Biomechanics
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Lecture - 56
Stress Strain Curve and Mechanical Properties of Biological Materials

Vanakkam. Welcome to this video on biomechanics. We have been looking at mechanics of biological materials. In particular, we were looking at bone as a biological material. And in the previous video, we defined the elastic modulus, the shear modulus and the relationship between elastic modulus and shear modulus using Poisson's ratio.

We defined the limitations of these in terms of modeling the biological material as a Hookean material.

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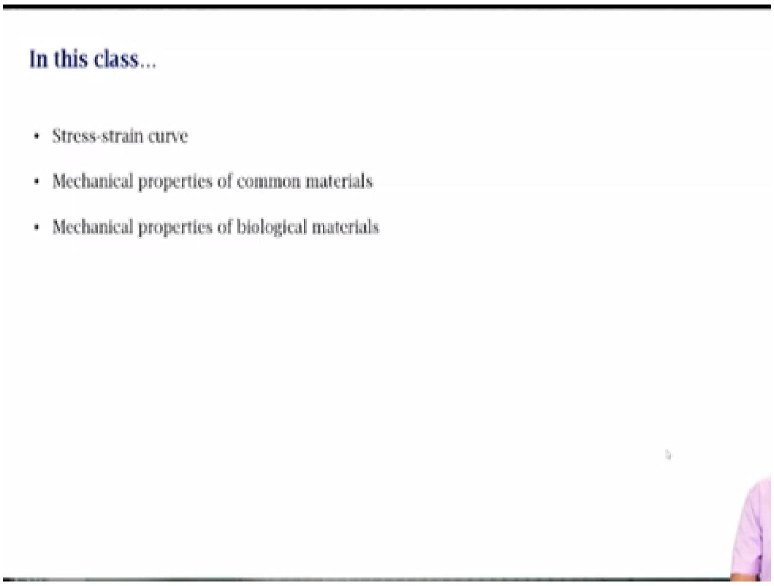

So in this video, we will be looking at the stress-strain curve or the stress-strain relationship for biological materials. We will give some examples of engineering materials for comparison, but that is where the comparison stops. So our aim here is to let you get a sense of the biological material. For that you need a comparison material. So we use some engineering materials as comparison.

So you have an idea of, because we are the engineers and we like to build things and we like to have an idea of the strength of the materials that we use in the objects that we or in the products that we fabricate, right? But what about the body that is a product of evolution, what about that, right? So we can, we still need some basis for comparison. So we will compare that with other engineering materials.

Mechanical properties of common materials, usually the engineering materials and mechanical properties of some biological materials.

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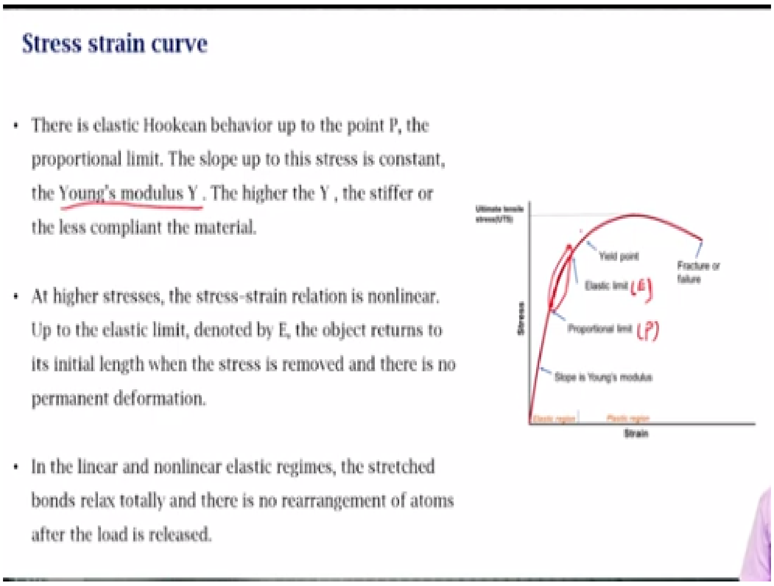

So if you plot the stress and the strain for materials, example being some engineering material let us take, steel or some engineering material. There is a particular point until which the stress and strain are related linearly, right? We will call this point P. That is elastic or Hookean behavior. There is a linear relationship between stress and strain until this point P, which is the proportional limit.

