Composite Materials, PhD

Week 1

INTRODUCTION to Composite Materials

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First Rule of Composite Materials

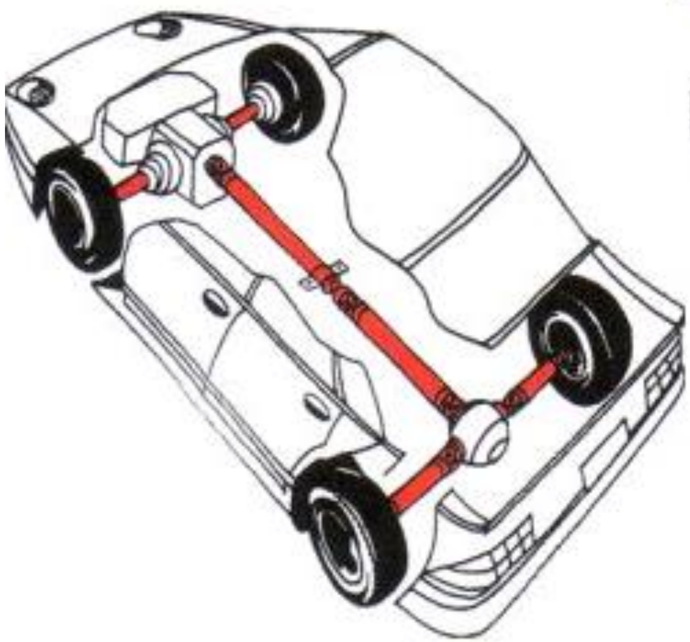
- *If you don't let a teacher know at what level you are - by asking a question, or revealing your ignorance - you will not learn or grow. You can't pretend for long, for you will eventually be found out. Admission of ignorance is often the first step in our education.*

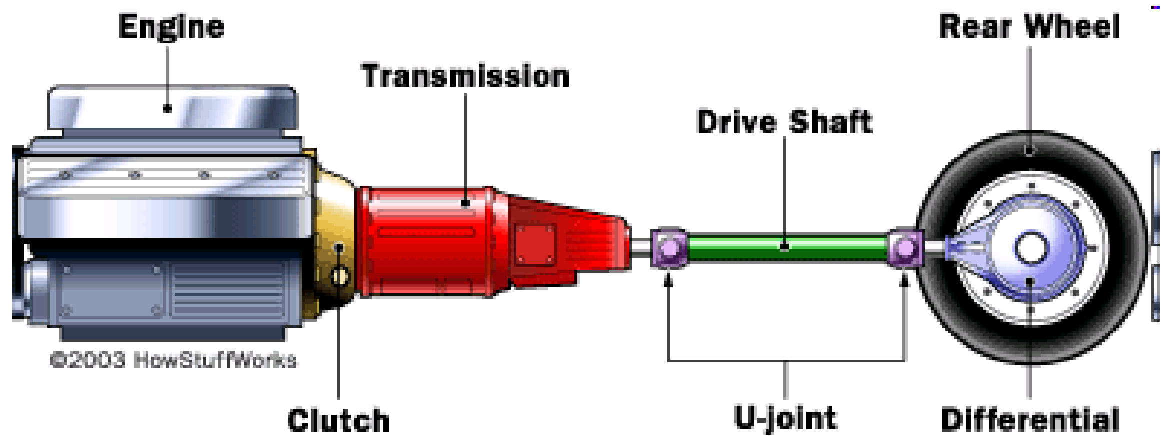
Steven Covey - *Seven Habits of Highly Effective People*

Why Composites?

Problem Statement

A drive shaft for a Chevy Pickup truck is made of steel. Check whether replacing it with a drive shaft made of composite materials will save weight?





Design of a Composite Drive Shaft

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The Nissan 350Z uses a composite driveshaft for added power.

Topics to Be Covered

- - Introduction to Composite Materials
- - Historical Perspective of Composites
- - Advantages and Drawbacks of Composites
- - Applications and Market Trends
- - Design Parameters for Composite Structures
- - Comparison Between Composites and Metals
- - Fiber and Matrix Classification
- - Mechanical and Thermal Properties of Composites
- - Manufacturing Techniques of Composites

INTRODUCTION

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- Although man-made composites have existed for thousands of years, the high technology of advanced composites has been used in the aerospace industry only for the last thirty years.
- The applications are becoming diverse ranging from aircraft structures and missile canisters to tennis racquets and fishing rods. The objective of this course is to analyze and design fiber reinforced composite materials.

By end of this course, you will

- Be able to know terminology of advanced composite materials and their applications.
- Be able to develop fundamental relationships for predicting the mechanical and hygrothermal response of multi-layered materials and structures.
- Be able to develop micromechanical and macromechanical relationships for lamina and laminated materials with emphasis on continuous filaments.
- Design composite material structures such as thin pressure vessels and thin-walled drive shafts.

Historical Perspective

- 4000 B.C. Fibrous composites were used in Egypt in making laminated writing materials
- 1300 BC: Reference to Book of Exodus
- 1700 AD: French Scientist, Reumer talked about potential of glass fibers

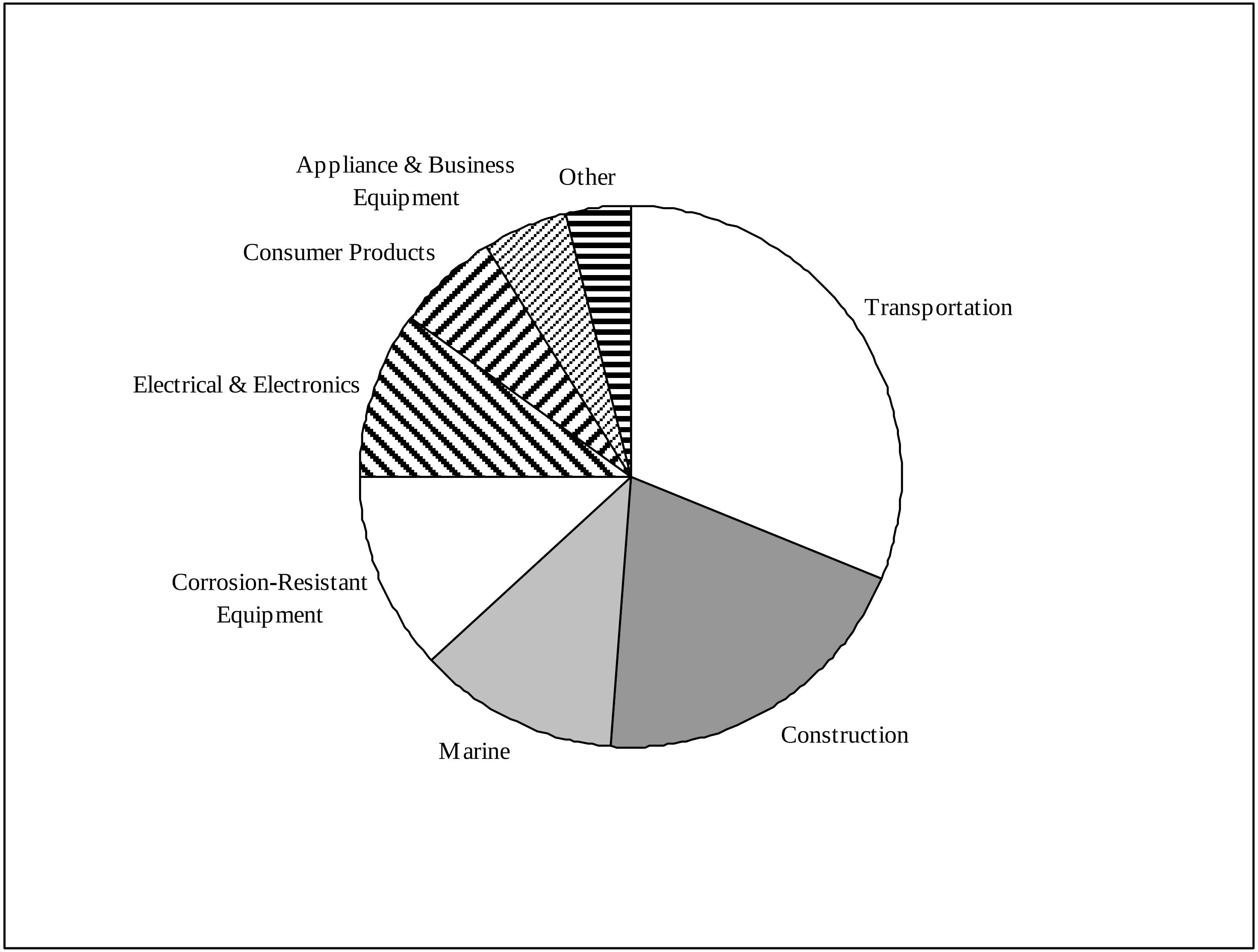
Historical Perspectives (continued)

