3. Behaviour That’s Not Elastic

LEARNING GOALS

Learning Objectives

1. Contrast plastic deformation with elastic deformation
2. Provide at least one atomic level definition of plastic deformation and one macroscopic definition
3. Explain why the term "plastic" is used to refer to permanent deformation
4. Sketch generalized curves for the stress-strain behaviour of metals, ceramics, and polymers
5. Summarize the need to test ceramics in bending, rather than in a tensile test
6. Describe the general theory behind tempered glass, whether thermally or chemically
7. Illustrate the final stress distribution through the thickness of a sheet of tempered glass
8. Explain how residual stresses increase the strength and improve the safety of tempered glass
9. Given all of the others, calculate any one of the following for a 3-point bend test on a rectangular sample: sample height, sample width, span between lower supports, load, peak stress in sample
10. Justify the statement that a scientific model need only be as good as it needs to be for the present discussion
11. Using two examples from the fields of materials science or solid state chemistry, demonstrate the usefulness and the limitations of a scientific model

Deformation That is Not Elastic; What Should We Call It?

[Link to this video on U of T servers.]

Exciting! Now we can start to think about what would happen to the atoms when we apply enough load

Exciting! Now we can start to think about what would happen to the atoms when we apply enough load to move beyond the elastic region. Let's call this type of deformation permanent deformation since the sample dimensions will have changed if we load beyond the elastic region, even if the load is removed. If the dimensions change permanently and the sample is made up of atoms we can once again consider our simple hard sphere model and state that during permanent deformation the atoms must move to new positions, even when the load is released.

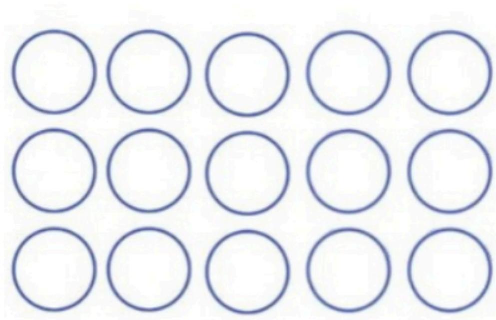


Figure 1: Atoms as spheres at equilibrium, with no load applied

This is illustrated in Figure 1 for the sample before loading, and in Figure 2 while the load is applied. Atoms have moved to new positions and the sample dimensions have changed. Even when the load is removed, although the elastic strain is reversed (the atoms move closer to one another) the atoms remain in their new positions, as shown in Figure 3).

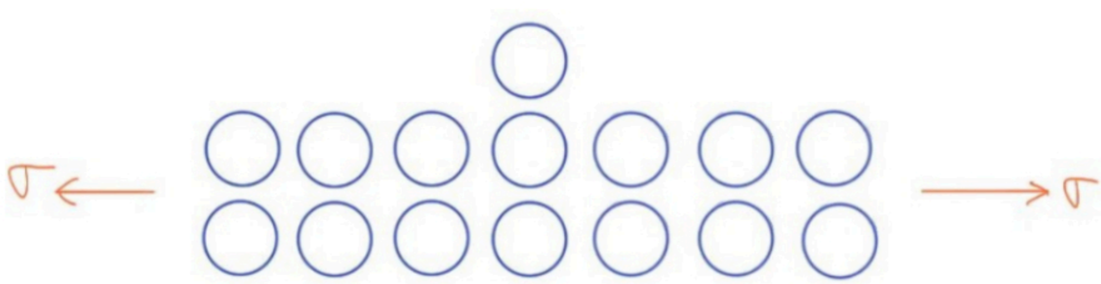


Figure 2: Schematic sketch of atoms as spheres, loaded and having experienced plastic deformation.

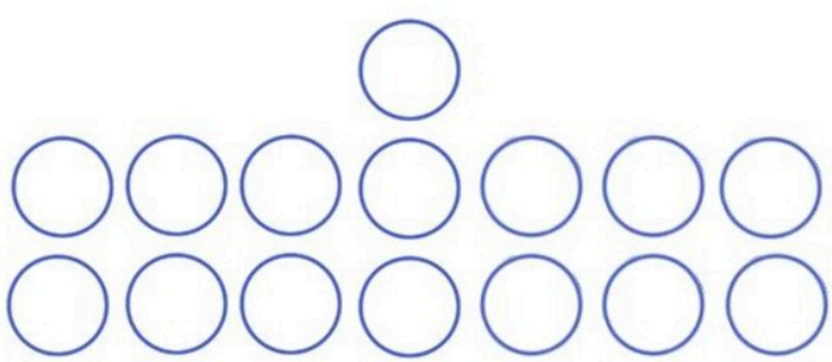


Figure 3: Atoms as spheres at equilibrium, with no load applied, after having been plastically deformed.

