STRENGTH OF MATERIALS

MECHANICAL ENGINEERING

MECHANICAL ENGINEERING-ME

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STUDY MATERIAL

STRENGTH OF MATERIALS

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CONTENT

CHAPTER 1

SIMPLE STRESSES AND STRAINS

STRESS (σ):

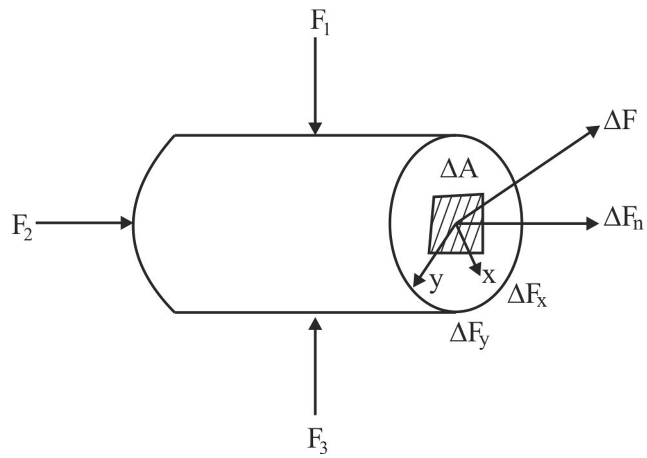
It is the internal resistance offered by a body against the deformation numerically, it is given as force per unit area.

Stress on elementary area ΔA,

i.e. $\boxed{\sigma = \lim_{\Delta A \to 0} \frac{\Delta F}{\Delta A} = \frac{dF}{dA}}(N/m^2)$ This unit is called

Pa(Pascal)

In case of normal stress *d*F always ⊥ (perpendicular) to area *d*A.



Pascal is a small unit in practice. These units are generally used

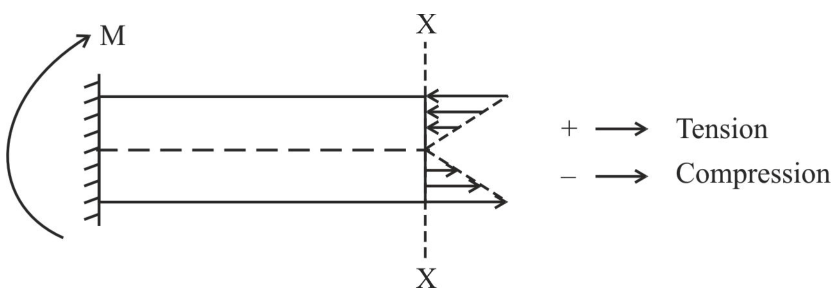
$$1\text{kPa} = 10^3\ \text{Pa} = 10^3\ \text{N/m}^2$$
$$1\text{MPa} = 10^6\ \text{Pa} = 10^6\ \text{N/m}^2$$
$$1\text{GPa} = 10^9\ \text{Pa} = 10^9\ \text{N/m}^2$$

1. **Normal Stress:** It may be tensile or compressive depending upon the force acting on the material.

   Tensile and compressive stresses are called **direct stresses.**

   When, $\sigma > 0$, Tensile
   When, $\sigma < 0$, Compressive

   ➢ The other types of normal stress is bending normal stress.



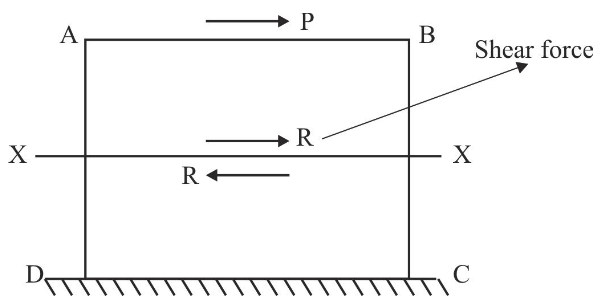
Bending stress are linearly distributed from zero at neutral axis to maximum at surface.

➢ In bending, the cross-sectional area rotates about transverse axis and the axis about which the cross-sectional area rotates is called neutral axis hence in bending, neutral axis is always transverse axis.

2. **Shear Stress (τ):** It is the intensity of shear resistance along a surface (Let X-X).

$$\boxed{\tau = \frac{Shear\ \ force}{Shear\ \ Area}}(N/m^2)$$

In case of shear stress force always parallel to the sheared area *i.e.* P is parallel to sheared area in figure.



