4. FIBER-REINFORCED COMPOSITE

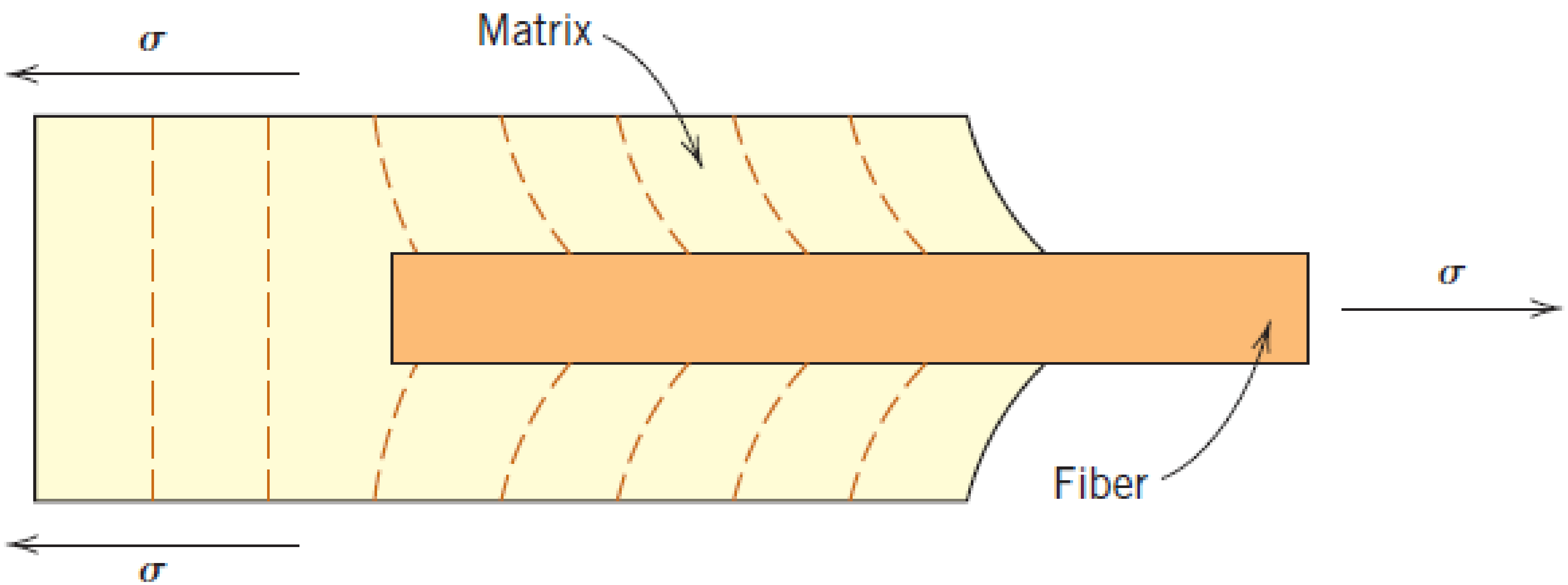
- This form of composite (fiber-reinforced) is grown in the matrix are usually softer, so that the resulting product with a high strength / weight ratio.
- Matrix material to pass on the burden of fiber / fiber that absorbs stress.
- To get an effective strengthening and stiffening, then keep in mind the long critique of fiber.

EFFECT OF FIBER LENGTH

- Mechanical properties of fiber-reinforced composite is influenced by the nature of the fiber and how to load forwarded / transmitted on the fiber.

- Load transmittance is affected by the magnitude of the interfacial bonding between the fiber and the matrix.

- Under certain stress, the bond between the fiber and the matrix ends at the end of the fiber, so the resulting matrix deformation pattern is as shown in the following slide.



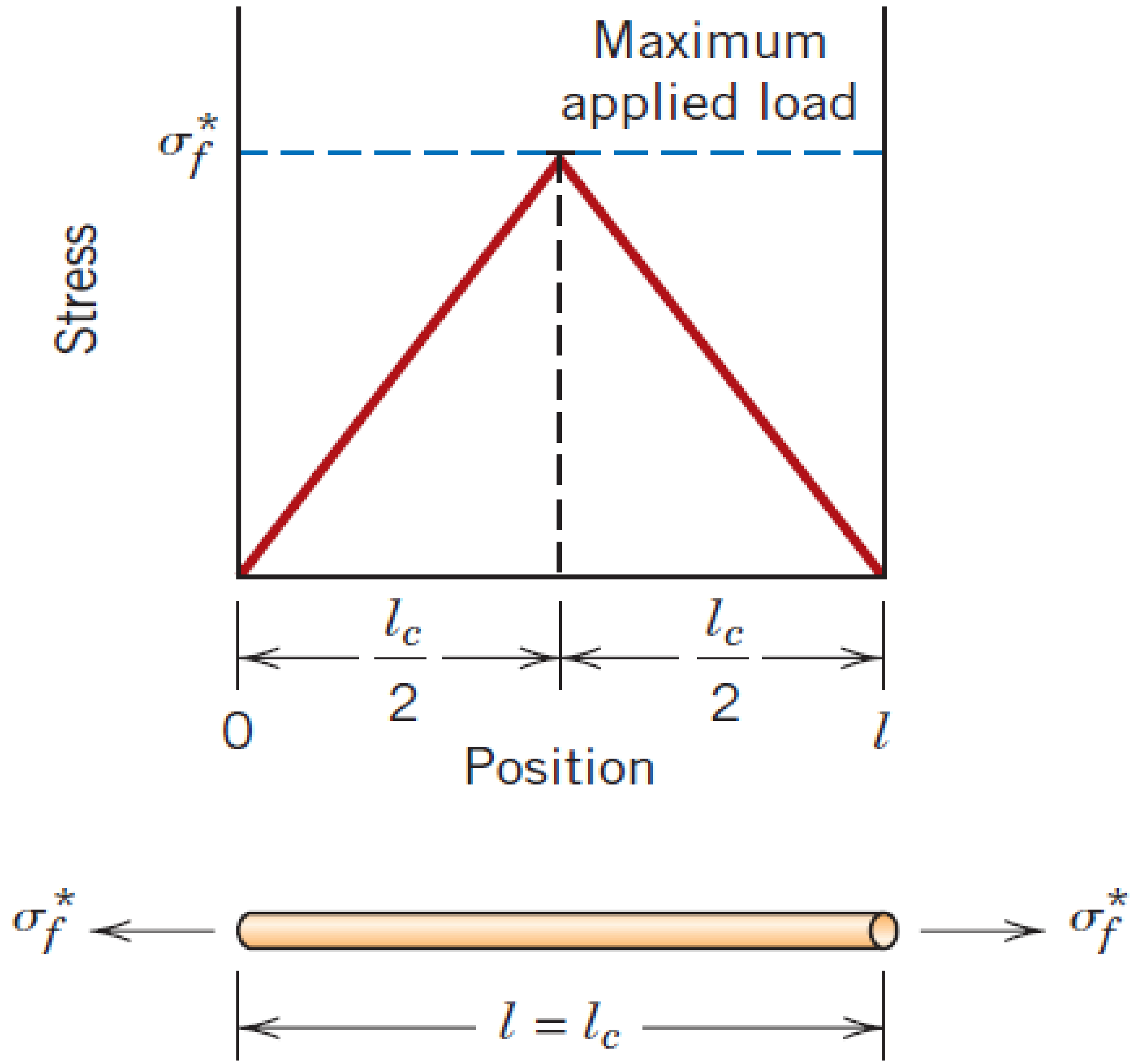
The deformation pattern in the matrix surrounding of fiber, subjected to an applied tensile.