The obvious name for this type of deformation is *permanent deformation* but there is another name that is very commonly used - *plastic deformation*.

EXERCISE YOUR KNOWLEDGE

Q3.1.1
Review

Mark as: None

A low carbon steel component experiences a strain of .001. Determine the stress, in MPa, responsible for this strain. Express your answer to two significant figures and do not include units in your response.

Type your numeric answer and submit

$E = 200\,GPa \quad \varepsilon = 0.001 \quad \sigma = E\varepsilon$

$= 200(0.001)$

$= 0.2\,GPa = 200\,MPa$

Correct Answer:

✓ 200.0

Show Submitted Answer | Hide Correct Answer | Check My Answer

Q3.7.1
Review

Mark as: None

Which of the following would you expect to accompany plastic deformation?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	Permanent change in the macroscopic dimensions of the sample
b	Atoms moving to new equilibrium positions
c	Tensile strain does not return to zero when load is reduced to zero
d	All of the above

Correct Answer:

✓ d - All of the above

Show Submitted Answer | Hide Correct Answer | Check My Answer

Exciting Etymology! Metals, Ceramics, and Plastic Surgery

Okay, I'm being intentionally a little provocative with my title here, but the usage of the term plastic to refer to permanent deformation does cause confusion for many students first learning this topic since the term plastic is often misused in general usage. We often say, "plastic" when we really mean, "polymer." Of *course, polymer sounds a little more technical and unfamiliar to many people, so I can understand the familiar ease of the term plastic. However, plastic actually refers to the permanence of the deformation and derives from the Greek* ***plastikos*** *meaning to sculpt or shape. Although polymers are very important and useful in plastic surgery it is the permanence of the changes to anatomical features, whether cosmetic or reconstructive that gives the medical specialization its name.*

EXERCISE YOUR KNOWLEDGE

Q3.9.1
Review

Mark as: None

Which of the following is the correct etymology of the word plastic?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	This deformation is typical of the polymers, or "plastics"
b	Plastic materials don't degrade and so are permanent
c	None of these options
d	From the Greek plastikos, meaning to sculpt

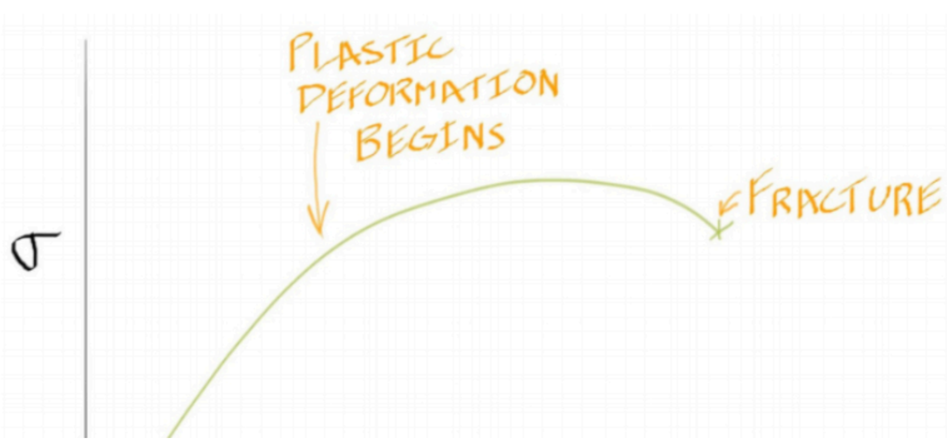
Correct Answer:

✓ **d** - From the Greek plastikos, meaning to sculpt

Show Submitted Answer | Hide Correct Answer | Check My Answer

What Then Does Plastic Deformation Look Like?

Previously we saw that most metals have an initial linear elastic region. But what happens to the stress-strain behaviour if we load beyond this elastic region?



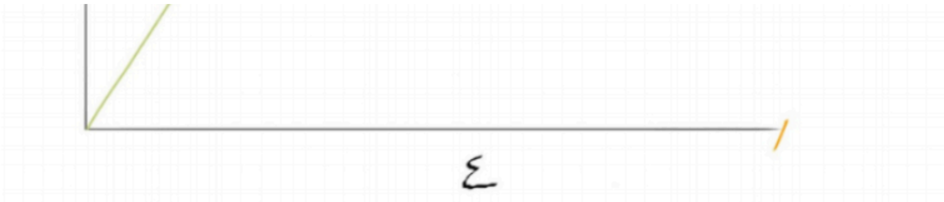


Figure 4: A generalized stress=strain curve for a metallic sample.

