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4.7 Bulk Properties of Solids

PHYSICS

AQA A Level Revision Notes

A Level Physics AQA

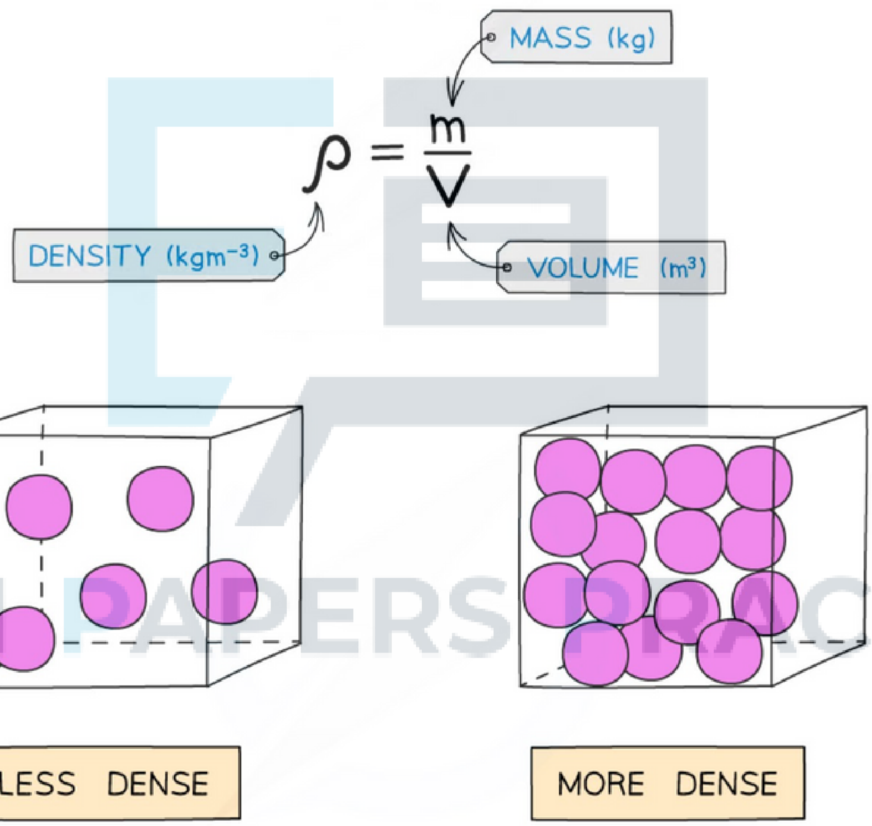
4.7 Bulk Properties of Solids

CONTENTS

4.7.1 Density

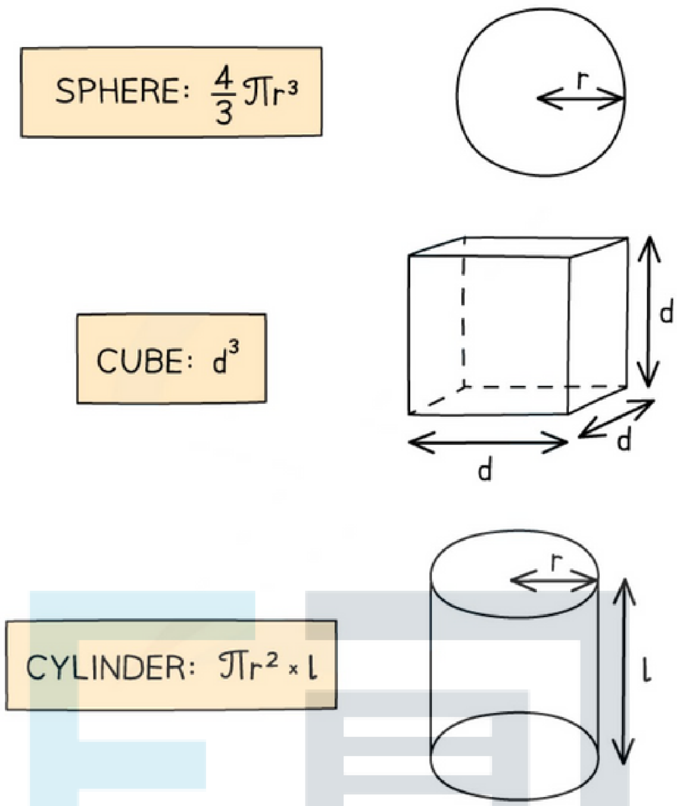
Density

- Density is the **mass per unit volume** of an object
  - Objects made from low-density materials typically have a lower mass
  - For example, a balloon is less dense than a small bar of lead despite occupying a larger volume
- The units of density depend on the units used for mass and volume:
  - If the mass is measured in *g* and volume in **cm³**, then the density will be in **g / cm³**
  - If the mass is measured in *kg* and volume in **m³**, then the density will be in **kg / m³**



Gases are less dense than a solid

- The volume of an object may not always be given directly, but can be calculated with the appropriate equation depending on the object's shape

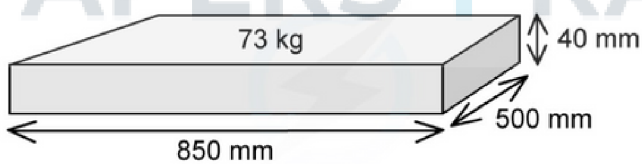


Volumes of common 3D shapes

Worked Example

A paving slab has a mass of 73 kg and dimensions 40 mm × 500 mm × 850 mm.

Calculate the density, in kg m^{-3} of the material from which the paving slab is made.



STEP 1 — EQUATION FOR DENSITY

$$\rho = \frac{M}{V}$$

STEP 2 — CALCULATE THE VOLUME

$$V = 40\ \text{mm} \times 500\ \text{mm} \times 850\ \text{mm} = 1.7 \times 10^{7}\ \text{mm}^3$$

STEP 3 — CONVERT mm^3 TO m^3

$$1\ \text{mm} = 0.001\ \text{m} = 1 \times 10^{-3}\ \text{m}$$

$$1\ \text{mm}^3 = (0.001)^3\ \text{m}^3 = (1 \times 10^{-3})^3\ \text{m}^3 = 1 \times 10^{-9}\ \text{m}^3$$

$$V = 1.7 \times 10^{7} \times 1 \times 10^{-9} = 1.7 \times 10^{-2}\ \text{m}$$

STEP 4 — SUBSTITUTE MASS AND VOLUME INTO DENSITY EQUATION

$$\rho = \frac{73\ \text{kg}}{1.7 \times 10^{-2}\ \text{m}^3} = 4300\ \text{kgm}^{-3}\ \ (2\ \text{s.f.})$$

Exam Tip

- When converting a **larger** unit to a **smaller** one, you **multiply (×)**
    - E.g. 125 m = 125 × 100 = 12 500 cm
- When you convert a **smaller** unit to a **larger** one, you **divide (÷)**
    - E.g. 5 g = 5 / 1000 = 0.005 or 5×10^{-3} kg
- When dealing with squared or cubic conversions, cube or square the conversion factor too
    - E.g. 1 mm^3 = $1/(1000)^3$ = $1 \times 10^{-9}\ m^3$
    - E.g. 1 cm^3 = $1/(100)^3$ = $1 \times 10^{-6}\ m^3$

4.7.2 Hooke's Law

Hooke's Law

- When a force *F* is added to the bottom of a vertical metal wire of length *L*, the wire **stretches**
- A material obeys Hooke's Law if:

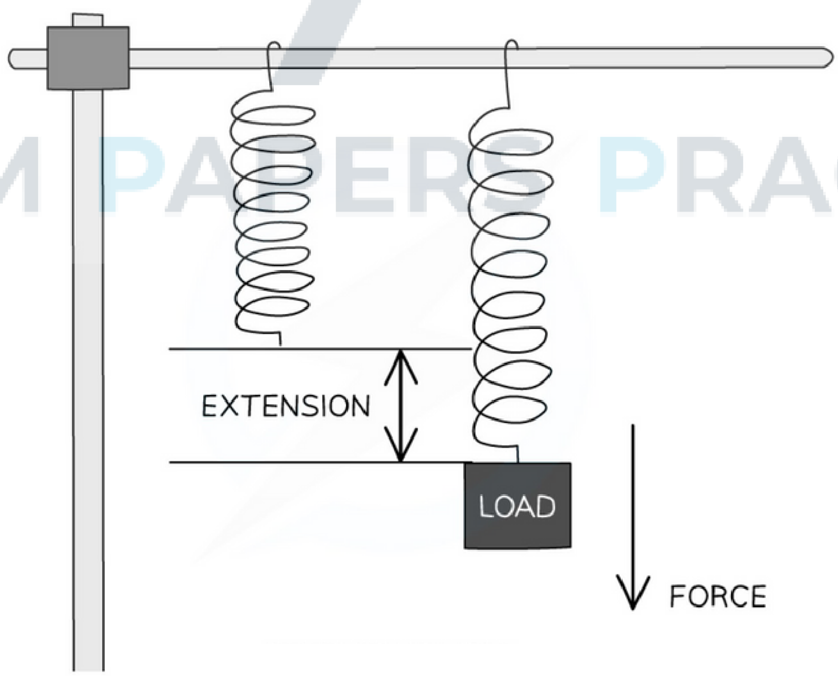
The extension of the material is directly proportional to the applied force (load) up to the limit of proportionality

