CHAPTER 3 MECHANICAL PROPERTIES OF MATERIAL

1. THE TENSION AND COMPRESSION TESTS

The strength of a material depends on its ability to sustain a load without undue deformation or failure. The strength of a material is inherent to the material itself and needs to be determined experimentally. One of these experimental tests is a **tension test**.

The tension (or compression) test is used to determine the relation between the average normal stress and the average normal strain. This test is applied to engineering materials such as metals, ceramics, polymers and composites.

When preparing a tension or compression test of a certain material, a specimen of the material of standard shape and size is prepared.

• Before the test, two punch marks are placed along the specimen's uniform length.

• The initial cross section area, A_o, and ***gauge–length*** distance, L_o, between marks are measured.

• The specimen is mounted on a machine that applies the load.

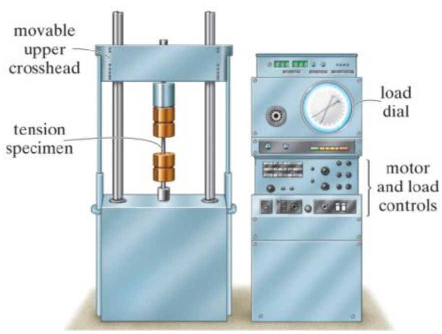
• Frequent measurements of the applied load and the elongation $\delta = L - Lo$ of the specimen are recorded.

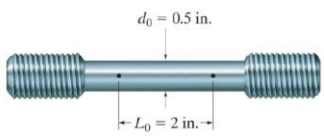
• A plot of P vs. δ is meaningless since specimens with different cross section areas or different gauge lengths will behave differently. Instead, in order to eliminate the dependence on the cross section the normal stress ($\sigma = P/A_o$) is plotted on the ordinates axis instead of force P.

• And to eliminate the dependence on length, normal strain ($\varepsilon = \delta /L_o$) is plotted instead of the change in length on the axis of the abscissae.

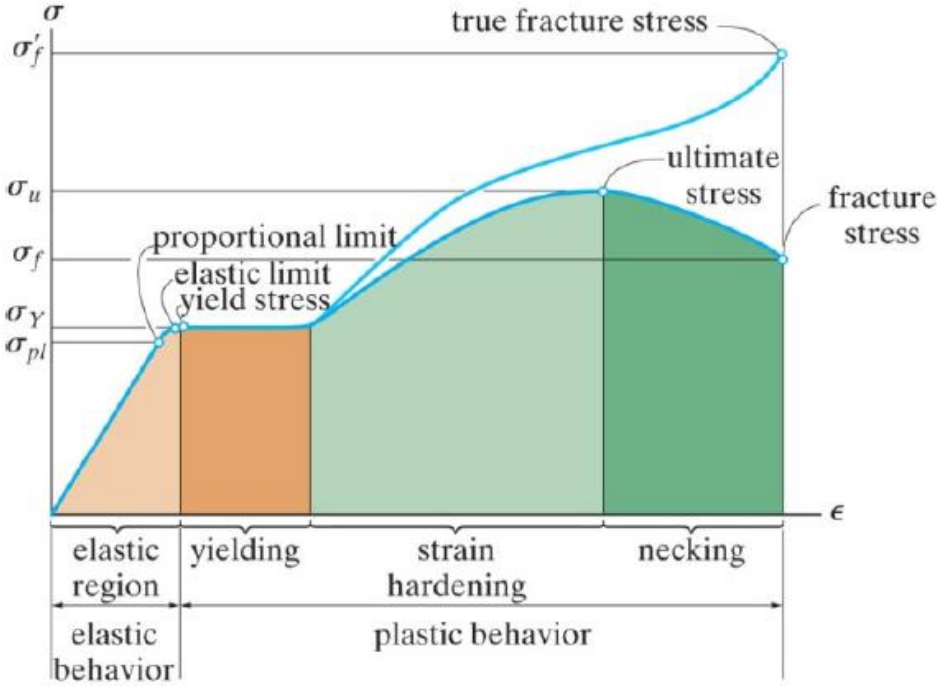
• Thus, a plot of ε vs. σ will then be substantially the same for multiple test specimens of the same material but different sizes and lengths.

