Introduction to Aerospace Structures and Materials

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Partly funded by the TU Delft Extension School (online-learning.tudelft.nl) as part of the development of a Massive Open Online Course in Introduction to Aerospace Structures and Materials.
ISBN E-Pub: 978-94-6366-077-8
ISBN hardcopy: 978-94-6366-074-7
ISBN PDF: 978-94-6366-075-4

1. Material physics & properties

1.1 Introduction

This chapter will discuss the elementary physics of materials related to the loads acting on a material and as a consequence their response. The response is related to physical properties of materials which can substantially differ from one material to another. This chapter highlights some of the differences in the material properties that are observed in commonly used structural materials.

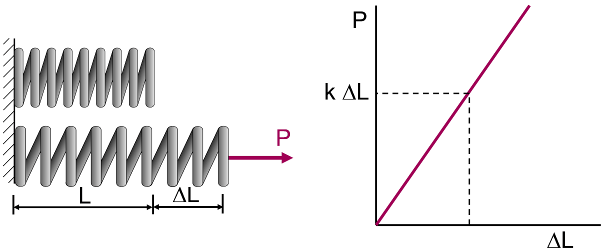

Figure 1.1
Illustration of a spring loaded with load P and its subsequent load-elongation diagram (Alderliesten, 2011, 1-1.jpg. Own Work)

When applying a load P to a spring with length L, it will elongate with ΔL, Figure 1.1. This elongation relates linearly to the applied load P and is often formulated as

$$P = k\Delta L \tag{1.1}$$

where k is called the spring constant. While loading the spring, one may observe that the diameter of the spring becomes smaller, the longer the spring is stretched. This loaded spring represents the elastic behaviour of materials in general when loaded uni-axially; for given load the material will elongate, while the cross-section becomes slightly smaller.

1.2 Stress-strain

The material behaviour referred to earlier is represented by other parameters than elongation and load, because the magnitude of the load for a given elongation (represented by for example a spring constant, k), depends on the shape or geometry of the material. Different geometries or original lengths of the same material will thus give different load-displacement curves, which is inconvenient when comparing materials.

The parameters used to evaluate the material properties are selected based on what is called the similitude principle. To physically equate the proportional relationship between load and material response, dimensional aspects should be left out of the equation.

Example: Elongation

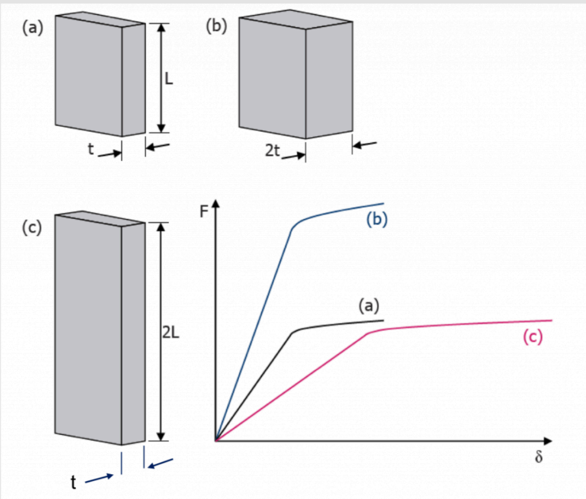

Figure 1.2
Illustration of the geometry influence on the force displacement response (Alderliesten, 2011, 1-2.jpg. Own work.)

Consider the three samples illustrated in Figure 1.2. To elongate the samples (a) and (b) equally, the load F applied on sample (b) should be twice as large as on sample (a). In the force-displacement diagram this results in a curve for sample (b) twice as high as sample (a). For the same applied force F, sample (c) will elongate twice as much as sample (a). In the diagram this results in a curve that is stretched twice as much as curve (a).

Although all three samples are made of the same material, the curves appear to be different. To exclude the dimensional aspects from the material's response to load, the selected parameters should be chosen 'dimensionless', i.e. independent of dimensions. Based upon curves (a) and (b), the force must be divided by the cross section of the sample, resulting in stress **σ**, and based upon curves (a) and (c) the elongation must be divided by the sample's length, resulting in the dimensionless strain **ε**.

For this reason the extension of the material is represented by strain, which is the extension normalized by its initial length according to

$$\varepsilon = \frac{\Delta L}{L} \tag{1.2}$$

Similarly, the effect of geometry is excluded by representing the load application in terms of stresses

$$\sigma = \frac{P}{A} \tag{1.3}$$

where A is the cross section of the material.

There are two ways to calculate the stress with equation (1.3):

- Dividing the load by the original or initial cross-section, A_0. The stress is then called the engineering stress
- Dividing the load by the actual cross-section A. The stress is then called the true stress

Since the actual cross-section is often not exactly known, the engineering stress is often taken for stress analysis.