- This linear relationship is represented by the Hooke's law equation:

$$F = k\Delta L$$

- Where:
  - F = force (N)
  - k = spring constant (N m^{-1})
  - ΔL = extension (m)

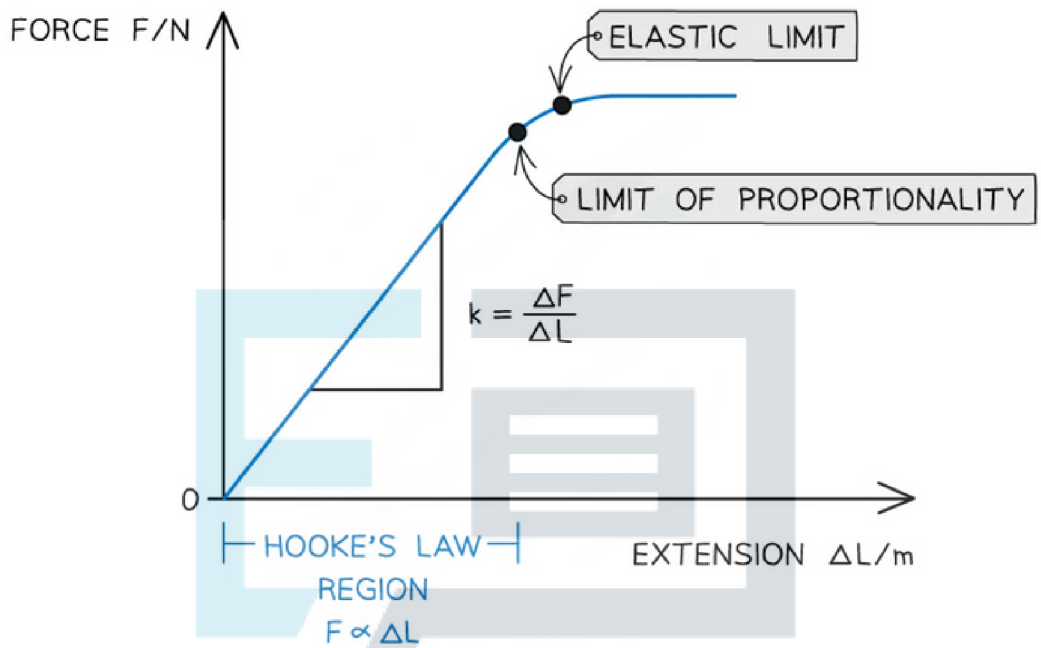
- The spring constant is a property of the material being stretched and measures the **stiffness** of a material
  - The larger the spring constant, the stiffer the material
- Hooke's Law applies to both **extensions** and **compressions**:
  - The extension of an object is determined by how much it has **increased** in length
  - The compression of an object is determined by how much it has **decreased** in length



Stretching a spring with a load produces a force that leads to an extension

Force-Extension Graphs

- The way a material responds to a given force can be shown on a force-extension graph
- Every material will have a unique force-extension graph depending on how brittle or ductile it is
- A material may obey Hooke's Law up to a point
    - This is shown on its force-extension graph by a **straight line through the origin**
- As more force is added, the graph may start to curve slightly



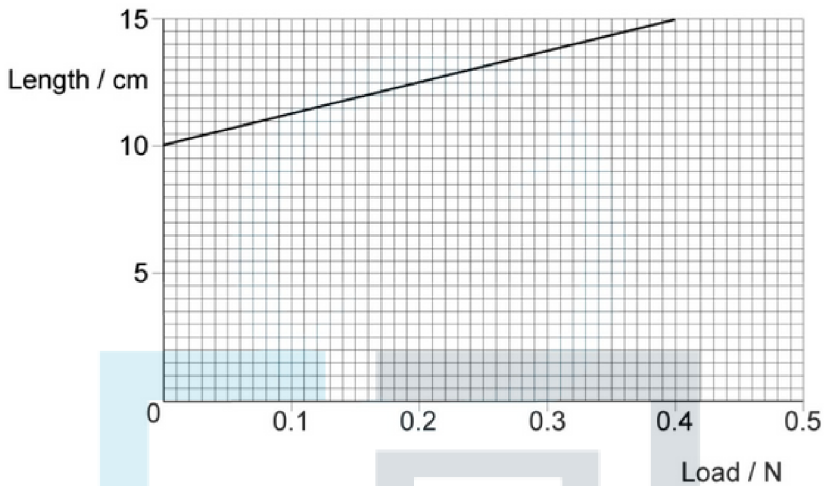
The Hooke's Law region of a force-extension graph is a straight line. The spring constant is the gradient of that region

- The key features of the graph are:
    - **The limit of proportionality:** The point beyond which Hooke's law is no longer true when stretching a material i.e. the extension is no longer proportional to the applied force
        - The point is identified on the graph where the line starts to curve (flattens out)
    - **Elastic limit:** The maximum amount a material can be stretched and still return to its original length (above which the material will no longer be elastic). This point is always **after** the limit of proportionality
        - The **gradient** of this graph is equal to the **spring constant *k***

Worked Example

A spring was stretched with increasing load.

The graph of the results is shown below.



What is the spring constant?

STEP 1

REARRANGE FROM HOOKE'S LAW, THE SPRING CONSTANT IS

$$k = \frac{F}{\Delta L}$$

STEP 2

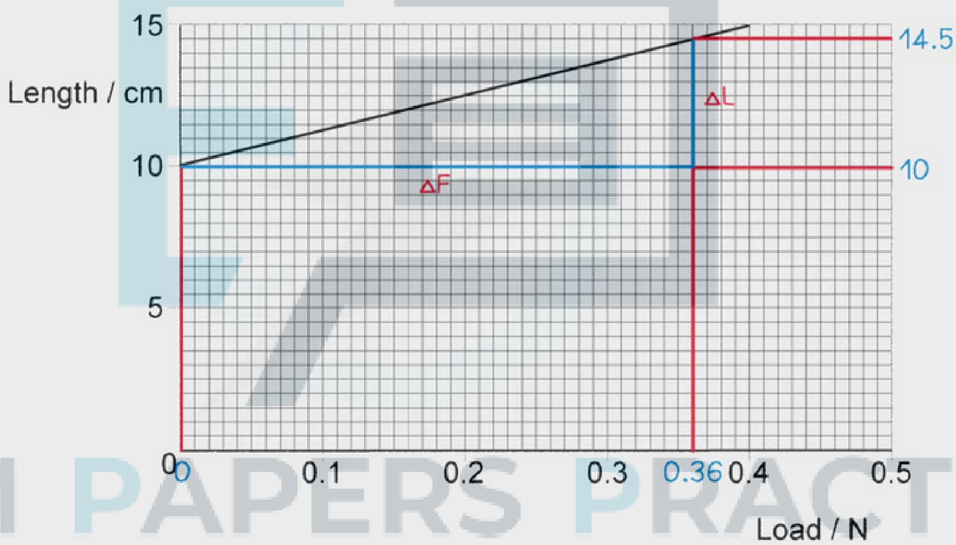
THE GRADIENT OF A FORCE-EXTENSION GRAPH IS THE SPRING CONSTANT

$$k = \frac{\Delta F}{\Delta L}$$

STEP 3

THIS PARTICULAR GRAPH HAS THE LENGTH ON THE y-AXIS AND THE FORCE ON THE x-AXIS.

THEREFORE THE SPRING CONSTANT IS $\frac{1}{\text{GRADIENT}}$



STEP 4

FIND THE GRADIENT

$$\frac{\Delta L}{\Delta F} = \frac{(0.145 - 0.10)\text{m}}{0.36\text{ N}} = \frac{1}{8.0}\text{ mN}^{-1}$$

GRADIENT = $\frac{\Delta y}{\Delta x}$

STEP 5

SPRING CONSTANT = $\frac{1}{\text{GRADIENT}}$

$$1 \div \frac{1}{8.0} = 8.0\text{ Nm}^{-1}$$

Exam Tip

Always double check the axes before finding the spring constant as the gradient of a force-extension graph. Exam questions often swap the force (or load) onto the x-axis and extension (or length) on the y-axis. In this case, the gradient is **not** the spring constant, it is **1 ÷ gradient** instead.

