IntroductiontoEngineeringMaterials

Composites

Issuesto address…

- Whatarecomposites?
- Classificationof composites.
- Whycomposites?
- Mechanicalpropertiesof composites.
- Applications.

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Composites:definition&examples

- **Multiphasematerialswithchemicallydifferentphasesand distinctinterfaces.**

- **Propertiesoftheresultantcombinationofmaterialsare superiortothepropertiesoftheindividual components.**

- **Advantages**:High-strength/light-weight,lowcost,environmentally resistant…

- **Naturalcomposites:**
  - -**Wood**:strong&flexiblecellulosefibers in stiffer lignin(surroundsthe fibers).
  - -**Bone**:strongbut soft collagen(protein)withinhardbut brittle apatite (mineral).
  - -Certain typesof rocks can alsobe consideredas composites.

-**Syntheticcomposites:**fiberglass,concrete,carbon-carbon composites….

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Bicycleforks

Braided and unidirectionalS-2 Glassandcarbon fibersare used to produce forkswith differentstiffness

HighStrengthWeight ReductionDesignFlexibilityCostPerformance

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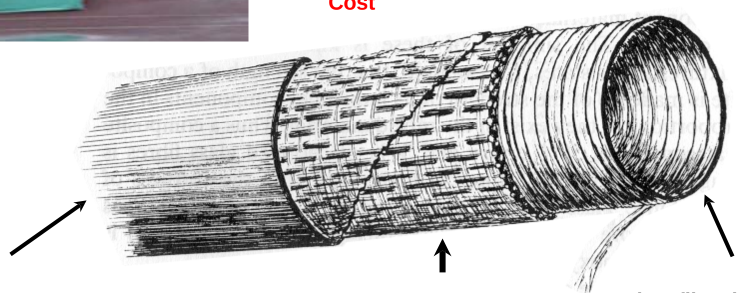
Pole-vaulting

Lightweight - lowdensityBucklingresistance - stiffnessStrong - yield strengthMinimaltwisting Cost



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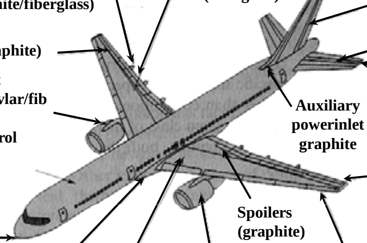

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Terminology

- **Matrix:**
  - – softer,moreflexibleandcontinuouspart that surrounds the otherphase.
  - – transfer stress to otherphases
  - – protectphasesfrom environment
    - **Reinforcement**(dispersedphase)**:**
  - – stiffer,highstrength part (particlesor fibersare the most common).
  - – enhancesmatrixproperties

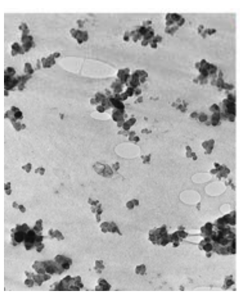
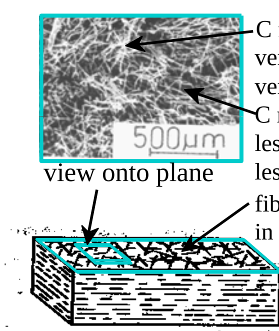


FIGURE 16.5 Electron micrograph showing the spherical reinforcing carbon black particles in a synthetic rubber tire tread compound. The areas resembling water marks are tiny air pockets in the rubber. 80,000×. (Courtesy of Goodyear Tire & Rubber Company.)



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Compositecharacteristics

Depends on:

- propertiesof thematrix material.

- propertiesof reinforcement material.

- ratio of matrixto reinforcement.

- matrix-reinforcementbonding /adhesion.

- mode offabrication.

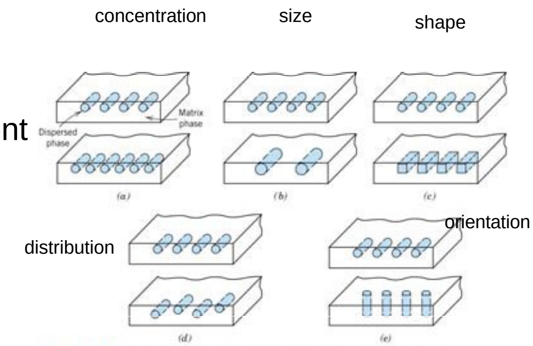

FIGURE 16.1 Schematic representations of the various geometrical and spatial characteristics of particles of the dispersed phase that may influence the properties of composites: (*a*) concentration, (*b*) size, (*c*) shape, (*d*) distribution, and (*e*) orientation. (From Richard A. Flinn and Paul K. Trojan, *Engineering Materials and Their Applications*, 4th edition. Copyright © 1990 by John Wiley & Sons, Inc. Adapted by permission of John Wiley & Sons, Inc.)

