Introduction to the Tensile Test

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 shown above in Figure 1. The capacity of this machine is 50kN (tension and compression). The specimen of a given material (i.e. steel, aluminum, cast iron) takes a cylindrical shape that is 50mm long and 10mm in diameter in its undeformed (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 also). Usually the cross-section of the truss members are determined by using the moduli and yield strength obtained from tensile tests, requiring that all members behave elastically and not deflect by significant amounts. Other examples of structural members operating in uniaxial tension include the cables in suspension bridges and the spokes in a bicycle wheel.

Figure 1a: The cables in suspension bridges, such as the Brooklyn bridge, and spokes in a bicycle wheel, as shown, both operate in uniaxial tension.
True Stress and True strain

Stress has units of a force measure divided by the square of a length measure, and the average stress on a cross-section in the tensile test is clearly the applied force divided by the cross-sectional area. Similarly, we may approximate the strain component along the long axis of the specimen as the change in length divided by the original, reference length.

It sounds simple enough, but you should realize that there are still some choices to make. Specifically, what area should be used for the cross-sectional area? Should you use the original area or the current area as the load is applied? By the same token, should changes in length always be compared to the original length of the specimen?

The answer is that we will define different types of stress and strain measures according to the way we perform the calculations. Engineering stress and strain measures are distinguished by the use of fixed reference quantities, typically the original cross-sectional area or original length. More precisely,

\[ \sigma_E = \frac{P}{A_0}, \quad \epsilon_E = \frac{\Delta l}{l_0}. \]  

\[ \sigma_T = \frac{P}{A}, \quad \epsilon_T = \frac{\Delta l}{l_0}. \]

\[ \text{Figure 3: Engineering stress measures vs. true stress measures. The latter accounts for the change in cross-sectional area as the loads are applied.} \]
Note that the true stress and strain are practically indistinguishable from the engineering stress and strain at small deformations, as shown in Figure 4. You should also note that as the strain becomes large and the cross-sectional area of the specimen decreases, the true stress can be much larger than the engineering stress.

<table>
<thead>
<tr>
<th>Engineering vs. True</th>
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<tbody>
<tr>
<td>Engineering stress and strain measures use undeformed cross-sectional area.</td>
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<tr>
<td>True stress and strain measures account for changes in cross-sectional area by using the instantaneous values for area, giving more accurate measurements for events such as the tensile test.</td>
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Note:

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Figure 4: Engineering stress-strain curve vs. a true stress, true strain curve.

Quick Quiz: What is the true strain of a steel rod that has been stretched from 10 inches to 10.18 inches?

- .018
- 1.018
- -4.017
- 0.01784
The stress-strain curve

The stress-strain curve characterizes the behaviour 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 relationship between stress and strain for a particular material. It provides the state of stress given the strain history for a specimen.

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,

A stress-strain curve with each region identified is shown below in Figure 5. The curve has been sketched using the assumption that the strain in the specimen is continuously increasing - no unloading occurs.

Figure 5: Various regions and points on the stress-strain curve. Click on the figure to launch it in a separate window, which might be useful as you read through this section.
Quick Quiz: What would be the correct outcome after a specimen has been loaded and unloaded to its .2 percent offset yield strength?

- The material will be .2 percent weaker in strength.
- The material will be .2 percent longer than before the test.
- The material will decrease in cross-sectional area by .2 percent.
- None of the above

**Elastic Region**

In the context of material behaviour, a structural component is said to behave *elastically* if during loading/unloading the deformation is *reversible*. In other words, when the loads are released the specimen will return to its original, undeformed configuration. On the contrary, if the material does not return to its initial undeformed state after unloading it is said to behave *in-elastically*. During tensile testing, the region shaded dark green in Figure 5 corresponds to elastic behavior. Thus if the load were removed within this region, the tensile specimen would return to its undeformed length.

