Mechanical properties of Solids

A Solid has definite shape and size. In order to change (or deform) the shape or size of a body, a force is required. If you stretch a helical spring by gently pulling its ends, the length of the spring increases slightly. When you leave the ends of the spring, it regains its original size and shape. The property of a body, by virtue of which it tends to regain its original size and shape when the applied force is removed, is known as elasticity and the deformation caused is known as elastic deformation. However, if you apply force to a lump of putty or mud, they have no gross tendency to regain their previous shape and they get permanently deformed such substances are called plastic and this property is called plasticity.

A change in one property usually causes a change in one or more additional properties. For Example, if the hardness of a metal is increased, the brittleness usually ~~use~~ increases and the toughness usually decreases. The atomic bonding of metals also effects their properties. These properties also helps to specify and identify the metals.

The most common mechanical properties are discussed below —

(i) Tensile strength
(ii) Compressive strength
(iii) Shear strength
(iv) Impact strength
(v) Fatigue strength
(vi) Creep
(vii) Elasticity
(viii) Plasticity
(ix) Resilience
(x) Ductility
(xi) Malleability
(xii) Brittleness
(xiii) Toughness
(xiv) Hardness
(xv) Stiffness
(xvi) Machinability
(xvii) Weldability
(xviii) Abrasion Resistance

Elastic and Plastic Bodies:

Elasticity: The property of a body by virtue of which, it tends to regain its original size and shape when the applied force is removed is known as elasticity and the deformation caused is known as elastic deformation.
e.g.: Steel is an elastic body.

Plasticity: The body which has no tendency to regain its original shape and get permanently deformed is called plastic body. This property is known as plasticity.
e.g. clay, wax, etc are plastic bodies.

Stress: A force which changes the length, shape or volume of a body is called a deforming force.
When an elastic body is subjected to a deforming force, a restoring force is developed in the body. This restoring force is equal in magnitude but opposite in direction to the applied force.

"The restoring force per unit area is known as stress"

If F is the applied force and A is the area of cross-section of the body, then

$$\text{stress} = \frac{F \text{ (restoring force)}}{A \text{ (area of cross section)}}$$

$$\boxed{\sigma = \frac{F}{A} \ N/m^2}$$

Types of Stress:

1. Longitudinal or Tensile Stress:

If the deforming forces are along the length of the body, we call

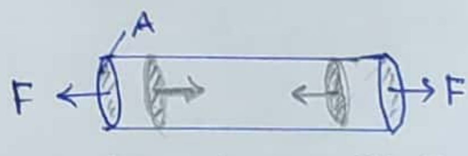


Fig: A Tensile Stress

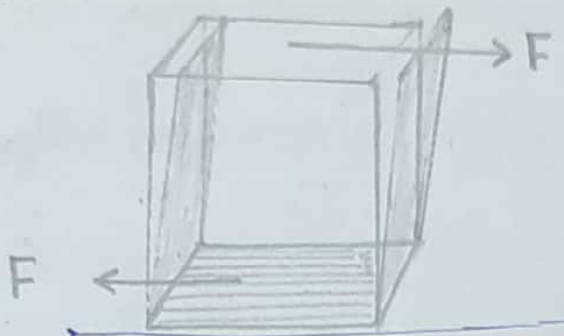
the stress produced as longitudinal stress, as shown in fig A and B.

Fig: B: Compressive stress

2. Shearing stress or Tangential stress:

It is the stress developed in the body, when the applied force produces, a change in shape of the body.

The deforming forces act tangentially or parallel to the surface so that shape of the body changes without change in volume, the stress is called shearing stress.



$$\boxed{\text{Shearing stress}(\sigma) = \frac{F}{A}}$$ ← tangential force.

3. Volume Stress or Bulk Stress.

It is the stress developed in the body, when the applied force produces a change in the volume of the body without change in shape.

Deforming force perunit area normal to the surface is called pressure while restoring force developed inside the body perunit area normal to the surface is known as stress.

$$\sigma = \frac{F}{A} \text{ OR } \frac{P}{A}$$

$P - P_0 = \Delta P$

Strain: Deforming forces produce changes in the dimensions of the body.

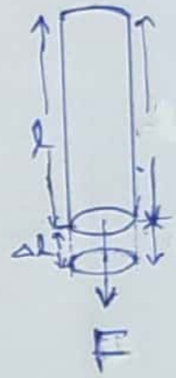
Strain is defined as the change in dimension (e.g. length, shape or volume) per unit dimension of the body.

