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CUET · PHYSICS · CLASS XI · CODE 322

Mechanical Properties of Solids

CUET unit: Mechanical Properties of Solids

By **UniDrill** · NCERT-grounded study material

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📌 Snapshot

- Establishes that real solids are not perfectly rigid: under a deforming force they develop an internal restoring force, and depending on the material they either recover (elastic) or stay deformed (plastic).
- Introduces the three forms of stress (tensile/compressive, shearing, hydraulic) and their matched strains, then ties them via Hooke's law and the three elastic moduli (Y, G, B).
- Builds the full stress-strain curve — proportional limit, yield point, plastic region, ultimate tensile strength, fracture — and contrasts metallic curves with elastomers (e.g., aorta tissue).
- Closes with quantitative applications: design of crane ropes, bending of beams (the I-section), pillar shapes, and the upper bound on mountain height (~10 km) from rock shear strength.
- CUET regularly tests these as numerical plug-ins (Y from F, L, A, ΔL), tabular comparison of moduli, and statement-based items on the stress-strain curve.

📖 Detailed Notes

2.1 Core concepts

The rigid body of mechanics is an idealisation. In reality every solid changes shape and size, however slightly, when forces act on it; steel beams sag, springs stretch, and even concrete pillars compress. The macroscopic origin is microscopic — the inter-atomic spacing rearranges when external forces disturb it, and the inter-atomic restoring forces try to bring the atoms back. The property of a body to regain its original size and shape on removal of the deforming force is called **elasticity**, and the residual permanent deformation seen in materials like putty or mud is called **plasticity** (NCERT §8.1, p. 167). Engineering choices — what to build a bridge cable, a clock spring, a bullet-proof vest or an artificial joint out of — are essentially choices among these mechanical responses.

When a deforming force acts on a body in equilibrium, an equal and opposite internal restoring force develops. The intensity of this restoring force is captured by **stress**, defined as restoring force per unit area: stress = F/A (NCERT §8.2, p. 168). The SI unit is the newton per square metre, N m^{-2}, also called the pascal (Pa); its dimensional formula is [M L^{-1} T^{-2}]. A force of a few newtons spread over a square metre is a tiny stress; the same force concentrated on a needle tip is enormous — which is why a tailor's needle pierces cloth easily.

There are three independent modes in which a body can be deformed, each with its own stress and strain (NCERT §8.2, Fig. 8.1, p. 168–169).

(a) Tensile/compressive stress (longitudinal). Two equal and opposite forces normal to the cross-section pull a rod apart (tensile) or push it together (compressive). The rod's length changes by ΔL and the **longitudinal strain** is $\varepsilon = \Delta L/L$. Both stress (F/A) and strain are along the length.

(b) Shearing (tangential) stress. Equal and opposite forces act parallel to opposite faces, so the cross-section slides relative to itself. A vertical face initially perpendicular to the base now tilts by an angle θ; the **shearing strain** is $\Delta x/L = \tan\theta$, which for small deformations is $\approx \theta$. A book pushed sideways on a table is the everyday picture.

(c) Hydraulic stress. A body is immersed in a fluid (or surrounded by gas) so that the fluid exerts the same normal pressure at every point on its surface. The body's shape stays the same but its volume decreases by ΔV; the **volume strain** is $\Delta V/V$.

Because strain is a ratio of like quantities, it is **dimensionless and unit-less** — an answer of "1.2×10^{-4} m" for a strain is automatically wrong (NCERT §8.2, p. 169).

The key empirical observation, due to Robert Hooke (1676), is that for small enough deformations stress is proportional to strain: stress = k × strain (NCERT §8.3, p. 169). The proportionality constant k is the **modulus of elasticity** of the material, with the same units as stress. Hooke's law is empirical, holds only for "small" deformations whose magnitude depends on the material, and is the foundation of nearly every engineering calculation in this chapter.

The full behaviour of a metal is captured in the **stress-strain curve** (NCERT Fig. 8.2, §8.4, p. 169). Plotting stress on the y-axis and strain on the x-axis, the curve has five distinct regions:

- **O → A**: A straight line where Hooke's law strictly holds; the slope is Young's modulus. The material is purely elastic.
- **A → B**: The curve bends but the deformation is still elastic — unloading returns the body to O. The point B is the **yield point** or **elastic limit**, and the stress at B is the yield strength σ_y.
- **B → D**: Beyond B the body enters the **plastic region**. If unloaded at, say, point C, it does not return to O but to a non-zero permanent set; the body has "yielded".
- **D**: The maximum stress the material can take, called the **ultimate tensile strength** σ_u.
- **D → E**: The strain keeps increasing even though the applied force begins to drop, until fracture occurs at E.

