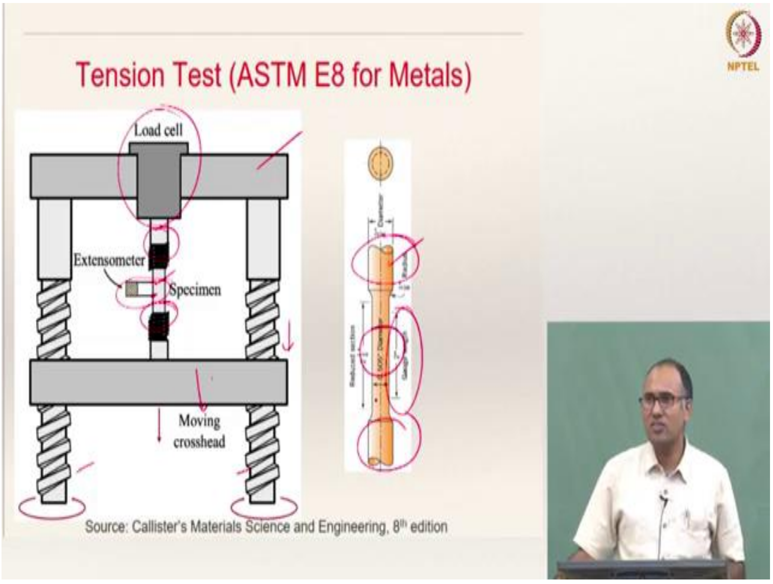
Basics of Materials Engineering
Prof. Ratna Kumar Annabattula
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture – 26
Mechanical Properties (Tension Test-Elastic Deformation)

(Refer Slide Time: 00:25)



In the last class, we had introduced the various mechanical tests. This is a specific test - the uniaxial tension test. We will discuss how to interpret the resulting stress-strain diagrams that we get from this test.

Here, you have a typical screw driven UTM. You have a specimen loaded between 2 cross heads, and you have a load cell which actually measures the load that you are applying. You move one of the cross heads down, while the other remains fixed, so as to pull the specimen.

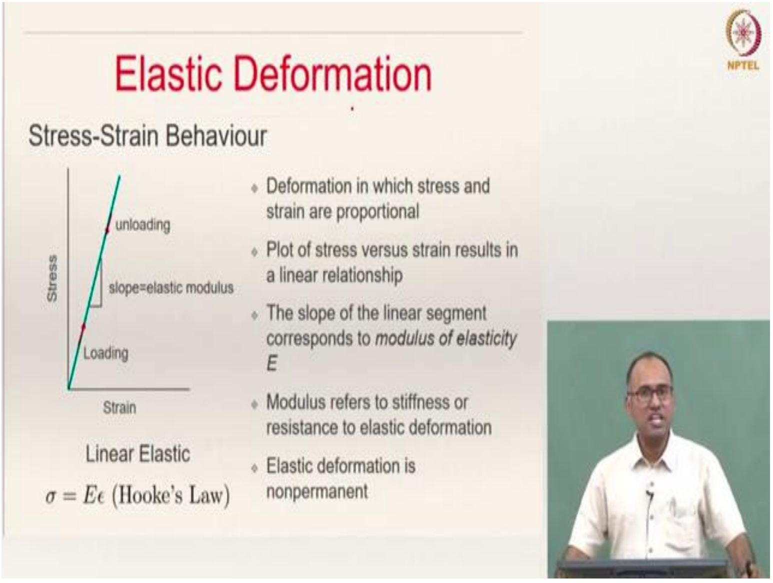
To measure the deformations accurately, we use an extensometer (or strain gauge). Sometimes, the displacement of the cross heads is used as the deformation; however, this will not be accurate due to the internal frictional losses in the screws, the stiffness of the machine, the slip in the grips, etc.

So, to avoid all these errors in your measurement, you use an extensometer which is connected between two points, typically, in the gauge section of the specimen. A typical tension specimen is cylindrical in shape. However, you also have tension specimens which are flat, called dog bone kind of specimens, wherein you have a central region, called gauge section, having reduced cross section compared to the area at the grip.bTherefore, the grippers that are used depend on the specimen type being tested. You may need to acquire additional grippers to test a different kind of specimen.

