Marine Composites
Webb Institute
Senior Elective
Spring, 2013

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

Marine Composites
Composite Material Concepts

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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

Material comes into the shipyard with properties predetermined

Composites take form at the shipyard, dependent on fabrication methods and worker skill
The strength of composite fibers are dramatically reduced as the angle to the applied load is increased.
Effect of Fiber Angle

Effect on Modulus of Fiber Angle for Unidirectional E-glass

Effect on Strength of Fiber Angle for Unidirectional E-glass

Strength and Stiffness Characteristics

Specific Strength and Stiffness

- Carbon (IM8)
- Carbon (T650/43)
- Aramid (Kevlar 49)
- S-glass
- Carbon (T300)
- E-glass
- Boron (on tungsten)
- SiC
- Aluminum (2024-T6)
- Alumina (FP)
- Steel (mild)

Stress/Strain Behavior

- Toray T300 Composite
- Kevlar 49 Composite
- E-glass Composite
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
### Laminate Mechanical Properties

#### Stiffness

<table>
<thead>
<tr>
<th>Direction</th>
<th>Tensile Modulus</th>
<th>Compressive Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>$E_x^t$</td>
<td>$E_x^c$</td>
</tr>
<tr>
<td>Y</td>
<td>$E_y^t$</td>
<td>$E_y^c$</td>
</tr>
<tr>
<td>Z</td>
<td>$E_z^t$</td>
<td>$E_z^c$</td>
</tr>
<tr>
<td>XY</td>
<td>Shear Modulus $G_{xy}$</td>
<td></td>
</tr>
<tr>
<td>XZ</td>
<td>Shear Modulus $G_{xz}$</td>
<td></td>
</tr>
<tr>
<td>YZ</td>
<td>Shear Modulus $G_{yz}$</td>
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</table>

#### Strength

<table>
<thead>
<tr>
<th>Direction</th>
<th>Tensile Strength</th>
<th>Compressive Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>$\sigma_x^{ult}$</td>
<td>$\sigma_x^{ult}$</td>
</tr>
<tr>
<td>Y</td>
<td>$\sigma_y^{ult}$</td>
<td>$\sigma_y^{ult}$</td>
</tr>
<tr>
<td>Z</td>
<td>$\sigma_z^{ult}$</td>
<td>$\sigma_z^{ult}$</td>
</tr>
<tr>
<td>XY</td>
<td>Shear Strength $\tau_{xy}^{ult}$</td>
<td></td>
</tr>
<tr>
<td>XZ</td>
<td>Shear Strength $\tau_{xz}^{ult}$</td>
<td></td>
</tr>
<tr>
<td>YZ</td>
<td>Shear Strength $\tau_{yz}^{ult}$</td>
<td></td>
</tr>
</tbody>
</table>

#### Poisson's Ratio

<table>
<thead>
<tr>
<th>Direction</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>XY (Major)</td>
<td>$\nu_{xy}^t$ $\nu_{xy}^c$</td>
</tr>
<tr>
<td>YX (Minor)</td>
<td>$\nu_{yx}^t$ $\nu_{yx}^c$</td>
</tr>
<tr>
<td>ZX</td>
<td>$\nu_{zx}^t$ $\nu_{zx}^c$</td>
</tr>
<tr>
<td>YZ</td>
<td>$\nu_{yz}^t$ $\nu_{yz}^c$</td>
</tr>
</tbody>
</table>
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)
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.]