Figure 4 shows the generalized stress-strain behaviour for a typical metal. Plastic deformation begins close to the end of the linear elastic region, al- though it is a little tricky to determine exactly where plastic deformation begins. We'll explore this in more detail a little later.

EXERCISE YOUR KNOWLEDGE

Q3.2.1
Review

Mark as: None

Which of the following is described by a material's strength? Choose all correct options.

Multiple answers: Multiple answers are accepted for this question

Select one or more answers and submit. For keyboard navigation... Show more

a	When a wooden stick that you are bending will snap
b	How far a climbing rope elongates when supporting a climber's mass
c	How much a window bends when a strong wind blows against a building
d	How hard a shopping cart needs to be pushed into the side of a car door to create a dent in the car
e	The reason an I-beam deflects less than a square cross-section beam of the same mass and same material
f	A 10 cm long elastic band and a 20 cm long elastic band with the same elastic modulus and under the same stress will elongate different amounts but have the same this.

G

Correct Answers:

- a - When a wooden stick that you are bending will snap
- d - How hard a shopping cart needs to be pushed into the side of a car door to create a dent in the car

Show Submitted Answer | Hide Correct Answer | Check My Answer

Q3.2.2
Review

Mark as: None

Which of the following could reasonably be described by the term "stiffness?" Choose all correct options.

Multiple answers: Multiple answers are accepted for this question

Select one or more answers and submit. For keyboard navigation... Show more

a	When a wooden stick that you are bending will snap
b	How far a climbing rope elongates when supporting a climber's mass
c	How much a window bends when a strong wind blows against a building
d	How hard a shopping cart needs to be pushed into the side of a car door to create a dent in the car
e	The reason an I-beam deflects less than a square cross-section beam of the same mass and same material
f	A 10 cm long elastic band and a 20 cm long elastic band with the same elastic modulus and under the same stress will elongate different amounts but have the same this.

Correct Answers:

- b - How far a climbing rope elongates when supporting a climber's mass
- c - How much a window bends when a strong wind blows against a building
- e - The reason an I-beam deflects less than a square cross-section beam of the same mass and same material

Show Submitted Answer | Hide Correct Answer | Check My Answer

Plastic Deformation of Other Materials

So, Figure 4 has shown us what plastic deformation looks like in a typical metallic sample, but what might it look like for the other material classes? It seems obvious that it should be possible to cause plastic deformation in polymers, since the common name for them is "plastics." (Of course, by this point you know better than to be so cavalier with your terminology as to call a polymer a plastic. Perish the thought.) But are all polymers capable of plastic deformation? What about ceramics? Great questions, all of them, but let's slow down a little and first look at the generalized stress-strain behaviour for typical polymers and ceramics.

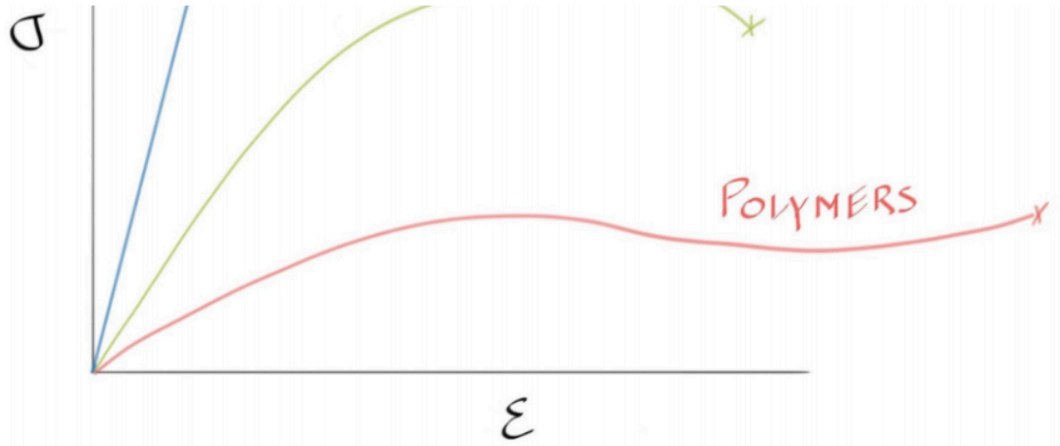


Figure 5; Generalized stress-strain curves for typical metals, ceramics and polymers, plotted on the same semi-arbitrary axes. Wow polymers have such strain to failure that the curve goes beyond the end of the x-axis! Okay you're right, I should have drawn the axis longer, but polymers do have a lot of strain to fracture.

