MECHANICAL PROPERTIES OF ENGINEERING MATERIALS

1. Introduction

Often materials are subject to forces (loads) when they are used. Mechanical engineers calculate those forces and material scientists how materials deform (elongate, compress, twist) or break as a function of applied load, time, temperature, and other conditions.

Materials scientists learn about these mechanical properties by testing materials. Results from the tests depend on the size and shape of material to be tested (specimen), how it is held, and the way of performing the test. That is why we use common procedures, or *standards*.

The engineering tension test is widely used to provide basic design information on the strength of materials and as an acceptance test for the specification of materials. In the tension test a specimen is subjected to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. The parameters, which are used to describe the stress-strain curve of a metal, are the tensile strength, yield strength or yield point, percent elongation, and reduction of area. The first two are strength parameters; the last two indicate ductility.

In the tension test a specimen is subjected to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. An engineering stress-strain curve is constructed from the load elongation measurements.

The tensile test is probably the simplest and most widely used test to characterize the mechanical properties of a material. The test is performed using a loading apparatus such as the Tinius Olsen machine. The capacity of this machine is 10,000 pounds (tension and compression). The specimen of a given material (i.e. steel, aluminum, cast iron) takes a cylindrical shape that is 2.0 in. long and 0.5 in. in diameter in its undeformed (with no permanent strain or residual stress), or original shape.

The results from the tensile test have direct design implications. Many common engineering structural components are designed to perform under tension. The truss is probably the most common example of a structure whose members are designed to be in tension (and compression).

2. Concepts of Stress and Strain

Stress can be defined by ratio of the perpindicular force applied to a specimen divided by its original cross sectional area, formally called engineering stress

To compare specimens of different sizes, the load is calculated per unit area, also called normalization to the area. Force divided by area is called stress. In tension and compression tests, the relevant area is that perpendicular to the force. In shear or torsion tests, the area is perpendicular to the axis of rotation. The stress is obtained by dividing the load (F) by the original area of the cross section of the specimen (A_O).

$$\sigma = \frac{F}{A_0}$$

The unit is the Megapascal = 10^6 Newtons/m^2.

There is a change in dimensions, or deformation elongation, ΔL as a result of a tensile or compressive stress. To enable comparison with specimens of different length, the elongation is also normalized, this time to the length l_o. This is called strain. So, Strain is the ratio of change in length due to deformation to the original length of the specimen, formally called engineering strain. strain is unitless, but often units of m/m (or mm/mm) are used

The strain used for the engineering stress-strain curve is the average linear strain, which is obtained by dividing the elongation of the gage length of the specimen, by its original length.

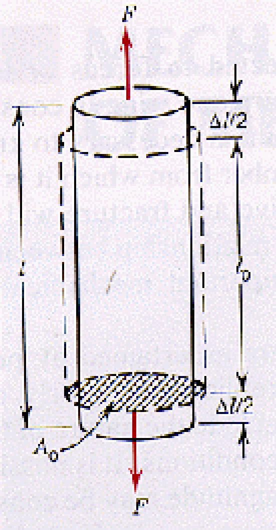
$$\varepsilon = \frac{l_i - l_o}{l_o} = \frac{\Delta l}{l_o}$$

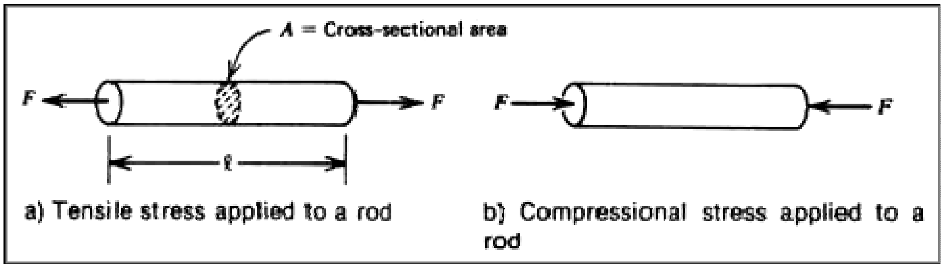
Since both the stress and the strain are obtained by dividing the load and elongation by constant factors, the load-elongation curve will have the same shape as the engineering stress-strain curve. The two curves are frequently used interchangeably.

The shape and magnitude of the stress-strain curve of a metal will depend on its composition, heat treatment, prior history of plastic deformation, and the strain rate, temperature, and state of stress imposed during the testing. The parameters used to to describe stress-strain curve are tensile strength, yield strength or yield point, percent elongation, and reduction of area. The first two are strength parameters; the last two indicate ductility.

The general shape of the engineering stress-strain curve requires further explanation. In the elastic region stress is linearly proportional to strain. When the load exceeds a value corresponding to the yield strength, the specimen undergoes gross plastic deformation. It is permanently deformed if the load is released to zero. The stress to produce continued plastic deformation increases with increasing plastic strain, i.e., the metal strain-hardens. The volume of the specimen remains constant during plastic deformation, $A \cdot L = A_0 \cdot L_0$ and as the specimen elongates, it decreases uniformly along the gage length in cross-sectional area.

