| Name | Date started | Target end date |
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GCE AS/A LEVEL — SOLIDS UNDER STRESS QUESTION PACK

1321-01 (Legacy PH1) · 1325-01 (Legacy PH5 Option C)

REVISE
.wales

# PHYSICS — PH1 & PH5

## *Hooke's law, stress & strain, Young modulus, force-extension & hysteresis*

***Every solids-under-stress question from the legacy WJEC PH1 papers and the PH5 Option C (Materials) papers, June 2009 – June 2016***

LEGACY 2008 SPECIFICATION

**Estimated time for entire question pack: ~2 hours 20 minutes**

*Pace: PH1 (Q1) at* ***~1 min/mark****; PH5 Option C (Q2–Q6) at* ***~1.3 min/mark*** *(20 marks in 25 minutes).*

*You are advised to* ***not*** *attempt to complete all of this in one sitting.*

## ABOUT THIS QUESTION PACK

This is a **comprehensive practice question pack**, not a single mock paper. It contains the only unused Hooke's-law question from the legacy WJEC PH1 papers (Jan 2009 – June 2016), followed by every *Option C: Materials* question from the A2 PH5 papers (June 2010 – June 2016) that maps onto the 2015 spec Topic 5 (Solids under stress).

Section A introduces the spring constant and elastic energy at AS-level; Section B then takes you into stress, strain, the Young modulus and material behaviour at A2-level.

*For Examiner's use only*

| Q | Source | Max | Mark |
|---|---|---|---|
| 1 | PH1 Jun 16 Q7 | 11 | |
| 2 | PH5 Jun 10 C9 | 20 | |
| 3 | PH5 Jun 14 Q10 | 20 | |
| 4 | PH5 Jun 13 Q10 | 20 | |
| 5 | PH5 Jun 11 C10 | 20 | |
| 6 | PH5 Jun 16 Q9 | 20 | |
| | Total | 111 | |

## INSTRUCTIONS

Use black ink or black ball-point pen. Answer all questions in the spaces provided.

*A calculator is required. The Data Booklet is allowed.*

# Solids under stress — what the legacy spec asks

WJEC GCE AS/A Level Physics (from 2008). The Hooke's-law strand lives in PH1.3 *Energy concepts*; the stress / strain / Young modulus content lives in the A2 PH5 *Option C: Materials* module. Together these map onto the 2015 spec Topic 5 — Solids under stress.

### Hooke's law & spring constant PH1.3

- Describe an experiment to investigate the load-extension behaviour of a spring.
- Recall and use Hooke's law: $F = k\,\Delta x$.
- Define the spring constant as force per unit extension. Unit: N·m$^{-1}$.

### Elastic potential energy PH1.3

- Show that work done in stretching a Hookean spring is $\frac{1}{2}F\Delta x = \frac{1}{2}k(\Delta x)^2$.
- Equivalent to the area under a force-extension graph.
- Apply to spring-launched objects, bungee cords, accelerometers.

### Stress, strain & Young modulus PH5 C

- Tensile stress $\sigma = F/A$ (Pa). Tensile strain $\varepsilon = \Delta l/l$ (dimensionless).
- Young modulus $E = \sigma/\varepsilon$ (Pa). Compare values for various solids.
- Describe an experiment to determine $E$ for a metal in the form of a wire.

### Strain energy PH5 C

- Strain energy in a deformed solid = area under the force-extension graph $= \frac{1}{2}F\Delta x$.
- Strain energy per unit volume $= \frac{1}{2}\sigma\varepsilon$.
- Apply to cases where K.E. is absorbed by a wire or rope (e.g. climbers' ropes).

### Ductile, brittle & polymeric PH5 C

- Force-extension and stress-strain graphs for a ductile metal (copper, low-carbon steel) versus a less-ductile metal (high-carbon steel).
- Brittle materials (glass): linear-elastic to a sudden fracture. Effect of surface flaws on UTS.
- Polymeric materials (rubber, polythene): nonlinear, large extensions, hysteresis loops.

### Molecular basis PH5 C

- Plastic deformation in metals as the motion of dislocations.
- Strengthening by dislocation barriers: foreign atoms, other dislocations, grain boundaries.
- Distinguish elastic from plastic strain at the molecular level.

## Section index for this question pack

# Solids under stress in one page

Quick-reference notes — revisit before each section.

