Material Types and Properties

1 Material Types

There are many kinds of materials, but most of them can be divided into four groups:

- Metals - Metals are composed of one or more metallic elements and often also nonmetallic elements in relatively small amounts.
- Ceramics - Ceramics are compounds between metallic and nonmetallic elements.
- Polymers - Most polymers are made up of organic compounds. Polymers have a very large molecular structure.
- Composites - A combination of two or more of the above material types is called a composite material.

When designing anything in general, an engineer has to keep in mind the product triangle, containing the materials, designing and processing. Some materials aren't suitable for a certain design, whilst other materials may be too difficult to process to meat certain design requirements. When choosing the right materials for a design, an engineer has to keep in mind what properties the material has. Important material properties are: strength, stiffness, durability, manufacturability and, especially important in aerospace engineering, the strength/density ratio.

2 Testing Materials

There are many different ways to test the properties of a material. The most common way is a tensile test. Here, a certain force F is put on a specimen with cross-sectional area A and length l. Now the stress σ and the strain ε (sometimes also indicated as ϵ) can be calculated:

$$\sigma = \frac{F}{A_0} \qquad \varepsilon = \frac{\Delta l}{l_0} \tag{1}$$

Where A_0 and l_0 are the cross-sectional area and length, respectively, of the specimen at the start of the test. The relation between stress and strain is known as Hooke's law:

$$E = \frac{\sigma}{\varepsilon} \tag{2}$$

Where E is the E-modulus, (also called modulus of elasticity or Young's modulus).

Other tests are the compressive test (where σ and ε are negative), the shear test and the torsion test. The tensile test is for basic material applications by far the most often used test.

When performing a shear test or torsion test, the shear strain $\tau = \frac{F}{A_0}$ can be found. The relation between the shear stress and the shear strain γ is known as $G = \frac{\tau}{\gamma}$, where G is the shear modulus.

When a material is put under tension, it elongates in the direction of the force (ε_z is positive), but the specimen length decreases in the directions perpendicular to the force (ε_x and ε_y are negative). The amount in which this happens, is the Poisson's ratio ν, for isotropic materials (meaning the material properties are the same in every direction) defined as:

$$\nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z} \tag{3}$$

The negative sign is included so that ν will always be positive. ν should theoretically be 0.25 and can be 0.50 at maximum. ν also has a relation with the modulus of elasticity and the shear modulus. This relation, for isotropic materials, is:

$$\frac{E}{G} = 2(1+\nu) \tag{4}$$

3 Tensile Test

The tensile test is an example of a quasi-static load. The load is not constant, but gradually increases. When performing a tensile test, the strain can be displayed with respect to certain stresses. This gives a stress-strain diagram. From this diagram certain properties can be derived. These properties have been sorted in table 1 and visualized in figure 1. All these properties depend on the material type and a number of other variables, for example temperature.

Name	Sign	Property for high values	Property for low values
E-modulus	E	Stiff	Flexible
Yield stress	$\sigma_{0.2}$	Rigid	Soft
Ultimate stress	$\sigma_{ultimate}$	Strong	Weak
Plastic strain	$\varepsilon_{plastic}$	Ductile	Brittle
Strain hardening	$\sigma_{ultimate} - \sigma_{0.2}$	Large strain hardening	Small strain hardening

Table 1: Material properties and their corresponding names.