Initially the strain hardening more than compensates for this decrease in area and the engineering stress (proportional to load P) continues to rise with increasing strain. Eventually a point is reached where the decrease in specimen cross-sectional area is greater than the increase in deformation load arising from strain hardening. This condition will be reached first at some point in the specimen that is slightly weaker than the rest. All further plastic deformation is concentrated in this region, and the specimen begins to neck or thin down locally. Because the cross-sectional area now is decreasing far more rapidly than strain hardening increases the deformation load, the actual *load* required to deform the specimen falls off and the engineering stress likewise continues to decrease until fracture occurs.

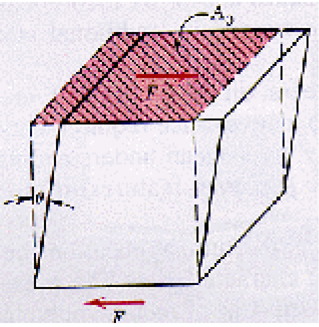


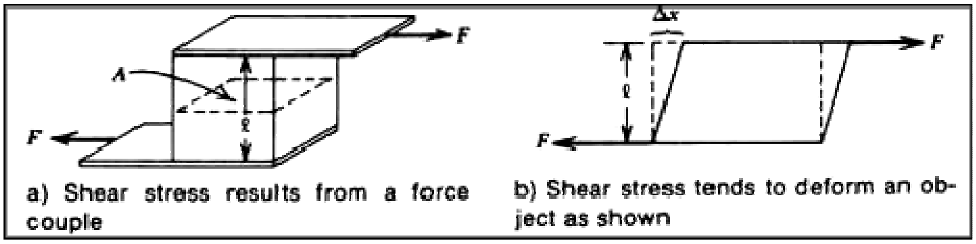


a) Tensile stress applied to a rod

b) Compressional stress applied to a rod

Tensile and compressional stress can be defined in terms of forces applied to a uniform rod.

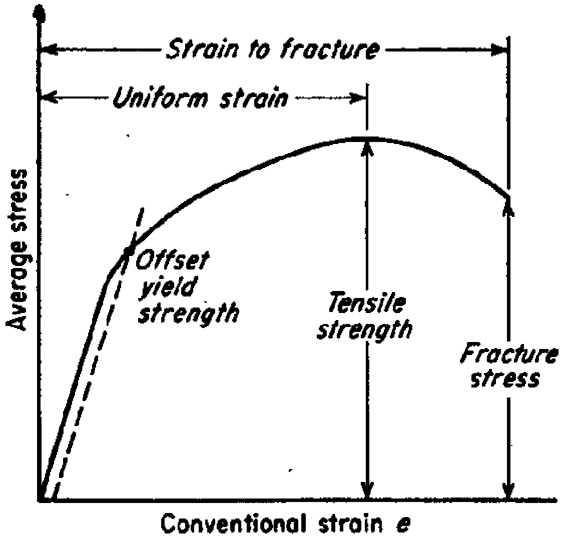


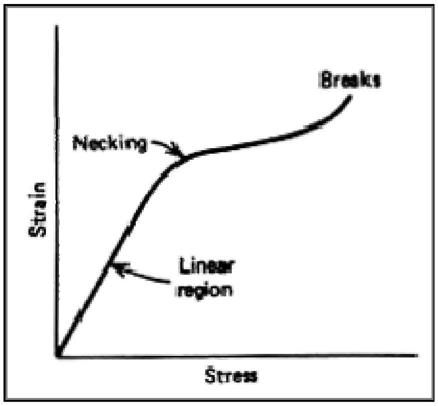


a) Shear stress results from a force couple

b) Shear stress tends to deform an object as shown

Shear stress is defined in terms of a couple that tends to deform a joining member





A typical stress-strain curve showing the linear region, necking and eventual break.

Shear strain is defined as the tangent of the angle theta, and, in essence, determines to what extent the plane was displaced. In this case, the force is applied as a *couple* (that is, *not* along the same line), tending to shear off the solid object that separates the force arms.

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

where ,
Dx = deformation in m
l = width of a sample in m

In this case, the force is applied as a *couple* (that is, *not* along the same line), tending to shear off the solid object that separates the force arms. In this case, the stress is again The strain in this case is defined as the fractional change in dimension of the sheared member.

