Fiber Reinforced Polymer Composites

MSE 383 Unit 3-5
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Scope

- **General Introduction**
  - composite constitutents
  - applications
- **Strength and Fracture: Analysis**
- **Composite design**
- **Fabrication of Composites (Unit 4)**

Learning Objectives

How properties of E, σ and fracture toughness of FRP's are explained and predicted

properties of fibers and matrix

fiber-matrix interface

pattern of orientation of the fibrous phase

Definition of a Composite

The combination of different, relatively homogenous materials to produce a heterogeneous materials to produce a heterogeneous material of a more complex structure displaying properties which none of its constituents can exhibit in isolation.

Composite Constituents

Matrix materials (thermoplastics & thermosetting resins)
Fibers (particulate or fibrous glass or carbon etc.)
Fiber-Matrix interface
Fiber orientation
Voids

Polymer Composites vs. Conventional Materials

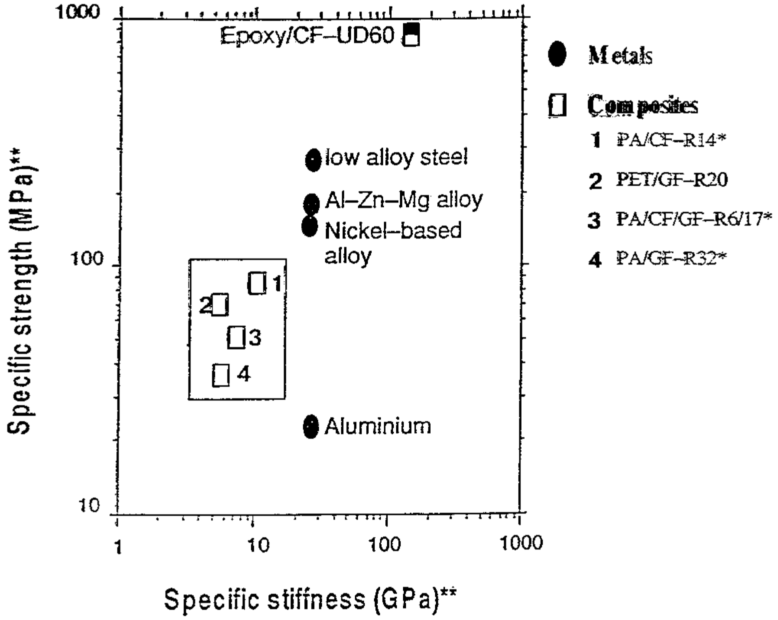
Lightweight
High specific stiffness and strength
High toughness
Corrosion resistant
High dimensional stability
Ease of fabrication
Tailorable mechanical and thermal properties

Applications of Composites

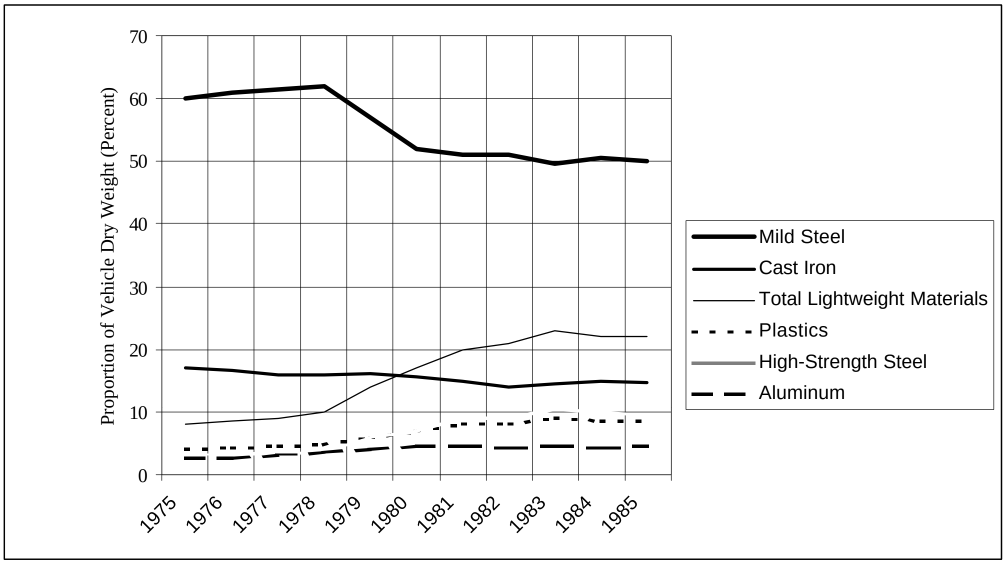
Aerospace (Carbon, Kevlar®, GF composites in nose cones, helicopter blades, body panels, etc.)
Automotive Engineering (GFRP in Pontiac Fiero, for instance, in front-end moldings, fascias, bumper back-up beams, etc.)
Bioengineering (CFRP in prosthetic applications such as orthopedic fracture fixation plates, Mandibular prosthesis, e.g., jaw remodeling)
Chemical Engineering (GFRP in chemical plant for pressure vessels, valves, etc.)
Structural/Civil Engineering (GRC in the building industry etc.)
Domestic (injection molded reinforced thermoplastics & polyester molding compounds in furniture, television, & computer casings, kitchen equipment, crash helmets, etc.)
Electrical Engineering (GFRP in high strength insulators, structural componenets for switch gear, etc.)
Marine Engineering (GFRP in pleasure craft, etc.)
Sport (CFRP & boron fiber composites in vaulting poles, tennis rackets, golf clubs, surf & skate boards, etc.)
ILLUSTRATE

