재료의 기계적 거동 (Mechanical Behavior of Materials)

Composite Materials

Myoung-Gyu Lee (이명규)

Department of Materials Science & Engineering
Seoul National University
Seoul 151-744, Korea
email : myounglee@snu.ac.kr

TA: Chanmi Moon (문찬미)
30-521 (Office)
chanmi0705@snu.ac.kr (E-mail)

2021-05-23

Introduction

• **We've addressed the improvement of the mechanical properties of materials by modifying the internal structure of the material system either by alloying or processing.**

• **We can also develop materials with even different properties by introducing additional phases/materials into a host material. This mixture of phases is termed a composite.**

• **In general, composites are relatively macroscopic mixtures of phases/materials. These mixtures are sometimes natural, but are generally artificial.**

• **By mixing two different phases or materials, we can develop materials that have properties which are an average of those of the two components.**

Introduction

- In a composites, strength/properties = average of strength/properties of the individual materials. We design composites so as to obtain the best attributes of the individual constituents.

- Microstructure of a composite = matrix + reinforcement

–Matrix:
- phase that holds reinforcement together
- protects the reinforcement
- transmits load to the reinforcement.

–Reinforcement:
- filaments, fibers, whiskers, etc., which have intrinsically high strength and modulus ; reinforcements are often too brittle to use in monolithic forms. Sometimes "soft" reinforcements are used too.

Introduction

- **Interface between reinforcement and matrix is often the most critical element in determining materials properties and performance.**

- **Interface influences transfer of stress from matrix to fiber.**

- **Interface influences crack propagation.**

- **Chemical reactions in interface change the properties of the fiber and matrix locally as well as the chemistry.**

- **Stress concentration occurs.**

Classification of Composites

• On basis of matrix:
– Polymer matrix composites (PMCs)
– Metal matrix composites (MMCs)
– Ceramic matrix composites (CMCs)

• On basis of reinforcement
– Particle reinforced composites (e.g. Precipitates)
– Short fiber or whisker reinforced composites (e.g. Continuous fiber or sheet reinforced MMCs)

Classification of Composites

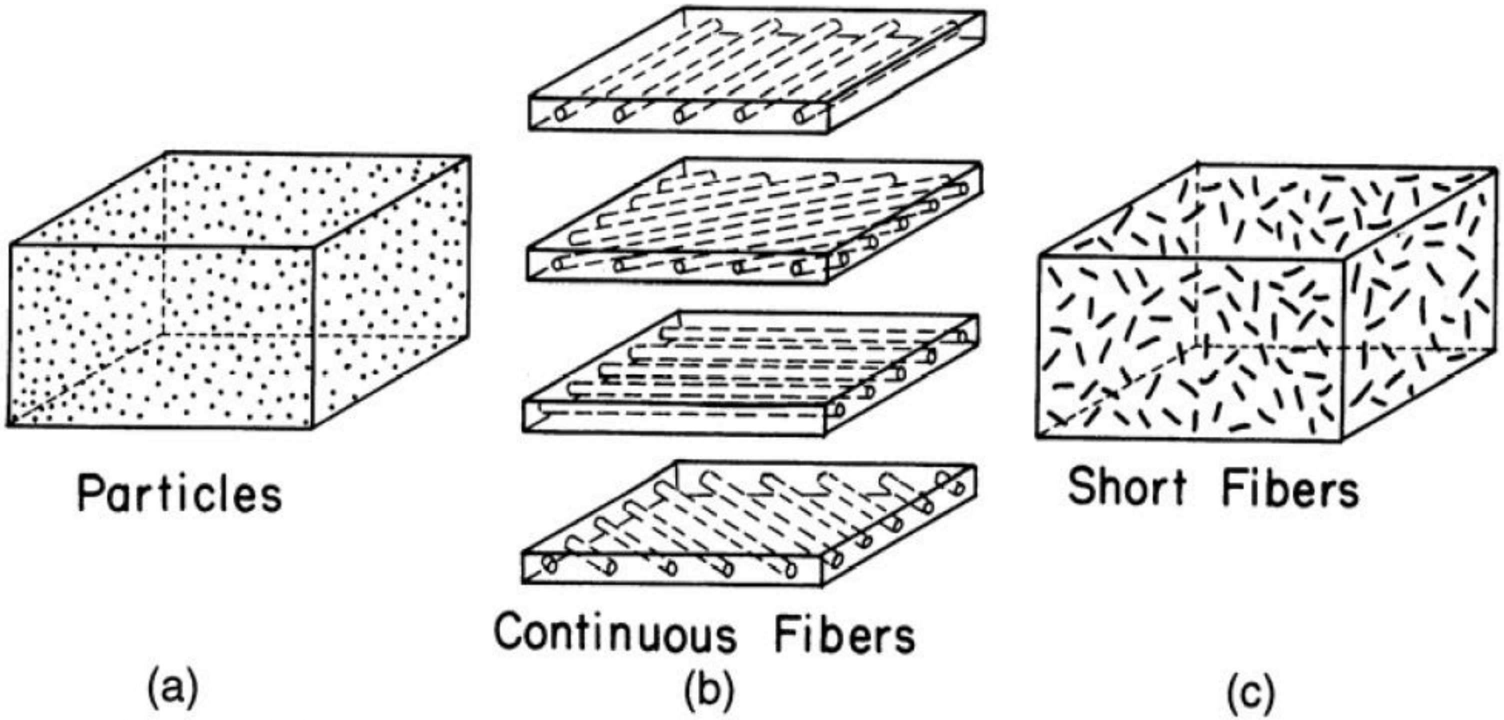


Figure 1.4 Different kinds of reinforcement in composite materials. (a) Composite with particle reinforcement. (b) Composite with continuous fibers with four different orientations (shown separately for clarity). (c) Composite reinforced with short, discontinuous fibers.

