Mechanics of Material

ARA 205

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TYPES OF LOAD

There are a number of different ways in which load can be applied to a member. Typical loading types are:

A) **Dead/ Static load**- Non fluctuating forces generally caused by gravity

B) **Live load**- Load due to dynamic effect. Load exerted by a lorry on a bridge

C) **Impact load or shock load**- Due to sudden blows

D) **Fatigue or fluctuating or alternating loads**: Magnitude and sign of the forces changing with time

Types of Loads

Load is defined as the set of external forces acting on a mechanism or engineering structure which arise from service conditions in which the components work

In the mechanics of the deformable bodies, the following types of loads are commonly considered:

- Dead loads—static in nature, such as the self-weight of the roof.
- Live loads—fluctuating in nature, do not remain constant- such as a weight of a vehicle moving on a bridge.
- Tensile loads.
- Compressive loads.
- Shearing loads

Sign convention followed: Tensile forces are positive and compressive negative

Classification of Materials

From an engineering point of view, properties concerned with metals are:
1. Elasticity
2. Plasticity
3. Brittleness
4. Malleability
5. Ductility

Many of these properties are contrasting in nature so that a given metal cannot exhibit simultaneously all these properties. For example, mild steel exhibits the property of elasticity, copper possesses the property of ductility, wrought iron is malleable, lead is plastic and cast iron is brittle.

Elastic Material

II undergoes a deformation when subjected to an external loading such that the deformation disappears on the removal of the loading (rubber).

Plastic Material

It undergoes a continuous deformation during the period of loading and the deformation is permanent. It does not regain its original dimensions on the removal o\ the loading (aluminum).

Rigid Material

It does not undergo any deformation when subjected to an external loading (glass and cast iron).

Malleability

Materials ability to be hammered out into thin sheets, such as lead, is called malleability.

Brittle Materials

They exhibit relatively small extensions to fracture such as glass and cast iron. There is little or no necking at fracture for brittle materials

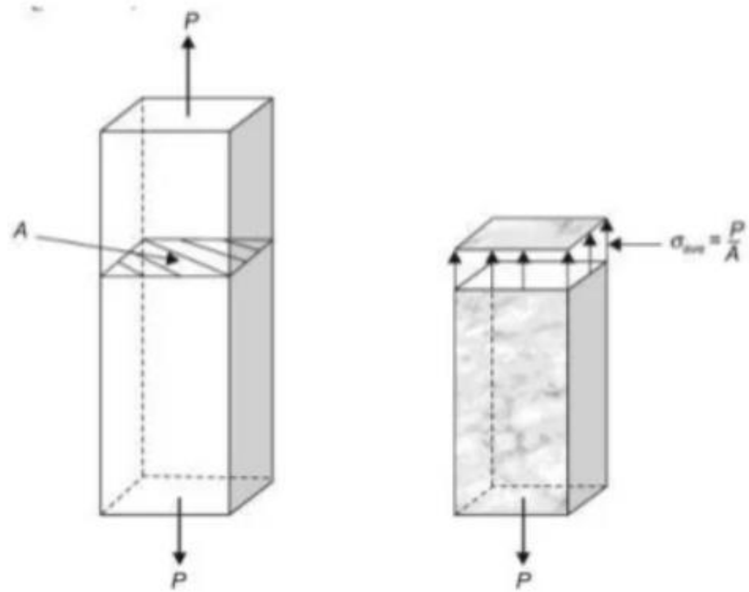
STRESS

- Stress is an internal resistance offered by a unit area of the material, from which a member is made, to an externally applied load. Alternatively, the force per unit area or intensity of the forces distributed over a given section is called the stress on that section. The resistance of material or the internal force acting on a unit area may act in any direction.

Direct or normal stress *G* is calculated by using the following formula:

$$\sigma = \frac{\text{Applied load}}{\text{Original cross-sectional area resisting the force}}$$

$$\sigma = \frac{P}{A} \qquad \text{Unit - N / m2} \qquad (1.1)$$



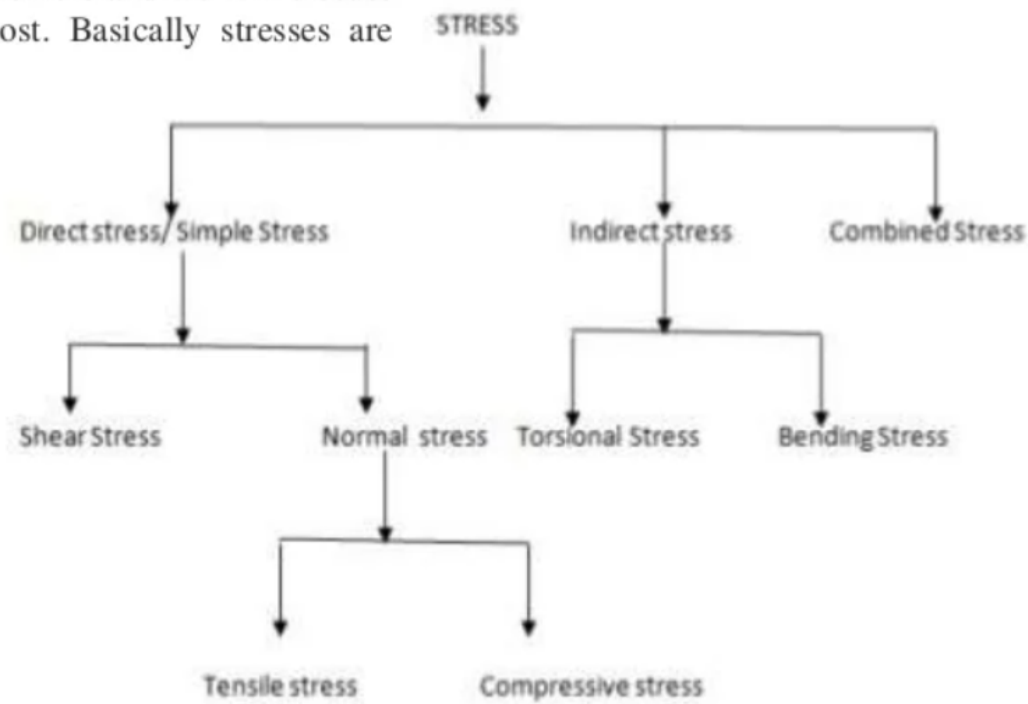
Types of Stresses

The stress may be normal stress or a shear stress. Normal stress is the stress which acts in a direction perpendicular to the area. It is represented by ζ (sigma). The normal stress is further divided into tensile stress and compressive stress.

Types of stress

There are following type of stresses as displayed in figure here and we will discuss each type of stress in detail with the help of this post. Basically stresses are classified in to three types.

1. Direct stress or simple stress
2. Indirect stress
3. Combined stress



Normal stress

Normal stress is basically defined as the stress acting in a direction perpendicular to the area. Normal stress will be further divided, as we have seen above, in two types of stresses i.e. tensile stress and compressive stress.

Tensile Stress:

The stress induced in a body, when subjected to two equal and opposite pulls as shown in Fig. as a result of which there is an increase in length, is known as tensile stress. The ratio of increase in length to the original length is known as *tensile strain.* The tensile stress acts normal to the area and it pulls on the area.

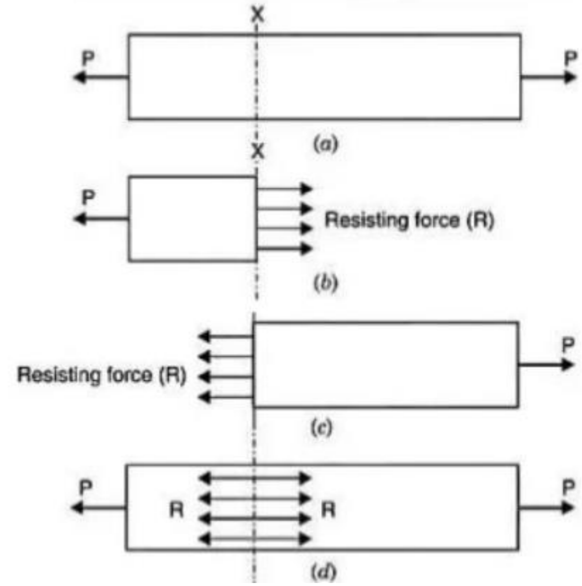
Fig. (a) shows a bar subjected to a tensile force P at its ends. Consider a section *x-x,* which divides the bar into two parts. The part left to the section *x-x,* will be in equilibrium if P = Resisting force (R). This is shown in Fig. (b). Similarly the part right to the section *x-x,* will be in equilibrium if P = Resisting force as shown in Fig. (c). This resisting force per unit area is known as stress or intensity of stress.

$$\therefore \text{ Tensile stress } = \sigma = \frac{\text{Resisting force } (R)}{\text{Cross-sectional area}} = \frac{\text{Tensile load } (P)}{\text{A}}$$

$$\sigma = \frac{P}{A}$$

And tensile strain is given by,

$$e = \frac{\text{Increase in length}}{\text{Original length}} = \frac{dL}{L}.$$

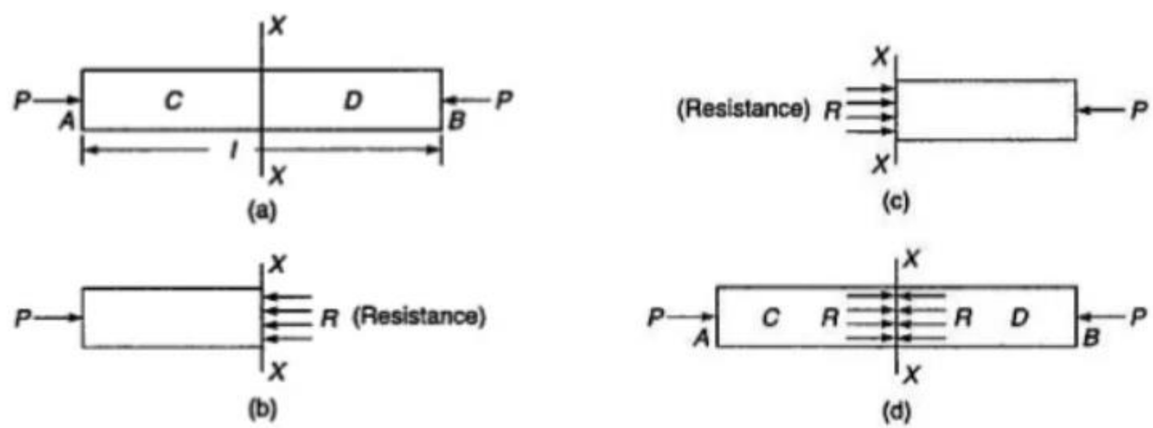


Compressive Stress:

- The stress induced in a body, when subjected to two equal and opposite pushes as shown in Fig. (a) as a result of which there is a decrease in length of the body, is known as compressive stress. And the ratio of decrease in length to the original length is known as *compressive strain.*

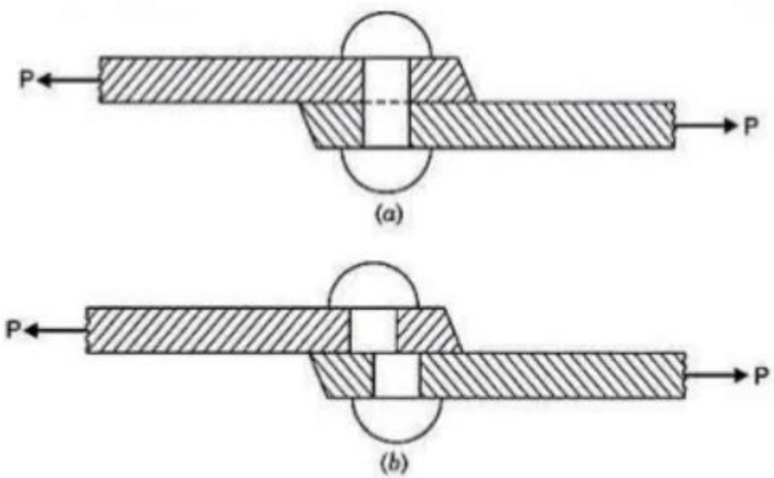
The compressive stress acts normal to the area and it pushes on the area. Let an axial push P is acting on a body in cross-sectional area A. Due to external push P, let the original length L of the body decreases by dL

$$\sigma = \frac{\text{Resisting Force }(R)}{\text{Area }(A)} = \frac{\text{Push }(P)}{\text{Area }(A)} = \frac{P}{A}$$



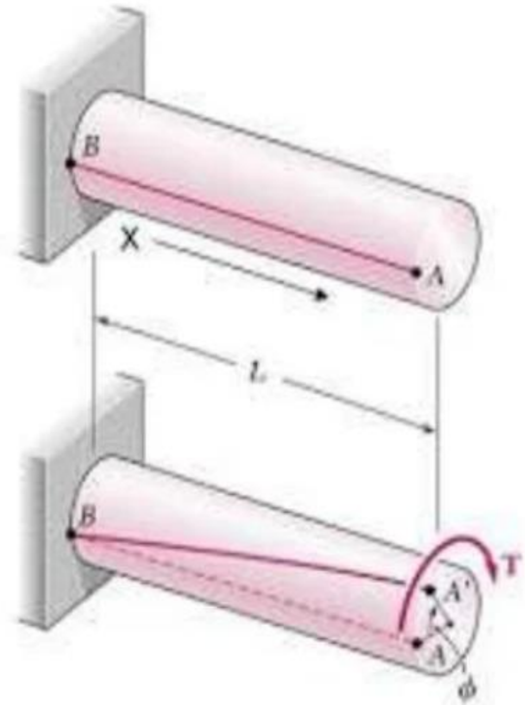
Shear Stress

The stress induced in a body, when subjected to two equal and opposite forces which are acting tangentially across the resisting section as shown in Fig. 1.4 as a result of which the body tends to shear off across the section, is known as shear stress. The corresponding strain is known as *shear strain*. The shear stress is the stress which acts tangential to the area. It is represented by τ.



Torsional stress

Torsional stress is one special type of stress in a member where one end of member will be secured and other end of member will be twisted. Let us see one example, let we have one shaft and its one end is supported by a ball bearing and other end of shaft is free to rotate.



Let if bearing is seized, then there will be twisting mechanism because one end of rotating shaft will be fixed due to seized bearing and other end of shaft will be twisted and therefore there will be produced stress in shaft and that stress will be termed as torsional stress.

From here, we can also say that torsional stress will exist in rotating members such as rotating shaft. Torsional stress will be indicated by symbol

Bending stress

Let we have one beam which one end is fixed at A and other end is loaded by force P and hence beam is deflected here as shown in figure.

Bending stress will be determined with the help of following formula as displayed here in following figure.

We will study and analyze each type of strain in detail in our next post.

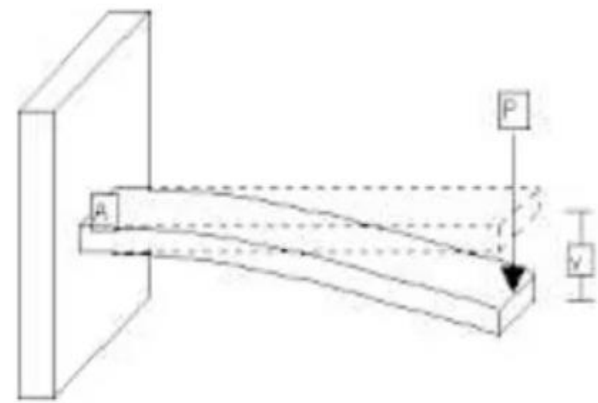
$$\sigma_b = \frac{My}{I}$$

σ_b – Bending stress

M – Calculated bending moment

y – Vertical distance away from the neutral axis

I – Moment of inertia around the neutral axis



STRAIN

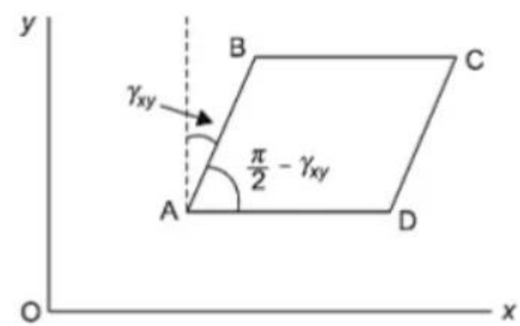
When a body is subjected to some external force, there is some change of dimension of the body. The ratio of change of dimension of the body to the original dimension is known as strain. Strain is dimensionless. Strain may be :

- Tensile strain
- Compressive strain,
- Volumetric strain
- Shear strain

If there is some increase in length of a body due to external force, then the ratio of increase of length to the original length of the body is known as *tensile strain*. But if there is some decrease in length of the body, then the ratio of decrease of the length of the body to the original length is known as *compressive strain.* The ratio of change of volume of the body to the original volume is known as *volumetric strain.* The strain produced by shear stress is known as shear strain.

$$\varepsilon = \frac{\text{Change in length}}{\text{Small original length}} = \frac{\delta L}{L_o}$$

$$\varepsilon = \lim_{\Delta x \to 0} \frac{\Delta(\delta L)}{\Delta x} = \frac{d(\delta L)}{dx}$$



TYPES OF STRAIN IN STRENGTH OF MATERIALS

Types of strain

There are following types of strain and we will discuss each type of strain in detail with the help of this post.

Strain is classified on the basis of the type of loading

Tensile strain

Compressive strain

Shear strain

Strain is also classified on the basis of type of deformation

Temporary or elastic strain

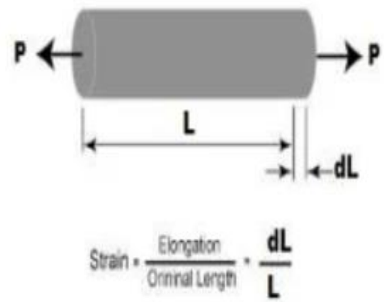
Permanent or plastic strain

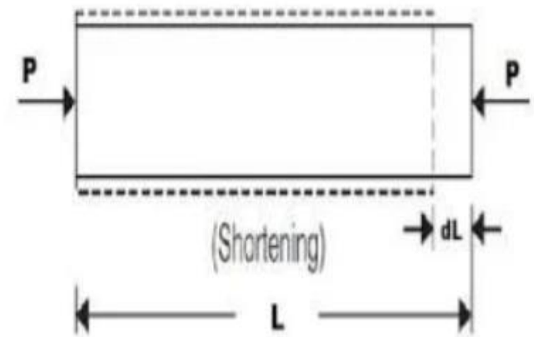
Strain is also classified as mentioned here

Linear strain

Lateral strain

Volumetric strain





Tensile strain

Let us see here the following figure; we have one bar of length L. There are two equal and opposite pulling type of forces P, acting axially and trying to pull the bar and this pulling action will result increase in the length of the bar under the action of tensile loading, but diameter of the bar will be reduced under the action of tensile loading.

Therefore we can define the tensile strain as the strain developed in a member due to the pulling action of two equal and opposite direction of forces. ε_t is the symbol which is used to represent the tensile strain in a member.

Tensile strain will be determined with the help of following formula.

Tensile strain (ε_t) = Increase in length (dL) / Original length (L)

$\varepsilon_t = dL / L$

Compressive strain

Let us see here the following figure; we have one bar of length L. There are two equal and opposite push type of loading P, acting axially and trying to push the bar and this pushing action will result the decrease in the length of the bar under the action of compressive loading, but diameter of the bar will be increased under the action of compressive loading. ε_c is the symbol which is used to represent the tensile strain in a member.

Compressive strain will be determined with the help of following formula.