- 1939: Glass fiber manufactured commercially for high temperature electrical applications
- 1950s: Boron and carbon fibers were produced to make ropes.
- 1960s: Matrix added to make polymeric matrix composites

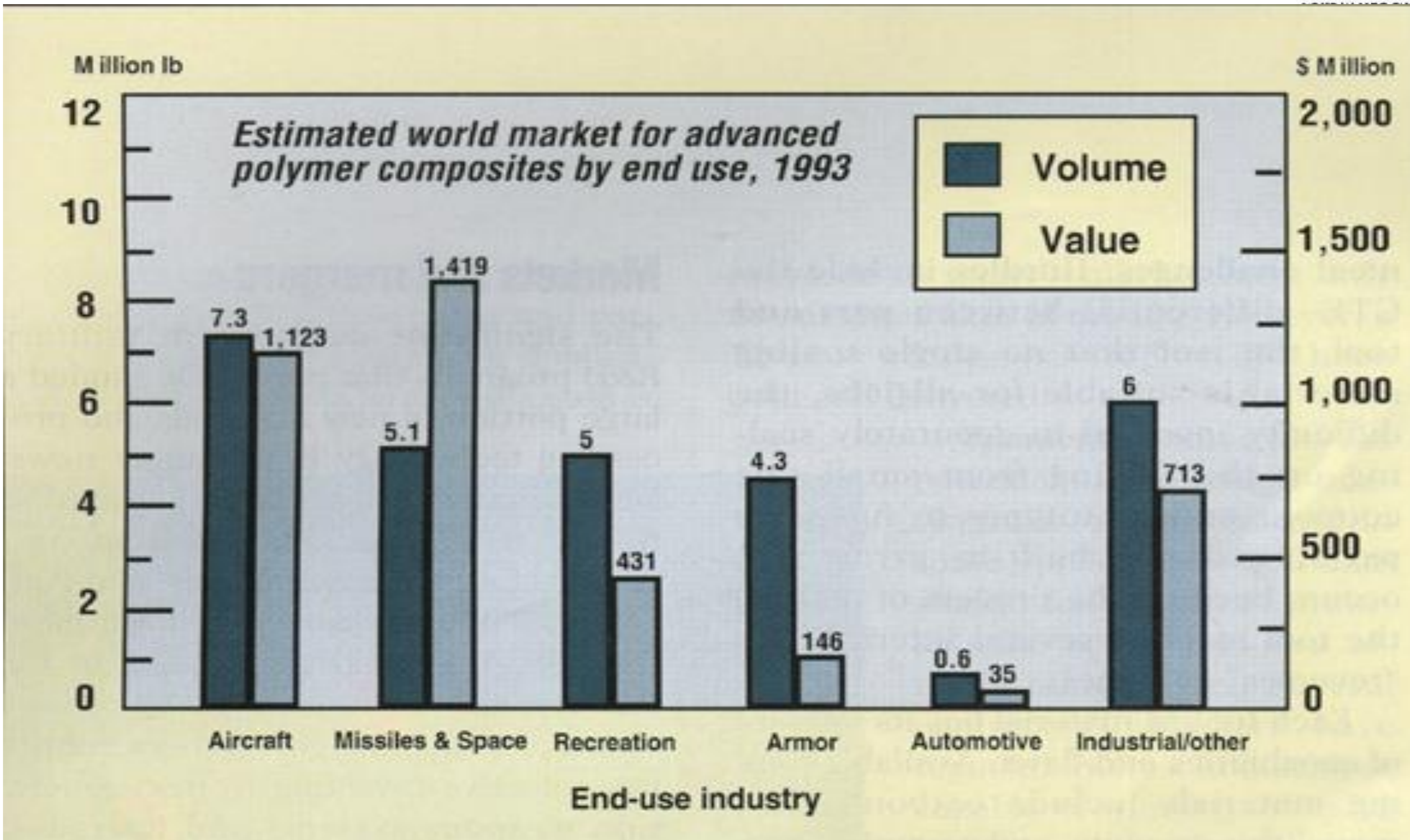
Historical Perspectives (continued)

- 1970s: Cold war forces development of metal matrix composites for military aircrafts and missile guidance systems
- 1990s: High temperature ceramic matrix composites are being aggressively researched for use in next generation aircraft engines and power plant turbines