Fiber Characteristics

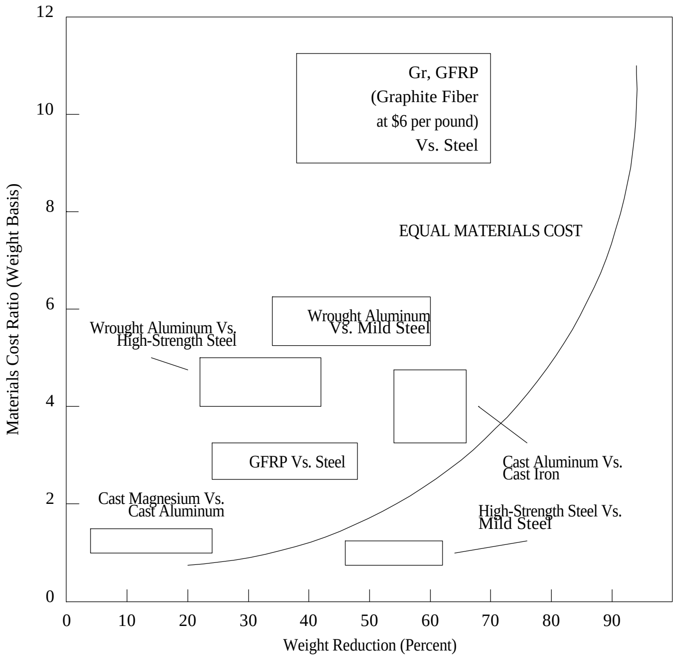
Inorganic Fibers and Whiskers (e.g., metal filaments and Al_2O_3 whiskers are used to reinforce metals)
High Modulus Organic Fibers (e.g., poly paraphenylene terephthalate - KEVLAR - are used in polymers)
SHOW TABLE



Comparison of specific stiffness and strength of some engineering materials
(*this work. other data taken from Hull (1981) and Piggott (1980): **unit of density is Mg/m^3)

