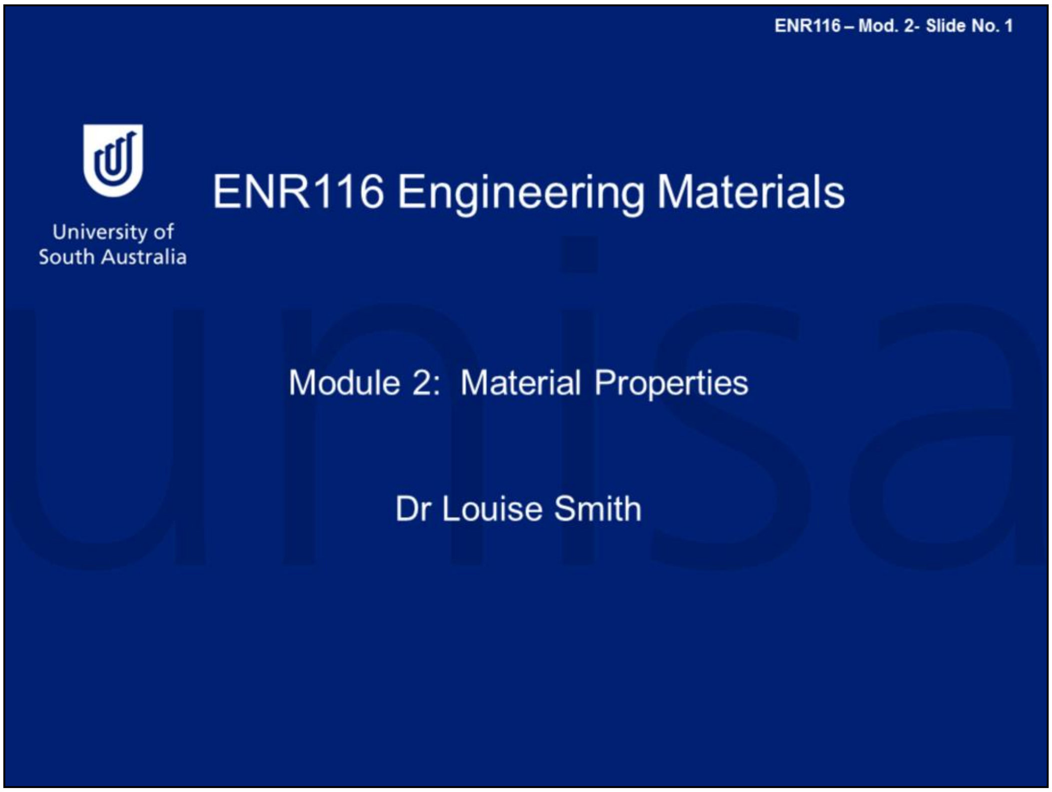

Welcome to ENR116 Engineering Materials. This lecture summary is part of module 2, Material Properties.

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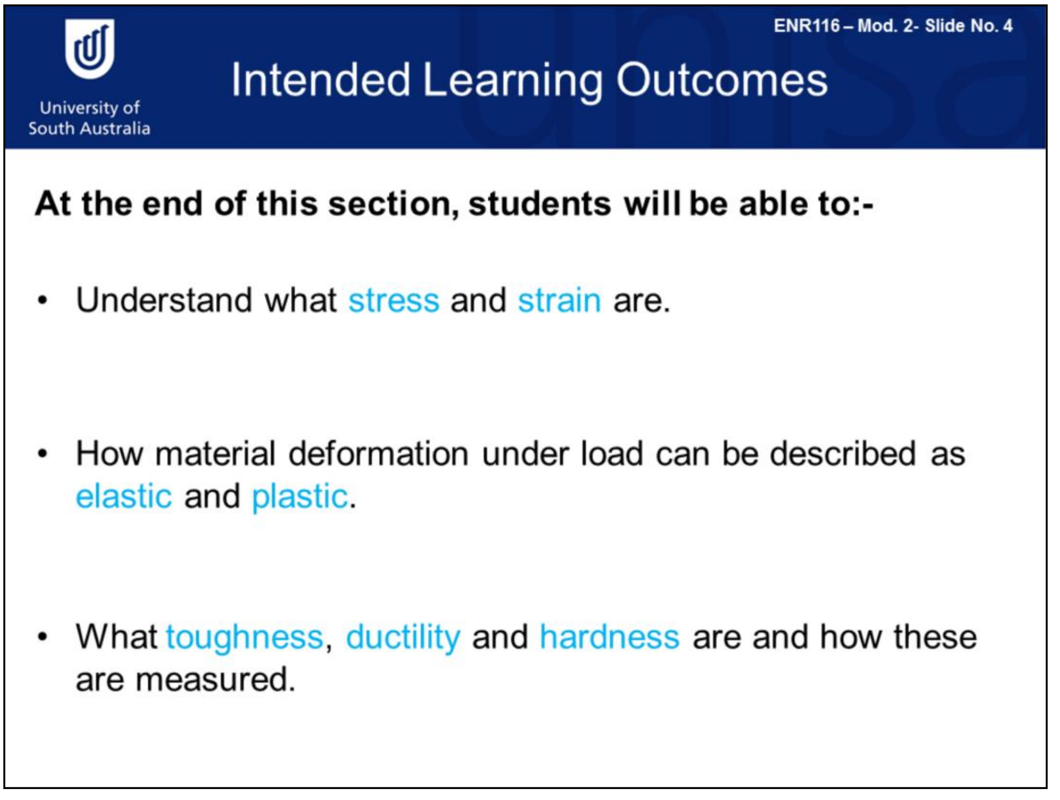
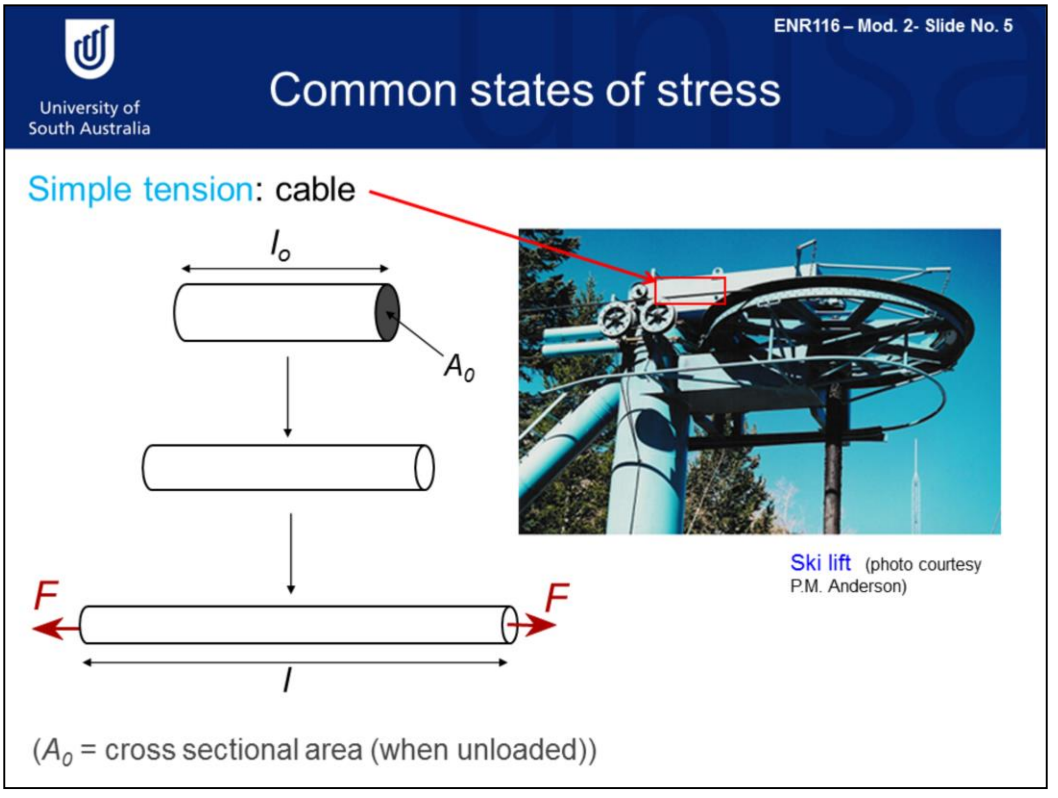
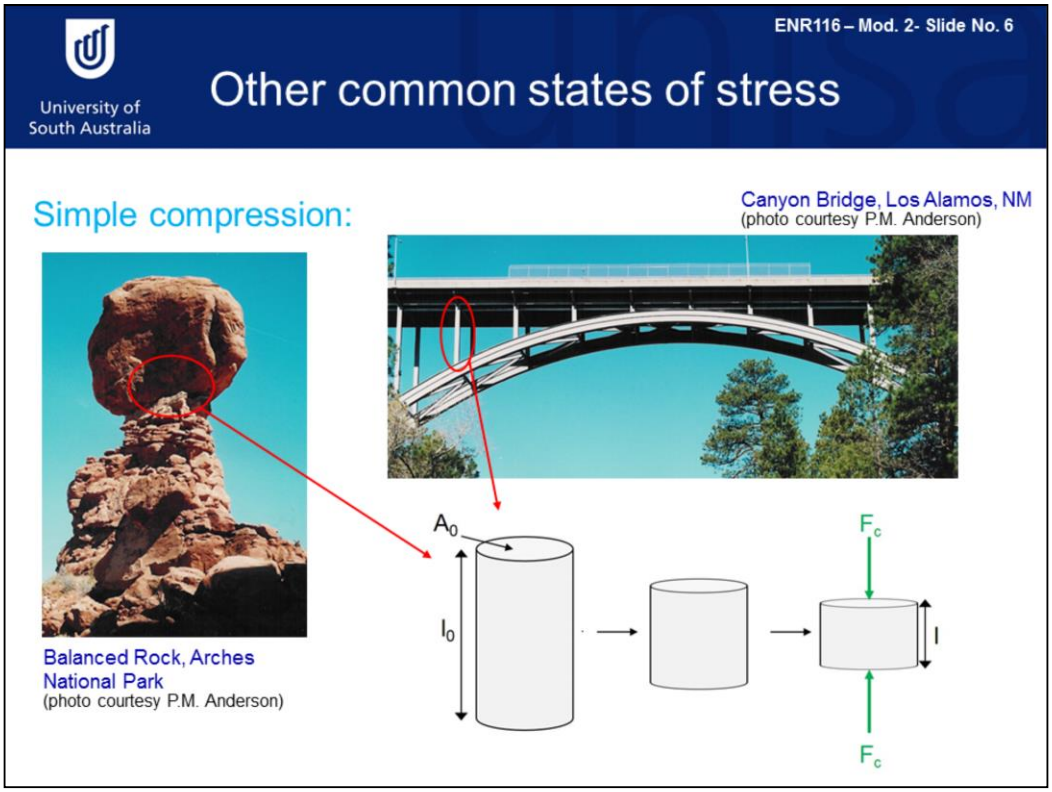
Mechanical properties.