3. Stress—Strain Behavior

3.1. Hooke's Law

- for materials stressed in tension, at relatively low levels, stress and strain are proportional through:

$$\sigma = \mathbf{E}\varepsilon$$

- constant E is known as the modulus of elasticity, or Young's modulus.
    - Measured in MPa and can range in values from ~4.5x104 - 40x107 MPa

The engineering stress strain graph shows that the relationship between stress and strain is linear over some range of stress. If the stress is kept within the linear region, the material is essentially *elastic* in that if the stress is removed, the deformation is also gone. But if the elastic limit is exceeded, permanent deformation results. The material may begin to "neck" at some location and finally break. Within the linear region, a specific type of material will always follow the same curves despite different physical dimensions. Thus, it can say that the linearity and slope are a constant of the type of material only. In tensile and compressional stress, this constant is called the *modulus of elasticity* or *Young's modulus (E).*

$$E = \frac{F/A}{\Delta l/l}$$

where stress = F/A in N/m^2

strain = Dl/l unitless

E = Modulus of elasticity in N/m^2

The modulus of elasticity has units of stress, that is, N/m^2. The following table gives the modulus of elasticity for several materials. In an exactly similar fashion, the shear modulus is defined for shear stress-strain as modulus of elasticity.

Material	Modulus (N/m^2)
Aluminum Copper Steel	6.89×10^{10} 11.73 X 10'° 20.70 X 10^{10} 2.1×10^8

3.2 Sress-strain curve

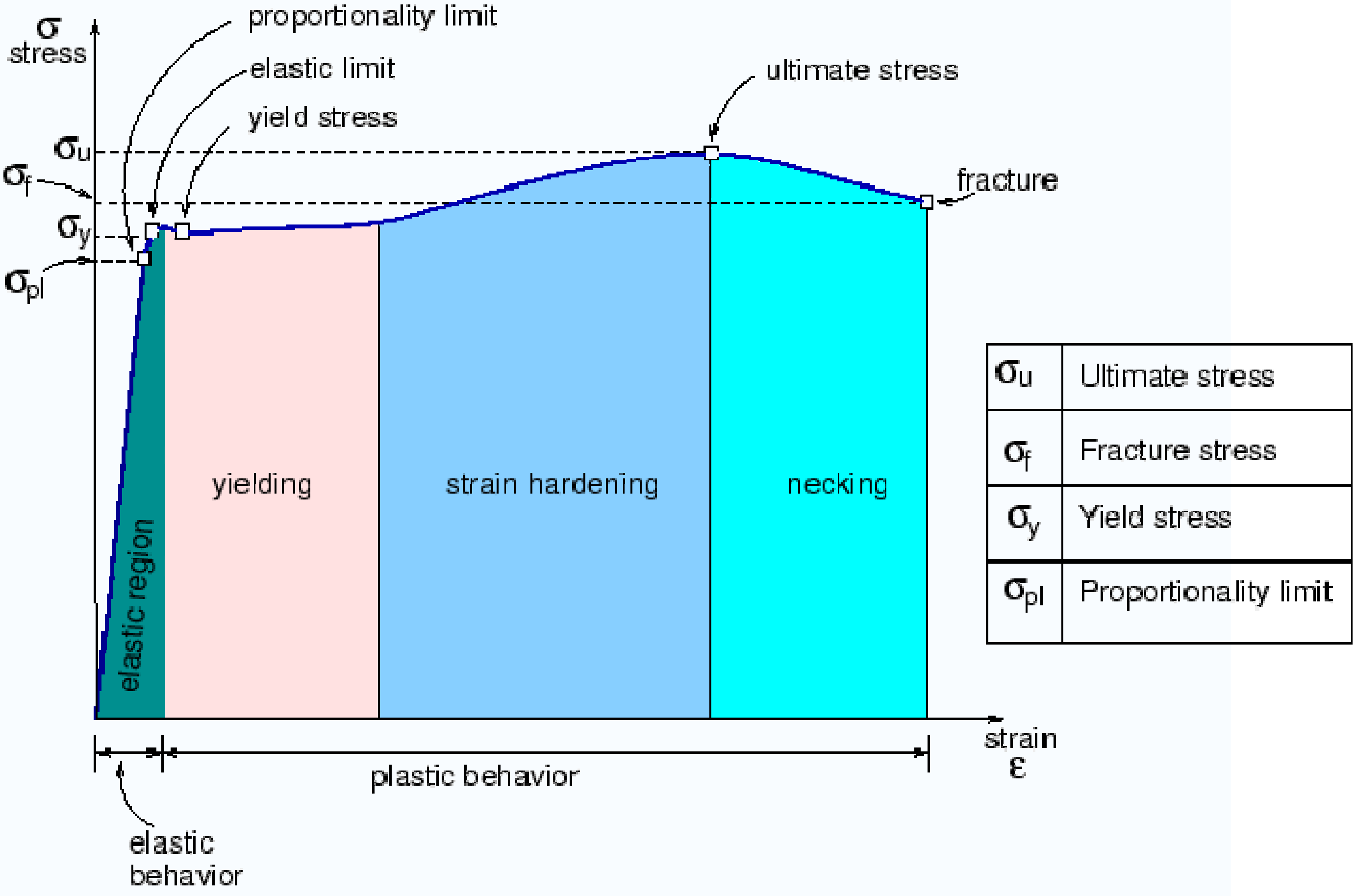
The stress-strain curve characterizes the behavior of the material tested. It is most often plotted using engineering stress and strain measures, because the reference length and cross-sectional area are easily measured. Stress-strain curves generated from tensile test results help engineers gain insight into the constitutive relationship between stress and strain for a particular material. The constitutive relationship can be thought of as providing an answer to the following question: Given a strain history for a specimen, what is the state of stress? As we shall see, even for the simplest of materials, this relationship can be very complicated.