Applications of Composites



World Market of Composites



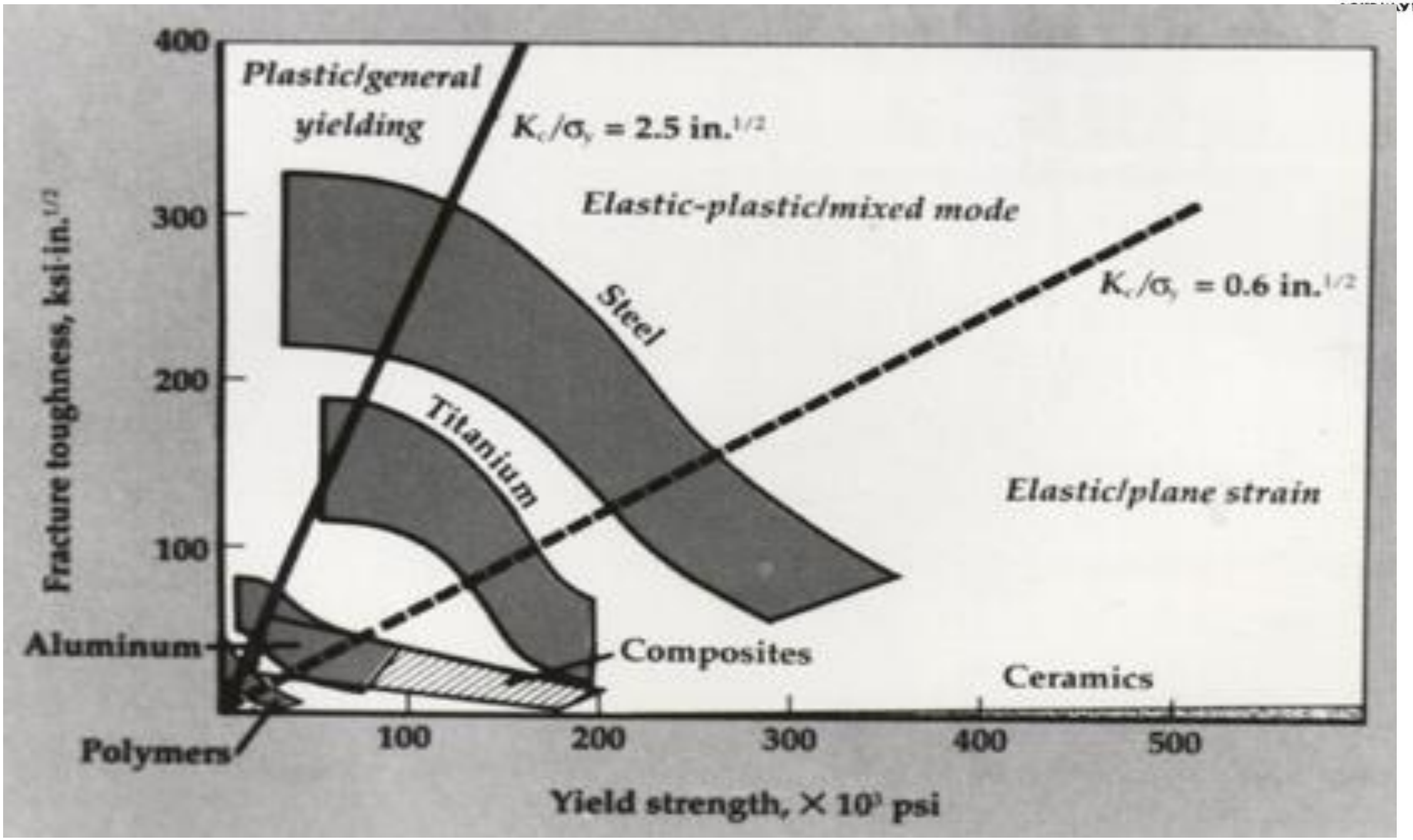
Advantages of Composites

- Specific Strength and Stiffness
- Tailored Design
- Fatigue Life
- Dimensional Stability
- Corrosion Resistance
- Cost-Effective Fabrication

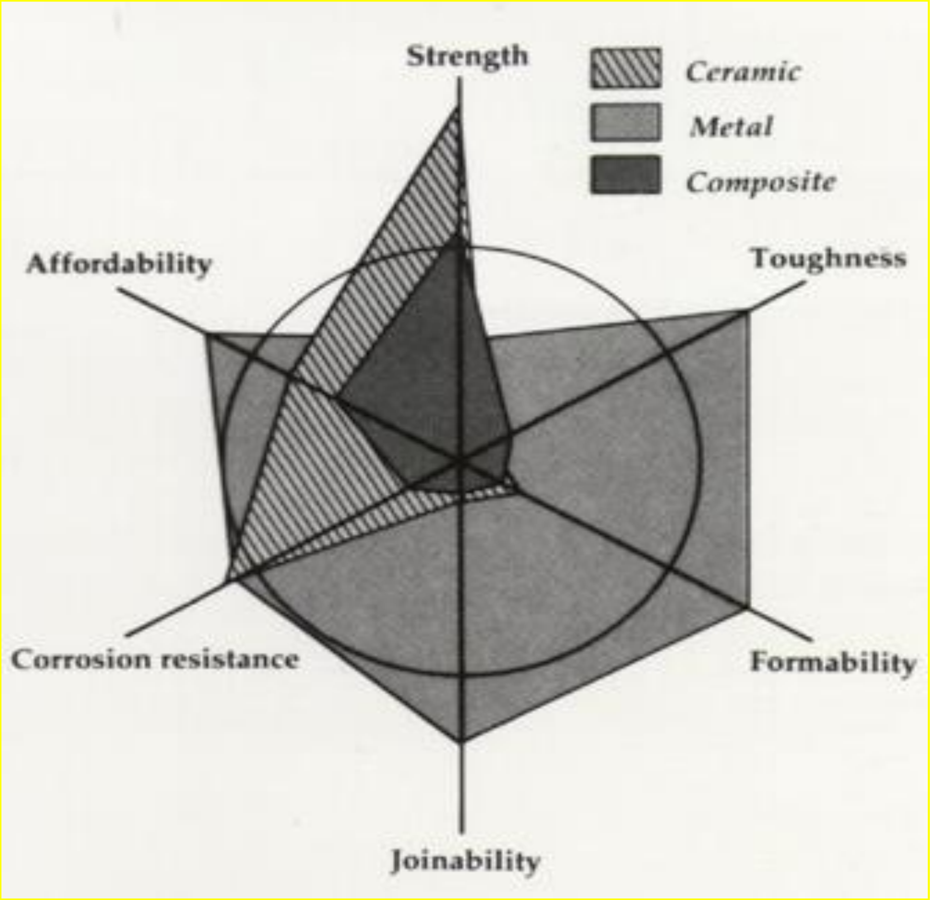
Drawbacks of Composites

- High cost of fabrication of composites
- Complex mechanical characterization
- Complicated repair of composite structures
- High combination of all required properties may not be available