As the strain is ratio of two similar quantities, it is dimensionless quantity.

Depending on the kind of stress applied, strains are of three types (i) Longitudinal, (ii) shearing strain and (iii) volume (bulk) strain.

1. **Longitudinal Strain**: If the deforming force produces a change in length, the strain produced in the body is called longitudinal strain or tensile strain or linear strain.

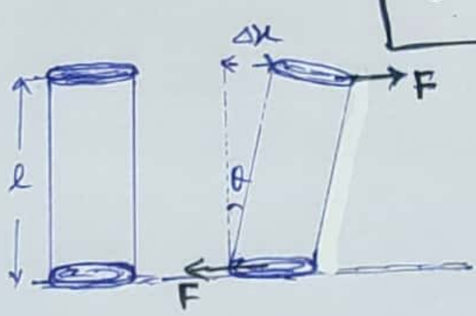
$$\text{Longitudinal strain} = \frac{\text{Change in length}}{\text{Original length}} = \frac{\Delta l}{l}$$



2. **Shearing strain**: If the deforming force produces a chang in shape of the body without changing volume, the strain produced is called shearing strain.

$$\text{Shearing strain} = \frac{\Delta x}{l}$$

$$\boxed{\theta = \frac{\Delta x}{l}}$$



The shearing strain is given by the angle θ through which a line perpendicular to the fixed plane is turned due to deformation.
The angle θ is usually very small.

3. **Volume Strain**: If the deforming force produces a change in volume, the strain produced in the body is called volume strain.

$$\text{Volume strain} = \frac{\text{Change in vol.}}{\text{original vol.}} = \frac{\Delta V}{V}$$

Relation between Stress & Strain

According to Hook's law, "with in the elastic limit stress is directly proportional to strain."

i.e. $\text{Stress} \propto \text{Strain}$

$$\text{Stress} = E \times \text{strain}$$

$$\boxed{E = \frac{\text{Stress}}{\text{Strain}}}$$

Unit N/m^2 or Pascal

Where, E is the proportionality constant called modulus of elasticity.

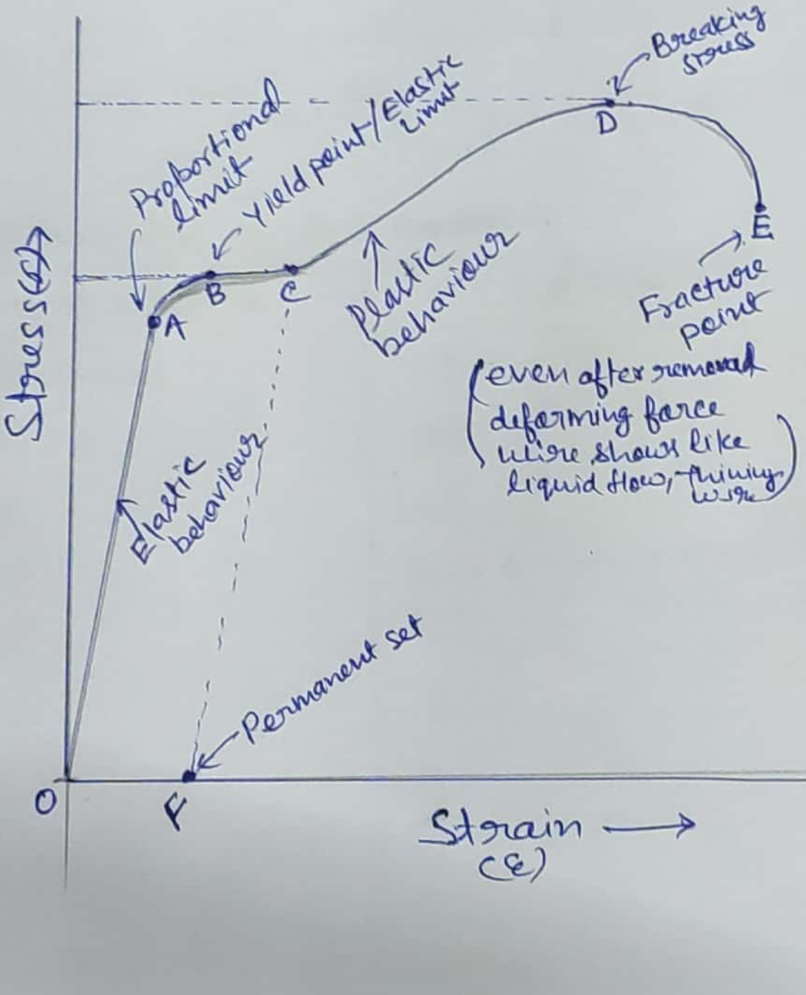
* Note: Modulus of elasticity depends on:
  (i) Nature of the material of the body and
  (ii) Temperature

hardness.