3. **Conventional or Engineering Stress (σ_0):** It is defined as the ratio of load (P) to the original area of cross-section (A_0):

$\therefore$ $$\boxed{\sigma_0 = \frac{P}{A_0}}$$

4. **True Stress (σ):** It is defined as the ratio of load (P) to the instantaneous area of cross-section (A):

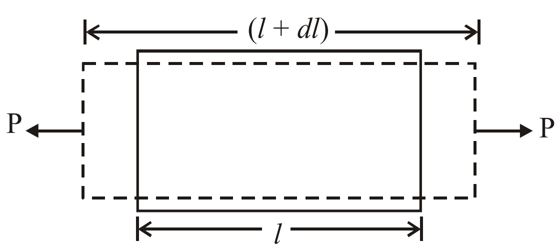
$\therefore$ $\boxed{\sigma = \frac{P}{A}}$ $or,$ $\boxed{\sigma = \sigma_0(1+\varepsilon)}$ Where ε = strain $\left[Al = A_0 l_0\right]$ Initial volume = Final volume

$l = l_0(1+\varepsilon)$

STRAINS (ε):

It is defined as the change in length per unit length. It is a dimensionless quantity.

i.e. $$\boxed{\varepsilon = \frac{\text{change in length}}{\text{original length}} = \frac{dl}{l}}$$



1. **Conventional or Engineering strain:** It is defined as the change in length per unit original length.

$$\boxed{\varepsilon = \frac{l - l_0}{l_0}}$$

Where,

l = Deformed length l_0 = Original length *e.g.* from above figure.

$$\varepsilon = \frac{l + dl - l}{l} \qquad \boxed{\varepsilon = \frac{dl}{l}}$$

2. Natural Strain: It is defined as the change in length per unit instantaneous length.

$$\boxed{\bar{\varepsilon} = \int_{l_0}^{l} \frac{dl}{l} = \ln\frac{l}{l_0} = \ln(1+\varepsilon) = \ln\left(\frac{A_0}{A}\right) = 2\ln\left(\frac{d_0}{d}\right)}$$

Also, $\because \quad \bar{\varepsilon} = \ln(1+\varepsilon)$

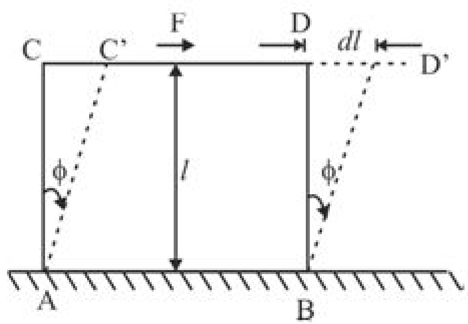
$\Rightarrow \; 1+\varepsilon = e^{\bar{\varepsilon}}$

$\Rightarrow \; \varepsilon = e^{\bar{\varepsilon}} - 1$

Volume of the specimen is a assumed to be constant during plastic deformation

$\because \quad \boxed{A_0L_0 = AL}$ -Valid till neck formation.

3. Shear Strain (ϕ): It is the strain produced under the action of shear stresses.



Shear Strain = tan ϕ

For small strain, $\boxed{\tan\phi \approx \phi}$

From figure, $\Delta ACC'$ or $\Delta BDD'$

$$\tan\phi = \frac{dl}{l} = \frac{CC'}{l}$$

$$\boxed{\phi = \frac{dl}{l} = \frac{\text{Transverse displacement}}{\text{Distance from lower face}}}$$

- Shear strain cause deformation in shape but volume remains same.

4. Superficial strain (ε_s): It is defined as the change in area of cross section per unit original area.

$$\boxed{\varepsilon_s = \frac{A - A_0}{A_0}}$$

Where, A = Final area $\qquad A_0$ = Original area

5. Volumetric Strain (ε_v): It is defined as the change in volume per unit original volume.

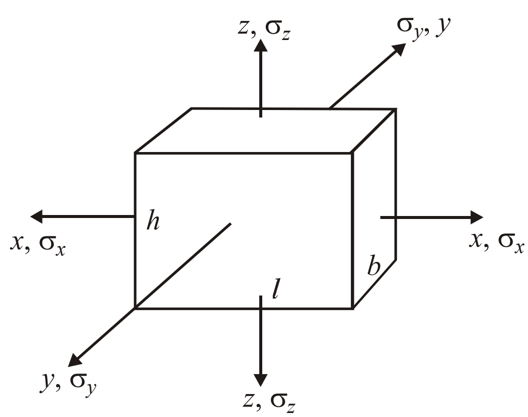
$$\boxed{\varepsilon_V = \frac{V - V_0}{V_0}}$$

Where, V = Final volume V_0 = Original volume

- Stress and strain are tensor (*neither vector nor scalar*) of 2nd order.