How convenient, Figure 5 shows these very curves along with the curve for a typical metal all plotted on the same axes. You'll notice a few important features of the curves. First off, the Young's modulus of ceramics is higher than that of metals which is in turn higher than the "Young's Modulus" of polymers.

You'll also notice in Figure 5 that the strength seems to follow the same trend with ceramics being strongest and polymers the weakest. This is generally true, but it is worth mentioning now that this is only when ceramics are loaded in compression. In tension ceramics are really weak. You may think that the ceramic curve appears to be entirely linear elastic until fracture. You are correct. This is because ceramics are brittle. That is, they don't undergo plastic deformation, at least, not around room temperature. The polymer curve also has an interesting appearance in that it dips down and then comes back up a little. That can happen with a lot of polymers. The reason for this we'll explore a little later.

EXERCISE YOUR KNOWLEDGE

Q3.2.3
Review

Mark as: None

Which of the following is described by a material's strain? Choose all correct options.

Multiple answers: Multiple answers are accepted for this question

Select one or more answers and submit. For keyboard navigation... Show more

a	When a wooden stick that you are bending will snap
b	How far a climbing rope elongates when supporting a climber's mass
c	How much a window bends when a strong wind blows against a building
d	How hard a shopping cart needs to be pushed into the side of a car door to create a dent in the car
e	The reason an I-beam deflects less than a square cross-section beam of the same mass and same material

f	A 10 cm long elastic band and a 20 cm long elastic band with the same elastic modulus and under the same stress will elongate different amounts but have the same this.

Correct Answer:

✓ f - A 10 cm long elastic band and a 20 cm long elastic band with the same elastic modulus and under the same stress will elongate different amounts but have the same this.

Show Submitted Answer | Hide Correct Answer | Check My Answer

Q3.2.4
Review

Mark as: None

Which of the following is described by a material's Young's modulus? Choose all correct options.

Multiple answers: Multiple answers are accepted for this question

Select one or more answers and submit. For keyboard navigation... Show more

a	When a wooden stick that you are bending will snap
b	How far a climbing rope elongates when supporting a climber's mass
c	How much a window bends when a strong wind blows against a building
d	How hard a shopping cart needs to be pushed into the side of a car door to create a dent in the car
e	The reason an I-beam deflects less than a square cross-section beam of the same mass and same material
f	A 10 cm long elastic band and a 20 cm long elastic band with the same elastic modulus and under the same stress will elongate different amounts but have the same this.

Correct Answers:

✓ b - How far a climbing rope elongates when supporting a climber's mass
✓ c - How much a window bends when a strong wind blows against a building

Show Submitted Answer | Hide Correct Answer | Check My Answer

Q3.3.1
Review

$F = 83 kN = 0.083$ $d = 12 mm = 0.012 m$ $A = \frac{\pi d^2}{4} = 1.131 \times 10^{-4} m^2$

Mark as: None

A cylindrical tensile tie (component that supports a tensile load) is loaded with a 83 kN force. The tie has a diameter of 12 mm. Determine the engineering stress, in MPa in this tie. Express your final answer with two significant figures and do not include units in your response.

Type your numeric answer and submit

$\sigma = \frac{F}{A} = \frac{0.083}{1.13 \times 10^{-4}} = 733 \simeq 730$ GPa

Correct Answer:

✓ 730.0

Show Submitted Answer | Hide Correct Answer | Check My Answer

Q3.10.1
Review

Mark as: None

Which of the following best describes the generalized mechanical behaviour of a polymer?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	Higher elastic modulus than metals only, higher strain to fracture than ceram- ics only, fractures soon after necking
b	Lower elastic modulus than metals and ceramics, higher strain to fracture than metals and ceramics, significant load bearing after necking
c	Lower elastic modulus than ceramics only, higher strain to fracture than ceramics and metals, fractures soon after necking
d	Lower elastic modulus than metals only, higher strain to fracture than metals and ceramics, significant load bearing after necking

Correct Answer:

✓ **b** - Lower elastic modulus than metals and ceramics, higher strain to fracture than metals and ceramics, significant load bearing after necking

Show Submitted Answer | Hide Correct Answer | Check My Answer

Side Note: Is it Young's Modulus or "Young's Modulus?"