Classification of Composites

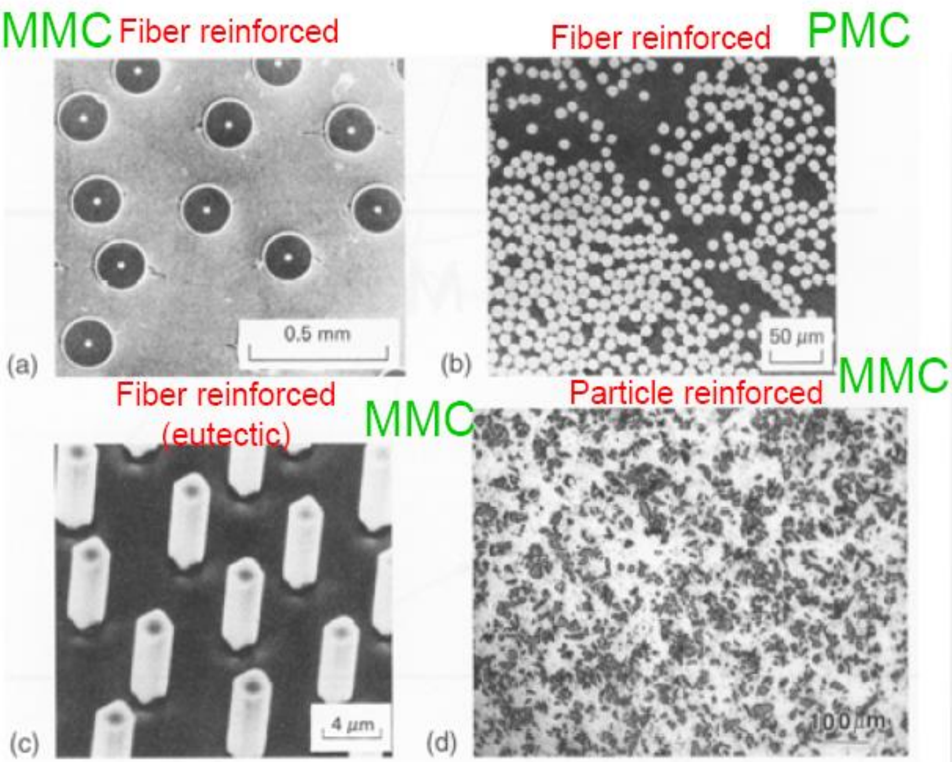


Figure 15.1 (a) Transverse section of a boron fiber reinforced aluminum composite. $V_f = 10\%$. (b) Transverse section of a carbon fiber reinforced polyester resin. $V_f = 50\%$. (Optical.) (c) Deeply etched transverse section of a eutectic composite showing NbC fibers in an Ni–Cr matrix. (Courtesy of S. P. Cooper and J. P. Billingham, GEC Turbine Gnerators Ltd, U.K.) (d) SiC particles in an Al alloy matrix (SEM). $V_p = 17\%$.

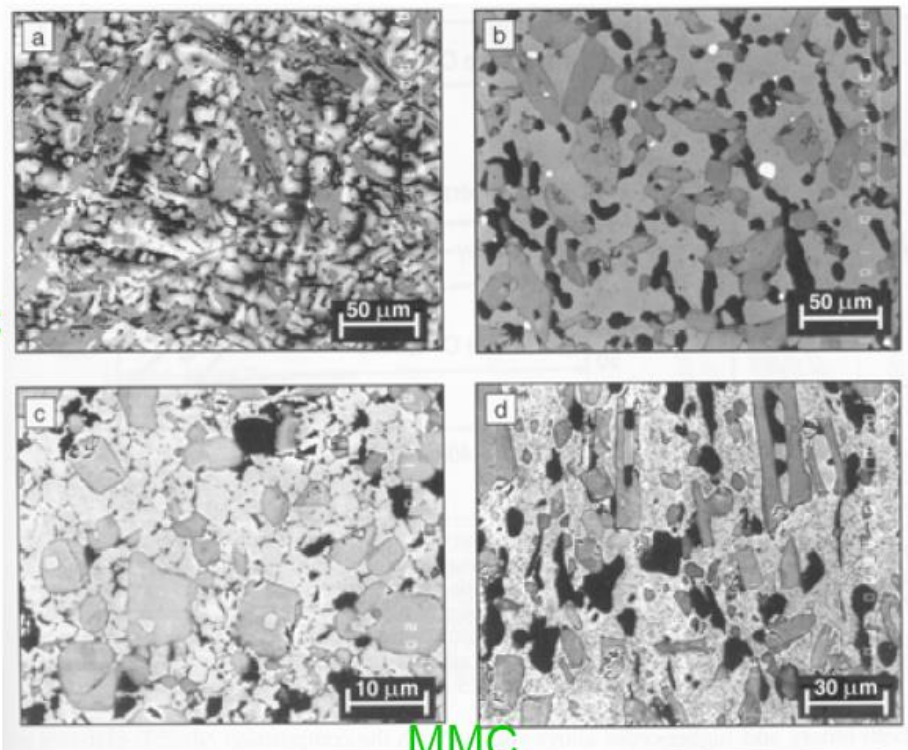


Figure 5. Microstructural evolution in Alloy 2 (see Table I for composition) in the following conditions: (a) as-cast, (b) homogenized (1300°C/24 h + 1400°C/76 h), and (c), (d) extruded (1350°C at 6:1 ratio), transverse and longitudinal sections, respectively. The light phase is Nb, the gray phase is $(Nb)_5Si_3$, and the black phase is the $Cr_2(Nb)$-type Laves phase.

What do properties depend upon?

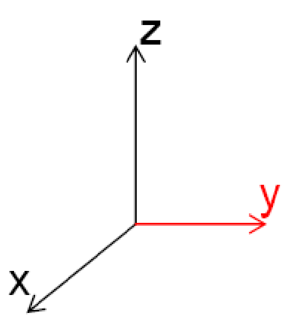
- **Matrix type – Structure and intrinsic properties**
- **Reinforcement – Concentration, Shape, Size, Distribution, Orientation**