The slope, of course because it is linear, then the slope is a constant right, the slope is constant. That is the slope. It is essentially a straight line. That slope, what is that slope? We know what that slope is. That is the elastic modulus or the Young's modulus Y. In general, the higher the elastic modulus or the Young's modulus, the stiffer or the less compliant the material is, most engineering materials, right?

So this is something that we know by our study of engineering materials. As the stress keeps increasing, as the stress keeps on increasing, the stress strain relationship becomes nonlinear. From here, for example here, it is no longer linear. It can be considered to be linear at specific limits, or it can be somewhat piecewise linear, but that is a material, you know, material to material variation will be there, that non-linearity.

So it is better to assume a general nonlinear behavior for engineering materials beyond that proportional limit, right? And that continues until the elastic limit. So that means that there is a point beyond the proportional limit, after which, if you stop applying the stress, the material will go back to its original state. So it still exhibits elastic behavior just that in this regime, the relationship is not linear.

It is a nonlinear spring or it is a, it is exhibiting nonlinear property, but it still is elastic, okay? The object returns to its initial length when that stress is removed. So that is not permanent deformation. This is called as elastic limit. But suppose you keep applying further stress what happens? That is something that we need to see.

So in both these linear and nonlinear regimes, if you relax or if you remove the stress, the bonds are totally realized and there is no rearrangement of atoms. So essentially it goes back to its state. So there is no damage, right?

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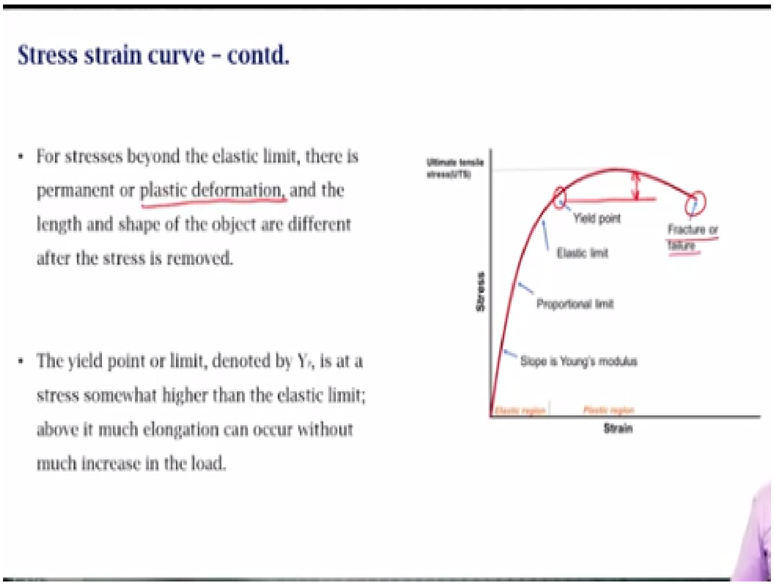

But if I keep applying stress beyond the elastic limit, that is what is called as, because you are beyond the elastic limit, we are beyond the elastic regime, you have what is called as permanent limit or permanent change or deformation called as plastic deformation. Now once you reach beyond that elastic point or the elastic limit, the object will not go back to its original state, right?

The shape of the object will be different and it will remain different, right? And you further apply, if there is a point at which beyond the elastic limit if you further apply stress, there is a particular point at which a lot of elongation can happen, a lot of elongation can happen with a very small change in stress. For very small changes of stress, the elongation will be very high, right?

This is the yield point. From this point onwards, if I want a greater elongation, I only need to apply very small amounts of stress, right? Something that is mind boggling or something that is weird, because earlier I had to apply large amounts of stress. Suddenly once you, so that is you have to go till the yield point after which this becomes like magic, right?

Of course this is, of course then if you keep pushing it beyond a limit there is you know fracture or failure of the material that happens.

