Basic Construction Materials
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Lecture – 5
Materials Engineering Concepts – Part 2
(Characteristic Value and Stress-Strain Behaviour)

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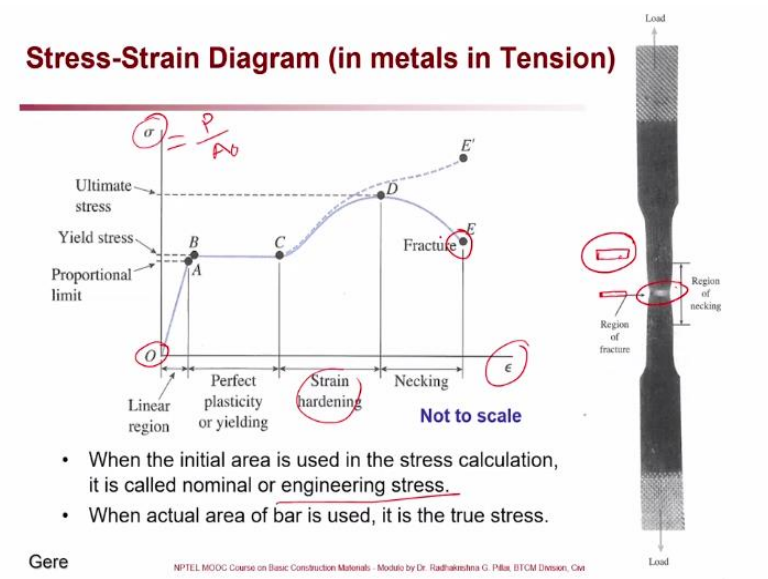

Stress-Strain Diagram (in metals in Tension)

- When the initial area is used in the stress calculation, it is called nominal or engineering stress.
- When actual area of bar is used, it is the true stress.

Gere

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Now let us talk about the stress-strain diagram in metals in tension. So this is a textbook drawing from Gere. Now you can see here this is how the blue curve here is how a typical stress-strain diagram would look like for metal and here when the initial area is used in the stress calculation. So on the vertical axis, you have stress, and on the abscissa, you have strain. Now when you calculate the stress, assume that this is a specimen on the right side.

It is a steel specimen, and we usually call it a coupon specimen. So it is a flat piece. The cross-section would be something like this, or you can take circular whatever it is. So typically, it is a flat coupon specimen. Now here, the initial area is known. So let us say, so here the cross-section area is like this, and here the cross-sectional area is like this, and here it is a much thinner cross-section area. So the necking is happening there okay.

The specimen's initial area is considered to calculate the stress. As we know that Stress is force divided by the area, we calculate the stress. For that calculation, if you use the initial cross-sectional area of the specimen that is this area here if you use that, then as you know, after some tension is applied, the material’s cross-section can change can reduce and something called necking can happen here.

Furthermore, in that process, the actual stress observed is actually not used in the calculation because the area changes, and it is tough to get that change in the area during the testing. So there is an engineering practice that uses the original area, and we call that engineering stress that is what this is here engineering stress.

So how do we get it? So you put the specimen in the testing machine. You pull it, and then you keep on applying a load, and then you calculate the stress corresponding to that load. That stress is nothing but the force divided by the area, whatever the force you are applying by the original area, I will call it as A_0 here, we do not change that okay. So that is how the stress is calculated, and this blue curve here follows that.

If the actual stress at every point of time is considered, it will follow this curve, so that is true stress, not the engineering stress but the true stress. However, how do we get the actual area? During the testing, it is pretty challenging to do because it is difficult to measure that during the test, so what we do? In most of the testing, we will use only $A_{0,}$ and then we use engineering stress as a parameter for comparison of various materials.

Now let us see with different points or portions in this stress-strain graph here. So here is the origin that is the point of the application initially, and then you have a point A called proportional limit. That means up to point A from O it is a straight line. It follows Hooke's law. So it is a straight line and then at point B is where we call it is yield strength. After B, you can see a flat region that is yield Plateau from B to C.

So this is from B to C the material is perfectly plastic or yielding. The material is yielding without really experiencing more stress, but after point C it experiences more stress, so that we call this region strain hardening okay from C to D.

At D, something like necking happens, so that I have shown here this is what is necking. So why necking because you have very small area or comparatively less area at that neck region than the remaining section.

So that region has strained so much that now it is started necking. So neck is the portion where you have the smallest cross-section even on our body, right. Maybe that is why we started calling it neck, it looks like that, the neck of the specimen, and then finally you have a fracture point which is E. At that point, this material breaks into two, okay.

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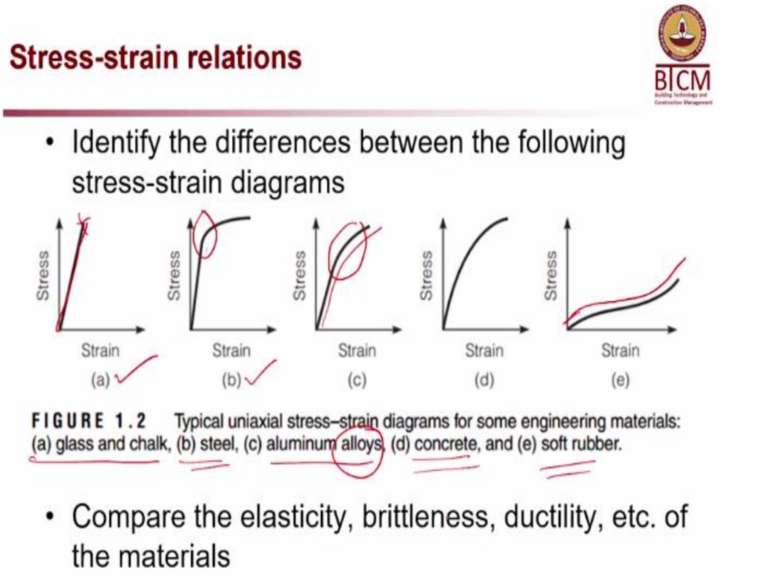

Stress-strain relations

- Identify the differences between the following stress-strain diagrams

FIGURE 1.2 Typical uniaxial stress–strain diagrams for some engineering materials: (a) glass and chalk, (b) steel, (c) aluminum alloys, (d) concrete, and (e) soft rubber.