## Hooke's law

For a spring (or any Hookean object) below its elastic limit:

$$F = k\,\Delta x$$

- $F$ = applied force (N), $\Delta x$ = extension from natural length (m).
- $k$ = spring constant (N·m$^{-1}$) — gradient of the force-extension graph.
- Above the elastic limit the graph curves and Hooke's law fails.

## Elastic PE in a spring

Work done stretching by $\Delta x$ = area under the $F$–$\Delta x$ triangle:

$$E_\text{p} = \tfrac{1}{2}F\Delta x = \tfrac{1}{2}k(\Delta x)^2$$

Conservation of energy: $\frac{1}{2}k(\Delta x)^2 \to$ K.E. when released, $\frac{1}{2}mv^2$.

## Stress, strain & Young modulus

$$\sigma = \frac{F}{A},\quad \varepsilon = \frac{\Delta l}{l},\quad E = \frac{\sigma}{\varepsilon}$$

- $\sigma$ in Pa, $\varepsilon$ dimensionless, $E$ in Pa (typically GPa).
- Steel $\approx$ 200 GPa, copper $\approx$ 130 GPa, glass $\approx$ 70 GPa, rubber $\sim$ MPa.
- $E$ is a property of the material, not the specimen.

## Young modulus experiment

Long thin wire clamped at one end, loaded over a pulley:

- Measure $l$ (original length, metre ruler), $d$ (diameter, micrometer at 3+ points).
- Load $F$, read $\Delta l$ from a pointer or vernier on the wire.
- Plot $F$ against $\Delta l$. Gradient $= EA/l$, so $E = \dfrac{l}{A}\cdot(\text{gradient})$.

## Strain energy

Stored elastic energy = area under the $F$–$\Delta l$ graph:

$$W = \tfrac{1}{2}F\Delta l = \frac{F^2 l}{2AE}$$

Per unit volume: $w = \frac{1}{2}\sigma\varepsilon$.

Used by climbers' ropes & tendons to absorb kinetic energy.

## Stress-strain graph (ductile metal)

- **Linear elastic**: $\sigma \propto \varepsilon$, gradient $= E$.
- **Elastic limit**: end of recoverable strain.
- **Yield point**: large strain for tiny extra stress.
- **Plastic region**: permanent deformation, necking.
- **Breaking point** (UTS): fracture.

## Brittle vs ductile

**Brittle (glass)**: linear-elastic up to fracture, no plastic region. UTS depends strongly on surface flaws.

**Ductile (copper, low-C steel)**: yields and plastically deforms before fracture. Energy-absorbing.

*Thin glass fibres are stronger than bulk glass because there are fewer surface cracks.*

## Dislocations

A line defect in the crystal lattice that moves through it under stress, allowing planes of atoms to slip past each other one row at a time.

- Plastic deformation = dislocation motion.
- Strengthening = pinning dislocations.

## Strengthening mechanisms

Anything that obstructs dislocation motion:

- **Alloying**: foreign atoms distort the lattice (brass, steel).
- **Work hardening**: tangled dislocations block each other.
- **Grain refinement**: many small grains, more grain boundaries.
- **Quench hardening**: rapid cooling locks dislocations.

## Rubber & hysteresis

A polymer of long tangled chains. Loading uncoils them, unloading recoils them — but along a different path:

- The loading curve sits *above* the unloading curve.
- Area of the loop = energy dissipated as heat per cycle.
- Useful for vibration damping (tyres, engine mounts).

## Composite wires

Two wires in series carry the *same load* $F$ but each has its own $E$ and so its own extension:

$$\Delta x = \frac{Fl_0}{AE}$$

Total $\Delta x = \sum \Delta x_i$. A stiffer material (larger $E$) stretches less.

## Strategy — 4 steps

1. Read the question: which property — $k$, $E$, energy stored, breaking stress?
2. Convert all units (mm $\to$ m, mm$^2$ $\to$ m$^2$, GPa $\to$ Pa).
3. For composites or two-stage stretches, treat each wire / segment separately first.
4. For graph questions: gradient gives $k$ or $E\cdot A/l$; area gives energy stored.

