Section 7

Material Failure

7.1 How materials fail

There is no single, universally accepted explanation covering the way that materials (particularly metals) fail. Figure 7.1 shows the generally accepted phases of failure. Elastic behaviour, up to yield point, is followed by increasing amounts of irreversible plastic flow. The fracture of the material starts from the point in time at which a crack initiation occurs and continues during the propagation phase until the material breaks.

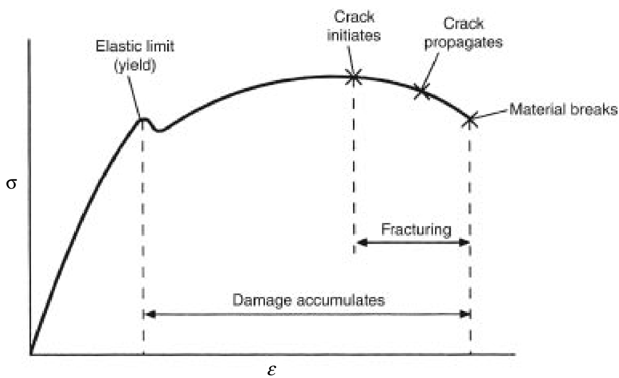

Figure 7.1

There are several approaches to both the characteristics of the original material and the way that the material behaves at a crack tip (see Fig. 7.2). Two of the more common ones are:

- the linear elastic fracture mechanics (LEFM) approach with its related concept of fracture toughness (K_{1c}) parameter (a material property);
- fully plastic behaviour at the crack tip, i.e. 'plastic collapse' approach.

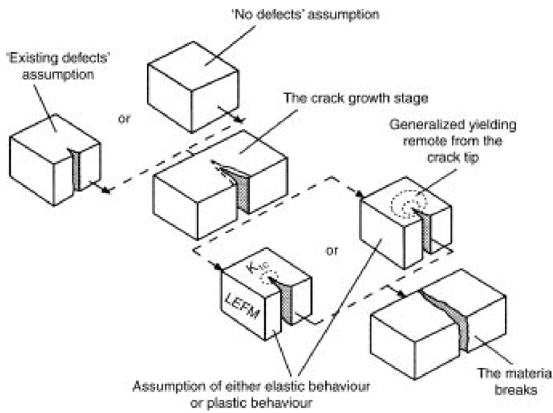

Figure 7.2

7.2 LEFM method

This is based on the 'fast fracture' equation:

$$K_{1c} = K_1 \equiv y\sigma\sqrt{\pi a}$$

K_{1c} = plane strain fracture toughness
K_1 = stress intensity factor
a = crack length
y = dimensionless factor based on geometry

Typical y values used are shown in Figure 7.3.

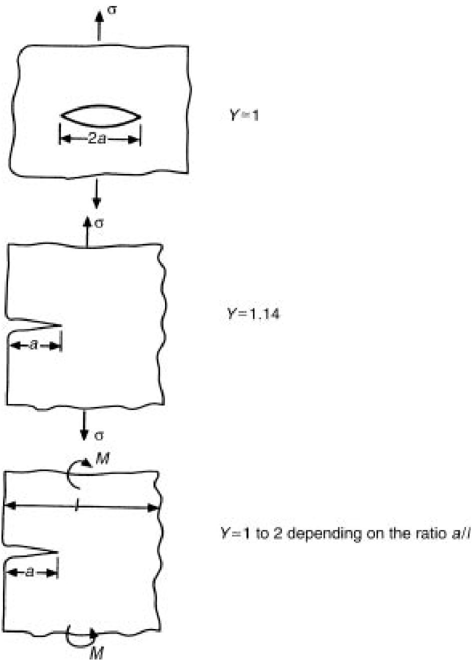

Figure 7.3

7.3 Multi-axis stress states

When stress is not uniaxial (as in many real components), yielding is governed by a combination of various stress components acting together. There are several different 'approaches' as to how this happens.

7.3.1 Von Mises criterion (or 'distortion energy' theory)

This states that yielding will begin to take place when

$$\left(\frac{1}{\sqrt{2}}\right)\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{\frac{1}{2}} = \pm\sigma_y$$

where σ_1, σ_2, σ_3 are the principal stresses at a point in a component.