- Compare the elasticity, brittleness, ductility, etc. of the materials

Now we look at how stress-strain grafts of different materials would look like. So here we can say this is from Mamluk and Janoski's book. So you can say here, figure 1.2 in that book. Now identify the difference between the following stress-strain diagram. Here the first one you can look at it is either for a glass or chalk. So you take a chalk piece, you try to pull, it will suddenly break without any deformation, or there is no ductile behavior in that. That means when you draw a stress-strain graph, a straight line and then suddenly the material breaks there. There is no ductility at all. Imagine you take a chalk piece and pull it. It will just break. It is not going to reduce the diameter of the chalk, etc. It just breaks, right.

If you take steel and try to pull it using a machine, it will not break suddenly like glass or chalk-like in figure a. In case b where steel is used, that will have some ductility which is indicated by this portion here. Now that means here you have elastic deformation and then you have yielding and then some you can very clearly see the ductile region in that graph. So this portion indicates the ductile region.

In the case of aluminum again, you will have ductility. One thing I want to tell you here in this slide you notice that none of the pictures or none of these sketches here diagrams have any number on them.

So it is not that all are of the same height and width and all that, they are of different magnitudes, but the general trend of the graph is going to be like this, do not compare the size of one graph to the other, just look at the trend or the shape of the graph from one to the other okay. So in the case of aluminum, you can see a gradual change in the curvature, and the curve is gradually changing, whereas, in the case of steel over here, there is a relatively sharp change.

So the yield point is better defined in the case of steel, and the yield point in the case of aluminum alloy is not well defined. You have a gradual transition that is mainly because of the alloys in that because alloys mean where there are different type of bonds, so the in the microstructure level as you pull or as you apply the stress, there will be movement of dislocations, and bonds are of a different type, all these will lead to, we will talk about this later in coming sections.

However, because of that, there is a gradual transition from a straight line to a curvature. So that yield point is not well defined in the case of alloys. Now in the case of concrete, also a similar case, you have a different variety of different materials in the concrete. So there is no well-defined yield point in the case of concrete also. This linear region is not that long compared to that in the steel, but again this graph is for compression for concrete that is also important.

Then you have rubber, and when you pull rubber, you can see that initially, there is a change in the curvature. You see here, and then the curve comes down like this and then again goes up like this. So that indicates the rubber initially will take some load, and then it tries to straighten all the molecules or chains in that, and then after some time, you start seeing this strain hardening behavior in the rubber.

Now you can compare all these materials based on elasticity, brittleness, and ductility, which are very important to look at while choosing a material.

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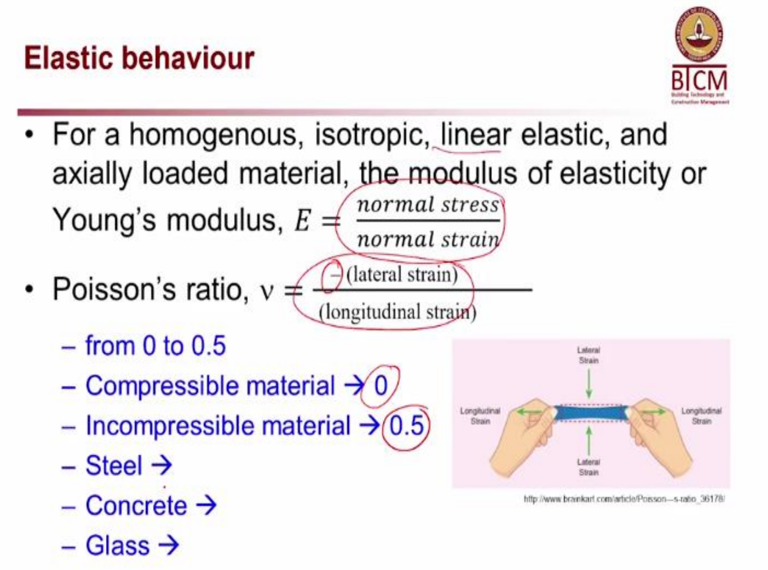

Elastic behaviour

- For a homogenous, isotropic, linear elastic, and axially loaded material, the modulus of elasticity or Young's modulus, $E = \frac{normal\ stress}{normal\ strain}$
- Poisson's ratio, $\nu = \frac{-(\text{lateral strain})}{(\text{longitudinal strain})}$
  - from 0 to 0.5
  - Compressible material → 0
  - Incompressible material → 0.5
  - Steel →
  - Concrete →
  - Glass →

http://www.brainkart.com/article/Poisson--s-ratio_36178/

Elastic behavior:

For a homogeneous isotropic and linear elastic and axially loaded material, i.e., Material has to be very homogeneous. Otherwise, like concrete, there will not be a long straight line available for it. In this case, the straight line is only for this much, maybe for concrete, so it is not as homogeneous as steel. In the case of steel, you have a very long straight portion. Isotropic means the same property in all directions. The modulus of elasticity, can be defined as normal stress divided by normal strain that is a material property. It does not change as a function of the cross-section of the specimen which you use to test, and Poisson's ratio is negative of lateral strain divided by the longitudinal strain.

In this picture here you can see a person is pulling that blue strip, and as you pull, the length of the longitudinal strain is more, the length is increasing, and the width of the specimen or the strip is decreasing, and because one is increasing the other is decreasing that is why we introduce this negative sign here in the numerator of the Poisson's ratio.

Now, how the Poisson's ratio? What is the range it goes?

Typically, it is from 0 to 0.5, and for compressible material, it is close to 0, and incompressible material is close to 0.5.