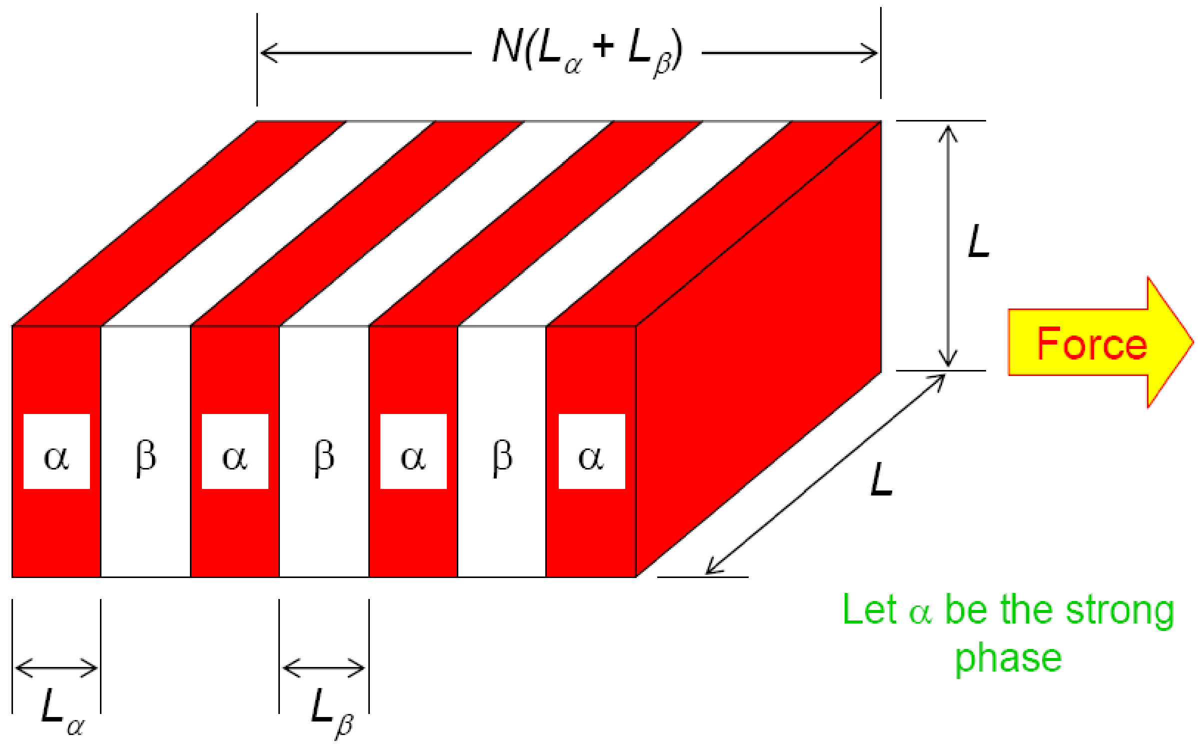
To begin, we consider a laminate composite in order to develop the basic principles of reinforcement.

Basic mechanics (1)

$$V_\alpha = \frac{L_\alpha}{(L_\alpha + L_\beta)}$$

$$V_\beta = \frac{L_\beta}{(L_\alpha + L_\beta)}$$





What do properties depend upon?

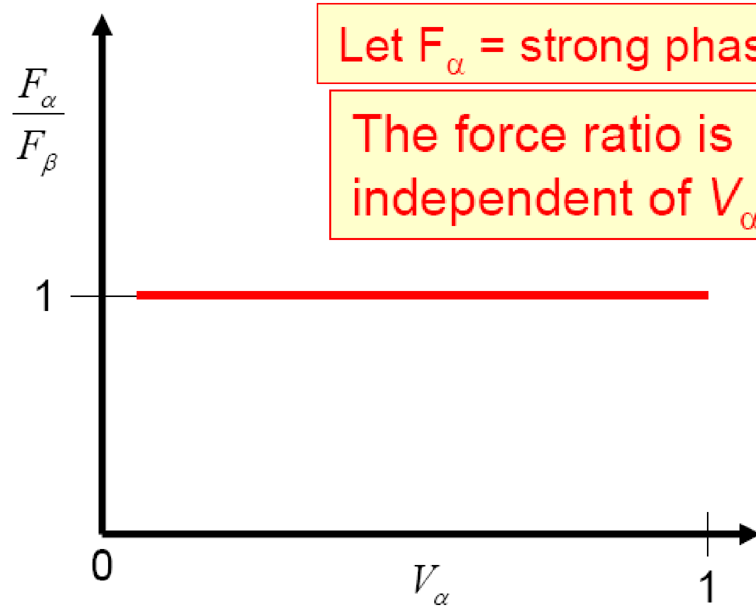
- Consider the case where a force is applied along the y-direction. In this instance, the stresses on the α and β lamellae are equal (i.e., $\sigma = F/L^2$).
- The composite strain is the weighted average of the individual strains in each lamellae.

$$\varepsilon_c = V_\alpha \varepsilon_\alpha + V_\beta \varepsilon_\beta$$

- The composite modulus is given by:

$$E_c = \frac{E_\alpha E_\beta}{V_\alpha E_\beta + V_\beta E_\alpha}$$

Iso-stress case



Let F_α = strong phase.

The force ratio is independent of V_α.

With this type of loading, both phases experience the same force and thus the same stress. Therefore, $F_\alpha/F_\beta = 1$.

What do properties depend upon?

- Point 1:
  - $V_\alpha = 0.5$; $V_\beta = 0.5$
  - $E_\alpha = 100$ GPa; $E_\beta = 10$ GPa

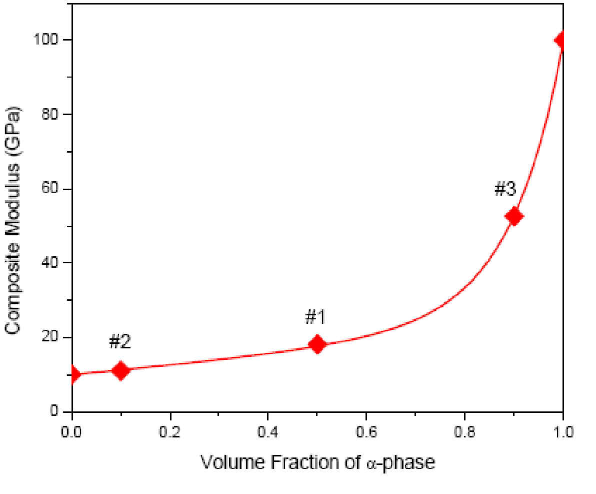
$$E_c = \frac{1000 \text{ GPa}^2}{(0.5 \times 10 \text{ GPa} + 0.5 \times 100 \text{ GPa})} = \frac{1000}{55} \text{ GPa} = 18.1 \text{ GPa}$$

- Point 3:
  - $V_\alpha = 0.9$; $V_\beta = 0.1$
  - $E_\alpha = 100$ GPa; $E_\beta = 10$ GPa

$$E_c = \frac{1000 \text{ GPa}^2}{(0.9 \times 10 \text{ GPa} + 0.1 \times 100 \text{ GP}} = \frac{1000}{19} \text{ GPa} = 52.6 \text{ GPa}$$