$$\boxed{\text{Volumetric strain } \varepsilon_V = \varepsilon_x + \varepsilon_y + \varepsilon_z}$$

Volumetric strain for various shapes:



(*i*) Rectangular body:

V = *lbh* on partial differentiation

$$\delta V = \delta l(b.h) + \delta b(l.h) + \delta h(b.l)$$

$$\varepsilon_V = \frac{\delta V}{V} = \frac{\delta l}{l} + \frac{\delta b}{b} + \frac{\delta h}{h}$$

$$\boxed{\varepsilon_V = \varepsilon_x + \varepsilon_y + \varepsilon_z}$$

Note: $\varepsilon_x, \varepsilon_y, \varepsilon_z$ are the strain corresponding to the stresses $\sigma_x, \sigma_y, \sigma_z$ in *x*-direction, *y*-direction, *z*-direction respectively

$$\boxed{\varepsilon_V = \frac{\sigma_x + \sigma_y + \sigma_z}{E}(1 - 2\upsilon)}$$ $\upsilon \rightarrow$ POISSON Ratio

υ= 0.5 For rubber

(*ii*) For cylindrical body:

$$V = \frac{\pi}{4} d^2 l$$

$$\delta V = 2\, dl \,.\, \delta d . \frac{\pi}{4} + \frac{\pi}{4} d^2 \delta l$$

$$\varepsilon_V = \frac{\delta V}{V} = 2\frac{\delta d}{d} + \frac{\delta l}{l}$$

$$\boxed{\varepsilon_V = 2\varepsilon_d + \varepsilon_l}$$

(*iii*) For spherical body

$$\boxed{\varepsilon_V = 3\frac{\delta d}{d}} \qquad \boxed{V = \frac{4}{3}\pi r^3} \qquad d = 2r$$

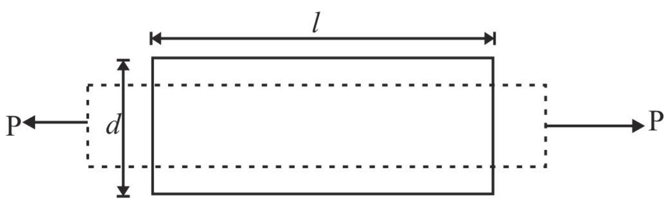
Gauge Length: It is that portion of the test specimen over which extension or deformation is measured.

i.e. this length is used in calculating strain value.

Poisson's ratio $\left(\upsilon \text{ or } \frac{1}{m}\right)$: Value of μ varies between (–1 to 0.5)

The ratio of the lateral strain to longitudinal strain is called the Poisson's ratio.

$$\boxed{\upsilon = \frac{\text{Lateral strain}}{\text{Longitudinal strain}}} \quad \text{or} \quad \boxed{\upsilon = \frac{-\left(\frac{\delta d}{d}\right)}{\left(\frac{\delta l}{l}\right)}}$$



- For a given material, the value of 'υ' is constant throughout the linearly elastic range.
- For most of the metals the value of 'υ' lie between 0.25 – 0.42
- 'υ' varies from (– to 0.5)

Note: 'υ' for ductile material is greater than 'υ' for brittle metals.

Table

Material	Value of 'υ'	Remarks
Cork	0	∴ Used in bottle to withstand pressure
Foam	–1	
Rubber	0.5	
Concrete	0.1 – 0.2	
C.I.	0.23 – 0.27	

For cork $\quad v = 0$

For rubber $\quad v = 0.5$

For concrete $\quad v = 0.1 - 0.2$

Isotropic Material: These materials have same elastic properties in all directions.

No. of independent elastic constants = 2, *i.e.* if any of 2 elastic constants is known then other can be derived.

Orthotropic Material: The number of independent elastic constants is 9.

Anisotropic materials: These materials don't have same elastic properties in all directions.

Elastic modulii will vary with additional stresses appearing. $\because$ There is a coupling between shear stress and normal stress for an isotropic material.

The number of independent elastic constants is 21.

Hooke's Law: It states that when a material is loaded such that the intensity of stress is within a certain limit, the ratio of the intensity of stress to the corresponding strain is a constant which is characteristics of that material.

i.e. $\boxed{\frac{\text{Stress}}{\text{Strain}} = \text{Constant} = E}$ *i.e.,* $\sigma = E\varepsilon$

Where, E = Young's Modulus (N/m^2)

Or

Modulus of Elasticity

- For steel, value of E = 210 GPa (1 GPa = 10^3 N/m^2)
- For aluminum, value of E = 73 GPa $E_{Al} \simeq \frac{1}{3}\text{rd } E_{steel}$
- For Plastic, value of E = 1 GPa – 14 GPa

  Note : As flexibility increases, value of young's modulus decreases.