Compressive strain (ε_c) = Decrease in length (dL) / Original length (L)

$\varepsilon_c = dL / L$

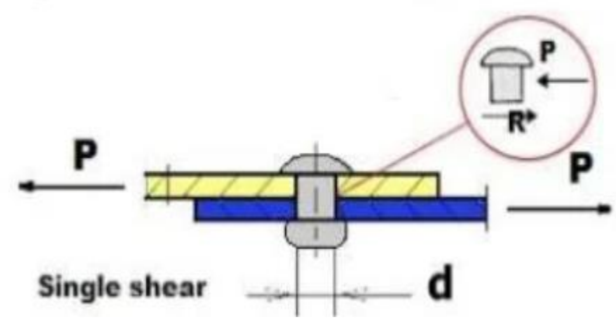
Shear strain

Let us see here the following figure; we have two plates and these two plates are connected with each other with the help of a pin or a rivet as shown in figure. There are two equal and opposite forces (P) acting tangentially across the resisting section.

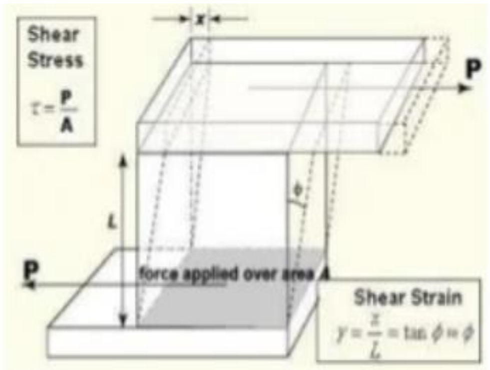
One force is acting on top plate towards left direction and second force is acting towards right side as shown in figure and hence such type of loading will try to shear off the body across the resisting section.

This type of loading action will be termed as shear loading and stress developed in material of the body will be termed as shear stress and corresponding strain will be termed as shear strain.

Shear strain will be determined as displayed in following figure:



Shear strain will be determined as displayed in following figure



Temporary or elastic strain

Temporary strain or elastic strain is such type of strain which will be disappeared on removal of external load or we can say that body will return to its original shape and size.

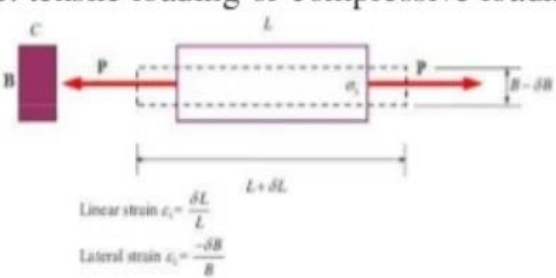
Permanent or plastic strain

Permanent strain or plastic strain is such type of strain which will not be disappeared on removal of external load or we can say that body will not return to its original shape and size.

Linear strain

Let us consider one rectangular bar as shown in figure, its length is L and breadth is B. There are two equal and opposite pulling type of forces P, acting axially and trying to pull the rectangular bar and this pulling action will result increase in the length of the rectangular bar under the action of tensile loading, but breadth of the rectangular bar will be reduced under the action of tensile loading.

Linear strain will be basically defined as the ratio of change in length of the body to the original length of the body. Linear strain might be tensile or compressive depending on the type of loading i.e. tensile loading or compressive loading. Here in this example, linear strain will be tensile strain because tensile loading is here.



Lateral strain

Consider the same figure as displayed above, Lateral strain will be the strain at perpendicular or right angle to the direction of applied force.

Therefore we can define here lateral strain as; lateral strain will be basically defined as the ratio of change in breadth of the body to the original breadth of the body.

Volumetric strain

When an object will be subjected with a system of forces, object will undergo through some changes in its dimensions and hence, volume of that object will also be changed.

Volumetric strain will be defined as the ratio of change in volume of the object to its original volume. Volumetric strain is also termed as bulk strain.

ε_v= Change in volume /original volume

$\varepsilon_v = dV/V$

HOOK'S LAW

For elastic bodies, the ratio of stress to strain is constant and is known as *Young's modulus* or the *modulus of elasticity* and is denoted by *E,* i.e.,

$$\sigma \propto \varepsilon$$

$$\sigma = E\varepsilon$$

$$E = \frac{\text{Tensile stress}}{\text{Tensile strain}} \quad \text{or} \quad \frac{\text{Compressive stress}}{\text{Compressive strain}}$$

$$E = \frac{\sigma}{e}$$

- Strain has no units as it is a ratio. Thus, *E* has the same units as stress.
- The materials that maintain this ratio are said to obey *Hooke s law* which states that within elastic limits, strain is proportional to the stress producing it. The elastic limit of a material is determined by plotting a tensile test diagram. Young's modulus is the stress required to cause a unit strain.
- Similarly, for elastic materials, the shear strain is found to be proportional to the applied shear stress within the elastic limit. *Modulus of rigidity* or *shear modulus* denoted by *G* is the ratio of shear stress to shear strain, i.e.,

$$\tau = G\gamma$$

- The ratio between the volumetric (Identical) stress and the volumetric strain is called Bulk modulus of elasticity and is denoted by K.

Lateral strain

The strain at right angles to the direction of applied load is known as lateral strain. Let a rectangular bar of length L, breadth b and depth d is subjected to an axial tensile load P as shown in Fig. The length of the bar will increase while the breadth and depth will decrease.

Let

δL = Increase in length,

δb= Decrease in breadth, and

δd = Decrease in depth.

Note:

1) If longitudinal strain is tensile, the lateral strains will be compressive.
2) If longitudinal strain is compressive then lateral strains will be tensile.
3) Hence every longitudinal strain in the direction of load is accompanied by lateral strains of opposite kind in all directions perpendicular to the load.

$$\text{Lateral strain} = \frac{\delta b}{b} \text{ or } \frac{\delta d}{d}$$

Longitudinal strain

When a body is subjected to an axial tensile load, there is an increase in the length of the body. But at the same time there is a decrease in other dimensions of the body at right angles to the line of action of the applied load. Thus the body is having axial deformation and also deformation at right angles to the line of action of the applied load (i.e., lateral deformation).

The ratio of axial deformation to the original length of the body is known as longitudinal (or linear) strain. The longitudinal strain is also defined as the deformation of the body per unit length in the direction of the applied load.

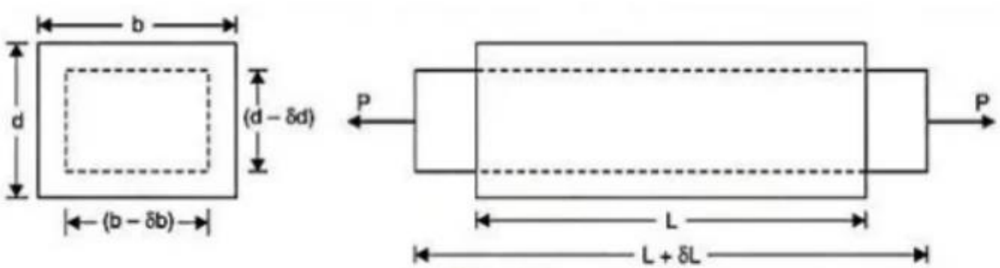
Let L = Length of the body,

P = Tensile force acting on the body,

δL = Increase in the length of the body in the direction of *P*.

Then,

$$\text{Longitudinal strain} = \frac{\delta L}{L}$$



POISON'S RATIO

The ratio of lateral strain to the longitudinal strain is a constant for a given material, when the material is stressed within the elastic limit. This ratio is called **Poisson's ratio** and it is generally denoted by μ or ν or 1/m. Hence mathematically:

$$\text{Poisson's ratio, } \mu = \frac{\text{Lateral strain}}{\text{Longitudinal strain}}$$

Modular ratio

Modular ratio is the **ratio** of Modulus of Elasticity of one material to Modulus of Elasticity of another material.

LINEAR ELASTICITY AND ELASTIC LIMIT

When an external force acts on a body, the body tends to undergo some deformation. If the external force is removed and the body comes back to its original shape and size (which means the deformation disappears completely), the body is known as *elastic body*. This property, by virtue of which certain materials return back to their original position after the removal of the external force, is called *elasticity*. The body will regain its previous shape and size only when the deformation caused by the external force, is within a certain limit. Thus there is a limiting value of force up to and within which, the deformation completely disappears on the removal of the force.

The value of stress corresponding to this limiting force is known as the *elastic limit* of the material. If the external force is so large that the stress exceeds the elastic limit, the material loses to some extent its property of elasticity. If now the force is removed, the material will not return to its original shape and size and there will be a residual deformation in the material.