- Point 2:
  - $V_\alpha = 0.1$; $V_\beta = 0.9$
  - $E_\alpha = 100$ GPa; $E_\beta = 10$ GPa

$$E_c = \frac{1000 \text{ GPa}^2}{(0.1 \times 10 \text{ GPa} + 0.9 \times 100 \text{ GPa})} = \frac{1000}{91} \text{ GPa} = 11 \text{ GPa}$$

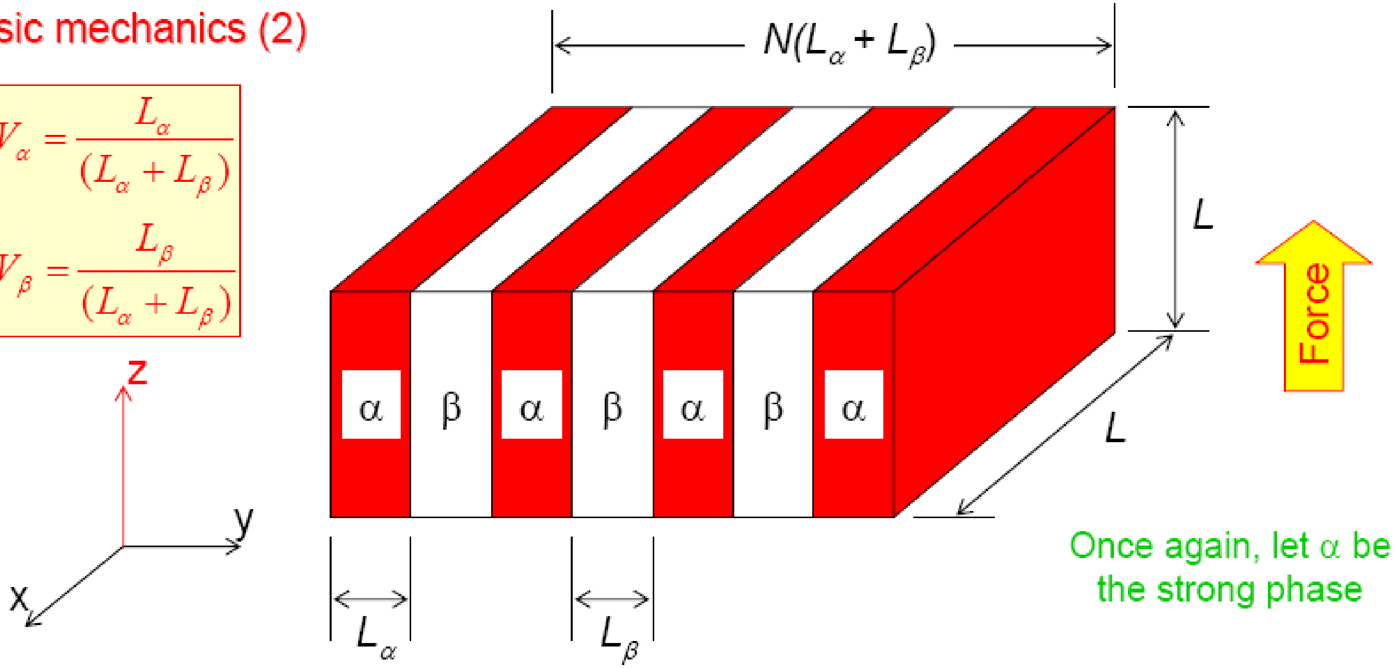


What do properties depend upon?

Basic mechanics (2)

$$V_\alpha = \frac{L_\alpha}{(L_\alpha + L_\beta)}$$

$$V_\beta = \frac{L_\beta}{(L_\alpha + L_\beta)}$$



Once again, let α be the strong phase

- Consider the case where a force is applied along the z-direction. In this instance, the stresses on the α and β lamellae are not equal.
- The strains on the α and β lamellae are equal.

$$\varepsilon_c = \varepsilon_\alpha = \varepsilon_\beta$$

- The composite modulus is given by:

$$E_c = V_\alpha E_\alpha + V_\beta E_\beta$$

Iso-strain case

$$\sigma_c = V_\alpha \sigma_\alpha + V_\beta \sigma_\beta$$

What do properties depend upon?

- Point 1:
  - $V_\alpha = 0.5$; $V_\beta = 0.5$
  - $E_\alpha = 100$ GPa; $E_\beta = 10$ GPa

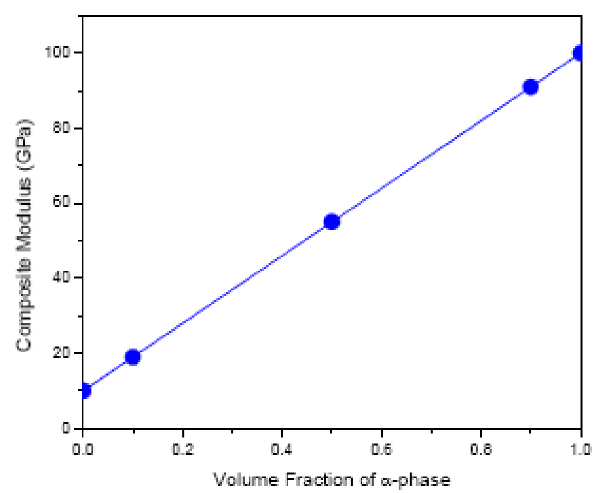
$$E_c = (0.5 \times 100\text{ GPa} + 0.5 \times 10\text{ GPa})$$
$$= 55\text{ GPa}$$

- Point 3:
  - $V_\alpha = 0.9$; $V_\beta = 0.1$
  - $E_\alpha = 100$ GPa; $E_\beta = 10$ GPa