- There are some critics long it takes for the fiber reinforcement to be effective.

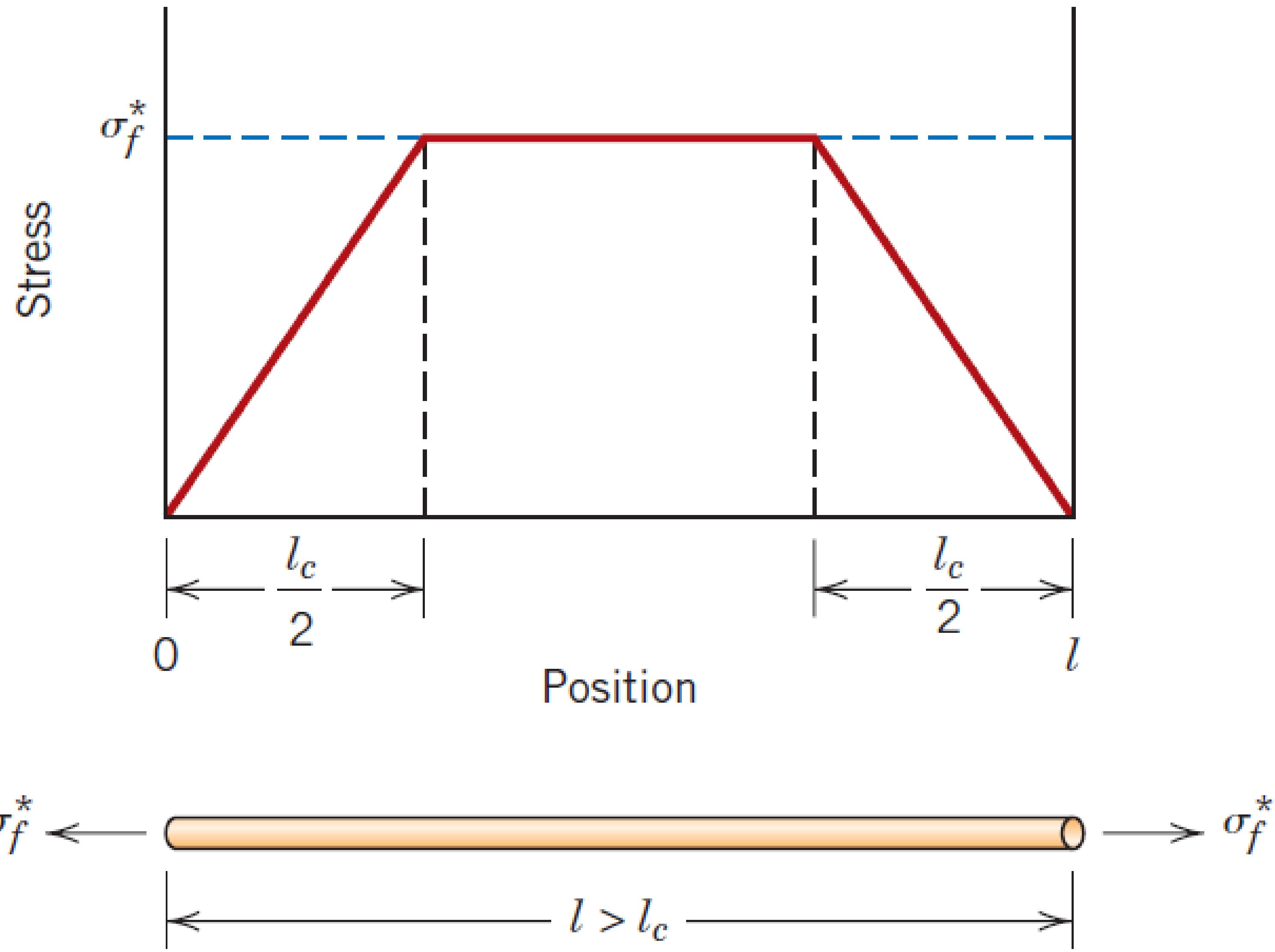
- **Critical length** l_c depends on the fiber diameter and tensile strength σ^*_f , also on the fiber-matrix bond strength τ_c, according to the following equation:

$$l_c = \frac{\sigma^*_f d}{2\tau_c} \tag{3}$$

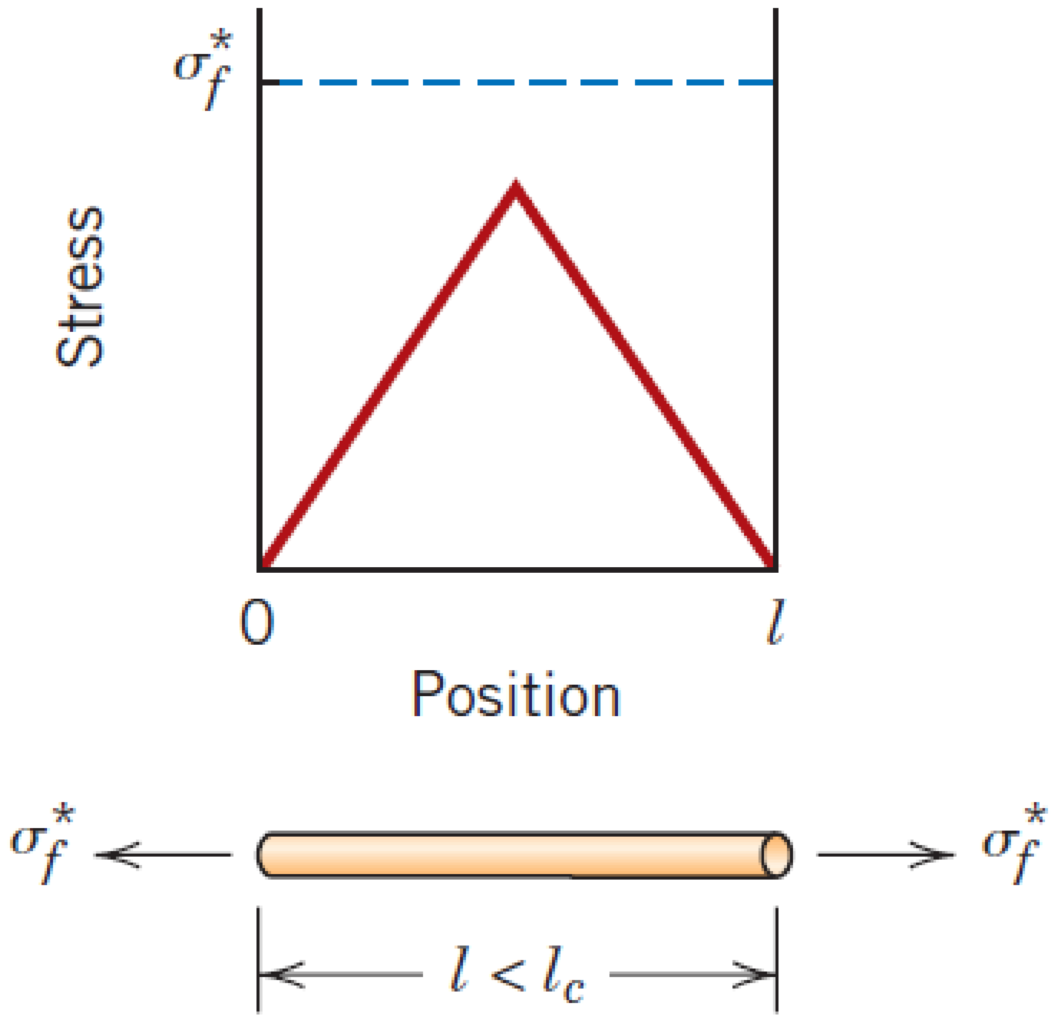
Example: for a combination of glass and carbon fiber, l_c = **1 mm**



Stress–position profiles when fiber length is equal to the critical length



Stress–position profiles when fiber length is greater than the critical length



Stress–position profiles when fiber length is less than the critical length

- Composite strength is due to the bonding between the fiber reinforcement with the matrix.
- The ratio length / diameter (called the aspect ratio) of the fiber will affect the properties of the composite. The larger aspect ratio, the stronger composite.
- Therefore for composite construction, the fiber length is better than short fibers.
  However, the fiber length is more difficult to produce than short fibers.
  Short fibers arranged in a matrix easier, but the effect is less good gains compared to the fiber length.

Hence the need for trade-offs between the type of fibers used to strengthen the desired effect.
The amount of fiber also affects the strength of the composite; increasing numbers of fibers, the stronger the resulting composite.
The maximum limit of the amount of fiber is about 80% of the composite volume. If the number of fibers> 80% then the matrix can not cover the entire fiber perfectly.

- Fibers with l >> lc (normal: l> 15 lc) is called continuous, while fibers with l <15 lc called discontinuous.
- If the fiber length <lc, then the resulting composite is basically the same as the particulate composites.

Mechanical properties of some reinforcing fibres

Material	*Density, ρ* ($kg \times m^{-3} \times 10^3$)	*Young's Modulus, E (GPa)*
• E-glass fibres	2.56	76
• Carbon fibres (High modulus)	1.75	390
• Carbon fibres (High strength)	1.95	250
• Kevlar fibres	1.45	125
• Silicon carbide (Monofilament)	3.00	410
• Silicon carbide (Nicalon)	2.50	180
• Alumina (Saffil)	2.80	100

Mechanical properties of some reinforcing fibres

Material	*Tensile strength* σ^* *(GPa)*	*Fibre radius,* r *(μm)*
• E-glass fibres	1.4-2.5	10
• Carbon fibres (High modulus)	2.2	8.0
• Carbon fibres (High strength)	2.7	8.0
• Kevlar fibres	3.2	12
• Silicon carbide (Monofilament)	8.6	140
• Silicon carbide (Nicalon)	5.9	14
• Alumina (Saffil)	1.0	3

EFFECT OF FIBER ORIENTATION AND CONCENTRATION

Arrangement or orientation of fibers to other fibers, fiber concentration, and uniformity of distribution will affect the strength and other properties of fiber-reinforced composites.

There are two extreme orientations: (i) regular parallel, and (ii) entirely random.

Continuous fibers are usually regularly aligned, discontinuous fiber can while regular or random.