Stress-Strain Diagram:

The stress-strain diagram is important for establishing a number of strength and elastic characteristics of a material. To better predict the response of a structure to applied loads, the designer requires knowledge to the yield point, proportional limit, elastic limit and ultimate strength of the material of which the structure is made.

This information can be obtained from the stress-strain diagram. The diagram also provides information regarding how ductile or brittle the material is.



OA → Stress ∝ Strain (Hooke's Law obeyed)

AB → Stress ~~∝~~ Strain (not directly proportional)

After B, small stress large strain (i.e. elasticity not present) Permanent strain

BD → Plastic Region

D → max stress OR Breaking stress

E → Fracture point

Moduli of Elasticity:

These are three types as given below —

(i) Young's modulus

(ii) Shear modulus or rigidity modulus

(iii) Bulk modulus

(i) **Young's Modulus**: The ratio of the longitudinal stress to the longitudinal strain is called Young's modulus for the material of the body.

Since, longitudinal stress $= \frac{F}{A}$

and longitudinal strain $= \frac{\Delta l}{l}$

Hence, Young's modulus $Y = \frac{F/A}{\Delta l/l} = \frac{F \times l}{A \times \Delta l}$

If the material has circular cross section, then

$$A = \pi r^2$$

$$\text{so, } \boxed{Y = \frac{Fl}{(\pi r^2)\Delta l}} \ N/m^2$$

$$\text{OR} \quad Y = \frac{Mgl}{(\pi r^2)\Delta l} \qquad (\because F = Mg)$$

Young's modulus of few materials:

Name of substance	$Y\ (10^9\ N/m^2)$
Aluminium	70
Copper	120
Iron	190
Steel	200 ← steel is the most elastic
Glass	65
Bone	9
Polystyrene	3

(ii) Shear modulus or Rigidity modulus:

The ratio of the shearing stress to shearing strain is called modulus of rigidity of the body.

If a tangential force F acts on an area A and θ is the shearing strain, the modulus of rigidity

$$\text{Shearing Modulus} = \frac{\text{Shearing stress}}{\text{Shearing strain}} = \frac{F/A}{\theta} = \frac{F}{A\theta}$$

(iii) Bulk Modulus:

The ratio of volume stress to the corresponding volume strain is defined as bulk modulus. It is denoted by 'B'.

If due to increase in pressure P, volume V of the body decreases by ΔV without change in shape, then

Normal stress $= \Delta P$

Volume strain $= \Delta V/V$

$$\boxed{\text{Bulk modulus } B = \frac{\Delta P}{\Delta V/V} = \frac{V \cdot \Delta P}{\Delta V}}$$

* The reciprocal of bulk modulus of a substance is called compressibility.

$$K = \frac{1}{B} = \frac{1}{V} \cdot \frac{\Delta V}{\Delta P}$$

* Gases being most compressible are elastic while solids are most elastic or least compressible —

i.e. $B_{solid} > B_{liquid} > B_{gas}$

Example: A steel wire, 0.5 mm^2 in cross-sectional area, and 10 m long is extended elastically 1.68 mm by a force of 18 N. Calculate the modulus of elasticity for the steel.

$$\text{Stress} = \frac{\text{Force}}{\text{Cross-Sectional area}}$$

$$= \frac{18}{0.5} \ N/mm^2$$

$$= 36 \ N/mm^2$$

$$\text{Associated strain} = \frac{1.68 \times 10^3}{10m}$$

$$= 0.000168$$

$$\text{modulus of elasticity} = \frac{\text{Stress}}{\text{Strain}}$$

$$= \frac{36}{0.000168} \ N/mm^2$$

$$= 21.42 \times 10^4 \ N/mm^2$$

$$= 0.2142 \ MN/mm^2$$

Strength: It is the property that enables a metal to resist repture under load. It is the ability of material to withstand the stress causing a partcular deformation codition.

The minimum stress needed to cause predetermined permanent deformation is called yield strength.

Fracture strength is defined as the stress at fracture.

(1) Tensile strength: Tensile strength is defined as the maximum load in tesion a material will withstand before fracturing, or the ability of a material to resist being pulled apart by opposing forces.