In addition to providing quantitative information that is useful for the constitutive relationship, the stress-strain curve can also be used to qualitatively describe and classify the material. Typical regions that can be observed in a stress-strain curve are:

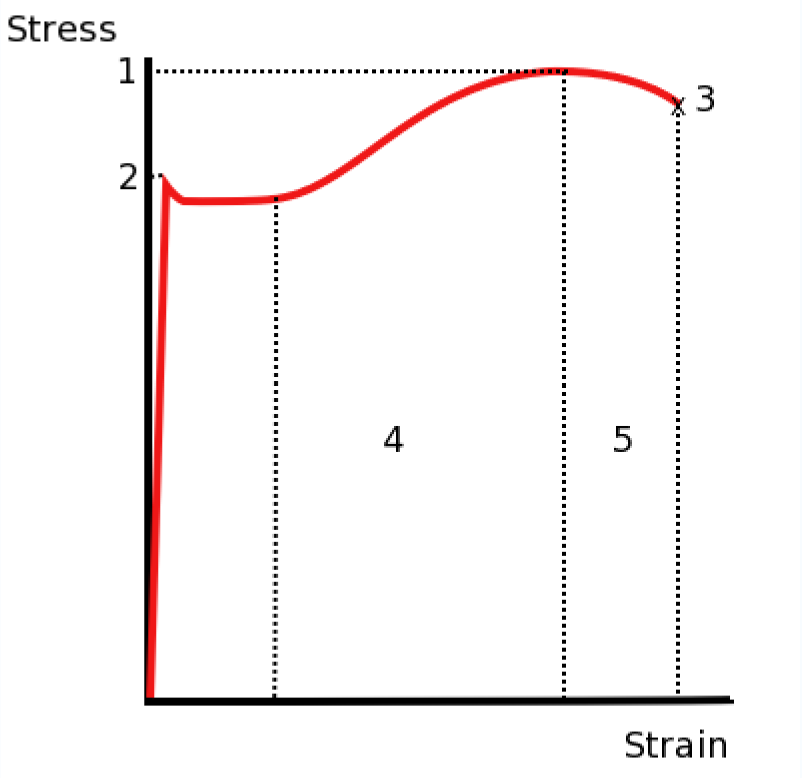
1. Elastic region
2. Yielding
3. Strain Hardening
4. Necking and Failure

A stress-strain curve with each region identified is shown below. The curve has been sketched using the assumption that the strain in the specimen is monotonically increasing - no unloading occurs. It should also be emphasized that a lot of variation from what's shown is possible with real materials, and each of the above regions will not always be so clearly delineated. It should be emphasized that the extent of each region in stress-strain space is material dependent, and that not all materials exhibit all of the above regions.

A stress-strain curve is a graph derived from measuring load (stress - σ) versus extension (strain - ε) for a sample of a material. The nature of the curve varies from material to material. The following diagrams illustrate the stress-strain behaviour of typical materials in terms of the engineering stress and engineering strain where the stress and strain are calculated based on the original dimensions of the sample and not the instantaneous values. In each case the samples are loaded in tension although in many cases similar behaviour is observed in compression.



Various regions and points on the stress-strain curve.



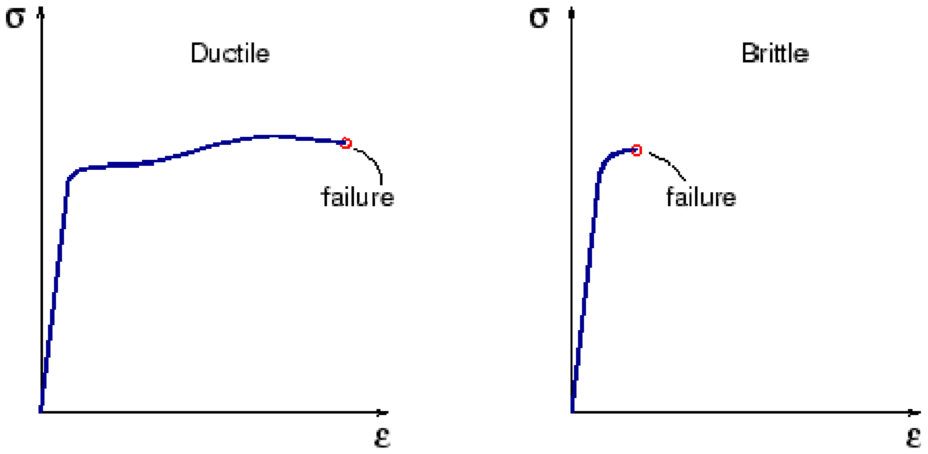
Stress vs. Strain curve for mild steel steel (Ductile material).