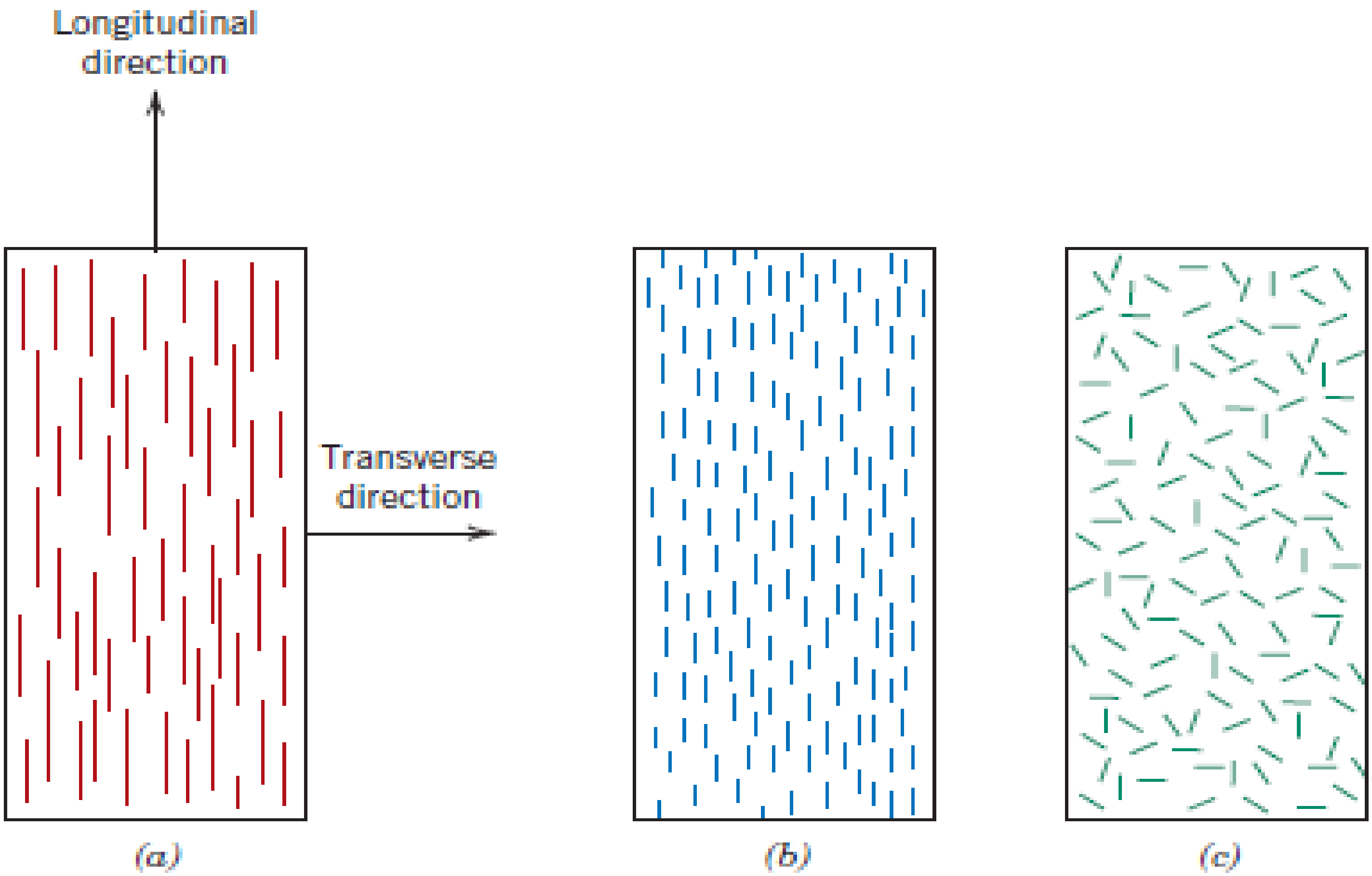
Continuous and Aligned Fiber Composites

Mechanical properties of the composite type of this depends on:

- Stress-strain behavior of the fiber and matrix
- Volume fraction of each component
- Direction of stress or strain on the composite material.

The properties of fiber composites with highly anisotropic regular, ie. the value of the properties depend on the direction of measurement.

We note the stress-strain behavior when stress applied parallel to the direction of the fiber material, the longitudinal direction, as shown in Figure (a).



Ilustrasi dari *fiber-reinforced composites* yang (a) kontinyu dan teratur, (b) diskontinyu dan teratur, and (c) diskontinyu dan acak stress vs. strain behavior of the fiber and the matrix phase, as shown in the following slide.

In this case the fiber is very fragile / brittle and the matrix is sufficiently elastic / ductile.