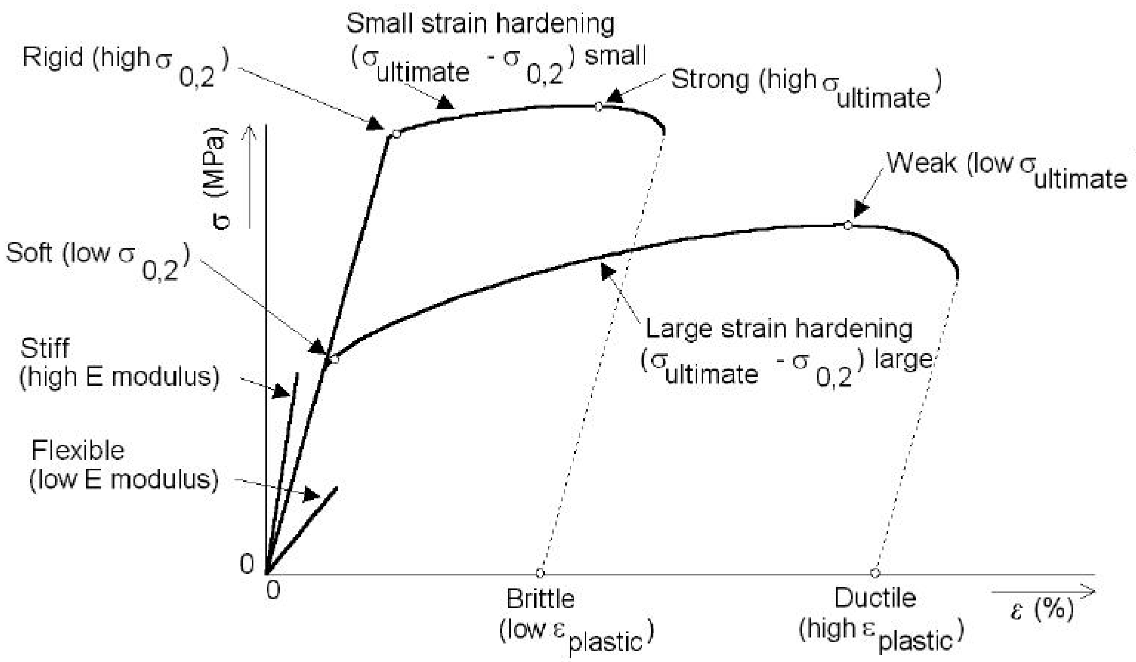

Figure 1: Important terms following from a stress-strain diagram.

The first part of the graph is elastic deformation. When the stresses are released, the structure returns to its former shape. The yield stress, also known as the yield strength, was originally the point at which the deformation switches from elastic to plastic deformation. However, for practical reasons, the yield point is defined as the point at which plastic deformation occurs causing a permanent strain of 0.002. Plastic deformation is permanent deformation. Next to elastic and plastic deformation, there is also anelastic deformation. When anelastic deformation occurs, the structure will return to its original shape over time.

The ultimate stress, also known as the tensile strength, occurs at the necking point. When this stress is reached, necking occurs. Necking is the local deformation of the specimen at the end of the tensile test. This means that at a certain position in the specimen, the cross-sectional area decreases rapidly. This is also the point at which fracture will occur.

It may look like the strength of the material after ultimate stress is decreasing. This is not true. The reason for the diagram to go downward, lies more in the fact that the cross-sectional area decreases because necking occurs. It is sometimes convenient to look at true stress σ_T, defined as $\sigma_T = \frac{F}{A_i}$ where A_i is the cross-sectional area over which deformation is occurring. The true strain is defined as $\varepsilon_T = \ln \frac{l_i}{l_0}$. After the yield point, the true stress and true strain for metals often have the relation $\sigma_T = K\varepsilon_T^n$ where K and n are constants. n is called the strain-hardening exponent.

4 Material Properties

There are many kinds of material properties that influence decisions made by designers. Some of them, the yield strength and the tensile strength, have already been discussed in the previous chapter.

Ductility is the degree of plastic deformation that has been sustained at fracture. It can be expressed as either percent elongation $\%EL$ or percent reduction in area $\%RA$ as follows:

$$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100\% \qquad \%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100\% \tag{1}$$

Where l_f and A_f are the length and cross-sectional area, respectively, of the specimen. $\%EL$ and $\%RA$ are usually not equal for a given material. Ductility usually decreases when temperature decreases.