Tensile Stress & Strain

- Opposite forces can deform an object
- If the forces **stretch** the object, then they are tensile forces
- Tensile forces lead to the two properties of materials known as **tensile stress** and **tensile strain**

Tensile Stress

- Tensile stress is defined as the **force exerted per unit cross-sectional area** of a material

$$\text{Tensile stress, } \sigma = \frac{F}{A}$$

- Where:
  - σ = tensile stress (Pa)
  - F = force applied (N)
  - A = cross-sectional area (m^2)

- The **ultimate tensile stress** is the **maximum** force per original cross-sectional area a wire is able to support until it breaks
- σ is the greek letter lower-case 'sigma'
- σ has the units of pascals (Pa), which is the same units as pressure (also force ÷ area)

Tensile Strain

- Strain is the **extension per unit length**
- This is a deformation of a solid due to stress in the form of elongation or contraction

$$\text{Tensile strain} = \frac{\Delta L}{L}$$

- Where:
  - ΔL = extension (m)
  - L = original length (m)

- The strain is a **dimensionless** unit because it's the ratio of lengths
- Sometimes strain might be written as a **percentage**
  - For example, extending a 0.1 m wire by 0.005 m would produce a strain of (0.005 ÷ 0.1) × 100 = 5 %

Worked Example

A brass wire of length 4.50 m and a radius of 0.2 mm is extended to a total length of 4.53 when a tensile force of 50 N is applied. Calculate for the brass wire: (i) The tensile stress (ii) The tensile strain

(i) Calculate the tensile stress

Step 1: Write down the tensile stress equation

$$\text{Tensile stress} = \text{Force} \div \text{Cross-sectional area}$$

Step 2: Calculate the cross-sectional area, *A* of the wire

- A wire has a circular cross-sectional area = πr^2

$$\text{Area} = \pi \times (0.2 \times 10^{-3})^2 = 1.2566 \times 10^{-7}\ \text{m}^2$$

Step 3: Substitute values in the tensile stress equation

$$\text{Tensile stress} = 50 \div (1.2566 \times 10^{-7}) = 397.899 \times 10^6\ \text{Pa} = 400\ \text{MPa}$$

(ii) Calculate the tensile strain

Step 1: Write down the tensile strain equation

$$\text{Tensile strain} = \text{Extension} \div \text{Original length}$$

Step 2: Determine the extension

- The extension is total length – the original length

$$\text{Extension} = 4.53 - 4.50 = 0.03\ \text{m}$$

Step 3: Substitute values in the tensile strain equation

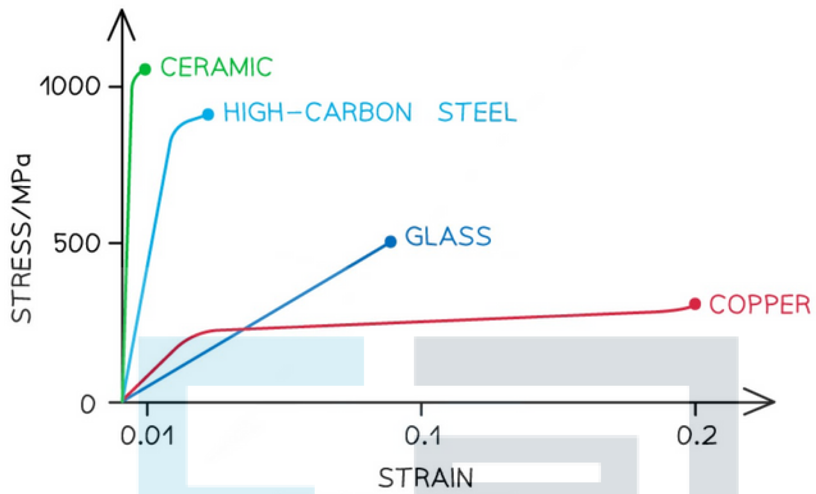
$$\text{Tensile strain} = 0.03 \div 4.50 = 6.7 \times 10^{-3}$$

Exam Tip

Since strain is a ratio, the extension and original length do not have to be calculated in metres. As long as they **both** have the same units, the strain will be correct

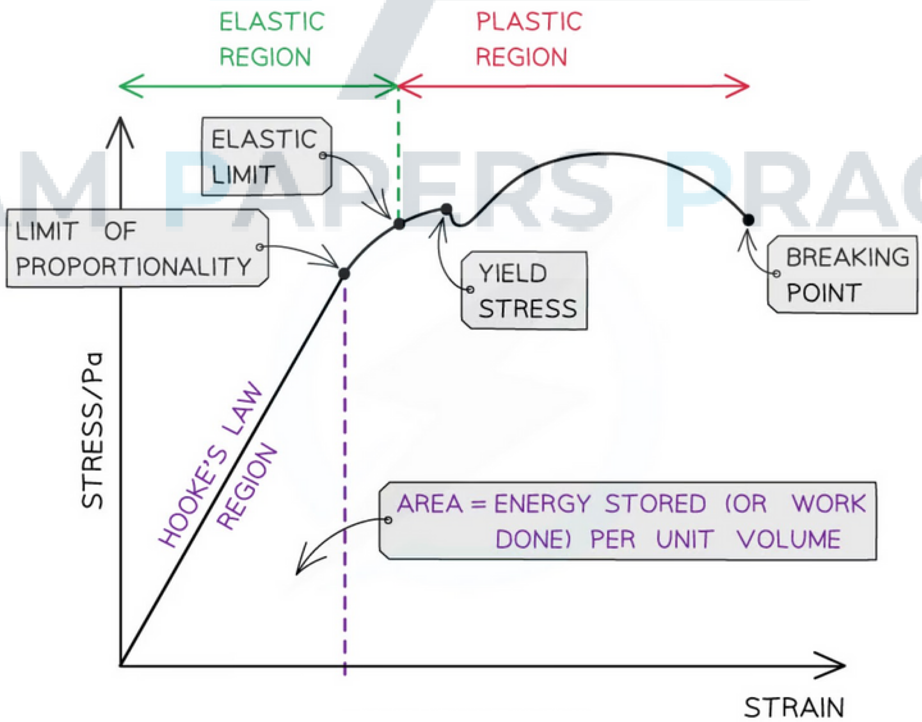
Stress-Strain Curves

- Stress-strain curves describe the properties of materials such as whether they are brittle, ductile and up to what stress and strain they obey Hooke's Law and have elastic and / or plastic behaviour
- Each material will have a unique stress-strain curve



Stress-strain graph for different materials up to their breaking stress

- There are important points on the stress-strain graph, some are similar to the force-extension graph

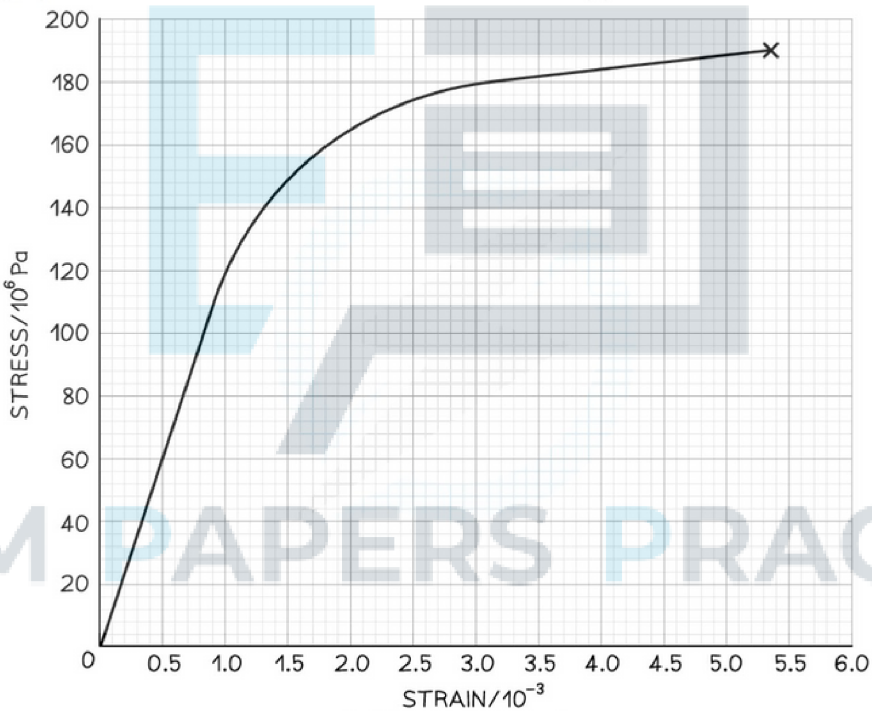


The important points shown on a stress-strain graph

- The key points that are unique to the stress-strain graph are:
  - **Yield Stress:** The force per unit area at which the material extends plastically for no / a small increase in stress
  - The elastic strain energy stored per unit volume is the **area** under the Hooke's Law (straight line) region of the graph
  - **Breaking point:** The stress at this point is the breaking stress. This is the maximum stress a material can stand before it fractures
  - **Elastic region:** The region of the graph up till the elastic limit. In this region, the material will return to its original shape when the applied force is removed
  - **Plastic region:** The region of the graph after the elastic limit. In this region, the material has deformed permanently and will not return to its original shape when the applied force is removed

Worked Example

The graph below shows a stress-strain curve for a copper wire.