• The resulting curve is called ***conventional stress–strain diagram.*** From the conventional stress–strain diagram four different ways in which a material behaves depending on the amount of strain induced in the material.





2. THE STRESS-STRAIN DIAGRAM



Conventional and true stress-strain diagrams for ductile material (steel) (not to scale)

Elastic Behavior. In general, there is an initial region which is linear. This is called the elastic or proportional region. In this region, stress and strain are related to one another by the slope of the curve which is called the **modulus of elasticity** or ***E***.

• Thus, this region is governed by the relation $\sigma = E\,\varepsilon$, which is known as **Hooke's Law**.

• At the top of the proportional region is the proportional limit σ_{pl}.

• Most materials exhibit the elastic region.

• When a material is loaded with a stress within the elastic region and then unloaded, the material will return to the original size and shape, i.e., there is no permanent deformation.

The elastic region is generally slightly larger than the proportional region, but for practical purposes can be considered to be the same. The top of the elastic region, called the elastic limit, is then basically the same as the proportional limit.

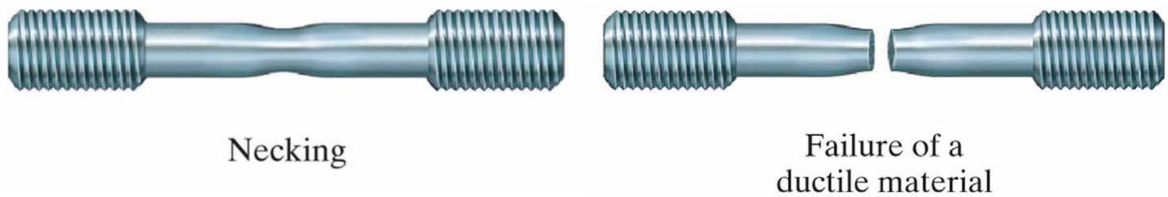
Yielding. A slight increase in stress beyond the elastic limit will result in a breakdown of the material causing *permanent deformation*. This behavior is called **yielding**. Once yielding is reached large increases in strain occur with no further increase in stress. Yielding point is generally very near the elastic limit and proportional limit.

• Mild steel exhibits a well-defined yield point, σ_y but not all materials do.

• For practical purposes, the yield point, elastic limit and proportional limit can be taken to be the same.

Strain Hardening. Once yielding has ended an increase in load can be supported by the specimen resulting in a curve that rises continuously. This curve becomes flatter as it reaches a maximum stress known as ***ultimate stress,*** σ_u. The rise in the curve is called ***strain hardening.***

Necking. Up to the ultimate stress, as the specimen elongates its cross section area decreases uniformly. However after the ultimate stress is reached the cross section area starts decreasing at a *localized* region. This reduction of the cross section area at a localized region results ultimately on the fracture of the specimen at the fracture stress, σ_f.



True Stress–Strain Diagram. Instead of always using the *original* cross-sectional area A_0 and specimen length L_0 to calculate the (engineering) stress and strain, we could have used the *actual* cross-sectional area *A* and specimen length *L* at the *instant* the load is measured. The values of stress and strain found from these measurements are called ***true stress*** and ***true strain***, and a plot of their values is called the ***true stress–strain diagram***. When this diagram is plotted, it has a form shown by the upper blue curve in Figure above. Note that the conventional and true σ-ε diagrams are practically coincident when the strain is small. The differences begin to appear in the strain-hardening range, where the magnitude of strain becomes more significant. From the conventional σ-ε diagram, the specimen appears to support a *decreasing* stress (or load), since A_0 is constant when calculating engineering stress, $\sigma = P/A0$. In fact, the true σ-ε diagram shows the area *A* within the necking region is always *decreasing* until fracture, σ'_f, and so the material *actually* sustains *increasing stress,* since

$\boldsymbol{\sigma = P/A}$.