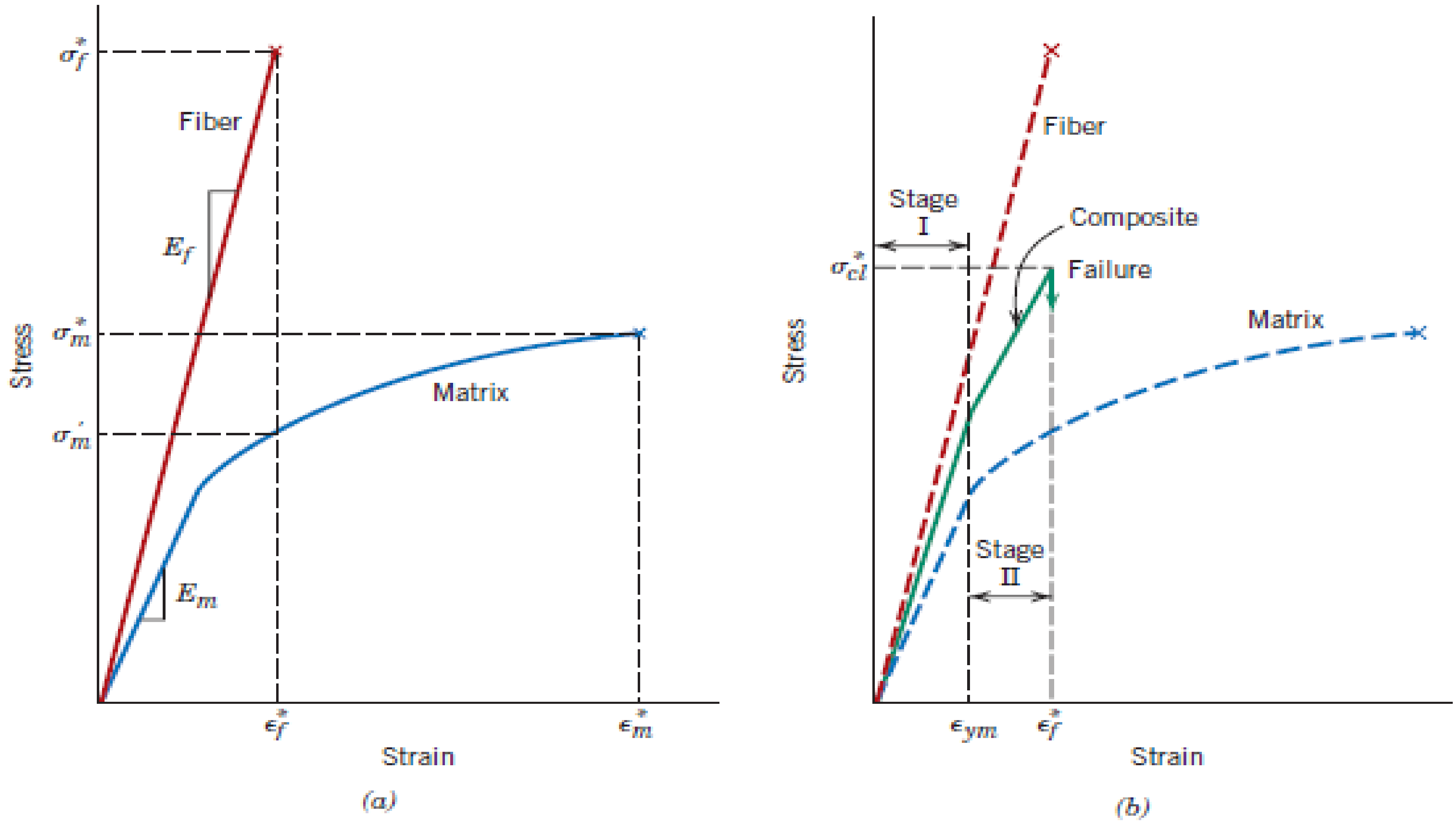
On the picture:

σ^*_f : **fracture strength in tension for fiber**

σ^*_m : **fracture strength in tension for matrix**

ε^*_f : **fracture strain in tension for fiber**

ε^*_m : **fracture strain in tension for matrix**



(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.

Stress-strain behavior of the composite material is shown in the figure (b).

In the area of Stage I, fiber and matrix deform elastically; stress-strain behavior is usually a linear curve. Matrix deforms plastically, whereas fibers have elastic stretch.

In the area of Stage II, the relationship between stress and strain is almost linear with a slope smaller than stage I.

The onset of composite failure is characterized by current fiber starts to break down, when the strain = ε^*_f.

In this condition has not been damaged composite true, because Not all fiber is damaged at the same time,

Although most fiber had been damaged, but the matrix is still intact because $\varepsilon^*_f < \varepsilon^*_m$

Elastic Behavior—Longitudinal Loading

Let us now consider the elastic behavior of a continuous and oriented fibrous composite that is loaded in the direction of fiber alignment.

First, it is assumed that the fiber–matrix interfacial bond is very good, such that deformation of both matrix and fibers is the same (an isostrain situation).

Under these conditions, the total load sustained by the composite F_c **is equal to the sum of the loads carried by the matrix phase F_m and the fiber phase F_f, or:**

$$F_c = F_m + F_f \qquad \textbf{(4)}$$

From the definition of stress:

$$F = \sigma A$$

Equation (4) can be written as:

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f \qquad (5)$$

dividing through by the total cross-sectional area of the composite, we have:

$$\sigma_c = \sigma_m \frac{A_m}{A_c} + \sigma_f \frac{A_f}{A_c} \qquad (6)$$

where A_m/A_c and A_f/A_c are the area fractions of the matrix and fiber phases, respectively.

If the composite, matrix, and fiber phase lengths are all equal, A_m/A_c is equivalent to the volume fraction of the matrix, V_m, and A_f/A_c and likewise for the fibers, $V_f = A_f/A_c$.
Eq. (6) now becomes:

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \qquad (7)$$

The previous assumption of an isostrain state means that:

$$\varepsilon_c = \varepsilon_m = \varepsilon_f = \varepsilon \qquad (8)$$

and when each term in eq. (7) is divided by its respective strain

$$\frac{\sigma_c}{\varepsilon_c} = \frac{\sigma_m}{\varepsilon_m} V_m + \frac{\sigma_f}{\varepsilon_f} V_f \qquad (9)$$

Furthermore, if composite, matrix, and fiber deformations are all elastic, then

$$\sigma_c / \varepsilon_c = E_c \qquad \sigma_m / \varepsilon_m = E_m \qquad \sigma_f / \varepsilon_f = E_f$$

the E's being the moduli of elasticity for the respective phases. Substitution into eq. (9) yields an expression for the modulus of elasticity of a continuous and aligned fibrous composite in the direction of alignment (or longitudinal direction), as

$$E_{cl} = E_m V_m + E_f V_f \qquad (10.a)$$

$$E_{cl} = E_m (1 - V_f) + E_f V_f \qquad (10.b)$$

Thus, E_{cl} is equal to the volume-fraction weighted average of the moduli of elasticity of the fiber and matrix phases.