# SECTION A

## *Hooke's law & elastic energy*

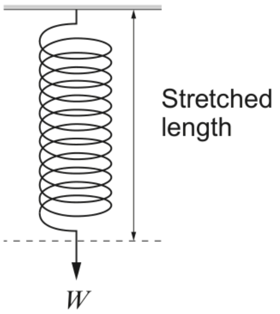
Questions 1 – 2 · 31 marks

Examiner only

**7.** *(a)* (i) State what is meant by the spring constant, $k$. [1]

(ii) Show that the unit of $k$ may be written as $\text{kg}\,\text{s}^{-2}$. [2]

*(b)* A brief experiment is carried out in order to determine $k$ for a spring. The following results are obtained.




| Weight, $W$, attached to spring / N | Stretched **length** of spring / m |
|---|---|
| 1.0 | 0.25 |
| 5.0 | 0.45 |

(i) Determine the value of $k$, stating any assumptions you make. [3]

(ii) Determine the unstretched length of the spring. Show your reasoning. [2]

(iii) Calculate the elastic potential energy stored in the spring when $W = 5.0\,\text{N}$. [3]

**Option C: Materials Option**

**C9.** *(a)* (i) By drawing simple diagrams showing positions of atoms, give a detailed description, in terms of dislocations, of plastic deformation in a ductile material such as a pure metal. [4]

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(ii) Describe at the atomic level **one** method of making pure metals stronger and stiffer. [2]

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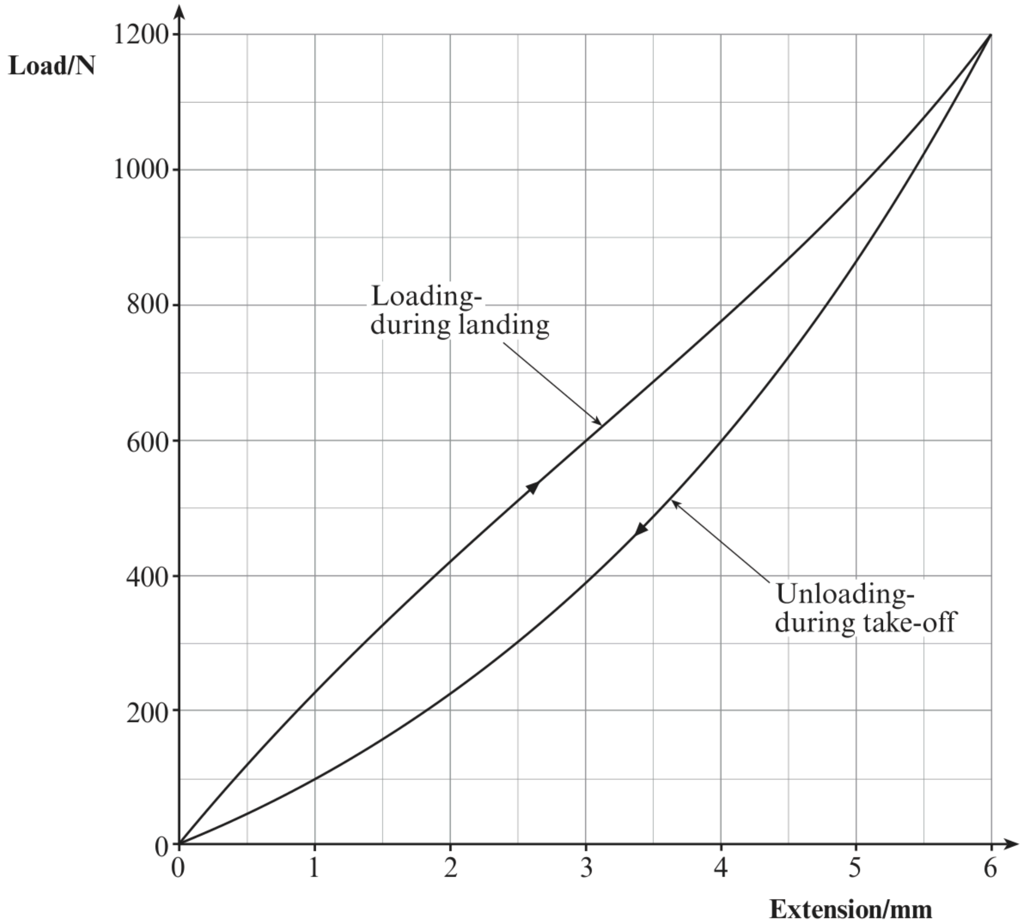
*(b)* A kangaroo stores much of its kinetic and potential energy in its achilles tendons during 'hopping'. The achilles tendon is, in fact, well suited to serve as an effective spring (or rubber band) for energy recovery. During one 'hop', **most** of the energy that is used to stretch the tendon during 'landing' can be recovered elastically to aid 'take off' thus helping to offset the work the muscles have to do.