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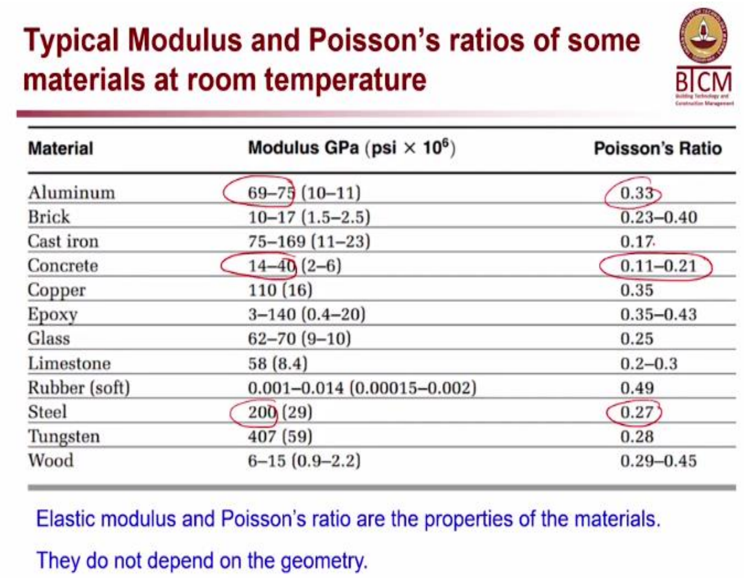

Typical Modulus and Poisson's ratios of some materials at room temperature

Material	Modulus GPa (psi × 10^6)	Poisson's Ratio
Aluminum	69–75 (10–11)	0.33
Brick	10–17 (1.5–2.5)	0.23–0.40
Cast iron	75–169 (11–23)	0.17
Concrete	14–40 (2–6)	0.11–0.21
Copper	110 (16)	0.35
Epoxy	3–140 (0.4–20)	0.35–0.43
Glass	62–70 (9–10)	0.25
Limestone	58 (8.4)	0.2–0.3
Rubber (soft)	0.001–0.014 (0.00015–0.002)	0.49
Steel	200 (29)	0.27
Tungsten	407 (59)	0.28
Wood	6–15 (0.9–2.2)	0.29–0.45

Elastic modulus and Poisson's ratio are the properties of the materials.

They do not depend on the geometry.

Now we can look at how these numbers are for steel, concrete, glass, etc. Here is a table that shows Poisson's ratio, the range for various materials, both Poisson's ratio and modulus. So you can see aluminum modulus ranges from 69 to 75 GPa, whereas Poisson's ratio is typically 0.33. In the case of steel, you can say the modulus is about 200, most of the steel it is about 200, and Poisson's ratio is 0.2.

In concrete, the modulus has significant variation 14 to about 40, and even we have today modulus concrete with more than 40. The Poisson's ratio is also significantly varying from 0.11 to 0.21. So the point here is these properties also can vary depending on the homogeneity of the material, depending on various properties.

So these two are key material properties of any material that we consider for use in construction. When I say they are material properties, they are not dependent on the geometry of the specimen.

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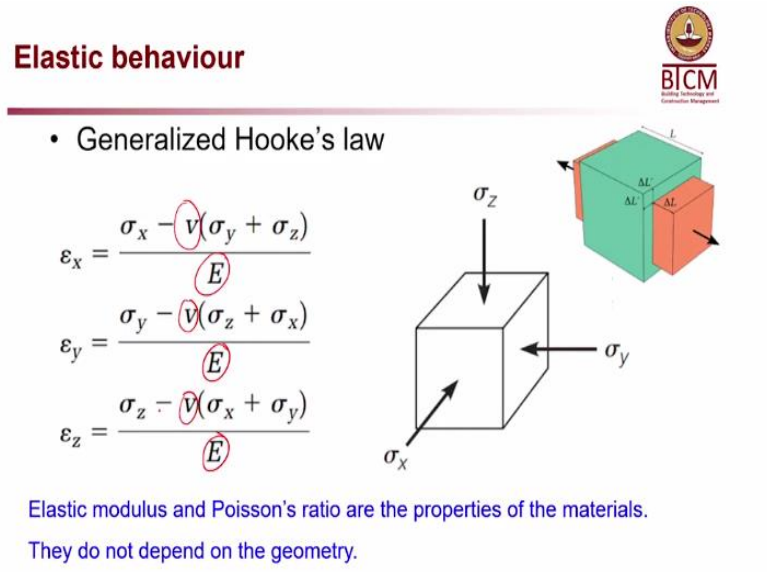

Elastic behaviour

- Generalized Hooke's law

$$\varepsilon_x = \frac{\sigma_x - \nu(\sigma_y + \sigma_z)}{E}$$

$$\varepsilon_y = \frac{\sigma_y - \nu(\sigma_z + \sigma_x)}{E}$$

$$\varepsilon_z = \frac{\sigma_z - \nu(\sigma_x + \sigma_y)}{E}$$

Elastic modulus and Poisson's ratio are the properties of the materials.

They do not depend on the geometry.

We have to look at the three-dimensional behavior. There is a generalized Hooke's law which you can see in these three equations over here that only E and Poisson's ratio are material properties. So I can calculate the strain in a particular direction if I know the stress supplied in all three directions okay. So with immaterial of the shape, I can calculate the strain using the stress applied and the material properties like elastic modulus and Poisson's ratio. So that is mainly the idea in this slide here.

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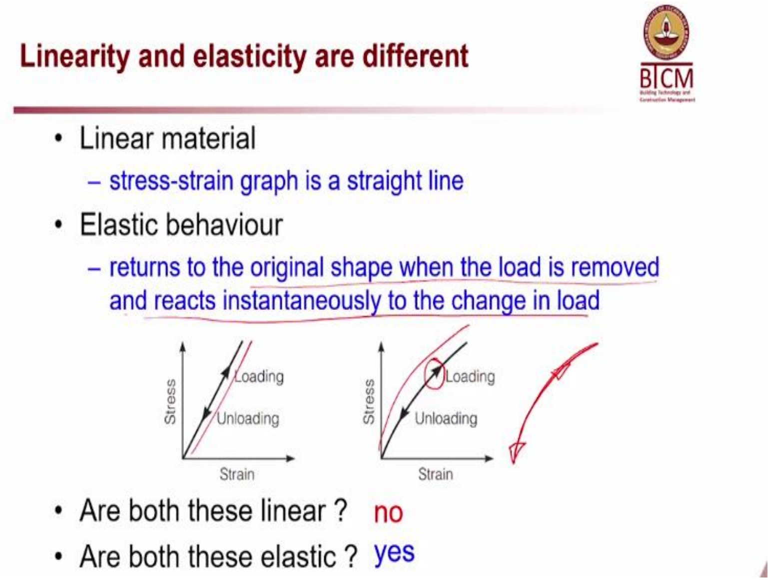

Linearity and elasticity are different

- Linear material
  - stress-strain graph is a straight line
- Elastic behaviour
  - returns to the original shape when the load is removed and reacts instantaneously to the change in load

- Are both these linear ? no
- Are both these elastic ? yes

When you look at stress-strain behavior, you can sometimes see the graph look like a straight line, sometimes curved like this on the second. For linear material, the graph will be like a straight line like the first one, and for elastic behavior, you can have elasticity, but it need not be linear all the time. So there could be sometimes curved graph like this also. So the question is, are both these linear? The answer is no.