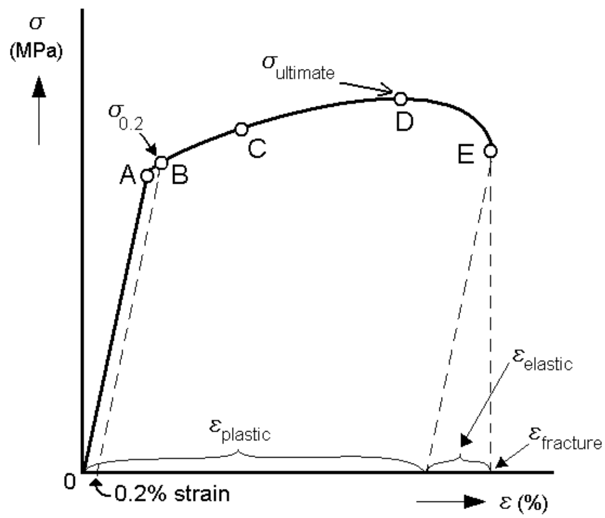

Figure 1.3

Typical stress-strain curve for a metal; initial slope is linear elastic, beyond yielding the material behaviour is plastic (TU Delft, n.d. 1-3.jpg. Own work)

The stress with equation (1.3) can be plotted against the strain calculated with equation (1.2), which for many elastic-plastic materials like metals, gives a curve as illustrated in Figure 1.3.

The initial slope of the curve is linear-elastic, which means that when unloading, the material will return to its original length and shape. Beyond a certain load, the material will permanently deform. This transition point in the stress-strain curve is called the yield point. Because often the yield point is a gradual transition from the linear elastic curve into the plastic region, it is hard to determine the yield stress exactly in an equal manner for all materials. For this reason, a common (but arbitrary) approach is to take the intersection between the stress-strain curve and the 0.2% offset of the linear elastic slope, illustrated with the dotted line in Figure 1.3.

1.3 Loading modes

The examples so far (i.e. elongation of spring or material) assumed a uni-axial loading mode in tension. Often compression is assumed to be identical to tension except for the sign (direction). These two loading modes are illustrated in Figure 1.4 together with the shear loading and torsional loading mode. Depending on the shape of material or structure and the load applied, the material may face either one of these four modes, or a combination of them.

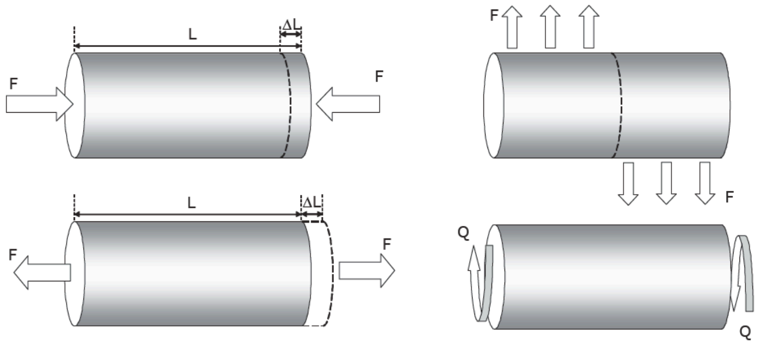

Figure 1.4
Four loading modes: compression, tension, shear and torsion (Alderliesten, 2011, 1-4.jpg. Own Work.)

1.4 Engineering terminology

The stress-strain curve illustrated in Figure 1.3 contains terminology that requires some explanation. For that purpose, two different curves are being given in Figure 1.5.

Concerning the linear elastic part (initial slope of the curves), the slope may be either steep (high resistance against deformation) or gentle (representing low resistance against deformation). The first curve indicates a stiff material, whereas the second curve indicates a flexible material.