It is called a Universal testing machine because you can do other kinds of tests; not just tensile test. If you have appropriate fixtures, you can do a shear test, 3 point bending test, etc. The critical thing is that when doing a specific test, you need to ensure that the specimen is prepared according to certain standards. This particular society called American Society for Testing of Materials, ASTM, has come up with several standards for each and every kind of a test. For instance, the standard to be used for a tensile test on metals is ASTM E8. The specimen needs to be prepared according to these standards.

The various dimensions of the specimen must be prepared in accordance to these standards, so that you can actually corroborate your result with the results available in the literature. If ASTM standards are not available for a new material you may be testing, then you must indicate all the dimensions and parameters that were used in the test while reporting the results.

(Refer Slide Time: 05:27)



The tests, generally, report load displacement results. These results can then be used to generate the stress-strain diagrams for the specimen material. Here, a part of the stress-strain diagram is shown. If you have done this experiment on a metal such as mild steel, you would have seen a linear elastic response.

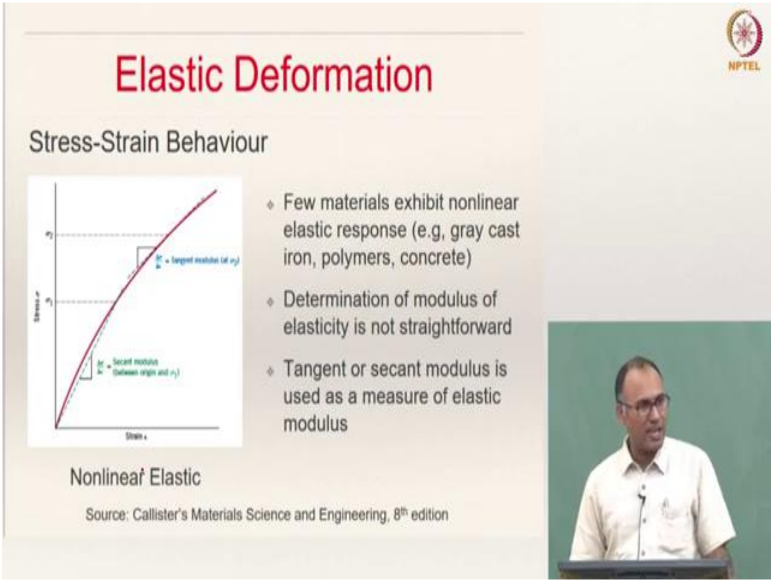
The initial response of the material is going to be elastic. The material undergoes elastic deformation before you can plastically deform it. In elastic deformation, you are basically stretching the bonds between the atoms. In this region, since you have a linear response, the stress and strain are proportional to each other. Within the elastic regime, if you unload the specimen, it goes back along the same path. The slope of this stress-strain curve is what is called the elastic modulus or Young's modulus.

The Young's modulus, E, which we have defined as a material property, comes from the elastic regime of the uniaxial tension test. This elastic deformation is completely recoverable; it is non-permanent deformation. As soon as you unload, you will go back to the original configuration, i.e. zero stress and zero strain state. So, the constitutive response that relates stress to strain in this regime is called Hooke's law, given by

$$\sigma = E\epsilon$$

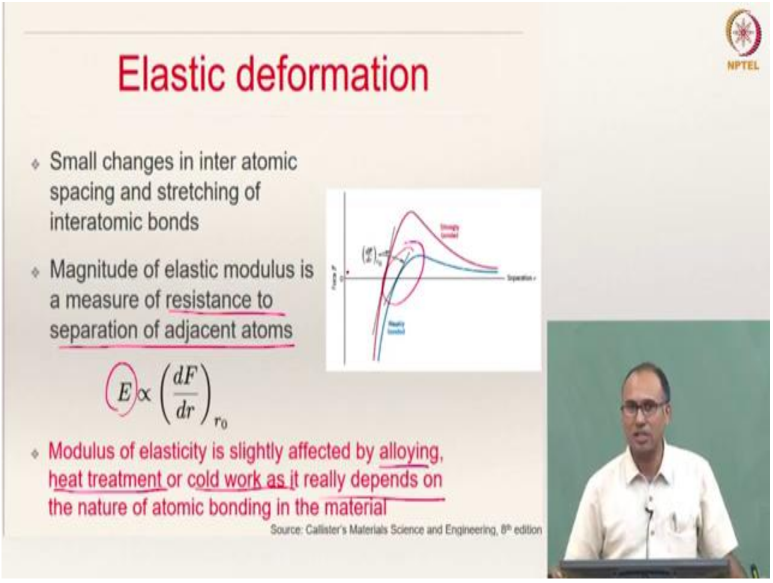
This is all for a linear elastic material. If it is non-linear elastic material, then this curve will be non linear in the elastic regime. Then, the Young's modulus will not be a constant and it will vary with deformation. Several times, we observe such a behavior in elastomers and polymers.