  It is resistance to elastic strain.

Shear Modulus of Elasticity OR Modulus of Rigidity (G or C): It is defined as the ratio of shearing stress to shearing strain.

$\boxed{G \text{ or } C = \frac{\text{Shear stress}}{\text{Shear strain}}}$ *i.e.* $\tau = G\phi$

Bulk Modulus (K):

It is defined as the ratio of uniform stress intensity to volumetric strain within the elastic limits.

$\boxed{K = \frac{\text{Stress}}{\text{Volumetric Strain}}}$

Note: Elastic constant relationship

(i) $E = 2C(1+v)$, where, v = Poisson's ratio.

(ii) $E = 3K(1-2v)$

(iii) $v = \frac{3K-2C}{6K+2C}$

(iv) $E = \dfrac{9KC}{3K + C}$

STRESS-STRAIN DIAGRAM:

1. Ductile material (Mild Steel):

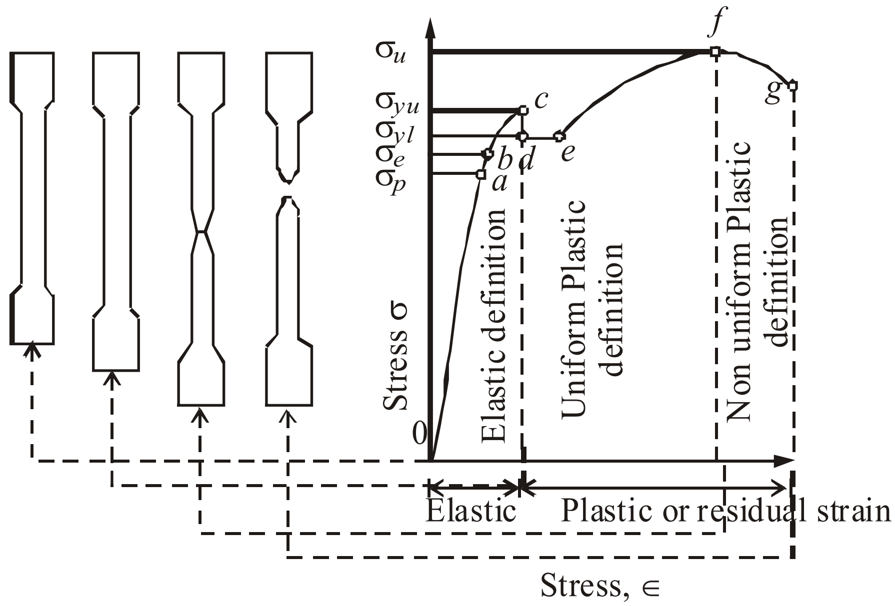


Figure: ***Typical stress-strain diagram for a ductile material***

- Point 'a'→ Limit of proportionality: Up to this point 'a', Hooke's law is obeyed; 'oa' is a straight line.

  Stress corresponding to this point is called 'proportional limit stress, σ_p'

Comparison of Engineering and true stress strain curve:

- The true stress-strain curve is also known as **flow curve.**
- True stress-strain curve gives a true indication of deformation characteristics because it is **based on the instantaneous dimension of specimen.**
- In engineering stress-strain curve, the stress drops down after necking since it is **based on the original area.**
- In true stress strain curve, the stress however increases after necking since the cross section area of the specimen **decreases rapidly after necking.**
- The flow curve of many metals in the region of uniform plastic deformation can be expressed by **simple power law.**

$$\sigma_T = K(\in_T)^n$$

where, K is the strength co-efficient, σ_T is time stress.

n is the strain hardening coefficient.

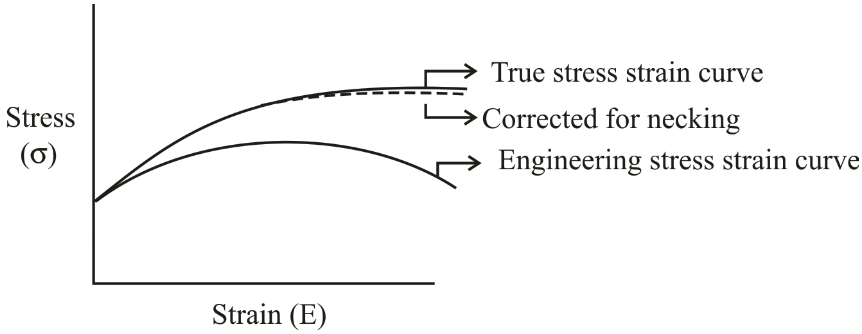
$n = 0$ for perfectly plastic solid

$n = 1$ In elastic solid

For most metals $0.1 < n < 0.5$

$\sigma_{True} > \sigma_{Nominal} \rightarrow$ if force is tensile, since area decreases.