The first one is linear, the second one is not linear or non-linear, and are both these elastic? Both are elastic, so do not say elasticity is only dependent on linear graphs or non-linear graphs also like. In the second graph, the first arrow this arrow here indicates the loading time. So I load the material okay. If I load it like this and when I unload it if that follows the same path in coming back, then we can say it is an elastic material.

In other words, it means it retains the original shape, or it comes back to its original point okay when the load is removed, or in other words, there is no permanent strain that happened during the loading-unloading process. If that is the case, then we can say it is elastic, so it returns. In elastic behavior, it returns to the original shape when the load is removed and reacts instantaneously to the change in load. Instantaneously means the moment you release the load, it reacts immediately, there is no time lag between that. If there is a time lag, then we call it something called viscoelastic behavior. We will talk about that later. So here it is elastic behavior.

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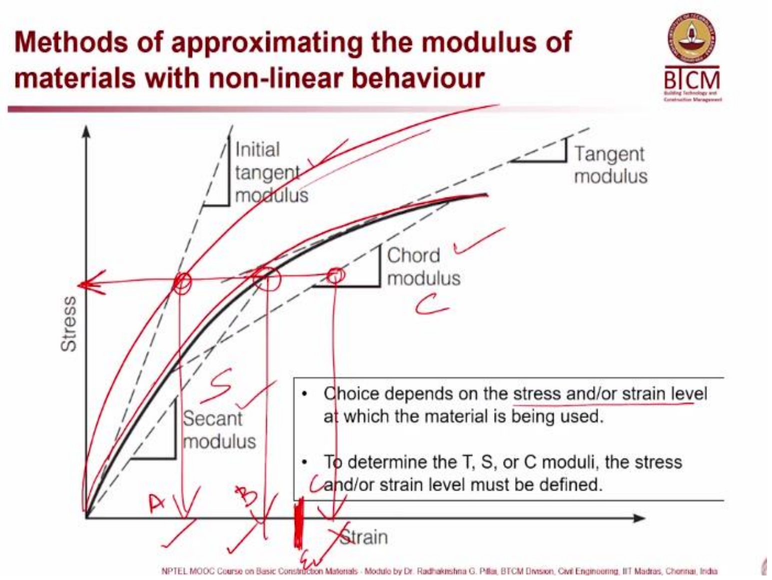

Methods of approximating the modulus of materials with non-linear behaviour

- Choice depends on the stress and/or strain level at which the material is being used.
- To determine the T, S, or C moduli, the stress and/or strain level must be defined.

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Now how do we get some numbers for design purposes based on this elastic? There are different moduli that we consider initial tangent modulus, then secant modulus(S), chord modulus(C), and tangent modulus(T).

- How do we choose a material considering all this? So that depends on the stress or strain level at which the material is being used.

  So when we get this stress-strain graph, you can see the stress-strain graph here, this thick black line. Now when you have a stress-strain graph of material and if you know in service what is the typical stress level, the material will go through or based on the applied loads. So I can calculate that in-service stress level, and then I can use that value and these types of curves from different materials to compare.

For example, if I want to design, I can say that secant modulus I will use this point here this is my stress level which I will consider. What you do is you get one curve like this, and maybe another curve will be something like this. So you take this value and something like that, and for a third material, the curve maybe something like this, for then you compare this value so you can get the corresponding strain in three cases okay.

Based on that, you can decide what would be the strain experienced by the material if my option A, B, and C. Three options that I draw three vertical lines here. So like that you can get the stress-strain behavior stress-strain graph of various materials which are available for use, then decide the stress level which the material will experience while in use, and then based on that you can decide which material to take whether the strain is beyond the limit or not.

In this case, maybe I will go with if my limiting strain value is here, then I can pick either this(A) or this(B) but not the third one(C). So if I say this is A, material B. That material C. If my limit is here that is limit, I will call it epsilon limit, is here then I can say A or B are fine but not C. These are some of the uses, so like this, we can decide the values for or compare the values chord modulus, tangent modulus, all these different moduli we can use and then compare all that.

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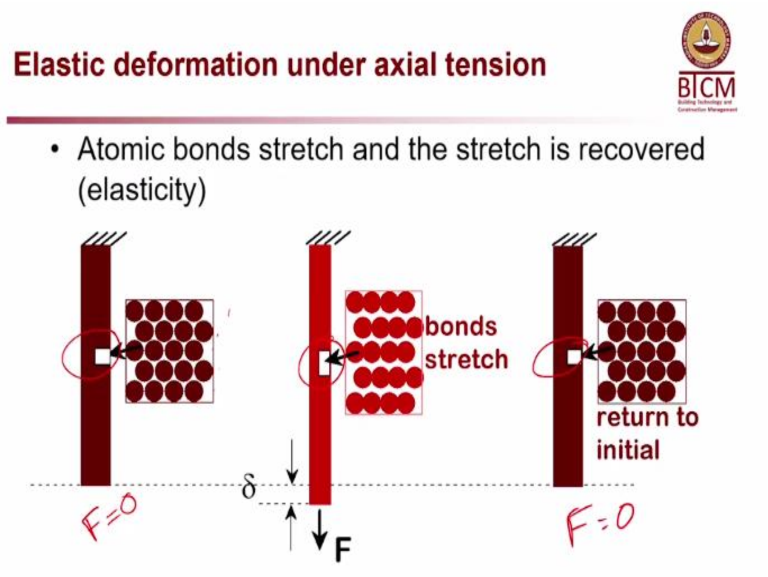

Elastic deformation under axial tension

- Atomic bonds stretch and the stretch is recovered (elasticity)

Elastic deformation under axial tension

Atomic bonds stretch and stretch are recovered when we talk about elasticity. To understand what is actually happening, look at the first image here where you have all these circles can be thought of as an atom, and they are bonded, so you have atom in every line 1, 2, 3, 4; four atoms in each line.