Reference numbers are:

1- Ultimate strength
2- Yeild Strength
3- Ruputure
4- Strain hardenining region
5- Necking region

3.3. Brittle and Ductile Behavior

The behavior of materials can be broadly classified into two categories; brittle and ductile. Steel and aluminum usually fall in the class of ductile materials. Glass, ceramics, plain concrete and cast iron fall in the class of brittle materials. The two categories can be distinguished by comparing the stress-strain curves, such as the ones shown in Figure.



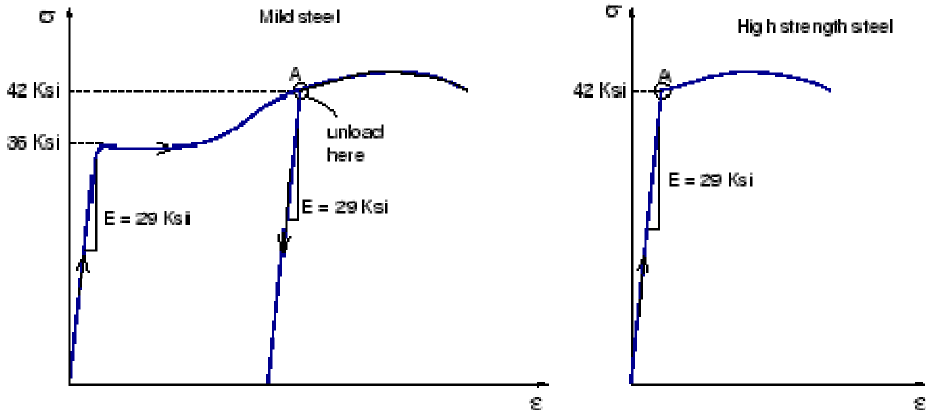
Ductile and brittle material behavior

The material response for ductile and brittle materials are exhibited by both qualitative and quantitative differences in their respective stress-strain curves. Ductile materials will withstand large strains before the specimen ruptures; brittle materials fracture at much lower strains. The yielding region for ductile materials often takes up the majority of the stress-strain curve, whereas for brittle materials it is nearly nonexistent. Brittle materials often have relatively large Young's moduli and ultimate stresses in comparison to ductile materials.

These differences are a major consideration for design. Ductile materials exhibit large strains and yielding before they fail. On the contrary, brittle materials fail suddenly and without much warning. Thus ductile materials such as steel are a natural choice for structural members in buildings as we desire considerable warning to be provided before a building fails. The energy absorbed (per unit volume) in the tensile test is simply the area under the stress strain curve. Clearly, by comparing the curves in Figure_, It can be observed that ductile materials are capable of absorbing much larger quantities of energy before failure.

Finally, it should be emphasized that not all materials can be easily classified as either ductile or brittle. Material response also depends on the operating environment; many ductile materials become brittle as the temperature is decreased. With advances in metallurgy and composite technology, other materials are advanced combinations of ductile and brittle constituents.

Often in structural design, structural members are designed to be in service below the yield stress. The reason being that once the load exceeds the yield limit, the structural members will exhibit large deformations (imagine for instance a roof sagging) that are undesirable. Thus materials with larger yield strength are preferable.



After work hardening, the stress-strain curve of a mild steel (left) resembles that of high-strength steel (right).

We will for now concentrate on steel, a commonly used structural material. Mild steels have a yield strength somewhere between 240 and 360 N/mm^2. When work-hardened, the yield strength of this steel increases. Work hardening is the process of loading mild steel beyond its yield point and unloading as shown in Figure. When the material is loaded again, the linear elastic behavior now extends up to point A as shown. The negative aspect of work hardening is some loss in ductility of the material. It is noteworthy that mild steel is usually recycled. Because of this, the yield strength may be a little higher than expected for the mild steel specimens tested in the laboratory.