Composites vs. Metals



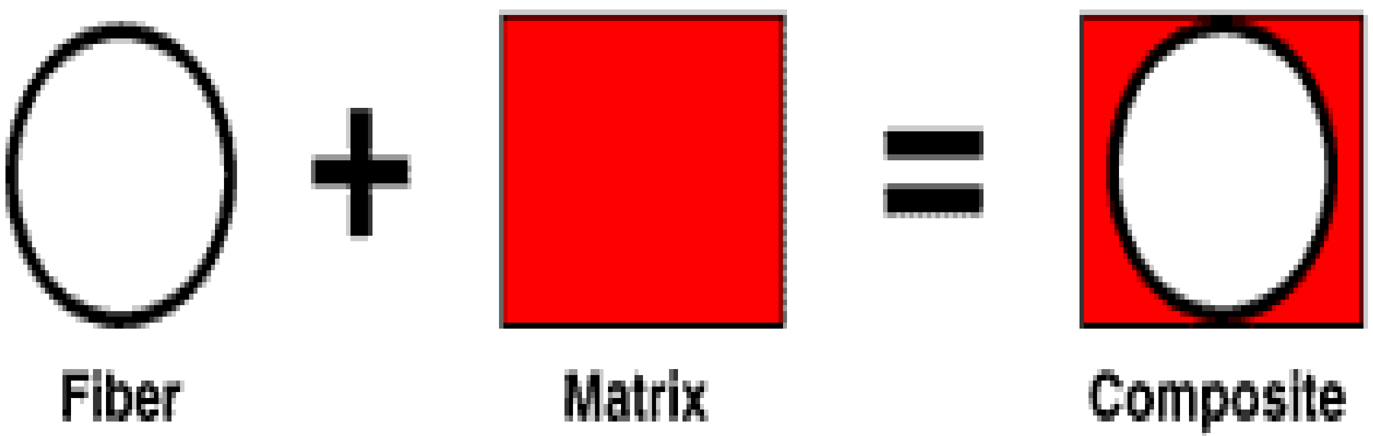
Composites vs. Metals



- Comparison based on six primary material selection parameters

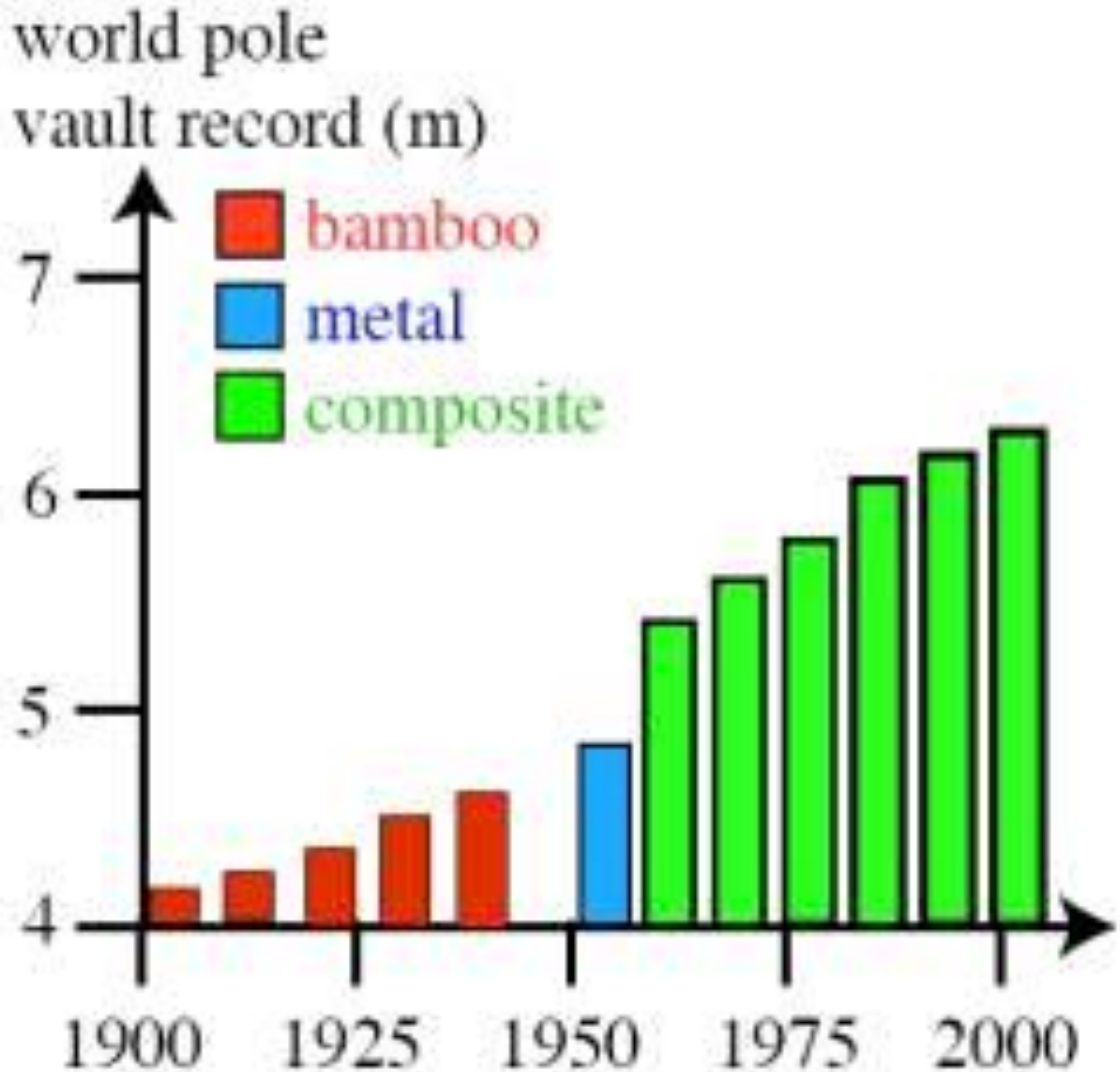
Fibrous Composites

- Generally there are two phases
  - Fiber as a reinforcement
  - Matrix as a binder



Design Parameters

- Torque Resistance.
  - Should carry load without failure
- Not rotate close to natural frequency.
  - Need high natural frequency otherwise whirling may take place
- Buckling Resistance.
  - May buckle before failing


world pole
vault record (m)
bamboo
metal
composite
7
6
5
4
1900
1925
1950
1975
2000

- By end of this course, you will be able to answer the following three questions about design and analysis of composite materials.

Three Questions

Question 1

How do I design a drive shaft made of composite materials and is it any better than making it out of steel or aluminum?

Why composite materials?

- Light weight — reduces energy consumption; increases amount of power transmitted to the wheels. About 17-22% of engine power is lost to rotating the mass of the drive train.
- Fatigue resistant — durable life.
- Non-corrosive — reduced maintenance cost and increased life.
- Single piece — reduces manufacturing cost.

Why composite materials?

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- Prevent injuries – the composite drive shaft "broom" on failure

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Problem Description

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Design Constraints

1. Maximum horsepower= 175 HP @4200rpm
2. Maximum torque = 265 lb-ft @2800rpm
3. Factor of safety = 3
3. Outside radius = 1.75 in
4. Length = 43.5 in

Design Parameters

- Torque Resistance.
  - Should carry load without failure
- Not rotate close to natural frequency.
  - Need high natural frequency otherwise whirling may take place
- Buckling Resistance.
  - May buckle before failing

Three Questions

Question 2

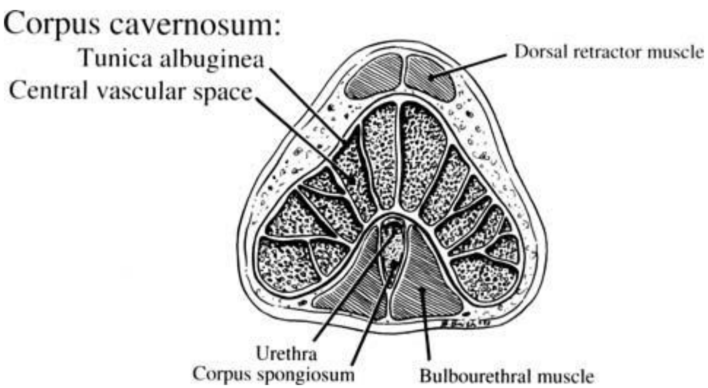
Why does the two-ply balsa-wood laminate *twist and bend* under bending load when stacked one way, and why does it *only bend* when stacked another way?

Question 3

How do I design a pressure vessel? Is it better than building it out of steel?

Question 3

Why does the penis not bend on erection?



