OCR A Physics A-level

Topic 3.4: Materials

Notes

Springs

Deformation

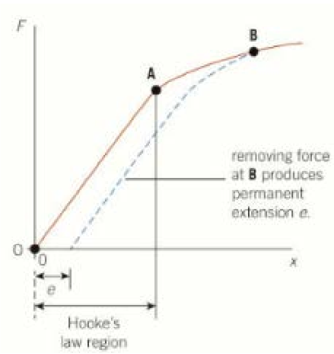
To shape a spring or wire, a pair of **equal and opposite** forces are required. Tensile forces act away from the centre of the spring in both directions, and will stretch it out. This is known as **extension**. Forces acting towards the centre of the spring in both directions are called compressive forces. The spring undergoes **compressive deformation** as a result and will be shortened.

Hooke's law

Hooke's law can be used to model the behavior of springs or wires when compressive or tensile force is applied to them. Hooke's law states that *for a material within its elastic limit, the force applied is directly proportional to the extension of the material*. Once the **elastic limit** of the material is reached, Hooke's law is **no longer obeyed** and the material will not return to its original shape.

Hooke's law states that $F \propto x$, and this can be expressed as a formula $F = kx$, where k is the **force constant** of the material. K is a measure of stiffness, and the larger it is, the stiffer the material will be. The force constant is measured in Nm^{-1}, and can only be used **within the elastic limit** of the material.

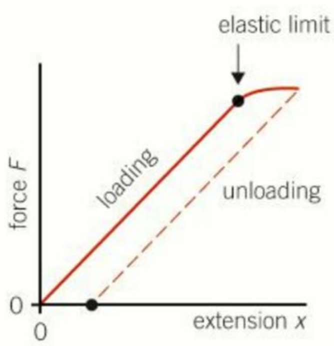
Force-extension graph for a spring



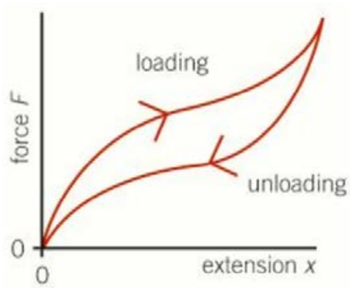
Up until point A, the force acting on the spring is proportional to the extension. The spring shows **elastic deformation**, meaning that it will return to its original shape when the force is removed. The gradient of the line here is equal to the force constant.

Following point A, Hooke's law is no longer obeyed. The spring shows **plastic deformation**, meaning that when the force is removed, the spring will experience permanent deformation and will not return to its original length.

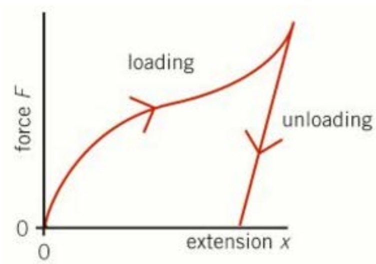
Force extension graphs for different materials



A metal wire obeys Hooke's law and shows elastic deformation until its elastic limit. The loading curve is the same as the unloading curve in this region. Beyond this point it experiences plastic deformation. The unloading curve shows how this plastic deformation leaves a **permanent extension** of the wire.



Rubber is does not experience plastic deformation, but it does not obey Hooke's law. The area between the loading and unloading curves is a **hysteresis loop**. This area represents the **energy** that was required to **stretch the material out**, which was transferred to thermal energy when the force was removed.



Polyethene is a polymeric material. It does not obey Hooke's law, and experiences plastic deformation when any force is applied to it. This makes it very **easy to stretch** in to new shapes.

Techniques to investigate force-extension characteristics

This test setup can be used to determine the force-extension characteristics for a range of materials, including springs, rubber bands, and polythene strips. The material is suspended using a clamp stand with a clamp and boss, adjacent to a meter ruler. A **fiducial marker** is applied to the ruler to mark the original length of the material. Standard masses are attached to the bottom of the material (applying a force of *mg* to the material), and the extension of the spring for each mass is recorded.

Error can be reduced in this experiment by reading the values for the extension at eye-level and using a set square to make sure the ruler is straight. The force constant for the material can be determined by drawing a graph of force against extension, and finding the **gradient**. To reduce error here, ensure that only the gradient of the **straight section** of the line, within the elastic limit of the material, is used.

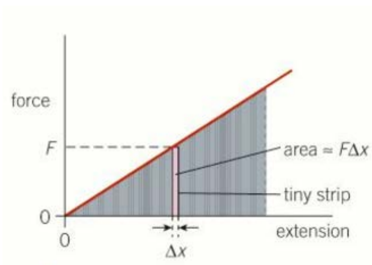
When springs are used in series and parallel, the spring constant for the total combination varies.