Why did I put Young's modulus in quotes just then? Good question. Although we commonly do use the term Young's modulus when referring to the elastic behaviour of polymers, some purists will argue that this is misleading or even inaccurate since the elastic response of polymers depends on many different bond types including various primary bonds and secondary bonds; more to come on these later. As you'll recall from the previous notes, the Young's modulus is related to the behaviour of a single bond type. For this reason, you will sometimes see the term ***elastic modulus*** *used instead of Young's modulus when referring to polymers and composite materials.*

EXERCISE YOUR KNOWLEDGE

Q3.4.1

Mark as: None

Review

Mark as: None

The Young's modulus of a specific steel alloy following extensive plastic de- formation would be expected to be the same as the Young's modulus of the same steel alloy after being annealed for a long time.

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	True
b	False

Correct Answer:

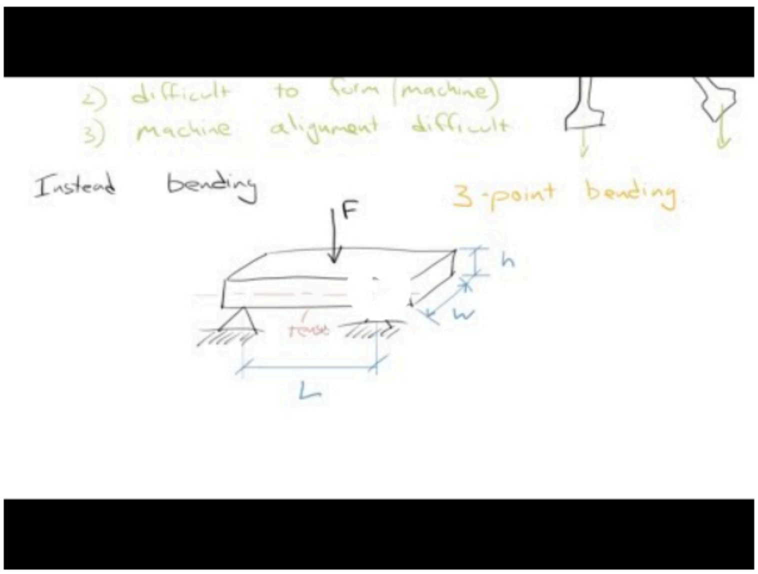
✓ **a** - True

Show Submitted Answer

Hide Correct Answer

Check My Answer

Mechanical Testing of Ceramics



[Link to this video on U of T Servers.]

Say you decide that it is a good choice to include a ceramic component in a design. How do you validate the strength provided by the suppliers? For that matter, how do you determine the strength of a ceramic in the first place? Well, since ceramics are so strong and brittle it is very difficult to machine them into the nice tensile coupons that we saw earlier and are used for metals and polymers. The high strength causes your cutting tools to become dull very quickly and what's more, the ceramic itself is likely to shatter during the machining operation. Finally, and this is a little more subtle, even if we did manage to make a nice ceramic tensile sample, it is very challenging to align a ceramic sample exactly along the loading axis. You see, metals and polymers are relatively ductile, that is, they have high plastic strain to fracture.