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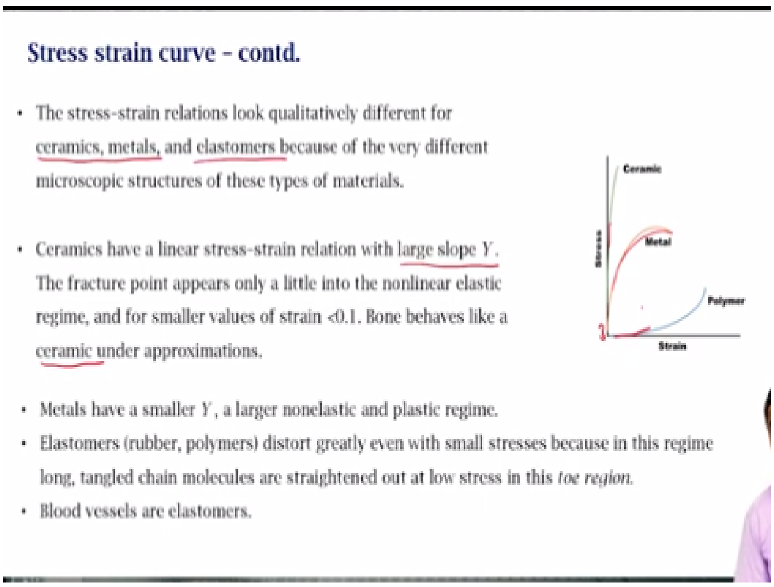

Of course, this is a general stress strain curve, this varies between materials, right? So they do look different for different materials, different engineering materials such as ceramics, metals, elastomers, because they are structurally different at the nano or micro levels or the nano level they are structurally different, right? So they will exhibit different properties.

Ceramics have a linear stress-strain relationship with the large Young's modulus, right? And the fracture point appears only a little into the nonlinear elastic region right for smaller values of strain less than 0.1. Bone can be modeled or can be compared to a ceramic under many approximations, under many assumptions bone behaves almost like a ceramic.

Metals have a smaller elastic modulus and a large non-elastic and plastic region. So something to keep in mind. So look at this is ceramic and this is metal, right? Polymers, they have this kind of a characteristic. They distort greatly even with small stresses, right? These are very small stresses, they distort to a great extent. So the deformation that they go through is very high right, in polymers, elastomers, rubber.

In this the material property is such that, that tangled chain molecules are straightened out at the so called toe region, something that we will revisit when we are looking at tendons, right? We will be discussing models of non-linear elasticity in the toe region of the tendon, right? Something to keep in mind is that blood vessels are elastomers, so they exhibit this kind of a property.

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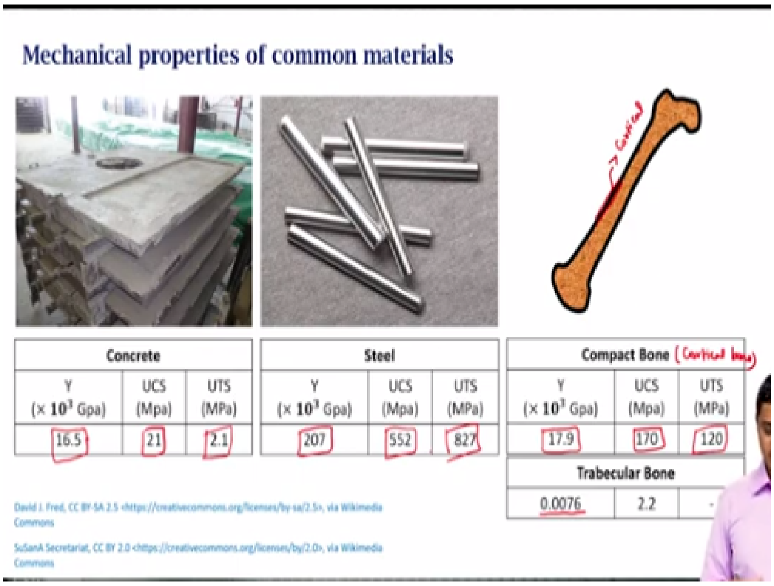

Now let us take some time and compare the biomaterial of our interest for this part of the course, just bone with some engineering materials whose properties we know very well. Now let us look at concrete. So if you keep comparable units, concrete has 16.5 units of elastic modulus. Compact bone is having a higher elastic modulus. It is about 18, right? Compact bone means not the entire bone.