2007 Titus Racer X Exogrid

The Full Page Ad for 2007 Titus Racer X Exogrid

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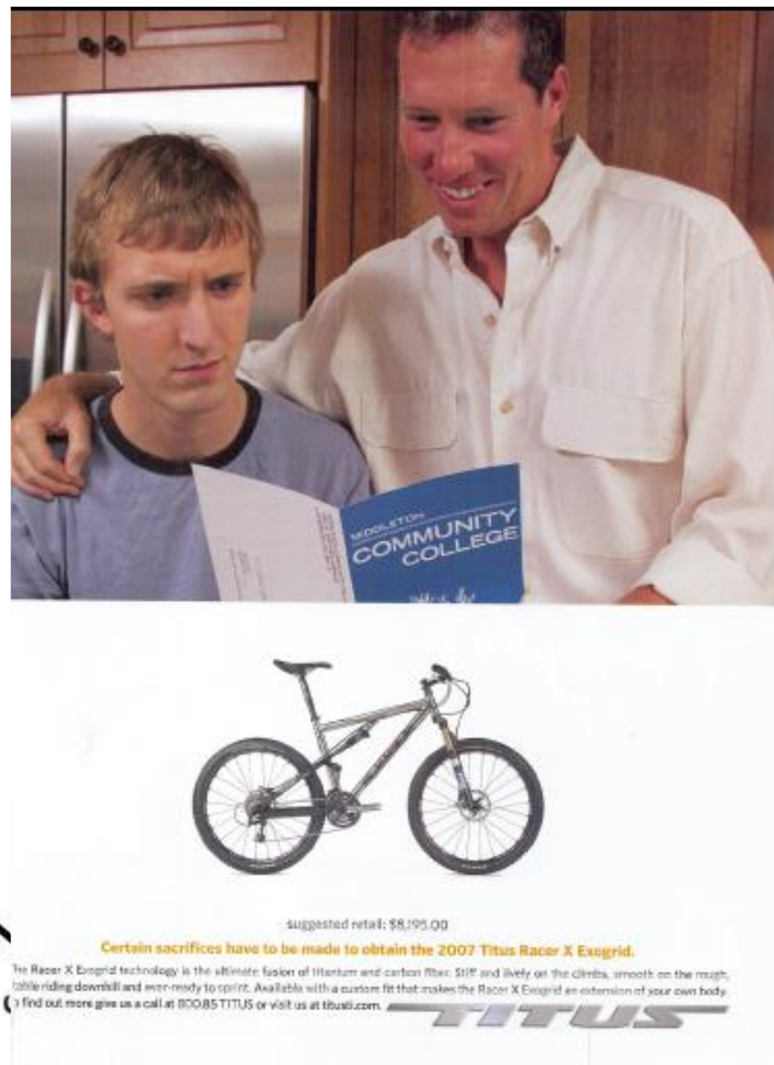

My wish!

What are you going to learn?

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- What are composite materials?
- How are they manufactured?
- What advantages and drawbacks do composites have over metals?
- Develop mathematical models to understand the mechanical response of composites to mechanical and hygrothermal loads?
- Use the above mathematical models to optimally design structures made of composites.

What is a composite?

- A composite is a structural material which consists of combining two or more constituents
- Examples:
  - Flesh in your leg reinforced with bones
  - Concrete reinforced with steel
  - Epoxy reinforced with graphite fibers.

- “You are no longer to supply the people with straw for making bricks; let them go and gather their own straw” - Exodus 5.7.

Shift in Paradigm About Materials

"More important than any one new application is the new 'materials' concept itself "

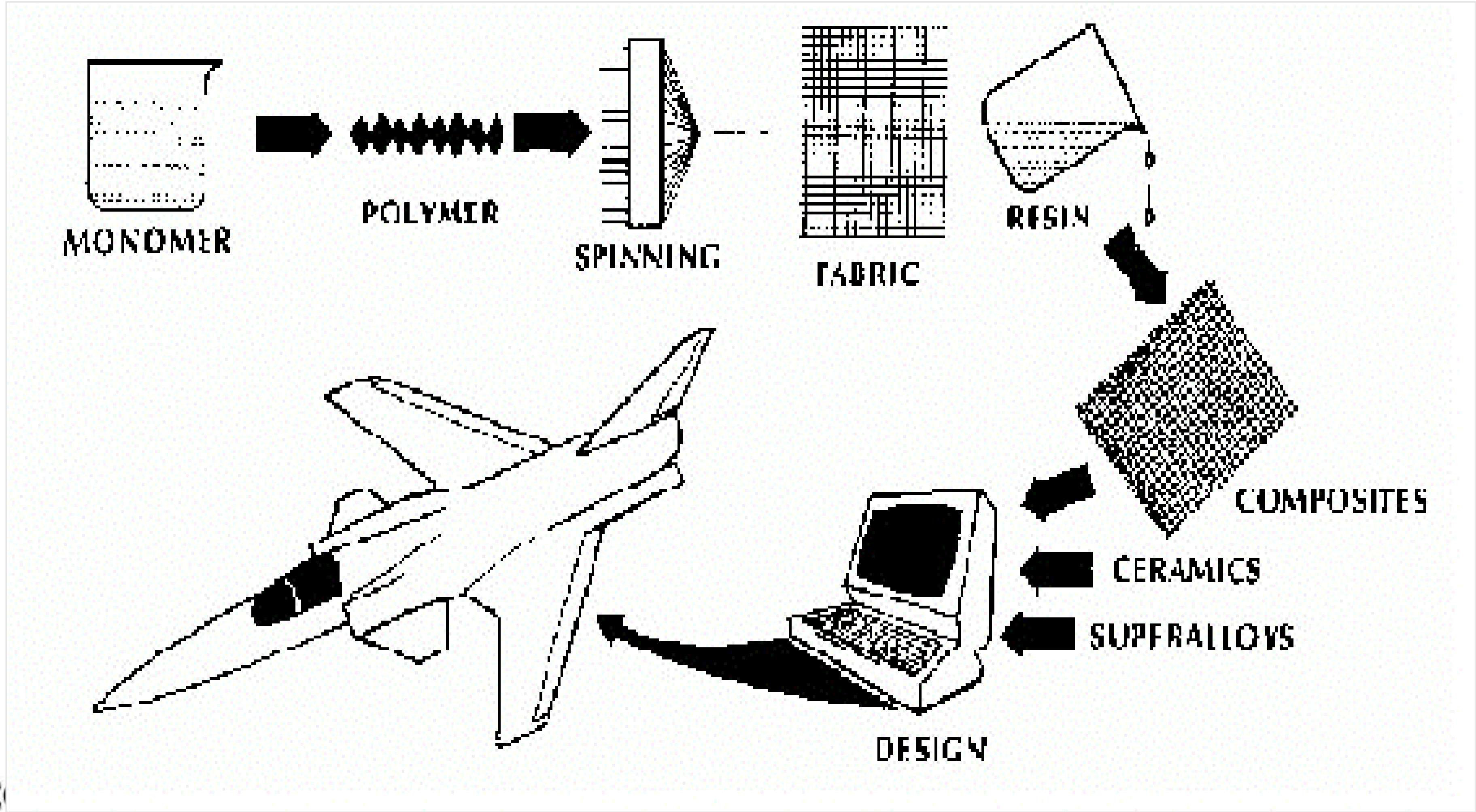
Peter F. Drucker

The Age of Discontinuity, 1969

What is this paradigm shift in materials?

- From substance to structures
- From artisan to science
- From workshop to mathematical modeling
- From what nature provides to what man can accomplish

From constituents to application



Objectives

- What is a composite?
- What are the advantages and drawbacks of composites over monolithic materials?
- What factors influence mechanical properties of a composite

Objectives (continued)

- How do we classify composites?
- What are the common types of fibers and matrices?
- How are composite materials manufactured?
- What are the mechanical properties of composite materials?