From the graph state the value of:

(i) The breaking stress

(ii) The stress at which plastic deformation begins

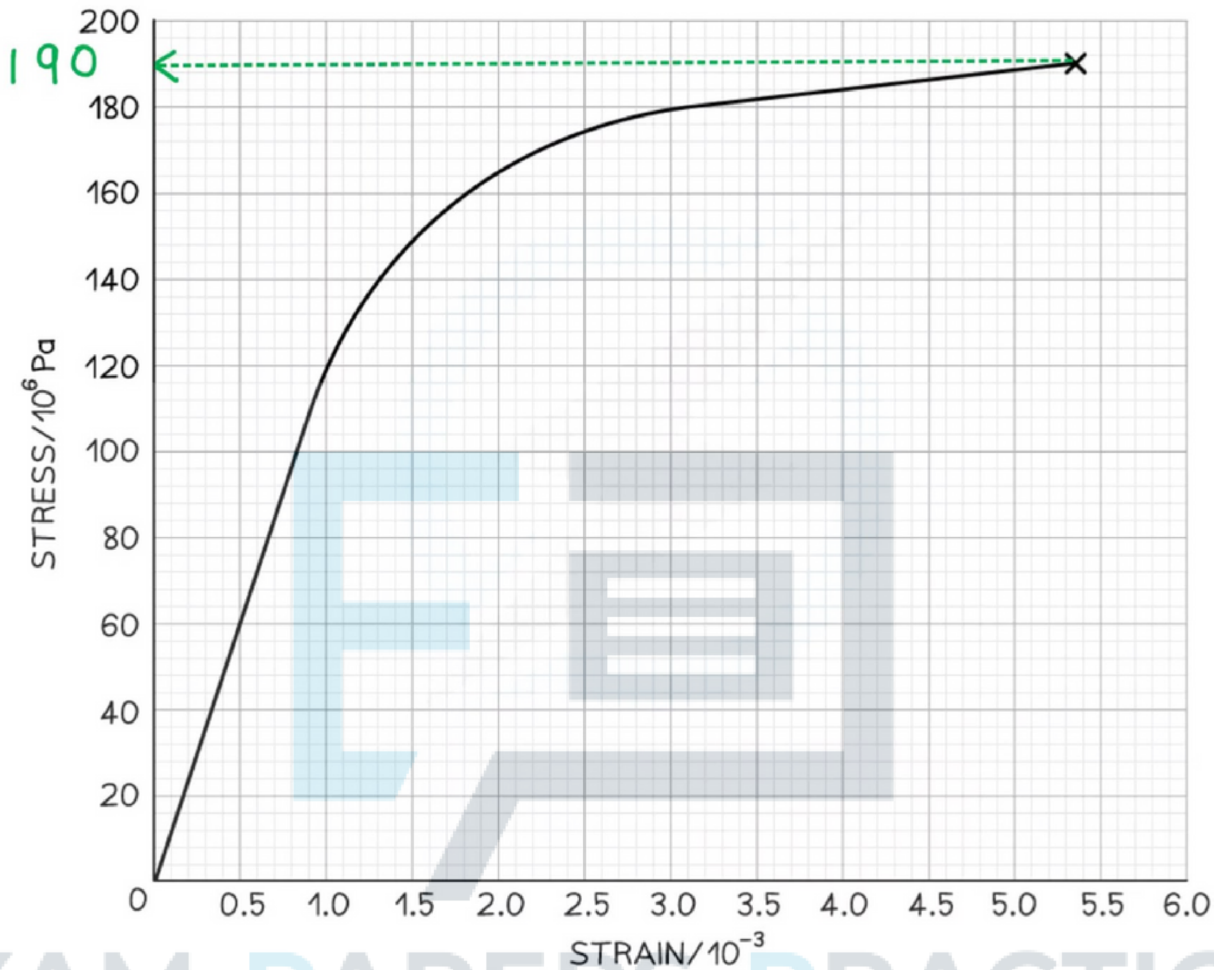
(i) The breaking stress

Step 1: Define breaking stress

The breaking stress is the maximum stress a material can stand before it fractures. This is the stress at the final point on the graph

Step 2: Determine breaking stress from the graph

Draw a line to the y axis at the point of fracture



The breaking stress is 190 MPa

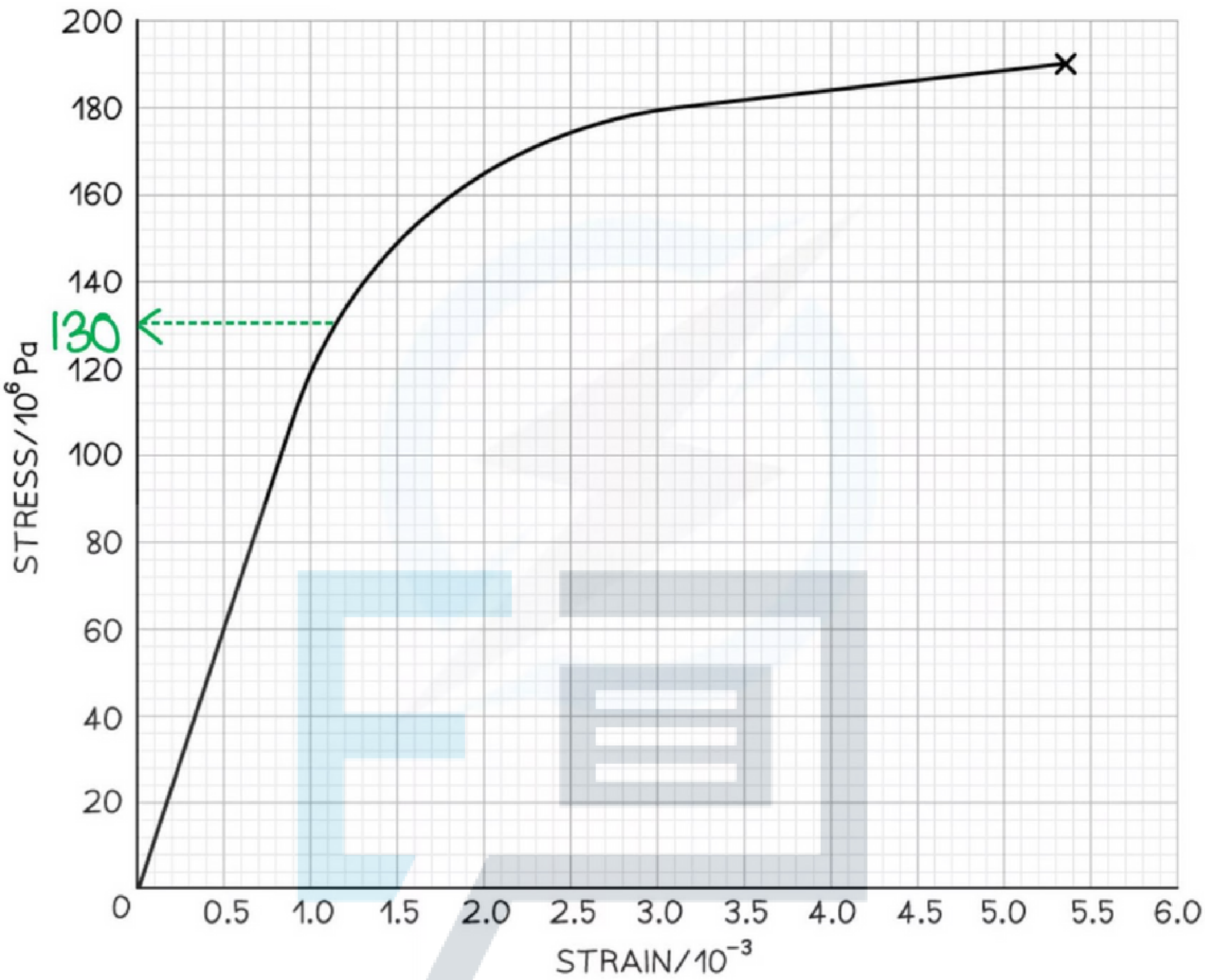
(ii) The stress at which plastic deformation begins