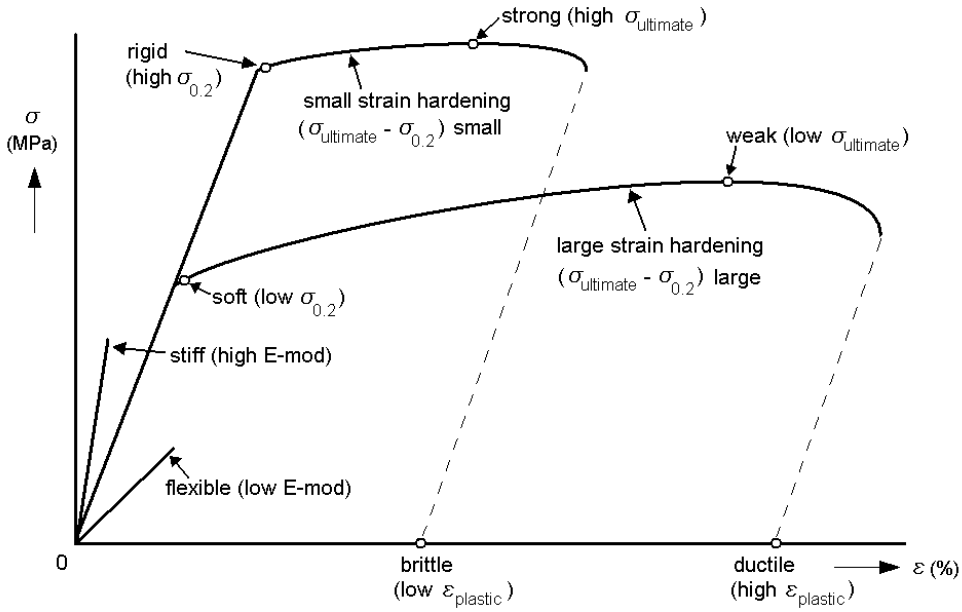

Figure 1.5
Stress-Strain Diagram which shows the difference between stiff and flexible (high or low E-modulus, respectively) material, soft and rigid (low or high yield stress, resp.) and small and large strain hardening (small or large difference between ultimate and yield stress, resp.) and weak and strong material (low or high ultimate stress, resp.) and brittle and ductile material, (low or high plastic strain resp.). (TU Delft, n.d. 1-5.jpg. Own Work)

The yield point (transition from elastic to plastic) may either be located at small values of the stress (low yield strength) or at high values of stress (high yield strength). The first transition point indicates a soft material, whereas the second indicates a rigid material.

After yielding, the curves continue to increase gradually. The hypothetical case where the material becomes fully plastic after yielding, i.e. the slope continues horizontally, is often denoted as perfect plastic. In all other cases, there is a slope that is either rather steep (large strain hardening) or gentle (small strain hardening).

The highest point in the stress strain curve is called the ultimate strength of a material. If this strength value is very high, it indicates a strong material. If the strength is low, it indicates a weak material.

Fracture occurs at the end of the curve. The elastic deformation still present causes spring back. This is illustrated by the dotted lines parallel to the initial elastic slope of the curve. The remaining deformation is plastic deformation. A small degree of plastic deformation indicates a brittle material. A high degree of plastic deformation indicates a ductile material.

Note, that there is a fundamental difference in *strength and stiffness* (see Figure 1.6).

Figure 1.6
Illustration of the difference between stiffness and strength; the flexibility of the wings relates to stiffness (low stiffness gives significant wing bending), whereas strength relates to final failure of the structure. Derivative from NASA, (2003), Public Domain.

1.5 Normal stress

In the case of tension and compression (see Figure 1.4) normal stresses occur in the material. According to the sign convention, these stresses are either positive (tension) or negative (compression). Similar to the spring constant, the relation between stress and strain is characterized by a constant in the linear elastic part of the stress strain curve.

$$\sigma = E\varepsilon \tag{1.4}$$

The constant E is called the modulus of elasticity, or the Young's modulus. The value of this Young's modulus is a characteristic value for a material; a high value indicates a stiff material, a low value a flexible material.

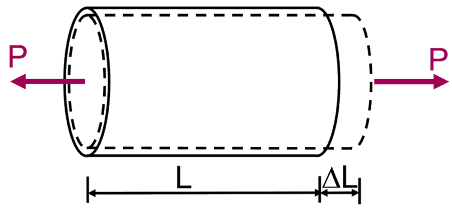

Figure 1.7
Illustration of axial elongation and lateral contraction of a rod under uni-axial loading P (Alderliesten, 2011, 1-7.jpg. Own Work.)

As mentioned in the introduction, the diameter of a spring becomes smaller than its initial diameter when loaded. A similar contraction can be observed in any material under axial loading in the linear elastic part of the curve. This transverse contraction is illustrated in Figure 1.7.

To visualise this contraction in transverse direction, one may as a first qualitative illustration consider the elongation of rubber. During elongation, rubber will not only elongate but also become thinner. Elongation in lateral (loading) direction must then be compensated by transverse contraction.

Quantitatively, this visualisation is incorrect. The exact amount of contraction during uni-axial loading is determined by the material. The relation between the lateral and transverse strain is represented by another constant

$$\varepsilon_t = -\nu\varepsilon_l = \nu\frac{\sigma_l}{E} \tag{1.5}$$

This constant ν is called the Poisson's ratio. Both the Young's modulus E and the Poisson's ratio ν are considered material constants.