Material Engineering, May, 1978 p. 29
Micro-scale Fiber/Resin Interface

Laminate Failure

• The key criterion for composite failure is the local strain to failure: $\varepsilon'$ a.k.a. elongation at break and not stress (note that $\varepsilon'$ for the fiber/matrix interface i.e. transverse fibers $\equiv 0.25 \%$)

• Matrix cracking:
  • polyester resin $\varepsilon' = 0.9-4.0 \%$
  • vinyl ester $\varepsilon' = 1.0-4.0 \%$
  • epoxy resin $\varepsilon' = 1.0-3.5 \%$
  • phenolic resin $\varepsilon' = 0.5-1.0 \%$

• Fiber fracture:
  • S/R-glass $\varepsilon' = 4.6-5.2 \%$
  • E-glass $\varepsilon' = 3.37 \%$
  • Kevlar 49 $\varepsilon' = 2.5 \%$
  • HS-carbon $\varepsilon' = 1.12 \%$
  • UHM-carbon $\varepsilon' = 0.38$

John Summerscales, University of Plymouth, Oct. 2006
Elastic Properties

- **Young’s moduli** - uniaxial stress/uniaxial 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**

\[
\nu = - \left( \text{strain normal to the applied stress} \right) / \left( \text{strain parallel to the applied stress} \right)
\]

\[-1 < \nu < \frac{1}{2}\]

**Orthotropic: \( \nu_{ij} \)**

Maxwell’s reciprocal theorem

\[
\nu_{12} E_2 = \nu_{21} E_1
\]

Lemprière constraint

\[
\nu_{ij} \leq \left( \frac{E_i}{E_j} \right)^{1/2} \quad \text{and} \quad \nu_{21} \nu_{23} \nu_{13} < \frac{1}{2}
\]

<table>
<thead>
<tr>
<th></th>
<th>UD C1</th>
<th>UD C1</th>
<th>WR A2</th>
<th>WR A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_{12} )</td>
<td>0.308</td>
<td>1.606</td>
<td>0.140</td>
<td>0.942</td>
</tr>
<tr>
<td>( \nu_{21} )</td>
<td>0.123</td>
<td>0.623</td>
<td>0.109</td>
<td>1.061</td>
</tr>
<tr>
<td>( \nu_{13} )</td>
<td>0.354</td>
<td>1.687</td>
<td>0.408</td>
<td>1.285</td>
</tr>
<tr>
<td>( \nu_{31} )</td>
<td>0.124</td>
<td>0.593</td>
<td>0.247</td>
<td>0.778</td>
</tr>
<tr>
<td>( \nu_{23} )</td>
<td>0.417</td>
<td>1.051</td>
<td>0.380</td>
<td>1.364</td>
</tr>
<tr>
<td>( \nu_{32} )</td>
<td>0.414</td>
<td>0.952</td>
<td>0.297</td>
<td>0.733</td>
</tr>
</tbody>
</table>

John Summerscales, University of Plymouth, Oct. 2006
Shear and Bulk Modulus

<table>
<thead>
<tr>
<th></th>
<th>Shear Modulus</th>
<th>Bulk Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Isotropic</strong></td>
<td>$G = \frac{E}{2(1+\nu)}$</td>
<td>$K = \frac{E}{3(1-2\nu)}$</td>
</tr>
<tr>
<td><strong>Orthotropic</strong></td>
<td>$G_{12} = \frac{\sqrt{E_x E_y}}{2(1+\sqrt{\nu_{xy} \nu_{yx}})}$</td>
<td>$K = \frac{3\sqrt{E_x E_y E_z}}{3\left(1-2.3\sqrt{\nu_{xy} \nu_{xz} \nu_{yz}}\right)}$</td>
</tr>
</tbody>
</table>

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.
Isotropy Property Influence

Specific Strength versus Specific Modulus


Quasi-isotropic Laminates

- Laminates are often described by an orientation code.
- Example: \([0/-45/90/+45/0/0/+45/90/-45/0]\)
- Short hand: \([0/-45/90/+45]_S\)
- Short hand: \([0/-45/90/+45]_N\)
- Other Examples: \([0/+45/-45/90]_2S\)
  \([0_2/+45/-45/90]_S\)
  \([0_U/+45_{CL}]\)

Mechanical Behavior of Orthotropic Materials

Three Young’s moduli $E_1, E_2, E_3$, Poisson’s ratios $\nu_{12}, \nu_{13}, \nu_{23}$, 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

$$
\begin{bmatrix}
\sigma_{11} & \sigma_{12} & \sigma_{13} \\
\sigma_{21} & \sigma_{22} & \sigma_{23} \\
\sigma_{31} & \sigma_{32} & \sigma_{33}
\end{bmatrix}
$$