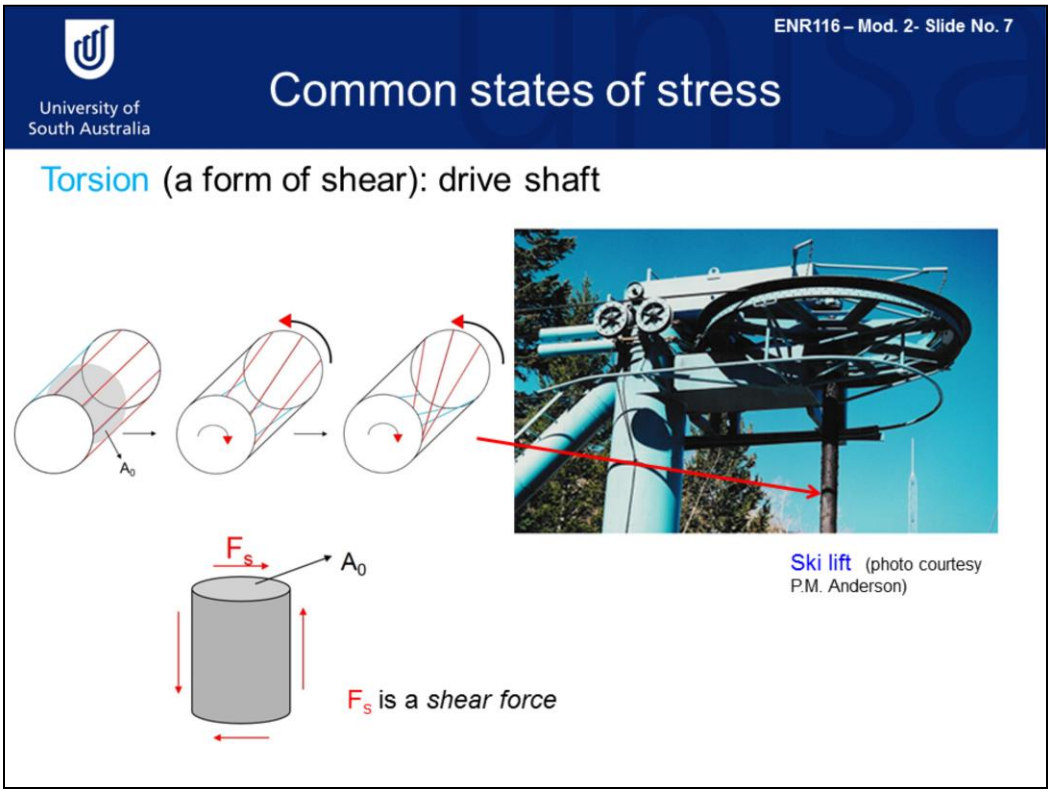
The intended learning outcomes from this lecture summary are that you will understand what stress and strain are, and how material deformation can be described as elastic or plastic. You will also understand what toughness and ductility are, as well as how both of these properties are measured.



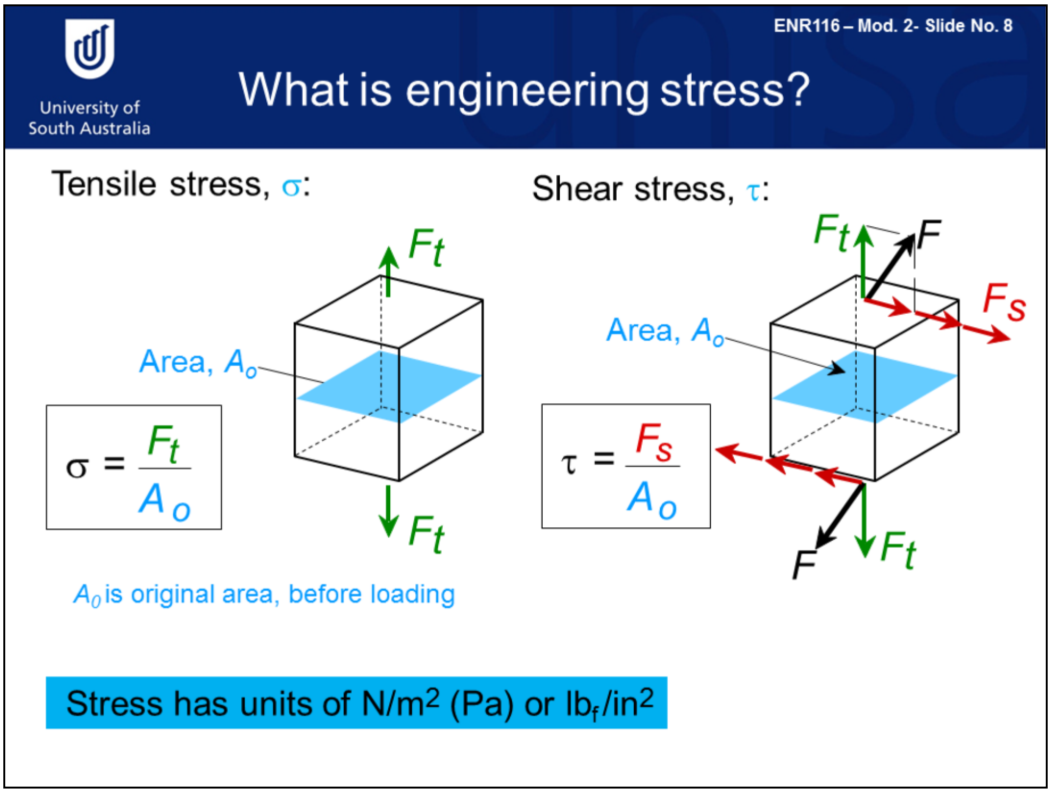
We'll start by looking at some everyday situations where materials are placed under a load. There are three principle ways in which a load may be applied, these are tension, compression and shear. In this ski lift photo, we can see some metal cables that are experiencing a tensile load. The schematic here illustrates how a tensile load causes elongation of the sample, and a corresponding reduction in the diameter of the original cross section of the sample.



Compressive loads are another form of applied stress. Here the force acts to reduce the length of the sample, and increases the diameter of the cross section. You can see an illustration of this process here.