1.6 Shear stress

In the case of shear or torsion loading (see Figure 1.4), shear stresses occur in the material. The shear stress τ is defined in a similar way as the normal stress; the force is divided by the area A to which it is applied, see Figure 1.8.

$$\tau = \frac{F}{A} \tag{1.6}$$

The relation between the shear strain γ and the shear stress is characterized by a relation similar to equation (1.4)

$$\tau = G\gamma \tag{1.7}$$

where G is the shear modulus of elasticity and γ the shear strain (equal to $\tan\theta$, see Figure 1.8). For linear elastic materials, there is a relation between E and G, given by

$$G = \frac{E}{2(1+\nu)} \tag{1.8}$$

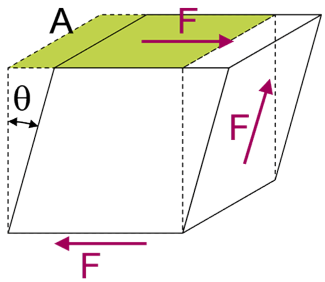

Figure 1.8

Illustration of the shear deformation due to shear forces acting on the surface of the element (TU Delft, n.d. 1-8.jpg. Own Work.)

1.7 Bi-axial loading

In the case of elastic bi-axial loading, i.e. loads are being applied in two directions, the stresses that occur in the material can be calculated using superposition. This superposition is allowed, because the stress relates linearly to the load that is applied. If two load systems are applied simultaneously, the stress may thus be superimposed.

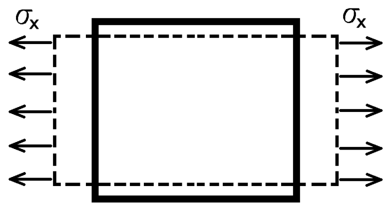

Figure 1.9
Illustration of a sheet loaded in either x-direction (TU Delft, n.d. 1-9.jpg. Own Work)

For the sheet loaded in x-direction (Figure 1.9), the strains in both directions can be given by

$$\varepsilon_x = \frac{\sigma_x}{E} \quad ; \quad \varepsilon_y = -\nu \frac{\sigma_x}{E} \tag{1.9}$$

For the sheet loaded in y-direction, the strains are given by

$$\varepsilon_x = -\nu \frac{\sigma_y}{E} \quad ; \quad \varepsilon_y = \frac{\sigma_y}{E} \tag{1.10}$$

Superimposing both load cases, as illustrated in Figure 1.10, the stresses in equation (1.9) and (1.10) can be superimposed. This gives

$$\varepsilon_x = \frac{\sigma_x}{E} - \nu \frac{\sigma_y}{E} \quad ; \quad \varepsilon_y = -\nu \frac{\sigma_x}{E} + \frac{\sigma_y}{E} \tag{1.11}$$

Equation (1.11) is known as *the Hooke's law* for a sheet in bi-axial stress condition.

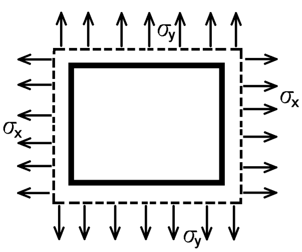

Figure 1.10
Illustration of a sheet loaded in lateral and transverse direction simultaneously (TU Delft, n.d. 1-10.jpg. Own Work.)

1.8 Stiffness and apparent stiffness

Stiffness, expressed by the Young's modulus, is the material's resistance against deformation, see Figure 1.5. A higher stiffness (E-modulus) means that a higher force must be applied to obtain a specified elongation (or strain).
For a uni-axially loaded sheet, the stiffness relates directly to the Young's modulus, E. In a bi-axially loaded situation however, the apparent stiffness may be different from the material stiffness. This can be illustrated with the Hooke's law, given by equation (1.11), and a wide sheet clamped at both sides over its full length and loaded in one direction, see Figure 1.11.

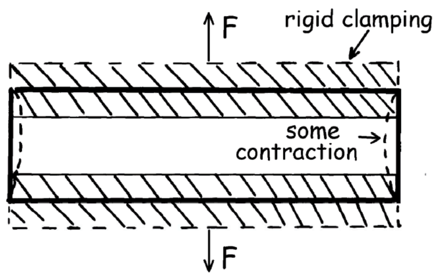

Figure 1.11
Illustration of a wide sheet rigidly clamped at both ends and loaded in lateral direction (TU Delft, n.d. 1-11.jpg. Own Work.)

The transverse strain ε_x is equal to zero as the clamping prohibits the contraction. With equation (1.11) this implies that

$$\varepsilon_x = 0 = -\nu\frac{\sigma_y}{E} + \frac{\sigma_x}{E} \quad \rightarrow \quad \sigma_x = \nu\sigma_y \tag{1.12}$$

Substitution of this relation between the longitudinal and transverse strain into the expression in longitudinal direction, equation (1.11), yields

$$\varepsilon_y = \frac{\sigma_y}{E} - \nu\frac{(\nu\sigma_y)}{E} = (1-\nu^2)\frac{\sigma_y}{E} \tag{1.13}$$

