CHAPTER 15

COMPOSITES

A composite is simply a thing made up of different elements. Reinforced concrete, for instance, is a composite of steel rebar and concrete. They used to build "composite" wooden boats, with iron frames. Typically when the word "composite" is used today, it relates to some type of fiber reinforced polymer.

15.1 Fiber Reinforced Polymers

Fiber Reinforced Polymers are a composite material made of a polymer matrix that is reinforced with fibers.

The matrix is a resin that holds the fibers together. Three commonly used resins are:

- Epoxy – Strong and flexible to resist cracking. This resin is good for FRP-wood construction, in which the swelling and shrinking of the wood can cause delamination
- Polyester – This is very low cost, but somewhat more brittle than epoxy.
- Vinylester – This is in between epoxy and polyester for cost and performance.

The reinforcing fibers also vary, including

- Glass – inexpensive "fiberglass" Available in different types, like E-glass (standard) and S-glass (with higher strength)
- Carbon Fiber – Very high tensile strength, and high modulus of elasticity (stiffness)
- Kevlar – Similar tensile strength to carbon fiber, but more deflection

15.2 What are Polymers?

The matrix, or resin that holds the fibers together is made of polymers. Polymers are "repeating chains of organic material." A mer is the basic unit and there are many of them in a repeating structure. Natural polymers include wood, rubber, wool, leather and methane. Man-made polymers are made from small organic molecules and include plastic, rubber and fibers. Figure 1 represents a simple polymer. Because of the connection details, the polymer can bend in 3 dimensions.

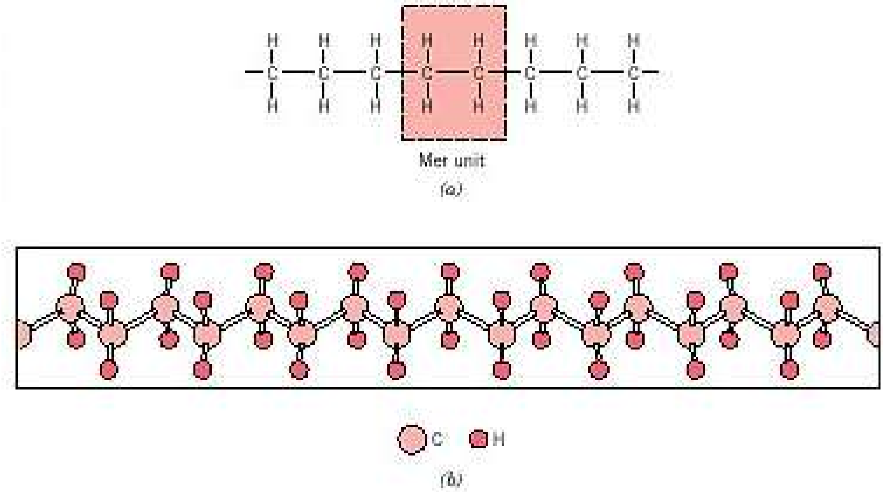

Figure 1: Notional Hydrocarbon

Polymers form very large molecules because of the repeating structure. The carbon atom is the backbone of the polymer. The average molecular weight of a polymer changes the melting temperature. For instance:

$\overline{M} < 100 \frac{g}{mole}$ Liguid/Gas

$\overline{M} \approx 1000 \frac{g}{mole}$ Waxy solids

$\overline{M} \approx 10^4 to 10^6 \frac{g}{mole}$ Solids (high polymers)

Figure 2 shows a typical polymer chain. The intertwining gives it elastic properties.

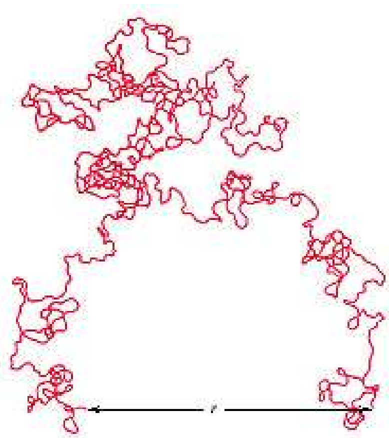

Figure 2: Typical Polymer Chain

Unlike metals, polymers do not create completely crystalline structures. There may be regions of crystallinity, along with amorphous regions. These variations affect how hard the structure is. Figure 3 shows the structure of a polymer solid.