Other properties, including density, also have this dependence on volume fractions.

for longitudinal loading, that the ratio of the load carried by the fibers to that carried by the matrix is:

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m} \qquad (11)$$

EXAMPLE 1

A continuous and aligned glass fiber-reinforced composite consists of 40 vol% of glass fibers having a modulus of elasticity of 69 GPa and 60 vol% of a polyester resin that, when hardened, displays a modulus of 3.4 GPa.

a. **Compute the modulus of elasticity of this composite in the longitudinal direction.**
b. **If the cross-sectional area is 250 mm^2 and a stress of 50 MPa is applied in this longitudinal direction, compute the magnitude of the load carried by each of the fiber and matrix phases.**
c. **Determine the strain that is sustained by each phase when the stress in part (b) is applied.**

SOLUTION

a. **The modulus of elasticity of the composite is calculated using eq. (10.a):**

$$E_{cl} = E_m V_m + E_f V_f = (3.4\ GPa)(0.6) + (69\ GPa)(0.4)$$

$$= 30\ \text{GPa}$$

b. **To solve this portion of the problem, first find the ratio of fiber load to matrix load, using eq. (11); thus,**

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m} = \frac{(69\ \text{GPa})(0.4)}{(3.4\ \text{GPa})(0.6)} = 13.5$$

$$F_f = 13.5 F_m$$

In addition, the total force sustained by the composite F_c may be computed from the applied stress σ and total composite cross-sectional area A_c according to

$$F_c = A_c\sigma = (250\ mm^2)(50\ MPa)$$

$$= (250\times10^{-6}\ m^2)(50\times10^{6}\ N/m^2) = 12500\ N$$

this total load is just the sum of the loads carried by fiber and matrix phases; that is,

$$F_c = F_m + F_f = 12500\ N$$

$$F_m + 13.5\ F_m = 12500\ N$$

$$F_m = 860\ N$$

$$F_f = 13.5\ F_m = 11640\ N$$

c. **The stress for both fiber and matrix phases must first be calculated. Then, by using the elastic modulus for each (from part a), the strain values may be determined.**

$$A_m = V_m A_c = (0.6)\left(250\,\text{mm}^2\right) = 150\,\text{mm}^2 = 150 \times 10^{-6}\,\text{m}^2$$

$$A_f = V_f A_c = (0.4)\left(250\,\text{mm}^2\right) = 100\,\text{mm}^2 = 100 \times 10^{-6}\,\text{m}^2$$

$$\sigma_m = \frac{F_m}{A_m} = \frac{860\,\text{N}}{150 \times 10^{-6}\,\text{m}^2} = 5.73 \times 10^6\,\text{Pa} = 5.73\,\text{MPa}$$

$$\sigma_f = \frac{F_f}{A_f} = \frac{11640\,\text{N}}{100 \times 10^{-6}\,\text{m}^2} = 116.4 \times 10^6\,\text{Pa} = 116.4\,\text{MPa}$$

$$\varepsilon_m = \frac{\sigma_m}{E_m} = \frac{5.73\ \text{MPa}}{3.4 \times 10^3\ \text{MPa}} = 1.69 \times 10^{-3}$$

$$\varepsilon_f = \frac{\sigma_f}{E_f} = \frac{116.4\ \text{MPa}}{69 \times 10^3\ \text{MPa}} = 1.69 \times 10^{-3}$$

Elastic Behavior—Transverse Loading

A continuous and oriented fiber composite may be loaded in the transverse direction; that is, the load is applied at a 90° angle to the direction of fiber alignment.

For this situation the stress σ to which the composite as well as both phases are exposed is the same, or

$$\sigma_c = \sigma_m = \sigma_f = \sigma \qquad \textbf{(12)}$$

This is termed an isostress state. Also, the strain or deformation of the entire composite is:

$$\varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f \qquad \textbf{(13)}$$

But since $E = \sigma / \varepsilon$

$$\varepsilon_c = \frac{\sigma_c}{E_{ct}} = \frac{\sigma}{E_{ct}}$$

$$\varepsilon_m = \frac{\sigma_m}{E_m} = \frac{\sigma}{E_m}$$

$$\varepsilon_f = \frac{\sigma_f}{E_f} = \frac{\sigma}{E_f}$$

Substituting the above three to equations (13) yields:

$$\frac{\sigma}{E_{ct}} = \frac{\sigma}{E_m} V_m + \frac{\sigma}{E_f} V_f \qquad \textbf{(14)}$$

where is E_{ct} the modulus of elasticity in the transverse direction.

Now, dividing through by σ yields

$$\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \tag{15}$$

which reduces to

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f E_m} = \frac{E_m E_f}{(1 - V_f)E_f + V_f E_m} \tag{16}$$

EXAMPLE 2

Compute the elastic modulus of the composite material described in Example 1, but assume that the stress is applied perpendicular to the direction of fiber alignment.

SOLUTION

According to eq. (13):

$$E_{ct} = \frac{E_m E_f}{(1 - V_f)E_f + V_f E_m}$$

$$= \frac{(3.4\ \text{GPa})(69\ \text{GPa})}{(0.6)(69\ \text{GPa}) + (0.4)(3.4\ \text{GPa})} = 5.5\ \text{GPa}$$

Longitudinal Tensile Strength

We now consider the strength characteristics of continuous and aligned fiber-reinforced composites that are loaded in the longitudinal direction.

Under these circumstances, strength is normally taken as the maximum stress on the stress–strain curve.

Often this point corresponds to fiber fracture, and marks the onset of composite failure.

Table 1 lists typical longitudinal tensile strength values for three common fibrous composites.

Failure of this type of composite material is a relatively complex process, and several different failure modes are possible.

The mode that operates for a specific composite will depend on fiber and matrix properties, and the nature and strength of the fiber–matrix interfacial bond.