Now the first figure is the case with no load that means F = 0, there is no load here. In the second figure, some load is applied, so you can see that this point has changed from a square to a rectangle. That means the bond the vertical lines over here is a stretching happening in the vertical direction. So you can see the gap between these have increased, between these, this gap here, this gap here, this gap here.

The vertical gap has increased between each layer of the atoms. So that is indicating that the bond has stretched. Now when you rerelease the load, the F = 0 here. That distance between the individual layers, the five layers of atoms, has come back to the original shape, so it has become square. So from square to rectangle to back to square.

So that means there is no residual strain after the load is removed means the system has regained its original shape. So this is a perfect example of what happens when we talk about elastic behavior or elastic deformation. It deforms under the load, and when the load is removed, it goes back to its original shape.

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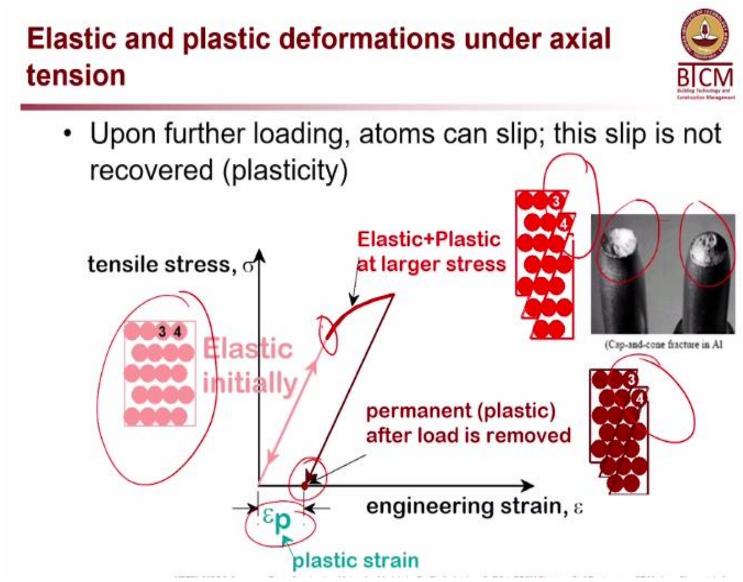

Elastic and plastic deformations under axial tension

- Upon further loading, atoms can slip; this slip is not recovered (plasticity)

Whatever I showed in the previous slide was dealing with the elastic region or initial elastic region, where you can see that in this sketch here 3 and 4. So you have to monitor where the positioning of 3 and 4, the relative position of 3 and 4 is in this whole sketch here. So after this point (where Elastic region ends) when the load is applied, more and more load is applied stress is increasing, and there some slip happens.

So you can see here the 4 has slipped down to the lower layer. Now, this kind of behavior is known as slipping. In the previous slide, we were talking about the stretching of the atomic bond. Here what is happening is the slipping of the atoms from one layer to the other. When it slips, it does not go back to its original position. Even after the load is removed right this point here, you can see that 4 is not going back to the first layer.

So slip is permanent, but stretching is not really permanent. Here atoms slip, and then they stay there itself. They do not come back to their original position. So that is why we have permanent deformation in the material. We can see this photograph where inclined shape or cup and cone behavior is mainly because of this slipping happening in about 45 degrees in typical cases.

From this sketch, we can get the plastic strain that is ε_P indicates a plastic strain. That means this much deformation is permanent deformation. Even after unloading, it does not come back to the origin of the curve, so it is the permanent deformation.

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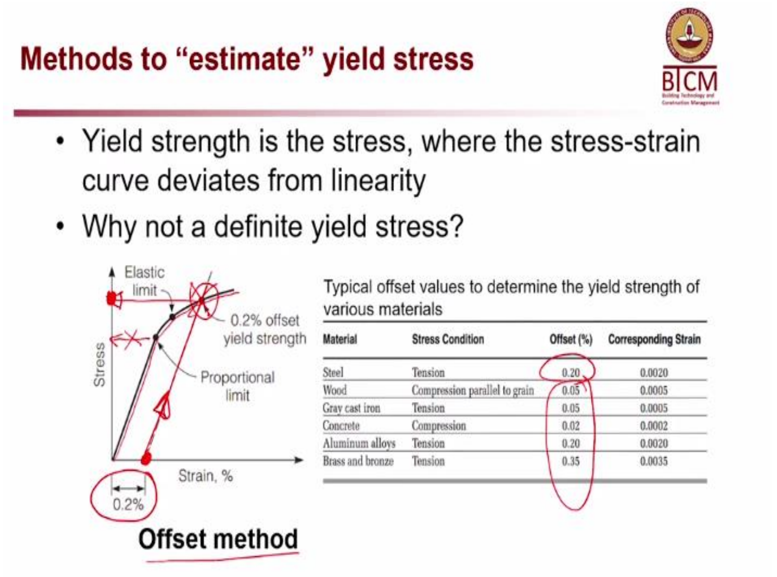

Methods to “estimate” yield stress

- Yield strength is the stress, where the stress-strain curve deviates from linearity
- Why not a definite yield stress?

Offset method

Typical offset values to determine the yield strength of various materials

Material	Stress Condition	Offset (%)	Corresponding Strain
Steel	Tension	0.20	0.0020
Wood	Compression parallel to grain	0.05	0.0005
Gray cast iron	Tension	0.05	0.0005
Concrete	Compression	0.02	0.0002
Aluminum alloys	Tension	0.20	0.0020
Brass and bronze	Tension	0.35	0.0035

Now how to get or estimate the yield strength?

So there is one method that is widely used. We call that as offset method. Another method is called the extension method, and I am not going to cover that here. In the offset method, we use this method for most applications. Now, what is yield strength? It is the stress from the stress-strain graph we can get a stress value where the stress-strain curve deviates from linearity.