A typical Load-extension graph for a kangaroo achilles tendon is shown for one complete 'hop'.




(i) The tendon returns to its original length after unloading, but not along the same curve as during loading. What is this effect called? [1]

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(ii) Compare the energy stored in the tendon after loading with that recovered form it after unloading and account for the difference. [No calculations are required here]. [2]

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(iii) Estimate the percentage efficiency of the tendon in re-using the energy stored in it. [3]

(iv) I. If it is assumed that the tendon obeys Hooke's law, show that

$$W = \frac{F^2 l}{2AE}$$

Where $W$ is the energy stored during loading, $A$ is the mean cross-sectional area of the tendon, $l$ is the original length, $F$ is the load on the tendon and $E$ is the Young Modulus. [3]

II. The cross-sectional area of the tendon is $0.55 \text{cm}^2$ and its original length is 30 cm. Hence estimate the Young modulus for the tendon. [3]

(v) What particular mechanical properties should scientists look for in order to make artificial tendons? [2]

# SECTION B

## *Stress, strain & Young modulus*

Questions 3 – 6 · 80 marks

Examiner only

## Option C: Materials

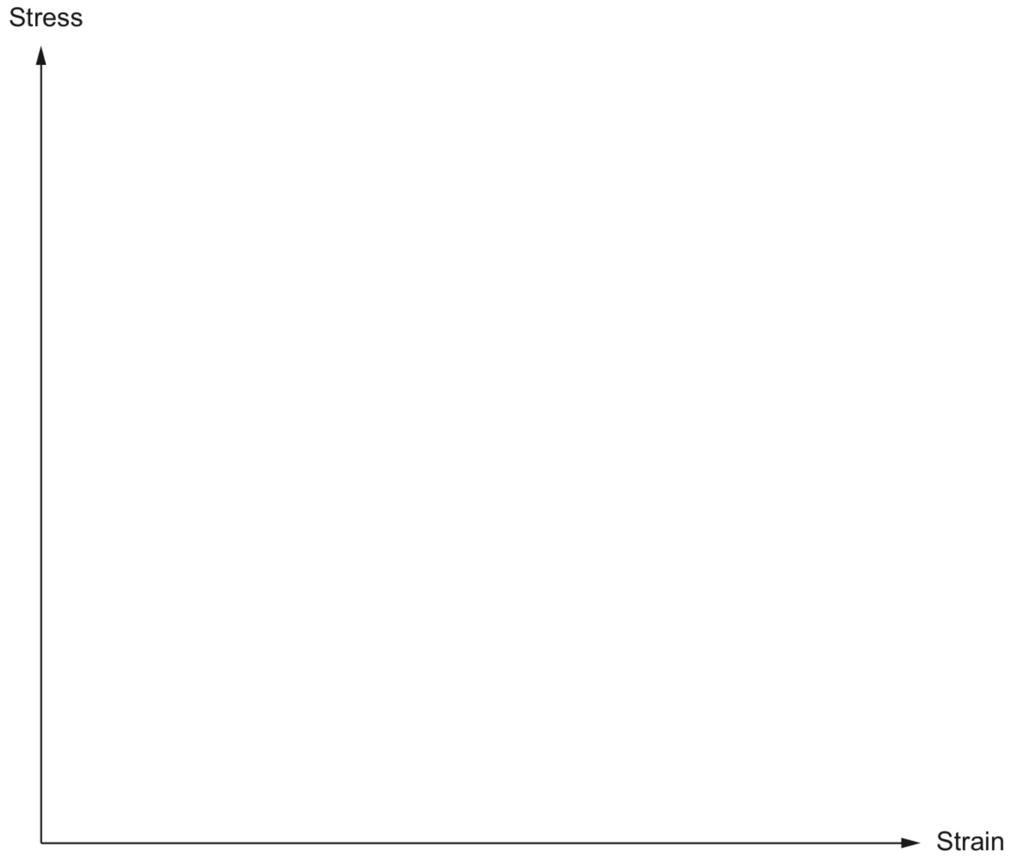
**10.** *(a)* Sketch a typical stress-strain graph for the stretching to breaking point of a ductile metal such as copper. Label on your graph:

(i) the elastic limit;

(ii) the yield point;

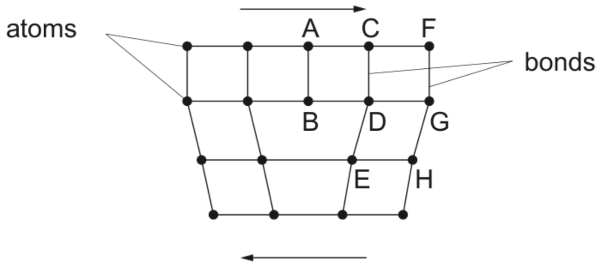
(iii) the region of plastic deformation;

(iv) the breaking point. [6]



Examiner only

*(b)* The diagram shows the arrangement of atoms in a metal crystal in the region of a dislocation.