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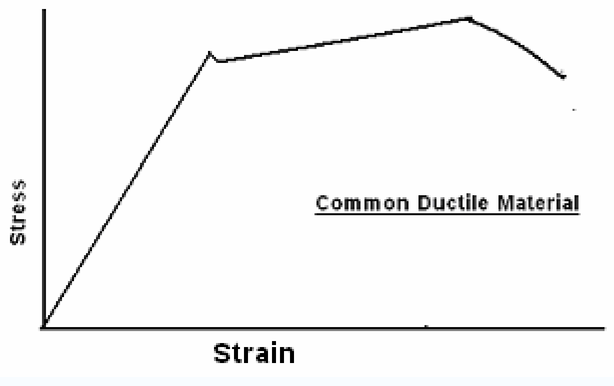
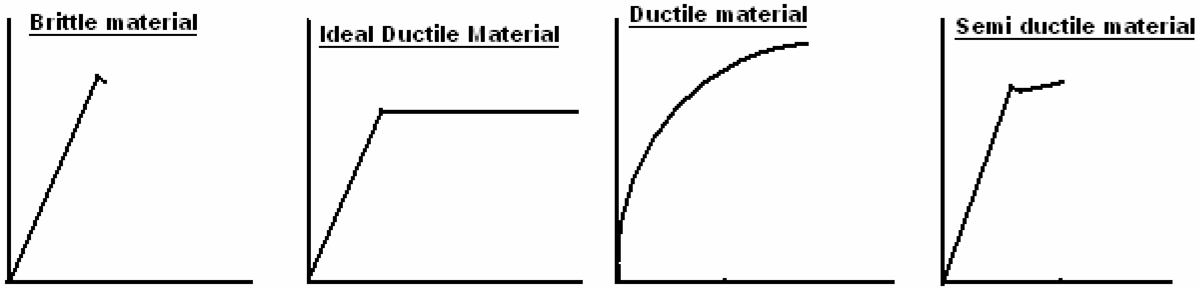
Generally, the stress strain distribution varies from a material to another and could be in different forms as follows. Consequently, the type of material and fracture pattern can be defined and determined according to its stress-strain distribution diagram.





Various stress-strain diagrhams for different engineerin materials

3.5. Yield strength

The yield point, is defined in engineering and materials science as the stress at which a material begins to plastically deform. Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. Once the yield point is passed some fraction of the deformation will be permanent and non-reversible. Knowledge of the yield point is vital when designing a component since it generally represents an upper limit to the load that can be applied. It is also important for the control of many materials production techniques such as forging, rolling, or pressing.

In structural engineering, **yield** is the permanent plastic deformation of a structural member under stress. This is a soft failure mode which does not normally cause catastrophic failure unless it accelerates buckling.

It is often difficult to precisely define yield due to the wide variety of stress-strain behaviours exhibited by real materials. In addition there are several possible ways to define the yield point in a given material.

Yeild occurs when dislocations first begin to move. Given that dislocations begin to move at very low stresses, and the difficulty in detecting such movement, this definition is rarely used.

Elastic Limit - The lowest stress at which permanent deformation can be measured. This requires a complex iteractive load-unload procedure and is critically dependent on the accuracy of the equipment and the skill of the operator.

Proportional Limit - The point at which the stress-strain curve becomes non-linear. In most metallic materials the elastic limit and proportional limit are essentially the same.

Offset Yield Point (proof stress) - Due to the lack of a clear border between the elastic and plastic regions in many materials, the yield point is often defined as the stress at some arbitrary plastic strain (typically 0.2%). This is determined by the intersection of a line offset from the linear region by the required strain. In some materials there is essentially no linear region and so a certain value of plastic strain is defined instead. Although somewhat arbitrary this method does allow for a consistent comparison of materials and is the most common.

Yield point.

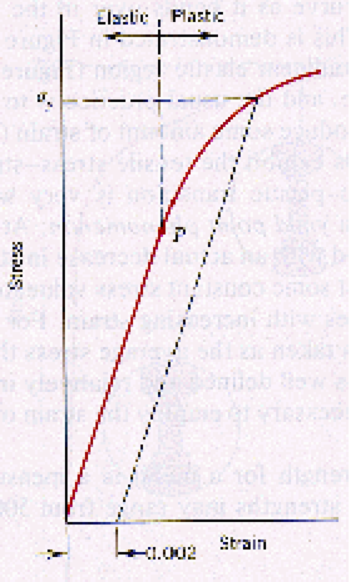
If the stress is too large, the strain deviates from being proportional to the stress. The point at which this happens is the *yield point* because there the material yields, deforming permanently (plastically).

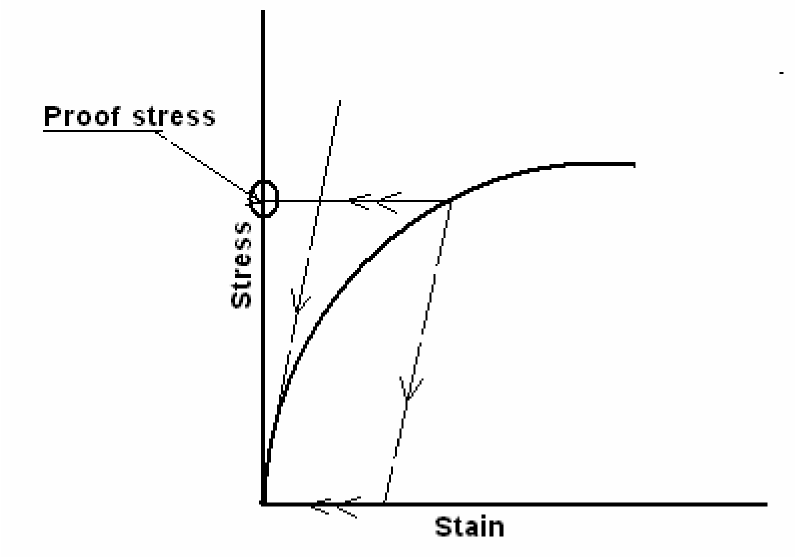
Yield stress. Hooke's law is not valid beyond the yield point. The stress at the yield point is called *yield stress*, and is an important measure of the mechanical properties of materials. In practice, the yield stress is chosen as that causing a permanent strain of 0.002, which called as **proof stresss**. The yield stress measures the resistance to plastic deformation.