So like this here from here until here it is a straight line and then this point, it starts deviating. So you have a proportional limit, you have an elastic limit, and but these two proportional limits if you take this is a perfect textbook drawing, but when you do actual testing in laboratories, you may not get a perfect curve which looks like this and also there is no sharp change in the curvature, so there is a gradual change.

So what will happen? I mean, it is difficult for us to have fix a point. So to standardize the procedure, people have used some values like this 0.2 %. It is used as an offset of 0.2 % in tension for steel, as you see in this table. For other materials, different numbers are proposed okay. So anyway, let us look at this graph here 0.2 % you take for steel, and so you draw, 0.2% is here and then draw a parallel line to the original curve.

And wherever that curve hits this point here on the top right and the value corresponding to that this one here, we call it yield stress or yield strength. So this is the point which is of importance okay on the let us say yield strength. That is the value we use for design purpose and not the value over here, not this but the higher number for the design purpose.

It is not really more conservative, but that is a better way that is what is being used, I should not say that it is conservative.

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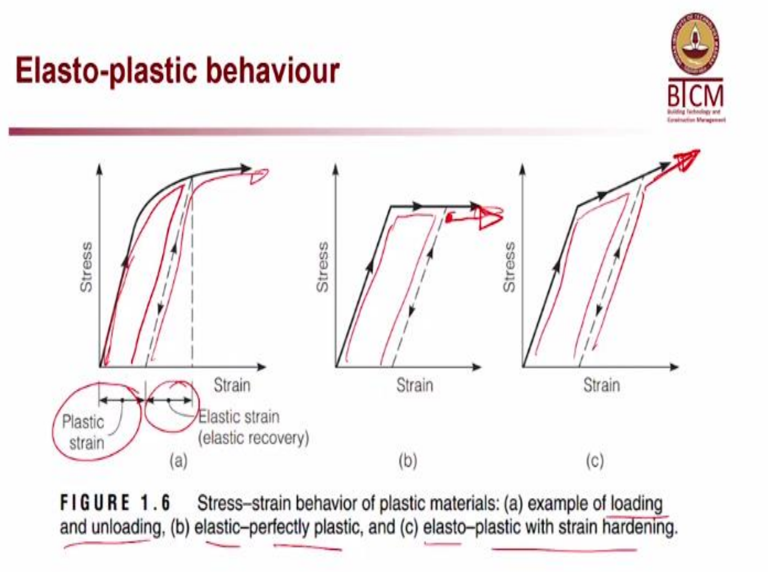

Elasto-plastic behaviour

FIGURE 1.6 Stress–strain behavior of plastic materials: (a) example of loading and unloading, (b) elastic–perfectly plastic, and (c) elasto–plastic with strain hardening.

Now there are different types of elastoplastic behavior. So you can see here in the first one this is typically for steel or any alloy. It will some look something like this where the example of loading and unloading. So the graph goes like this, and then it comes back, and then if you load it again, it goes back and then follows like this. So here you have plastic strain and then elastic strain.

Now second one elastic and then perfectly plastic. So this is the elastic region, and then it goes back and then perfectly this goes flat okay, so that means perfectly plastic

And then elasto and then plastic with strain hardening. So here it is, an elastic region it comes back and then plastic with strain hardening. Strain hardening means there is also an increase in stress after that point. In the previous case, the stress is not increasing, only strain was increasing in the second case, that is the perfectly plastic scenario.

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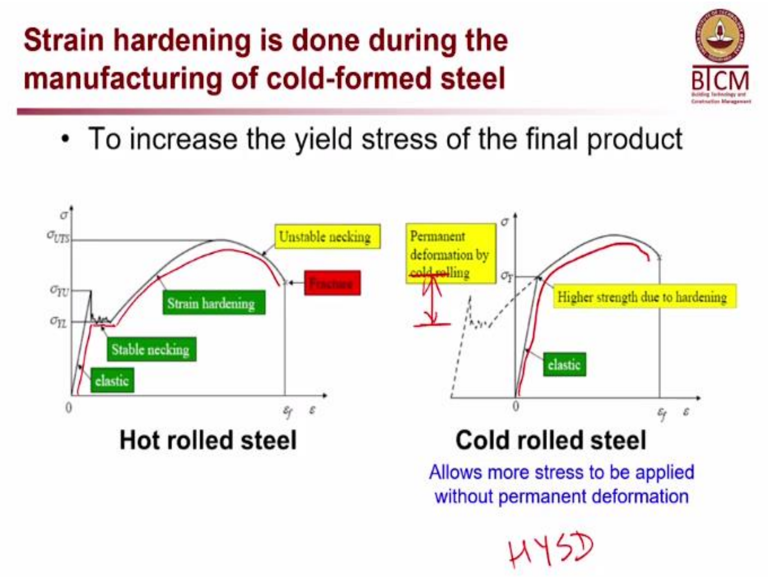

Strain hardening is done during the manufacturing of cold-formed steel

- To increase the yield stress of the final product

Hot rolled steel

Cold rolled steel

Allows more stress to be applied without permanent deformation

HYSD

Now strain hardening is done during the manufacturing of cold-formed steel because in the earlier time hot rolled steel was used, and that did not have very high strength, around 250 MPa was the typical yield strength which was possible to achieve with hot rolled steel.

So there was a demand for higher strength steel. When I say higher strength, I mean high yield strength steel HYSD.

So what the industry did was they use this strain hardening technology. So what they did was? They strain hardened the steel or cold-formed the rolled steel when the temperature was below the recrystallization temperature. At that point, they strained the steel so that when the final product would have a curve like this. Whereas the original curve is something like this, this is the original curve, the dashed portion on the second sketch.

So the first sketch shows the elastic region, then stable necking, and then the strain hardening happens. In the second one, you are actually translating the graph to the left side so you can see here that if the steel is cold rolled steel or cold formed steel when you do the tension test, it will behave like this. This will be the curve you get as a stress-strain graph. So this portion, this dash portion, will be missing.

Now you compare the yield limit in both the curve. This much is extra yield strength which you gain. So that is the advantage of going for cold-formed steel. With the same material properties, everything you strain harden the steel I mean a little during the manufacturing itself. You get a higher yield strength at the construction site, or the final product used in concrete will have a higher yield strength.

