Stress strain diagrams for engineering materials pdf

The engineering tension test is widely used to provide basic design information on images/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. An engineering stress-strain curve is constructed from the load elongation measurements (Fig. 1). Figure 1. The engineering stress-strain curve It is obtained by dividing the load by the original area of the cross section of the specimen. (1) 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, d, by its original length. (2) 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, 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. The general shape of the engineering stress-strain curve (Fig. 1) 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·L = A0·L0 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. Tensile Strength The tensile strength, or ultimate tensile strength (UTS), is the maximum load divided by the original cross-sectional area of the specimen. (3) 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. Measures of Yielding The stress at which plastic deformation or yielding is observed to begin depends on the sensitivity of the strain measurements. With most materials there is a gradual transition from elastic to plastic behavior, and the point at which plastic deformation begins is hard to define with precision. Various criteria for the initiation of yielding are used depending on the sensitivity of the strain measurements and the intended use of the data. True elastic limit based on micro strain measurements at strains on order of 2 x 10-6 in | in. This elastic limit is a very low value and is related to the motion of a few hundred dislocations. Proportional limit is the highest stress at which stress is directly proportional to strain. It is obtained by observing the deviation from the straight-line portion of the stress-strain curve. Elastic limit is the greatest stress the material can withstand without any measurable permanent strain remaining on the complete release of load. With increasing sensitivity of strain measurement, the value of the elastic limit is decreased until at the limit it equals the true elastic limit determined from micro strain measurements. With the sensitivity of strain usually employed in engineering studies (10-4in | in), the elastic limit is greater than the proportional limit. Determination of the elastic limit requires a tedious incremental loading-unloading test procedure. 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 (Fig. 1). 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). (4) 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. 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. Measures of Ductility 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: To indicate the extent to which a metal can be deformed without fracture in metalworking operations such as rolling and extrusion. 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. 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 Lf and Af . (5) (6) Because an appreciable fraction of the plastic deformation will be concentrated in the necked region of the tension specimen, the value of ef will depend on the gage length L0 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 ef. Therefore, when reporting values of percentage elongation, the gage length L0 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 e0. From the constancy of volume relationship for plastic deformation A*L = A0*L0, we obtain (7) 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 eu 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. Stress-strain curve typical of a low carbon steel. For broader coverage of this topic, see Stress–strain analysis. In engineering and materials science, a stress–strain curve for a material gives the relationship between stress and strain. It is obtained by gradually applying load to a test coupon and measuring the deformation, from which the stress and strain can be determined (see tensile testing). These curves reveal many of the properties of a material, such as the Young's modulus, the yield strength and the ultimate tensile strength. Definition Generally speaking, curves representing the relationship between stress and strain in any form of deformation can be regarded as stress-strain curves. The stress and strain can be normal, shear, or mixture, also can be uniaxial, biaxial, or multiaxial, even change with time. The form of deformation can be compression, stretching, torsion, rotation, and so on. If not mentioned otherwise, stress–strain curve refers to the relationship between axial normal stress and axial normal strain of materials measured in a tension test. Engineering stress and strain Consider a bar of original cross sectional area A 0 {\displaystyle A_{0}} being subjected to equal and opposite forces F {\displaystyle F} pulling at the ends so the bar is under tension. The material is experiencing a stress defined to be the ratio of the force to the cross sectional area of the bar, as well as an axial elongation: σ = F A 0 {\displaystyle \sigma ={\tfrac {F}{A_{0}}}} ε = L − L 0 L 0 = Δ L L 0 {\displaystyle \varepsilon ={\tfrac {L-L_{0}}{L_{0}}}={\tfrac {\Delta L}{L_{0}}}} Subscript 0 denotes the original dimensions of the sample. The SI unit for stress is newton per square metre, or pascal (1 pascal = 1 Pa = 1 N/m2), and strain is unitless. Stress-strain curve for this material is plotted by elongating the sample and recording the stress variation with strain until the sample fractures. By convention, the strain is set to the horizontal axis and stress is set to vertical axis. Note that for engineering purposes we often assume the cross-section area of the material does not change