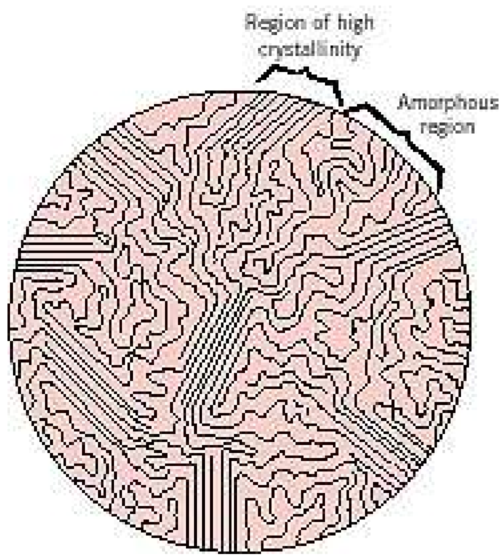

Figure 3: Crystalline and Amorphous structures of Polymers

15.3 FRP Fiber Orientation

can be varied, meaning composites are not isotropic. The strength can be increased in the direction needed by the design. Fiber can come in the following orientations:

- Chopper Gun – These are short fibers that are sprayed onto the inside of the mold along with the resin. This is the lowest strength-to-weight ratio, but the cheapest (many production boats are made this way)
- Chopped Strand Mat – This is like a roll of cloth, but with randomly oriented strands.
- Bi-axial – comes in a roll with two directions. Can be laid up “on the bias” at 45 degrees as well.
- Uni-axial – Strength in one-direction

Figure 4: Laying up a fiberglass boat with a chopper gun (Fibers and resin are sprayed on)

Figure 5: Chopped Strand Mat

Figure 6: Woven Roving – Bi-Axial

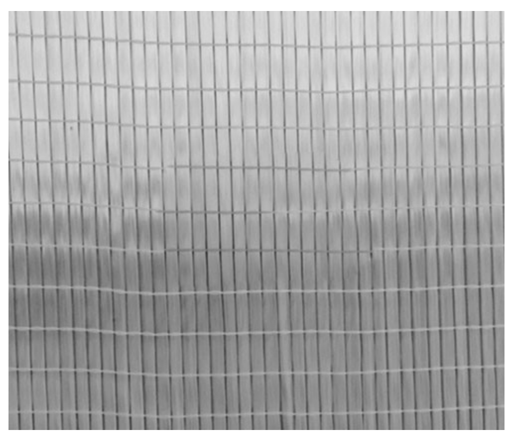

Figure 7:Uniaxial Fibers

15.4 FRP Fabrication

For production boats, pools, hot tubs, etc, there is generally a female mold with a smooth interior surface.

- They first spray it with a **release agent** to keep the hull from sticking to the mold.

- Then they spray on "**gel coat**" which is a hard shiny surface that you see on the outside of the boat or the inside of the hot tub.
- If the boat is cheap (like most) then they get the **chopper gun** and spray. The inside will then be very rough.
- More expensive **hand layup** requires a layer of **chopped strand mat** first, so that the bi-axial fibers don't "**print through**." Then generally they alternate **woven roving** and chopped strand mat for each subsequent layer (this keeps the woven parts from bunching up and leaving voids).
- In specialized custom design boats, like racing yachts, they will use **uniaxial** fibers to increase the strength in particular directions. This requires careful design and understanding of the loads.
- Hulls sometimes include a **core** material so that there is strong fiberglass on the outside and the inside, with a core to space them apart. This increases the moment of inertia and hence the stiffness and strength.

Figure 8: Boat Molds in Shop

15.5 Vacuum Bagging

Once there is enough resin to bond the fibers together, more resin doesn't add strength. It costs money to buy and adds weight. As a result, efforts are sometimes taken to reduce the amount of resin in a particular layup. Vacuum bagging is used to put a suction over the layup to compress it and reduce the amount if resin. This works well, but increases the difficulty of the job. For very thin layups, it can sometimes result in pinhole leaks.