Step 1: Define plastic formation

Plastic deformation is when the material is deformed permanently and will not return to its original shape once the applied force is removed. This is shown on the graph where it is curved

Step 2: Determine the stress of where plastic deformation beings on the graph

Draw a line to the y axis at the point where the graph starts to curve

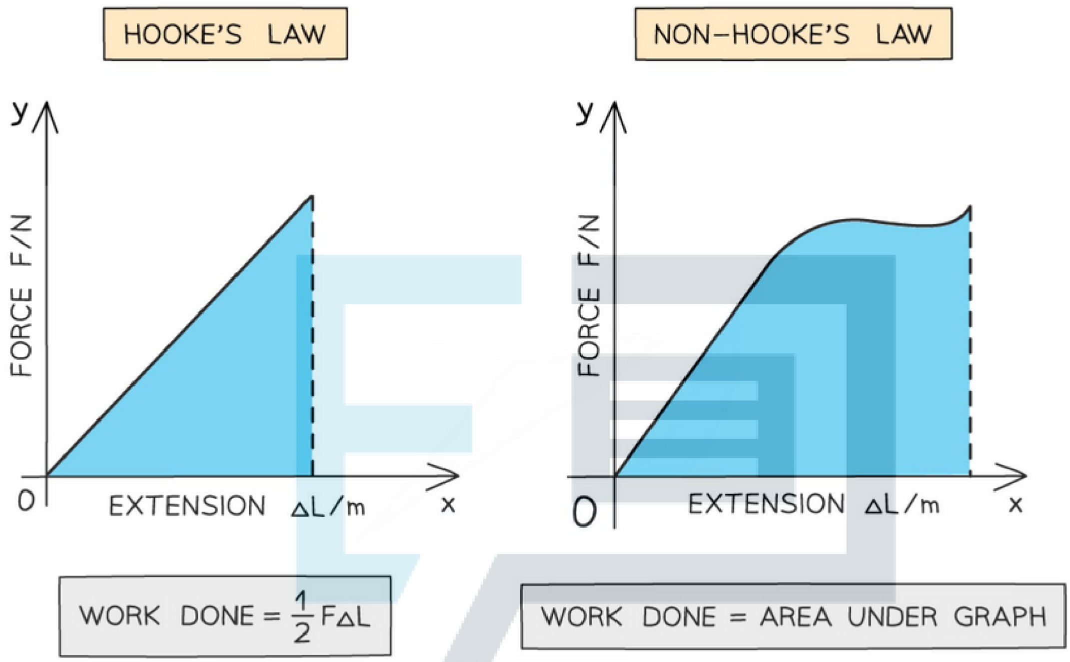


Plastic deformation begins at a stress of 130 MPa

4.7.4 Elastic Strain Energy

Elastic Strain Energy

- Work has to be done to stretch a material
- Before a material reaches its elastic limit (whilst it obeys Hooke's Law), all the work is done is stored as **elastic strain energy**
- The work done, or the elastic strain energy is the **area under the force-extension graph**



Work done is the area under the force-extension graph

- This is true for whether the material obeys Hooke's law or not
  - For the region where the material **obeys** Hooke's law, the work done is the area of a **right-angled triangle** under the graph
  - For the region where the material **doesn't obey** Hooke's law, the area is the **full region** under the graph. To calculate this area, split the graph into separate segments and add up the individual areas of each
- When a material **does** obey Hooke's law, the elastic strain energy, *E* can be calculated with an equation
  - The equation is the area of a right-angled triangle under the force-extension graph

$$E = \frac{1}{2}F\Delta L$$

- Where:
  - E = elastic strain energy (or work done) (J)
  - F = average force (N)
  - ΔL = extension (m)

- Since Hooke's Law states that $F = k\Delta L$, the elastic strain energy can also be written as:

$$E = \frac{1}{2}k(\Delta L)^2$$

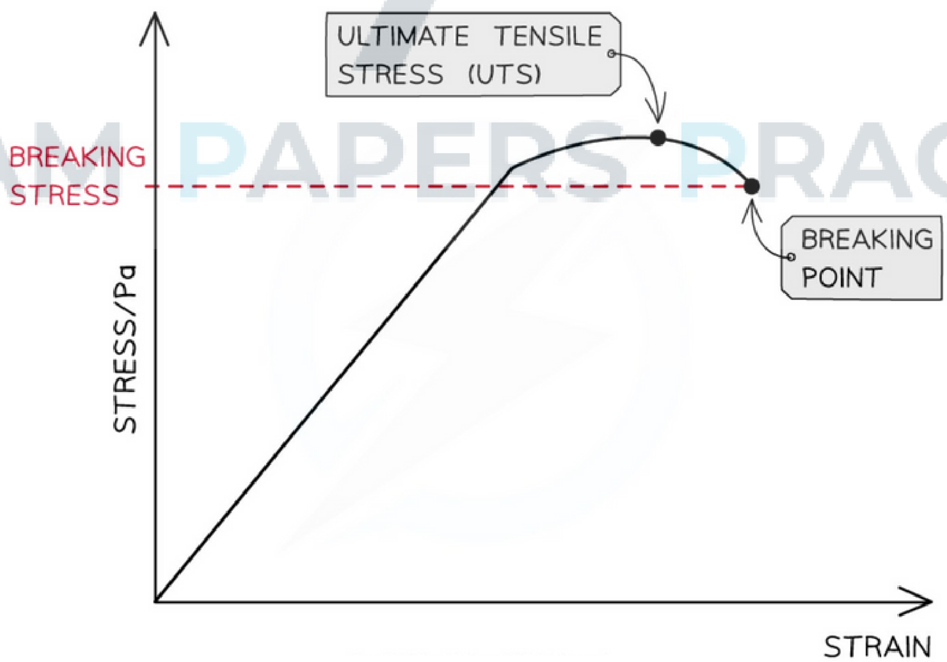
- Where:
  - k = spring constant (N m^{-1})

Breaking Stress

- As greater force is applied on a material, the **stress** on it increases
- The breaking stress is the **maximum stress a material can stand before it fractures (breaks)**
  - A material with high breaking stress is considered **ductile**, which means it can extend more before breaking because of plastic deformation
  - A common example of this is copper, as well as being a good electrical conductor, copper is ductile so it is a suitable material for making wires

- The ultimate tensile stress (UTS) is sometimes also marked on a stress-strain graph
  - This is the **maximum stress that the material can withstand**

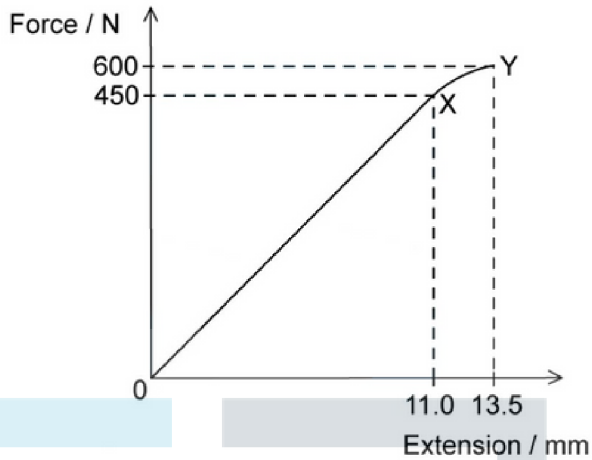
- The UTS and breaking stress can depend on the condition of the material such as its temperature
  - This is very important for engineers when considering materials for a particular structure
  - The material might need to stand extreme temperatures and loads which are taken into consideration



The ultimate breaking stress is the point on the stress-strain graph of maximum stress. The breaking point is where the material fractures

Worked Example

The graph shows the behaviour of a sample of a metal when it is stretched until it starts to undergo plastic deformation.