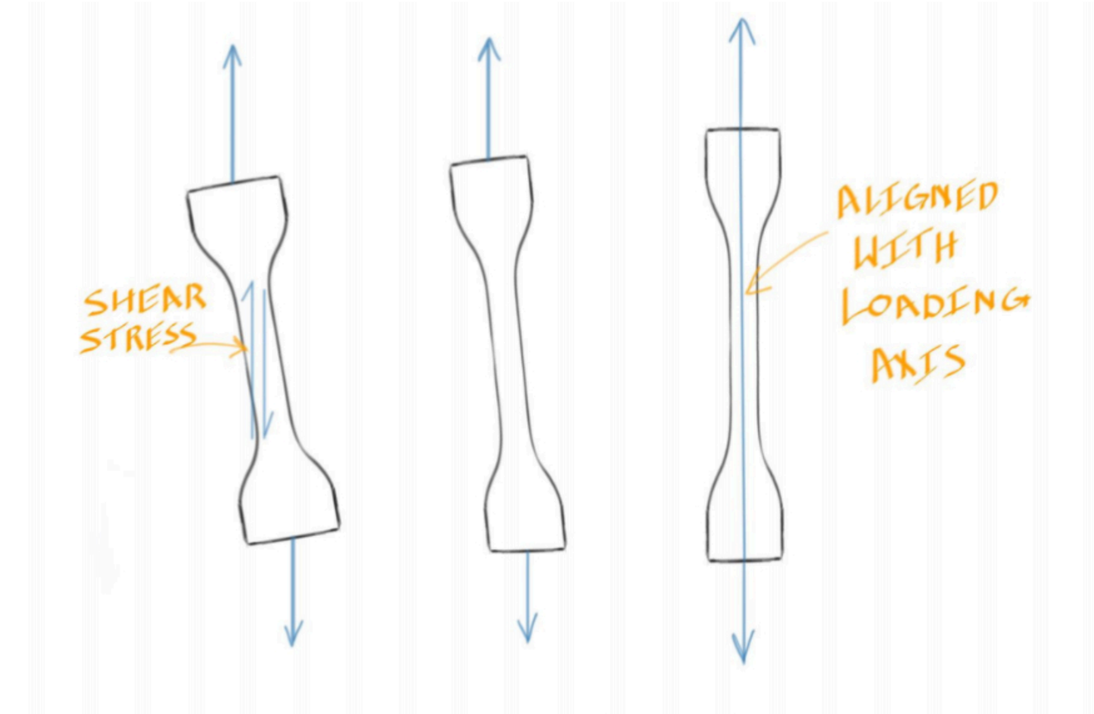


Figure 6: The challenge of aligning a sample with the tensile loading axis. Metals and polymers, even when loaded slightly off axis (exaggerated here) will deform and self-align with the loading axis. Ceramics fracture at a very low strain values while the sample is still subjected to significant shear stress.

For this reason, even if we put a metal or polymer sample into a tensile testing machine at a slight angle, once the test starts the sample will deform and become aligned with the tensile loading axis, as show in Figure 6. A ceramic will fracture at a very low value of strain while the sample is still experiencing significant shear stresses. A valid tensile test should expose the sample to only a uniaxial tensile load. For these reasons we often test ceramics in bending. The beam geometry is quite simple and relatively easy to prepare on a water cooled diamond saw, for example. A common form of bend test is the three-point bend test and is illustrated in Figure 7.

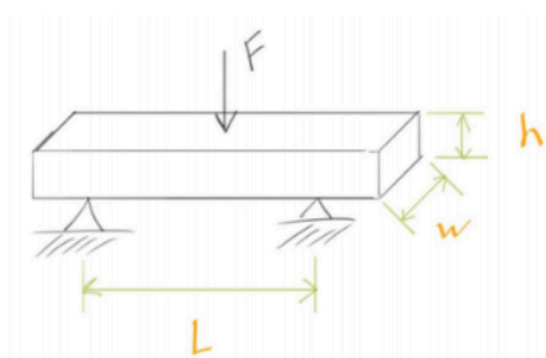


Figure 7: A cartoon sketch of a three point bend test on a rectangular cross-section beam.

The lower surface of a beam loaded as shown will be in tension, while the top surface will be in compression. This means that the stress state on the top and bottom surfaces actually have opposite sign. To have opposite sign, the stress therefore must have passed through zero stress. This is called the neutral axis and you'll learn more about this in your mechanics course. Anyway, since the stress varies through the thickness we need to think about where on (or in) the beam we are interested in knowing the stress. Since ceramics perform poorly in tension, the beam will fracture first on the lower surface, specifically near the middle, underneath where the load is applied. The equation that determines the stress in the middle of the lower surface is

$$\sigma = \frac{3FL}{2wh^2} \tag{1}$$

EXERCISE YOUR KNOWLEDGE

Q3.3.2
Review

Mark as: None

A rectangular cross section tie (component that supports a tensile load) is loaded with a 35 kN force. The cross section of the tie is 30 mm × 10 mm. The tie is 1.3 m long and elongates by 0.72 mm. Determine the engineering strain experienced by this tie while under load. Express your final answer with two significant figures and in scientific notation in the format of this example: to write 3.3×10^{-8}, please write 3.3e-8.

$\varepsilon = \frac{\Delta l}{l_0} = \frac{0.72}{1300} = 0.0005538 = 5.5 \times 10^{-4}$

Type your answer and submit

Write your response here...