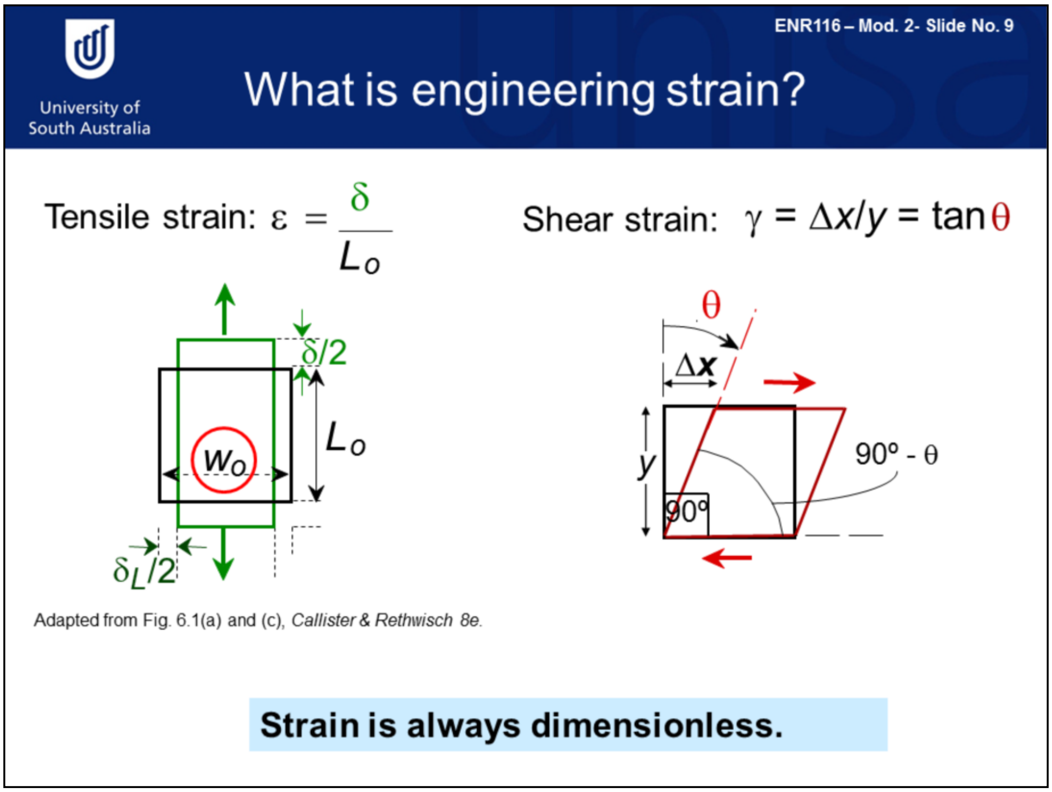
Torsion, or twisting forces, are a variation of a pure shear force. Here the ski lift drive shaft is experiencing a torsional force.



Now we've identified the principle ways in which a load may be applied, we'll define engineering stress.   In this illustration, a sample is experiencing a tensile load, or force, equal to 'F_t'. The stress that this sample is experiencing is described as the value of this instantaneous force, F_t, divided by the original cross sectional area of the sample.

In this second illustration, the same sample is experiencing a shear force, which is applied parallel to the upper and lower faces of the block. The stress is now defined as the shear force, F_s, again divided by the original area of the sample cross section.

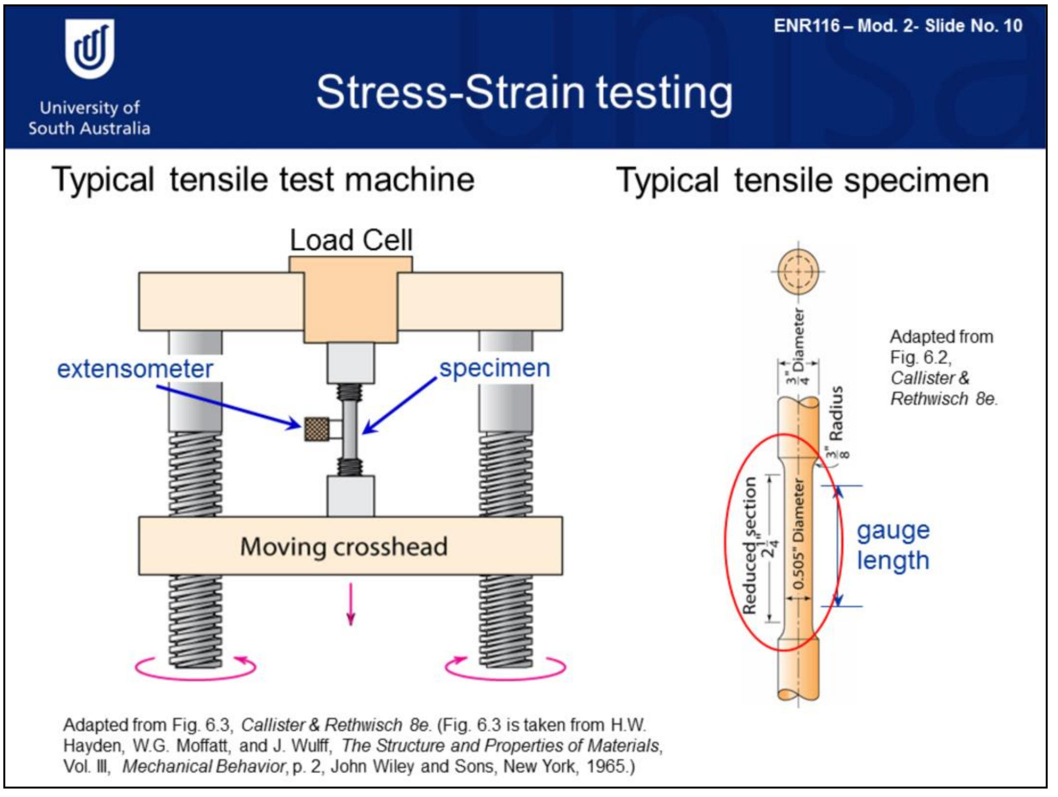
The units of stress are Newtons per meter squared, or Pascals, as 1 newton per meter squared to equivalent to 1 pascal. You may also occasionally see stress given in units of pounds per square inch, but this is less common.



Now we'll define engineering strain. Tensile strain is defined as the change in the length of the material, divided by the original sample length. The same relationship holds in the lateral direction, shown here as *W*, although here the change in length is negative as the original sample diameter is reduced, rather than increased, in this direction.

Shear strain is defined as the tangent of the strain angle, shown in the schematic here.

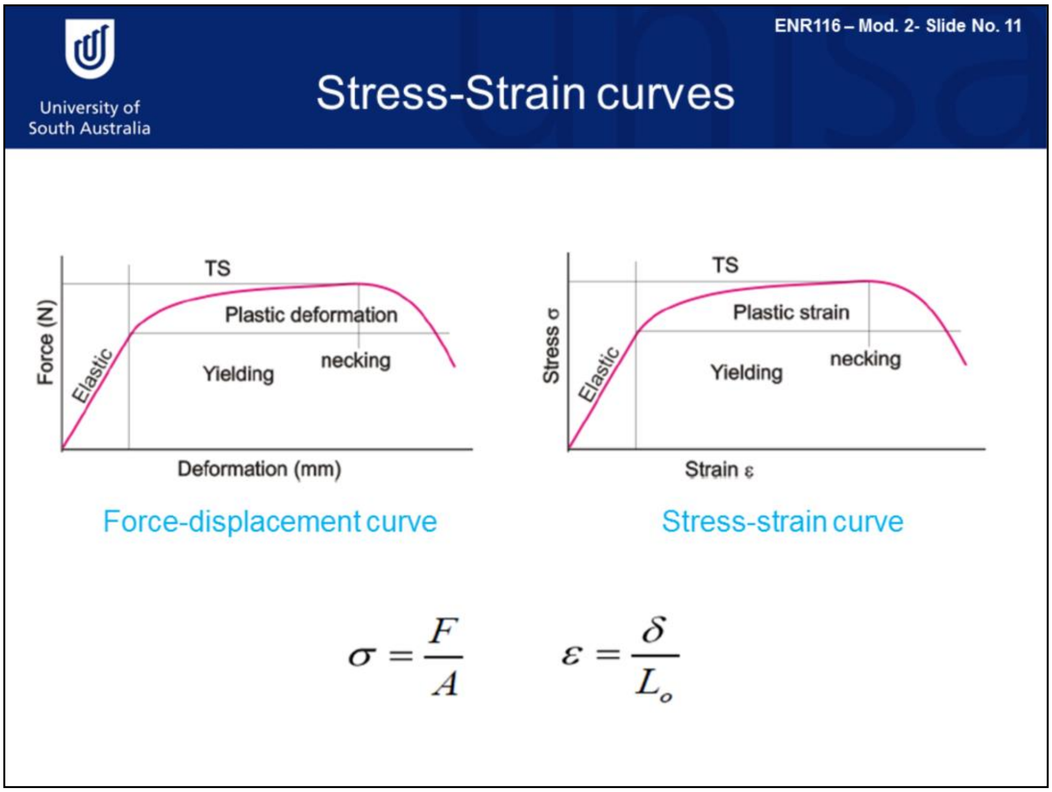
Strain is dimensionless quantity, that is, it has no units.



As the parameters of stress and strain are so important, there are international standards governing testing devices, samples and testing regimes. The important parts of a typical tensile testing machine are shown here. Every machine has a load cell to measure the applied force. The specimen is then mounted between the load cell and a moving crosshead. The crosshead moves at a set rate, as governed by the standards and the test being conducted. The rate at which the cross head moves is normally noted as an experimental condition as it can influence the behaviour of the material.

Attached to the specimen is a strain gauge or extensometer. This measures the change in length of the specimen.