It is a useful theory for ductile metals. It is more conservative than the Von Mises approach.

7.3.2 Tresca criterion (or maximum shear stress theory)

$$\frac{(\sigma_1-\sigma_2)}{2} \text{ or } \frac{(\sigma_2-\sigma_3)}{2} \text{ or } \frac{(\sigma_3-\sigma_1)}{2} \text{ or } = \pm\frac{\sigma_y}{2}$$

This is also a useful theory for ductile materials.

7.3.3 Maximum principal stress theory

This is a simpler theory which is a useful approximation for brittle metals.

The material fails when

$$\sigma_1 \text{ or } \sigma_2 \text{ or } \sigma_3 = \pm\sigma_y$$

7.4 Fatigue

Ductile materials can fail at stresses significantly less than their rated yield strength if they are subject to fatigue loadings. Fatigue data are displayed graphically on a *S–N* curve. Some materials exhibit a 'fatigue limit', representing the stress at which the material can be subjected to (in theory) an infinite number of cycles without exhibiting any fatigue effects. This

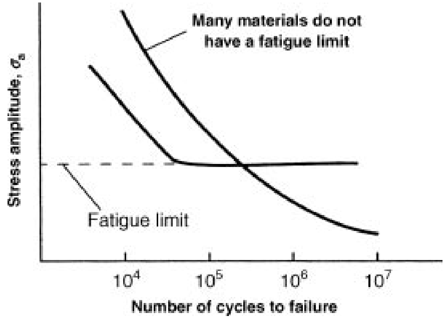

Figure 7.4

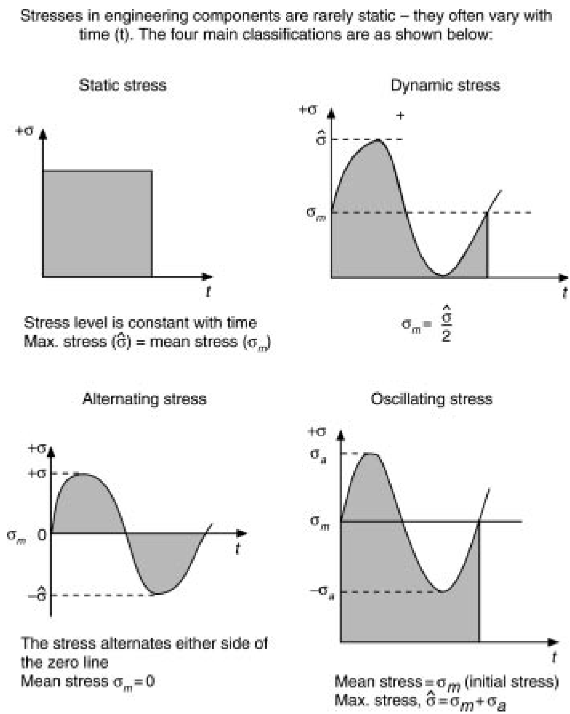

Figure 7.5 Types of Stress Loading

fatigue limit is influenced by the size and surface finish of the specimen, as well as the material's properties.

Characteristics of fatigue failures are:

- visible crack-arrest and 'beach mark' lines on the fracture face;
- striations (visible under magnification) - these are the result of deformation during individual stress cycles;

- an initiation point such as a crack, defect, or inclusion, normally on the surface of the material.

Table 7.1 Typical fatigue limits

Material	*UTS* (B_m)(MN/m^2)	*Fatigue limit* (MN/m^2)
Low-carbon steel	450	≅200
Cr Mo steel	950	≅480
Cast iron	300	≅110
S.G. cast iron	380	≅170
Titanium	550	≅320
Aluminium	100	≅ 40
Brass	320	≅100
Copper	260	≅ 75

7.4.1 Typical fatigue limits

7.4.2 Fatigue strength – rules of thumb

The fatigue strength of a material varies significantly with the size and shape of section and the type of fatigue stresses to which it is subjected. Some 'rules of thumb' values are shown in