This part of the bone is called as the compact bone or the cortical bone, okay? That property is what we are studying. Compact bone means cortical bone. Of course, for trabecular bone that varies to a relatively much smaller number because the trabecular bone is spongy, you do expect this value to be a very small number, so that is fine. Compare that with steel.

Of course, steel will have a higher modulus, right? And the compressive strength of concrete is about 21 units, for compact bone it is about 170, mostly 8 to 10 times, about 8 times the compressive strength of comparable Young's modulus but about 8 times the compressive strength.

Of course, we discussed this when we discussed the bone properties, we said that, bones have very high strength in compression and much lesser strength in tension and they are the weakest in shear, which is why many of the fractures happen due to shear stress or application of force in the shear direction. So something to keep in mind, right?

So compressive strength is extremely higher, very high than compared with concrete. Tensile strength, tensile strength is also very high for compact bone when compared with concrete. And compare this with steel, which is much, which is going to be much heavier, right? So something to keep in mind. So you may have to, you know, model this as a function of the density, as a function of many different things.

So it is not a fair comparison, but still, it is not much lower for bones when compared with steel. It is not as comparable. It is not as strong in compression and tension, but it is not very less either, right? It almost has 1/3 the strength in compression right, about 1/6 or 1/7 in tension, something to keep in mind.

So what this shows to us is that bone although is a biomaterial has some unique characteristics right that make it very strong and very preferable for a biomaterial. And there are other things that come into the picture. We will discuss this in future classes. Because if I had the cortical bone compact bone throughout right that is going to be an inefficient model, which is why you have the cortical bone and the compact bone.

You have the cortical bone and the cancellous bone. You have the trabecular bone and the compact bone, both of this. This is what helps the system to maintain strength while at the same time maintaining the total mass at a acceptable level, something to keep in mind.

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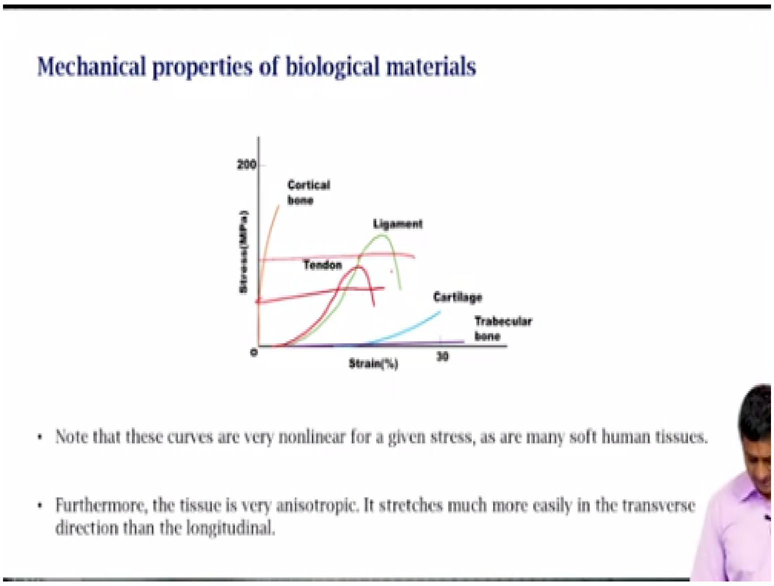

Of course, for given stresses right, for biomaterials, for biological materials, the curves are very nonlinear, right? For ligaments they are looking like this. So that means that for any given stress, there are going to be two different strains. So depending on the regime within which you are working for this stress for example, there are going to be two different strains and for the tendon etc., very nonlinear.

And this is true of many soft tissues in humans. Also the biological materials are not isotropic, right? It stretches much more easily in the transverse direction when compared with the longitudinal direction. So it depends on the direction in which you are applying the force.