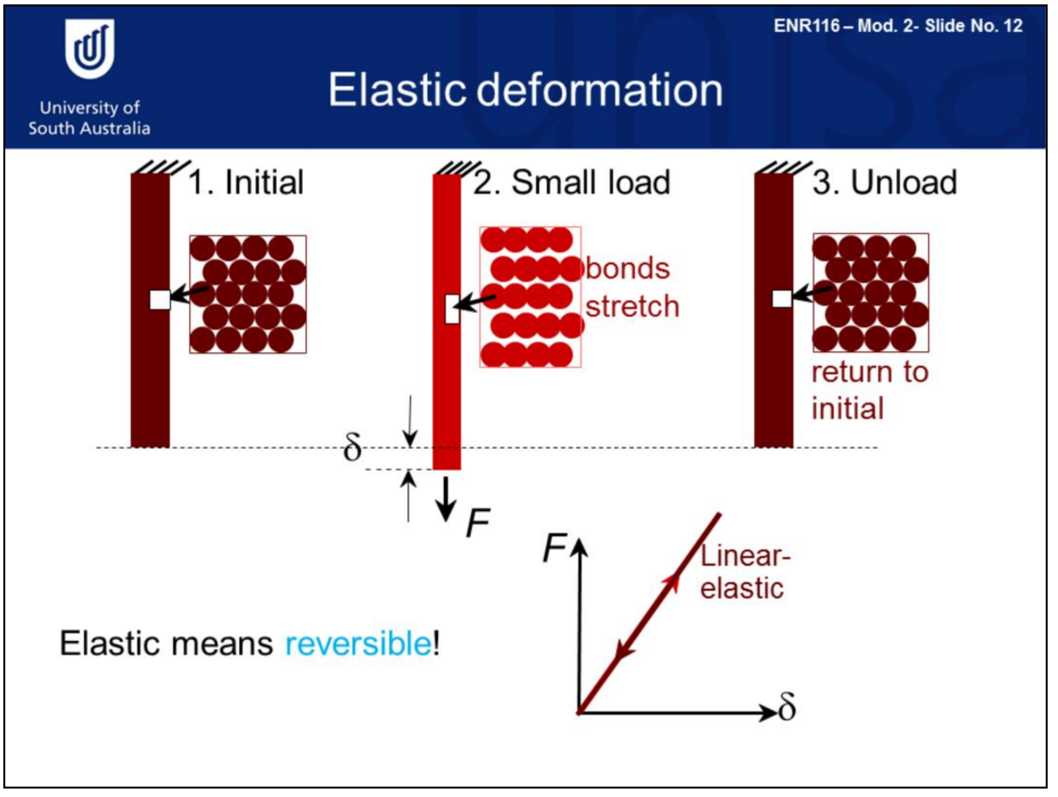
The dimensions of a typical tensile test specimen are also carefully described. The dog bone specimen shown is the one most typically used, as this allows the deformation and failure to be confined to the reduced area, which has a uniform cross section along its length. The strain gauge is normally attached to this reduced section of the specimen to measure the change in the gauge length.



Data from the stress strain experiment are given as a plot of the applied force vs the sample displacement.

However, this force displacement data is usually converted into stress strain data so that it becomes sample independent. As before, stress is equal to the force applied divided by the original cross sectional area of the sample specimen, whilst the strain is equal to the change in length divided by the original length.

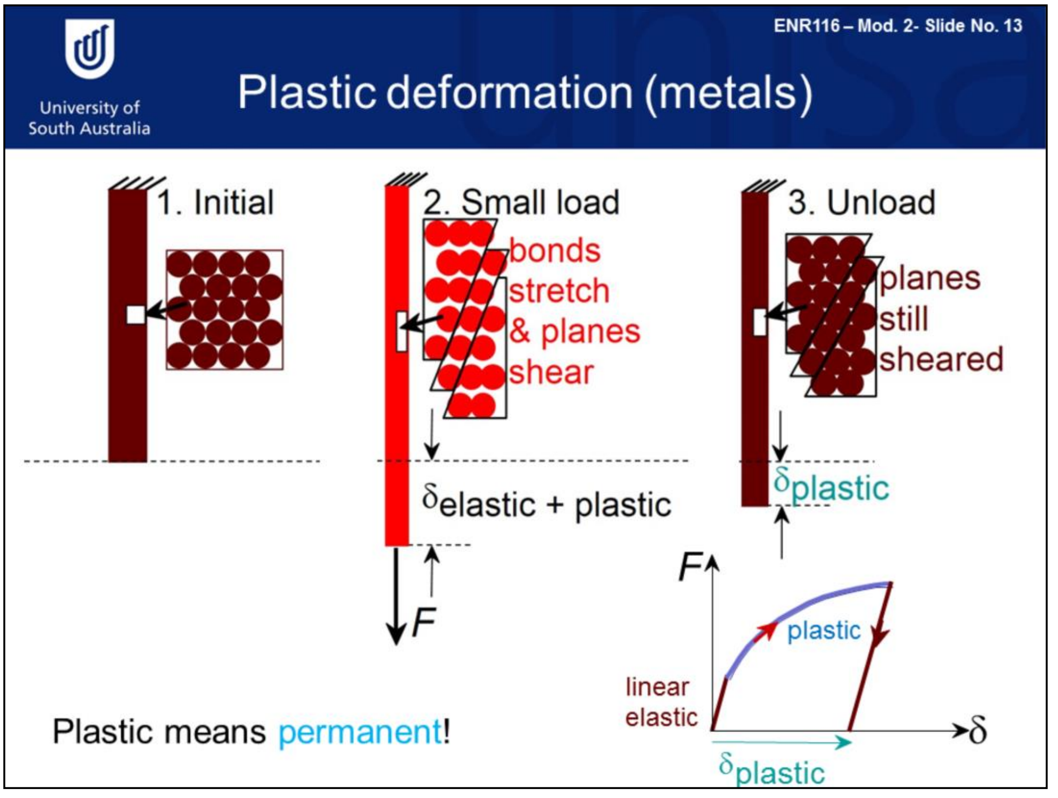
You can see from these two graphs that there is no difference in the shape of the graph. Both plots have the same initial linear portion, followed by a curved region. The next part of this lecture will look at some of these features of the stress – strain plot and their significance.



The deformation of materials can be described as either elastic or plastic. In the first of these cases, elastic deformation, the change in the sample is reversible.

This illustration represents a metal bar. If we apply a small force to the bottom of the bar, shown here as ‘F’, the bonds between the atoms will be pulled apart. The force is not enough to break the bonds, but rather just stretches them out. Under these conditions, the relationship between the load applied to the sample and the change in the length of the bar is proportional.

When the load is removed, the atoms move back to their original positions and the bond lengths revert to normal.

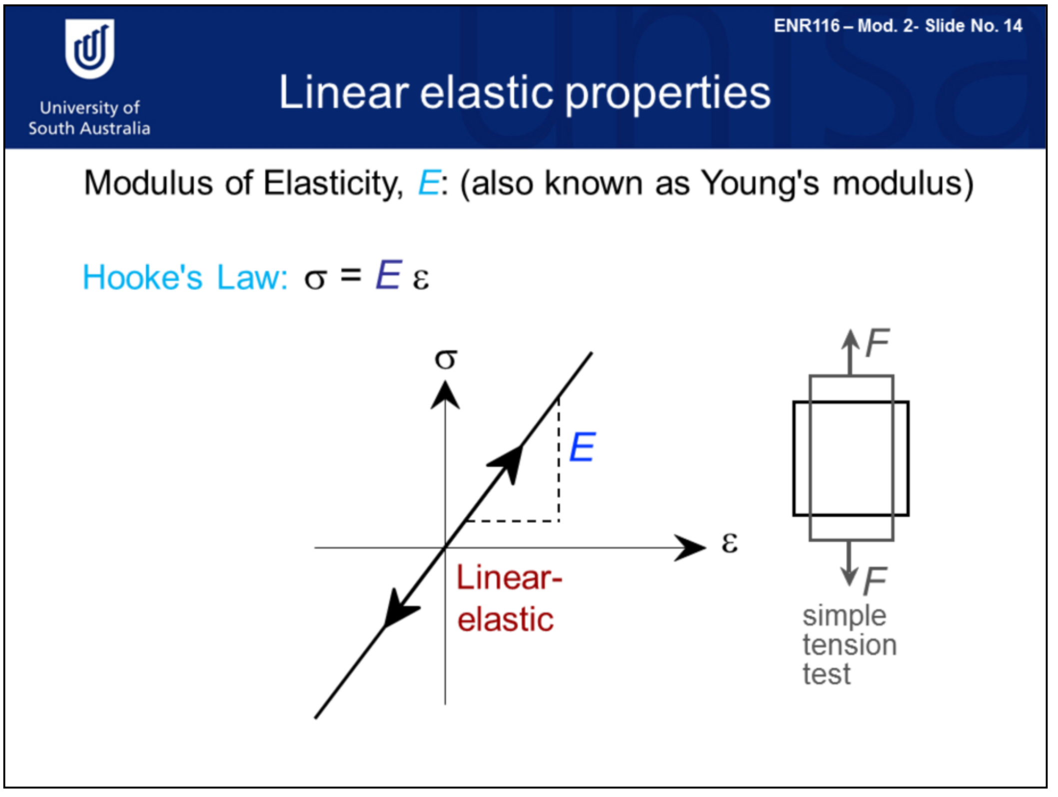


If we continue with the previous experiment, and now increase the load applied to our metal bar, we will start to see plastic or permanent deformation of the sample.