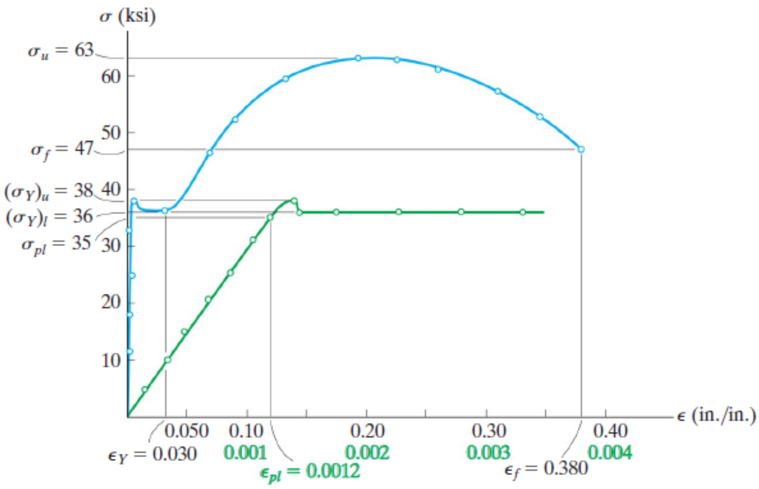
Although there is this divergence between these two diagrams, we can neglect this effect since most engineering design is done only within the elastic range. This will generally restrict the deformation of the material to very small values, and when the load is removed the material will restore itself to its original shape. The conventional stress–strain diagram can be used in the elastic region because the true strain up to the elastic limit is small enough, so that the error in using the engineering values of σ and ε is very small (about 0.1%) compared with their true values.

Steel. A typical conventional stress–strain diagram for a mild steel specimen is shown in Figure below. In order to enhance the details, the elastic region of the curve has been shown in green using an exaggerated strain scale, also shown in green. Following this curve, as the load (stress) is increased, the proportional limit is reached at σ_{pl} = 35 ksi (241 MPa), where ε_{pl} = 0.0012 in.>in. When the load is further increased, the stress reaches an upper yield point of $(\sigma_Y)_u$ = 38 ksi (262 MPa), followed by a drop in stress to a lower yield point of $(\sigma_Y)_l$ = 36 ksi (248 MPa). The end of yielding occurs at a strain of ε_Y = 0.030 in.>in., which is 25 times greater than the strain at the proportional limit! Continuing, the specimen undergoes strain hardening until it reaches the ultimate stress of σ_u = 63 ksi (434 MPa); then it begins to neck down until fracture occurs, at σ_f = 47 ksi (324 MPa). By comparison, the strain at failure, ε_f = 0.380 in.>in., is 317 times greater than ε_{pl}!

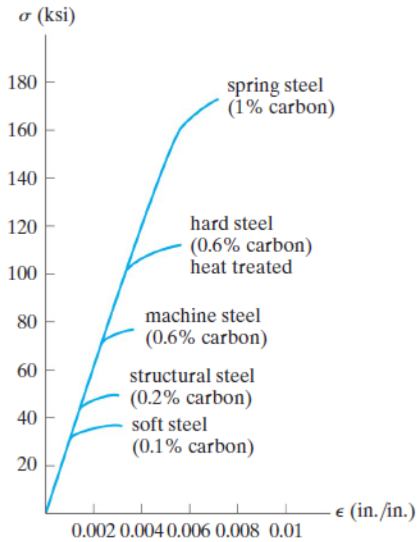
Since σ_{pl} = 35 ksi and ε_{pl} = 0.0012 in.>in., we can determine the modulus of elasticity. From Hooke's law, it is

$E = \sigma_{pl} / \varepsilon_{pl}$ = 35 ksi /0.0012 in.>in. = 29 (10^3) ksi

Although steel alloys have different carbon contents, most grades of steel, from the softest rolled steel to the hardest tool steel, have about this same modulus of elasticity, as shown in Figure.