$\sigma_{ij}$ where ($i$ and $j = 123$)

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

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Orthotropic Elastic Properties

Orthorhombic nine independent

\[ E_1 \quad G_{13} \quad \nu_{31} \]
\[ E_2 \quad G_{12} \quad \nu_{21} \]
\[ E_3 \quad G_{23} \quad \nu_{32} \]

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

\[
\begin{align*}
G & = \frac{E}{2(1+\nu)} \\
K & = \frac{2G\nu}{1-2\nu} + G \\
\text{Hence:} & \quad E_3, \quad E_1 = E_2 \\
\text{five independent} & \quad G_{23} = G_{13}, \quad G_{12} \\
\nu_{32} & = \nu_{31}, \quad \nu_{21}
\end{align*}
\]

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 $V_c = (1 - V_f)$. 

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

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

$$E_c = E_m V_m + E_f V_f$$

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

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

Composite part design, manufacture and support

Requirements Concepts

Material systems and processes

Preliminary Design

Specify Ply/Grid/Zone for Laminate

Design

Define laminate (plies), including:
- Sequence
- Drop offs

Manufacturing

Define manuf. design

Support

Health monitoring & Repair

Verify Design data According to Stress/Design/Manufacturing constraints

Simulate productivity

Manuf and Tests

P1 Priority 1

P2 Priority 2

P3 Priority 3

P4 Priority 4

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

<table>
<thead>
<tr>
<th>Hand Layup</th>
<th>Spray-up</th>
<th>Resin Infusion</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Hand Layup Diagram" /></td>
<td><img src="image2.png" alt="Spray-up Diagram" /></td>
<td><img src="image3.png" alt="Resin Infusion Diagram" /></td>
</tr>
</tbody>
</table>

**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](http://www.netcomposites.com)
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.

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°.

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.

www.netcomposites.com

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## Manufacturing Metrics

<table>
<thead>
<tr>
<th>Manufacturing Process</th>
<th>Labor Content</th>
<th>Cycle Time, minutes</th>
<th>Production Quantity Potential</th>
<th>Product Surface Area, m²</th>
<th>Typical Mold Cost</th>
<th>Typical Equipment Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Layup</td>
<td>very high</td>
<td>100-1500</td>
<td>1-400</td>
<td>.1-1,000</td>
<td>$2,000</td>
<td>$100</td>
</tr>
<tr>
<td>Spray-up</td>
<td>high</td>
<td>60-500</td>
<td>5-1500</td>
<td>.1-100</td>
<td>$2,000</td>
<td>$15,000</td>
</tr>
<tr>
<td>Resin Infusion</td>
<td>high</td>
<td>80-800</td>
<td>1-200</td>
<td>.1-1,000</td>
<td>$2,000</td>
<td>$2,000</td>
</tr>
<tr>
<td>Prepregs (autoclave)</td>
<td>very high</td>
<td>100-1500</td>
<td>1-200</td>
<td>.2-100</td>
<td>$5,000</td>
<td>$400,000</td>
</tr>
<tr>
<td>Pultrusion</td>
<td>low</td>
<td>n/a</td>
<td>10,000-1,000,000 meters</td>
<td>n/a</td>
<td>$10,000</td>
<td>$250,000</td>
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<tr>
<td>Filament Winding</td>
<td>moderate</td>
<td>40-650</td>
<td>1-100</td>
<td>.1-50</td>
<td>$2,000</td>
<td>$50,000</td>
</tr>
</tbody>
</table>
Manufacturing Method Trade-Offs

Contact moulding

Vac bag/autoclave

Filament winding

RTM

Pultrusion

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

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Composite Material Concepts
Takeaway Summary

• Composite materials are the combination of reinforcement and thermostet 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