(Refer Slide Time: 08:44)



Here, we see a typical non-linear elastic response. The slope of the curve is not a constant here. There are two ways to define the instantaneous elastic modulus at a point. Firstly, we have the tangent modulus. The tangent modulus is the slope of the tangent line drawn at the point of interest. On the other hand, we have the Secant modulus which is defined as the slope of the line joining the origin to our point of interest. This does not require differentiation to find the slope, and it is consequently simpler. However, the tangent modulus is more accurate

(Refer Slide Time: 09:46)



Elastic deformation is actually nothing but the stretching of the bonds. In other words, the inter-atomic spacing increases, but you are not breaking the bonds. So, this diagram shows the inter-atomic bonding force separation response. From this, we actually say that the elastic modulus is a measure of resistance to separation of adjacent atoms. Or,

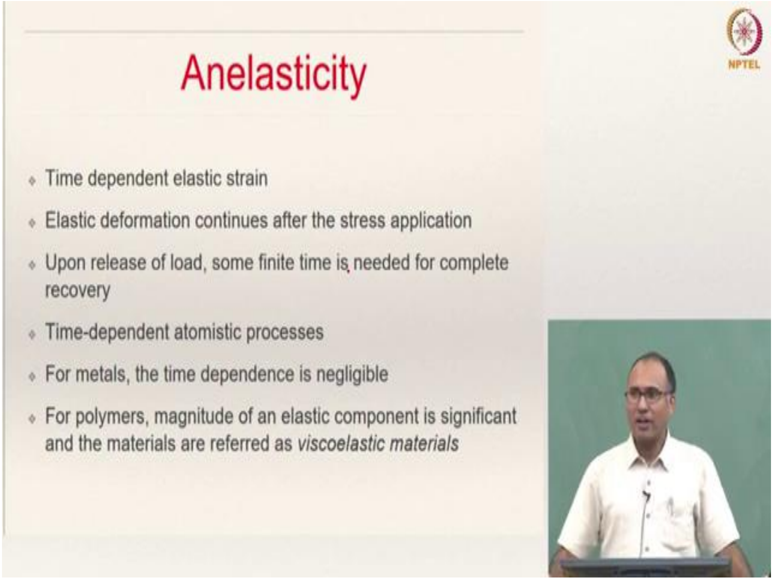
$$E \propto \left(\frac{dF}{dr}\right)_{r_0}$$

In other words, it is stiffness of your stress strain curve; which is the resistance to separation of atoms which are adjacent to each other when you are applying a tensile load. So, typically for materials, the modulus of elasticity is slightly affected by alloying, heat treatment or cold work. It is not significantly affected, and it really depends on the nature of atomic bonding in the material. If you do not change the nature of the bonding, you are not going to change the elastic modulus.

As you increase the temperature of the material, however, the elastic modulus changes. That is because the inter-atomic force separation law, as a function of temperature, is going to change. As a result, the slope of this curve is going to change as you increase the temperature, and hence you would see a difference in elastic modulus.

Many times, within certain range of temperatures, you do not see a much of a change of elastic modulus, but at very high temperatures, you start seeing the effect of temperature on elastic modulus. Hence, when you are analyzing materials, you should know what its operating temperature is and, depending on the operating temperature, you should decide whether or not to include temperature effects. Otherwise, you will be making a mistake in calculating the stress state of the material within elastic regime itself.