In this situation not only are the bonds between the metal atoms stretched, but the crystallographic planes of the material are forced to move and change position.

Once the load is removed, the stretched out bonds will relax and recover. However the planes that were sheared will stay in their new position and overall, the sample has experienced a mixture of both elastic (temporary) deformation and permanent plastic deformation.

If we look at a graph of force versus displacement we can see both a linear elastic region and a non-linear plastic region.



The linear elastic properties of materials can be described using Hookes Law. Here the stress is equal to the strain, multiplied by a constant of proportionality known as the Elastic modulus.

The Elastic Modulus can be determined by calculating the gradient of the elastic part of stress strain graph.

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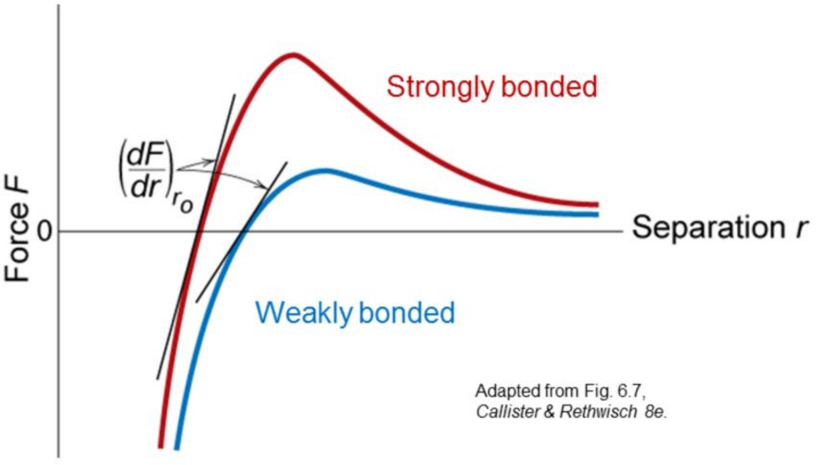
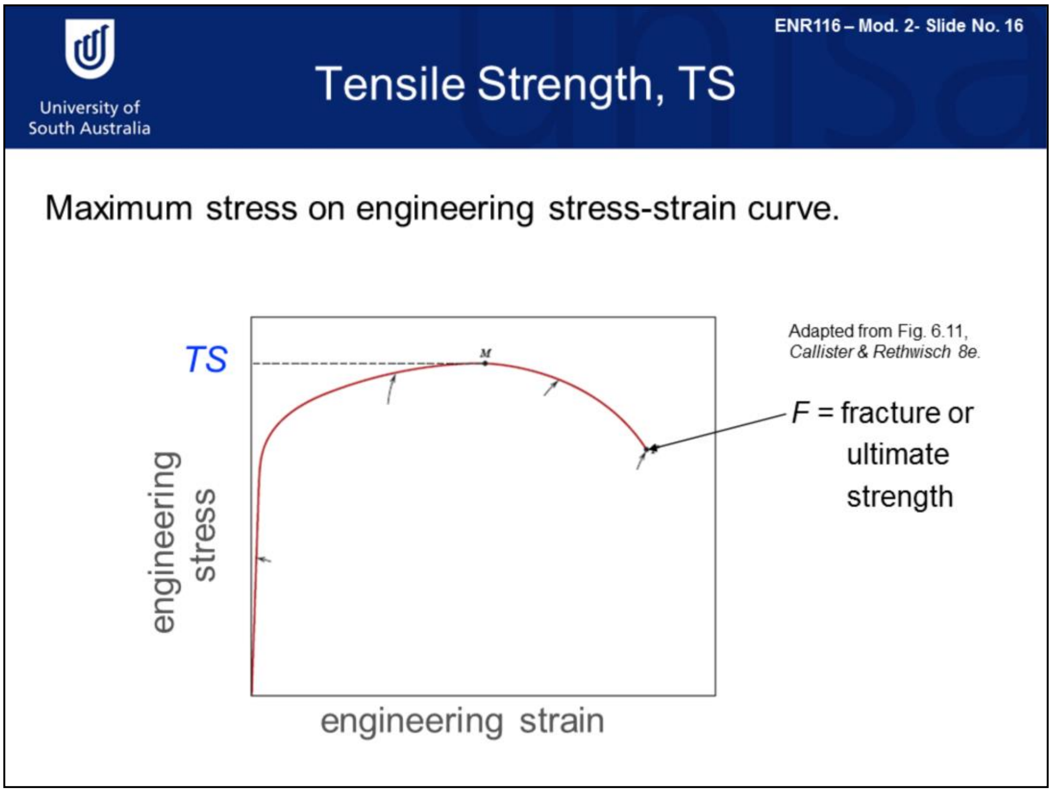
Mechanical Properties

Slope of stress strain plot (which is proportional to the elastic modulus) depends on bond strength of metal



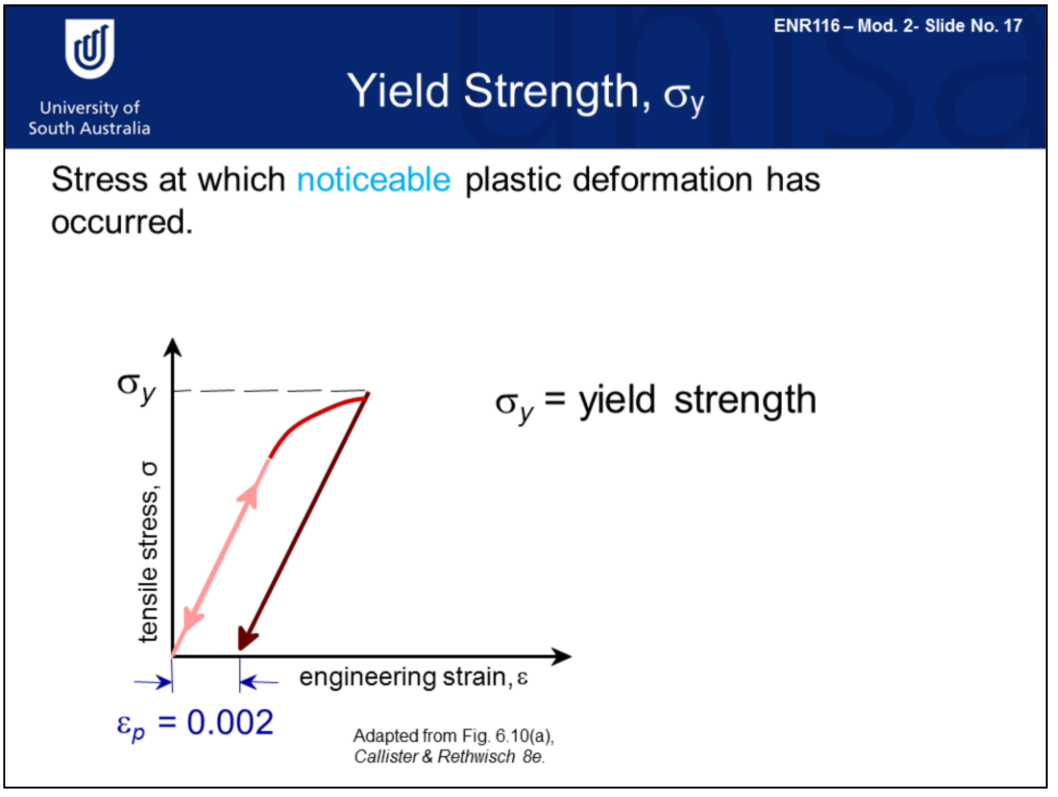
The elastic modulus provides a measure of how stiff a material is. Weakly bonded materials have a low elastic modulus and a correspondingly shallow linear elastic portion of the stress strain curve. Stiffer materials contain stronger bonds and have a sharper linear gradient.



The stress strain curve can provide more information than just the elastic modulus and yield stress. Other information includes the tensile tensile strength or ultimate tensile strength of the material. This is the stress at the maximum on the stress strain curve and is the greatest stress that the material can sustain. If this stress is applied continuously the material will fracture and fail.

All the stress in the material up to this point is uniform, however at the ultimate tensile strength the dog bone shaped tensile test specimen starts to neck. You can see this progression in the illustrations on your screen. The narrowing of the test area acts as a stress concentrator and fracture or failure will eventually occur at this site. Whilst useful to know, the ultimate tensile strength is not normally used as a design factor. This is because by the time a material has seen this load so much plastic deformation has occurred that the material is virtually useless.

A final point is the fracture, or ultimate strength of the material. This is point at which the material fails.



Lets now know take a closer look at the transition from elastic to plastic deformation.

The yield strength of a material is the point at which plastic deformation begins. Most metals experience a gradual transition from elastic to plastic behaviour. The yield strength is taken as the point at which the linear elastic region ends, and non linear plastic deformation begins.

Sometimes this transition can be difficult to determine exactly and so conventionally, a straight line is constructed parallel to the elastic portion of the stress strain graph at a specific strain offset. This is normally a strain of 0.002 or 0.2%. The stress where this line intercepts the stress strain curve is then defined as the yield stress.