The strain in a regular tensile test, where the transverse contraction is not prohibited ($\sigma_t = 0$), is given by

$$\varepsilon_y = \frac{\sigma_y}{E} \tag{1.14}$$

This means that the apparent Young's modulus is given by

$$E^* = \frac{1}{1-\nu^2}E \tag{1.15}$$

1.9 Isotropic and anisotropic sheet deformation

An isotropic sheet is a sheet that is considered to have equal properties in any direction of the sheet. For the tensile (longitudinal and transverse) and the shear deformation of such a sheet, see Figures 1.13 and 1.14, the equations are obtained by combining equations (1.7) and (1.11)

$$\begin{aligned}\varepsilon_x &= \frac{\sigma_x}{E} - \nu\frac{\sigma_y}{E}\\ \varepsilon_y &= -\nu\frac{\sigma_x}{E} + \frac{\sigma_y}{E}\\ \gamma_{xy} &= \frac{\tau_{xy}}{G}\end{aligned} \tag{1.16}$$

The subscripts for the normal stress **σ** and normal strain **ε** indicate the direction of the stress and strain. For the shear stress τ_{xy} and shear strain γ_{xy} the first subscript indicates the axis perpendicular to the face that the shear stress and strain are acting on, while the second subscript indicates the positive direction of the shear stress and strain, see Figure 1.12.

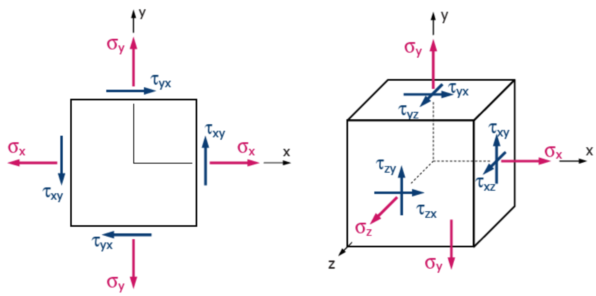

Figure 1.12
Illustration of normal and shear stresses acting on a two-dimensional and three-dimensional element (Alderliesten, 2011, 1-12.jpg. Own Work)

This set of equations can also be written in matrix formulation

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E} & \frac{-\nu}{E} & 0 \\ \frac{-\nu}{E} & \frac{1}{E} & 0 \\ 0 & 0 & \frac{1}{G} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \tag{1.17}$$

An anisotropic sheet has different properties in the different material directions. An example of an anisotropic sheet can be the fibre reinforced ply. Because the tensile and shear deformation is dependent on the properties in the particular directions, see Figure 1.13 and Figure 1.14, equation (1.17) must be extended to

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & \frac{-\nu_{yx}}{E_y} & 0 \\ \frac{-\nu_{xy}}{E_x} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \tag{1.18}$$

The subscript 'xy' for the Poisson's ratio describes the contraction in y-direction for an extension (direction of load) in x-direction.

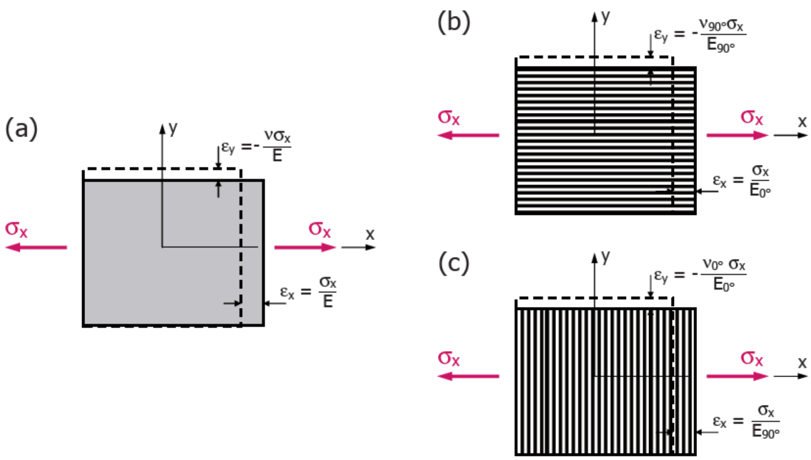

Figure 1.13
Illustration of tensile deformation under tensile stress for isotropic sheet (a), and anisotropic sheet (b,c) (Alderliesten, 2011. 1-13.jpg. Own Work.)