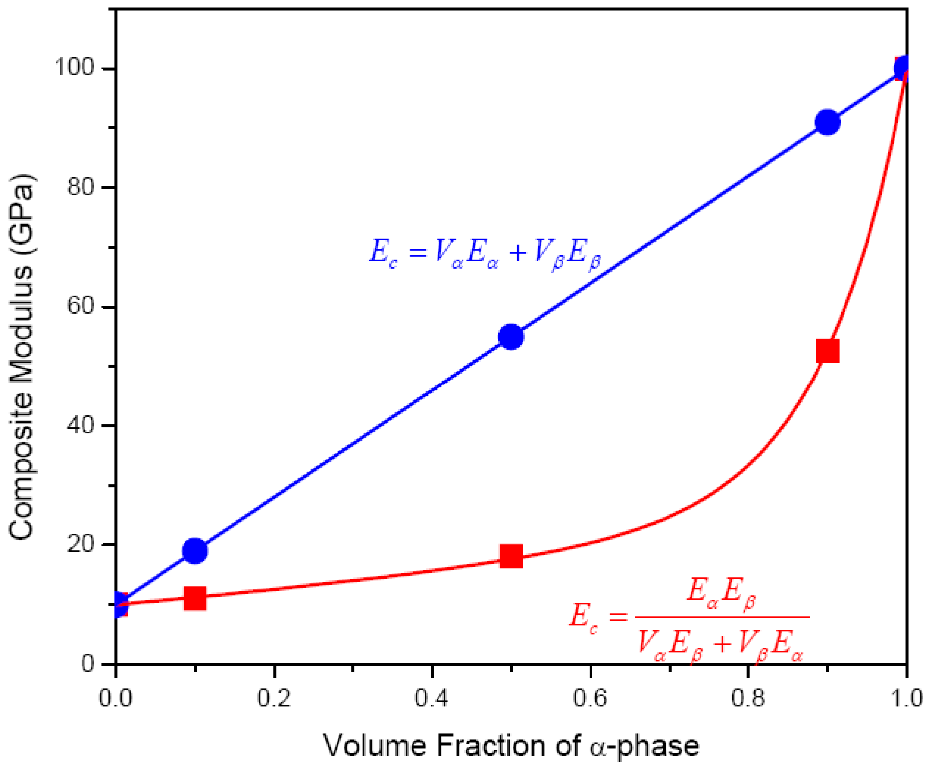
$$E_c = (0.9 \times 100\text{ GPa} + 0.1 \times 10\text{ GP}$$
$$= 91\text{ GPa}$$

- Point 2:
  - $V_\alpha = 0.1$; $V_\beta = 0.9$
  - $E_\alpha = 100$ GPa; $E_\beta = 10$ GPa

$$E_c = (0.1 \times 100\text{ GPa} + 0.9 \times 10\text{ GPa})$$
$$= 19\text{ GPa}$$



What do properties depend upon?



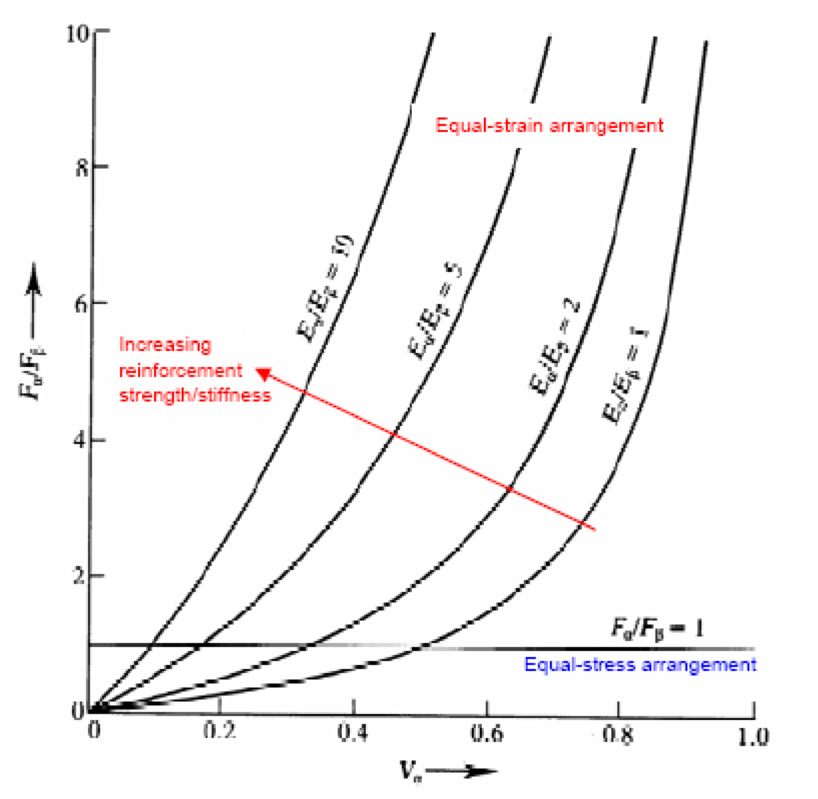
The blue curve shows the upper bound for modulus and the red curve shows the lower bound as calculated using the rule of mixtures. The moduli of particle-reinforced materials generally lies between the values predicted for laminate composites, but near the lower bound.

What do properties depend upon?

$\boxed{E_c = V_m E_m + K_c V_p E_p}$ and $\boxed{\sigma_c = V_m \sigma_m + K_s V_p \sigma_p}$,

where K_c and K_s are empirical constants with values of less than 1

$(K_c \neq K_s)$



- What this plot shows is that the equal-strain condition for reinforcement (i.e., strong phase aligned parallel to applied force) is most useful for reinforcement.

- Under these conditions, the strengthening phase (i.e., the reinforcement) is much more effective at carrying load.

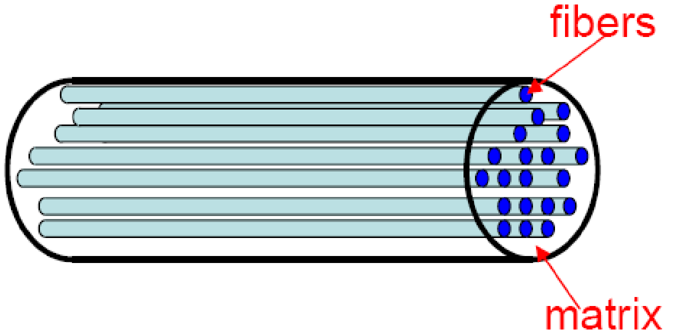
Reinforcement with continuous fibers

Material class	Material	E (GN/m^2)	T.S. (GN/m^2)	ρ (Mg/m^3)	E/ρ (MNm/kg)	T.S./ρ (MNm/kg)
Metals	Be	315	1.3	1.8	175	0.72
	Pearlitic steel	210	4.2	7.9	27	0.53
	Stainless steel	203	2.1	7.9	26	0.27
	Mo	343	2.1	10.3	33	0.20
	β-Ti	119	2.3	4.6	26	0.50
	W	350	3.9	19.3	18	0.20
Ceramics	Al_2O_3	380–480	1.4–2.4	3.9–4.0	95–123	0.35–0.62
	Al_2O_3 whiskers	300–1500	2–20	3.3–3.9	77–455	0.51–6.1
	B	386–400	3.1–7.0	2.6	148–154	1.2–2.7
	BN	90	1.4	1.9	47	0.74
	Graphite whiskers	700	20	2.2	318	9.1
	Graphite	390–490	1.5–4.8	1.95–2.2	177–251	0.68–2.5
	E Glass	72–76	3.5	2.55	28–30	1.4
	S Glass	72	6	2.5	29	2.4
	SiC	380–400	2.4–3.9	2.7–3.4	112–148	0.71–1.4
	SiC whiskers	400–700	3–20	3.2	125–219	0.94–6.3
	Si_3N_4	380	5–7	3.2–3.8	100–119	1.3–2.2
Polymer	Kevlar	133	2.8–3.6	1.4–1.5	89–95	1.9–2.6