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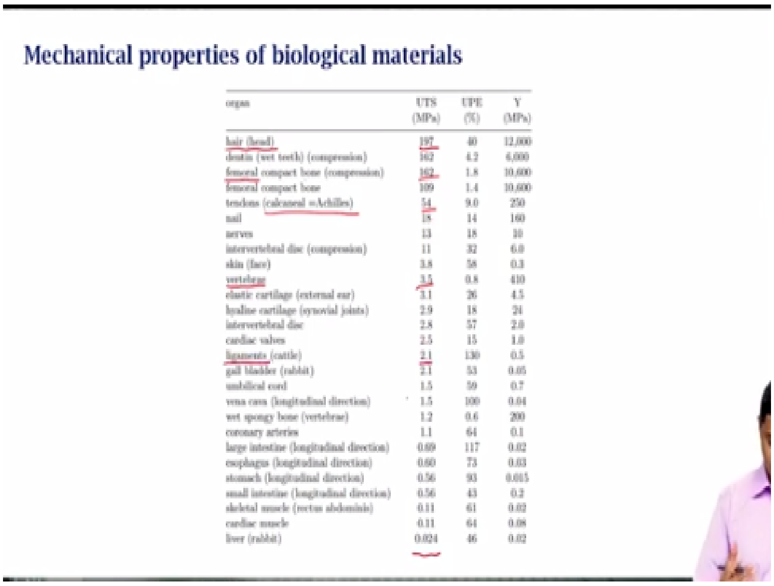

organ	UTS (MPa)	UPE (%)	Y (MPa)
hair (head)	197	40	12,000
dentin (wet teeth) (compression)	162	4.2	6,000
femoral compact bone (compression)	162	1.8	10,600
femoral compact bone	109	1.4	10,600
tendons (calcaneal =Achilles)	54	9.0	250
nail	18	14	160
nerves	13	18	10
intervertebral disc (compression)	11	32	6.0
skin (face)	3.8	58	0.3
vertebrae	3.5	0.8	410
elastic cartilage (external ear)	3.1	26	4.5
hyaline cartilage (synovial joints)	2.9	18	24
intervertebral disc	2.8	57	2.0
cardiac valves	2.5	15	1.0
ligaments (cattle)	2.1	130	0.5
gall bladder (rabbit)	2.1	53	0.05
umbilical cord	1.5	59	0.7
vena cava (longitudinal direction)	1.5	100	0.04
wet spongy bone (vertebrae)	1.2	0.6	200
coronary arteries	1.1	64	0.1
large intestine (longitudinal direction)	0.69	117	0.02
esophagus (longitudinal direction)	0.60	73	0.03
stomach (longitudinal direction)	0.56	93	0.015
small intestine (longitudinal direction)	0.56	43	0.2
skeletal muscle (rectus abdominis)	0.11	61	0.02
cardiac muscle	0.11	64	0.08
liver (rabbit)	0.024	46	0.02

So this is an example of some biological materials and their properties, right? So some, we can take some examples. So vertebra having an UTS of 3.5 MPa, right? Whereas, if you take hair, so that is going to have 197 MPa as the UTS. So a very strong material. So you would think that the hair is not a strong material. It turns out the hair is one of the strongest material if you take UTS as the measure of strength.

If you take UTS as the measure of strength, then hair is a very strong material, right? So it depends really. So of course you see a huge variation between the liver which is 0.024 to the hair which is 197. So it is huge variation. So the biological materials come in various properties, come with various properties. So compact bone of the femur right, under compression is 162, right?

Tendons is going to have 54 etc., right? Cattle ligaments sample have 2.1. So some numbers.