If a material does not have a linear elastic region then this method cannot be used and the yield stress is simply defined as the stress required to produce some specified amount of strain.

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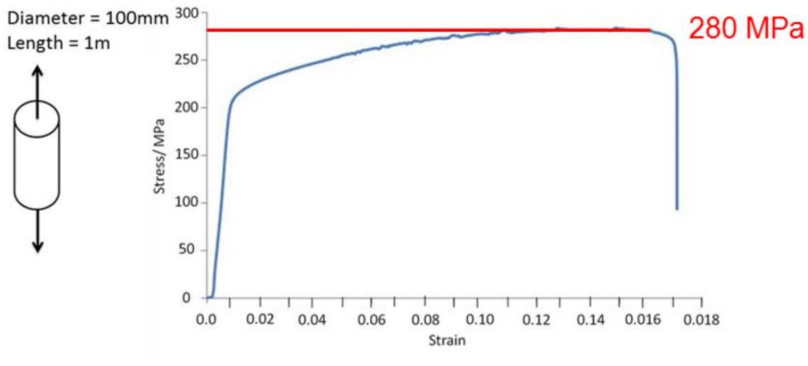
Using Stress – strain curves

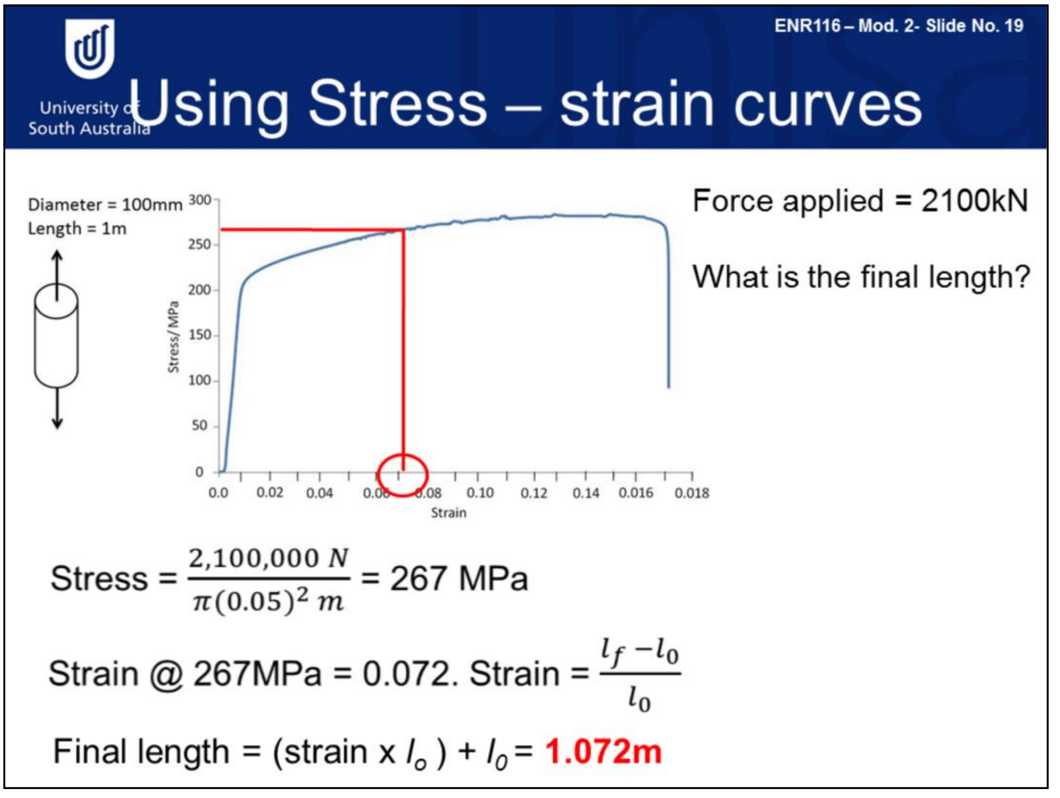
Force applied = 3000 kN. Will the piece fail?



$$\text{Stress} = \frac{3{,}000{,}000\ N}{\pi r^2\ m} = \frac{3{,}000{,}000\ N}{\pi\ (0.05)^2\ m} = 381\text{MPa}$$

Now we'll work though some practical uses of stress strain curves. Here we want to apply a tensile force of 3000kN to a metal coupon with a diameter of 100mm but before do, we want to know will the sample fail under this load?

We start by calculating the stress on the sample by dividing the load – 3000 kN – by the cross sectional area of the sample. The area of a circle is pi r^2 and we need to remember to convert the diameter given to the radius in m, and make sure that the applied force is in N. That calculation is shown here. The resulting stress on the sample is 381MPa, which we can see from the stress strain curve is much greater than the sample can tolerate. The ultimate tensile stress for this material is about 280MPa.

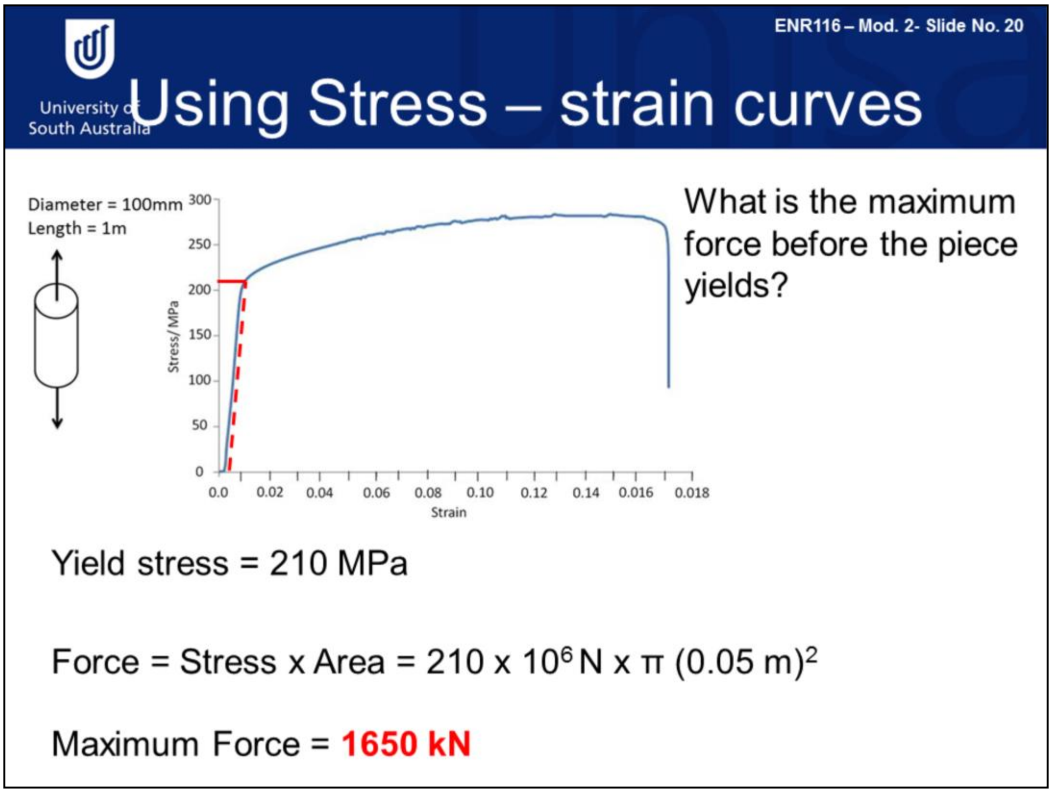


Now we are going to apply a tensile force of 2100 kN to the same sample and this time want to know what the final length of the sample will be.

We start, as before, by converting that force value to engineering stress. The process is just the same as in the previous slide, force divided by area. You can see this calculation here. The stress on the sample is 267 MPa.

Now we have a value for the stress, we can use the stress – strain curve to look up the strain on the sample at 267 MPa. You can see here that this is 0.072.