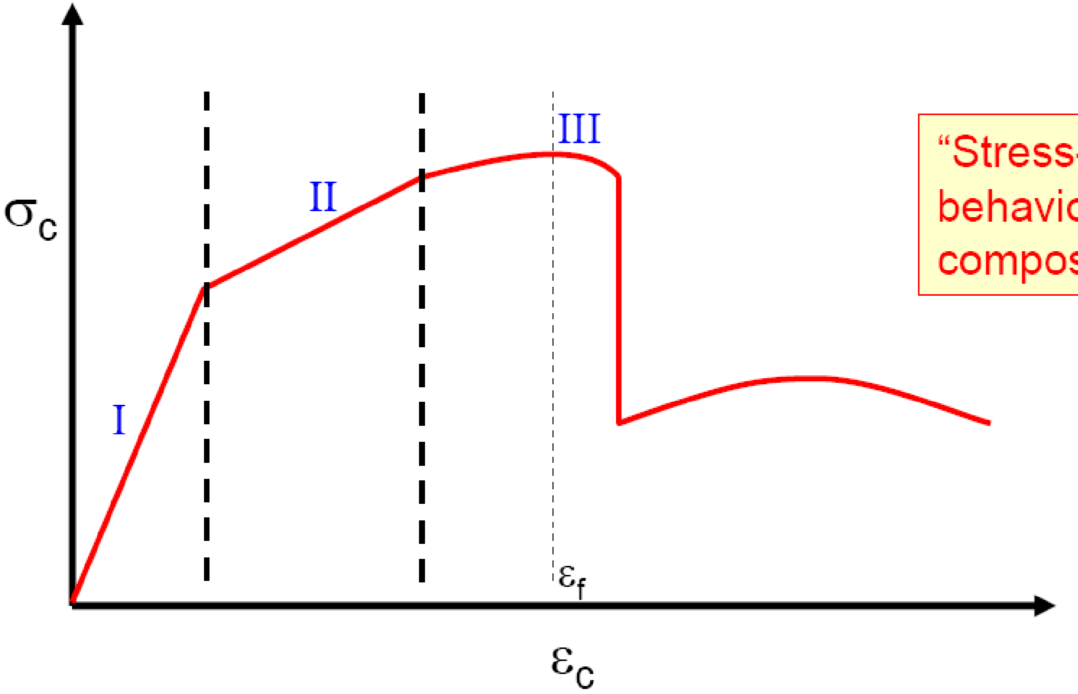
Notes: Variations in properties for a given material result from different processing conditions employed to manufacture them. *Data from*: (1) *Modern Composite Materials*, ed. L. J. Broutman and R. H. Krock, Addison-Wesley, Reading, Mass., 1967, articles of P. T. B. Shaeffer (p. 197), J. A. Roberts (p. 228), F. E. Wawner, Jr., (p. 244). (2) J. D. Embury, in *Strengthening Methods in Crystals*, ed. A. Kelly and R. B. Nicholson, Wiley, New York, 1971, p. 331. (3) *Metal Matrix Composites: Processing and Interfaces*, ed. R. K. Everett and R. J. Arsenault, *Treat. Matls. Sc. and Tech.*, Academic Press, San Diego, 1991, articles by W. C. Harrigan, Jr. (p. 1) and R. B. Bhagat (p. 43). (4) D. Hull, *Introduction to Composite Materials*, Cambridge University Press, Cambridge, England, 1981.

Table 6.1
Properties of Selected Fibers and Whiskers

Reinforcement with continuous fibers



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



"Stress-strain behavior is a composite too"

Reinforcement with continuous fibers

- Stage I
  - Both fiber and matrix deform elastically.

$$\sigma_c = \varepsilon_c E_c = \varepsilon_c \left[V_f E_f + V_m E_m \right]$$

- Stage II
  - Generally, the matrix will begin to deform plastically at a strain that is less than the elastic limit of the fiber.

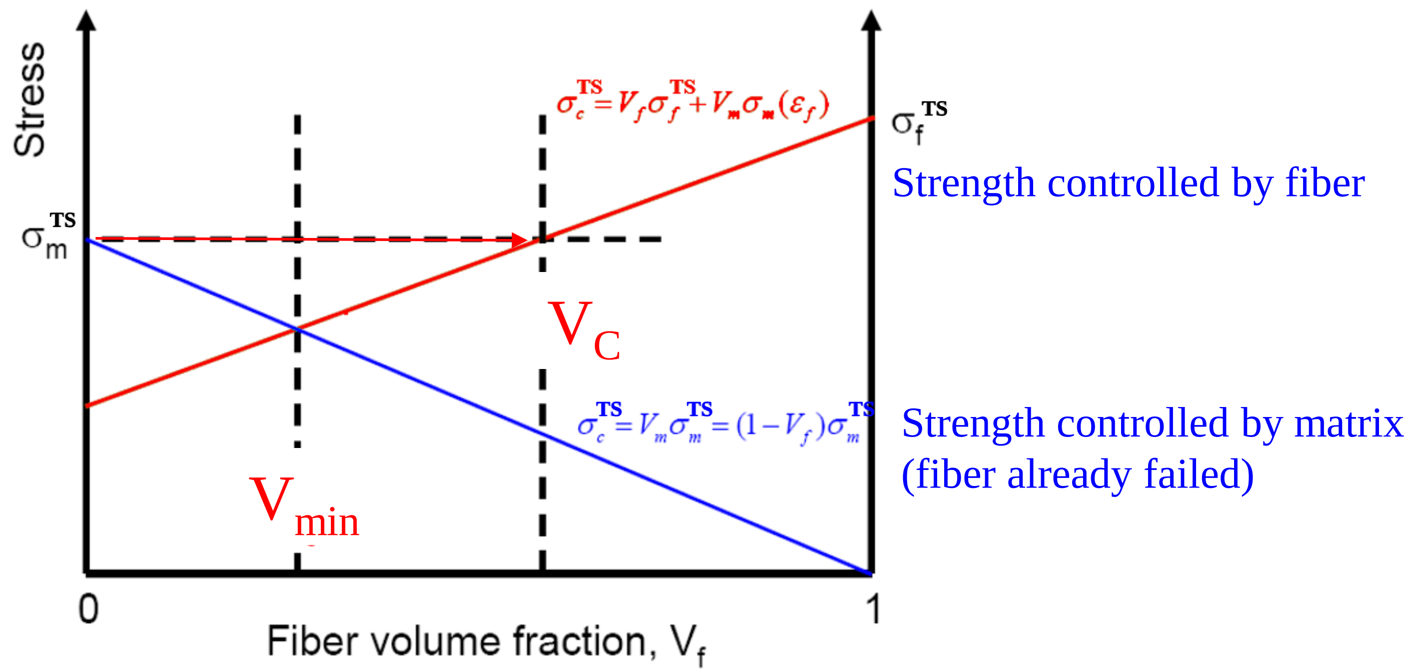
$$\sigma_c = V_f \varepsilon_c E_f + V_m \sigma_m \left(\varepsilon_c \right)$$