Table 7.2

	Bendin			*Tension*		*Torsion*		
	$\sigma_{w(b)}$	$\sigma_{a(b)}$	$\sigma_{y(b)}$	σ_w	σ_a	$\tau_{w(t)}$	$\tau_{a(t)}$	$\tau_{y(t)}$
Steel (structural)	$0.5R_m$	$0.75R_m$	$1.5R_e$	$0.45R_m$	$0.59R_m$	$0.35R_m$	$0.38R_m$	$0.7R_m$
Steel (hardened and tempered)	$0.45R_m$	$0.77R_m$	$1.4R_e$	$0.4R_m$	$0.69R_m$	$0.3R_m$	$0.5R_m$	$0.7R_m$
Cast Iron	$0.38R_m$	$0.68R_m$	–	$0.25R_m$	$0.4R_m$	$0.35R_m$	$0.56R_m$	–

$\sigma_{w(b)}$ Fatigue strength under alternating stress (bending)
$\sigma_{a(b)}$ Fatigue strength under fluctuating stress (bending)
$\sigma_{y(b)}$ Yield point (bending)
σ_W Fatigue strength under alternating stress (tension)
σ_a Fatigue strength under fluctuating stress (tension)
R_e Yield point (tension)
$\tau_{w(t)}$ Fatigue strength under alternating stress (torsion)
$\tau_{a(t)}$ Fatigue strength under fluctuating stress (torsion)
$\tau_{y(t)}$ Yield point (torsion)

Table 7.2. Note how they relate to R_e and R_m values in pure tension.

7.5 Factors of safety

Factors of safety (FOSs) play a part in all aspects of engineering design. For statutory items such as pressure vessels and cranes FOSs are specified in the design codes. In other equipment it is left to established practice and designers' preference. The overall FOS in a design can be thought of as being made up of three parts:

1. the R_e/R_m ratio;
2. the nature of the working load condition; i.e. static, fluctuating, uniform, etc.;
3. unpredictable variations such as accidental overload.

Table 7.3 Typical overall FOSs

Equipment	*FOS*
Pressure vessels	5–6
Heavy duty shafting	10–12
Structural steelwork (buildings)	4–6
Structural steelwork (bridges)	5–7
Engine components	6–8
Turbine components (static)	6–8
Turbine components (rotating)	2–3
Aircraft components	1.5–2.5
Wire ropes	8–9
Lifting equipment (hooks etc.)	8–9

Design factors of safety are mentioned in many published technical standards but there is no dedicated standard on the subject.

7.6 United states practice

Table 7.4

	Yield strength	*Ultimate tensile strength*	*Modulus*
SI/European	R_e (MN/m^2)	$\mathbf{R}_{\boldsymbol{m}}$ (MN/m^2)	E (GN/m^2)
USCS	F_{ty} (ksi)	$\boldsymbol{F}_{\mathbf{tu}}$ (ksi)	E_t(psi 10^6)

Conversions are 1 ksi = 1000 psi = 6.89 MPa = 6.89 MN/m^2 = 6.89 N/mm^2

Technical standards in the USA often follow the United States Customary System (USCS) of units or its derivatives. Material strength definitions and equivalent units are as shown in Table 7.4.

7.7 Ultimate jigsaw – what everything is made of

Rocks, trees, water, fish, sheep and goats must have been the first conclusion. Common comparisons probably helped to decide that sheep's wool and goat's wool looked much the same, and that air was a useful thing to have around, making it impossible to dive for fish or shells for very long. Gradually, people wondered whether all the things of the world were there to see and hold or whether there might be others. It must have been difficult to know where to start – a large jigsaw with an unknown shower of pieces, and no picture on the box (and no box).

Bits of the jigsaw started to develop with the identification of the common elements by experiment or by chance. Gold, silver, phosphorus and tin grew to a list of about 33 in the year 1800. These weren't exactly the corners of the jigsaw (who said it had corners?) but, importantly, some of them did fit crudely together.

- Elements with similar physical and chemical properties showed similar atomic weights.
- Some elements seemed to have a similar willingness to bond with others – a property that was called *valency*.

Under the hypothesis that there must be an order (of some sort), others were gradually discovered. It's likely that most new findings were elements similar to those discovered already rather than completely blind shots in the dark.

The problem of completely false theorems

There has never been a scientific development that didn't have to fight its way through a soup of completely false theorems. Much time and effort was spent on the search for a mystical, atmospheric substance known as 'the ether' – a medium believed to exist to enable the propagation of light. Similar mediums were thought to exist in relation to fire and water. All were fake, and still are.