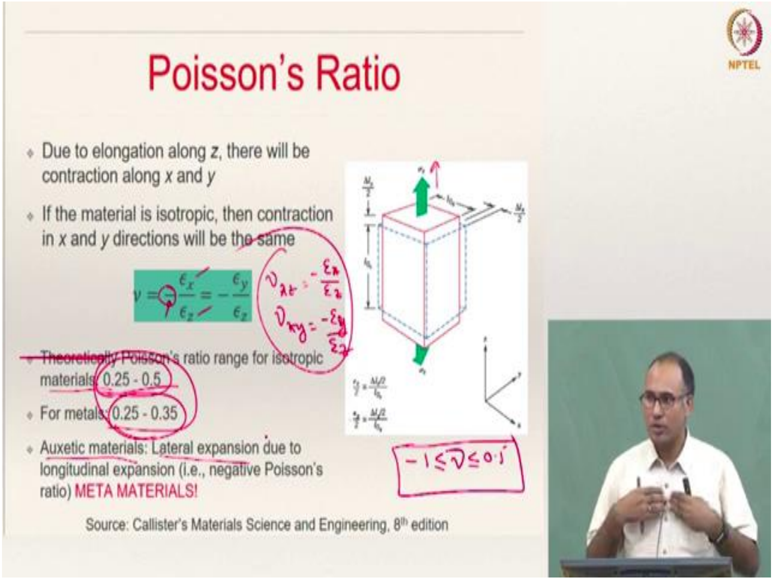
(Refer Slide Time: 12:17)



Further, you have another property called anelasticity, which is nothing but a time dependent elastic strain. In the case of elastic deformation, if you holding a particular constant load, then strain remain constant unless you further increase the stress. However, in the case of anelasticity, strain may continue to change in spite of the stress being constant. Similarly, in the case of elastic deformation, the moment you unload the specimen, it immediately comes back to its original configuration. There is no time factor involved here. In anelastic materials, the specimen will regain its original configuration only after some time. Not immediately. There is a time factor involved here.

Therefore, if you were to immediately measure, it may appear as though there is some plastic deformation. However, this will disappear with time. For metals, usually it is negligible, but for polymers, this is one of the important deformation mechanisms.

(Refer Slide Time: 14:01)



The next important property is Poisson's ratio. If you expand a material longitudinally, it contracts in the lateral direction. In other words, extension or contractions in one direction affects the strains in the other, lateral directions. If your loading direction is X, then Poisson's ratio is defined as

$$\nu_{xz} = -\frac{\epsilon_x}{\epsilon_z}$$

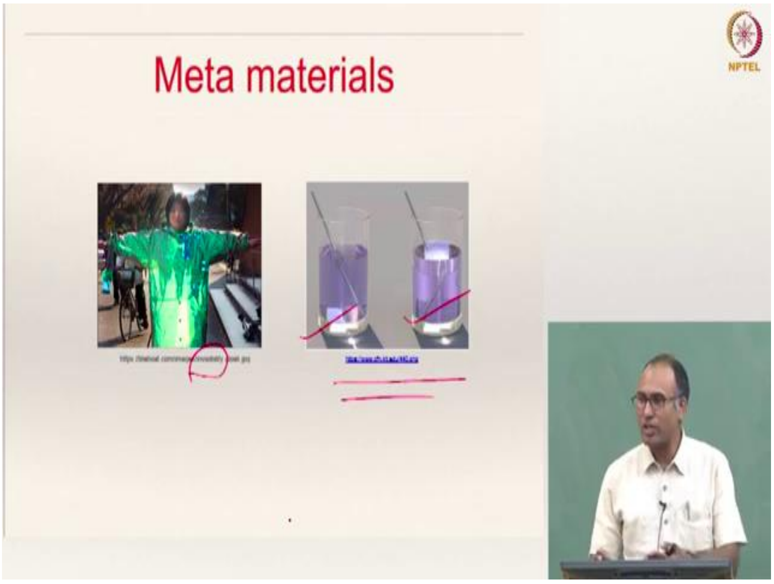
$$\nu_{yz} = -\frac{\epsilon_y}{\epsilon_z}$$

Typically, for isotropic materials, these 2 values are going to be same. For isotropic materials, the Poisson's ratio is simply defined as the negative ratio between longitudinal and lateral strain.