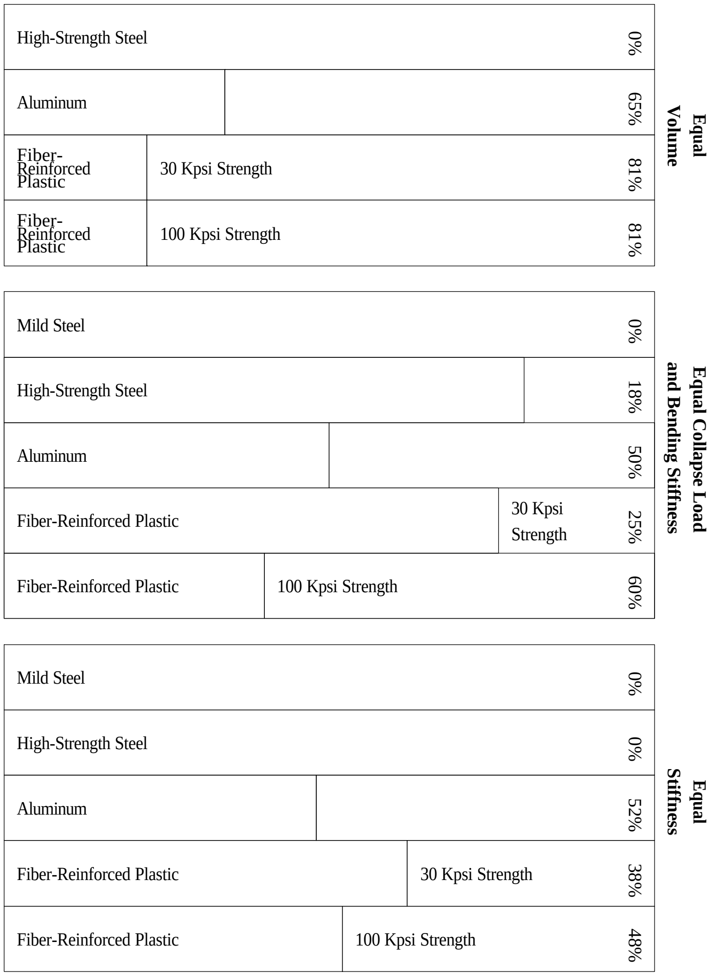


LIGHTWEIGHT MATERIALS CONTENT of the average U.S. vehicle has increased sharply since the mid-1970's. The data are for a sales-weighted average of the Ford U.S. passenger fleet. Plastics, aluminum and high-strength steel currently account for about a fourth of the dry weight of a Ford passenger car. These lightweight materials began supplanting cast iron and mild steel in U.S. vehicles about a decade ago. Manufacturers were then faced with the weight increases that resulted from technology adopted to meet Federal safety and emissions regulations and with rising fuel costs. In response they decreased the size of their vehicles and also increased the lightweight materials content.



COST OF SUBSTITUTING a lightweight material depends on the weight saving and the prices of the two materials. The horizontal axis shows the weight reduction made possible by each substitution and the vertical axis shows the cost of the lightweight material in relation to its conventional counterpart. (GFRP is plastic reinforced with glass fibers. Gr,GFRP is plastic reinforced with fibers of graphite and glass; the data for that material assume a cost for graphite fiber of $6 per pound, a third of its current cost.) For certain substitutions the two materials will be equal in cost. Most lightweight materials have not yet reached the break-even point; an exception is high-strength steel. In many instances, however, savings in processing and assembly costs for the lightweight material offset the additional cost of the material. The data were compiled by Magee.

Weight Savings (%)



Hypothetical aluminum part, the weight saving would be 56 percent. In neutral design situations the weight saving offered by the substitution of aluminum for cast iron ranges from 35 to 60 percent. Similarly, aluminum and fiber-reinforced plastics are much lighter than mild (ordinary) steel by volume. The weight savings, however, are much smaller if equal stiffness or equal collapse load and bending stiffness (a measure of structural strength) is needed. High-strength steel is no lighter by volume than mild steel, nor is it stiffer. Where structural strength is the main concern, however, high-strength steel does offer a weight saving: 18 percent in this example. The hypothetical examples in the illustration were developed by Christopher L. Magee of the Ford Motor Company.

Fiber Characteristics, Cont'd

Table 1: Lightweight Materials Weight Savings (%) (From Ford)

Material	Equal Stiffness	Equal Strength
Cast Iron	Base	Base
Cast Al	11	56
Cast Mg	9	64
SHEET		
Mild Steel	Base	Base
HS Steel	0	18
Aluminum	52	50
FRP	38	25
CrFRP	48	60

Successful application of reinforced polymers.