STRESS – STRAIN RELATIONSHIPS

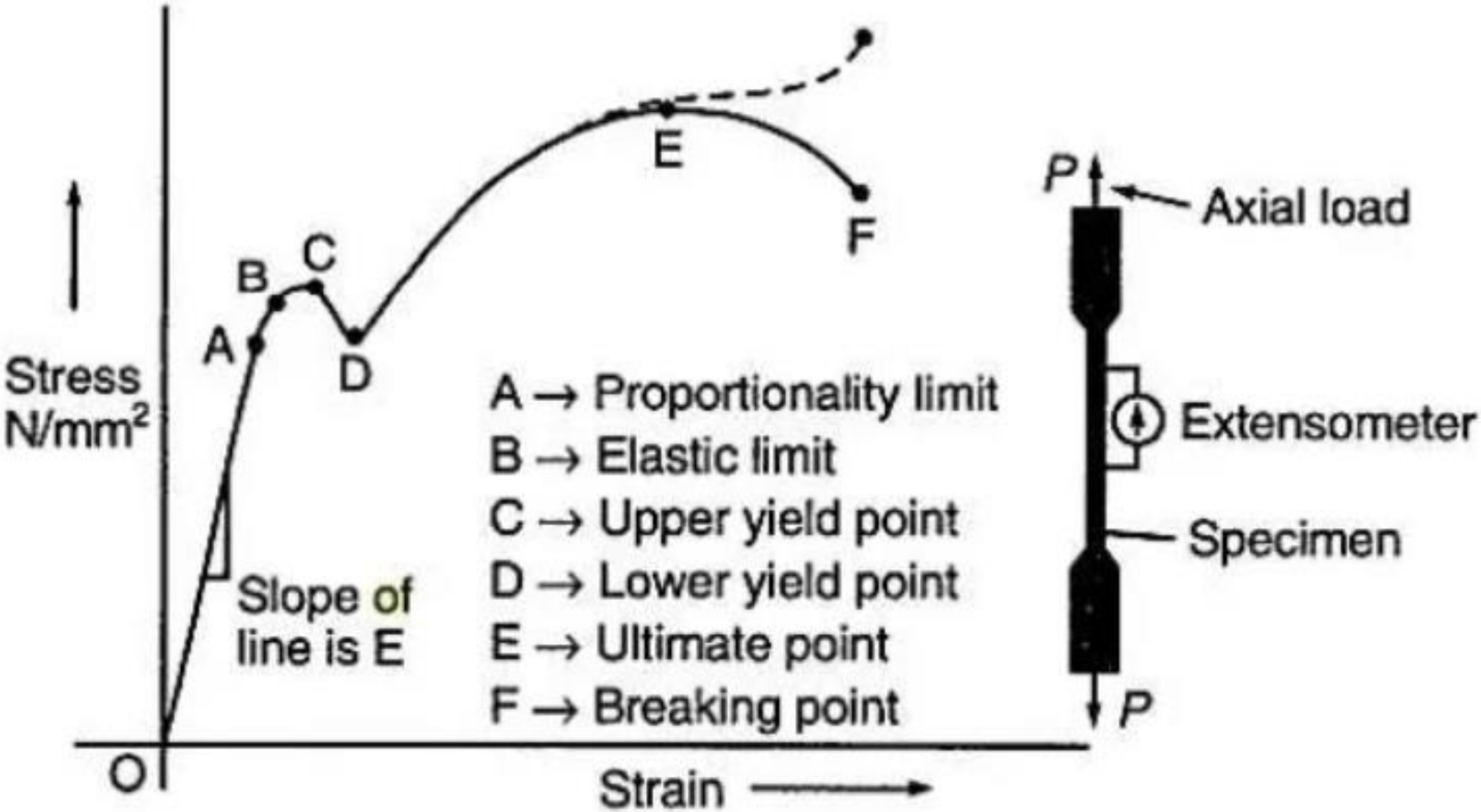
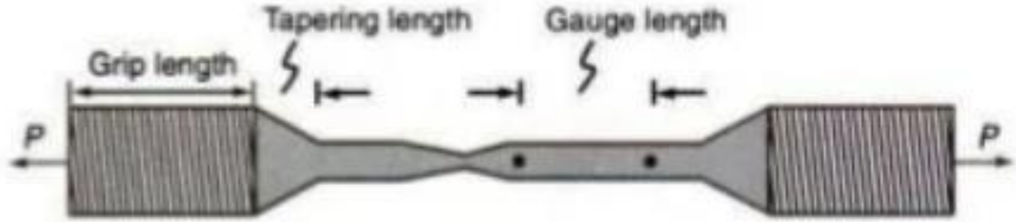
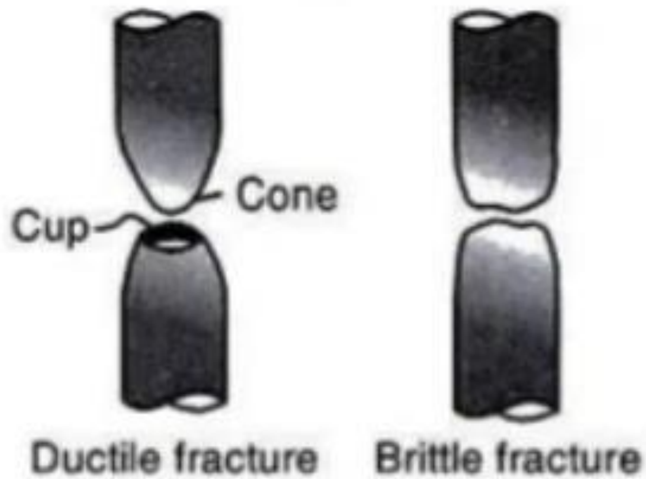


Figure: Stress-strain curve for structural steel



(b)



- Percentage increase in length is a measure of ductility of the metal. It is given by

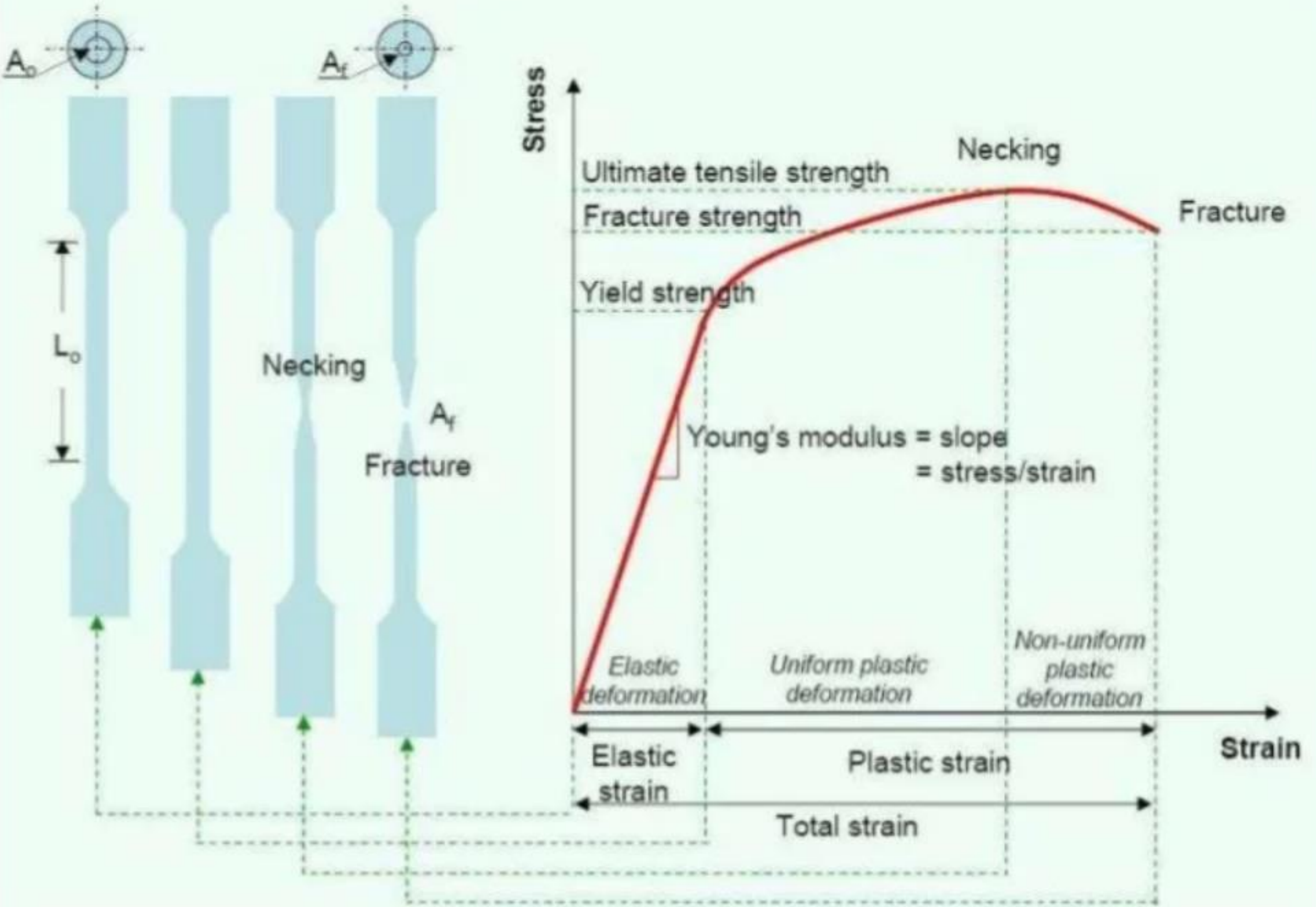
$$\text{percentage elongation} = \frac{l_f - l_o}{l_o}$$

where, l_f = length of test specimen at fracture, l_o = original length.

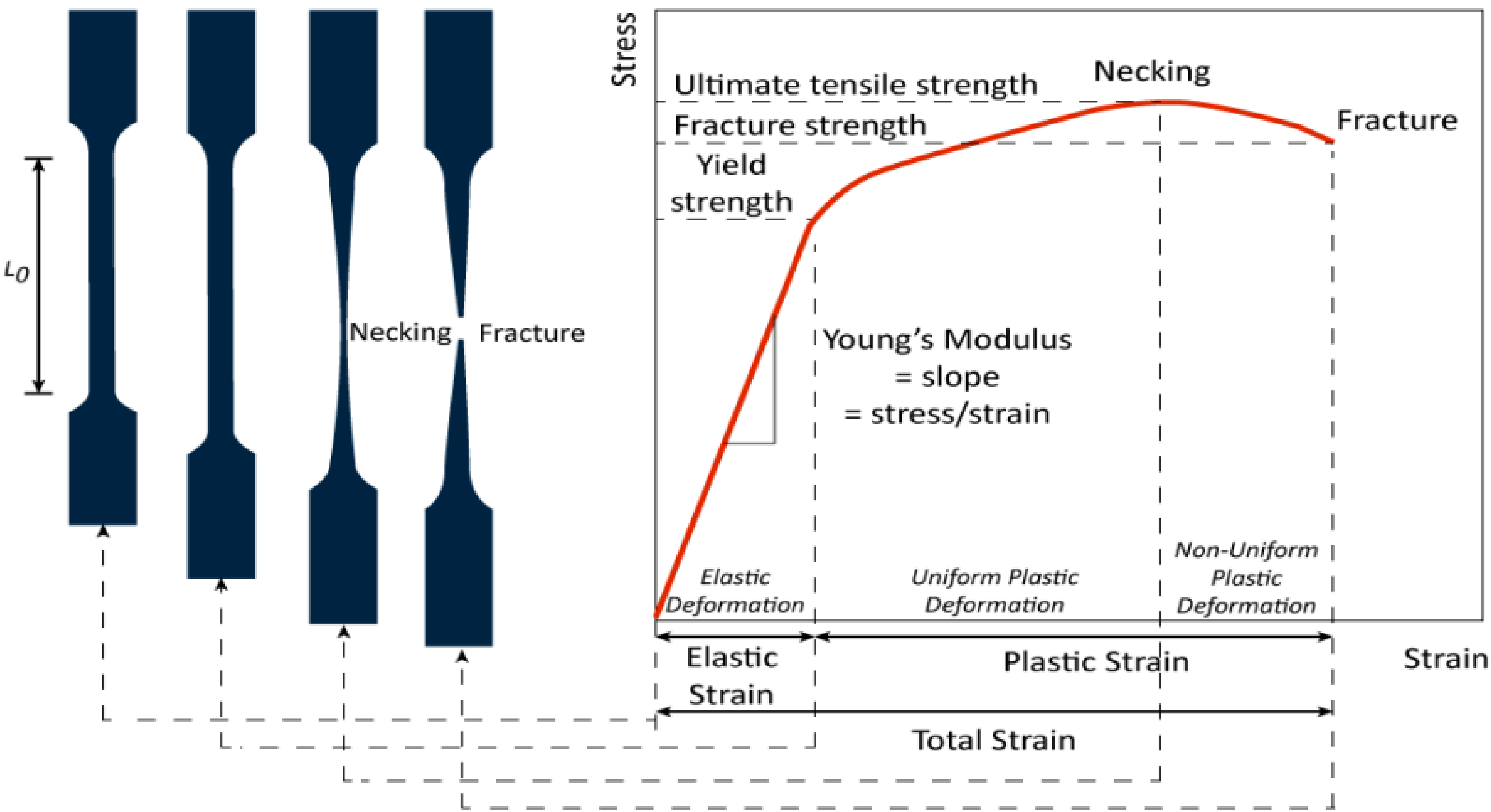
- Percentage reduction in cross sectional area: Ductility can also be measured by percentage decrease in cross sectional area as given by