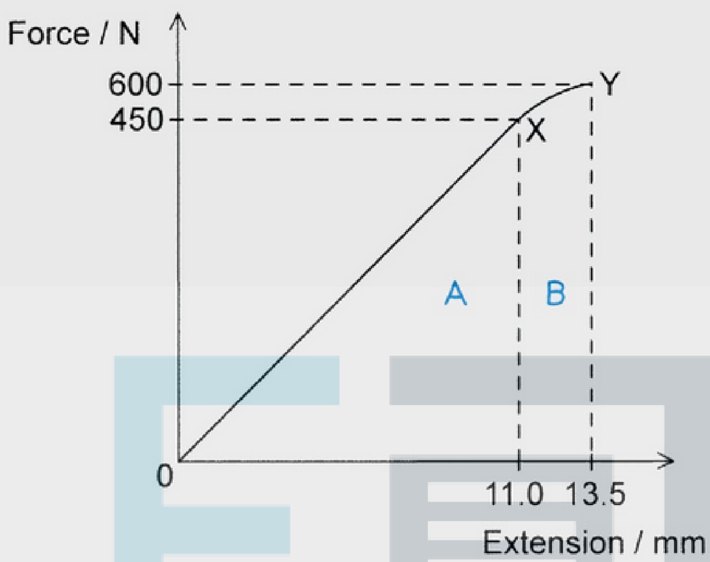


What is the total work done in stretching the sample from zero to 13.5 mm extension?

Simplify the calculation by treating the curve XY as a straight line.

STEP 1 — WORK DONE = AREA UNDER THE FORCE–EXTENSION GRAPH

STEP 2 — SPLIT GRAPH INTO THE TWO AREAS



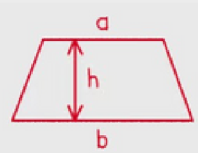
STEP 3 — CALCULATE AREA A

AREA OF A RIGHT ANGLED TRIANGLE = $\frac{1}{2}$ × BASE × HEIGHT

AREA = $\frac{1}{2} \times 11 \times 10^{-3} \times 450 = 2.475$ J

STEP 4 — CALCULATE AREA B

AREA OF TRAPEZIUM = $\left(\frac{a+b}{2}\right) \times h$

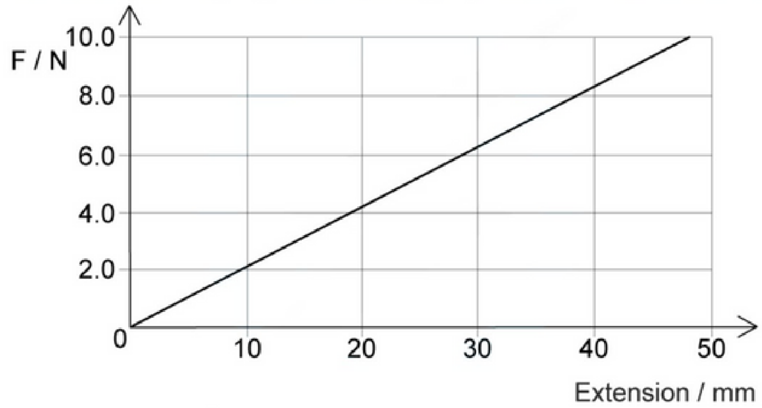


AREA = $\left(\frac{450 + 600}{2}\right) \times 2.5 \times 10^{-3} = 1.313$ J

STEP 5 — TOTAL AREA = 2.475 + 1.313 = 3.79 J (3 s.f.)

Worked Example

A spring is extended with varying forces; the graph below shows the results.



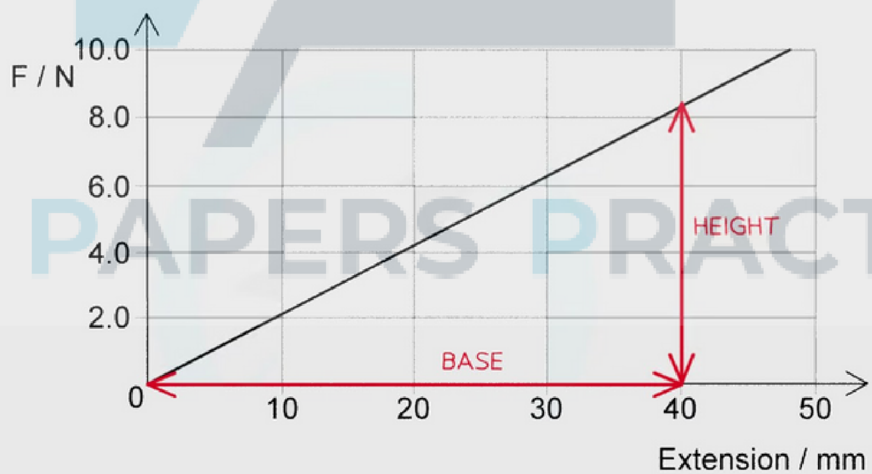
What is the energy stored in the spring when the extension is 40 mm?

STEP 1

ENERGY STORED = AREA UNDER THE GRAPH

STEP 2

CALCULATE AREA UNDER GRAPH FOR EXTENSION OF 40mm



AREA OF TRIANGLE = $\frac{1}{2}$ × BASE × HEIGHT

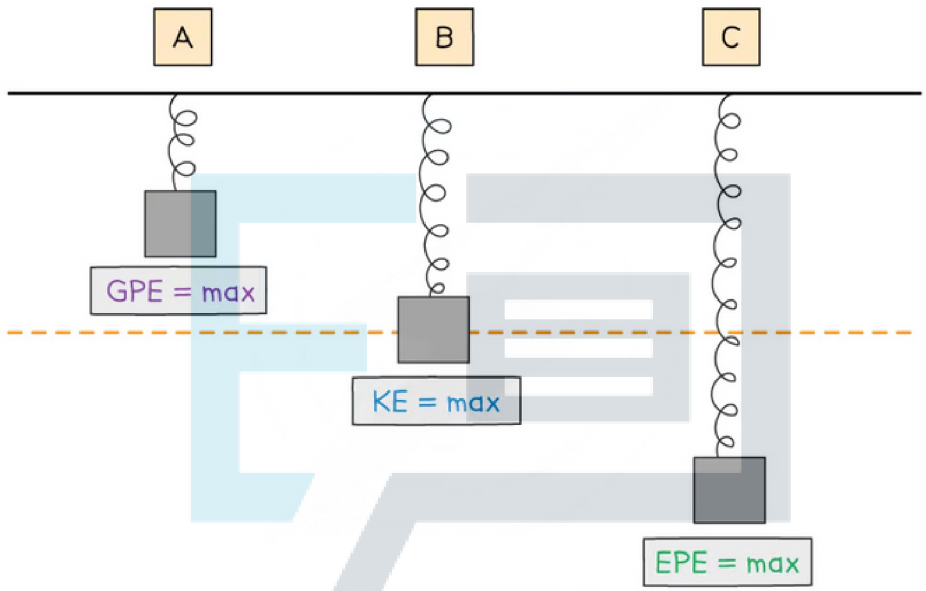
AREA = $\frac{1}{2}$ × 40 × 10^{-3}m × 8.1 N = 0.16 J

STEP 3

ENERGY STORED = 0.16 J

Spring Energy

- When a vertical spring is extended and contracted, its energy is converted into other forms
- Although the total energy of the spring will remain constant, it will have changing amounts of:
  - **Elastic** potential energy (EPE)
  - **Kinetic** energy (KE)
  - **Gravitational** potential energy (GPE)
- When a vertical mass is hanging on a spring and it moves up and down, its energy will convert between the three in various amounts



- At position **A:**
  - The spring has some EPE since it is slightly compressed
  - Its KE is 0 since it is stationary
  - Its **GPE is at a maximum** because the mass is at its highest point
- At position **B:**
  - The spring has some EPE since it is slightly stretched
  - Its **KE is at a maximum** as it passes through the equilibrium position at its maximum speed
  - It has some GPE since the mass is still above the ground
- At position **C:**
  - The spring has its maximum EPE because it is at its maximum extension
  - Its KE is 0 since it is stationary
  - Its **GPE is at a minimum** because it is at its lowest point above the Earth's surface
- For a horizontal mass on a spring system, there is no gravitational potential energy to consider. The spring only converts between kinetic and elastic potential energy

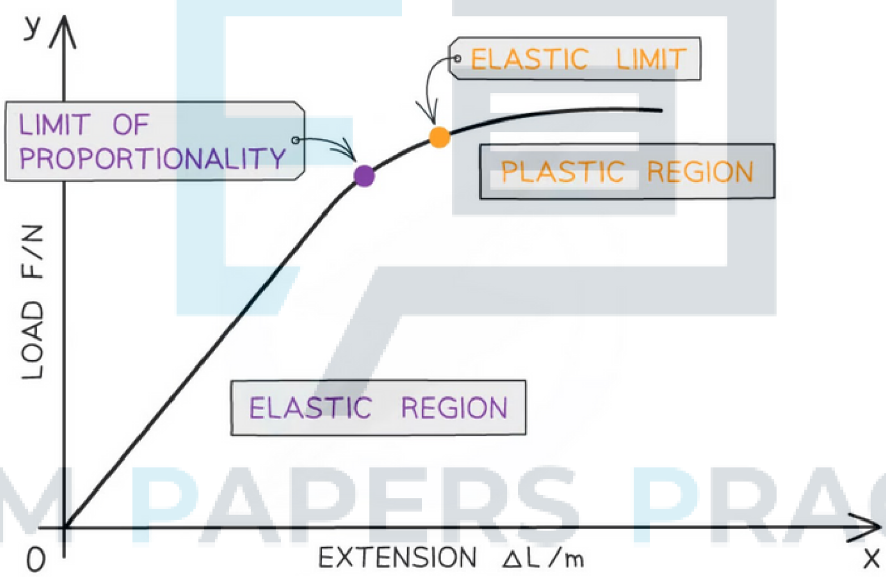
Exam Tip

It is important to remember at which position the mass has the greatest amount of which type of energy (and which type of energy is 0).