Most of the elastic region shown in Figure 5 corresponds to *linear-elastic* response. Linear elasticity refers to the notion that stress is linearly proportional to strain. So if you double the stress in this region, the change in length of the specimen will also double. In the elastic region, the slope of the stress-strain curve is the **Young's Modulus** $E$.

So we have:

$$\sigma = E \cdot \epsilon$$

in the elastic region.

Young's modulus $E$ is defined as:

$$E \equiv \frac{\text{stress}}{\text{strain}},$$

or the slope of the stress-strain graph. $E$ is the change in stress divided by the change in strain, so the units are psi per unit strain. Since strain is a unitless quantity, the units for Young's modulus are simply Pa or MPa.

It is also possible for materials to behave elastically but not linear-elastically. A small portion of the elastic region shown in Figure 5 is above the **proportionality limit**, where strain increases nonlinearly with increasing stress. You should recognize, however, that there are some materials for which the elastic region is mostly nonlinear.

As loads are increased and the stress in the specimen continues to rise, the material eventually reaches the **elastic limit**. Beyond this limit, any additional loading will result in some permanent change to the specimen geometry upon unloading. For many materials, this point is indistinguishable from the **proportionality limit**.
Quick Quiz: What is the Young's Modulus of a steel bar that has a cross-sectional area of 420mm\(^2\), is 100mm long, and supports a load of 175kN, deforming .2 percent?

- $E = 4166667$ Mpa
- $E = 208 \times 10^6$ MPa
- $E = 208333$ MPa
- $E = 208333$ kPa
Yielding

Any increase in stress beyond the **yield point** will cause the material to be deformed permanently. Also in this so-called yielding region, the deformation will be relatively large for small, almost negligible increases in the stress. This process, characterized by a near-zero slope to the stress-strain curve, is often referred to as perfect plasticity.

In the tensile test, the strain in the specimen is gradually increased and no unloading occurs. If the yield point was passed during loading and the specimen was then unloaded, however, the behaviour would be very different from that in the elastic region. At the end of the unloading, there would exist a permanent strain (sometimes referred to as a "set") in the material. In other words, the specimen would appear to be stretched in comparison to its original configuration, even though no loads would be acting on it. This notion is illustrated in **Figure 6**.

![Stress-strain curve](image)

**Figure 6**: Stress-strain curve for a process of loading past the elastic region, followed by unloading. Subsequent reloading proceeds up a new linear curve, until the original loading curve is reached.

Subsequent loading would proceed up this new loading curve, with the slope again being the Young's Modulus of the material. In this region the material will again behave linear elastically. You should also note that the process introduces a new yield point as shown in the Figure.

![New Yield Point](image)

**Figure 6a**: Linear elasticity is again exhibited in the unloading curve.
Quick Quiz: True or false? During plastic deformation, the volume of the specimen, as well as its cross-sectional area, decrease.

- True
- False

Strain Hardening

When loading is carried beyond the yielding region, the load needs to increase for additional strain to occur. This effect is called strain hardening, and it is associated with an increased resistance to slip deformation at the microscale (for polycrystalline materials). Eventually, the stress-strain curve reaches a maximum at the point of **ultimate stress**. For many materials, the decrease in the cross-sectional area of the specimen is not readily visible to the naked eye until this limit point is passed.

*Figure 6b:* Small changes in cross-sectional area are invisible to the naked eye.
Necking and Failure

When the loading is continued beyond the ultimate stress, the cross-sectional area decreases rapidly in a localized region of the test specimen. Since the cross-sectional area decreases, the load carrying capacity of this region also decreases rapidly. The load (and stress) keeps dropping until the specimen reaches the fracture point.

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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 7.

The offset yield strength is usually specified as a strain of 0.2 percent (e = 0.002).

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.

Figure 7: Determination of yield strength.

Quick Quiz

Question 1: True or false? The yield strength is the stress required to produce a small-specified amount of plastic deformation.

- True
- False
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 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 8.

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 8, we observe 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.