$$\text{percentage reduction in area} = \frac{A_o - A_f}{A_o}$$

where, A_o is original area of cross section and A_f is area of cross section at fracture.



Shape of Ductile Specimen at Various Stages of Testing



Stress
Ultimate tensile strength
Necking
Fracture strength
Fracture
Yield
strength
L_0
Necking
Fracture
Young's Modulus
= slope
= stress/strain
Elastic
Deformation
Uniform Plastic
Deformation
Non-Uniform
Plastic
Deformation
Elastic
Strain
Plastic Strain
Strain
Total Strain

True Stress-Strain Diagram

In plotting stress-strain diagram, we make use of original area of cross section while computing all stress values and original length while calculating corresponding strains. In this context it is pertinent to define the following:

Nominal or Conventional or Engineering Stress

The ratio of load over original area of cross section of a component is nominal stress.

True Stress

The ratio of load over instantaneous area of cross section is true stress. Thus, under tensile load, instantaneous area is less than original area and under compressive load, instantaneous area is more than original area.

Nominal or Engineering Strain

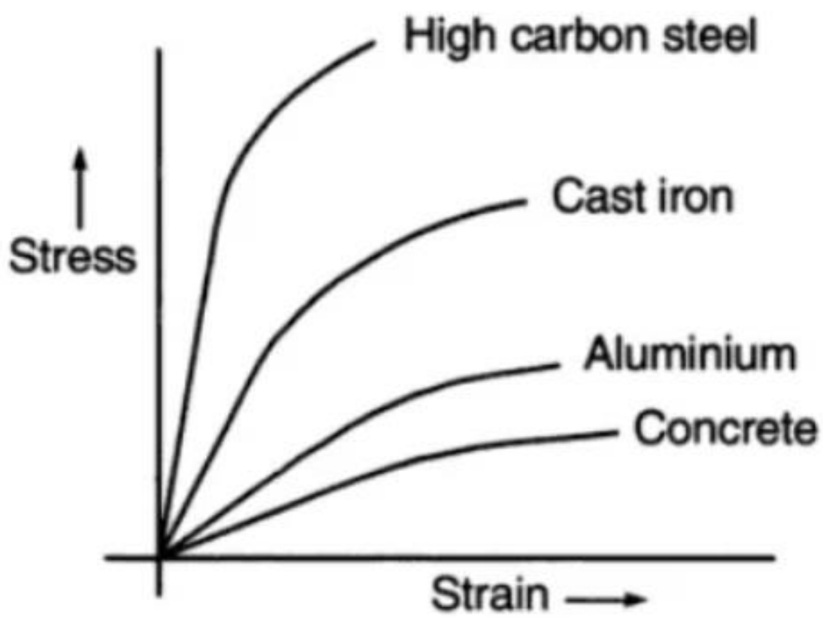
Strain values are calculated at various intervals of gradually increasing load considering original gauge length of the specimen, such a strain is nominal or engineering strain. Nominal strain is change in dimension to corresponding original dimension.

True Strain

As the load keeps on increasing, the gauge length will also keep on varying (e.g., gauge length increases under tensile loading). If actual length is used in calculating the strain, the strain

obtained is true strain.

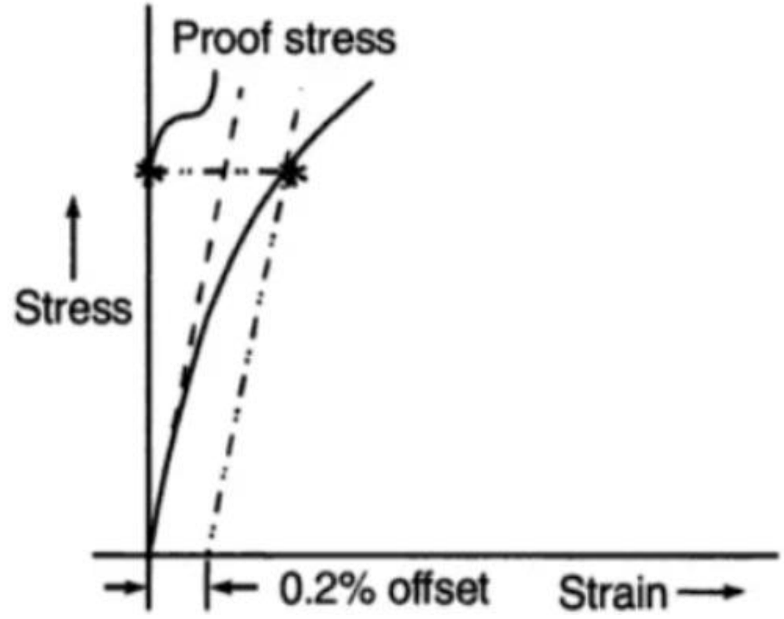
Stress-Strain Diagram for Other Materials



13 Stress-strain diagram for non-ferrous metals.

Proof Stress

Most of the metals except steel, do not show well-defined yield point and yet undergoes large strains after the proportional limit is exceeded. An arbitrary yield stress called proof stress for these metals can be found out by offset method. On the stress-strain diagram of the metal under consideration, a line is drawn parallel to initial linear part of the curve (Figure) this line is drawn at a standard offset of strain value, such as 0.002 (0.2%). The intersection of the offset line and the stress-strain curve (point A in the figure) defines the yield point for the metal and hence yield stress. Proof stress is not an inherent property of the metal. Proof stress is also called offset yield stress .



Factor of Safety

A very basic equation to calculate **FoS** is to divide the ultimate (or maximum) **stress** by the typical (or working) **stress**. A **FoS** of 1 means that a structure or component will fail exactly when it reaches the design load, and cannot support any additional load.

Factor of safety: It is defined as ratio of Maximum stress to the working stress

(permissible /design stress

Mathematically, $\text{Factor of safety} = \dfrac{\text{Maximum stress}}{\text{working stress / Designstress}}$

For Ductile Material, $\text{Factor of safety} = \dfrac{\textit{Yield stress}}{\textit{working stress / Designstress}}$

For Brittle material, $\text{Factor of safety} = \dfrac{\textit{Ultimate stress}}{\textit{working stress / Designstress}}$ ---------

In design analysis, number of parameters which are difficult to evaluate accurately such as

a) Variation in the properties of material like yield strength or ultimate strength.
b) Uncertainty in magnitude of externals forces acting on the components.
c) Variations in the dimensions of the components due to imperfect workmanship.

In order to ensure the safety against such circumstances, factor of safety is useful in design.

Margin of safety

- Many government agencies and industries (such as aerospace) require the use of a *margin of safety* (*MoS* or *M.S.*) to describe the ratio of the strength of the structure to the requirements.

$$\text{Margin of safety} = \frac{\text{failure load}}{\text{design load}} - 1$$

$$\text{Margin of safety} = \text{factor of safety} - 1$$

- M.S. as a measure of structural capability: This definition of margin of safety commonly seen in textbooks describes what additional load beyond the design load a part can withstand before failing.
- M.S. as a measure of requirement verification: Many agencies and organizations such as NASAand AIAA define the margin of safety including the design factor, in other words, the margin of safety is calculated after applying the design factor. In the case of a margin of 0, the part is at exactly the *required* strength (the safety factor would equal the design factor).

Behaviour and Manufacturing Properties of Engineering Materials
Structure of Material
Physical and Chemical Properties
Mechanical Properties
Property Modification
➢ Atomic Bond: Metallic, Ionic, Covalent
➢ Crystalline
➢ Amorphous or Non-Crystalline
➢ Partly Crystalline
➢ Polymer Chains
➢ Melting Point
➢ Density
➢ Specific Heat
➢ Thermal Conductivity
➢ Thermal Expansion
➢ Electrical Conductivity
➢ Magnetic Properties
➢ Oxidation
➢ Corrosion
➢ Strength
➢ Ductility
➢ Elasticity
➢ Stiffness
➢ Hardness
➢ Toughness
➢ Fatigue
➢ Creep
➢ Resistance to Wear, Corrosion, Oxidation
➢ Hot Hardness and Strength
➢ Heat Treatment
➢ Annealing
➢ Tempering
➢ Normalizing
➢ Hardening
➢ Alloying
➢ Reinforcements
➢ Composites
➢ Laminations
➢ Fillers
➢ Surface Treatment

- **Strength**

The property of a material which opposes the deformation or breakdown of material in presence of external forces or load. Materials which we finalize for our engineering products, must have suitable mechanical strength to be capable to work under different mechanical forces or loads.