If the interval D-to-E is small, the material fractures soon after reaching σ_u — it is **brittle** (cast iron, glass). If D and E are far apart, the material is **ductile**: it can be drawn into wires (copper, steel). The same metal can be made more or less ductile by heat treatment.

Elastomers like rubber bands and the elastic tissue of the aorta show a very different curve (NCERT Fig. 8.3, p. 170). They can be stretched to several times their original length and still recover their shape — i.e., the elastic region is enormous — but the curve is almost entirely non-linear, so Hooke's law fails over most of the region; and there is no well-defined plastic region preceding fracture.

The three elastic moduli — one for each kind of stress-strain pair — quantify the slope of the linear region.

Young's modulus Y (NCERT §8.5.1, p. 170). Y = tensile (or compressive) stress / longitudinal strain = $(F \cdot L)/(A \cdot \Delta L)$. Units Pa. Y is a property of the material, not the specimen — a thicker wire of the same steel has the same Y. Metals have large Y (steel ≈ 2×10^{11} Pa, copper ≈ 1.2×10^{11} Pa), so they need huge stresses for small strains; wood, bone, glass and concrete have much smaller Y. As a useful benchmark (NCERT p. 171), to stretch a thin steel wire of cross-section 0.1 cm^2 by 0.1 % needs 2000 N — far more than the 690 N needed for aluminium of identical dimensions, so steel is "more elastic" than aluminium (the material that returns more for a given load is the one that hardly let itself be deformed in the first place).

Shear modulus G (modulus of rigidity) (NCERT §8.5.2, p. 172). G = shearing stress / shearing strain = $(F \cdot L)/(A \cdot \Delta x) = F/(A \cdot \theta)$. Equivalent statement: $\sigma\_s = G \cdot \theta$. For most materials G ≈ Y/3. Soft metals like lead have small G (5.6×10^9 Pa) and tungsten has very high G (150×10^9 Pa).

Bulk modulus B (NCERT §8.5.3, p. 173). $B = -p/(\Delta V/V)$. The minus sign is essential because increasing pressure produces a decrease in volume — the ratio $p/(\Delta V/V)$ is itself negative, and the minus sign restores B to a positive number, which is what we need for a stable solid or liquid. Solids have the largest B (steel ≈ 160×10^9 Pa), liquids smaller (water 2.2×10^9 Pa), and gases by far the smallest (air at STP ≈ 10^5 Pa). Hence gases are about 10^6 times more compressible than solids. The reciprocal **compressibility** k = 1/B captures the same information.

Poisson's ratio σ (NCERT §8.5.4, p. 174). When a wire is stretched longitudinally, its lateral dimensions contract. The ratio (lateral strain)/(longitudinal strain) is Poisson's ratio σ. It is dimensionless and a property of the material alone — for steel about 0.28–0.30, for aluminium alloys about 0.33.

Elastic potential energy (NCERT §8.5.5, Eq. 8.14, p. 174). Work done against the restoring force during elastic stretching is stored as potential energy. The energy density (per unit volume) of a stretched specimen is u = ½ × stress × strain = ½ × Y × ε^2. Total stored energy U = ½ × stress × strain × volume.

The closing applications (NCERT §8.6, p. 174–176) take these moduli into engineering practice. A steel rope for a crane lifting 10 tonnes needs only ~1 cm radius if pushed to the yield stress, but real designs use ~3 cm radius so the working stress is well below

σ_y and safety is built in. A horizontal beam of length l, breadth b, depth d, supported at both ends and loaded at the centre with weight W, sags by $\delta = W \cdot l^3/(4 \cdot b \cdot d^3 \cdot Y)$. The depth appears as d^3 so doubling d cuts sag by a factor of 8 — a far better strategy than doubling b — but a deep thin beam tends to **buckle** sideways. The compromise that engineers settled on is the **I-section**: most of the material at the top and bottom, a thin web in between, balancing strength against buckling. Similarly, pillars with distributed (flared) ends carry larger loads than rounded-end pillars. Finally, the maximum height of a mountain on Earth (~10 km, comparable to Everest) is set by the **shear elastic limit** of rock (~3×10^8 N m^{-2}) via the condition $h\rho g \leqslant \sigma_{critical}$; rocks at greater depth would flow plastically.