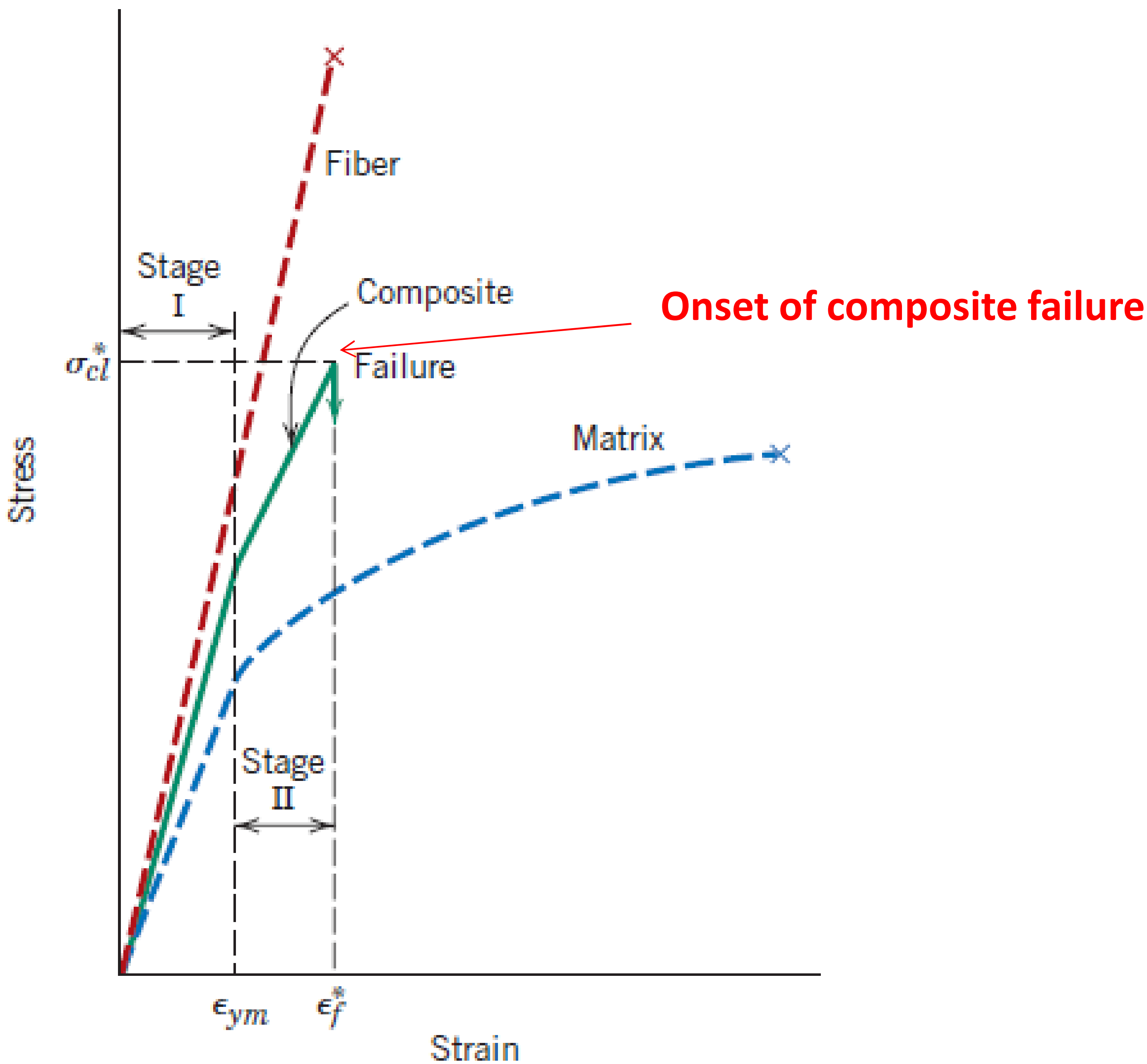

Fiber
Stage
I
Composite
Onset of composite failure
σ_{cl}^*
Failure
Matrix
Stress
Stage
II
ϵ_{ym}
ϵ_f^*
Strain

Table 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

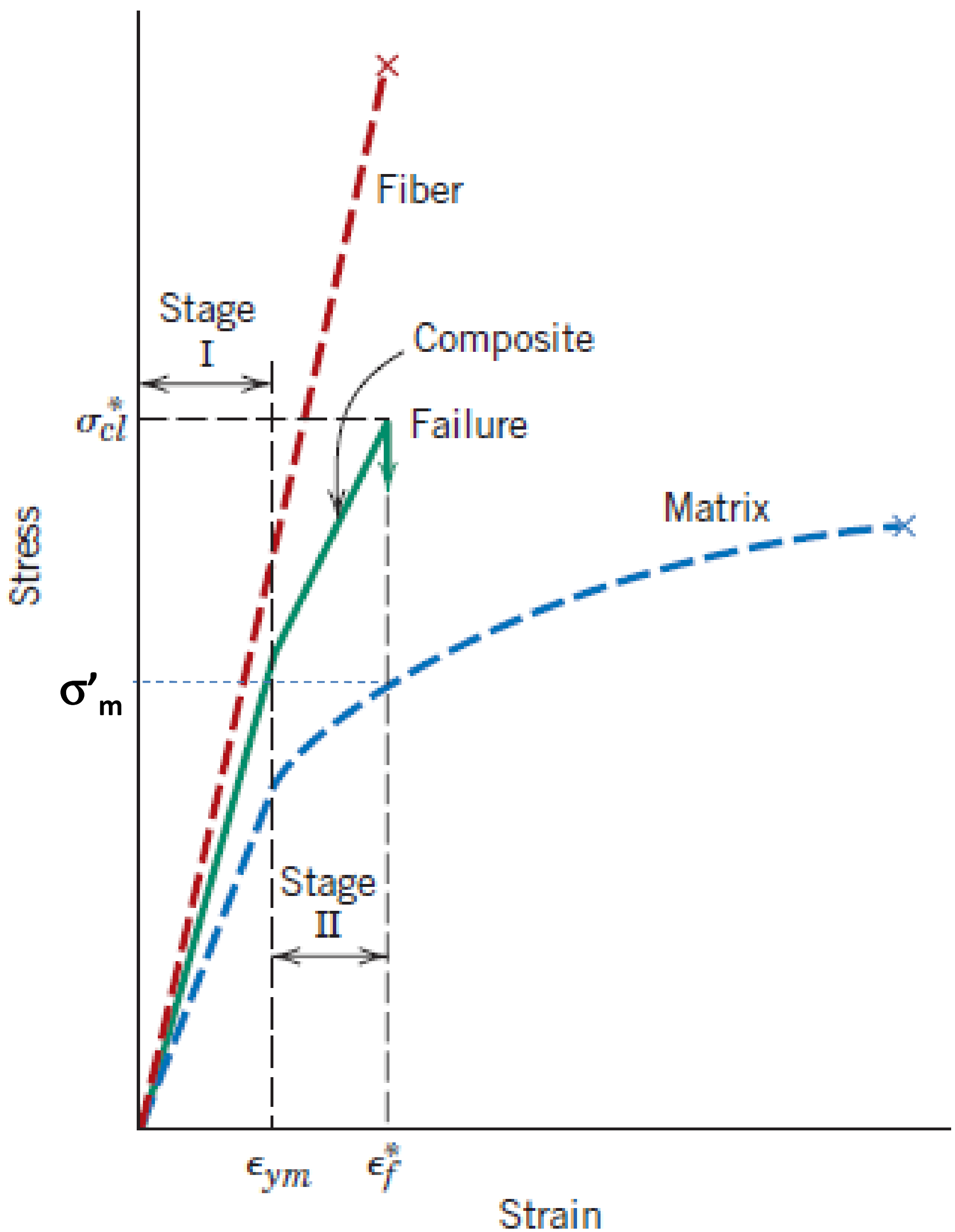
Source: D. Hull and T. W. Clyne, *An Introduction to Composite Materials*, 2nd edition, Cambridge University Press, 1996, p. 179.