The ***yield strength*** is the stress required to produce a small-specified amount of plastic deformation. The usual definition of this property is the ***offset yield strength*** determined by the stress corresponding to the intersection of the stress-strain curve and a line parallel to the elastic part of the curve offset by a specified strain. In the United States the offset is usually specified as a strain of 0.2 or 0.1 percent (**e** = 0.002 or 0.001).

$$R_{p0.2} = \frac{P_{(strain\,offset=0,002)}}{A_0}$$

A good way of looking at offset yield strength is that after a specimen has been loaded to its 0.2 percent offset yield strength and then unloaded it will be 0.2 percent longer than before the test. The offset yield strength is often referred to in Great Britain as the ***proof stress***, where offset values are either 0.1 or 0.5 percent. The yield strength obtained by an offset method is commonly used for design and specification purposes because it avoids the practical difficulties of measuring the elastic limit or proportional limit.



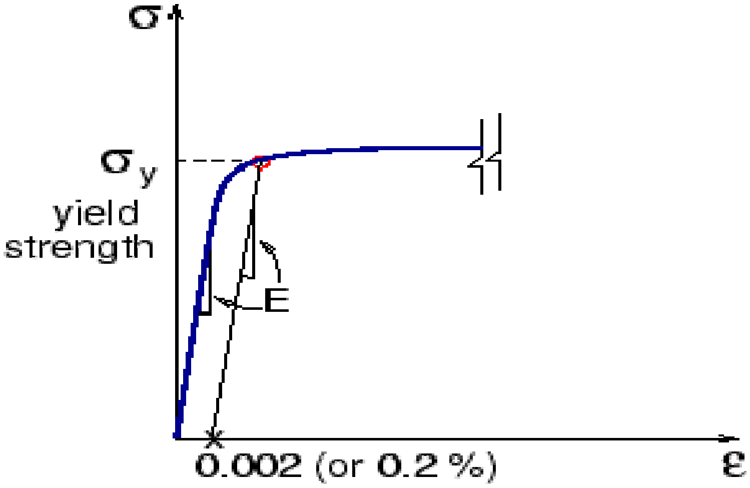


Determination of proof stress

Some materials have essentially no linear portion to their stress-strain curve, for example, soft copper or gray cast iron. For these materials the offset method cannot be used and the usual practice is to define the yield strength as the stress to produce some total strain, for example, **e** = 0.005.

Determination of Yield Strength in Ductile Materials

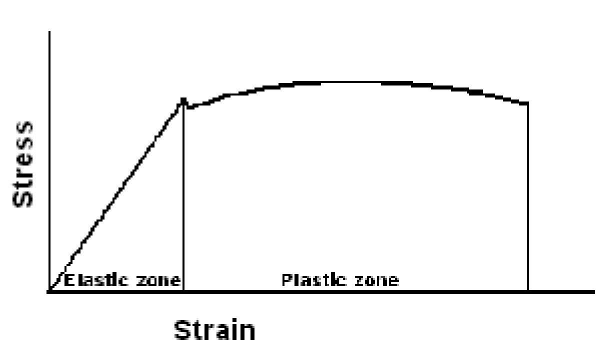
In many materials, the yield stress is not very well defined and for this reason a standard has been developed to determine its value. The standard procedure is to project a line parallel to the initial elastic region starting at 0.002 strain. The 0.002 strain point is often referred to as the $0.2\ \%$ offset strain point. The intersection of this new line with the stress-strain curve then defines the *yield strength* as shown in Figure_.



4. Elastic Properties of Materials

When the stress is removed, the material returns to the dimension it had before the load was applied. Valid for small strains (except the case of rubbers).

Deformation is *reversible, non permanent*



Materials subject to tension shrink laterally. Those subject to compression, bulge. The ratio of lateral and axial strains is called the *Poisson's ratio.*

When a material is placed under a tensile stress, an accompanying strain is created in the same direction.

Poisson’s ratio is the ratio of the lateral to axial strains.

$$\nu = -\frac{\varepsilon_x}{\varepsilon_z} = \frac{\varepsilon_y}{\varepsilon_z}$$

The elastic modulus, shear modulus and Poisson's ratio are related by $E = 2G(1+\nu)$

$$\mathbf{E} = 2\mathbf{G}(1+\nu)$$

- Theoretically, isotropic materials will have a value for Poisson’s ratio of 0.25.
- The maximum value of ν is 0.5
- Most metals exhibit values between 0.25 and 0.35

9. Plastic deformation.

When the stress is removed, the material does not return to its previous dimension but there is a *permanent*, irreversible deformation.