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Classificationof Composites

- <u>Matrix-based</u>:
  - – MetalMatrixComposites(MMC)
  - – CeramicMatrixComposites(CMC)
  - – PolymerMatrixComposites(PMC)

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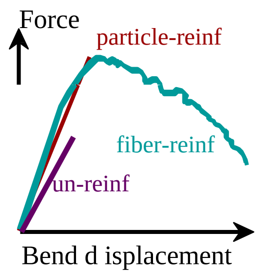
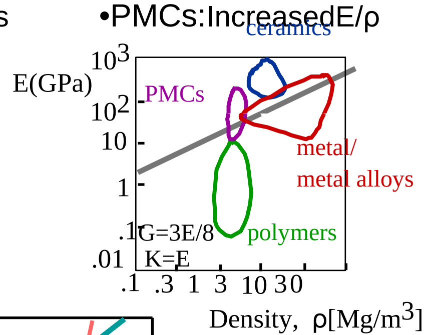
COMPOSITEBENEFITS

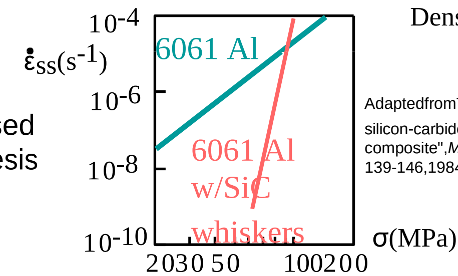
- CMCs:Increasedtoughness



- PMCs:IncreasedE/ρ



- MMCs:
  Increased creepresis tance



AdaptedfromT.G. Nieh,"Creepruptureofa silicon-carbide reinforcedaluminum composite",*Metall.Trans.A* Vol.15(1),pp. 139-146,1984.Used withpermission.

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Figure 16.2 A classification scheme for the various composite types discussed in this chapter.

Reinforcement-based

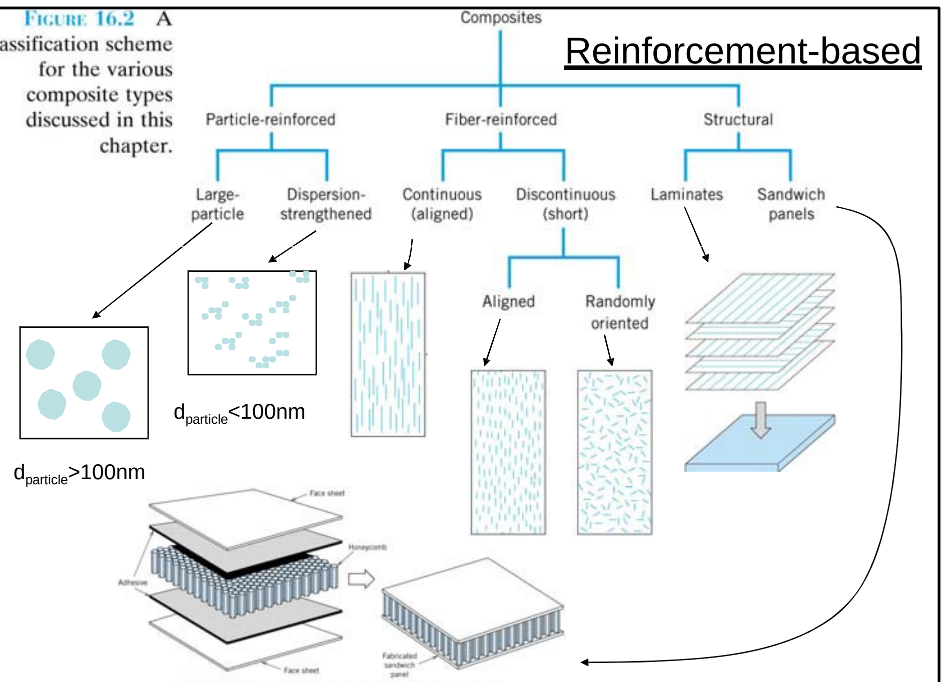


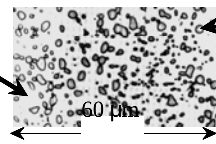
Figure 16.17 Schematic diagram showing the construction of a honeycomb core sandwich panel. (Reprinted with permission from *Engineered Materials Handbook*, Vol. 1, *Composites*, ASM International, Metals Park, OH, 1987.)

COMPOSITE SURVEY: Particle-I

Particle-reinforced | Fiber-reinforced | Structural

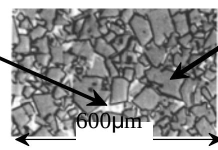
- Examples:

-Spheroidite steel — matrix: ferrite(α) (ductile); particles: cementite (Fe_3C) (brittle)



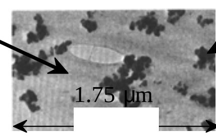
Adapted from Fig. 10.10, *Callister 6e*. (Fig. 10.10 is copyright United States Steel Corporation, 1971.)

- WC/Cobalt cemented carbide — matrix: cobalt (ductile) V_m: 10-15 vol%!; particles: WC (brittle, hard)



Adapted from Fig. 16.4, *Callister 6e*. (Fig. 16.4 is courtesy Carboloy Systems, Department, General Electric Company.)

- Automobile tires — matrix: rubber (compliant); particles: C (stiffer)



Adapted from Fig. 16.5, *Callister 6e*. (Fig. 16.5 is courtesy Goodyear Tire and Rubber Company.)