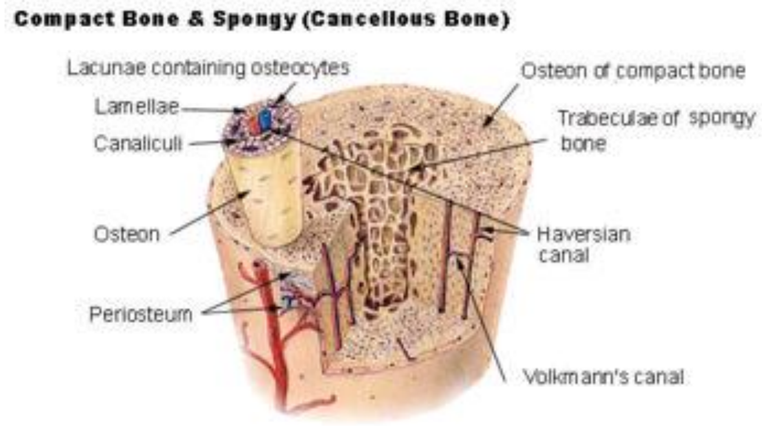
What is an advanced composite?

- Advanced composites are composite materials which were traditionally used in aerospace industries

  Examples include graphite/epoxy, Kevlar/epoxy and Boron/aluminum

Examples of Natural Composites

- Wood
  - Cellulose Fibers
  - Lignin Matrix
- Bones
  - Collagen Fibers
  - Mineral Matrix



Why composites over metals?

- High Strength and High Stiffness
- Tailored Design
- Fatigue Life
- Dimensional Stability
- Corrosion Resistance

Why Composites over Metals?

- **How is the mechanical advantage of composite measured?**

$$\text{Specific modulus} = \frac{E}{\rho},$$

$$\text{Specific strength} = \frac{\sigma_{ult}}{\rho}.$$

where

E = Young's Modulus

ρ = Density

σ_{ult} = Ultimate Strength

Specific Strength vs. Year

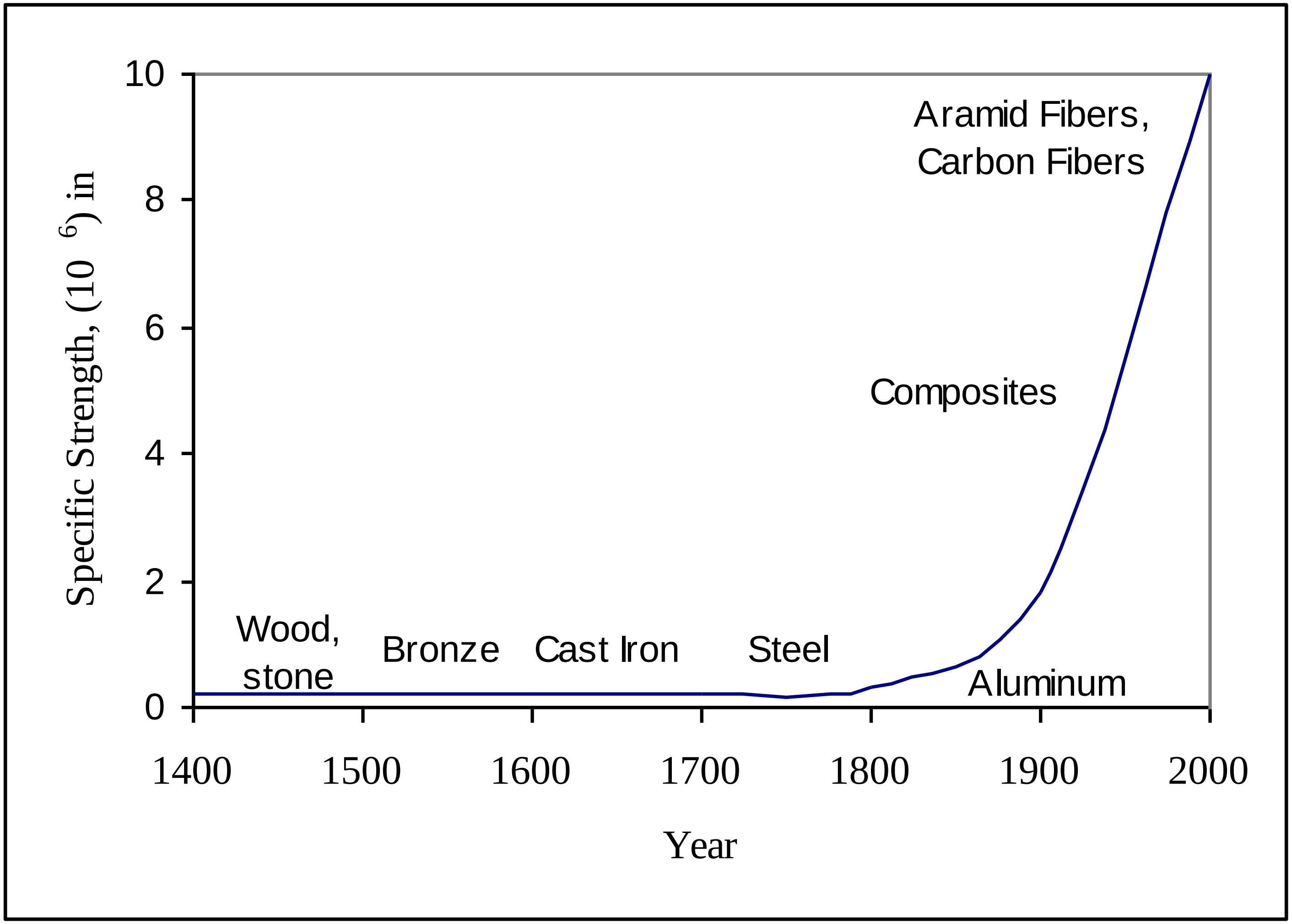


Table 1.1. Specific modulus and strength of typical fibers, composites and bulk metals