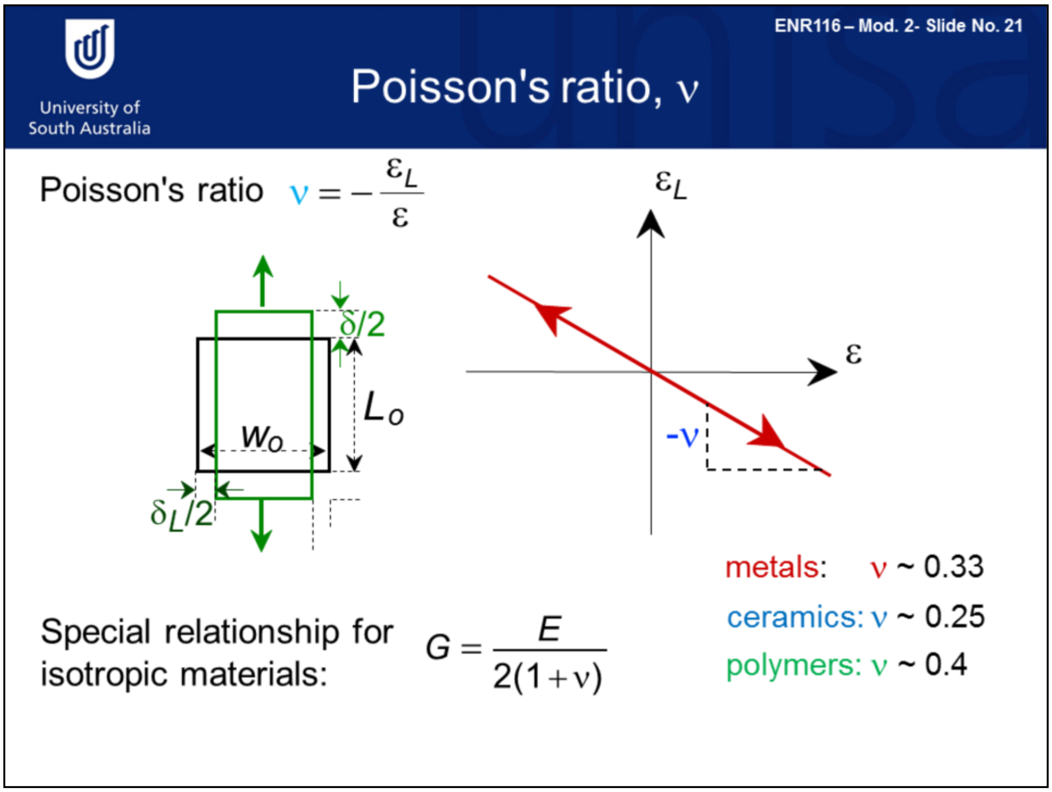
Strain is equal to the change in sample length, divided by the original length of the sample. So we can get at the final sample length by multiplying the strain value by the sample starting length, and then adding that value to the start length. The answer is 1.072 m.



We'll take a look at one last example of using stress strain curves. Here we're asked, what is the maximum force that the sample can tolerate before it yields, that is, before it moves from deforming elastically to deforming plastically?

To answer this question, we need to measure the yield point of the sample from the stress-strain curve. This is the point at which the curve deviates from a linear stress strain relationship. It's quite clear on this plot, and occurs at 210 MPa.

Now we have this value, we'll use the definition of stress to calculate the force on the sample. As before, we convert the stress to Pa (or N m^{-2}) and have the area in m^2. The force on the sample at the yield point is then 1650,000N, or 1650 kN.



Poisson’s ratio describes how a material changes shape when a force is applied.

Because material is not destroyed, the total volume of the material stays the same. As we have seen previously, when a sample stretches there is a corresponding contraction of the material in the x-y directions, or those directions perpendicular to the direction of the applied force.

If the material is isotropic (that is, it has identical properties in all crystallographic directions) then the strain in the x direction is identical to that in the y direction.

Poisson’s ratio is defined as the ratio of these lateral and axial strains and is nearly always positive.

Metals typically have a poisons ratio around 0.33, ceramics around 0.25 and polymers around 0.4. As with strain, Poisson’s ratio is dimensionless.

In the case of isotropic materials, there is also a relationship between the elastic modulus, the shear modulus and Poisson's ratio, where the shear modulus is equal to the elastic modulus divided by two times one plus Poisson's ratio. Note that Poisson's ratio only holds in the elastic region.

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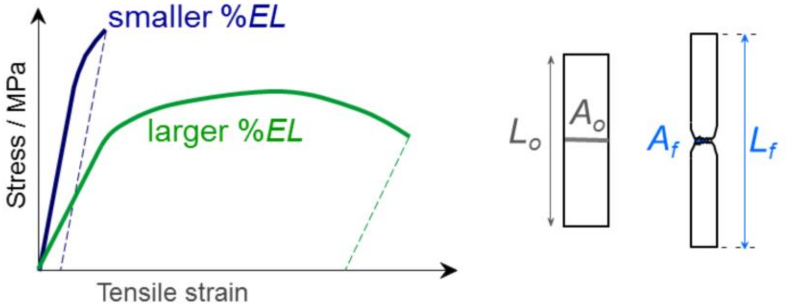
Ductility



Adapted from Fig. 6.13, *Callister & Rethwisch 8e.*

Percentage elongation: $$\%EL = \frac{L_f - L_o}{L_o} \times 100$$

Percentage reduction in area: $$\%RA = \frac{A_o - A_f}{A_o} \times 100$$

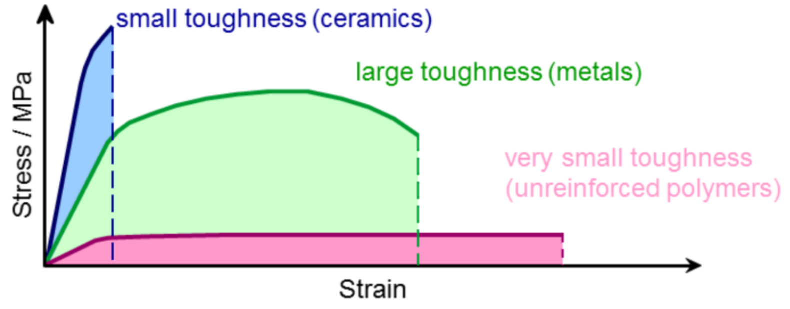
In this final part of this lecture summary we will be looking at ductility and toughness.

The ductility of a material is a measure of the amount of plastic deformation that the material has experienced prior to fracture. A material that does not experience a lot of plastic deformation is termed a brittle material, whilst a material that experiences a lot of plastic deformation is termed ductile. Brittle materials typically have a fracture strain of less than 5 percent.

We can determine the ductility of a sample from its stress strain curve. Ductility is expressed as either the percentage elongation of the sample, or, as percentage reduction in area of the original cross section of the sample. Percentage reduction in area measurements are independent of both the original area and length. It is useful to note that for a given material the magnitude of the percentage reduction in area and the magnitude of the percentage elongation will generally be different. A knowledge of the ductility of a material is important as it allows an engineer an appreciation of the amount of plastic deformation a material will undergo before fracture and failure occur. It also specifies how much allowable deformation can occur during fabrication. In this sense, ductile materials are often described as being more forgiving materials than their brittle counterparts.

Toughness

Energy to break a unit volume of material.
Approximate by the area under the stress-strain curve.



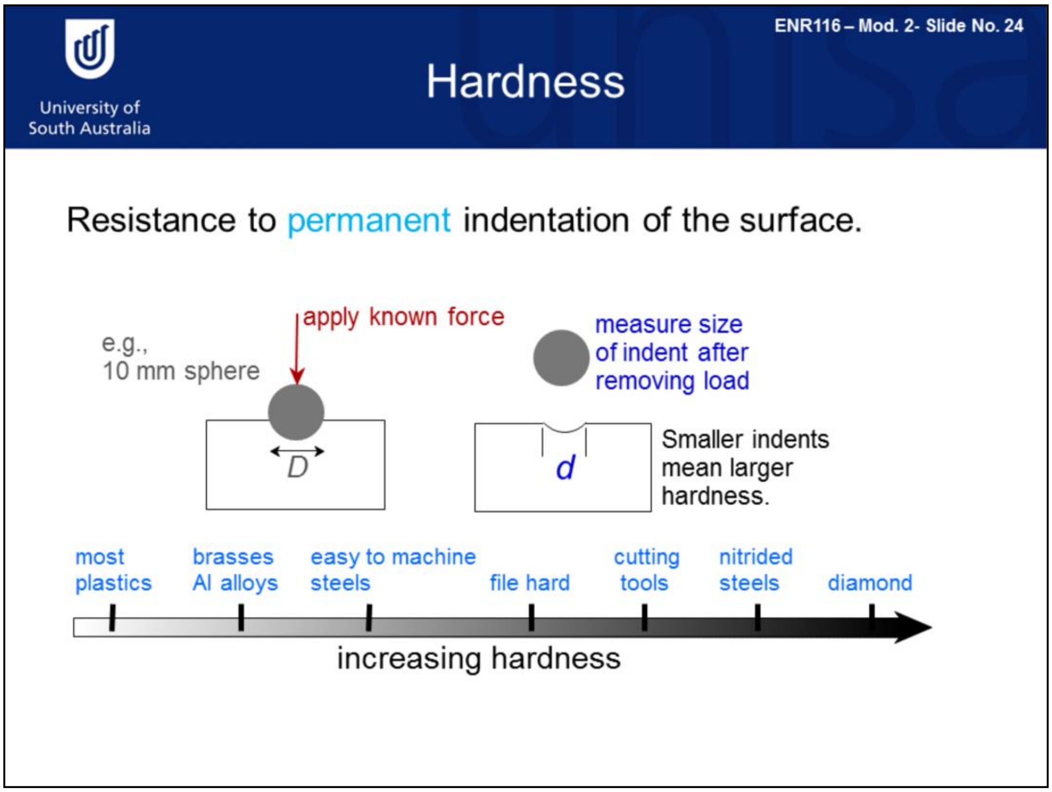
Adapted from Fig. 6.13, *Callister & Rethwisch 8e.*

Brittle fracture:	elastic energy
Ductile fracture:	elastic + plastic energy

Toughness is a term that can be used in more than one way in materials science. Fracture toughness is a material property, and defines the ability of a material to resist fracture in the presence of a flaw. Another way to define toughness is as the ability of a material to absorb energy and deform plastically before fracturing.