- Stage III
  - This stage only occurs if the fibers deform plastically prior to fracture

$$\sigma_c = V_f \sigma_f \left(\varepsilon_c \right) + V_m \sigma_m \left(\varepsilon_c \right)$$

- ε_f = fiber failure strain
  - Fibers begin to deform locally or fracture.

Reinforcement with continuous fibers (Tensile strength)



* V_{min}= min. fiber volume fraction for having larger tensile strength than matrix does…

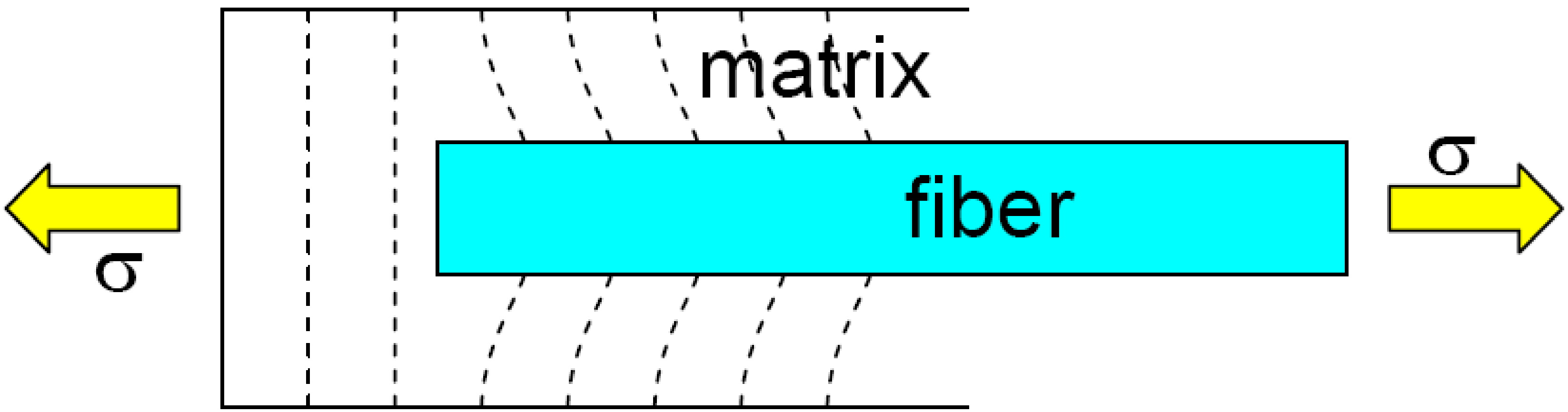
$$V_{min} = \frac{\sigma_m^{TS} - \sigma_m(\varepsilon_f)}{\sigma_f^{TS} + \sigma_m^{TS} - \sigma_m(\varepsilon_f)}$$

* V_c= critical fiber volume fraction to ensure the composites has at least same strength of matrix

$$V_C = \frac{\sigma_m^{TS} - \sigma_m(\varepsilon_f)}{\sigma_f^{TS} - \sigma_m(\varepsilon_f)}$$

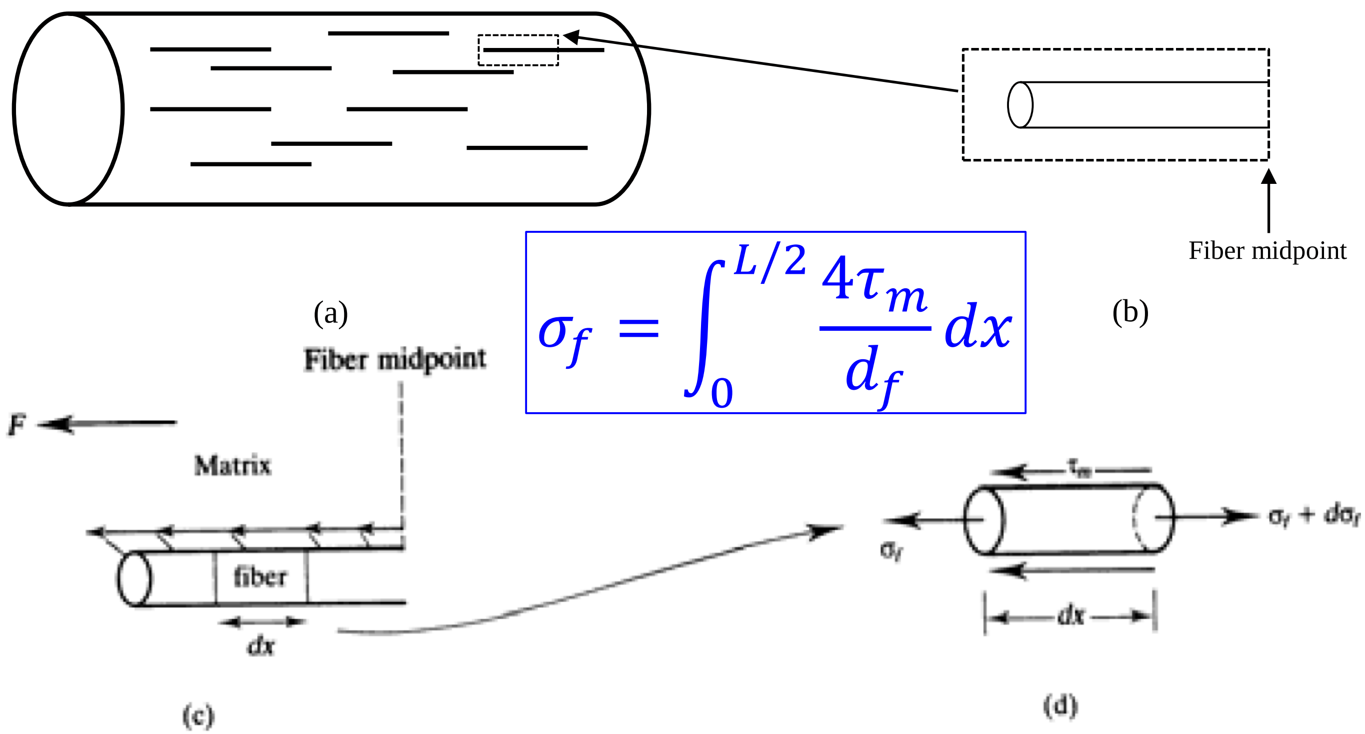
Typical values for V_c and V_{min} range from 0.02 to 0.10