Stress–strain diagram for mild steel



3. STRESS-STRAIN BEHAVIOR OF DUCTILE AND BRITTLE MATERIALS

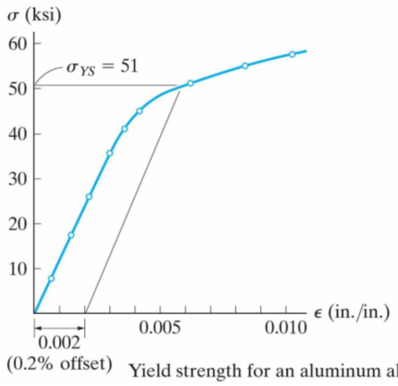
Depending on their stress–strain characteristics a material can be **Ductile** or **Brittle**.

Ductile Materials can be subjected to large strains before a fracture occurs.

• The ***ductility*** of a material can be defined in terms of its percent of elongation or percent of reduction in area at the moment of fracture.

$$\text{Percent elongation} = \frac{L_f - L_0}{L_0}(100\%)$$

$$\text{Percent reduction of area} = \frac{A_0 - A_f}{A_0}(100\%)$$



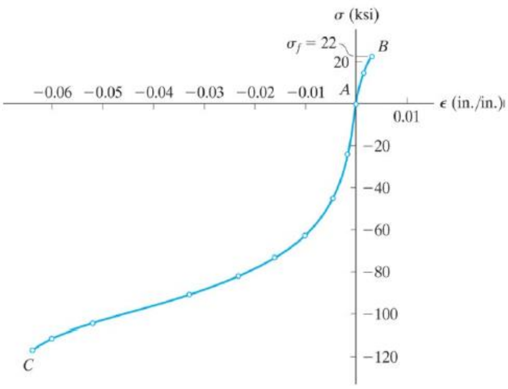
Yield strength for an aluminum alloy

• The final area is measured at the region of necking.

• Not all materials exhibit a well-defined yield point.

• In this event, it is customary to use the **0.2% offset stress as the yield strength** (***offset method***): Starting from a strain value of 0.002 a line parallel to the proportional region is drawn until it intersects the stress vs. strain curve.

Brittle Materials exhibit little or no yielding before failure such as gray cast iron. They usually exhibit a much higher resistance to axial compression compared with their behavior in tension.



σ–ϵ diagram for gray cast iron


Compression causes material to bulge out


Tension failure of a brittle material

4. HOOKE'S LAW

Most engineering materials exhibit a linear relationship between stress and strain within the elastic region.

$$\sigma = E\epsilon$$

- *E* is the modulus of elasticity or Young's modulus.
- *E* represents the slope of the initial straight–lined portion of the stress–strain diagram.
- *E* is a mechanical property that indicates the ***stiffness*** of a material.
- The relation is valid only for the region where the material shows **linear elastic behavior**.
- If the stress in the material has exceeded the proportional limit, it is no longer valid.
- When a ductile material is loaded into the plastic region and then unloaded there will be some permanent deformation.
- The unloading path is nearly linear and parallel to the proportional region. Thus, there is an *elastic strain* which is recovered when the material is unloaded. $\varepsilon_E = \sigma / E$.
- Subtracting the *elastic strain* from the total strain, the *permanent or plastic strain* is determined, ε_P. This plastic strain is known as the *permanent set.*
- If the material is reloaded, the behavior will follow the unloading path back to the original curve. Thus the new stress-strain diagram, defined by *O'A'B'*, has a higher yield point. This phenomenon is called **work or strain hardening**. However, it has less ductility.