Biomechanics of Joints and Orthopaedic Implants
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Lecture No. 27
Bone Adaptation and Viscoelastic Behaviour

Good morning everybody, in this lecture we will be discussing about Bone Adaptation and Viscoelastic Behaviour.

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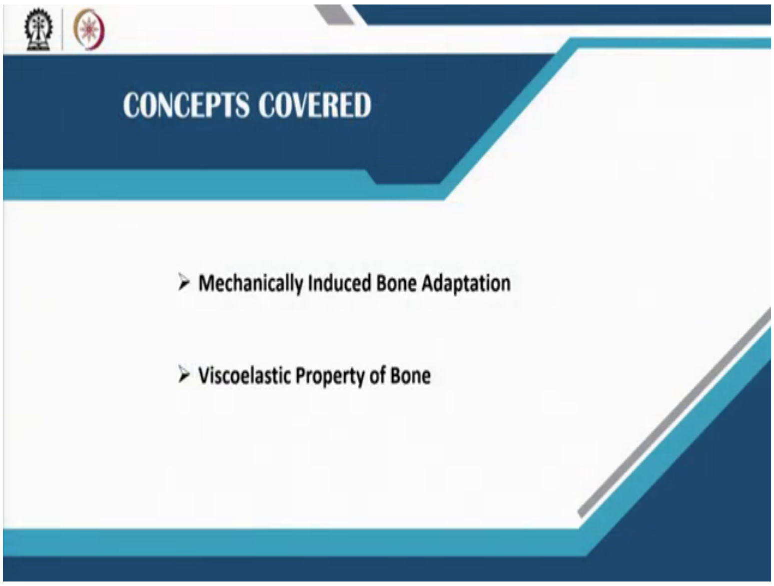

The concepts covered in this lecture are mechanically induced bone adaptation and viscoelastic property of bone.

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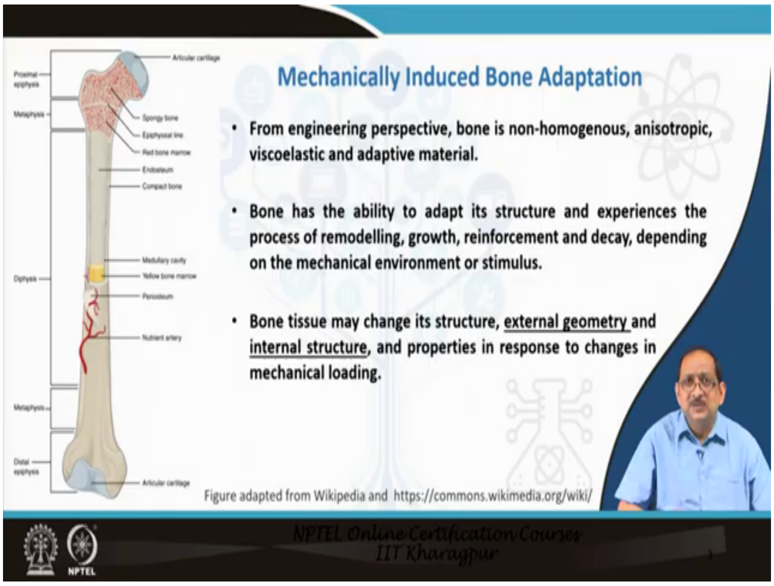

From engineering perspective, bone is non-homogenous, anisotropic, viscoelastic, and adaptive material. Bone has the fascinating property of adapting its structure through the process of remodeling, growth, reinforcement and decay, depending on the mechanical environment or stimulus it receives. Bone tissue may change its structure that is the external geometry and the internal structure and properties in general in response to changes in mechanical loading.