→

Consider a rod attached to a fixed beam holding a weight, the load is stretching the rod. Refer figure, the force acting on the rod is tensile force and the rod is said to be in tension. The material from which the rod is made should have tensile strength to resist the tensile load to be applied on rod during service conditions.

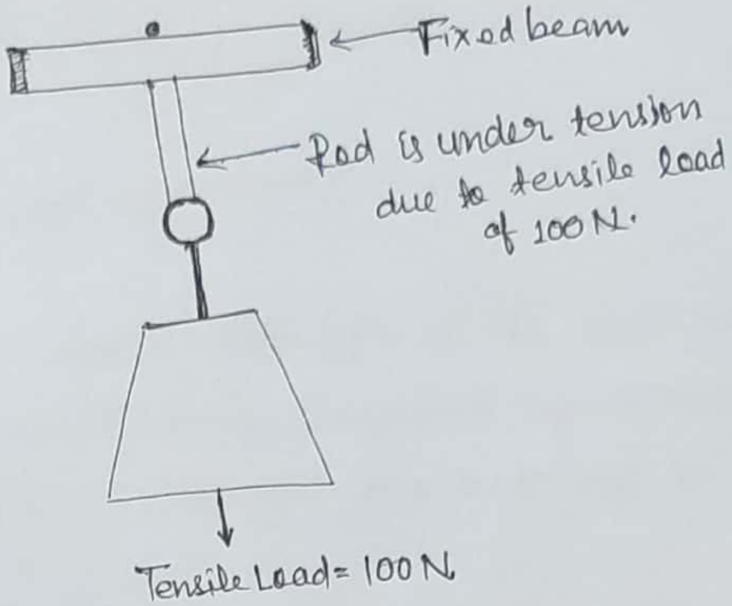


Fig. Tensile strength.

2. <u>Compressive Strength</u>: Compressive strength is the maximum load in compression a material can sustain before crushing or a predetermined amount of deformation.

The compressive strength of cast iron is greater than its tensile strength. Compressive strength is calculated by dividing the maximum load with the original cross section area of a specimen in a compression test. In the figure, the load is compressing the component. The material from which the component is made needs to have compressive strength to withstand the load.

Figure →

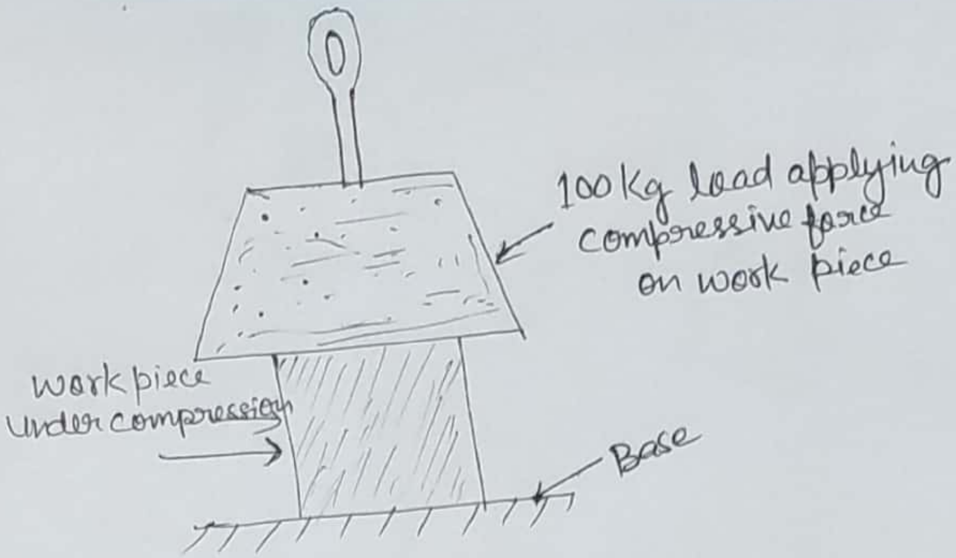


Fig: compressive strength

Shear Strength : Shear strength is the ability of a material to resist being fractured by opposing parallel forces acting on a straight line but not in same plane.

Shear strength.

Impact Strength:

Impact strength is an indication of the toughness of a material. It is energy required to fracture a specimen subjected to impact. Highly brittle material have low impact strength.

Example: Shock absorbers used in automobiles and trains are designed to have impact strength.

