Transition of mechanical behaviour from elastic to plastic depends upon the material type and its condition as tested (hot-rolled, cold-rolled, heat treated, etc.). This section presents material properties in plastic region.

“Tensile strength”, also known as “ultimate strength”, is the capacity of a material to resist tensile loads without fracture (kg/mm\(^2\), Pa, psi, or bar).

\[ 1 \text{ kg/mm}^2 = 9.81 \times 10^{-3} \text{ Pa} = (9.81 \times 0.145) \times 10^{-6} \text{ psi} = 9.81 \times 10^{-8} \text{ bar} \]

Though tensile strength is the most commonly employed design parameter, “compressive strength” of a material may not necessarily be equal to its tensile strength. Fig. 12 shows tensile versus compressive strengths of glass and gray cast iron. However, making a design based on the tensile strength is not incorrect since most materials are weaker in tension.
In Fig. 13, for aluminum oxide and natural rubber, stresses corresponding to the maximum tensile load and the rupture of specimens are coincident. However, for low carbon steel, the stress for maximum tensile load is not destructive and its value considerably differs than the stress for rupture.

The results of a failure due to plastic deformation would not be as severe as in the case of fracture. Hence, even though designer chooses the working stresses within the elastic limit, tensile strength is a reference point to define a suitable factor of safety against overloading.

![Figure 13](image-url)
Fig. 14 shows tensile strength of various material groups and their relative cost per unit weight.

- **Steels** are good for high strength applications. Different types of steels are available according to application and cost demands.

- **Cast irons** are noted for high compressive strength although malleable and nodular CI also have good strengths in tension.

- **Nonferrous metals** offer narrow choice when high strength is the primary design parameter. The exceptions are alloys of titanium, nickel and leaded beryllium copper, which can be precipitation hardened to increase strength and high-temperature resistance.
Due to their high melting points, **refractory metals** are good for high-strength & high-temperature applications. However, oxidation problem forces their uses with protective coatings.

**Ceramics** are significant for their high-temperature properties, and preferred in specific applications even though they are costly and present some design problems.

**Polymers** are far from being strong materials. On the other hand, **composite materials** (offering choices with reinforcements) have improved the tensile properties of polymers as they can compete with carbon steels.
“Compressive strength” is an important property when the element is subjected primarily to compression. In principle, it is opposite of tensile strength. The material first goes through the elastic strain range, and then deforms plastically.

For ductile materials, specimen bulges as the load increases in plastic range (Fig. 15a), and hence it is not possible to define ultimate and/or fracture strength. In fact, compressive strength is the stress value at which specimen has distorted to a degree regarded as effective failure.

Unlike ductile materials, a definite strength value can be obtained for brittle materials. Large lateral deformations are not produced, but failure occurs by shear and sliding along an inclined plane (Fig. 15b).
Plastic Behaviour - Compressive Strength

- Obtaining stress-strain curves in compression is more difficult due to:
  - *irregularites of alignment* introducing bending stresses additionally.
  - *lateral straining* caused by friction between specimen and platens.
  - *possibility of a failure by buckling* if the specimen is too long.

- Modulus of elasticity (*E*) and yield strength (*S_y*) for **many metals and alloys** are approximately equal in tension and compression.

- For **polymers**, *always properties in tension* are specified.

- **Brittle materials** have big difference in tensile and compressive strengths.

- **Gray iron** has a compressive strength of 63-130 kg/mm², which is 3-5 times greater than its tensile strength.

- **Ceramics** and **refractory hard metals (cermets)** are also characterized by their high compressive strength.
“Bauschinger effect” refers to change in the material's $\sigma$-$\varepsilon$ characteristics as a result of microscopic stress distribution of material.

It is normally associated with conditions where yield strength of a material decreases when direction of strain is changed. For instance, an increase in tensile yield strength occurs at the expense of compressive yield strength.
“Hyperelastic resilience” is the energy released when the plastic loading upon material is removed. When the load is released, the unloading curve follows a path that is almost parallel to the elastic portion of $\sigma$-$\varepsilon$ diagram (Fig. 16). The energy within triangle ABC or CDE is hyperelastic resilience.

It is an important property in metal forming operations with “springback” from initial deformation. Take a bar to be bent into U-shape. Suppose that the permanent strain for required curvature is point C. Material must be strained to point D to achieve such required permanent strain. If material is not ductile enough, point D will be beyond ultimate limit strain. This will cause necking, and it is impossible to have desired shape.
“Ductility” and “brittleness” are the terms for describing that how much a material could be deformed plastically. A ductile material (like steels) undergoes plastic deformation before fracture. In contrast, a brittle material (e.g. certain types of brass, cast iron and glass) does not deform plastically or exhibits negligible amount of plastic deformation prior to fracture.