- **Ductility**

Ductility is a property of a solid material which indicates that how easily a material gets deformed under tensile stress. Ductility is often categorized by the ability of material to get stretched into a wire by pulling or drawing. This mechanical property is also an aspect of plasticity of material and is temperature dependent. With rise in temperature, the ductility of material increases.

- **Brittleness**

Brittleness of a material indicates that how easily it gets fractured when it is subjected to a force or load. When a brittle material is subjected to a stress it observes very less energy and gets fractures without significant strain. Brittleness is converse to ductility of material. Brittleness of material is temperature dependent. Some metals which are ductile at normal temperature become brittle at low temperature.

- **Toughness**

It is the ability of a material to absorb the energy and gets plastically deformed without fracturing. Its numerical value is determined by the amount of energy per unit volume. Its unit is Joule/ m^3. Value of toughness of a material can be determined by stress-strain characteristics of a material. For good toughness, materials should have good strength as well as ductility.

For example: brittle materials, having good strength but limited ductility are not tough enough. Conversely, materials having good ductility but low strength are also not tough enough. Therefore, to be tough, a material should be capable to withstand both high stress and strain.

- **Resilience**

Resilience is the ability of material to absorb the energy when it is deformed elastically by applying stress and release the energy when stress is removed. Proof resilience is defined as the maximum energy that can be absorbed without permanent deformation. The modulus of resilience is defined as the maximum energy that can be absorbed per unit volume without permanent deformation. It can be determined by integrating the stress-strain cure from zero to elastic limit. Its unit is joule/m^3.

- **Hardness**

It is the ability of a material to resist to permanent shape change due to external stress. There are various measure of hardness – Scratch Hardness, Indentation Hardness and Rebound Hardness.

  - **Scratch Hardness**
    Scratch Hardness is the ability of materials to the oppose the scratches to outer surface layer due to external force.
  - **Indentation Hardness**
    It is the ability of materials to oppose the dent due to punch of external hard and sharp objects.
  - **Rebound Hardness**
    Rebound hardness is also called as dynamic hardness. It is determined by the height of "bounce" of a diamond tipped hammer dropped from a fixed height on the material.

- **Hardenability**

It is the ability of a material to attain the hardness by heat treatment processing. It is determined by the depth up to which the material becomes hard. The SI unit of hardenability is meter (similar to length). Hardenability of material is inversely proportional to the weld-ability of material.

- **Malleability**

Malleability is a property of solid materials which indicates that how easily a material gets deformed under compressive stress. Malleability is often categorized by the ability of material to be formed in the form of a thin sheet by hammering or rolling. This mechanical property is an aspect of plasticity of material. Malleability of material is temperature dependent. With rise in temperature, the malleability of material increases.

- **Creep and Slip**

Creep is the property of a material which indicates the tendency of material to move slowly and deform permanently under the influence of external mechanical stress. It results due to long time exposure to large external mechanical stress with in limit of yielding. Creep is more severe in material that are subjected to heat for long time. Slip in material is a plane with high density of atoms.

- **Fatigue**

Fatigue is the weakening of material caused by the repeated loading of the material. When a material is subjected to cyclic loading, and loading greater than certain threshold value but much below the strength of material (ultimate tensile strength limit or yield stress limit), microscopic cracks begin to form at grain boundaries and interfaces. Eventually the crack reaches to a critical size. This crack propagates suddenly and the structure gets fractured. The shape of structure affects the fatigue very much. Square holes and sharp corners lead to elevated stresses where the fatigue crack initiates.

Mechanical properties (In Short)

- Brittleness: Ability of a material to break or shatter without significant deformation when under stress; opposite of plasticity, examples: glass, concrete, cast iron, ceramics etc.
- Bulk modulus: Ratio of pressure to volumetric compression (GPa) or ratio of the infinitesimal pressure increase to the resulting relative decrease of the volume.
- Coefficient of restitution: the ratio of the final to initial relative velocity between two objects after they collide. Range : 0-1, 1 for perfectly elastic collision.
- Compressive strength: Maximum stress a material can withstand before compressive failure (MPa)
- Creep: The slow and gradual deformation of an object with respect to time
- Ductility: Ability of a material to deform under tensile load (% elongation)
- Durability: Ability to withstand wear, pressure, or damage; hard-wearing.
- Elasticity: Ability of a body to resist a distorting influence or stress and to return to its original size and shape when the stress is removed
- Fatigue limit: Maximum stress a material can withstand under repeated loading (MPa)
- Flexibility: Ability of an object to bend or deform in response to an applied force; pliability; complementary to stiffness
- Flexural modulus
- Flexural strength : The stresses in a material just before it yields.
- Fracture toughness: Ability of a material containing a crack to resist fracture (J/m^2)
- Friction coefficient: The amount of force normal to surface which converts to force resisting relative movement of contacting surfaces between material pair.

Mechanical properties (In Short)

- Hardness: Ability to withstand surface indentation and scratching (e.g. Brinell hardness number)
- Malleability: Ability of the material to be flattened into thin sheets under applications of heavy compressive forces without cracking by hot or cold working means.
- Mass diffusivity: Ability of one substance to diffuse through another
- Plasticity: Ability of a material to undergo irreversible or permanent deformations without breaking or rupturing; opposite of brittleness
- Poisson's ratio: Ratio of lateral strain to axial strain (no units)
- Resilience: Ability of a material to absorb energy when it is deformed elastically (MPa); combination of strength and elasticity
- Shear modulus: Ratio of shear stress to shear strain (MPa)
- Shear strength: Maximum shear stress a material can withstand
- Slip: A tendency of a material's particles to undergo plastic deformation due to a dislocation motion within the material. Common in Crystals.
- Specific modulus: Modulus per unit volume (MPa/m^3)
- Specific strength: Strength per unit density (Nm/kg)
- Specific weight: Weight per unit volume (N/m^3)
- Stiffness: Ability of an object to resist deformation in response to an applied force; rigidity; complementary to flexibility
- Surface roughness: the deviations in the direction of the normal vector of a real surface from its ideal form.
- Tensile strength: Maximum tensile stress of a material can withstand before failure (MPa)
- Toughness: Ability of a material to absorb energy (or withstand shock) and plastically deform without fracturing (or rupturing); a material's resistance to fracture when stressed; combination of strength and plasticity
- Viscosity: A fluid's resistance to gradual deformation by tensile or shear stress; thickness
- Yield strength: The stress at which a material starts to yield plastically (MPa)
- Young's modulus: Ratio of linear stress to linear strain (MPa)

Strain Energy And Resilience

Strain energy is elastic — that is, the material tends to recover when the load is removed. ... **Resilience** is typically expressed as the modulus of **resilience**, which is the amount of **strain energy** the material can store per unit of volume without causing permanent **deformation**.

Strain energy stored **in a** specimen when strained within elastic limit is known as **Resilience**. The maximum energy stored at elastic limit is known as **Proof Resilience**. The **proof resilience** per unit volume or strain energy per unit volume is known as **Modulus of Resilience**.

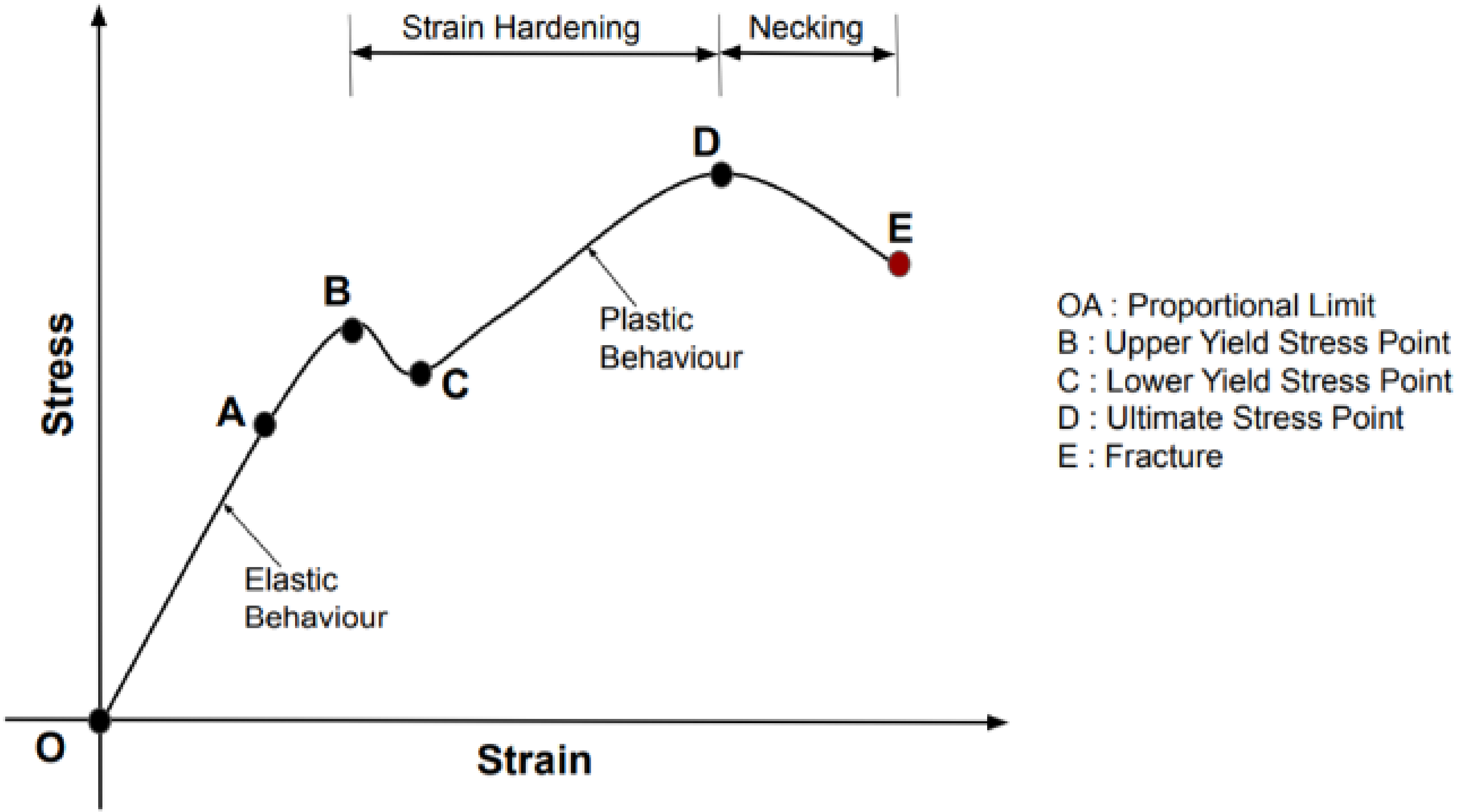
How Stress-Strain Graph is Plotted?