If we assume that $\varepsilon^*_f < \varepsilon^*_m$, which is the usual case, then fibers will fail before the matrix.

Once the fibers have fractured, the majority of the load that was borne by the fibers is now transferred to the matrix. This being the case, it is possible to adapt the expression for the stress on this type of composite, eq. (7), into the following expression for the longitudinal strength of the composite ε^*_{cl}

$$\sigma^*_{cl} = \sigma'_m (1 - V_f) + \sigma^*_f V_f \qquad (17)$$

Here σ'_m is the stress in the matrix at fiber failure and, σ^*_f as previously, is the fiber tensile strength.


Fiber
Stage
I
Composite
σ^*_{cl}
Failure
Matrix
Stress
σ'm
Stage
II
ϵ_{ym}
ϵ^*_f
Strain

Transverse Tensile Strength

The strengths of continuous and unidirectional fibrous composites are highly anisotropic, and such composites are normally designed to be loaded along the high strength, longitudinal direction.

However, during in-service applications transverse tensile loads may also be present.

Under these circumstances, premature failure may result inasmuch as transverse strength is usually extremely low—it sometimes lies below the tensile strength of the matrix.

Thus, in actual fact, the reinforcing effect of the fibers is a negative one.

Typical transverse tensile strengths for three unidirectional composites are contained in Table 1.

Whereas longitudinal strength is dominated by fiber strength, a variety of factors will have a significant influence on the transverse strength; these factors include properties of both the fiber and matrix, the fiber–matrix bond strength, and the presence of voids.

Measures that have been employed to improve the transverse strength of these composites usually involve modifying properties of the matrix.

Discontinuous and Aligned Fiber Composites

Even though reinforcement efficiency is lower for discontinuous than for continuous fibers, discontinuous and aligned fiber composites are becoming increasingly more important in the commercial market.

Chopped glass fibers are used most extensively; carbon and aramid discontinuous fibers are also employed.

These short fiber composites can be produced having moduli of elasticity and tensile strengths that approach 90% and 50%, respectively, of their continuous fiber counterparts.

For a discontinuous and aligned fiber composite having a uniform distribution of fibers and in which $l > l_c$, the longitudinal strength (σ^*_{cd}) is given by the relationship:

$$\sigma^*_{cd} = \sigma^*_f V_f \left(1 - \frac{l_c}{2l}\right) + \sigma'_m (1 - V_f) \qquad \textbf{(18)}$$

where σ^*_f and σ'_m represent, respectively, the fracture strength of the fiber and the matrix when the composite fails.

If $l < l_c$ then the longitudinal strength is given by

$$\sigma^*_{cd'} = \frac{l\tau_c}{d} V_f + \sigma'_m (1 - V_f) \qquad \textbf{(19)}$$

where d is the fiber diameter and τ_c is the smaller of either the fiber–matrix bond strength or the matrix shear yield strength.

Discontinuous and Randomly Oriented Fiber Composites

Normally, when the fiber orientation is random, short and discontinuous fibers are used.

Under these circumstances, a "rule-of-mixtures" expression for the elastic modulus similar to eq. (10.a) may be utilized, as follows:

$$E_{cd} = K E_f V_f + E_m V_m \qquad (20)$$

In this expression, K is a fiber efficiency parameter that depends on and the E_f/E_m ratio.

Of course, its magnitude will be less than unity, usually in the range 0.1 to 0.6.

Thus, for random fiber reinforcement (as with oriented), the modulus increases in some proportion of the volume fraction of fiber.

Table 2, which gives some of the mechanical properties of unreinforced and reinforced polycarbonates for dis-continuous and randomly oriented glass fibers, provides an idea of the magnitude of the reinforcement that is possible.

Table 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

Table 3. Reinforcement Efficiency of Fiber-Reinforced Composites for Several Fiber Orientations and at Various Directions of Stress Application

Fiber Orientation	*Stress Direction*	*Reinforcement Efficiency*
All fibers parallel	Parallel to fibers	1
	Perpendicular to fibers	0
Fibers randomly and uniformly distributed within a specific plane	Any direction in the plane of the fibers	$\frac{3}{8}$
Fibers randomly and uniformly distributed within three dimensions in space	Any direction	$\frac{1}{5}$

Source: H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964 [33].