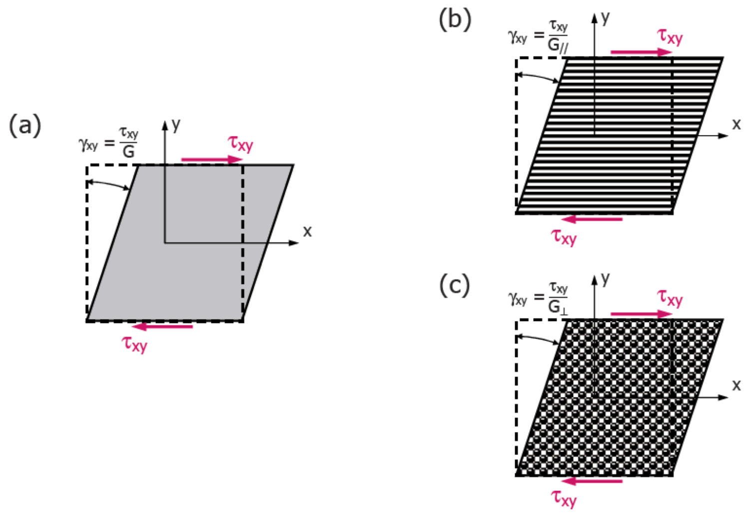

Figure 1.14
Illustration of shear deformation under shear stress for isotropic sheet (a), and anisotropic sheet (b,c) (Alderliesten, 2011. 1-14.jpg. Own Work.)

Here, one must realise that the excellent stiffness and strength properties often given for composite materials may be given for the longitudinal direction only. Table 1.1 illustrates the strength and stiffness properties for two thermoset fibre reinforced composites in the two principal material directions. Indeed, the stiffness and strength is significant in fibre directions, but perpendicular to the fibres the properties are very low.

Table 1.1
Comparison between stiffness and strength in the two principal material directions for E-glass and high modulus carbon thermoset composite

Material	E_x [kN/mm^2]	E_y [kN/mm^2]	σ_{U_x} [N/mm^2]	σ_{U_y} [N/mm^2]
E-glass epoxy (Uni-Directional) UD-60%	45	8	1020	40
High modulus (HM) carbon epoxy UD-60%	220	10	760	40

As a consequence, composite (aeronautical) structures are made of alternating various plies that are oriented in different directions to obtain sufficient strength in each direction. The amount of fibres in each direction may vary depending on the loads cases. This design freedom is illustrated by the shaded area in Figure 1.15.
In this figure, several laminate lay-ups are indicated to explain the presentation of this figure. One of the laminate lay-ups indicated in Figure 1.15 is the quasi-isotropic laminate. Quasi-isotropy can be defined as the approximation of isotropy by orienting plies in different directions.

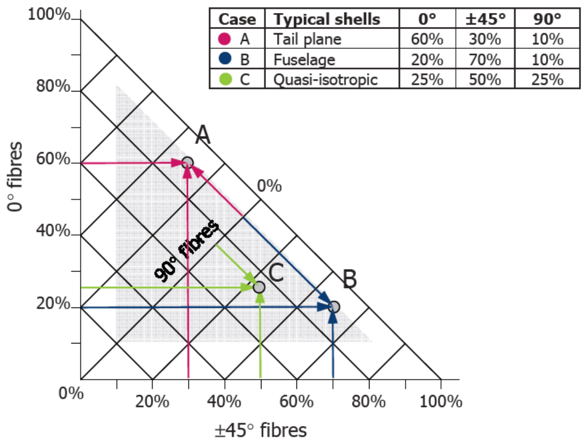

Figure 1.15
Illustration of the position of three typical laminate lay-ups in the design freedom for a fibre reinforced polymer composite panel mode of 0º, 90º, ±45º orientations only (Alderliesten, 2011. 1-15.jpg. Own Work.)

Table 1.2
Illustration of laminate properties for unidirectional E-glass epoxy plies (60%)

Orientation			Ex	Ey	σ_{U_x}	σ_{U_y}	Note
0°	±45°	90°	[kN/mm^2]	[kN/mm^2]	[N/mm^2]	[N/mm^2]	
100%	0%	0%	45	8	1020	40	Unidirectional
0%	0%	100%	8	45	40	1020	Unidirectional
50%	0%	50%	~26	~26	~530	~530	Cross-ply
25%	50%	25%	~20	~20	~325	~325	Quasi-isotropic

The consequence of the combination of various orientations in a laminate lay-up is that the mechanical properties of the laminate are generally an average of the individual ply properties. This is illustrated in Table 1.2 with the example of E-glass epoxy from Table 1.1.

The stress-strain relationship for a composite material, i.e. a polymer (matrix) reinforced by fibres depends on the stress-strain behaviour of the individual constituents. For a single unidirectional ply this relationship is illustrated in Figure 1.16. From this figure, it can be understood that the stiffness of the ply is a function of the stiffness of the fibre and the matrix. The ply stiffness depends on the amount of fibres in the ply, which is described by the fibre volume fraction. For example, with 100% of fibres in the ply, the stiffness will equal the fibre stiffness, while with 0% of fibres the stiffness will equal the matrix stiffness. This linear relationship is called the rule of mixtures and is discussed in chapter 3.