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COMPOSITE SURVEY: Particle-II

Particle-reinforced | Fiber-reinforced | Structural

- Elastic modulus, E_c, of composites:
  - --two approaches.

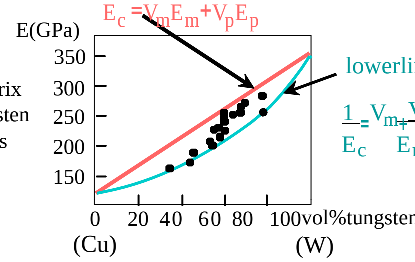
upper limit: "rule of mixtures"

$$E_c = V_m E_m + V_p E_p$$

lower limit:

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$$

Data: Cu matrix w/tungsten particles



Adapted Fig. 16.3, *Callister 6e*. (Fig. 16.3 is from R.H. Krock, *ASTM Proc*, Vol. 63, 1963.)

- Application to other properties:
  - --Electrical conductivity, σ_e: Replace E by σ_e.
  - --Thermal conductivity, k: Replace E by k.

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Analogy to resistors in series vs. parallel…

Fiber-reinforcedcomposites

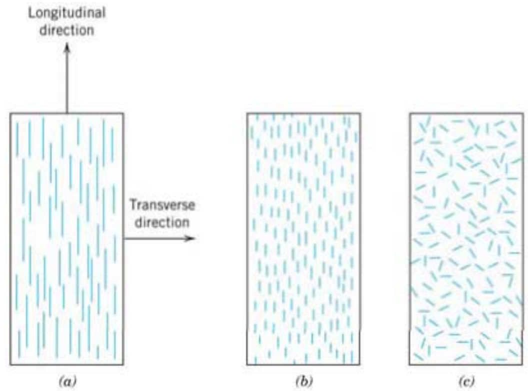

FIGURE 16.8 Schematic representations of (*a*) continuous and aligned, (*b*) discontinuous and aligned, and (*c*) discontinuous and randomly oriented fiber-reinforced composites.

Continuous &aligned

Discontinuous &aligned

Discontinuous &random

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Fiber-reinforcedcomposites

The Fiber Phase

Smaller diameterfiber is strongerthan bulkin most materials (especiallybrittle ones).Why? **Flaws!**

Whiskers:
• verythin singlecrystalsthat haveextremelylargeaspectratios.
• highdegreeof crystallinityand virtuallyflawfree – exceptionallyhigh strength.
• usuallyextremelyexpensive.
• somewhiskermaterials:graphite,SiC, siliconnitride,aluminumoxide.
Fibers:
• polycrystallineor amorphous.
• typically:polymersor ceramics(polymeraramids,glass, carbon,boron, SiC…
FineWires:
• relativelylargediameter, often metalwires.
• e.g. steel, molybdenum,tungsten…

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Fiber-reinforcedcomposites

The Matrix Phase

• canbemetal,polymers,orceramics.

• typically metalsandpolymerbecausesomeductilityisoften desired.

• mainfunctionsofthematrix:

-Holdfiberstogether.

-Transmitanddistributeexternalstresstothefibers.

-Protectfibersfromsurfacedamage:abrasions,chemical reactions…

• inCMCs,reinforcementsareusuallyaddedtoimprovefracture toughness.

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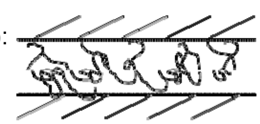
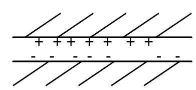
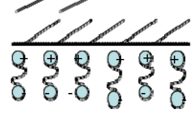
Fiber-reinforcedcomposites

TheFiber-Matrix Interface

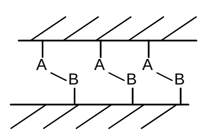
1. Molecularentanglement(interdiffusion):
    - Entanglementofmoleculesattheinterface.
    - Especiallyimportantinfibersthatarepre-coatedwithpolymers.
    - Molecularconformation/structuraland chemicalaspects.



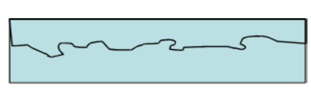




2. Electrostatic attraction
    - Dependsonsurfacechargedensity.
    - e.g.glassfibers,polymerswithchargeablegr oups.
3. Covalent bonding
    - Usuallythestrongestfiber-matrixinteraction.
    - Themostimportantinmanycomposites.



4. Mechanicaladhesion
    - Interlockingof2roughsurfaces
    - e.g.thermosettingresins



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Fiber-reinforcedcomposites

Properties dependon*LENGTH* and*ORIENTATION*of the fibers (as wellas isolated propertiesof eachof the components)!

Criticalfiber length

$$l_c = \frac{\sigma_f^* d}{2\tau_c}$$

σ_f^* =Fibertensilestrength

d= Fiberdiameter

τ_c = Smaller of:
- fiber-matrix bondstrength
- matrixshear yieldstrength.