Reinforcement with discontinuous fibers



- No load is transferred to the fiber at its ends.
- Load is transferred along the length of the fiber.

Reinforcement with discontinuous fibers

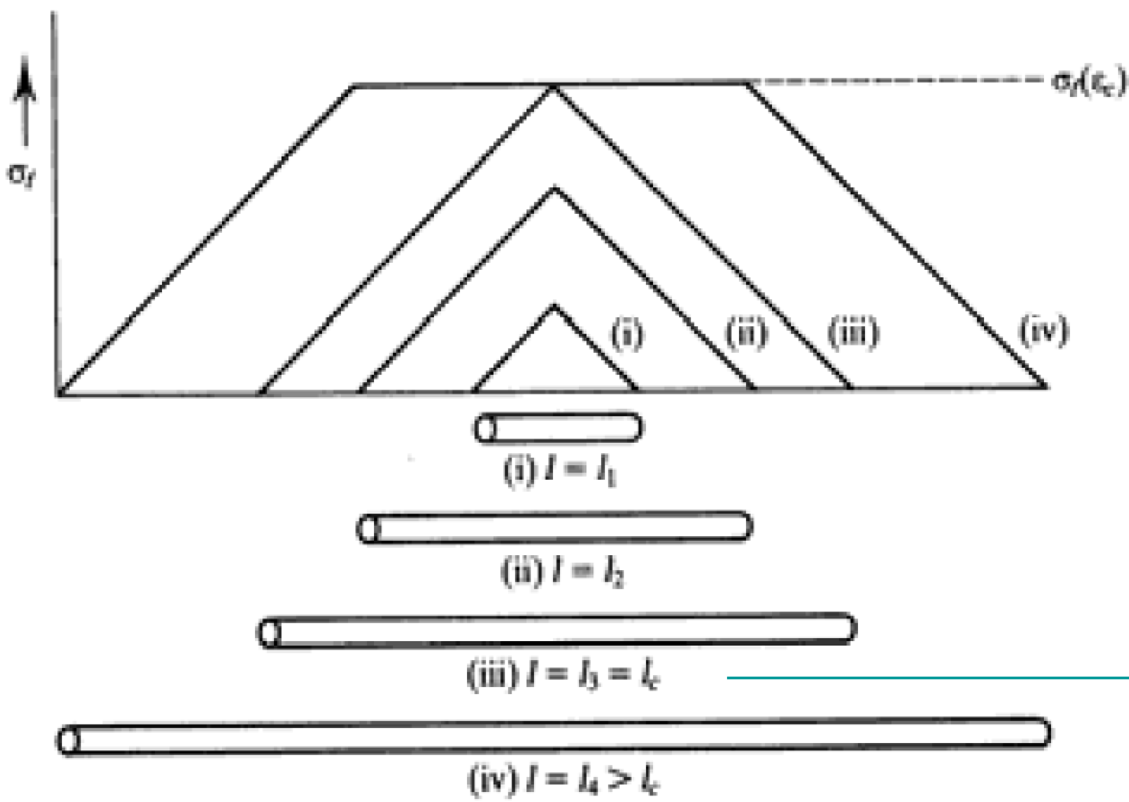


$$\sigma_f = \int_0^{L/2} \frac{4\tau_m}{d_f} dx$$

Figure 6.9 (a) A schematic of a matrix containing discontinuous fibers. (b) The geometry of one fiber is shown in the cross-hatched region. At the fiber end, tensile load cannot be transferred instantaneously to the fiber from the matrix. (c) The tensile load-transfer process is accomplished by development of a shear stresses at the fiber-matrix interface as a result of the relative displacement of the fiber and the matrix. This displacement is proportional to the arrows shown, and is zero at the fiber midpoint and a maximum at the fiber end. (d) A small increment dx of fiber length; the incremental fiber stress ($d\sigma_f$) is obtained by a balance of forces, i.e., $(\pi d_f^2/4)d\sigma_f = \tau_m(\pi d_f dx)$, where τ_m is the matrix shear stress.

Reinforcement with discontinuous fibers

Whether the fiber midpoint carries the same stress it would if it were continuous depends on its length. If the fiber length (e.g., l_1, l_2) is less than a certain critical length l_c, then σ_f does not attain this value. When the fiber length is greater than l_c (e.g., l_4) it does. In this diagram $l_3 = l_c$.



$$\sigma_f = \int_0^{L/2} \frac{4\tau_m}{d_f}\,dx$$

Critical fiber length
=> When the strength is the same as fiber tensile strength

Reinforcement with discontinuous fibers

- In discontinuous fibers, there is a critical fiber length L_c for effective strengthening.

$$L_c = d_f \, \sigma_f / 2 \, \tau_{my}$$

where σ_f= tensile strength of fiber, τ_{my}= shear strength of fiber-matrix interface, and d_f= fiber diameter.

- Fibers that are shorter than the critical length have less strengthening per unit volume than continuous fibers.