The emerging picture

Once under way, the picture on the jigsaw box emerged fairly quickly, in scientific terms. It started off being circular but was found to be better represented by a rectangle, as elements were found which fitted naturally as edge-pieces (because there was nothing similar that seemed lighter, or heavier, or with less enthusiasm to bond with anything else).

As with a jigsaw, leaving temporary gaps is a part of the exercise. Once a gap has been surrounded by linked pieces, it is then clear that something is missing, so you can begin to look for it. Once it is finished, the picture is complete – the ordered tabular display of all the chemical elements that there are, and ever will be:

The Periodic Table.

Seen as a collection of interlinking squares or boxes, the glue between them is pretty firm. Elements in the same row exhibit similar properties to their immediate neighbours in the same row, with decreasing similarity to those further away. It also works vertically, with the same continuity of similarity, although the properties that link them (chemical, physical, weight, valency or whatever) are different. As with any crowd, there are large and small family groups, inseparable partners, and the odd unlikely liaison. There won't be anyone else joining the party however, and no one is allowed to leave.

Figure 7.6 shows the Periodic Table. In essence the order is based on recurring (or 'periodic') chemical properties. The listing of the elements is based on the atomic number. The horizontal rows are known as *periods* and relate to the way that electrons fill the 'quantum shell' around each atom. Elements in the same column have similar chemical and physical properties. Of the current total of 118 elements, only 94 occur naturally –

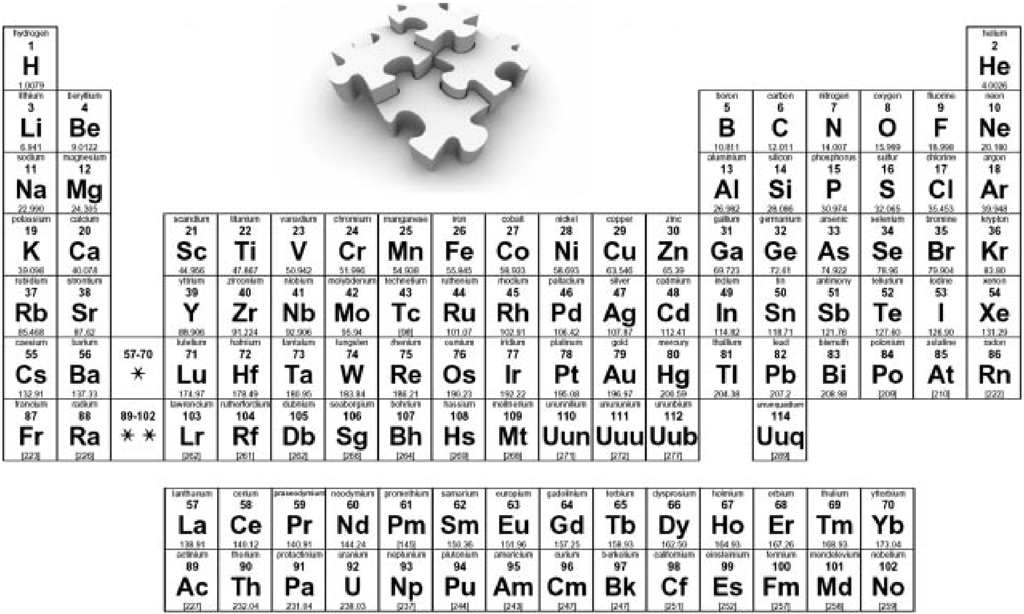

Figure 7.6 Ultimate jigsaw: The periodic table

the others are synthetic and need to be artificially produced. The left-hand edge column contains the common alkali metals and the right-hand edge the very light noble gases.

Within the table, several *blocks* exist, delineated in a rather complex manner by the atomic shell in which the last electron resides. The main blocks are:

- The s-block (alkali and alkali earth metals)
- The p-block (includes the so-called semi-metals)
- The d-block (transition metals)
- The f-block (offset below the rest of the table, it contains actinides and lanthanides, many of which are synthetics)

There is no real split as to those elements more common to the engineering world. Even the simplest manufactured engineering materials are usually a mixture of many of them, in addition to the iron (Fe) and carbon (C) that you would expect.