Continuouswhenfiber length>>l_c
Discontinuouswhenfiberlength< 15 l_c

Possiblefailuremodes:
1) fiberbreaking.
2) matrixbreaking.
3) fiberpullout(interface betweenfiberandmatrix fails)

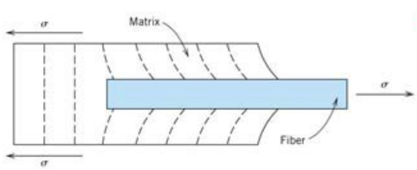

FIGURE 16.6 The deformation pattern in the matrix surrounding a fiber that is subjected to an applied tensile load.

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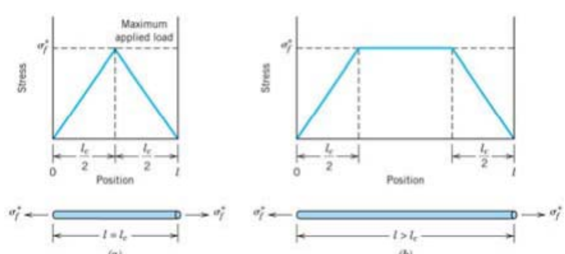
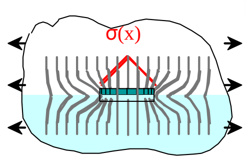
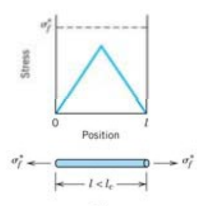
Fiber-reinforcedcomposites



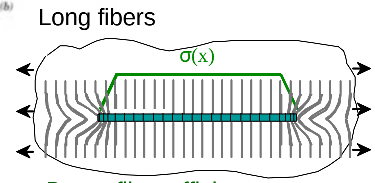
Short fibers



Poorer fiber efficiency



Long fibers



Better fiber efficiency

FIGURE 16.7 Stress–position profiles when fiber length l (*a*) is equal to the critical length l_c, (*b*) is greater than the critical length, and (*c*) is less than the critical length for a fiber-reinforced composite that is subjected to a tensile stress equal to the fiber tensile strength σ_f^*.

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Alignedfibers

Continuouswhenfiberlength>>l_c
Discontinuouswhenfiberlength<15l_c

ElasticModulus

Notsodetrimentalsince:
1) Notallfibersfailatthesametime
2) Matrixstillintact

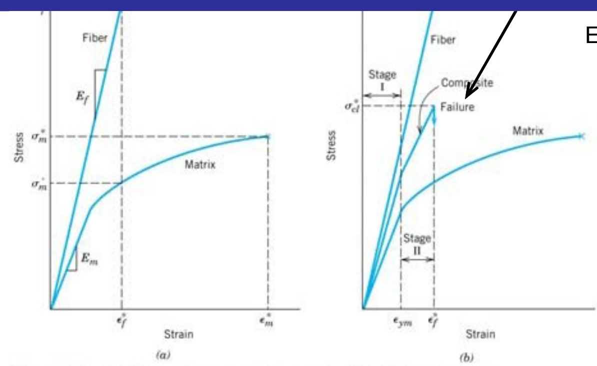
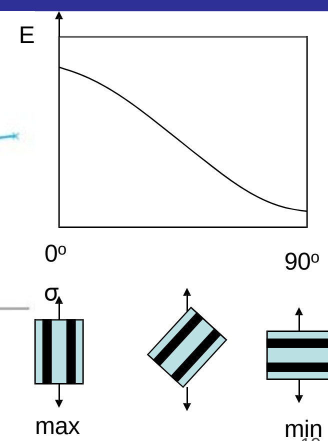


FIGURE 16.9 (*a*) Schematic stress–strain curves for brittle fiber and ductile matrix materials. Fracture stresses and strains for both materials are noted. (*b*) Schematic stress–strain curve for an aligned fiber-reinforced composite that is exposed to a uniaxial stress applied in the direction of alignment; curves for the fiber and matrix materials shown in part (*a*) are also superimposed.



COMPOSITE SURVEY: Fiber-I

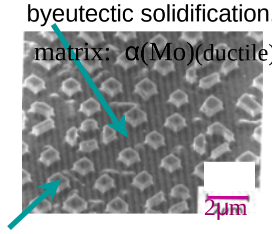
Particle-reinforced | Fiber-reinforced | Structural

AlignedContinuousfibers

- Examples:

--Metal:γ'(Ni_3Al)-α(Mo) byeutectic solidification.

matrix: α(Mo)(ductile)

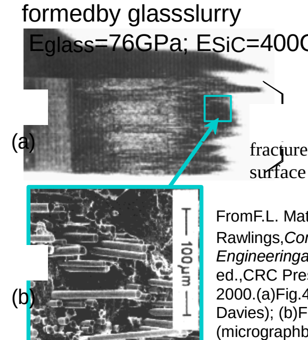


fibers:γ’(Ni_3Al)(brittle)

FromW.FunkandE. Blank,“Creep deformationof Ni3Al-Moin-situ composites",*Metall.Trans.A* Vol.19(4),pp. 987-998,1988.Used withpermission.