Other properties are resilience and toughness. Both indicate the energy a material can absorb under tension. Resilience is the energy absorbed per unit volume until yielding, and toughness is the energy per unit volume until fracture. Both properties are expressed as the area under the stress-strain diagram, for resilience the area until the yield point (U_{yield}), and for toughness the entire area (until fracture, $U_{ultimate}$).

A final material property is hardness: the measure of resistance against localized plastic deformation. In hardness tests a small indenter is forced into the surface of the material.

When using material properties, a certain safety factor always has to be used. The stresses occurring during usage of a material may not always be exactly what they were predicted to be. Therefore a safety factor N is introduced as follows:

$$\sigma_w = \frac{\sigma_y}{N} \tag{2}$$

Where σ_w is the working stress and σ_y is the yield stress. Since the working stress must be smaller than the yield stress, N is always greater than unity.

5 Isotropy and Homogeneity

Materials can be either homogeneous or inhomogeneous. Suppose you have a sheet of metal, take multiple specimens from it (in the same orientation) and test them. If the material properties are identical for every position in the metal sheet, the metal sheet is homogeneous. So if a piece of material is not homogeneous, the material properties depend on the place in the material from which the test specimen is taken. Almost all materials are homogeneous.

Materials can also be either isotropic or anisotropic. Isotropic materials have the same property in every direction. Suppose you have an homogeneous sheet of metal, and take two specimens from it, orientated in a different way (for example, one in the longitudinal axis, one in the axial axis). If the properties of the two specimens are identical, then the piece of material is isotropic. Otherwise it is not. Most metals and polymers are isotropic, but most composites are not. This is due to the orientation of the fibres in most composites. Metal sheets produced by a rolling process are often also anisotropic.

6 Materials with Fibres

Over the past decades, materials with fibres have become popular in material science. Applying fibres in a material is a way to tailor the properties of the material. To start, there are many different kinds of fibres. Also the length of the fibres matter. Fibres can be classified in short fibres (millimeters), long fibres (centimeters/decimeters) and continuous fibres (meters). Short fibres often result in isotropic materials, while continuous fibres almost always result in anisotropic materials.

In the case of continuous fibres, the fibre orientation matters for the material properties. A composite material where the fibres are continuous fibres and are orientated in one direction is called an Uni-Direction (UD) composite. Also, multiple UD-layers are possible in a composite. For example, two UD-layers, one tangent to the loading, and one perpendicular to it, is called "cross ply". Two UD-layers, one in the $X°$ direction, and one in the $-X°$ direction, with X as an angle, is called "angle ply".

Suppose two UD-layers of fibres, with perpendicular fibre orientations, are attached to each other. Both layers have different material properties in different directions. Therefore a force applied on the material results in a shear force between the layers (since one of the layers deforms more than the other, which isn't possible, since they are attached). If the shear force gets too big, the bonding between the layers will break. This is called delamination. In short, delamination is the cracking of the bond between layers.

7 Dynamic Loading

Next to quasi-static loading (as was discussed along with the tensile test), there are also static and dynamic loading (static loading will be discussed next paragraph). Dynamic loading can cause fatigue failure, which, especially in metals, is the most often occurring type of failure. Fatigue failure is caused by the repetition of relatively small loads (under the yield stress) causing crack growth. Cracks grow perpendicular to the loading direction. There are three stages of fatigue. Initiation, where the crack appears. Growth, where the crack grows, and failure, where the crack size reaches a critical level.

There are many indicators for dynamic loads, to characterize the fluctuating stress cycle. The stress amplitude alternates about a mean stress σ_m, defined as:

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{1}$$

Furthermore, the range of stress σ_r and the stress amplitude σ_a are defined as:

$$\sigma_r = \sigma_{max} - \sigma_{min} \qquad \sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{2}$$

Finally, the stress ratio R is the ratio of minimum and maximum stress amplitudes:

$$R = \frac{\sigma_{min}}{\sigma_{max}} \tag{3}$$

When looking at dynamic loading, the stress amplitude can be plotted against the number of cycles until failure. This $S - N$ curve (stress amplitude versus number of cycles) is often called the Whöler curve. Given a certain dynamic loading amplitude and mean stress, the fatigue life can be determined. The fatigue limit, is the maximum stress amplitude level at which no fatigue failure will occur during service. This is therefore the horizontal line to which the Whöler curve converges.