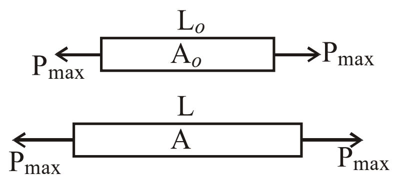
$\sigma_{True} > \sigma_{Nominal} \rightarrow$ if force is compressive, since area increase.



Relation between ultimate tensile strength and true stress at maximum load.

Ultimate tensile strength $\sigma_u = \frac{P_{max}}{A_o}$

True stress at maximum load = $(\sigma_u)_T = \frac{P_{max}}{A}$



True strain at max load $(\varepsilon_T) = \ln\frac{A_o}{A}$ or $\frac{A_o}{A} = e^{\epsilon_T}$

Eliminating P_{max} we get

$$(\sigma_u)_T = \frac{P_{max}}{A} \times \frac{A_o}{A_o}$$

$$= \frac{P_{max}}{A_o} \times e^{\epsilon_T}$$

$$\boxed{\Rightarrow (\sigma_u)_T = \sigma_u\, e^{\epsilon_T}}$$

Here, P_{max} is the max force.

A_o = original cross section area

A = instantaneous cross section area

- Based on the above theory two examples has been provided.

Example 1. Only elongation no neck formation.

In the tension test of rod shown initially it was $A_o = 50\,\text{mm}^2$ and $L_o = 100\,\text{mm}$. After the application of load its $A = 40\,\text{mm}^2$ and L = 125 mm.

Determine the true strain using changes in both length and area.

Solution: Here $A_o L_o = AL$

i.e., 50 × 100 = 40 × 125

$\Rightarrow$ $5000\,\text{mm}^2 = 5000\,\text{mm}^2$ $\therefore$ no neck formation.

$\therefore$ true strain can be calculated both by area and length formula as follows.

$$\in_T = \int_{l_o}^{l} \frac{dl}{l} = \ln\left(\frac{125}{100}\right) = 0.223$$

$$\in_T = \int_{A_o}^{A} \ln\left(\frac{A_o}{A}\right) = \ln\left(\frac{50}{40}\right) = 0.223$$

Example 2: A ductile material is tested such that necking occurs then the final gauge length is L = 140 mm and the final minimum cross section area is $A = 35\ mm^2$ though the rod shown initially was of area $A_o = 50\ mm^2$ and $L_o = 100\ mm$. Determine the true strain using change in both length and area.

Sol. Check $A_o L_o = 50 \times 100 = 5000\ mm^3$

$AL = 35 \times 140 = 4900\ mm^3$

i.e. $A_o L_o > AL$ $\therefore$ Necking occurs and force applied is tensile.

$$\therefore \quad \in_T = \ln\left(\frac{A_o}{A}\right) = \ln\left(\frac{50}{35}\right) = 0.357$$

$$\in_T = \int_{l_o}^{l} \frac{dl}{l} = \ln\left(\frac{140}{100}\right) = 0.336\ (\text{wrong})$$

Inference: After necking gauge length gives error but area and diameter can be used for the calculation of true strain at and before fracture.

It Elongation with neck formation.

- Upto point A, Hooke's law is obeyed and stress is proportional to strain. Therefore, OA is straight line. Point A is called limit of proportionality.
- Point 'b'→ Elastic limit point: '*ab*' is not a straight line but upto point '*b*' the material remains elastic. Stress corresponding to this point is called elastic limit stress, σ_e.

  Elastic limit > Proportional limit.

Generally, point '*a*' and '*b*' coincides.

- Point 'c'→ upper yield point: At this point the cross-sectional area starts decreasing.
- Point 'd'→ Lower yield point: At this point the specimen elongates by a considerable amount without any increase in stress. The value of stress at this point is $\sigma_y = 250 N/mm^2$ for mild steel.

  The value of strain at yield stress is about 0.0012 or 0.12%

  Lower yield point 'd' is observed, if rate of loading is slow.
- Upper yield point 'c' is observed, if rate of loading is fast.
- Portion '*de*' represents 'plastic yielding': -Typical value of strain is 0.014 or 1.4% i.e. strain in range '*de*' is at least 10 times the strain at the yield point.
- Portion '*ef*' represents 'strain hardening': Strain increases fast with strain, till the ultimate load is reached.
- Point '*f*' → Ultimate stress: Corresponding strain is 20% for mild steel. It is the maximum stress to which the material can be subjected in a simple tensile test. At this point necking of material begins.