--Glassw/SiCfibers formedby glassslurry

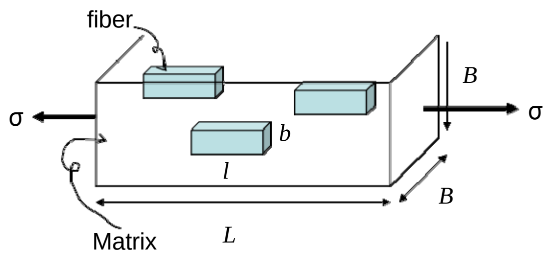
E_{glass}=76GPa; E_{SiC}=400GPa.



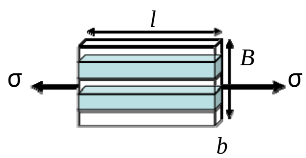
FromF.L. Matthews andR.L. Rawlings,*Composite Materials; EngineeringandScience*,Reprint ed.,CRC Press,BocaRaton,FL, 2000.(a)Fig.4.22,p.145(photoby J. Davies); (b)Fig.11.20,p.349 (micrographby H.S. Kim,P.S. Rodgers,andR.D. Rawlings). Used withpermissionof CRC Press,BocaRaton,FL.

Continuous-alignedfibers

Considera compositewithfibers havingsquarerod geometrywithstress in the**longitudinaldirection**…



When$l >> l_c$(typically$l > 15 l_c$), wecansimplify to:



then $\frac{\Delta L_{composite}}{l} = \frac{\Delta L_{fiber}}{l} = \frac{\Delta L_{matrix}}{l}$

since $\varepsilon \equiv \frac{\Delta L}{l}$,

$\varepsilon_{composite} = \varepsilon_{fiber} = \varepsilon_{matrix}$

ISOSTRAIN

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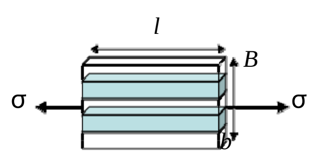
Continuous-alignedfibers

Longitudinalloading



Whatabout elasticmodulus?

Totalforce onthe compositeis simply the sum of forceson matrixandfibers.

$$F_{composite} = F_{matrix} + F_{fiber}$$

since $\sigma = \frac{F}{A}$ or $F = \sigma A$, wehave: $\sigma_c A_c = \sigma_m A_m + \sigma_f A_f$

Recallstress-strainrelation:$\sigma = E\varepsilon$

Sub-in for stresses…

$E_c \varepsilon_c A_c = E_m \varepsilon_m A_m + E_f \varepsilon_f A_f$

rearrange

$$E_c = \frac{E_m \varepsilon_m A_m}{\varepsilon_c A_c} + \frac{E_f \varepsilon_f A_f}{\varepsilon_c A_c}$$

Imposing isostraincondition$\varepsilon_c = \varepsilon_f = \varepsilon_m$,

$$E_c = E_m \frac{A_m}{A_c} + E_f \frac{A_f}{A_c}$$

"Area fractions"

Prefer volumefractions….

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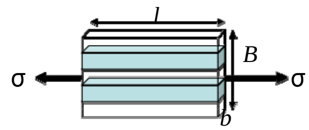
Continuous-alignedfibers

Longitudinalloading



Totalarea= Bb

A_f= numberof fibers x area of eachfiber $=Nb^2$

Thenwehave: $\frac{A_f}{A_c} = \frac{Nb}{B}$ Also, $A_m = A_c - A_f$

or

$$\frac{A_m}{A_c} = 1 - \frac{A_f}{A_c} = 1 - \frac{Nb}{B}$$

Forvolumefractions: $V_c = Bbl$

$V_f = Nb^2 l$

Then: $v_f = \frac{V_f}{V_c} = \frac{Nb^2 l}{Bbl} = \frac{Nb}{B} = \frac{A_f}{A_c}$ same as“areafraction”

Similarly, $v_m = \frac{A_m}{A_c}$

$$E_{cl} = v_m E_m + v_f E_f$$

Longitudinalelasticmodulus (upperboundforE_c)

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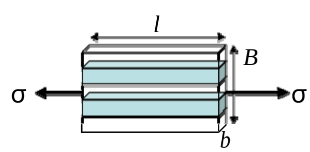
Continuous-alignedfibers

Longitudinalloading



Whatabout the loadonthe matrixand the fibers?

$\frac{F_f}{F_m} = ?$ $F = \sigma A$

$$\frac{F_f}{F_m} = \frac{\sigma_f A_f}{\sigma_m A_m} = \frac{\sigma_f v_f}{\sigma_m v_m}$$

With $\sigma = E\varepsilon$

$$\frac{F_f}{F_m} = \frac{E_f \varepsilon_f v_f}{E_m \varepsilon_m v_m}$$

Isostrainconditions →

$$\frac{F_f}{F_m} = \frac{E_f v_f}{E_m v_m}$$

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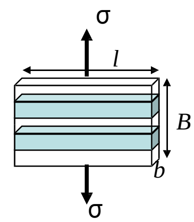
Continuous-alignedfibers

Transverseloading



Stress,ratherthan strain, is the same inthis case:

$$\sigma_c = \sigma_f = \sigma_m$$

ISOSTRESScondition

Thetotal elongationwillbethe sum ofelongationofthe components:

$$\Delta L_c = \Delta L_f + \Delta L_m$$

Strain= $\varepsilon_c = \frac{\Delta L_c}{L_c} = \frac{\Delta L_f}{L_c} + \frac{\Delta L_m}{L_c}$