In series, we can calculate the force constant (k) to be $\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}=\frac{1}{k_{Total}}$

In parallel, we can calculate force constant (k) as $k_{Total}=k_1+k_2+k_n$

Mechanical properties of materials

Force-extension graphs and work done



When a material is deformed elastically, **work is done**, and transferred in to the material. It is stored as **elastic potential energy**, E, and released when the material is allowed to return to its original length.

To calculate the elastic potential energy stored in a material, we can find the **area under a force extension graph**. As this is a triangle, using area = ½ base x height, we produce the formula $E = \frac{1}{2}Fx$. As F = kx, we can also express this as $E = \frac{1}{2}kx^2$.

If plastic deformation occurs, then the work done to achieve this deformation is not stored as elastic potential energy, it is used to **rearrange the atoms** in to their **new permanent positions**.

Stress, strain, and the Young modulus

Tensile stress is defined as the force applied to a material per unit cross-sectional area. It is measured in Nm^{-2}, or pascal (Pa).

$$\text{Stress } (\sigma) = \frac{F}{A}$$

Tensile strain is defined as the extension or compression of a material per unit of its original length. It has no unit, and is sometimes written as a percentage.

$$\text{Strain } (\varepsilon) = \frac{x}{L}$$

The Young modulus of a material is defined as the **ratio of stress to strain**. It is the gradient of a stress-strain graph (within the straight line section), and depends only on the material. It is a measure of the material's stiffness, independent of shape and size of the material.

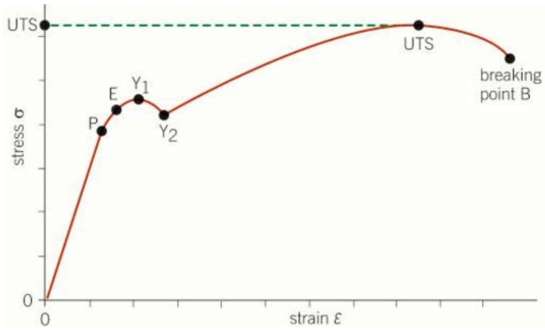
$$E = \frac{\text{Stress}}{\text{Strain}} = \frac{\sigma}{\varepsilon}$$

Techniques and procedure used to determine the Young modulus

The Young modulus of a metal, in the form of a wire, can be determine by applying various forces and measuring the extension of the wire. First, a micrometer is used to measure the diameter of the wire. To reduce error, take the diameter at **several points**, and take an average. This is used to find the cross-sectional area of the wire. Then the wire is clamped at one end and suspended taught using a pulley at the other end. A ruler is placed **parallel** to the wire with a **fiducial marker** placed so that the extension of the wire can be measured.

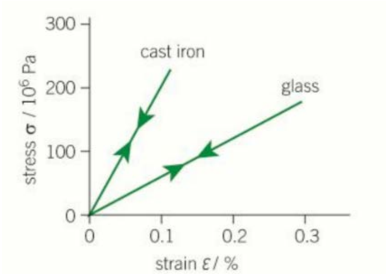
Different forces are then applied to the end of the wire, using slotted masses. The values for mass and extension of the wire are recorded. The masses correspond to the force applied to the wire, using F=*ma*. The stress and strain for each mass is then calculated and plotted on a graph, and the gradient for this graph can then be calculated. This will give the Young modulus for the material.

Ultimate tensile strength

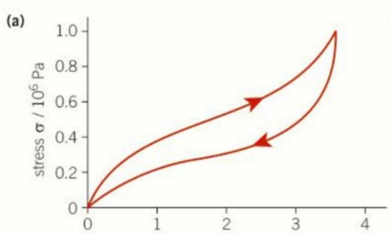


On a stress-strain graph for a wire, P is the **limit of proportionality**. Up until this point, Hooke's law is obeyed. E is the elastic limit, and beyond this point the wire will experience plastic deformation. Y1 and Y2 are yield points where there is rapid extension. UTS is the ultimate tensile strength, **the maximum breaking stress** that can be applied to the wire. Strong materials have a high UTS.

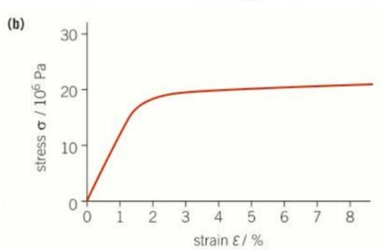
Stress-strain graphs for other materials



For a brittle material like glass, elastic behavior is shown until the breakpoint where the material snaps. There **is no plastic deformation**, and the loading and unloading curve are the same.



An elastic material such as rubber can endure a lot of tensile stress before breaking. There is **no plastic deformation**, but the unloading curve is different to the loading curve, as some energy has been lost as thermal energy.



A ductile material can be easily hammered in to thin sheets or drawn in to a wire. They generally experience elastic deformation until their **elastic limit**, and then undergo plastic deformation before reaching their UTS and breakpoint.