- Point 'g' → Breaking Stress: - Corresponding strain is called fracture strain. It is about 25% for mild steal .

Concept of reduced area (RA): $q = \dfrac{A_f - A_o}{A_o}$

- Reduction of area is more a measure of deformation required to produce failure and its chief contribution results from necking process.
- There is a complicate state of stress in necking condition.
- RA is the most sensitive ductility parameter and is useful in detecting quality changes in materials.

2. Brittle Material (Cast Iron):

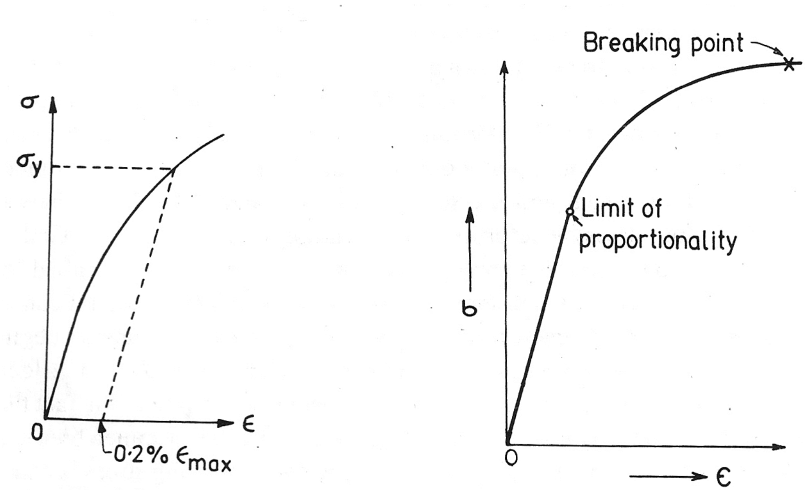


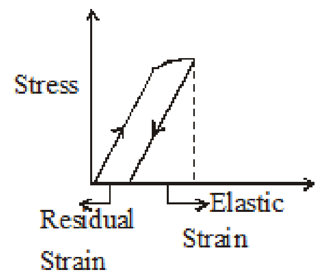
Figure: ***Typical stress-strain diagram for a ductile material***

- In these materials, elongation and reduction in area of the specimen is very small.
- The yield point is not marked at all.
- The straight portion of the diagram is very small.
- **Proof stress:** It is given corresponding to 0.2% of strain. A line parallel to linear portion of curve is drawn passing through 0.2% strain:

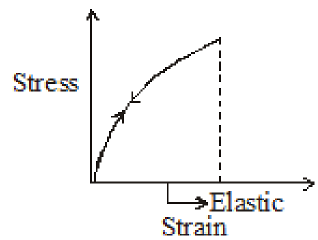
$$\boxed{\sigma = \epsilon_{Total} E - \epsilon_{Plastic} E = \epsilon_{Elastic} \times E}$$

Concept of Elastic and Plastic strain by graph:

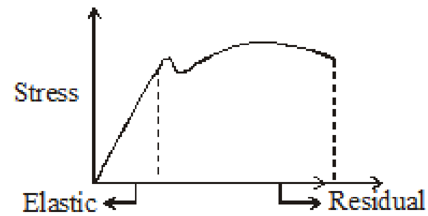
1.



2.



3.



PROPERTIES OF METALS:

1. **Ductility:** It is the characteristics of metal by virtue of which, it can be stretched. Large deformations are thus possible in these materials before the rupture takes place.
   - Those metals are ductile which has more than 5% post elastic strain (*i.e.,* plastic strain).

   e.g. - Mild Steel, Aluminium, Copper, Silver, Gold, Lead etc.
   - Yield failure occurs in ductile materials.

2. **Brittleness:** Tendency of fracture without any appreciable deformation. Hence, for brittle material, fracture point and ultimate points are same.
   - Generally non-elastic strain is less than 5%.

   e.g. - Cast iron, concrete etc.
   - Fracture occurs in brittle materials.

3. **Toughness:** It is the ability of a material to absorb energy and deform plastically before fracture. It is usually measured by the energy absorbed in a notched impact test like charpy and Izod test. Higher toughness is desirable property for materials used for gears, chains, crains etc.
   Bend the is used to detect toughness.

4. **Malleability:** It is the property by which a material can be uniformly extended in a direction without rupture. A malleable material possesses a high degree of plasticity. This property is of great use in operations like forging, hot rolling etc.