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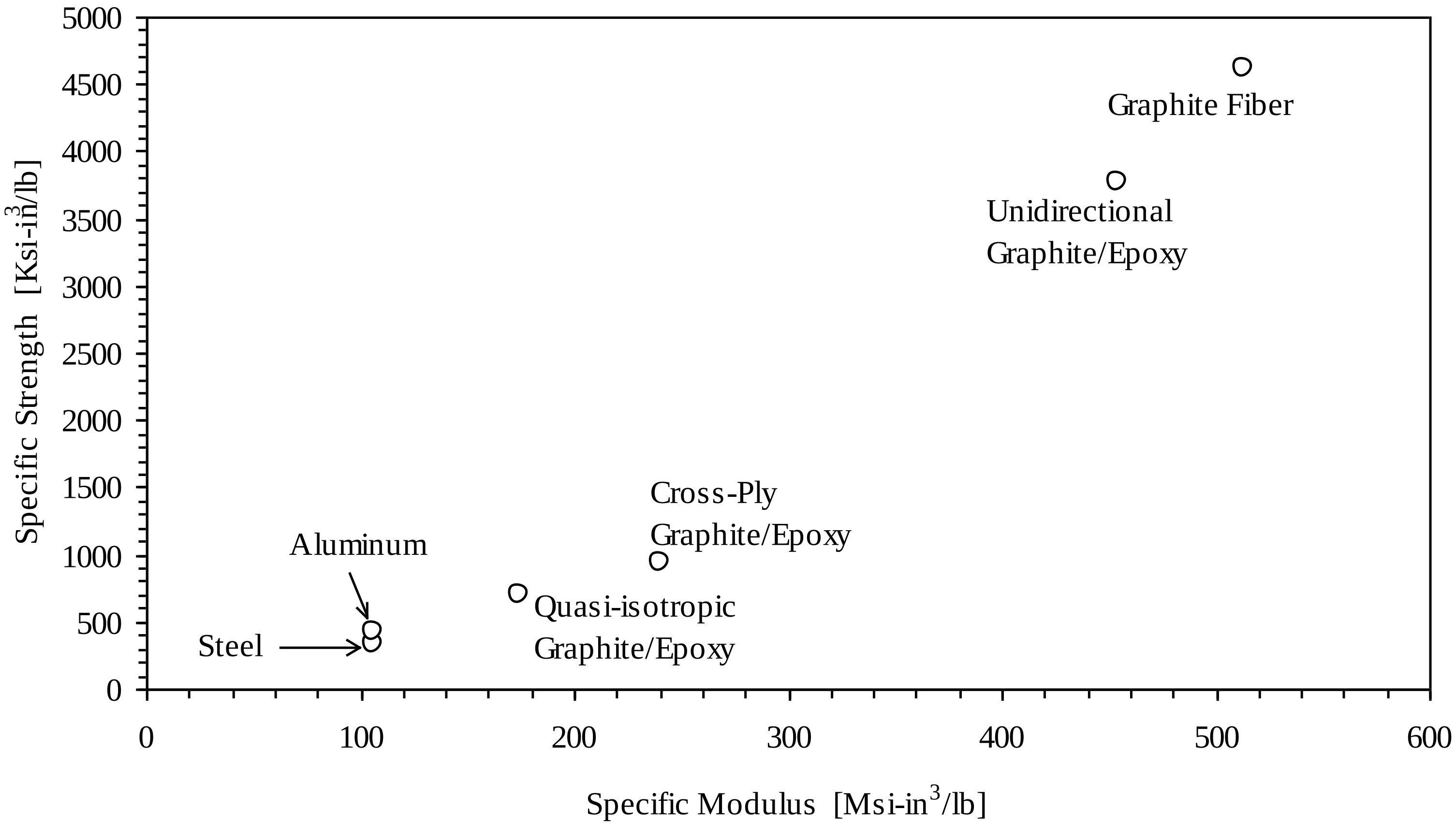
Material	Specific Gravity	Young's Modulus	Ultimate Strength	Specific Modulus	Specific Strength
Units		**GPa**	**MPa**	**GPa-m^3/kg**	**MPa-m^3/kg**
Graphite	**1.8**	**230**	**2067**	**0.13**	**1.1**
Unidirectional Graphite/Epoxy	**1.6**	**181**	**1500**	**0.11**	**0.94**
Cross-Ply Graphite/Epoxy	**1.8**	**96**	**373**	**0.060**	**0.23**
Quasi-Isotropic Gr/Epoxy	**1.8**	**70**	**276**	**0.043**	**0.17**
Steel	**7.8**	**207**	**648**	**0.026**	**0.083**
Aluminum	**2.6**	**69**	**276**	**0.026**	**0.106**

Comparative Thermal Expansion Coefficients (µin/in/°F)

Material	Direction-x	Direction-y
Steel	6.5	6.5
Aluminum	12.8	12.8
Graphite	-0.02	1.1
Unidirectional Graphite/Epoxy	0.01	12.5
Cross-Ply Graphite/Epoxy	0.84	0.84
Quasi-Isotropic Graphite/Epoxy	0.84	0.84

Specific Strength vs Specific Modulus



Other Mechanical Parameters

- Are specific modulus and specific strength the only mechanical parameters used for measuring the relative advantage of composites over metals? NO!!

$$\text{Critical load, } P_{cr} = \frac{\pi^2 EI}{L^2}$$

$$\text{Second moment of area, } I = \pi \frac{d^4}{64}$$

$$\text{Mass, } M = \rho \frac{\pi d^2 L}{4}$$

$$M = 2L^2 \rho \left(\frac{P_{cr}}{\pi E}\right)^{1/2} = 2L^2 \left(\frac{P_{cr}}{\pi}\right)^{1/2} \frac{\rho}{\sqrt{E}}$$

Tailored Design

- Engineered to meet specific demands as choices of making the material are many more as compared to metals.
- Examples of choices
  - fiber volume fraction
  - layer orientation
  - type of layer
  - layer stacking sequence

Fatigue Life

- Fatigue life is higher than metals such as aluminum.
- Important consideration in applications such as
  - aircrafts
  - bridges
  - structures exposed to wind

Dimensional Stability

- Temperature changes can result
  - in overheating of components (example engines)
  - thermal fatigue due to cyclic temperature changes (space structures)
  - render structures inoperable (space antennas)

Corrosion Resistance

- Polymers and ceramics matrix are corrosion resistant
- Examples include
  - underground storage tanks
  - doors
  - window frames
  - structural members of offshore drilling platforms

What is most limiting factor in the use of composites in structures?

Lack of engineers with the knowledge and experience to design with these materials!!!!

Cost Considerations

- Composites may be more expensive per pound than conventional materials. Then why do we use composite materials?

Factors in Cost Estimate

- For Composite Materials
  - Fewer pounds are required
  - Fabrication cost may be lower
  - Transportation costs are generally lower
  - Less maintenance than conventional materials is required

Fiber Factors

- What fiber factors contribute to the mechanical performance of a composite?
    - Length
    - Orientation
    - Shape
    - Material

Fiber Factor - Length

- Long Fibers
  - Easy to orient
  - Easy to process
  - Higher impact resistance
  - Dimensional stability
- Short Fibers
  - Low Cost
  - Fast cycle time

Fiber Factor - Orientation

- One direction orientation
  - High stiffness and strength in that direction
  - Low stiffness and strength in other directions
- Multi-direction orientation
  - Less stiffness but more direction independent

Fiber Factor - Shape

- Most common shape is circular
- Hexagon and square shapes give high packing factors

Fiber Factor - Material

- Graphite and aramids have high strength and stiffness
- Glass has low stiffness but cost less

Matrix Factors

- **What are the matrix factors which contribute to the mechanical performance of composites?**
  - Binds fibers together
  - Protects fibers from environment
  - Shielding from damage due to handling
  - Distributing the load to fibers.