(i) Using the letters in the diagram, explain how plastic deformation takes place in ductile metals when forces are applied as shown by the arrows. Space is provided so that you can illustrate your answer if you wish to do so (or you may add to the existing diagram). [3]

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(ii) 'Superalloys' in the form of single crystals have recently been developed to withstand extreme conditions of temperature and pressure. **In terms of atomic structure**, give one reason why superalloys can withstand higher temperatures and pressures than conventional multi-crystal alloys. [1]

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(iii) State one application of 'superalloys'. [1]

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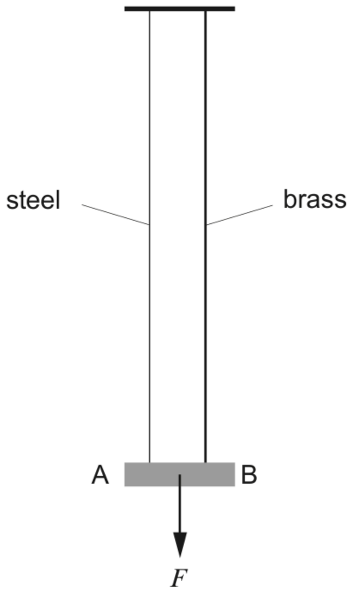
Examiner only

*(c)* A light bar (AB) is suspended horizontally from two vertical wires, one of steel and one of brass as shown in the diagram. Each wire is of the same length, though their cross-sectional areas ($A_{brass}$ and $A_{steel}$) are different. When a force $F$ is applied to the **centre** of AB the wires **extend by an equal amount** and the bar remains horizontal.




(i) Given that the Young modulus of steel is $2.0 \times 10^{11}\,\mathrm{N\,m^{-2}}$, and that of brass is $1.0 \times 10^{11}\,\mathrm{N\,m^{-2}}$, show clearly that $A_{brass} = 2A_{steel}$. [2]

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(ii) Determine the tension in each wire when $F = 100\,\mathrm{N}$. [1]

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(iii) Hence calculate the extension in the steel wire when $F = 100\,\mathrm{N}$. The initial length of wire is 2.0 m and its cross-sectional area is $2.8 \times 10^{-7}\,\mathrm{m^2}$. [2]

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(iv) Calculate the energy stored in the steel wire when $F = 100\,\mathrm{N}$. [2]

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(v) Without further calculation, comment on the energy stored in the brass wire when $F = 100\,\mathrm{N}$ and justify your answer. [2]

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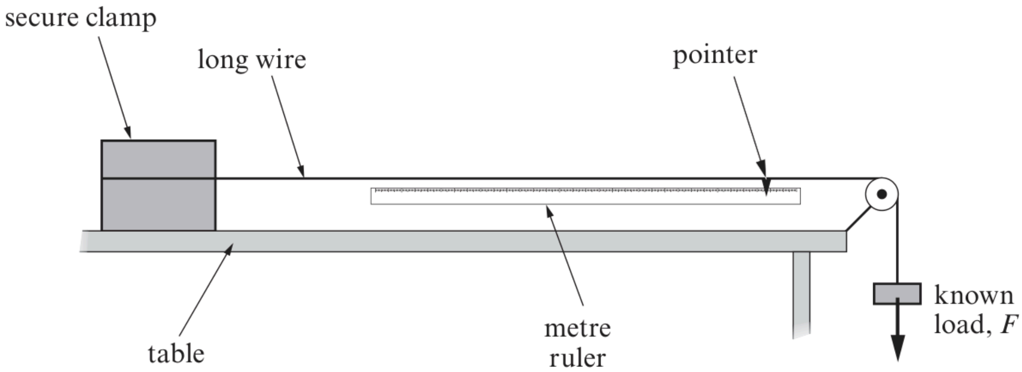
Examiner only

**Option C: Materials**

**10.** *(a)* The diagram shows apparatus that may be used to obtain a value for the Young modulus of a metal in the form of a long wire. A known load, $F$, is applied to one end of the wire. The extension, $\Delta x$, of the wire is measured using the pointer and metre ruler.