Ductility is measured by sometimes percentage elongation ($\delta_L$) and sometimes percentage reduction in area ($\delta_A$):

$$\delta_L = \left( \frac{L_f - L_0}{L_0} \right) \times 100$$

$$\delta_A = \left( \frac{A_0 - A_f}{A_0} \right) \times 100$$

$L_0$: original gauge length
$L_f$: gauge length after fracture
$A_0$: original cross sectional area
$A_f$: area of fractured cross section

The method of percentage elongation ($\delta_L$) is commonly used due to ease of measurement compared with reduction in area method.
If ductile material is strained beyond its ultimate strength, the deformation is no longer uniform over the gauge length, but concentrated in a region of weakness, called “necking” as shown in Fig. 17.

Necking is an indication of ductility, resulting in **cup & cone type of fracture** (Fig. 18). On the other hand, brittle materials do not have necking before fracture (Fig. 19).

Percentage elongation method may not give reliable results in necking region, and **reduction in area method** shall be employed in such cases.
Plastic Behaviour - Ductility and Brittleness

- A fully brittle material can be used if there is no danger of overloading and all stress concentration could be eliminated. Conversely, if retaining of shape is unimportant, then localized plastic flow could be tolerated.

- In metal forming operations, extent of forming depends upon ductility and strain hardening properties. “Strain hardening” refers to the resistance of a metal to further plastic deformation. The tendency of a metal to strain harden is indicated by tangent moduli of plastic curve (i.e. smaller slope refers to less tendency).

- The term “malleability” is used to describe such tendency. Malleable material could undergo severe plastic deformation without excessive strain hardening. Malleability is a desirable property in metal working processes, but is of limited interest to designer unless combined with some other useful property (such as strength).
“**Toughness**” is the ability of a material to absorb energy in plastic range. It is the area under plastic curve including fracture point, indicating amount of work per unit volume which can be done without causing rupture.

**Fig. 20** shows $\sigma$-$\varepsilon$ curve of a high-toughness steel. It is difficult to measure the area under plastic curve, thus “**Toughness Index Number** (\(T_0\))” is employed to compare toughness of different materials. It is approximately the area of rectangle 1-2-3-4: \(T_0 = S_{ut} \varepsilon_f\)

Above equation actually states that toughness comprises both strength and ductility. Thereby, it is a desirable property in parts subjected to shock or impact (axles, gears, automobile frames, etc.)
A tensile test was done on a steel specimen with cross-sectional area of 20 mm$^2$ and a gauge length of 100 mm. Following results were recorded:

<table>
<thead>
<tr>
<th>Load at yield point: 500 kg</th>
<th>Gauge length at yield point: 100.1225 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum load: 800 kg</td>
<td>Gauge length at fracture: 133.2 mm</td>
</tr>
<tr>
<td>Fracture load: 570 kg</td>
<td>Diameter of fractured cross-section: 3.8 mm</td>
</tr>
</tbody>
</table>

1. The yield stress: \[ S_y = \frac{F_y}{A} = \frac{500}{20} = 25 \text{ kg/mm}^2 \]

2. Modulus of elasticity: \[ E = \frac{S_y}{\varepsilon_y} = \frac{S_y}{(\delta/L)} = \frac{25}{(0.1225/100)} = 2.04 \times 10^4 \text{ kg/mm}^2 \]

3. Modulus of resilience: \[ U = \frac{S_y^2}{2E} = \frac{25^2}{2 \times 2.04 \times 10^4} = 15.32 \times 10^{-3} \text{ kg} \cdot \text{mm/mm}^3 \]

4. Total energy absorbed: \[ W = U \times A \times L = 15.32 \times 10^{-3} \times 20 \times 100 = 30.64 \text{ kg} \cdot \text{mm} \]
A tensile test was done on a steel specimen with cross-sectional area of 20 mm$^2$ and a gauge length of 100 mm. Following results were recorded:

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5. The tensile strength: $S_{ut} = \frac{F_{\text{max}}}{A} = \frac{800}{20} = 40$ kg/mm$^2$

6. The fracture strength: $S_f = \frac{F_{\text{fracture}}}{A} = \frac{570}{20} = 28.5$ kg/mm$^2$

7. Percentage elongation: $\delta_L = \frac{L_f - L_0}{L_0} * 100 = \frac{133.2 - 100}{100} * 100 = 33.2\%$

8. Percentage reduction in area: $\delta_A = \frac{A_0 - A_f}{A_0} * 100 = \frac{20 - \pi * (3.8/2)^2}{20} * 100 = 43.3\%$

9. Toughness index number: $T_0 = S_t * \varepsilon_f = S_t * \delta_L = 40 * 0.332 = 13.28$ kg · mm/mm$^3$