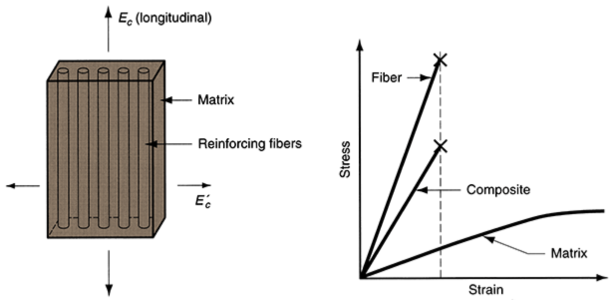

Figure 1.16
Illustration of the stress-strain curve for a fibre reinforced polymer (matrix) in relation to the constituent's stress-strain curve (TU Delft, n.d. 1-16.jpg. Own Work.)

Another observation from Figure 1.16, is that the strain to failure is in most cases not dependent on both constituents, but rather on the strain to failure of the fibres. Once the strain reaches the critical strain of the fibres, the fibres will fail, leaving the matrix with insufficient strength to carry the load, which will subsequently fail.

The earlier mentioned directionality of composite plies is important to consider. The high strength and stiffness of the composite may be described in fibre direction by the curve in Figure 1.16. However, perpendicular to the fibres, the strength and stiffness are described by the curve for the matrix, because there are no fibres in that direction to carry any load.

The directionality can be illustrated with the example shown in Figure 1.17. The high strength and stiffness of a composite may drop significantly to the low stiffness and strength of the (unreinforced) polymer in the direction perpendicular to the fibres. This means that if sufficient strength and stiffness is required in different directions, multiple plies should be placed on top of each other, each oriented in a different direction. However, the consequence is that the strength of that lay-up is no longer equal to the single ply strength, but rather a function of the individual plies in their direction of loading. A first estimation of the laminate strength or stiffness can be made with again assuming a linear relationship (rule of mixtures).

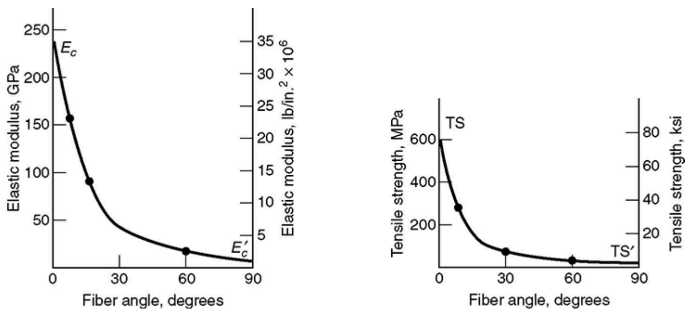

Figure 1.17
Relation between stiffness and strength of a composite ply and the angle or orientation of loading (TU Delft, n.d. 1-17.jpg. Own Work.)

Example: Laminate lay-up of multiple plies

Consider a laminate lay-up for vertical tail plane skins consisting of multiple plies for which the strength and stiffness of each ply are described by the curves in Figure 1.17. The lay-up is given by 60% of the fibres in 0°, 30% of the fibres in ±45° and 10% of the fibres in 90°. What is the stiffness of the laminate?
The modulus of elasticity is given in Figure 1.17. The values are approximately 240 GPa, 40 GPa, and 5 GPa for respectively 0°, ±45°, and 90°. The average stiffness of the laminate is proportional to the relative contribution of each ply. This means that

$$E_{lam} = v_0 E_0 + v_{\pm 45} E_{\pm 45} + v_{90} E_{90}$$

$$= 0.6 \cdot 240 + 0.3 \cdot 40 + 0.1 \cdot 5 = 156.5\ GPa$$

where v represents the laminate volume content of the plies in a given direction.

Since the vertical tail is primarily loaded in bending, most of the fibres are oriented in the span direction. However, for a fuselage a more quasi-isotropic lay-up is preferred because of the combined load cases in the fuselage. A typical lay-up that may be considered in that case is for example 20% of the fibres in 0°, 70% of the fibres in ±45° and 10% of the fibres in 90°. The laminate stiffness would then be

$$E_{lam} = v_0 E_0 + v_{\pm 45} E_{\pm 45} + v_{90} E_{90}$$

$$= 0.2 \cdot 240 + 0.7 \cdot 40 + 0.1 \cdot 5 = 76.5\ GPa$$

Note however, that this laminate has a stiffness in ±45° direction that is at least twice as high.

1.10 Toughness

The toughness of a material is often considered important in aeronautical structures because it represents the resistance of the material against fracture, formation of damage or impact. This parameter relates directly to the damage tolerance concept (see chapter 9) applied to ensure structural integrity during the entire operational life of, for example, an aircraft.