Fiber Characteristics, Cont'd

Table 2: Properties of carbon, glass and Kevlar 49 fibers at 20^{o}C

Property	Units	Carbon PAN-based Type 1	Carbon PAN-based Type II	E glass	Aromatic Polyamide Kevlar 49
Diameter	μm	7.0-9.7	7.6-8.6	8-14	11.9
Density	10^3 kg m^{-3}	1.95	1.75	0.56	1.45
Young's Modulus	GN m^{-2}	390	250	76	125
Modulus (perpendicular to fibre axis)	GN m^{-2}	12	20	76	
Tensile strength	GN m^{-2}	2.2	2.7	1.4 - 2.5 (typical) 3.5 (freshly drawn)	2.8 - 3.6
Elongation to fracture	%	0.5	1.0	1.8 - 3.2 (typical)	2.2 - 2.8
Coefficient of thermal expansion (0° to 100°C)	10^{-6} C^{-1}	-0.5 to -1.2 (parallel) 7-12 (radial)	-0.1 to -0.5 (parallel) 7-12 (radial)	4.9	-2 (parallel) 59 (radial)
Thermal conductivity (parallel to fibre axis)	Wm^{-1} C^{-1}	105	24	1.04	0.04

Notes:
1. Density of graphite single crystals is 2.26 x 10^3 kg m^{-3}.
2. Most of the information is obtained from manufacturer's data sheets; a wide range of values has been published and this information should only be used as a rough guide.

Commercially, E-glass fibers are the preferred reinforcing fibers for polymers because of their good strength, stiffness, electrical and weathering properties, and cost.

Usually supplied in the form of continuous rovings, woven rovings, CSM, continuous strand (swirl) mat and chopped rovings.

Matrix Materials & Their Functions in Composites

Thermosetting resins

e.g., unsaturated PET, phenolics, melamine, silicones, etc.

Thermoplastics

e.g., polyamides, PC, PP, SAN, acetals, etc.

Role of Matrix Materials in Composites?

Stress transfer medium
Fiber surface protection, in the case of glass
Prevents brittle failure of fibers

Voids

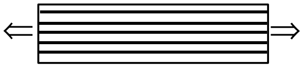
Spherical or elliptical cavities parallel to the fibers.
Voids between layers of fibers and in resin-rich regions ($0.005 \le V_v \le 0.02$)

$$V_v = \frac{W_c}{r_c} - \frac{(W_c - W_f)}{r_m} - \frac{W_f}{r_f}$$

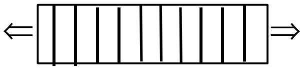
(Note: $V_f = 1 - V_m$ iff $V_v = 0$ or if negligible)

Fiber Orientation

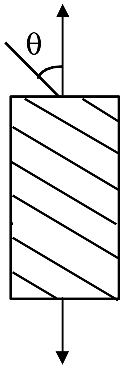
Most important microstructural feature of FRP
FRP are usually ANISOTROPIC



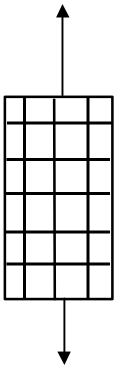
Unidirectional (K=1)



Perpendicular (K=0)



Transverse (K)

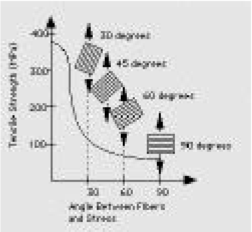


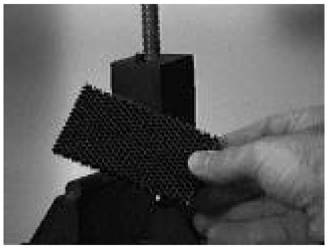
Bi-directional
[K_ε = 0.65 (stiffness)]
[K_σ = 0.30 (strength)]

$$K = \frac{1}{a_n} \sum_{i=1}^{n} a_i \cos^4 q$$

= 3/8 for planar - random fibers
= 1/5 for random fibers in 3 - dimensions

Fiber Orientation, Cont'd





Planar Isotropic Composites & ROM

Use random planar fiber mat
To first approximation

$$E_c = KV_fE_f + V_mE_m$$
$$\sigma_c = KV_f\sigma_f + V_m\sigma_m$$

(for perfect fiber - matrix adhesion)
Note: $V = \phi$ in class text. Derive later.