$\Delta l = 72 mm \quad l_0 = 1.3 m = 1300 mm$

Correct Answers:

✓ 5.6 e-4
✓ 5.5e-4

Show Submitted Answer | Hide Correct Answer | Check My Answer

Q3.11.1
Review

Mark as: None

Which of the following is generally a correct statement?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	Ceramics are brittle, with lower Young's moduli than metals, while metals are ductile
b	Ceramics are brittle, with higher Young's modulus than metals, while metals are ductile
c	Ceramics are ductile, with higher Young's modulus than metals, while metals are ductile
d	Ceramics are brittle, with higher Young's modulus than metals, metals are also typically brittle

Correct Answer:

✓ b - Ceramics are brittle, with higher Young's modulus than metals, while metals are ductile

Show Submitted Answer | Hide Correct Answer | Check My Answer

Q3.12.1
Review

Mark as: None

Which of the following is a reason that ceramics are tested in bending, rather than tension?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	Ceramics are difficult to machine
b	Ceramics fail at low values of strain
c	Ceramics are brittle and therefore difficult to grip
d	All of the above

Correct Answer:

✓ d - All of the above

Show Submitted Answer | Hide Correct Answer | Check My Answer

Q3.13.1
Review

Mark as: None

A rectangular cross-section beam having height 12 cm and width 42 cm is supported by two supports spaced 2.8 m apart. A load of 8900 N is applied to the top of the beam at mid span. Determine the maximum stress on the lower surface of this beam, in MPa. Express your final answer with two significant figures and do not include units in your response.

Type your numeric answer and submit

Given $h = 12cm = 0.12m$ $w = 42cm = 0.42m$

$L = 2.8m$ $F = 8900N$

Correct Answer:

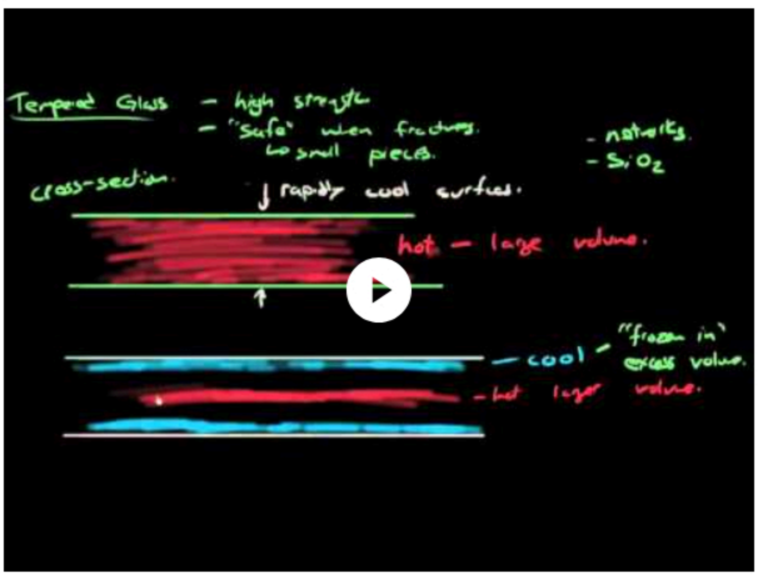
✓ 6.2

$$\sigma = \frac{3(8900)(2.8)}{2(0.42)(0.12^2)} \times 10^{-6} = 6.18 \simeq 6.2$$

Show Submitted Answer | Hide Correct Answer | Check My Answer

Why Would I Balance on a Thin Sheet of Glass?

If you were in lecture, you likely saw me standing on a thin piece of *tempered* glass and you may have even seen it deforming elastically. The glass that I stood on was conventionally thermally tempered glass. This is quite an interesting material. When the glass is at a high temperature the surfaces are rapidly cooled. The microstructure of glass is actually quite complicated and there are 3-dimensional networks of bonds within the glass. At elevated temperatures the molecules are further apart, however when the surfaces are rapidly cooled some of this excess volume from the higher temperature is locked into the glass. The central portion of the glass however continues to cool more slowly and the molecules are better able to organize and achieve a smaller final volume. This means that the final piece of tempered glass, once it has cooled, contains residual stresses. The surfaces are being pushed together as the center tries to contract. The surfaces are therefore in residual compression, while the center is in residual tension. Because of this, when I stand on the tempered glass beam and you see the beam bend the lower surface is still under a net compressive load. Since ceramics are strong in compression, the glass does not break and I don't get hurt. This is why tempered glass is stronger than conventional glass. It also explains why tempered glass breaks into small pieces if it does fracture. Ever seen a broken car window? The pieces of glass are really small. Ever broken a screen on your phone? Lots of small pieces, right? This is because the residual strain energy in the glass attempt to convert to surface energy in the form of new surfaces during fracture. How do you make a lot of surface energy? Lots of small pieces. (As a side note: your phone screen is chemically tempered, but the same principle with residual compressive stresses at the surfaces applies.)