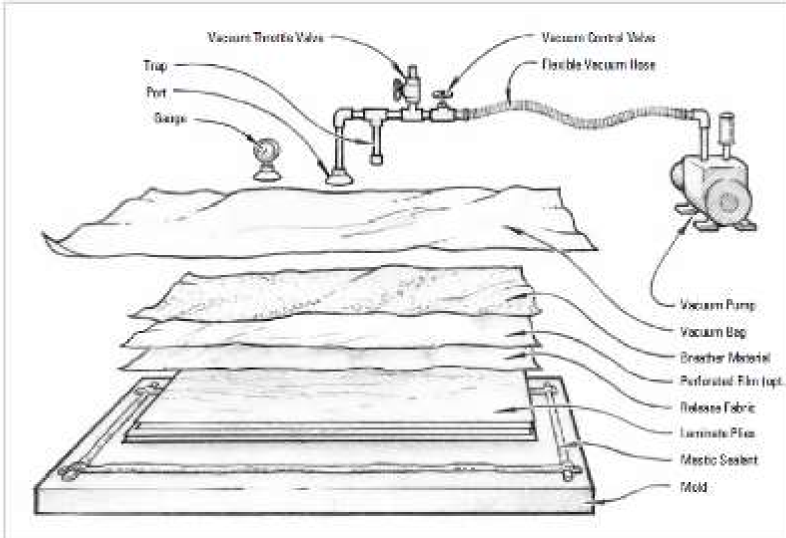

Figure 9: Vacuum Bagging (From Jamestown Distributers)

Figure 10: Small Vacuum Bagging Figure 11:Vacuum Bagging a Wind Turbine Blade

15.6 Mechanical Properties of FRP

The matrix and the fibers have different strengths and elasticity. When the forces are in the same direction as the fibers, assume isostrain – the fibers and the matrix elongate the same amount.

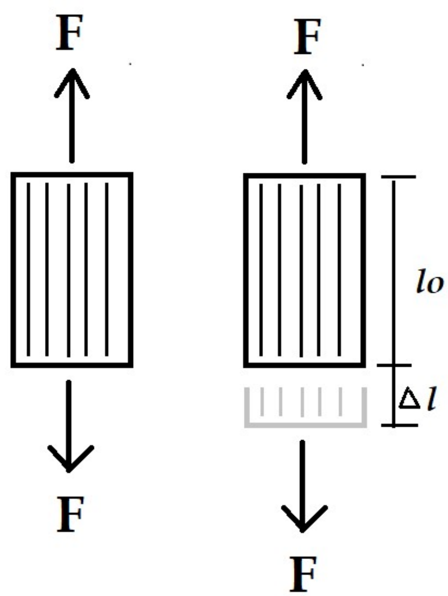

Figure 11: Elongation of Uni-axial Fiber

Using isostrain and the volume fraction of the fibers and matrix, we can use the Rule of Mixtures

$$E_{FRP} = E_M V_M + E_F V_F$$

Where, E_{FRP}, E_M, E_F is the modulus of elasticity of the FRP, the matrix and the fibers. V_M and V_F are the volume fractions of the matrix and the fibers.

$$V_M + V_F = 1$$

The ratio of the force carried by the fibers and the force carried by the matrix

$$\frac{F_F}{F_M} = \frac{E_F V_F}{E_M V_M}$$

Where, F_F and F_M = the force carried by the fibers and the matrix, in N or lb. The total load is then,

$$F_{FRP} = F_F + F_M$$

What if the loads are in the transverse direction? The fibers do not have significant strength in this direction, so it is not isostrain. Instead, assume isostress - -the same force per unit area.

$$E_{FRP-TRANSVERS} = \frac{E_M E_F}{E_M V_M + E_F V_F}$$

<u>Example 1a:</u> *A continuous uniaxial glass FRP has 40% by volume fibers ($E_F = 10 \times 10^6$ psi) in a polyester resin ($E_M = 0.5 \times 10^6$ psi). Compute the longitudinal elastic modulus of the composite.*

<u>*Answer*</u>

$$E_{FRP} = E_M V_M + E_F V_F$$

$$V_F = 0.4 \textit{ so } V_M = 1 - V_F = 0.6$$

$$E_{FRP} = 0.5 \times 10^6 psi \times 0.6 + 10 \times 10^6 psi \times 0.4 = 4.3 \times 10^6 psi$$

<u>Example 1b:</u> *If the cross-section area of the composite in the previous example of 0.4 square inches and a longitudinal stress of 7250 psi is applied, find the load carried by the fibers and by the matrix.*

<u>*Answer:*</u>

① load ratio $\frac{F_F}{F_m} = \frac{E_F V_F}{E_m V_m} = \frac{10 \cdot 10^6 psi \times 0.4}{0.5 \times 10^6 psi \times 0.6} = 13.3$

$$\boxed{F_F = 13.3 F_m}$$

② we also know that

$$F_{FRP} = F_F + F_m$$

$$\sigma_{FRP} A_{FRP} = F_F + F_m$$

$$7250 psi \times 0.4 in^2 = 13.3 F_m + F_m$$

$$2900 lb = 14.3 F_m \rightarrow \boxed{F_m = 202 lb}$$

$$\therefore F_F = 13.3 \times 202 lb = \boxed{2698 lb = F_F}$$

<u>Example 1c:</u> For the previous example, what is the strain sustained by each of the fibers and the matrix?