during the whole deformation process. This is not true since the actual area will decrease while deforming due to elastic and plastic deformation. The curve based on the original cross-section and gauge length is called the engineering stress-strain curve, while the curve based on the instantaneous cross-section area and length is called the true stress-strain curve. Unless stated otherwise, engineering stress-strain is generally used. True stress and strain The difference between true stress–strain curve and engineering stress–strain curve Due to the shrinking of section area and the ignored effect of developed elongation to further elongation, true stress and strain are different from engineering stress and strain. σ t = F A {\displaystyle \sigma _{\text{t}}={\tfrac {F}{A}}} ε t = ∫ δ L L {\displaystyle \varepsilon _{\text{t}}=\int {\tfrac {\delta L}{L}}} Here the dimensions are instantaneous values. Assuming volume of the sample conserves and deformation happens uniformly, A 0 L 0 = A L {\displaystyle A_{0}L_{0}=AL} The true stress and strain can be expressed by engineering stress and strain. For true stress, σ t = F A = F A 0 A 0 A = F A 0 L L 0 = σ (1 + ε) {\displaystyle \sigma _{\text{t}}={\tfrac {F}{A}}={\tfrac {F}{A_{0}}}{\tfrac {A_{0}}{A}}={\tfrac {F}{A_{0}}}{\tfrac {L}{L_{0}}}=\sigma (1+\varepsilon)} For the strain, δ ε t = δ L L {\displaystyle \delta \varepsilon _{\text{t}}={\tfrac {\delta L}{L}}} Integrate both sides and apply the boundary condition, ε t = ln (L L 0) = ln (1 + ε) {\displaystyle \varepsilon _{\text{t}}=\ln \left({\tfrac {L}{L_{0}}}\right)=\ln(1+\varepsilon)} So in a tension test, true stress is larger than engineering stress and true strain is less than engineering strain. Thus, a point defining true stress-strain curve is displaced upwards and to the left to define the equivalent engineering stress-strain curve. The difference between the true and engineering stresses and strains will increase with plastic deformation. At low strains (such as elastic deformation), the differences between the two is negligible. As for the tensile strength point, it is the maximal point in engineering stress-strain curve but is not a special point in true stress-strain curve. Because engineering stress is proportional to the force applied along the sample, the criterion for necking formation can be set as δ F = 0 {\displaystyle \delta F=0} . δ F = σ t δ A + A δ σ t = 0 {\displaystyle \delta F=\sigma _{\text{t}}\,\delta A+A\,\delta \sigma _{\text{t}}=0} − δ A A = δ σ t σ t {\displaystyle -{\tfrac {\delta A}{A}}={\tfrac {\delta \sigma _{\text{t}}}{\sigma _{\text{t}}}}} This analysis suggests nature of the UTS point. The work strengthening effect is exactly balanced by the shrinking of section area at UTS point. After the formation of necking, the sample undergoes heterogeneous deformation, so equations above are not valid. The stress and strain at the necking can be expressed as: σ t = F A neck {\displaystyle \sigma _{\text{t}}={\tfrac {F}{A_{\text{neck}}}}} ε t = ln (A 0 A neck) {\displaystyle \varepsilon _{\text{t}}=\ln \left({\tfrac {A_{0}}{A_{\text{neck}}}}\right)} An empirical equation is commonly used to describe the relationship between true stress and strain. σ t = K (ε t) n {\displaystyle \sigma _{\text{t}}=K(\varepsilon _{\text{t}})^{n}} Here, n {\displaystyle n} is the strain-hardening coefficient and K {\displaystyle K} is the strength coefficient. n {\displaystyle n} is a measure of a material's work hardening behavior. Materials with a higher n {\displaystyle n} have a greater resistance to necking. Typically, metals at room temperature have n {\displaystyle n} ranging from 0.02 to 0.5.[1] Stages A schematic diagram for the stress-strain curve of low carbon steel at room temperature is shown in figure 1. There are several stages showing different behaviors, which suggests different mechanical properties. To clarify, materials can miss one or more stages shown in figure 1, or have totally different stages. The first stage is the linear elastic region. The stress is proportional to the strain, that is, obeys the general Hooke's law, and the slope is Young's modulus. In this region, the material undergoes only elastic deformation. The end of the stage is the initiation point of plastic deformation. The stress component of this point is defined as yield strength (or upper yield point, UYP for short). The second stage is the strain hardening region. This region starts as the stress goes beyond the yielding point, reaching a maximum at the ultimate strength point, which is the maximal stress that can be sustained and is called the ultimate tensile strength (UTS). In this region, the stress mainly increases as the material elongates, except that for some materials such as steel, there is a nearly flat region at the beginning. The stress of the flat region is defined as the lower yield point (LYP) and results from the formation and propagation of Lüders bands. Explicitly, heterogeneous plastic deformation forms bands at the upper yield strength and these bands carrying with deformation spread along the sample at the lower yield strength. After the sample is again uniformly deformed, the increase of stress with the progress of extension results from work strengthening, that is, dense dislocations induced by plastic deformation hampers the further motion of dislocations. To overcome these obstacles, a higher resolved shear stress should be applied. As the strain accumulates, work strengthening gets reinforced, until the stress reaches the ultimate tensile strength. The third stage is the necking region. Beyond tensile strength, a neck forms where the local cross-sectional area becomes significantly smaller than the average. The