So there is no change in the chemical composition of the steel that is important to note down here. It is just the manufacturing procedure that has changed so that the steel's yield strength is more.

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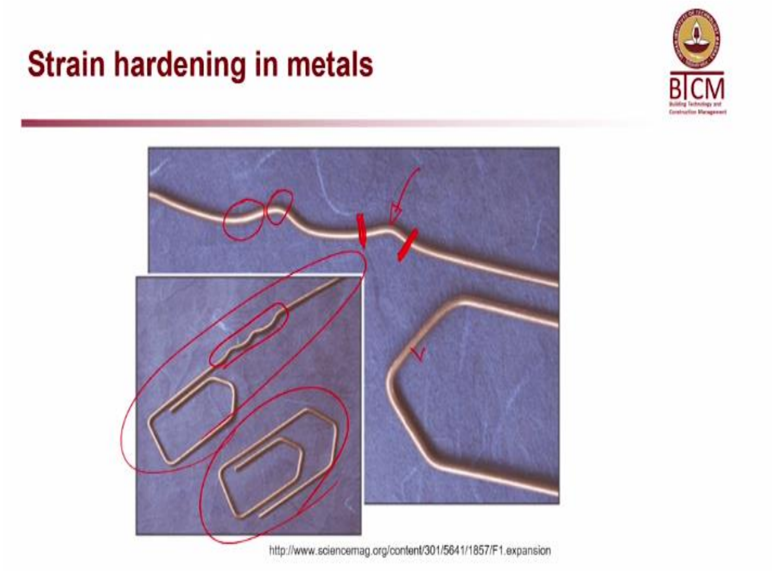

Strain hardening in metals

http://www.sciencemag.org/content/301/5641/1857/F1.expansion

Now strain hardening: This is an example that you may want to practice. Take a paper clip and try to open the paper clip. So this is the paper clip, and you open it like this, and then what happens is when you open it and you will see that you will not be able to keep it straight like this here. It is not easy because the bent portion has more strength than the points adjacent to it, so here this point here is having less strength than this point here because that is already bent.

So when you try to straighten, the bend portion is not getting straight. The point adjacent to that is getting straightened because the points adjacent to the bend are weaker. This point and this point are weaker than this point which is already bent. So when you try to straighten it, it will get straightened, so the bend point does not get straightened that easily.

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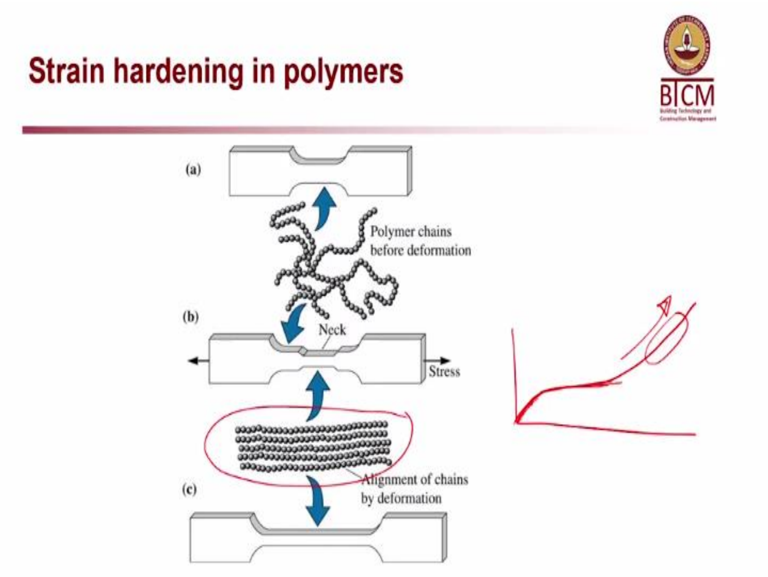

Strain hardening in polymers

In the case of polymers, what happens when you do a tension test? So the curve might look something like this. I showed this earlier also. So this portion here initially you will see some increase, but then after that sometimes you will see this flat region that is the time when the polymer chains try to get straightened. So this point here you see this first all the chains will try to get straightened, and once they are straight, they will try to take the load.

This portion is where they start taking the load, so that is why you have an increase in the stress strain curve, the strain hardening in polymers, this behavior on the right end of the graph. So all the chains are convoluted. They are not in a straight line, so as you pull in the beginning, they will try to become straight and once they become straight, only they will take the load applied.

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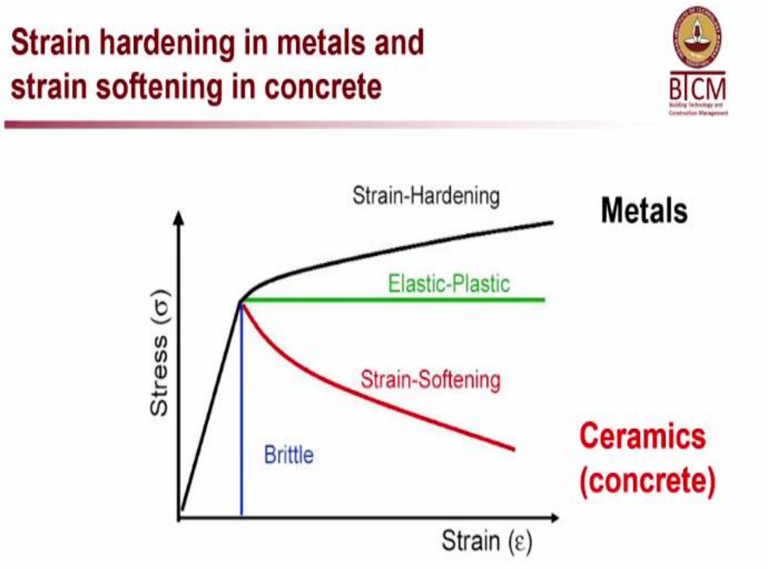

Strain hardening in metals and strain softening in concrete

Furthermore, one example of this is like the polythene bags which you use in shops and all that you know, you try to pull the handle of the plastic bag or the plastic handle if you try to pull initially it will be very easy to increase the length of the plastic. However, after sometimes it becomes very difficult because initially, when you pull it, the polymer chains try to get straight and after sometime they are already straight, so they start taking the load. So it becomes more stronger.