<u>Answer:</u>

① $E = \frac{\sigma}{\varepsilon} \Rightarrow \varepsilon = \frac{\sigma}{E} = \boxed{\varepsilon = \frac{F}{AE}}$

② $\varepsilon_{FRP} = \varepsilon_F = \varepsilon_m$

$$\therefore \varepsilon_{FRP} = \frac{F_{FRP}}{A_{FRP} E_{FRP}} = \varepsilon_F = \frac{F_F}{A_F E_F}$$

$A_F = V_F A_{FRP}$

$$\therefore \varepsilon = \frac{2900 \text{ lb}}{0.4 \text{ in}^2 \times 4.3 \times 10^6 \text{ psi}} = \underline{0.00169 \frac{\text{in}}{\text{in}}}$$

$$\varepsilon_F = \frac{F_F}{A_F E_F} = \frac{2{,}698 \text{ lb}}{(0.4 \times .4 \text{ in}^2) \times 10 \cdot 10^6 \text{ psi}} = \underline{\quad}$$

(0.4 = V_F)

<u>Example 1d:</u> What if we load in the transverse direction?

<u>Solution:</u>

a. Fibers do not have significant strength in this direction ⇒ <u>not</u> isostrain

b. instead assume isostress – same force per area

c. $$E_{FRP\,TRAN} = \frac{E_m E_F}{V_m E_F + V_F E_m}$$

d. For example:

$$E_{TRAN\,FRP} = \frac{0.5 \times 10^6 \text{ psi} \times 10 \times 10^6 \text{ psi}}{.6 \times 10 \cdot 10^6 \text{ psi} + 0.4 \times 0.5 \times 10^6 \text{ psi}}$$

$$\boxed{E_{TRAN\,FRP} = 0.81 \times 10^6 \text{ psi}}$$

(~20% of longitudinal modulus)

<u>Example 2:</u> For a uniaxial FRP that has a 50-50 ratio by volume of fibers ($E_F = 10 \times 10^6$ psi) in a polyester resin ($E_M = 0.5 \times 10^6$ psi).

a. Find the strain felt by the composite fibers and matrix if the applied force is 4500 lb and the total cross-section area is 0.6 sq inches.

(1) isostrain → $\varepsilon_{FRP} = \varepsilon_F = \varepsilon_m = \frac{\sigma}{E} = \frac{F}{AE}$

(a) $E_{FRP_{LON}} = E_F V_F + E_m V_m = 10 \cdot 10^6 psi \times 0.5 + 0.5 \times 10^6 psi \times 0.5$

$E_{FRP_{LON}} = 5.25 \times 10^6 psi$

(b) $\therefore \varepsilon_{FRP} = \frac{F_{FRP}}{A_{FRP} E_{FRP}} = \frac{4500 lb}{0.6 in^2 \times 5.25 \times 10^6 psi}$

$\varepsilon = 0.00143$ in/in

b. Find the load carried by the fibers in the matrix.

(2) (a) $\frac{F_F}{F_m} = \frac{E_F V_F}{E_m V_m} = \frac{10 \cdot 10^6 psi \times 0.5}{0.5 \times 10^6 psi \times 0.5} = 20 \rightarrow F_F = 20 F_m$

(b) $F_F + F_m = F_{FRP} = 4500 lb$

$21 F_m = 4500 \rightarrow$ $F_m = 214 lb$, $F_F = 4,286 lb$

c. The longitudinal elastic modulus of the composite

(3) ✓ $E_{FRP_{LON}} = 5.25 \times 10^6 psi$

d. The transverse elastic modulus of the composite.

(4) $E_{FRP_{TRAN}} = \frac{E_F E_m}{E_F V_m + E_m V_F} = \frac{10 \cdot 10^6 psi \times 0.5 \times 10^6 psi}{10 \cdot 10^6 psi \times 0.5 + 0.5 \times 10^6 psi \times 0.5}$

$E_{FRP_{TRAN}} = 0.95 \times 10^6 psi$

Note: $\frac{E_{LON}}{E_{TRAN}} = \frac{5.25 \cdot 10^6}{0.95 \cdot 10^6} = 5.5$