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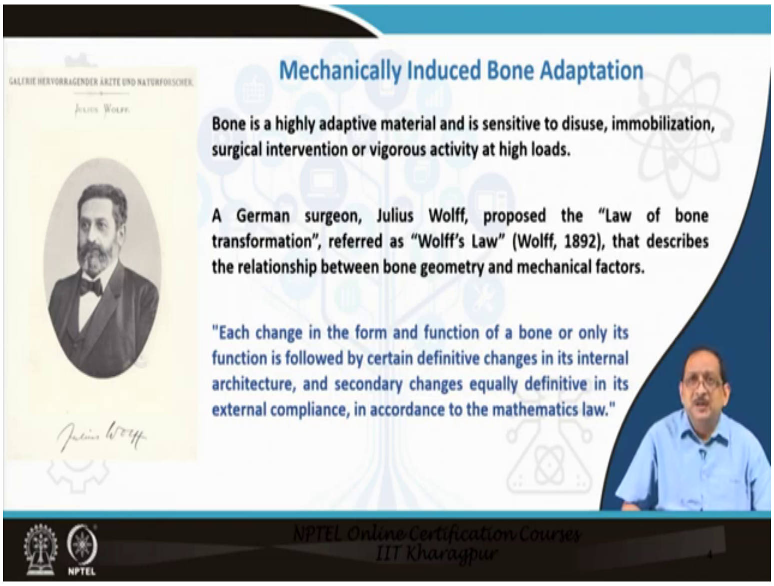

Bone is a highly adaptive material and is sensitive to disuse, immobilization, surgical intervention, or vigorous activity at high loads. A German surgeon, Julius Wolf, proposed the "law of bone transformation," which is properly referred to as the "Wolff's law" that describes the relationship between bone geometry and mechanical factors.

The law states that each change in the form and function of a bone or only its function is followed by certain definitive changes in its internal architecture and secondary changes equally definitive in its external compliance, in accordance to the mathematics law.

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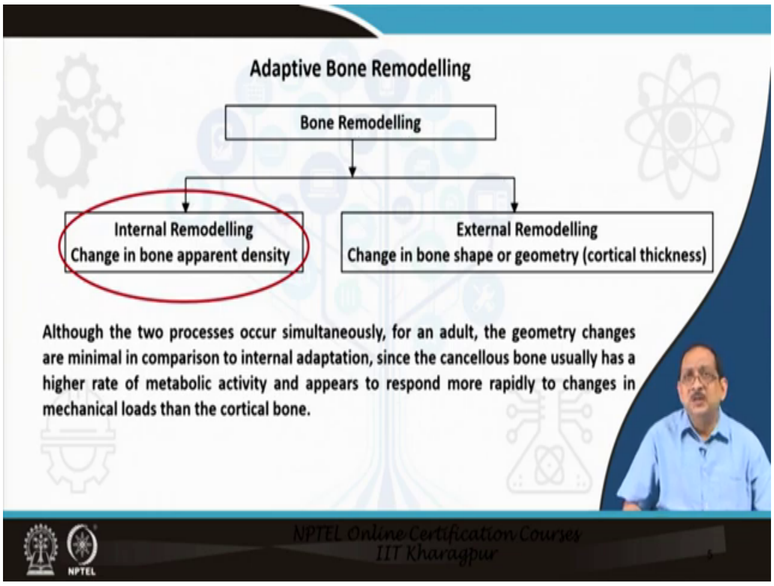

Now, Adaptive Bone Remodeling, can be classified into two types: one is the internal remodeling, another is the external remodeling. So, internal remodeling refers to change in bone apparent density, whereas external remodeling refers to change in bone shape or geometry, geometry mostly cortical thickness.

Although the two processes occur simultaneously, for an adult, the geometry changes are minimal in comparison to the internal adaptation that is, internal remodeling since the cancellous bone usually has a higher rate of metabolic activity and appears to respond more rapidly to changes in mechanical loads than the cortical bone.