(i) To obtain a value for the Young modulus, two other measurements must be made. State what these measurements are and what equipment you would use. [2]

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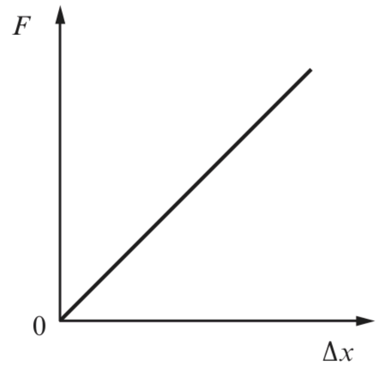
(ii) A graph of load, $F$, against extension, $\Delta x$, may be obtained from the experiment.




Explain how a value of the Young modulus may be obtained by using the measurements in part *(a)*(i) and information from the graph. [3]

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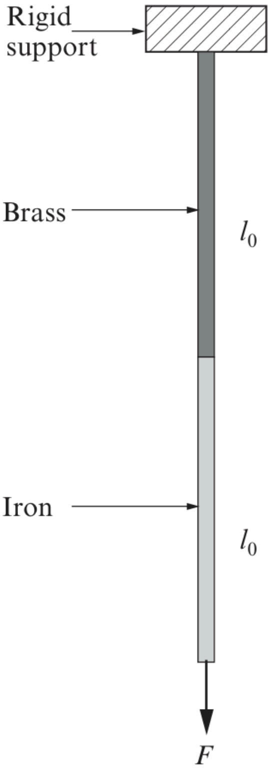
Examiner only

*(b)* Two wires, one of brass and one of iron, each of length $l_0$ and each with the same **diameter** are joined end to end and hung from a rigid support. A force, $F$, is applied as shown in the diagram.




(i) The extension in the brass wire, $\Delta x_{brass}$ is given by: $\Delta x = \dfrac{Fl_0}{AE_{brass}}$ where $A$ and $E_{brass}$ represent the cross-sectional area of the wire and the Young modulus of brass respectively. Write down a similar expression for the extension of the iron wire. [1]

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(ii) The strain energy, $W$, in the wire due to the stretching force $F$, is given by $\frac{1}{2}F\Delta x$, where $\Delta x$ represents the total extension in the wire combination. Show that

$$W = \frac{F^2 l_0}{2A}\left(\frac{1}{E_{brass}} + \frac{1}{E_{iron}}\right)$$ [2]

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(iii) Calculate $W$ when $F$ = 47.0 N. Assume the diameter of both wires is 1.0 mm and each has an unstretched length, $l_0$, of 2.0 m. [$E_{brass}$ = 100 GPa; $E_{iron}$ = 200 GPa.] [3]

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(iv) Hence, or otherwise, determine the overall extension of the combination of wires when $F = 47.0$ N. [1]

(v) Explain, using the Young moduli given, which of the two wires has undergone the greater extension and hence determine the ratio $\frac{\Delta x_{brass}}{\Delta x_{iron}}$. [4]

*(c)* Use the information in the table below:

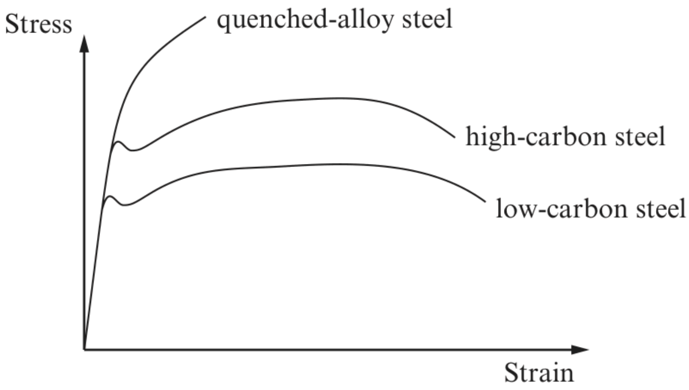
(i) to **complete** the table to determine whether the polymers given are examples of thermosetting or thermoplastic polymers; [2]

| Name | Tensile strength/MPa | Maximum strain/% | Young modulus/GPa | Thermosetting or thermoplastic? |
|---|---|---|---|---|
| Melamine formaldehyde | 65 | 0.6 | 12 | |
| Low density polyethylene | 17 | 500 | 0.3 | |