For metallic materials, elastic deformation only occurs to strains of about 0.005. After this point, plastic (non-recoverable) deformation occurs, and Hooke’s Law is no longer valid.

On an atomic level, plastic deformation is caused by *slip*, where atomic bonds are broken by dislocation motion, and new bonds are formed.

5. Anelasticity

Here the behavior is elastic but not the stress-strain curve is not immediately reversible. It takes a while for the strain to return to zero. The effect is normally small for metals but can be significant for polymers.

6. Tensile strength.

When stress continues in the plastic regime, the stress-strain passes through a maximum, called the *tensile strength* (s_{TS}) , and then falls as the material starts to develop a *neck* and it finally breaks at the *fracture point*.

Note that it is called strength, not stress, but the units are the same, MPa.

For structural applications, the yield stress is usually a more important property than the tensile strength, since once the it is passed, the structure has deformed beyond acceptable limits.

The tensile strength, or ultimate tensile strength (UTS), is the maximum load divided by the original cross-sectional area of the specimen.

$$R_m = \frac{P_{max}}{A_0}$$

The tensile strength is the value most often quoted from the results of a tension test; yet in reality it is a value of little fundamental significance with regard to the strength of a metal. For ductile metals the tensile strength should be regarded as a measure of the maximum load, which a metal can withstand under the very restrictive conditions of uniaxial loading. It will be shown that this value bears little relation to the useful strength of the metal under the more complex conditions of stress, which are usually encountered.

For many years it was customary to base the strength of members on the tensile strength, suitably reduced by a factor of safety. The current trend is to the more rational approach of basing the static design of ductile metals on the yield strength.

However, because of the long practice of using the tensile strength to determine the strength of materials, it has become a very familiar property, and as such it is a very useful identification of a material in the same sense that the chemical composition serves to identify a metal or alloy.

Further, because the tensile strength is easy to determine and is a quite reproducible property, it is useful for the purposes of specifications and for quality control of a product. Extensive empirical correlations between tensile strength and properties such as hardness and fatigue strength are often quite useful. For brittle materials, the tensile strength is a valid criterion for design.

7. Ductility

The ability to deform before braking. It is the opposite of **brittleness**. Ductility can be given either as percent maximum elongation e_{max} or maximum area reduction.

At our present degree of understanding, ductility is a qualitative, subjective property of a material. In general, measurements of ductility are of interest in three ways:

1. To indicate the extent to which a metal can be deformed without fracture in metal working operations such as rolling and extrusion.
2. To indicate to the designer, in a general way, the ability of the metal to flow plastically before fracture. A high ductility indicates that the material is "forgiving" and likely to deform locally without fracture should the designer err in the stress calculation or the prediction of severe loads.
3. To serve as an indicator of changes in impurity level or processing conditions. Ductility measurements may be specified to assess material quality even though no direct relationship exists between the ductility measurement and performance in service.

The conventional measures of ductility that are obtained from the tension test are the engineering strain at fracture ef (usually called the *elongation*) and the *reduction of area* at fracture q. Both of these properties are obtained after fracture by putting the specimen back together and taking measurements of L_f and A_f .

$$e_f = \frac{L_f - L_0}{L_0}$$

$$q = \frac{A_0 - A_f}{A_0}$$

Because an appreciable fraction of the plastic deformation will be concentrated in the necked region of the tension specimen, the value of $\mathbf{e}_f$ will depend on the gage length L_0 over which the measurement was taken. The smaller the gage length the greater will be the contribution to the overall elongation from the necked region and the higher will be the value of $\mathbf{e}_f$. Therefore, when reporting values of percentage elongation**,** the gage length L_0 always should be given.

The reduction of area does not suffer from this difficulty. Reduction of area values can be converted into an equivalent **zero-gage-length elongation** $\mathbf{e}_0$. From the constancy of volume relationship for plastic deformation $A*L = A_0*L_0$, we obtain

$$\frac{L}{L_0} = \frac{A_0}{A} = \frac{1}{1-q}, \qquad e_0 = \frac{L-L_0}{L_0} = \frac{A_0}{A} - 1 = \frac{1}{1-q} - 1 = \frac{q}{1-q}$$

This represents the elongation based on a very short gage length near the fracture.

Another way to avoid the complication from necking is to base the percentage elongation on the uniform strain out to the point at which necking begins. The uniform elongation $\mathbf{e}_u$ correlates well with stretch-forming operations. Since the engineering stress-strain curve often is quite flat in the vicinity of necking, it may be difficult to establish the strain at maximum load without ambiguity. In this case the method suggested by Nelson and Winlock is useful.

8. Resilience

The resilience of the material is the triangular area underneath the elastic region of the curve. **Resilience** generally means the ability to recover from (or to resist being affected by) some shock, insult, or disturbance. However, it is used quite differently in different fields.

In physics and engineering, **resilience** is defined as the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading to have