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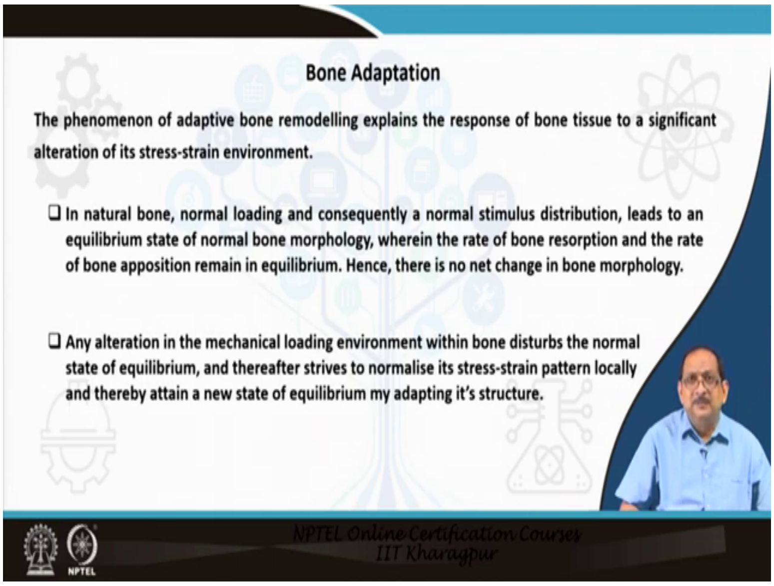

The phenomenon of adaptive bone remodeling explains the response of bone tissue to a significant alteration in the stress-strain environment within the bone. So, in a natural bone, normal loading and consequently a normal stimulus distribution leads to an equilibrium state of normal bone morphology, wherein the rate of bone resorption which is bone loss and the rate of bone apposition which is referred to as bone gain, remain in equilibrium. Hence, there is no net change in bone morphology.

Any alteration in the form of mechanical loading environment within the bone disturbs the normal state of equilibrium and thereafter strives to normalize its stress-strain pattern locally and try to attain a new state of equilibrium by adapting its structure.

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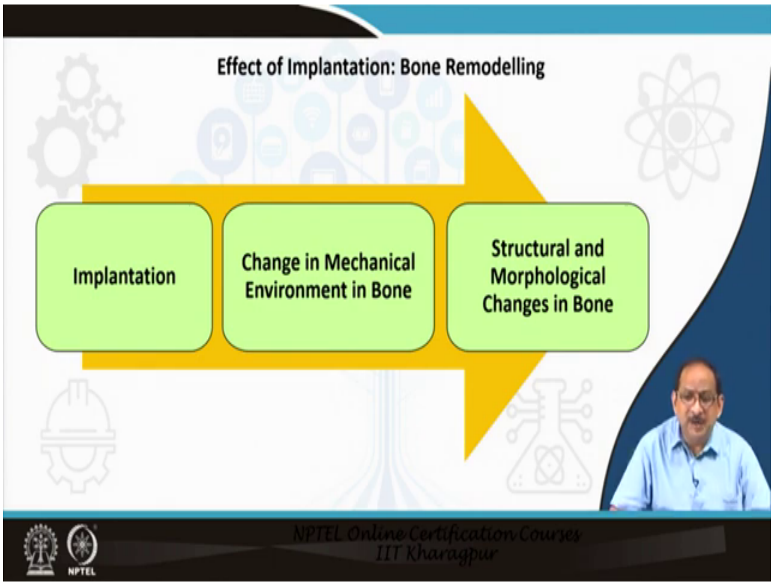

For example, effect of implantation on bone remodeling is a common phenomenon, so implantation leads to change in mechanical environment within bone, thereafter, triggering structural and morphological changes in bone.