2.2 Definitions to memorise

Term	Definition	Page
Rigid body	Idealised body whose shape and size do not change under any force	167
Elasticity	Property by which a body regains its original size and shape when the applied force is removed	167
Plasticity	Property by which a body undergoes permanent deformation (no tendency to regain shape)	167
Deforming force	External force that tries to change the shape or size of a body	167
Restoring force	Equal and opposite internal force that develops in a deformed body	168
Stress	Restoring force per unit area; SI unit N m^{-2} (Pa); dimensions $[M L^{-1} T^{-2}]$	168
Tensile/compressive (longitudinal) stress	Normal forces stretching/compressing a body; F/A	168
Shearing (tangential) stress	Tangential forces on opposite faces; F/A parallel to surface	168
Hydraulic stress	Equal normal pressure at every point of body surface (fluid)	169
Longitudinal strain	$\Delta L/L$ — change in length / original length	168
Shearing strain	$\Delta x/L = \tan\theta \approx \theta$ for small θ	168
Volume strain	$\Delta V/V$ — fractional change in volume under hydraulic stress	169
Hooke's law	For small deformations, stress = k × strain; k is the modulus of elasticity	169
Proportional (linear) limit	Stress up to which stress-strain curve is straight (point A)	169
Yield point (elastic limit)		169

Term	Definition	Page
	Point B on stress-strain curve beyond which deformation becomes plastic; stress at B is σ_y	
Plastic region	B → D portion of stress-strain curve in which permanent deformation occurs	169
Ultimate tensile strength	Maximum stress σ_u the material can withstand (point D)	169
Fracture point	Point E at which the body breaks	169
Brittle / ductile	Materials with small / large D-to-E gap on stress-strain curve	170
Elastomer	Material like rubber or aorta tissue with very large elastic strains, not obeying Hooke's law, no well-defined plastic region	170
Young's modulus (Y)	Tensile (or compressive) stress / longitudinal strain; unit Pa	170
Shear modulus (G)	Shearing stress / shearing strain; also called modulus of rigidity; typically $G \approx Y/3$	172
Bulk modulus (B)	$B = -p/(\Delta V/V)$; always positive in equilibrium; unit Pa	173
Compressibility (k)	Reciprocal of bulk modulus: $k = 1/B$; fractional change in volume per unit increase in pressure	173
Poisson's ratio (σ)	Lateral strain / longitudinal strain; dimensionless; steel 0.28–0.30, aluminium alloys ≈ 0.33	174
Elastic potential energy density	$u = ½ \times \text{stress} \times \text{strain} = ½ Y \varepsilon^2$	174

2.3 Diagrams / processes to remember

- **Fig. 8.1 (p. 168)** — Four cases of deformation: (a) cylinder under tensile stress, elongated by ΔL; (b) cylinder under shearing stress, deformed by angle θ; (c) book pushed horizontally, illustrating shear; (d) sphere under hydraulic stress with $\Delta V/V$ but no shape change. A standard CUET match-the-following template.
- **Fig. 8.2 (p. 169)** — Typical stress-strain curve for a metal showing OA (linear/Hookean), A–B (elastic, non-linear, ending at yield point B), B–D (plastic region; permanent set if unloaded at C), D (ultimate tensile strength), E (fracture). Identifying the labelled regions correctly is a recurring exam item.
- **Fig. 8.3 (p. 170)** — Stress-strain curve for the elastic tissue of aorta (an elastomer): very large elastic region, mostly non-linear, no clear plastic region.
- **Table 8.1 (p. 170)** — Young's moduli and yield strengths of common materials (steel highest among the listed metals, hence preferred in heavy-duty structures).
- **Table 8.2 (p. 172)** — Shear moduli G: lead 5.6, aluminium 25, brass 36, copper 42, iron 70, nickel 77, steel 84, tungsten 150 ($\times 10^9$ N m^{-2}).

- **Table 8.3 (p. 173)** — Bulk moduli B: glass 37, brass 61, aluminium 72, iron 100, copper 140, steel 160, nickel 260 (solids, $\times 10^9$ Pa); water 2.2, glycerine 4.76, mercury 25 (liquids); air at STP 1.0×10^{-4}.
- **Table 8.4 (p. 173)** — Consolidated chart of stress type, strain, change in shape/ volume, modulus formula, and state of matter.
- **Fig. 8.6 (p. 175)** — Beam loaded at the centre and supported at the ends (used in deriving $\delta = W \cdot l^3/(4 \cdot b \cdot d^3 \cdot Y)$).
- **Fig. 8.7 (p. 175)** — Cross-sections of a beam: (a) rectangular; (b) deep thin bar buckling; (c) I-section, the engineering compromise.
- **Fig. 8.8 (p. 176)** — Pillars: rounded ends (less load) vs distributed ends (more load).