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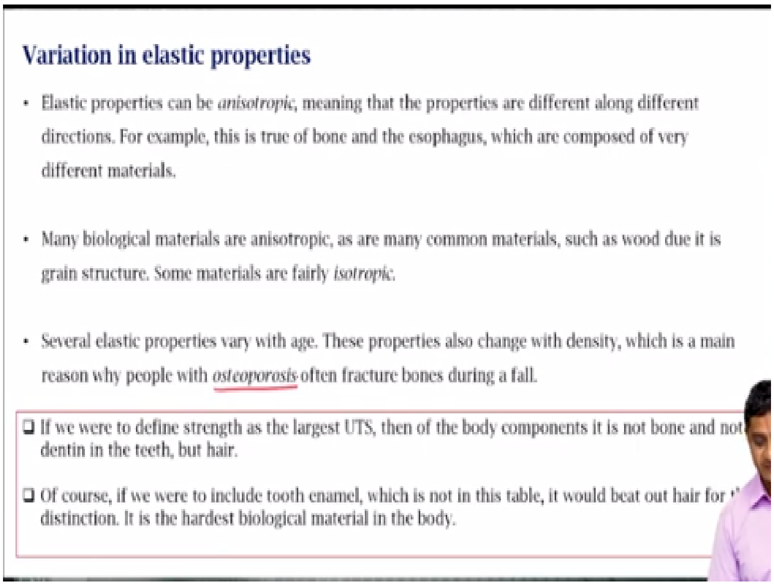

As I already mentioned, there is anisotropy that the properties, these properties are different along different directions, right? This is absolutely true of the bone on the esophagus although these are composed of very different materials. One is mostly an elastomer, esophagus is mostly an elastomer. Bone is bone, right? It is composed of both organic and inorganic materials, is a composite material.

Many biological materials are not isotropic as are many other non-biological materials or well the wood can also be considered a biological material. It is actually a composite due to its grain structure. Some materials are fairly isotropic but most biological materials are not isotropic. Important to note that these properties vary with age.

These properties change with the density which is why my point about keeping your strength high, exercising comes back. If the density is high right, then the elastic properties will remain at an acceptable level which is why it is important to keep the density high which is why it is important to not allow the pores to form. What is this problem, osteoporosis is a problem that happens due to pores.

So if the density is less that means that our pores are more, osteoporosis is the result. This happens due to loss of bone tissue because of biological reasons, because of age. Of course if I am to defend strength as the largest UTS then you know it is not bone that is the strongest but rather the hair.

But if I am considering the tooth enamel right, which is not mentioned in that table, it would beat out even the hair, right? Because the tooth enamel is the hardest biological material in the body. It is even harder than hair when you take UTS as the strength, okay.

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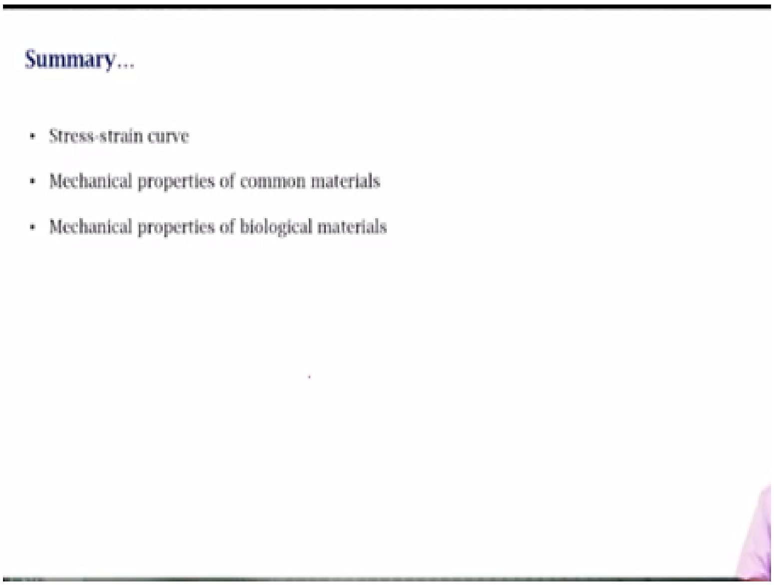

So in this video, we saw stress-strain curves and stress-strain curves for many biological materials and mechanical properties of common materials and compared it with some biological materials. So we took the biological material as the compact and trabecular bone and compared it with engineering materials like concrete and steel.

And we looked at the material properties of various biological materials starting from hair and bone and ligaments, tendons, etc. We have not discussed the entire table but I do encourage you to take a look at the entire table and compare for your own interest. Thank you very much for your attention.