Theoretically, the Poisson's ratio is between $0 \leq \nu \leq 0.5$. It is between 0.25 – 0.32 for metals. Using energy arguments, however, we can show that it is theoretically possible for the Poisson's ratio to be in the range $-1 \leq \nu \leq 0.5$. In other words, Poisson's ratio can be negative. This implies that when you are pulling the in one direction, the material expands in the other direction. So, normally in crystalline materials, you will not observe this negative Poisson's ratio. There are a new class of materials called auxetic materials which display this behavior.

Auxetic materials are a subset of a more general class of materials called metamaterials. That is the recent revolution. They can offer tremendous new possibilities. For instance, several biomedical devices which you send into arteries, you may want to pull them and laterally expand them at the same time. So, that kind of structures can actually be now designed as a reality. It was not possible, say, 20 years ago. Today, we can very well design these structures from a mechanical engineering point of view.

(Refer Slide Time: 19:25)



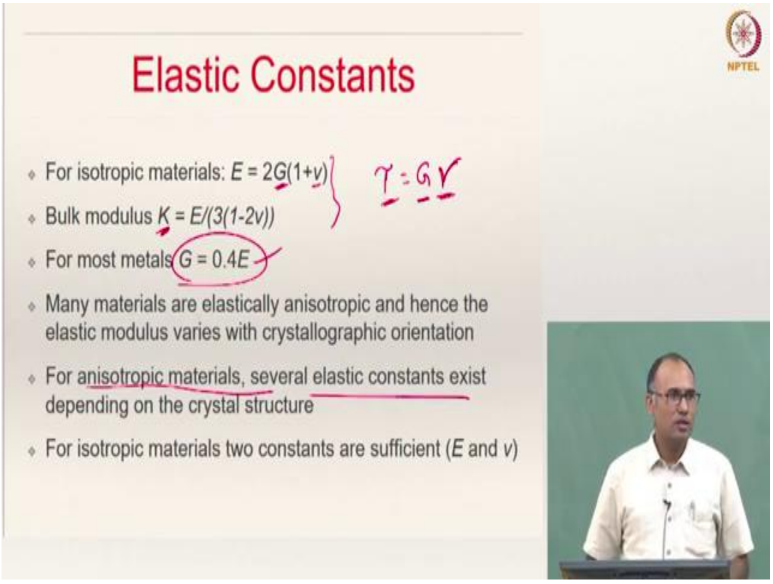
There are also other interesting metamaterials. This is an invisibility cloak, somewhat similar to the ones seen in movies such as Harry Potter. This is no longer Science fiction. It has been demonstrated. This is achieved by means of manipulating the refracting index of materials to create optical flow.

You are able to see objects because of light reflecting off the object and making its way to your eyes. However, we can send these light rays away from the object, after reflection, such that it doesn't reach your eyes. The object will no longer be visible.

Similarly, you can see the two glasses: one where the objects are normal, while the stick in the other beaker appears to be broken in two. This is again achieved by manipulating the refractive index.

Similarly, there are an infinite number of possibilities of new kinds of material design. All these things are possible now. Things that were only the domain of Science fiction are very much a reality now.

(Refer Slide Time: 22:18)



So, we have discussed about elastic constants: elastic modulus, E, and Poisson's ratio, ν. For isotropic materials, you only need these two constants to describe the elastic response. However, for anisotropic, you might need more constants.

For isotropic materials, both constants could have been measured by a single experiment where we measure both longitudinal and lateral strains along with the stress.

We also have the following relations between the constants whose derivations are left as exercises.

$$E = 2G(1 + \nu)$$

$$K = \frac{E}{3(1 - 2\nu)}$$

For anisotropic materials, several elastic constants exist. Theoretically, you need 81 elastic constants and then you can actually show that by using certain arguments 21 are enough. For isotropic, using symmetry arguments, eventually we will be able to show that just 2 are enough. If it is a fully anisotropic material, theoretically, you need 81, but you can actually reduce this using certain arguments. We might see this later in this course.