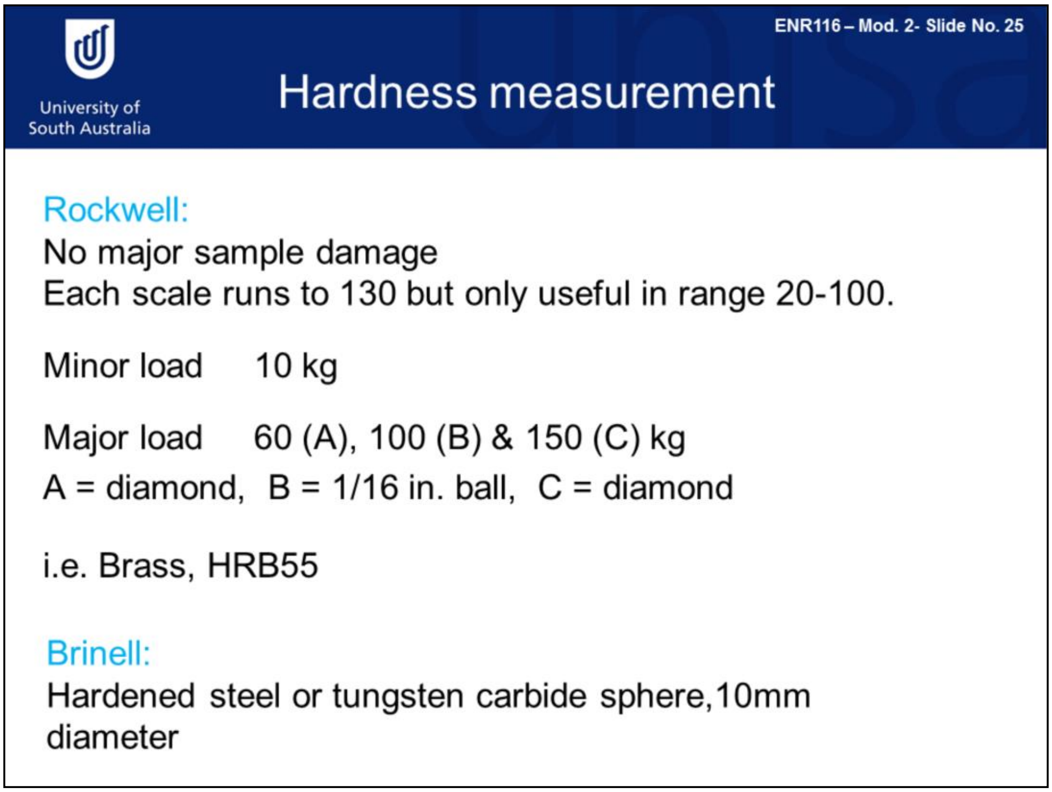
In a static, low strain rate situation, a measure of the toughness of a material can be obtained by calculating the area under the stress strain curve. Tough materials will have a large area under the stress strain curve, whilst materials will low toughness will have a corresponding low area under the curve.

The fracture toughness of a material is usually an important criterion when selecting a material for an application. The units of toughness are given as energy per unit volume of material.



The final mechanical property we will consider is material hardness. This is a measure of the resistance of a material to localised plastic deformation.

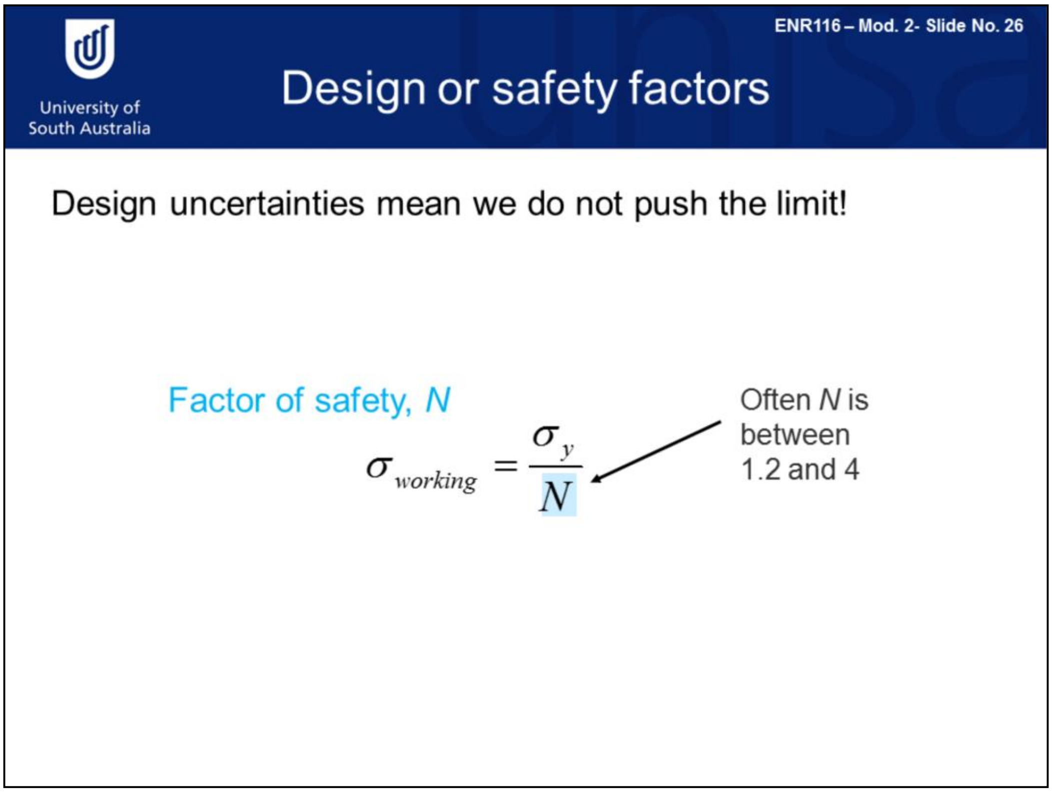
In the performance of a hardness test, a small indenter is forced into the material and the size of the resulting indent is measured. The deeper the indentation, the lower the hardness of the sample. Note however, that measured hardness values are comparative rather than absolute and therefore care should be taken when using them. That said, hardness tests tend to be performed more frequently than any other mechanical material test as they are simple and relatively inexpensive, they don't require a lot of sample preparation and other mechanical properties such as the tensile strength can be estimated from the hardness measurement.



There are a variety of hardness tests, each of which uses slightly different equipment and parameters. The Rockwell Hardness test involves initial minor load of 10 kg, followed by a major load, the magnitude of which depends on the indenter used. There are three, known as A, B and C. The resulting hardness value consists of a number, plus identifiers for both the scale and the indenter used. For example, a type of brass has a hardness of HRB55, Which represents a hardness of 55 on the Rockwell scale, indentor type B.

A Brinell Hardness test uses a hardened steel or tungsten carbide sphere of 10mm diameter. A load is applied for a specific amount of time. A Brinell hardness number includes the identifier HB, and a number that is a function of both the magnitude of the applied load and the diameter of the resulting indentation.

Other tests include the Knoop test, and the Vickers hardness test, which is sometimes called the diamond pyramid test.



Despite the extent of information we can gather about a material, there will always be uncertainties when determining exactly how a material will behaves in a set situation. Imperfections, stress concentrators and other flaws can be introduced during the manufacturing process and the part will experience some damage whilst in service.

Therefore when designing a part, the unexpected must be taken into account and we tend not to push materials to their limits.

In the early 20th century this notion was quantified by the incorporation of a design safety factor. A design stress is calculated using a estimated maximum load and a safe stress or working stress is determined using the yield strength of the material and a safety factor N which is usually between 1.2 and 4.

When choosing a safety factor it is important to remember that if N is too large then the component will be over designed. However, if it is too low, the component will potentially fail. Things that are taken into account when deciding on a safety factor include economics, previous experience, the accuracy with which the mechanical forces and material properties are known and most importantly, the consequences of component failure, including, but not limited to, damage to property and loss of life. Sudden catastrophic failure is simple not an option for the vast majority of cases.

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ENR116 – Mod. 2- Slide No. 27

Summary

- Stress and strain are size-independent measures of load and displacement.
- Elastic deformation is reversible (recoverable)
- Plastic deformation is permanent.
- Ductility is the degree of plastic deformation at failure, whilst Toughness is a measure of a material's ability to absorb energy
- Hardness values represent how a material resists localised plastic deformation

In summary, in this lecture we have discussed engineering stress and strain, and how these properties are independent of the size of the sample. Stress and strain are calculated using measures of load or applied force and displacement.

Elastic deformation is recoverable whilst plastic deformation is not.

The ductility of a material is a measure of the amount of plastic deformation that it will undergo prior to failing, whilst toughness is the ability of the material to resist deformation, or the amount of energy that the material can absorbs whilst deforming plastically, prior to fracture.

Hardness values respresent how well a material resists local indentation

Thank you