necking deformation is heterogeneous and will reinforce itself as the stress concentrates more at small section. Such positive feedback leads to quick development of necking and leads to fracture. Note that though the pulling force is decreasing, the work strengthening is still progressing, that is, the true stress keeps growing but the engineering stress decreases because the shrinking section area is not considered. This region ends up with the fracture. After fracture, percent elongation and reduction in section area can be calculated. Classification Stress–strain curve for brittle materials compared to ductile materials. It is possible to distinguish some common characteristics among the stress–strain curves of various groups of materials and, on this basis, to divide materials into two broad categories; namely, the ductile materials and the brittle materials.[2]:51 Ductile materials Ductile materials, which includes structural steel and many alloys of other metals, are characterized by their ability to yield at normal temperatures.[2]:58 Low carbon steel generally exhibits a very linear stress–strain relationship up to a well defined yield point (Fig.1). The linear portion of the curve is the elastic region and the slope is the modulus of elasticity or Young's modulus . Many ductile materials including some metals, polymers and ceramics exhibit a yield point. Plastic flow initiates at the upper yield point and continues at the lower one. At lower yield point, permanent deformation is heterogeneously distributed along the sample. The deformation band which formed at the upper yield point will propagate along the gauge length at the lower yield point. The band occupies the whole of the gauge at the luders strain. Beyond this point, work hardening commences. The appearance of the yield point is associated with pinning of dislocations in the system. For example, solid solution interacts with dislocations and acts as pin and prevent dislocation from moving. Therefore, the stress needed to initiate the movement will be large. As long as the dislocation escape from the pinning, stress needed to continue it is less. After the yield point, the curve typically decreases slightly because of dislocations escaping from Cottrell atmospheres. As deformation continues, the stress increases on account of strain hardening until it reaches the ultimate tensile stress. Until this point, the cross-sectional area decreases uniformly because of Poisson contractions. Then it starts necking and finally fractures. The appearance of necking in ductile materials is associated with geometrical instability in the system. Due to the natural inhomogeneity of the material, it is common to find some regions with small inclusions or porosity within it or surface, where strain will concentrate, leading to a locally smaller area than other regions. For strain less than the ultimate tensile strain, the increase of work-hardening rate in this region will be greater than the area reduction rate, thereby make this region harder to be further deform than others, so that the instability will be removed, i.e. the materials have abilities to weaken the inhomogeneity before reaching ultimate strain. However, as the strain become larger, the work hardening rate will decreases, so that for now the region with smaller area is weaker than other region, therefore reduction in area will concentrate in this region and the neck becomes more and more pronounced until fracture. After the neck has formed in the materials, further plastic deformation is concentrated in the neck while the remainder of the material undergoes elastic contraction owing to the decrease in tensile force. The stress-strain curve for a ductile material can be approximated using the Ramberg-Osgood equation.[3] This equation is straightforward to implement, and only requires the material's yield strength, ultimate strength, elastic modulus, and percent elongation. Brittle materials Brittle materials, which includes cast iron, glass, and stone, are characterized by the fact that rupture occurs without any noticeable prior change in the rate of elongation,[2]:59 sometimes they fracture before yielding. Brittle materials such as concrete or carbon fiber do not have a well-defined yield point, and do not strain-harden. Therefore, the ultimate strength and breaking strength are the same. Typical brittle materials like glass do not show any plastic deformation but fail while the deformation is elastic. One of the characteristics of a brittle failure is that the two broken parts can be reassembled to produce the same shape as the original component as there will not be a neck formation like in the case of ductile materials. A typical stress–strain curve for a brittle material will be linear. For some materials, such as concrete, tensile strength is negligible compared to the compressive strength and it is assumed zero for many engineering applications. Glass fibers have a tensile strength stronger than steel, but bulk glass usually does not. This is because of the stress intensity factor associated with defects in the material. As the size of the sample gets larger, the expected size of the largest defect also grows. See also Elastomers Plane strain compression test Strength of materials Stress–strain index Tensometer Universal testing machine References ^ Courtney, Thomas (2005). Mechanical behavior of materials. Waveland Press, Inc. pp. 6–13. ^ a b c Beer, F.; Johnston, R.; Dewolf, J.; Mazurek, D. (2009). Mechanics of materials. New York: McGraw-Hill companies. ^ "Mechanical Properties of Materials". External links British Society for Strain Measurement Stress–strain diagram Engineering stress–strain curve Retrieved from "