4.7.5 Elastic & Plastic Behaviour

Plastic Behaviour

- Materials can undergo two types of deformations:
- **Elastic deformation**
  - When the load is removed, the object **will** return to its original shape
  - This is shown in the elastic region of the graph
- **Plastic deformation**
  - The material is permanently deformed
  - When the load is removed, the object **will not** return to its original shape or length
  - This is beyond the elastic limit and is shown in the plastic region of the graph
- These regions can be determined from a Force-Extension graph:



Below the elastic limit, the material exhibits elastic behaviour. Above the elastic limit, the material exhibits plastic behaviour

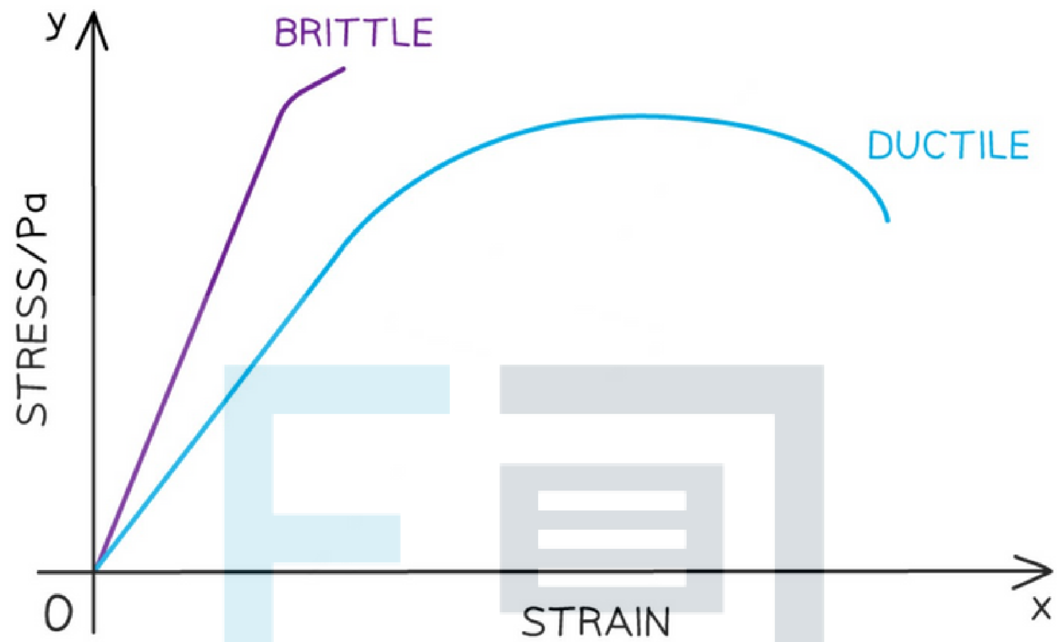
- The **elastic** region is where the extension is proportional to the force applied to the material (**straight line**)
- The **plastic** region is where the extension is no longer proportional to the force applied to the material (graph starts to **curve**)
  - These regions are divided by the elastic limit
- The plastic region starts at the elastic limit and ends at the point of fracture (the material breaks)

Brittle and Ductile Materials

- **Brittle** materials have very little to no plastic region e.g. glass, concrete

- The material breaks with little elastic and insignificant plastic deformation

- **Ductile** materials have a larger plastic region e.g. rubber, copper
  - The material stretches into a new shape before breaking

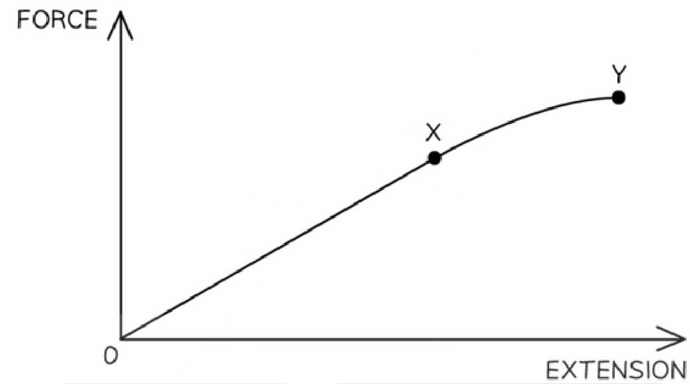


Brittle and ductile materials on a stress-strain graph. These are the same on a force-extension graph too

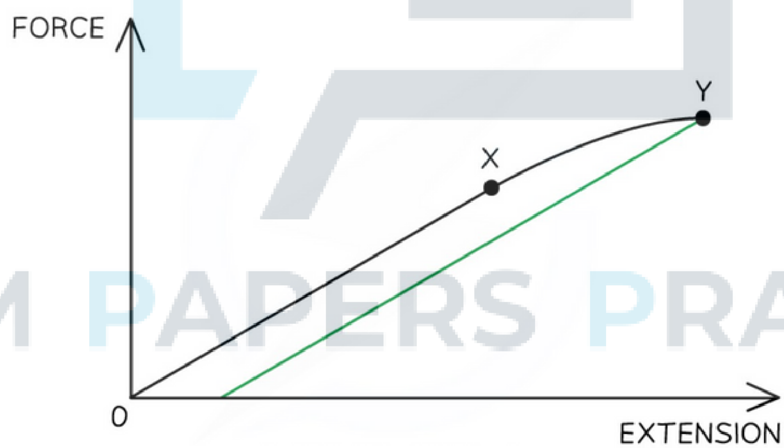
- To identify these materials on a stress-strain **or** force-extension graph up to their breaking point:
  - A brittle material is represented by a straight line through the origins with no or negligible curved region
  - A ductile material is represented with a straight line through the origin then curving towards the x-axis

Worked Example

A sample of metal wire is subjected to a force which increases as a series of masses are added to the wire. The extension is measured and a force-extension graph of the data is plotted as shown below.



When the wire has been extended to **Y**, the point just before the wire fractures, the masses are removed one by one and the extension is re-measured.(i) Describe the behaviour of the metal between **X** and **Y**.(ii) On the graph, sketch the result obtained after the masses are removed and explain why the graph has this shape.



(i)

- Since the graph is a straight line and the metal almost fractures, the point after **X** must be its elastic limit
- The graph starts to curve after this and would fracture beyond point **Y**
- This curve between **X** and **Y** denotes plastic behaviour
- Therefore, the metal exhibits plastic behaviour, but **not** elastic behaviour

(ii)

- Plastic deformation has occurred which results in permanent extension
- As the load is decreased, the bonds in the metal are re-aligned hence the y-intercept is now not through the origin

- The gradient remains the same because the intermolecular forces (the forces between bonds) are identical to before