Next to fatigue failure, also impact failure is a dynamic load. Impact is the deformation process during the collision of two or more objects. During the impact process kinetic energy is transformed. Part of this energy gets absorbed by the materials. The amount of energy a material can absorb depends on its toughness, as was discussed in paragraph 4.

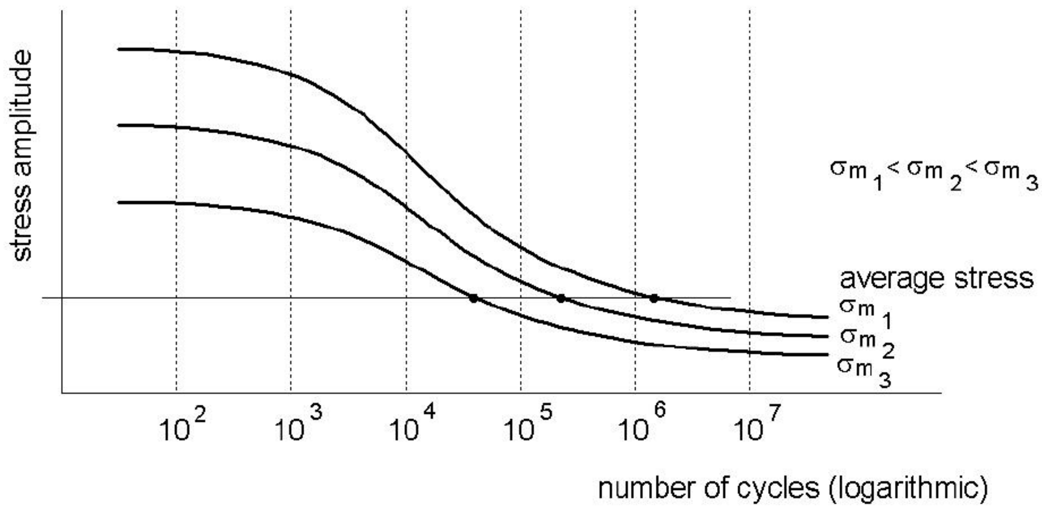

Figure 2: Three Whöler curves with a different average stress.

8 Static Loading

Creep is something that can occur in the case of static loading. Creep is a time dependent deformation under static loading due to an applied stress. Creep plays a role in materials that are under tension for a long time, and consists of three stages:

- Primary - During the primary stage the creep strain increases, but the speed at which this happens decreases.
- Secondary - During the secondary stage the creep strain increases more or less linearly. This is the most important part of the creep process, and the slope of the creep curve $\frac{\Delta\varepsilon}{\Delta t}$ is an important factor.
- Tertiary - During the tertiary stage the creep strain increases faster, until rupture occurs.

When creep has occurred in a specimen and the load is released, often anelastic deformation is present, meaning the specimen will return to its original shape over time.

Another thing that can be caused by static loading is stress relaxation. Stress relaxation is a time dependent change in stress under static loading due to an applied displacement.

9 Damage Tolerance

Damage tolerance shows to what extend damage of the structure influences the function of that structure. When talking about damage tolerance, often the residual strength is used. The residual strength of a damaged structure is the strength of the structure with damage. Because of damage, the strength of the structure might decrease, or stress concentrations might occur, which increases the chance of material failure.

Suppose there is a sheet of material loaded under a tension σ_n. If there is a hole in the sheet, stress concentrations will occur. Suppose that the hole is elliptical in shape, and has a diameter a perpendicular to the tension, and a diameter b tangential to the tension. The maximum load σ_{max} is then equal to $\sigma_{max} = k_t \sigma_n$ where the stress concentration factor k_t is $k_t = 1 + 2\frac{a}{b}$.