Where L_c= lengthof the composite along the directionof stress= B

Again, to expressin terms of volumefractions:

$L_f = Nb$

$\frac{L_f}{L_c} = \frac{Nb}{B} = v_f$

Rearrange $L_c = \frac{L_f}{v_f}$ Similarly, $L_c = \frac{L_m}{v_m}$

Sameas whatwederivedfor volumefraction

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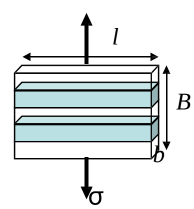
Continuous-alignedfibers

Transverseloading



$$\varepsilon_c = \frac{\Delta L_c}{L_c} = \frac{\Delta L_f}{L_c} + \frac{\Delta L_m}{L_c}$$

$$= \frac{\Delta L_f}{L_f / v_f} + \frac{\Delta L_m}{L_m / v_m} = v_f \left(\frac{\Delta L_f}{L_f} \right) + v_m \left(\frac{\Delta L_m}{L_m} \right)$$

ε_f ε_m

$$\varepsilon_c = v_m \varepsilon_m + v_f \varepsilon_f$$

From stress-strain relation; $\varepsilon = \frac{\sigma}{E}$

$$\frac{\sigma_c}{E_c} = v_m \frac{\sigma_m}{E_m} + v_f \frac{\sigma_f}{E_f}$$

Applyingisostressconditionand rearranginggives

Lowerboundfor E_c (transversemodulus)

$$E_{ct} = \frac{E_m E_f}{v_m E_f + v_f E_m}$$

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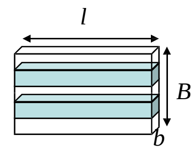
Continuous-alignedfibers

Many propertiesfollowthese upperandlowerbound relationsfor continuous-alignedfiber composities.

Ingeneral:



$$X_{cl} = X_c^{upper} = v_m X_m + v_f X_f$$

$$X_{ct} = X_c^{lower} = \frac{X_m X_f}{v_m X_f + v_f X_m}$$

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Continuous-alignedfibers:example

1. Calculatethe longitudinaland transverse modulus and thermal conductivityfor polyesterreinforcedwith60% volume fraction ofglassfiber (E-glass).

2. Calculatelongitudinalspecificstiffness.

3. Calculatethe percentageofthe loadon the fibers for longitudinalloading.

	E(GPa)	K(W/mK)	Specific gravity
Polyester	6.3	0.17	1.46
E-glass	72.4	0.97	2.58

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Continuous-alignedfibers:exampleMixedFibers

- Atwo-fibercomposite(continuousaligned) iscomposedof thefollowing components.

	E(GPa)	Vol.fraction
Kevlarfiber	131	30%
E-glassfiber	72.5	20%
Epoxymatrix	2.41	50%

- Calculatethe longitudinal elasticmodulus.

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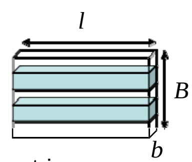
Continuous-alignedfibers



Tensilestrength

Longitudinal: $\sigma^*_{cl} = v_m \sigma'_m + v_f \sigma^*_f$ ← Similar to elastic modulus

Thisis assumingthat the fiber failsprior to the matrix.

σ'_m = Stress in the matrix at failure

σ^*_f = Tensilestrengthofthe reinforcementfiber

Transverse:more complexduetomany factors that affect it (e.g. matrix & fiberproperties,fiber-matrix bondstrength, presence of voidsetc…)

Ingeneral,strongeralong longitudinaldirection

Table 16.1 Typical Longitudinal and Transverse Tensile Strengths for Three Unidirectional Fiber-Reinforced Composites. The Fiber Content for Each Is Approximately 50 Vol%.

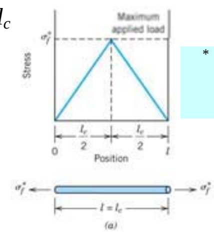
Material	*Longitudinal Tensile Strength (MPa)*	*Transverse Tensile Strength (MPa)*
Glass–polyester	700	20
Carbon (high modulus)–epoxy	1000	35
Kevlar–epoxy	1200	20

Source: D. Hull and T. W. Clyne, *An Introduction to Composite Materials,* 2nd edition, Cambridge University Press, 1996, p. 179.

Discontinuous& aligned fibers

Discontinuouswhenfiberlength< 15 l_c

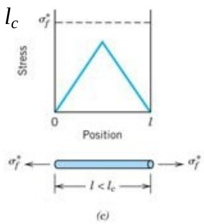
If$l > l_c$



$$\sigma^*_{cd} = \sigma^*_f v_f \left(1 - \frac{l_c}{2l}\right) + \sigma'_m v_m$$

Similar to continuouscase, exceptfor the lengthfactor.

If$l < l_c$



$$\sigma^*_{cd'} = \frac{l\tau_c}{d} v_f + \sigma'_m v_m$$

τ_c =Smallerof:
- fiber-matrixbondstrength
- matrixshearyield strength.