(ii) to explain which of the polymers given might be brittle and which of the two is the stiffer. [2]

**Option C: Materials.**

**C10.** A. Stress - Strain curves for several kinds of steel are shown.




*(a)* State, giving reasons, which steel

(i) is the most ductile; [1]

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(ii) has the highest breaking stress. [1]

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*(b)* What can be said about their Young moduli? [1]

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*(c)* Compare the physical properties of high-carbon steel with low-carbon steel and explain these properties in terms of molecular structure. [4]

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*(d)* (i) Long steel wires are used for towing oil platforms out at sea. If a wire were to break, about 25% of the stored elastic energy would be transformed to kinetic energy. Show that the speed, $v$, of the wire when it breaks can be estimated from

$$v = \frac{1}{2}\sqrt{\frac{\sigma\varepsilon}{\rho}}$$

where $\rho$ is the density of the steel and $\sigma$ and $\varepsilon$ have their usual meanings. [4]

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(ii) Estimate the speed of a quenched-alloy steel wire which breaks given that its breaking stress is 700 MPa and the corresponding strain is 0.2%. Assume $\rho = 8000 \text{ kg m}^{-3}$. [2]

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(iii) Using the graphs on page 22 as guides, explain how you would expect the speed of a breaking wire made of low-carbon steel of the same dimensions (i.e. length and diameter) to compare with your answer to *(d)*(ii). Assume the densities are equal. [2]

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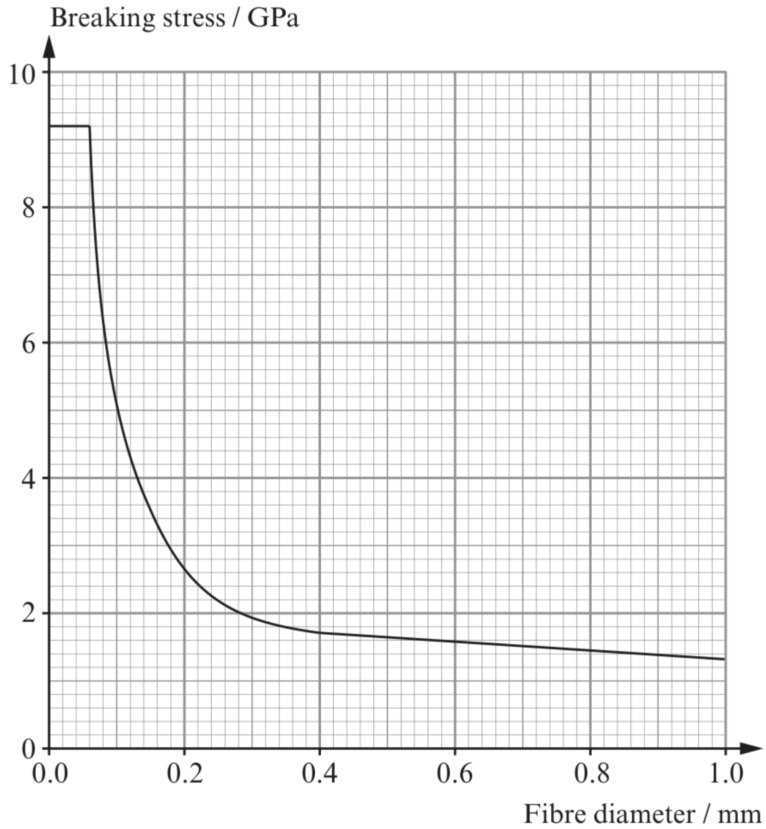
B. Glass is a brittle material. The graph shows how the tensile breaking stress of glass, in the form of thin fibres and rods, varies with the diameter of the fibre.




*(a)* Use the graph to estimate the greatest **mass** which can be hung from a glass fibre of diameter 0.20 mm. [2]

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*(b)* Explain why very thin fibres (or 'whiskers') have a greater breaking stress than thicker ones and suggest why there is a maximum value. [2]

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*(c)* 'Fibre-glass' is a widely used composite material. State what it consists of. [1]

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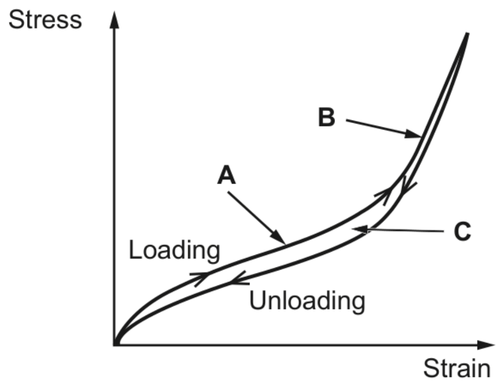
Examiner only

**Option C: Materials**

**9.** *(a)* A specimen of rubber is gradually loaded and then unloaded. A stress-strain diagram for the specimen is shown.