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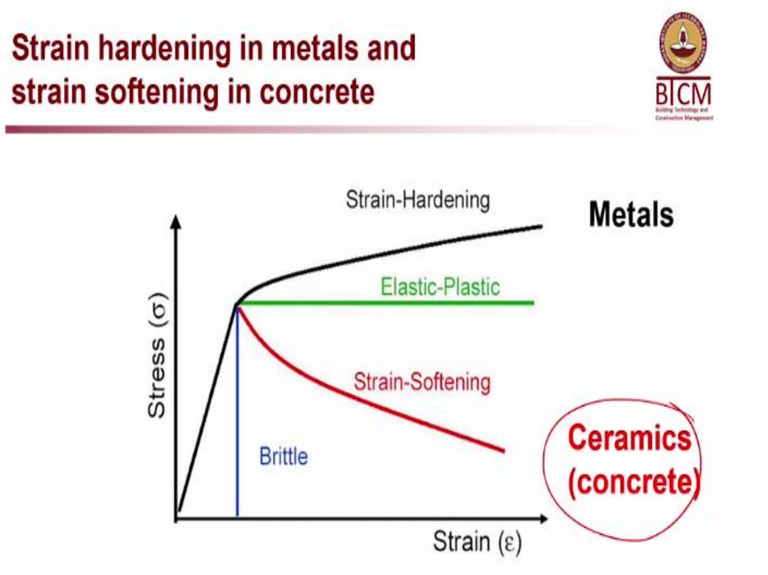

Strain hardening in metals and strain softening in concrete

Now in metals, strain hardening happens, and then in ceramics, the red graph here, the ceramic strain-softening happens, and we will see how and why this is the reason. So in ceramics, strain-softening happens, which means the from this point here, the graph is going downward, whereas, in metals, strain hardening happens where from this point the graphs go upward.

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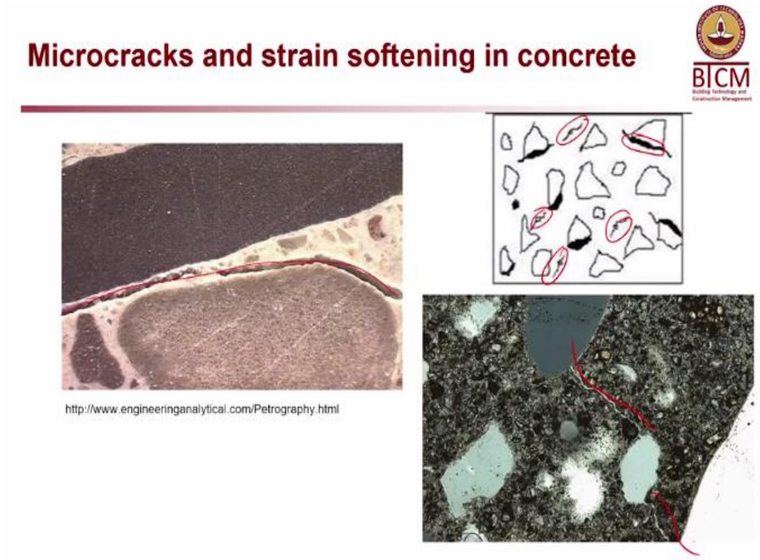

Microcracks and strain softening in concrete

http://www.engineeringanalytical.com/Petrography.html

Now why it happens because? In ceramics, you might have a lot of cracks. As you see, this is a sketch on the top right, a sketch of concrete you can say all these particles like aggregates, etc. and then you have small microcracks, and then there you have some bleed related gap between the aggregate and the cement. All these are cracks or microcracks in the concrete system, and you can see a photo or micrograph showing that kind of cracks here.

There is a crack here, and in the bottom right picture also, you can see cracks. Because of these microcracks that are present at this point, strain-softening happens and not strain hardening.

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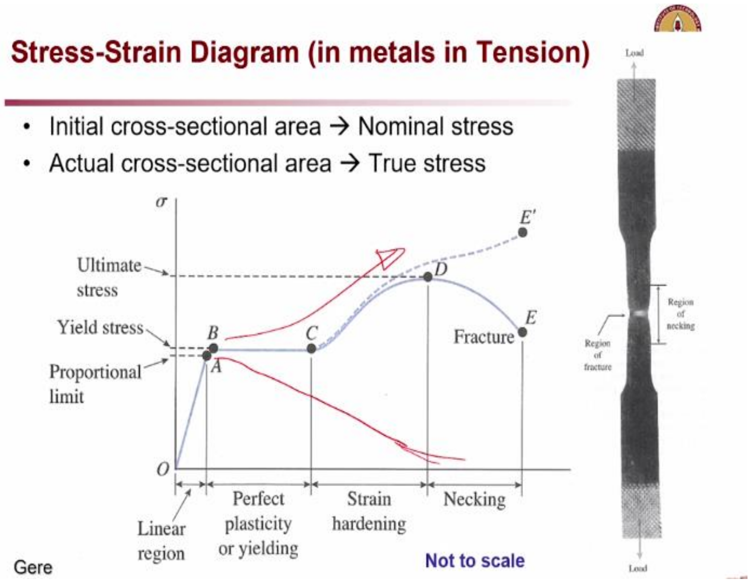

Stress-Strain Diagram (in metals in Tension)

- Initial cross-sectional area → Nominal stress
- Actual cross-sectional area → True stress

Gere

Not to scale

Now again, coming back to this stress-strain, so we covered this already. In ceramics, what will happen is the graph will kind of go downward from here itself. So that is the typical behavior of ceramics or concrete, unlike the metals where the graph goes upward.

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Summary

- Variability in material properties
- Characteristic value
- Stress-strain behaviour of various materials
  - Elastic modulus
  - Poisson's ratio
  - Yield
  - Strain hardening
  - Necking and Failure

Now to summarize, we looked at variability in material properties. We looked at the characteristic value, which is widely used for design purposes. We should not use the average values but rather a more conservative value, which is the characteristic value. We also looked at stress-strain behavior and various properties associated with the material's behavior like Elastic modulus, Poisson's ratio, yield strength, strain hardening, necking, and failure also we discussed. With that, I will close today. Thank you.