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Discontinuous&randomfibers

Discontinuous,random 2D fibers

- Example: Carbon-Carbon
  --process: fiber/pitch, then burn out at up to 2500C.
  --uses:diskbrakes, gas turbineexhaustflaps, nose cones.

$$E_c = E_m V_m + K E_f V_f$$

efficiencyfactor (dependson $v_f$and E_f/E_m):
--aligned1D: K= 1 (anisotropic)
--random 2D: K = 3/8 (2D isotropy)
--random 3D: K = 1/5 (3D isotropy)

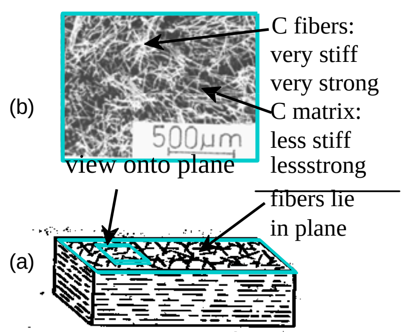


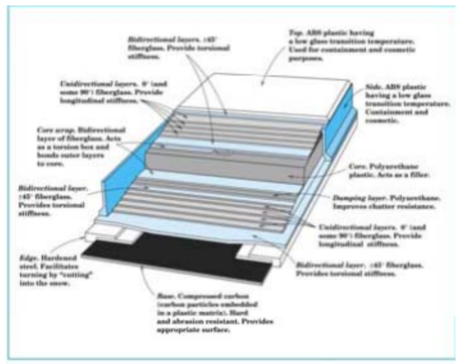
Table 16.2 Properties of Unreinforced and Reinforced Polycarbonates with Randomly Oriented Glass Fibers

		Fiber Reinforcement (vol%)		
Property	*Unreinforced*	*20*	*30*	*40*
Specific gravity	1.19–1.22	1.35	1.43	1.52
Tensile strength [MPa (ksi)]	59–62 (8.5–9.0)	110 (16)	131 (19)	159 (23)
Modulus of elasticity [GPa (10^6 psi)]	2.24–2.345 (0.325–0.340)	5.93 (0.86)	8.62 (1.25)	11.6 (1.68)
Elongation (%)	90–115	4–6	3–5	3–5
Impact strength, notched Izod (lb_f/in.)	12–16	2.0	2.0	2.5

Source: Adapted from Materials Engineering's *Materials Selector*, copyright © Penton/IPC.

Polymermatrixcomposites

- Glass fiber-reinforced polymer (GFRP) composites:fiberglass
  - Somereasonsforusing glassasfibers:
    - Easy to draw fibersfrom molten state.
    - Strength.
    - Readilyavailable/economic.
    - Chemicalinertness(e.g. non-corrosive).
  - Applications:automotive& marinebodies,storage containers,industrial flooring…



One relatively complex composite material is the modern ski. In this illustration, a cross section of a high-performance snow ski, are shown the various components. The function of each component is noted, as well as the material that is used in its construction. (Courtesy of Evolution Ski Company, Salt Lake City, Utah.)

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Polymermatrixcomposites

- Carbonfiber-reinforcedpolymer(CFRP)composites:
  - SomereasonforusingC-fibers:
    - Highestspecificmodulusandspecificstrengthofall reinforcingfibermaterials.
    - RetainhighmodulusandTSatelevatedT(chemical oxidationmaybeaproblem).
    - AtornearRT, veryinert.
    - Canengineerspecificmechanicalandphysicalproperties.
  - Some applications:fishingrods, golf clubs,bicycles, military and commercial aircraft structural components…

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Polymermatrixcomposites

- Aramid(e.g.Kevlar)fiber-reinforcedpolymercomposites:
  - High strength, highmodulus.
  - Muchbetter strength-to-weightthan metals.
  - Stable torelativelyhighT (highmechanicalpropertiesmaintainedfrom ~- 200 to 200^{o}C).
  - Relativelyinert chemically(exceptstrong acids).
  - Uses: bullet-proofvests, tires, ropes, missilecases, parts for automotive brake,clutchliningandgaskets…

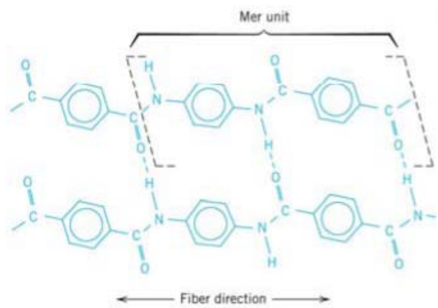

FIGURE 16.10 Schematic representation of mer and chain structures for aramid (Kevlar) fibers. Chain alignment with the fiber direction and hydrogen bonds that form between adjacent chains are also shown. [From F. R. Jones (Editor), *Handbook of Polymer-Fibre Composites*. Copyright © 1994 by Addison-Wesley Longman. Reprinted with permission.]

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Carbon-carboncomposites

- Carbonfiberreinforcedcarbonmatrixco mposites.
  - High modulus& TS (retainedtoT> 2000^{o}C).
  - Resistant tocreep.
  - Large fracturetoughness.
  - Small thermal expansioncoefficient.
  - Highthermalconductivity.
  - Uses:rocketmotors,frictionmaterialforaircraftand high-performanceautomobilebrakes, componentsfor turbine engines…
  - Very expensivemainlydueto relativelycomplex processing.