We need to perform material tensile testing on the standard specimen to plot the Engineering and *True Stress-Strain Curves* using *Universal Testing Machine*.

As shown in the above image, UTM consists of two claws. These claws hold and pull the extreme ends of the test specimen at a uniform rate.

During tensile testing, You need to record any change in the length of the test specimen for applied load at various time stamps until the test sample fractures. These values determine variation in stress acting on the test sample for strain value.

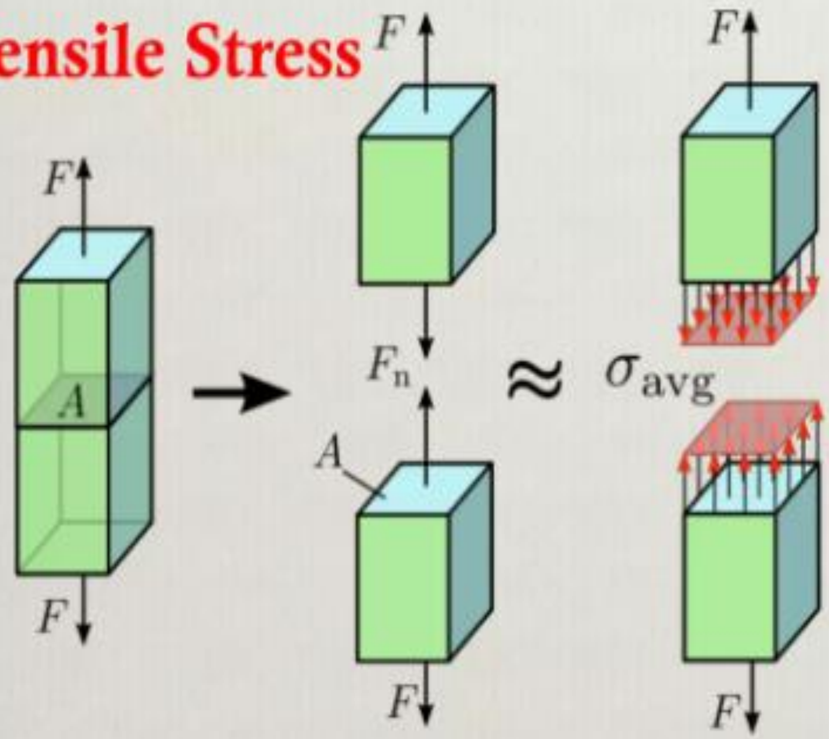
Afterward, We can plot the stress-strain graph keeping mechanical stress values on the vertical axis and strain on the horizontal axis.


Strain Hardening
Necking
D
E
B
C
A
Plastic
Behaviour
Elastic
Behaviour
Stress
Strain
O
OA : Proportional Limit
B : Upper Yield Stress Point
C : Lower Yield Stress Point
D : Ultimate Stress Point
E : Fracture

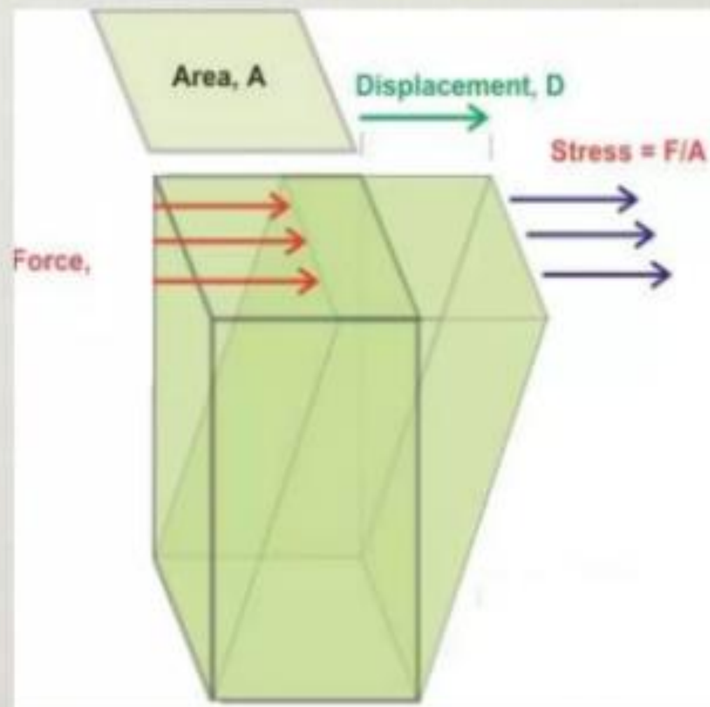
Stresses and strains

- In last lecture we looked at stresses were acting in a plane that was at right angles/parallel to the action of force.

Tensile Stress



Shear Stress



Stresses and strains

Compressive load

Failure in shear

Stresses are acting normal to the surface yet the material failed in a different plane

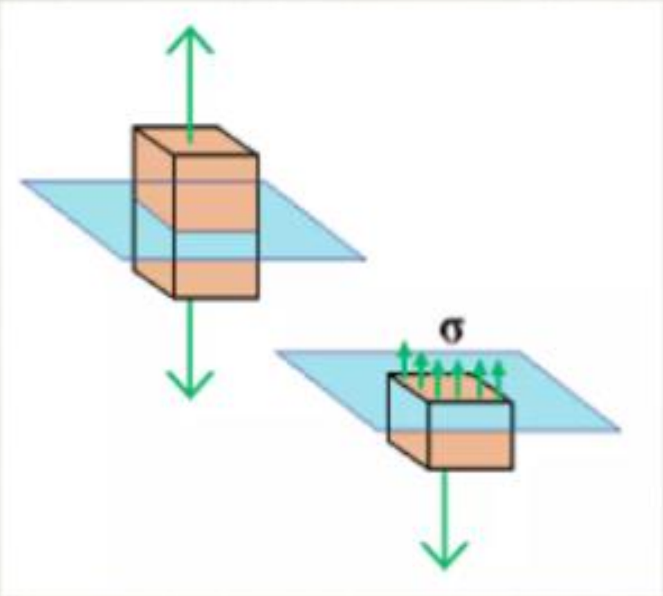
Principal stresses and strains

- What are principal stresses.
  - Planes that have no shear stress are called as principal planes.
  - Principal planes carry only normal stresses

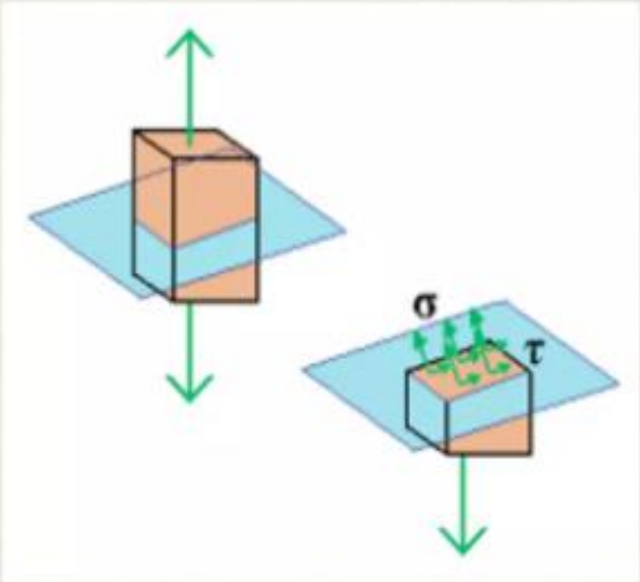
Stresses in oblique plane

- In real life stresses does not act in normal direction but rather in inclined planes.