5. **Hardness:** It is defined as the resistance of metal to plastic deformation or scratching, abrasion or cutting.
   Test on hardness is classified into:
   (a) Scratch test :

(b) Indentation test:

- Brinell Hardness method

Brinnell hardness number = $\dfrac{P}{\dfrac{\pi d}{2}[D - \sqrt{D^2 - d^2}\,]}$

Where, P = Standard load in kg
D = diameter of steel ball (mm)
d = diameter of indent (mm)

- Rockwell method
- Vicker hardness method

➢ Ductile materials are tough and brittle materials are hard.

6. **Fatigue:** It is a phenomenon which leads to fracture under repeated or fluctuating cyclic stresses below the tensile strength of the material.

➢ Fatigue fractures are progressive in nature.

➢ The number of cycles of stress that can be sustained prior to failure for a stated stress condition is called as fatigue life.

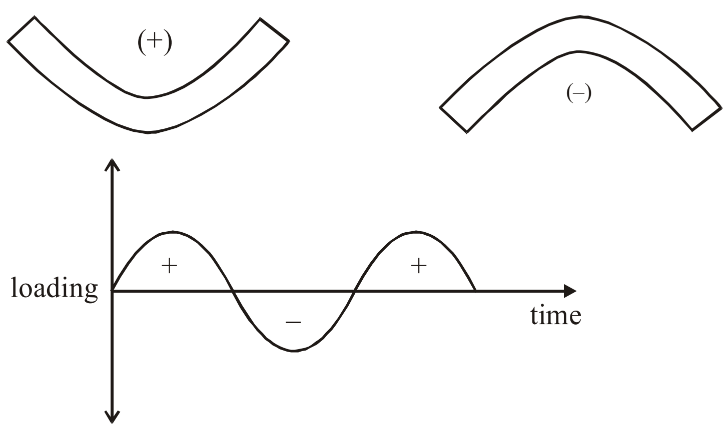
➢ Fatigue or Endurance limits → the maximum stress below which the material can endure an infinite number of stress cycle.

e.g. 1. Breaking of wire in reverse cycling bending.
2. Failure of fly-wheel

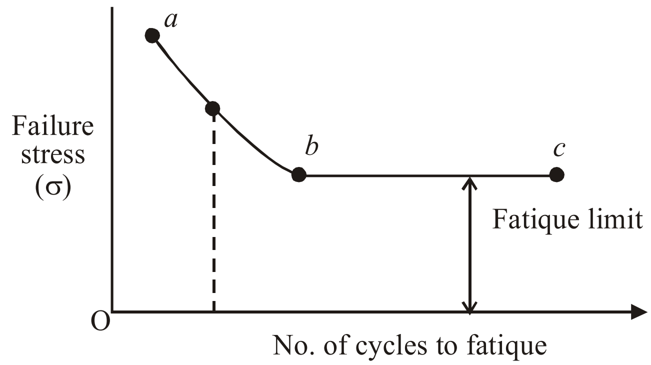
➢ Factors affecting fatigue are:

(a) Loading condition
(b) Frequency of loading
(c) Corrosion, temperature etc.

Fatigue failure in material depends on cycle frequency



Endurance curve or S – N diagram showing Fatigue limit



$\sigma_{induced} \leq 160$ MPs Infinite Life

$\sigma_{induced} > 160$ MPs Finite Life

Note: When the stress level below the endurance limit components posses infinite life vice versa.

7. **Creep and Stress Relaxation:** It is a time dependent phenomenon of progressive deformation of metal under constant stress below its yield point or proportional limit.
   - Primary or cold creep: It is a decreasing creep rate, because of the work/strain hardening resulting from the deformation.
   - Secondary creep: As a result of equilibrium attained between the work/strain hardening process and an annealing effect nearly constant creep rate, represents the actural croop rate of material.
   - Tertiary or accelerated creep: Final stage: It represents a process of progressive damage resulting in an imminent fracture of the material , rapid increases in creep rate due to decreasein in cross sectional area.