Factors Other Than Fiber and Matrix

- Fiber-matrix interface
  - Chemical bonding
  - Mechanical bonding

Fiber Types

- Glass Fiber (first synthetic fiber)
- Boron (first advanced fiber)
- Carbon
- Silicon Carbide

Types of Matrices

- Polymers
- Metals
- Ceramics

Polymer Matrix

- Thermosets
  - polyester
  - epoxy
  - polymide
- Thermoplastics
  - polypropylene
  - polyvinyl chloride
  - nylon

Metal Matrix

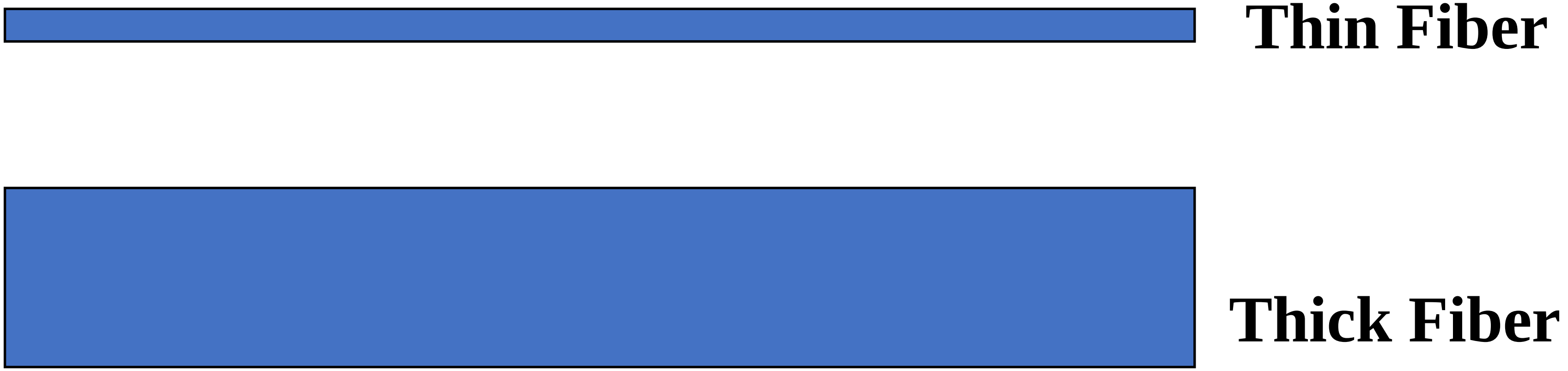
- Aluminum
- Titanium
- Copper

Ceramic Matrix

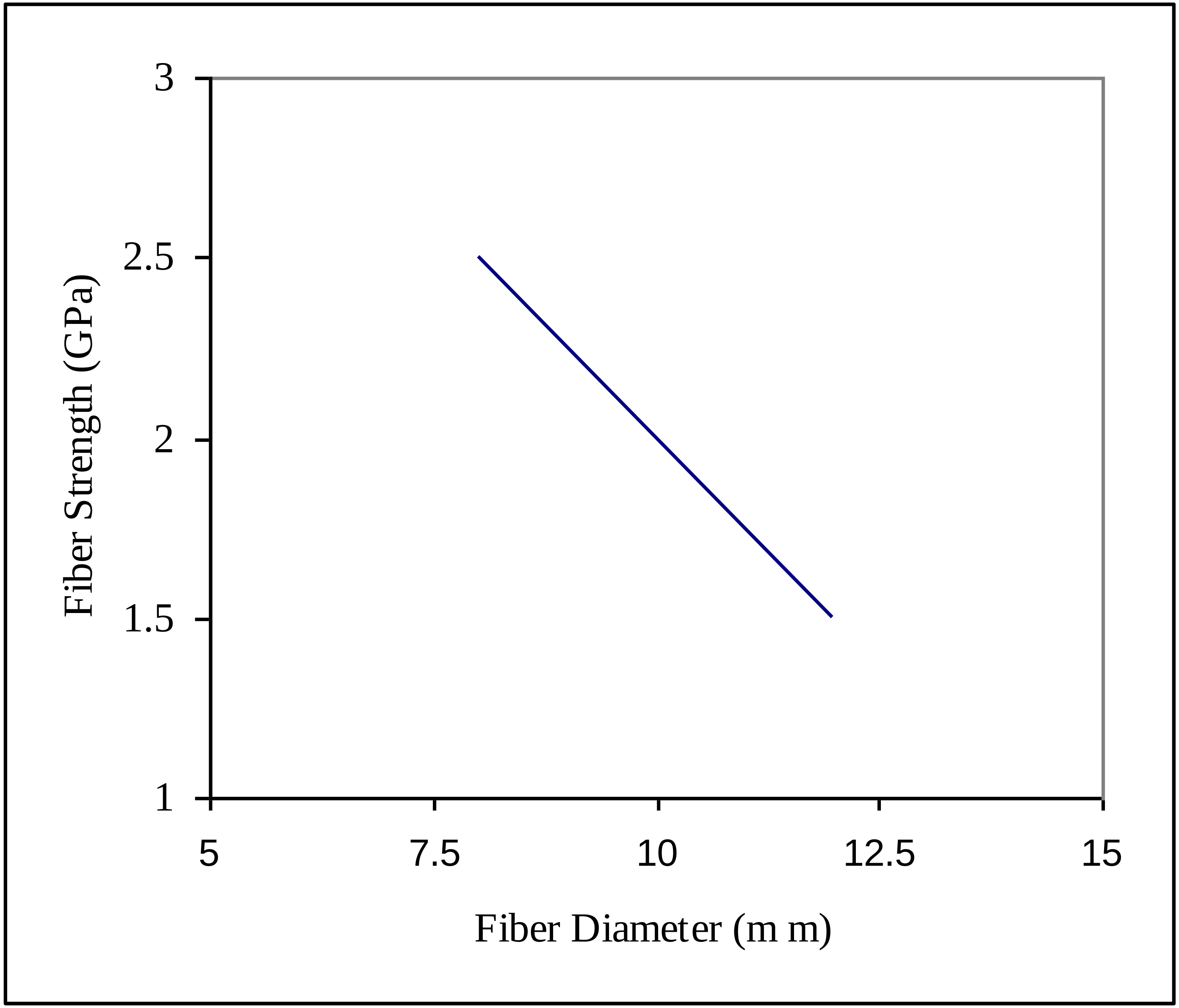
- Carbon
- Silicon Carbide
- Calcium AluminoSilicate
- Lithium AluminoSilicate

Why do fibers have thin diameter?

- Less flaws
- More toughness and ductility
- Higher flexibility



Less Flaws



More Toughness and Ductility

- Fiber-matrix interface area is inversely proportional to the diameter of the fibers
- Higher surface area of fiber-matrix interface results in higher ductility and toughness, and better transfer of loads.

More Flexibility

- Flexibility is proportional to inverse of
  - Young's modulus
  - Fourth power of diameter
- Thinner fibers hence have a higher flexibility and are easy to handle in manufacturing.

Are you ready?

What is a key advantage of composite materials over metals?

- A) Higher density
- B) Lower strength-to-weight ratio
- C) Corrosion resistance
- D) Higher thermal expansion

Which component acts as the reinforcement in fibrous composites?

- A) Matrix
- B) Fiber
- C) Resin
- D) Ceramic

Which industry was one of the earliest to use high-tech composite materials?

- A) Aerospace
- B) Automotive
- C) Construction
- D) Agriculture

Which fiber type was the first synthetic fiber used in composites?

- A) Carbon
- B) Boron
- C) Glass
- D) Aramid

Which factor does NOT influence the mechanical performance of a composite?

- A) Fiber length
- B) Fiber-matrix interface
- C) Fiber color
- D) Matrix type

Summary

- Composite materials offer high strength-to-weight ratio, corrosion resistance, and fatigue resistance.

- Various fiber and matrix materials influence composite properties.

- Historical advancements have led to widespread applications in aerospace, automotive, and structural engineering.

- Composite material selection depends on design requirements, cost, and performance factors.

- The course will provide a deeper understanding of composite material analysis and design.