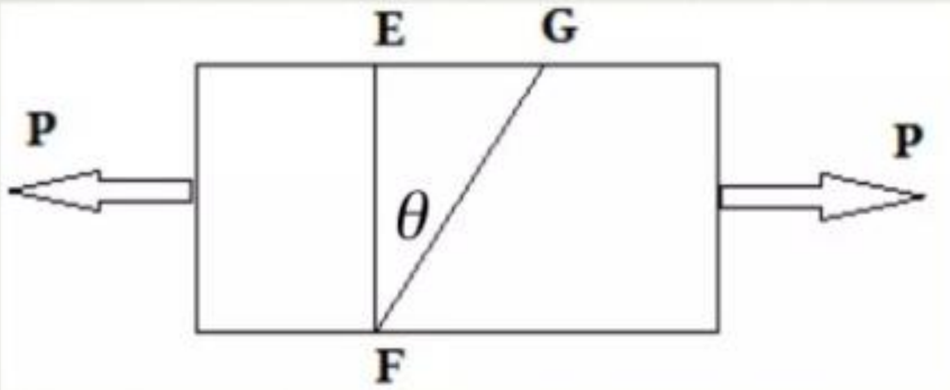
Normal Plane



Oblique Plane

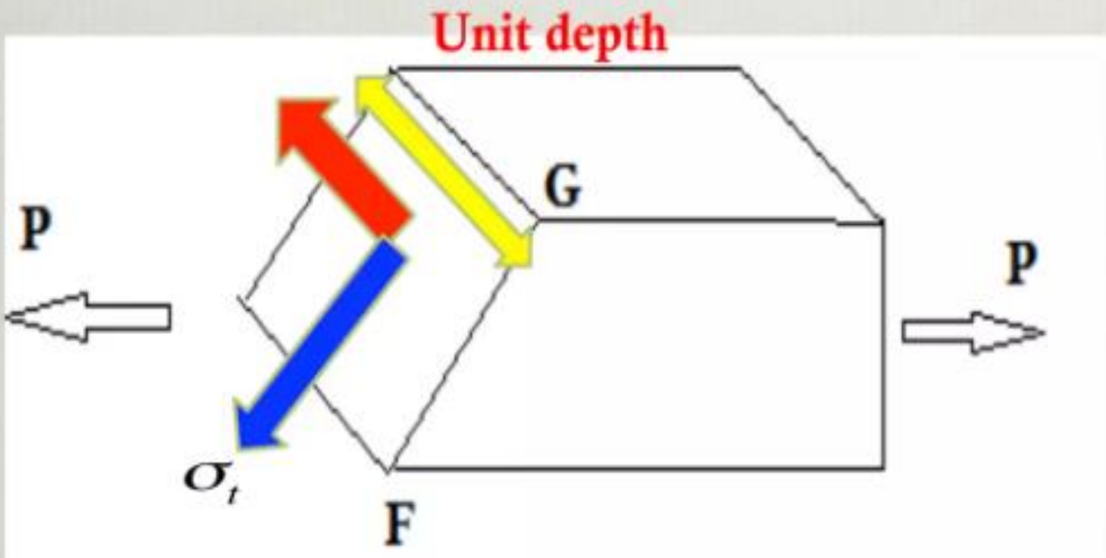


Stresses in oblique plane



$$\sigma = \frac{P}{A}$$

P =Axial Force
A=Cross-sectional area perpendicular to force



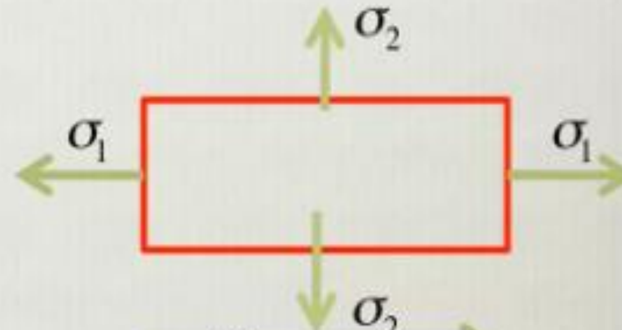
$$\sigma_n = \sigma \cos^2 \theta$$

$$\sigma_t = \frac{\sigma}{2} \sin 2\theta$$

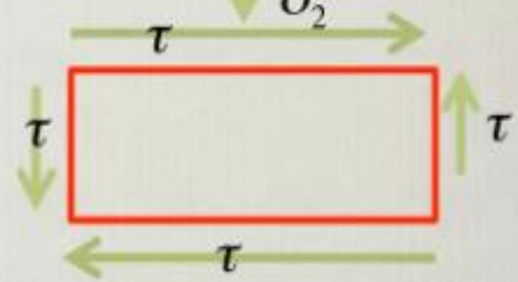
Stresses in oblique plane

- Member subjected to direct stress in one plane

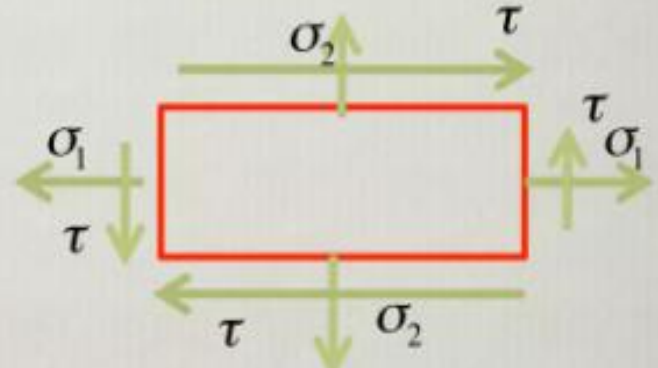
- Member subjected to direct stress in two mutually perpendicular plane



- Member subjected to simple shear stress.



- **Member subjected to direct stress in two mutually perpendicular directions + simple shear stress**



Stresses in oblique plane

- **Member subjected to direct stress in two mutually perpendicular directions + simple shear stress**

$$\sigma_n = \frac{\sigma_1 + \sigma_2}{2} + \frac{\sigma_1 - \sigma_2}{2}\cos 2\theta + \tau \sin 2\theta$$

$$\sigma_t = \frac{\sigma_1 - \sigma_2}{2}\sin 2\theta - \tau \cos 2\theta$$

Stresses in oblique plane

- **Member subjected to direct stress in two mutually perpendicular directions + simple shear stress**
  - **POSITION OF PRINCIPAL PLANES**
    - **Shear stress should be zero**

$$\sigma_t = \frac{\sigma_1 - \sigma_2}{2}\sin 2\theta - \tau\cos 2\theta = 0$$

$$\tan 2\theta = \frac{2\tau}{\sigma_1 - \sigma_2}$$

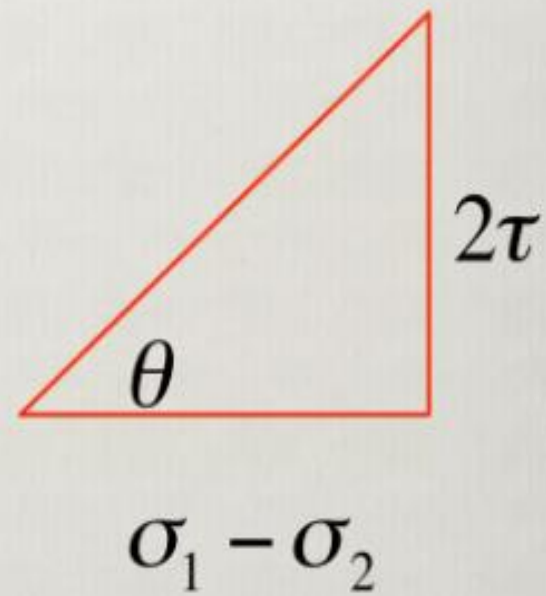
Stresses in oblique plane

- **Member subjected to direct stress in two mutually perpendicular directions + simple shear stress**
  - **POSITION OF PRINCIPAL PLANES**

$$\tan 2\theta = \frac{2\tau}{\sigma_1 - \sigma_2}$$

$$\sin 2\theta = \frac{2\tau}{\sqrt{(\sigma_1 - \sigma_2)^2 + 4\tau^2}}$$

$$\cos 2\theta = \frac{(\sigma_1 - \sigma_2)}{\sqrt{(\sigma_1 - \sigma_2)^2 + 4\tau^2}}$$



Stresses in oblique plane

- **Member subjected to direct stress in two mutually perpendicular directions + simple shear stress**

Major principal Stress $= \dfrac{\sigma_1 + \sigma_2}{2} + \sqrt{\left(\dfrac{\sigma_1 - \sigma_2}{2}\right)^2 + \tau^2}$

Minor principal Stress $= \dfrac{\sigma_1 + \sigma_2}{2} - \sqrt{\left(\dfrac{\sigma_1 - \sigma_2}{2}\right)^2 + \tau^2}$

Stresses in oblique plane

- **Member subjected to direct stress in two mutually perpendicular directions + simple shear stress**
  - **MAX SHEAR STRESS**

$$\frac{d}{d\theta}\left(\sigma_t\right) = 0$$

$$\frac{d}{d\theta}\left[\frac{\sigma_1 - \sigma_2}{2}\sin 2\theta - \tau\cos 2\theta\right] = 0 \Longrightarrow \tan 2\theta = \frac{\sigma_1 - \sigma_2}{2\tau}$$

Stresses in oblique plane

- **Member subjected to direct stress in two mutually perpendicular directions + simple shear stress**
  - **MAX SHEAR STRESS**

Evaluate the following equation at

$$\sigma_t = \frac{\sigma_1 - \sigma_2}{2}\sin 2\theta - \tau\cos 2\theta$$

$$\tan 2\theta = \frac{\sigma_1 - \sigma_2}{2\tau}$$

$$\boxed{\left(\sigma_t\right)_{\max} = \frac{1}{2}\sqrt{\left(\sigma_1 - \sigma_2\right)^2 + 4\tau^2}}$$

Stresses in oblique plane

- Member subjected to direct stress in one plane
- Member subjected to direct stress in two mutually perpendicular plane
- Member subjected to simple shear stress.
- **Member subjected to direct stress in two mutually perpendicular directions + simple shear stress**

Stresses in oblique plane

- Member subjected to direct stress in one plane

$$\sigma_n = \frac{\sigma_1 + \sigma_2}{2} + \frac{\sigma_1 - \sigma_2}{2}\cos 2\theta + \tau \sin 2\theta$$

$$\sigma_t = \frac{\sigma_1 - \sigma_2}{2}\sin 2\theta - \tau \cos 2\theta$$

Stress in one direction and no shear stress $\sigma_2 = 0 \quad \tau = 0$

$$\sigma_n = \frac{\sigma_1}{2} + \frac{\sigma_1}{2}\cos 2\theta = \sigma_1 \cos^2\theta$$

$$\sigma_t = \frac{\sigma_1}{2}\sin 2\theta$$

Stresses in oblique plane

- Member subjected to direct stress in two mutually perpendicular plane

$$\sigma_n = \frac{\sigma_1 + \sigma_2}{2} + \frac{\sigma_1 - \sigma_2}{2}\cos 2\theta + \tau \sin 2\theta$$

$$\sigma_t = \frac{\sigma_1 - \sigma_2}{2}\sin 2\theta - \tau \cos 2\theta$$

Stress in two direction and no shear stress $\tau = 0$

$$\sigma_n = \frac{\sigma_1 + \sigma_2}{2} + \frac{\sigma_1 - \sigma_2}{2}\cos 2\theta$$

$$\sigma_t = \frac{\sigma_1 - \sigma_2}{2}\sin 2\theta$$

Stresses in oblique plane

- Member subjected to simple shear stress.

$$\sigma_n = \frac{\sigma_1 + \sigma_2}{2} + \frac{\sigma_1 - \sigma_2}{2}\cos 2\theta + \tau \sin 2\theta$$

$$\sigma_t = \frac{\sigma_1 - \sigma_2}{2}\sin 2\theta - \tau \cos 2\theta$$

No stress in axial direction but only shear stress $\sigma_1 = \sigma_2 = 0$

$$\sigma_n = \tau \sin 2\theta$$

$$\sigma_t = -\tau \cos 2\theta$$