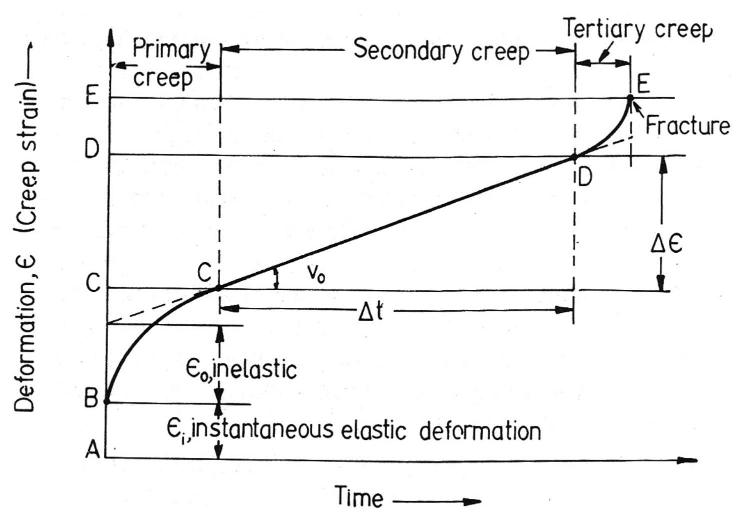
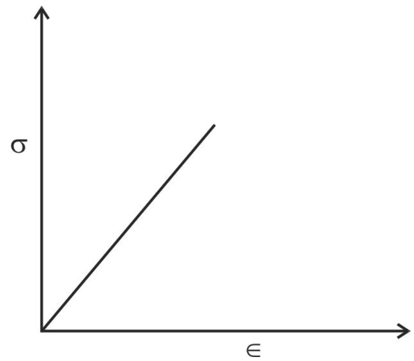


Figure: ***Stages of Creep***

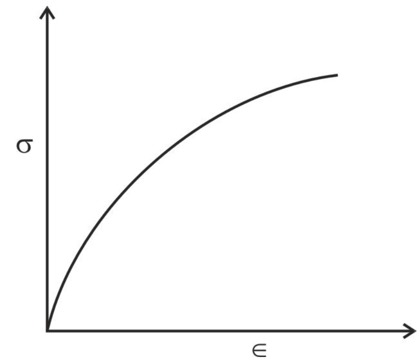
   - Creep is more pronounced at higher temperature hence must be considered for design of engines and furnaces.
   - When a wire is stretched between two immovable supports. So that it has an initial tensile stress (σ_0). The stress in the wire gradually diminishes, eventually reaching to a constant value. This process, which is a manifestation of creep, is called "Stress relaxation.

Types of Metal Behaviors (Types of stress-strain curves)

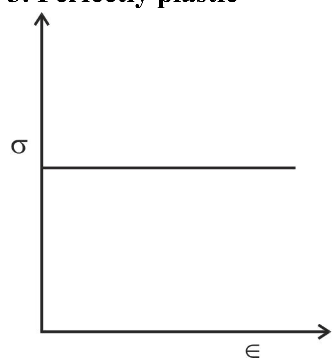
1. Linear Elastic



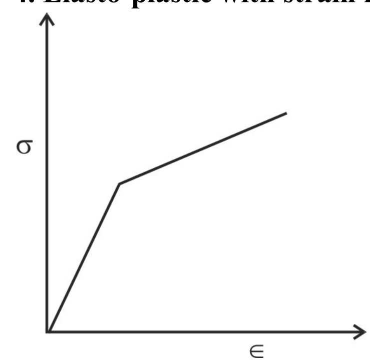
2. Non Linear Elastic



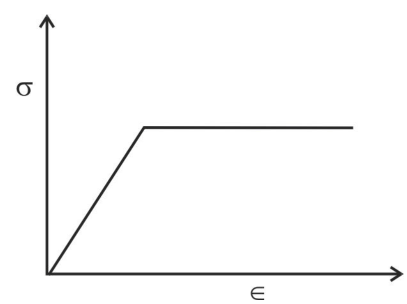
3. Perfectly plastic



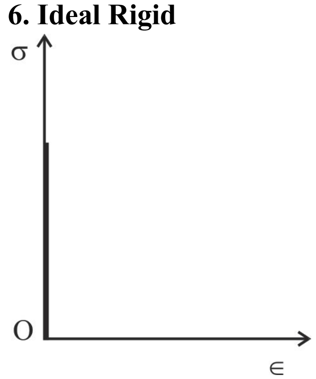
4. Elasto-plastic with strain hardening



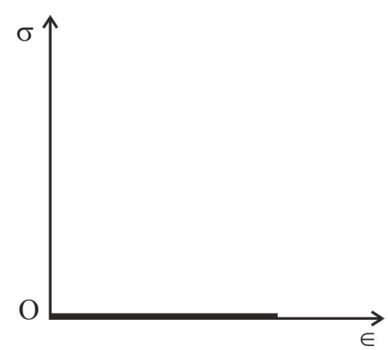
5. Elasto plastic or visco plastic



6. Ideal Rigid



7. Ideal Fluid



Resilience

It is the total elastic strain energy which can be stored in a given volume of metal and can be released after un-loading. It is equal to area under load-deflection curve within elastic limit.

Note: For suspension system and spring action, a metal should be used with high resilience.

Key Points