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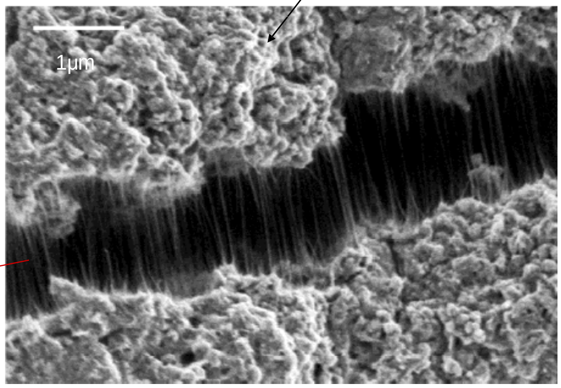
Carbonnanotubecomposite

Material	Young's Modulus
Aluminum alloys	72GPa
Steel	200GPa
Tungsten	400GPa
Carbon Nanotube	>1000GPa

Carbonmatrix



Nanotubebundles

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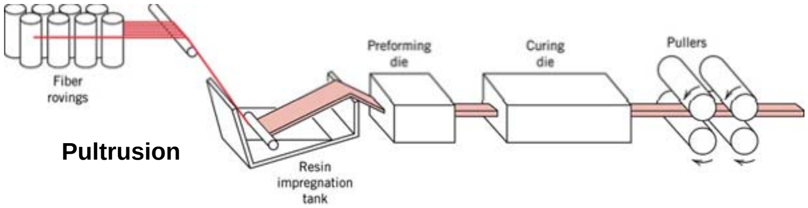
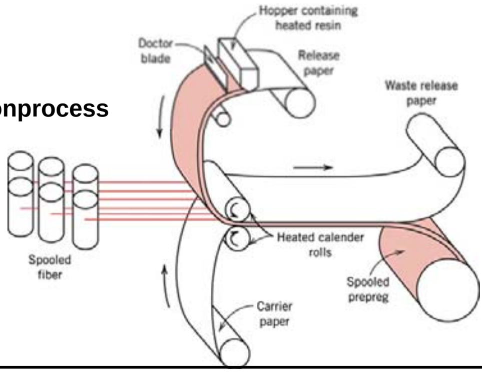
Processingof fiber-reinforcedcomposites

Pultrusion



Prepregproductionprocess



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Processingof fiber-reinforcedcomposites

Filamentwinding

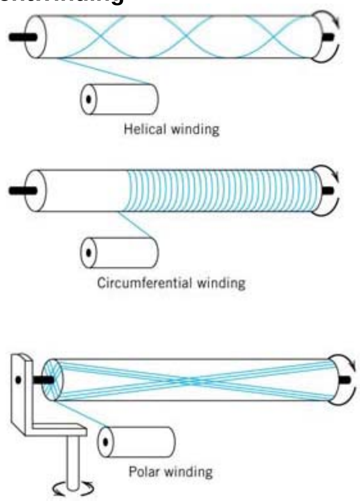

FIGURE 16.14 Schematic representations of helical, circumferential, and polar filament winding techniques. [From N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials*, The Macmillan Company, New York, 1981.]

Designexample

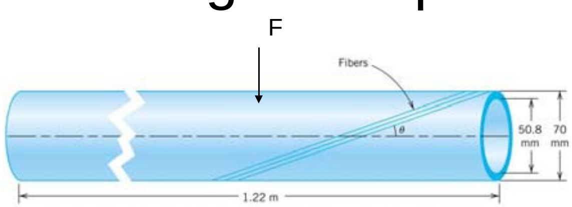

FIGURE 16.15 Schematic representation of a filament-wound composite shaft, which is the subject of Design Example 16.1.

Requirements -atF=890N,deflection<0.33mm

-Circumferentialwindingwithθ=15º

A) Whichfiber(s),ifembeddedinepoxymatrix,meetthethesecriteria?

B) Decideonthemostcost-effectivefiber.

Table 16.8 Elastic Modulus, Density, and Cost Data for Glass and Various Carbon Fibers and Epoxy Resin

Material	*Elastic Modulus (GPa)*	*Density (g/cm³)*	*Cost ($/kg)*
Glass fibers	72.5	2.58	2.50
Carbon fibers (standard modulus)	230	1.80	35.00
Carbon fibers (intermediate modulus)	285	1.80	70.00
Carbon fibers (high modulus)	400	1.80	175.00
Epoxy resin	2.4	1.14	9.00

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Conceptsto remember…

- Matrix& reinforcement.
- Whatcompositecharacteristics dependon.
- **Classification**:matrix-based– MMC,CMC, PMC; reinforcement-based.
- **Particlereinforcedcomposites**: upperandlower bound for E (rule of mixtures).
- **Fiber-reinforcedcomposites**
  - Continuous-aligned,discontinuous-aligned&discontinuous-randomcases.
  - Criticallength.
  - Longitudinal&transverse properties.
  - Isostrain&isostresscases.
- **Structuralcomposites**.

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