The toughness of a material is defined as resistance against fracture, and it is in general considered to be represented by the area underneath the stress-strain curve, see Figure 1.18. This area represents the mechanical deformation energy per unit volume prior to failure. Evaluating the units related to the area underneath the stress-strain curve, it can be shown that the unit of toughness is J/m^3, which is the energy [J] per unit volume.

$$\sigma \cdot \varepsilon = \frac{F}{A} \cdot \frac{\Delta L}{L} = \left[\frac{N}{m^2}\right] \cdot \left[\frac{m}{m}\right] = \left[\frac{Nm}{m^3}\right] = \left[\frac{J}{m^3}\right] \tag{1.19}$$

Aside from the toughness, often different definitions are considered. For example, the impact toughness is the minimum energy required to fracture a material of specified dimensions under impact. This energy is not only dependent on the material itself, but also on the dimensions of the sample being fractured. Therefore, the test to determine the fracture toughness and the specimen dimensions are prescribed in testing standards to enable correlation of different materials. The set-up and specimen are illustrated in Figure 1.19.

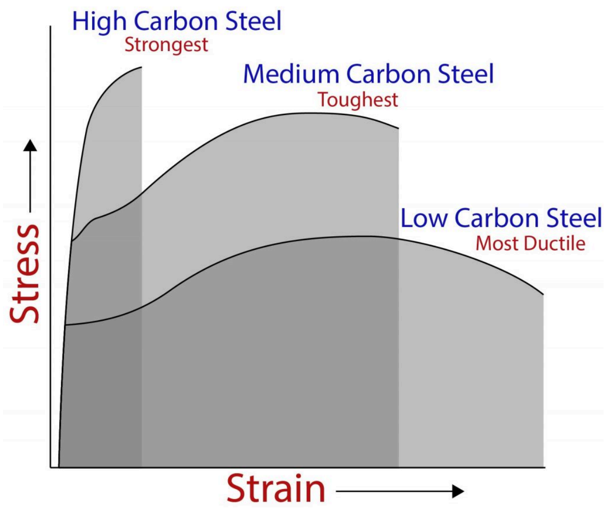

Figure 1.18
Three example stress-strain curves with the area underneath the curve shaded; the curve with the largest shaded area is considered to represent the toughest material. (TU Delft, n.d. 1-18.jpg. Own Work.)

Another important toughness parameter is the fracture toughness. This parameter represents the resistance of a material against fracture in presence of a crack. There is an important difference between toughness and fracture toughness. Although the area underneath the stress-strain curve, see Figure 1.18, qualitatively relates to the fracture toughness, the relation is not as straightforward as with toughness.

Materials with high fracture toughness usually fracture with significant ductile deformation, while materials with low fracture toughness fail in a brittle manner. In general, to fracture a material with high fracture toughness, a lot of energy or load is required, which implies that these materials are preferred for damage tolerant designs.

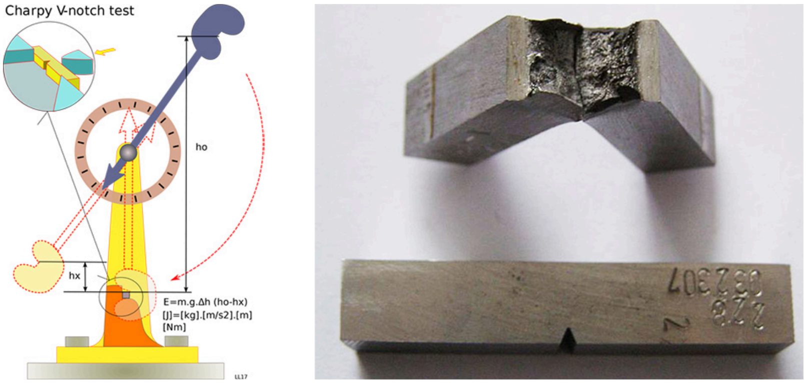

Figure 1.19
Test set-up for impact toughness measurements (left, Laurensvanlieshout, 2017, CC-BY-SA 4.0) and an intact and factured impact toughness specimen (right, Otrębski, 2013, CC-BY-SA 3.0)

Introduction to Aerospace Structures and Materials

Dr.ir. R.C. (René) Alderliesten

This book provides an introduction to the discipline of aerospace structures and materials. It is the first book to date that includes all relevant aspects of this discipline within a single monologue. These aspects range from materials, manufacturing and processing techniques, to structures, design principles and structural performance, including aspects like durability and safety. With the purpose of introducing students into the basics of the entire discipline, the book presents the subjects broadly and loosely connected, adopting either a formal description or an informal walk around type of presentation. A key lessons conveyed within this book is the interplay between the exact science and engineering topics, like solid material physics and structural analysis, and the soft topics that are not easily captured by equations and formulas. Safety, manufacturability, availability and costing are some of these topics that are presented in this book to explain decisions and design solutions within this discipline.

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© 2018 TU Delft Open
ISBN 978-94-6366-075-4
DOI https://doi.org/10.5074/t.2018.003

textbooks.open.tudelft.nl

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