoffs among performance variables. Table 2-12 is provided to give an overview of how constituent materials rank against their peers, on a qualitative basis. Combinations of reinforcement, resin and core systems may produce laminates that can either enhance or degrade constituent material properties.

Table 2-12 Qualitative Assessment of Constituent Material Properties

	Fiber			Resin					Core					
	E-Glass	Kevlar	Carbon	Polyester	Vinyl Ester	Epoxy	Phenolic	Thermoplastic	Balsa	Cross Link PVC	Linear PVC	Nomex/Alum Honeycomb	Thermoplastic Honeycomb	Syntactic Foam
Static Tensile Strength	■	■	■	□	□	■	□	□	■	■	■	□	□	□
Static Tensile Stiffness	□	■	■	□	□	□	□	□	■	□	□	■	□	□
Static Compressive Strength	■	□	□	□	□	□	□	□	■	□	■	■	□	□
Static Compressive Stiffness	□	□	■	□	□	□	□	□	■	□	□	■	□	□
Fatigue Performance	□	■	■	□	■	■	□	■	■	□	■	□	■	□
Impact Performance	■	■	□	□	■	■	□	■	□	■	■	□	□	□
Water Resistance	■	□	□	□	■	■	□	■	□	■	■	□	□	□
Fire Resistance	■	□	□	□	□	□	■	□	■	□	□	■	□	□
Workability	■	□	□	■	□	□	□	□	■	□	□	□	□	■
Cost	■	□	□	■	□	□	□	■	■	□	□	□	■	■

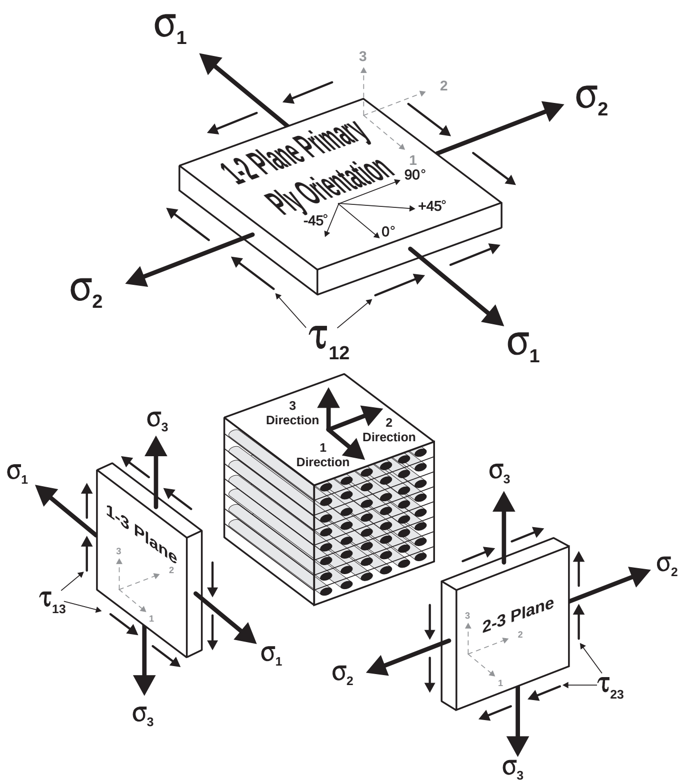
■ Good Performance
□ Fair Performance

Figure 2-14
Lamina

A lamina is a single ply (unidirectional) in a laminate, which is made up of a series of layers.

The illustration to the right depicts composite lamina notation used to describe applied stresses. The notation for primary ply axes is also presented.

The accompanying table denotes the strength and stiffness data used to characterize composite laminae based on this geometric description.



Stiffness	1	Longitudinal	Tensile Modulus E_1^t		Compressive Modulus	E_1^c
	2	Transverse	Tensile Modulus E_2^t		Compressive Modulus	E_2^c
	3	Thickness	Tensile Modulus E_3^t		Compressive Modulus	E_3^c
	12	Longitudinal/ Transverse		Shear Modulus	G_{12}	
	13	Longitudinal/ Thickness		Shear Modulus	$G_{13} = G_{12}$	
	23	Transverse/ Thickness		Shear Modulus	$G_{23} = E_2 / [2(1+\nu_{23})]$	
Strength	1	Longitudinal	Tensile Strength $\sigma_1^{t\ ult}$		Compressive Strength	$\sigma_1^{c\ ult}$
	2	Transverse	Tensile Strength $\sigma_2^{t\ ult}$		Compressive Strength	$\sigma_2^{c\ ult}$
	3	Thickness	Tensile Strength $\sigma_3^{t\ ult}$		Compressive Strength	$\sigma_3^{c\ ult}$
	12	Longitudinal/ Transverse		Shear Strength	τ_{12}^{ult}	
	13	Longitudinal/ Thickness		Shear Strength	$\tau_{13}^{ult} = \tau_{12}^{ult}$	
	23	Transverse/ Thickness		Shear Strength	τ_{23}^{ult}	

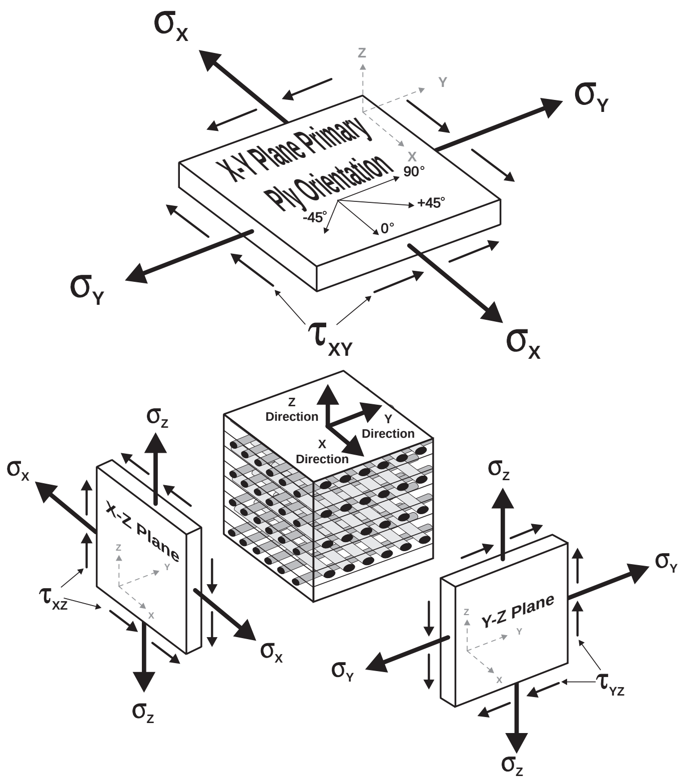
Poisson's Ratio				
Direction:	12 (Major)	21 (Minor)	31	23
Notation:	ν_{12}^t, ν_{12}^c	ν_{21}^t, ν_{21}^c	ν_{31}^t, ν_{31}^c	ν_{23}^t, ν_{23}^c

Figure 2-15
Laminate

A laminate consists of multiple layers of lamina with unique orientations.

The illustration to the right depicts composite laminate notation used to describe applied stresses. The notation for primary ply axes is also presented.

The accompanying table denotes the strength and stiffness data used to characterize composite laminates based on this geometric description.



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