[Link to this video on U of T servers.]

EXERCISE YOUR KNOWLEDGE

Q3.14.1
Review

Mark as: None

Which of the following best describes the way that thermally tempered glass is produced?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	Rapid cooling results in a higher density at the surface and slower cooling results in a lower density in the centre.

b	Rapid cooling results in a lower density at the top surface and slower cooling results in a higher density on the lower surface.
c	Rapid cooling results in a lower density at the surface and slower cooling results in a higher density in the centre.
d	Cooling rate does not influence the final density of the glass.

Correct Answer:

✓ c - Rapid cooling results in a lower density at the surface and slower cooling results in a higher density in the centre.

Show Submitted Answer Hide Correct Answer Check My Answer

Q3.15.1
Review

Mark as: None

Which of the following is generally an accurate description of the stress distribution through the thickness of an unloaded piece of chemically tempered glass, such as Gorilla Glass(R)?

Select an answer and submit. For keyboard navigation, use the up/down arrow keys to select an answer.

a	Compressive on top surface, tensile on lower surface
b	Tensile on top surface, compressive on lower surface
c	Tensile on top surface, compressive through centre, tensile on lower surface
d	Compressive on top surface, tensile through centre, compressive on lower surface

Correct Answer:

✓ d - Compressive on top surface, tensile through centre, compressive on lower surface

Show Submitted Answer Hide Correct Answer Check My Answer

Assigned as Review ⓘ

Q3.16.1

Peer Review - Explain how residual stresses increase the strength and improve the safety of tempered glass.

Responses

Reply

Showing All Responses

Models Have All the Fun

Link to this video on U of T servers.

Okay, this may seem obvious but I think it is worth mentioning: in science we strive to understand the world around us and in so doing come up with new ways to improve the world. In order for our human brains to attempt to understand the universe and the things in it we come up with scientific models. These scientific models are like analogies that allow us to simplify really complicated things and to predict behaviour. For example, one of the early models of the atom is the Bohr model, which is a planetary model. That is, if we are using the Bohr model we can think of the electrons as if they were little planets orbiting around the sun. It's familiar and that is comforting to humans. What's more? It even predicts some behaviour of the atom accurately, specifically energy absorbed and released by electrons when they move from one orbital to another. Of course, the Bohr model has some limitations and so along the way, as scientists came across data that the Bohr model did not predict, they released improvements, like firmware updates, to the Bohr model so that it still worked and then eventually when the updates just weren't cutting it, a new model was released. A little like an iPhone, but I digress. The point here is that a model does not need to be complete or accurate in every way. If it was, we wouldn't need a model. A model only needs to be as good as it needs to be for the purpose that you are using it. More on this later.

EXERCISE YOUR KNOWLEDGE

Assigned as Review

Q3.6.1

Peer Review - Using a specific example, discuss a scientific model that is currently used. Explain the circumstances when your example is useful and also elaborate on a scenario when your chosen model would be inadequate or inappropriate.

Responses

Reply

Showing All Responses Ordered by Newest Responses

Ethan Robertson 6 months ago

A scientific model that is currently used to show covalent and ionic bonding in simple compounds is the Lewis dot model of atoms. This model is useful to show how electrons are shared between atoms in covalent bonding and being taken by the more electronegative atom in ionic bonding. For covalent bonding, single, double, and triple bonds are represented by lines between molecules. This enables the visualization of simple atomic structure and can be used to explain polarity of simple compounds. This model fails however to explain resonance structure and the properties that would result from them, such as the electrical conductivity of graphene. In the Lewis model of graphene, carbons are bonded together in repeating hexagonal rings with alternating single and double bonds. This model for visualizing graphene fails to explain its conductivity and a 3-d orbital model is instead needed. This is because the secondary bond electrons are actually delocalized across the overlapping 2p orbitals of all carbons in the graphene sheet, which was not shown in the Lewis model showing it to be inadequate.

Comments 0 5

Wrapping it all up

So, we've learned that plastic, or permanent, deformation involves atoms moving to new equilibrium positions. These new equilibrium positions will still be at the same equilibrium interatomic spacing, but the atoms will be in new positions. Ceramics don't undergo plastic deformation at room temperature, which is another way of saying that they are brittle. Ceramics are hard to test in tension so the next best thing is a bend test.

All images and videos are created by author.