Cost of Composite

$$m_cC_c = C_fm_f + C_mm_m + C_im_c \text{ (\$ form } m_c\text{)}$$

It can be shown that (see class text):

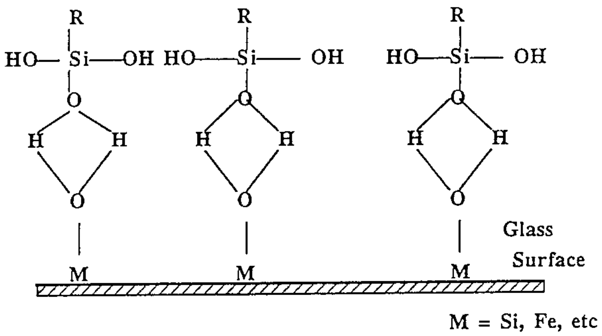
$$C_c = C_fV_f\,\rho_f/\rho_c + C_m(1-V_f)\,\rho_m/\rho_c + C_i \text{ (\$ / unit } m_c\text{)}$$

m = mass; C = cost; i = incorporation
c, f, m = composite, fiber, matrix

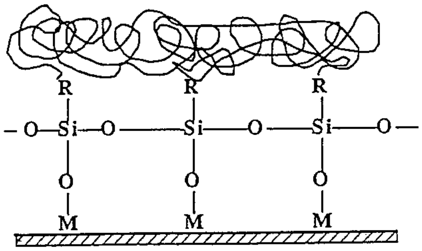
Interfacial Bonding Mechanism

(i) $RSi(OEt)_3 + 3H_2O \rightarrow RSi(OH)_3 + 3EtOH$

(ii)



(iii)



(i) Silanol Formation
(ii) H-Bond Formation
(iii) Polysiloxane & Polymer-Matrix Bond Formation

Usually a monolayer (0.1 – 0.5 wt %) is used. For optimum performance of composite, 1.5 wt % of coupling agent is used because of the imperfect availability of the coupling agent due to the surface geometry and impurities.

Role of “Sizing”

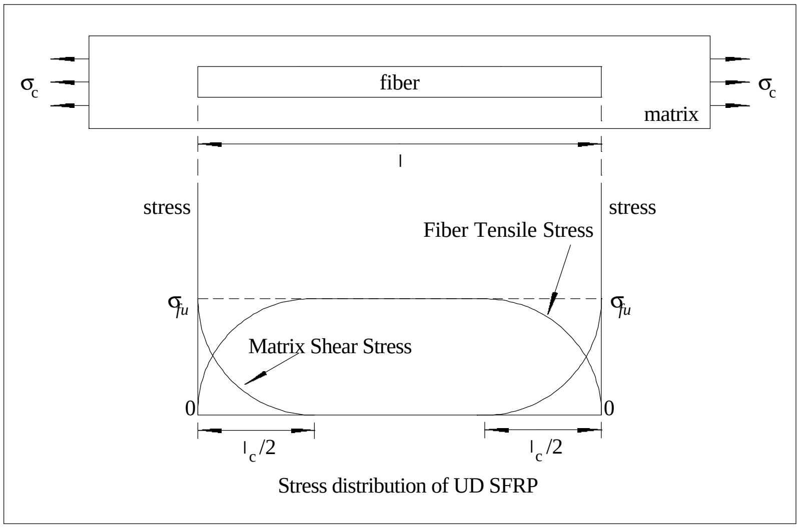
Usually contains coupling agent or adhesion promoter {e.g. $RSi(OEt)_3$}
promotes wetting between fibers and matrix
prevents fiber-fiber contact
protects fibers (especially glass) from corrosion during service

Interficial Bonding Mechanism

- *Illustrate*

Fiber - Matrix Interface

Physical, mechanical or chemical bond required for efficient load bearing capacity
Poor adhesion leads to fiber pull-out without breaking



Stress distribution of UD SFRP

Adhesion is less critical for E & σ than for toughness

As before

$E_c = a_{eff}V_fE_f + V_mE_m$
$\sigma_c = a_{eff}V_f\sigma_f + V_m\sigma_m$
(a_{eff} adhesion efficiency factor)
($a_{eff} = 1$ for perfect adhesion)

End of Lecture

Read Class text, Ch. 6
Optional additional reading
- >>Hull (1981)
- >>Piggott (1982)