Exam Tip

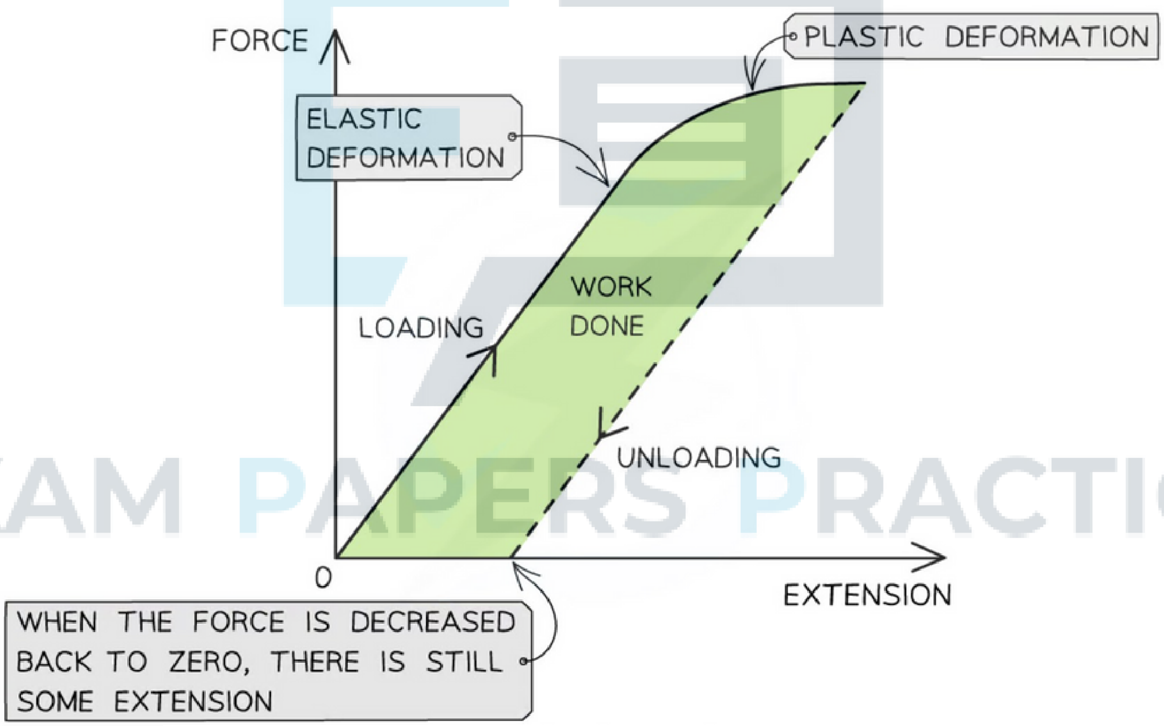
Avoid describing plastic deformation as 'does not obey Hooke's law'. Although this is mostly correct, it should be described as the material being **permanently deformed**

4.7.6 Energy Conservation

Conservation of Energy in Deformation

Loading and Unloading a Metal Wire

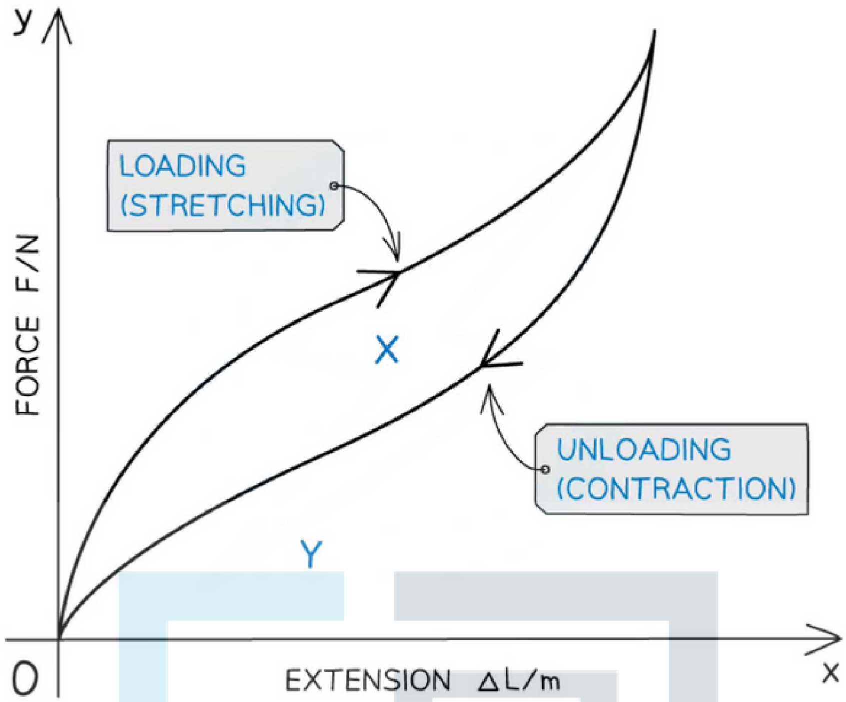
- When a metal wire is loaded with a force and stretched beyond its limit of proportionality, it will undergo **plastic deformation**
- When the force is removed, the wire is unloaded, this causes the extension to decrease
- The unloading line is parallel to the loading line (since *k* does not change) however, it **does not** go through the origin
    - If the wire is permanently deformed, it will **not** be at zero extension when there is no force as it is now **permanently extended**
- The area between the loading and unloading lines represents the work done to permanently deform the wire



Force-extension graph of a material that has undergone plastic deformation

Loading and Unloading a Rubber Band

- The force-extension graph for a material may not always be the same when loading (adding a force) and unloading (removing a force)
- The force-extension curve for stretching and contracting a rubber band is shown below

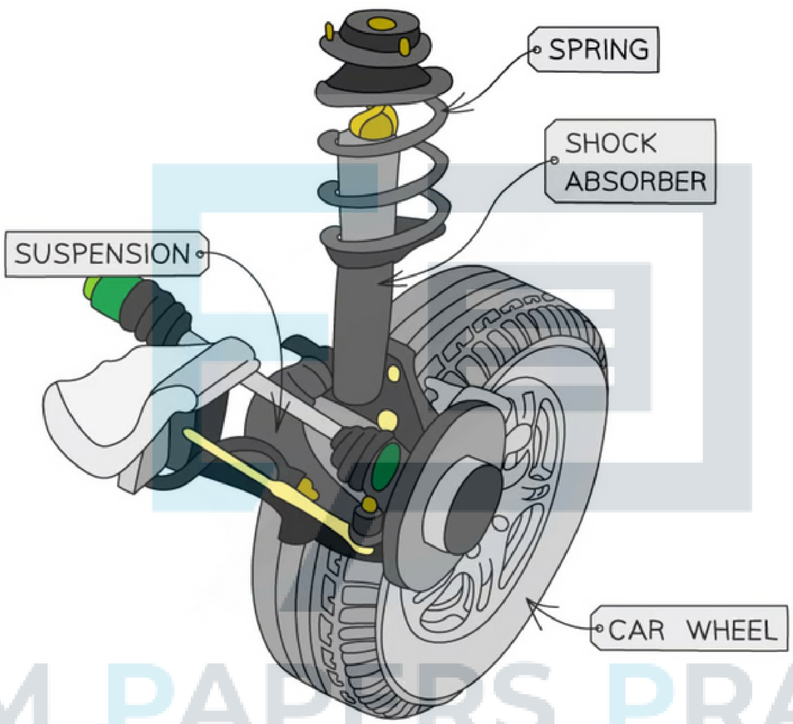


Loading and unloading on a force-extension graph

- Since the rubber band has no extension when the load is fully removed, it has no permanent extension
  - This means that the rubber band is **elastic**
- The graph shows the rubber band stores a greater amount of strain energy when it is loaded (stretched) than when it is being unloaded (contracted)
- The curve for contraction is always **below** the curve for stretching
- The key features of the area under the graph are:
  - Area **X** is the work done in heating the rubber (or the increase in thermal energy)
  - Area **Y** is the work done by the rubber when it is returned to its original shape
  - Area **X + Y** represents the work done in stretching the rubber band originally
- However, due to the conservation of energy, the difference in strain energy when loading and unloading must be accounted for
- A rubber band becomes warm when it is stretched and contracted hence some energy is transferred to heat energy

Energy Conservation Issues

- Vehicle suspension systems are made up of **tires**, **springs** and **shock absorbers** which provide comfortable handling of a vehicle and improve the comfort of passengers
- Roads are often very bumpy filled with potholes and speed bumps
  - A bump in the road causes the wheel of a vehicle to move up and down perpendicular to the road surface.
  - If a wheel loses contact with the road surface, it will slam back down again causing large vibrations within the car and potentially damage the vehicle
  - As well as this it would be very uncomfortable for the passengers and the driver could lose control of the vehicle



Vehicle suspension, springs and shock absorbers above the wheel help absorb any impact forces

- This energy is absorbed by **shock absorbers**
  - These are elastic objects designed to absorb or dampen the compression and rebound of the springs above a vehicle's tires
  - They help keep the tires on the road at all times

- When a vehicle hits a bump in a road, the shock absorbers dampen the movement of the springs in the suspension system
  - They do this by converting **kinetic energy**, from the movement of the car, into **thermal energy** which is dissipated

- The faster the springs in the suspension system move (say, if a vehicle hits a bump at a high velocity), the more resistance the shock absorber provides