(i) State the feature of the graph which confirms that the rubber was deformed elastically. [1]

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(ii) By referring to the molecular structure of rubber explain why the gradient at **A** is less steep than the gradient at **B**. [3]

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(iii) Write down the name given to the effect represented by the area enclosed between the loading and unloading curve, **C** and explain the significance of this area. [3]

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Examiner only

(iv) With reference to your answer to part *(a)*(iii), explain why it is inadvisable to drive cars with tyres which are under-inflated, that is, with less than the recommended air pressure. [1]

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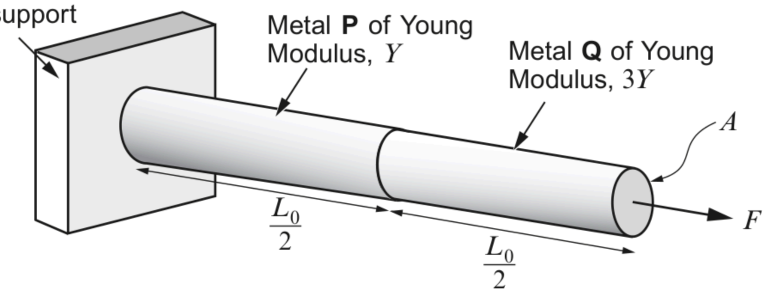
*(b)* The bar in the figure below is made from two different metals, **P** and **Q**, of equal length $\frac{L_0}{2}$ and cross-sectional area, $A$. The metals are welded securely to each other and to the rigid support.




(i) By considering the total extension of both metals under the action of a common force, $F$, show in clear steps that the energy, $W$, stored in the combination can be given by: [4]

$$W = \frac{F^2 L_0}{3AY}$$

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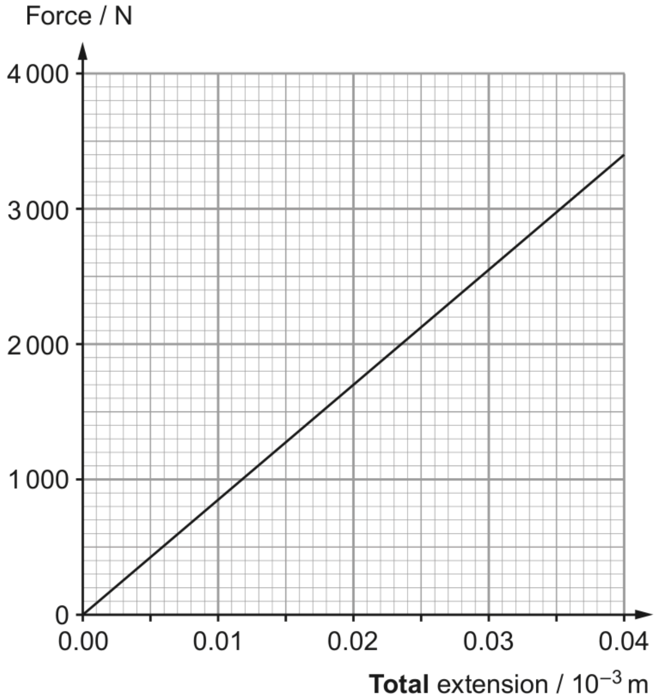
Examiner only

(ii) A force-extension graph for the combination is shown below.




Use the graph to determine the energy stored in the combination when the applied force = 2 800 N. [2]

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(iii) Using the equation in part *(b)*(i) and your answer to part *(b)*(ii) (or otherwise), determine $Y$ (the Young modulus of metal **P**). ($L_0$ = 0.300 m and the diameter of the bars = 14.5 mm.) [3]

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Examiner only

(iv) Explaining your reasoning carefully, determine the ratio: [3]

$$\frac{\text{extension of metal } \mathbf{P}}{\text{extension of metal } \mathbf{Q}}$$

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## END OF QUESTION PACK

### *6 questions · 111 marks · ~2 h 20 min*

Mark schemes available from WJEC and Physics & Maths Tutor.