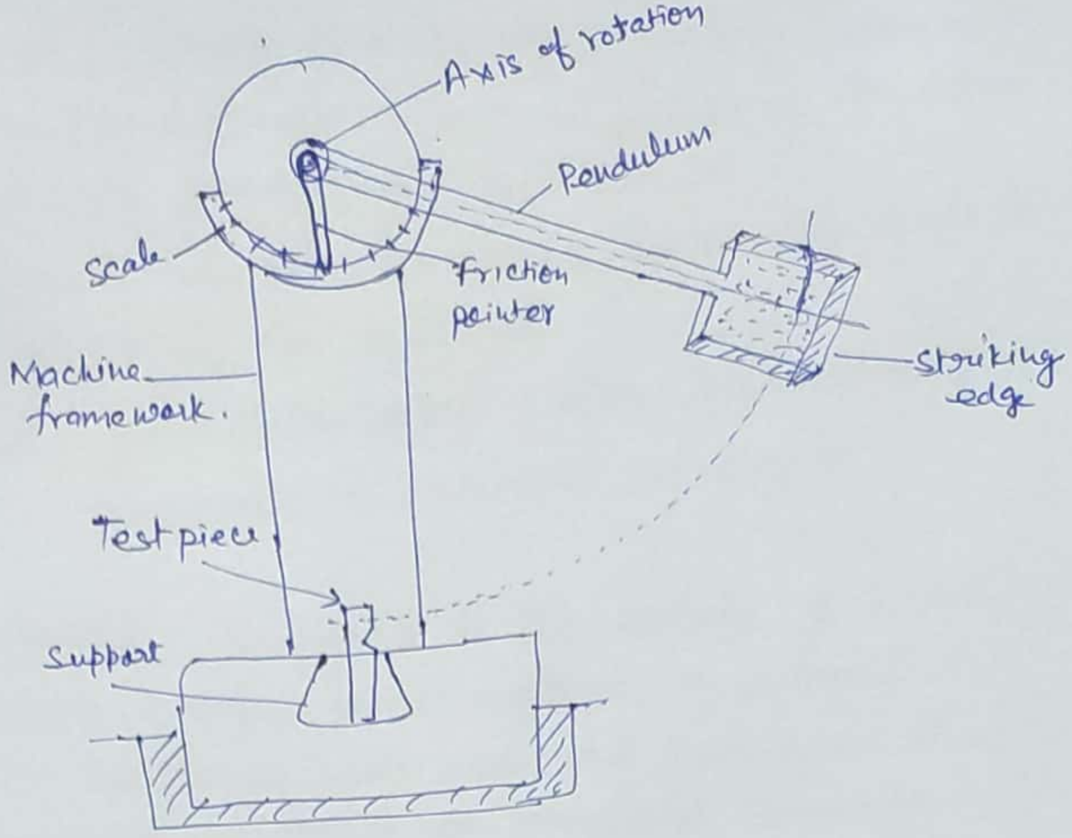


Fig: Impact Strength: Izod Test

Fatigue Strength: Fatigue is the progressive and localised structural damage that occurs when a material is subjected to cyclic loading.
Fatigue strength is the highest stress that a material can withstand for given number of cycle without breaking.

" Fatigue strength is the ability of material to resist various kinds of rapidly changing stresses and expressed by the magnitude of alternating stress for a specified number of cycles.

Examples: used in the design of motor shafts, gear teeth, turbine blades, etc.

Creep: Creep is a slowly progressing, permanent deformation that occurs over a period of time due to a steady force acting on material.
Creep extended over long time, eventually leads to the rupture of the material.

Example: gradual loosening of bolts, deformation of components of machines and engines.

Toughness: Toughness is the ability of a material to absorb energy before rupture. A material that possesses toughness will withstand tearing or shearing and may be stretched or otherwise deformed without breaking.
Toughness is measured by Impact test, high impact values indicating high toughness and is usually expressed as energy absorbed in an impact test.

Hardness: Hardness is the ability of a metal to resist localized plastic deformation. Hardness allows the material to withstand scratching, abrasion, penetration and wear by another material.

The hardness of a metal has a definite relationship to the ability of the metal to be plastically deformed, and to the amount of instantaneous load required for deformation to take place.

The relative hardness of minerals have in fact long been assessed by reference to Moh's Scale.

e.g. Diamond → Hardness Index ⇒ 10
Corundum → " " ⇒ 9
Gypsum → " " ⇒ 2

* Moh's scale is inadequate in the accurate determination of hardness of metallic alloys. 'Brunell Rockwell' hardness numbers are commonly used in industories to specify hardness.