2.4 Common confusions / NTA trap points

- "More elastic = stretches more" is wrong. A material which stretches less for a given load is more elastic (NCERT Points to Ponder 6, p. 177). Steel is more elastic than rubber.
- The wire-suspended-from-ceiling trap: ceiling pulls up with F, weight pulls down with F, but tension at any cross-section is just F (not 2F), so tensile stress is F/A (Points to Ponder 1, p. 177).
- Young's modulus and shear modulus apply only to solids (they need a definite length/shape). Bulk modulus is defined for solids, liquids and gases (Points to Ponder 3 & 4, p. 177).
- Yield point B is also called the elastic limit — same point on the curve, two names.
- Stress is **not** a vector: it cannot be assigned a unique direction (Points to Ponder 8, p. 177). Force is the vector; stress is force per area.
- Strain is dimensionless — beware MCQs offering "m" or "m^2" as the unit of strain.
- The negative sign in $B = -p/(\Delta V/V)$ is required so that B comes out positive (Δp positive $\Rightarrow$ ΔV negative).
- For an elastomer like aorta tissue or rubber, the curve is mostly elastic but **non-linear**, so Hooke's law does not hold over most of it (NCERT §8.4, p. 170).
- Compressibility $k = 1/B$ has units of Pa^{-1} — a frequent unit trap.
- Don't confuse Poisson's ratio σ with shearing stress σ_s — both use σ in NCERT but mean different things.
- Confusing ultimate tensile strength σ_u (max stress) with yield strength σ_y (onset of plastic region) — they are distinct points on the curve.
- Forgetting that beam depth d enters as d^3 in the sag formula $\delta = W \cdot l^3/(4 \cdot b \cdot d^3 \cdot Y)$ — depth matters far more than breadth.

2.5 Key formulas table

Symbol	Formula	Meaning	NCERT page
Stress	$\sigma = F/A$	Restoring force per unit area	168
Longitudinal strain	$\varepsilon = \Delta L/L$	Fractional change in length	168
Shearing strain	$\gamma = \Delta x/L = \tan\theta \approx \theta$	Tangential strain angle	168
Volume strain	$\varepsilon\_V = \Delta V/V$	Fractional change in volume	169
Hooke's law	$\sigma = k \times \varepsilon$	Stress proportional to strain	169
Young's modulus	$Y = (F·L)/(A·\Delta L)$	Tensile stress / longitudinal strain	170, Eq. 8.7–8.8
Shear modulus	$G = (F·L)/(A·\Delta x) = F/(A·\theta)$	Shearing stress / shearing strain	172, Eq. 8.10–8.11
Bulk modulus	$B = -p/(\Delta V/V)$	Pressure / volume strain	173, Eq. 8.12
Compressibility	$k = 1/B = -(1/\Delta p)(\Delta V/V)$	Inverse of bulk modulus	173, Eq. 8.13
Poisson's ratio	$\sigma = (\Delta d/d)/(\Delta L/L)$	Lateral over longitudinal strain	174
Strain energy density	$u = ½ \sigma \varepsilon = ½ Y \varepsilon^2$	PE per unit volume	174, Eq. 8.14
Total elastic PE	$U = ½ \times \text{stress} \times \text{strain} \times V$	Energy stored in stretched body	174
Shear modulus rule-of-thumb	$G \approx Y/3$	Empirical metal ratio	172
Yield stress σ_y	σ at point B of stress-strain curve	Onset of plastic flow	169
Ultimate tensile strength σ_u	σ at point D of stress-strain curve	Max stress before failure	169
Beam sag	$\delta = W·l^3 / (4·b·d^3·Y)$	Mid-span sag of beam supported at ends	175
Mountain-height limit	$h \rho g \leqslant \sigma\_critical$ ($\approx 3 \times 10^8$ Pa)	Upper bound from rock shear strength	176
Rope minimum radius	$A\_min = F/\sigma\_y$, $r = \sqrt{(A/\pi)}$	Crane-rope design	174
F for length change ΔL	$F = Y·A·(\Delta L/L)$	Inverse of Y formula	170
Pressure for $\Delta V/V$	$\Delta p = -B·(\Delta V/V)$	Inverse of B formula	173

🎯 Practice MCQs

📊 PYQ Alignment

This chapter is a perennial CUET favourite, typically yielding 6–8 MCQs a year — a mix of (i) plug-and-chug numericals using Y, G or B (Example 8.1–8.5 style), (ii) statement / assertion-reason items on the stress-strain curve (yield point, ultimate strength, ductile vs brittle), and (iii) match-the-following on stress type ↔ modulus ↔ defining formula. Tabular comparisons (largest Y, largest B, compressibility ranking) and the elastomer-vs-metal contrast are recurring traps.

CUET 2023–25 — Actual PYQs from this chapter

No PYQs from this chapter appeared in CUET 2023, 2024 or 2025.