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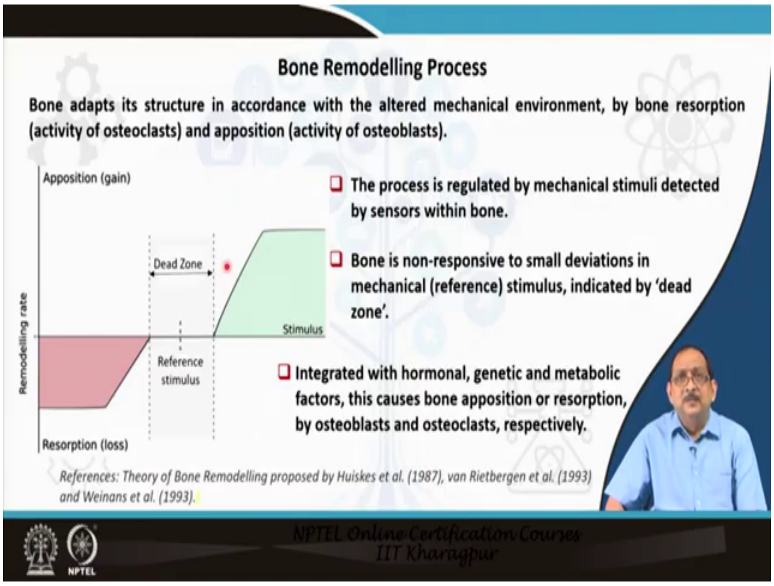

Now, bone adapts its structure in accordance to the altered mechanical environment, by bone resorption which is triggered by the activity of osteoclasts, and bone apposition triggered by the activity of osteoblasts. The figure presented here refers to a diagrammatic representation of bone resorption and bone apposition. The process is regulated by mechanical stimuli detected by sensors within the bone.

Now, if you look at the graph more in detail, there is a dead zone. Bone is non-responsive to small deviations or changes in the mechanical stimulus, indicated by the dead zone or the lazy zone. Anything beyond the dead zone or the lazy zone, left or right, triggers bone remodeling. Integrated with hormonal, genetic, and metabolic factors, this causes bone apposition or bone resorption by the activity of osteoblasts and osteoclasts, respectively.

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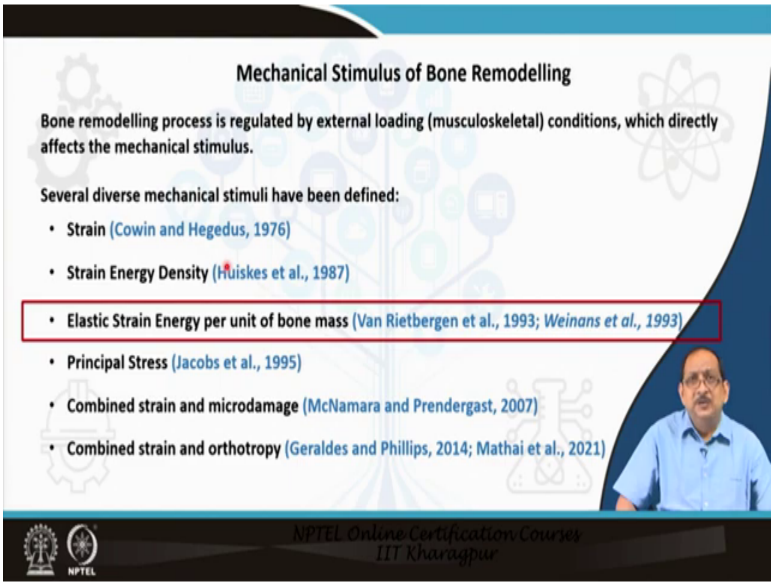

The bone remodeling process is regulated by external loading (musculoskeletal) loading conditions that directly affect the mechanical stimulus. The mechanical stimuli can be either strain, strain energy density, elastic strain energy per unit of bone mass, principle stress, combined strain and microdamage, and combined strain and orthotropy. The references are indicated in the slide as well.

However, the most popular mechanical stimulus that has been used to predict bone remodeling is the elastic strain energy per unit of bone mass.

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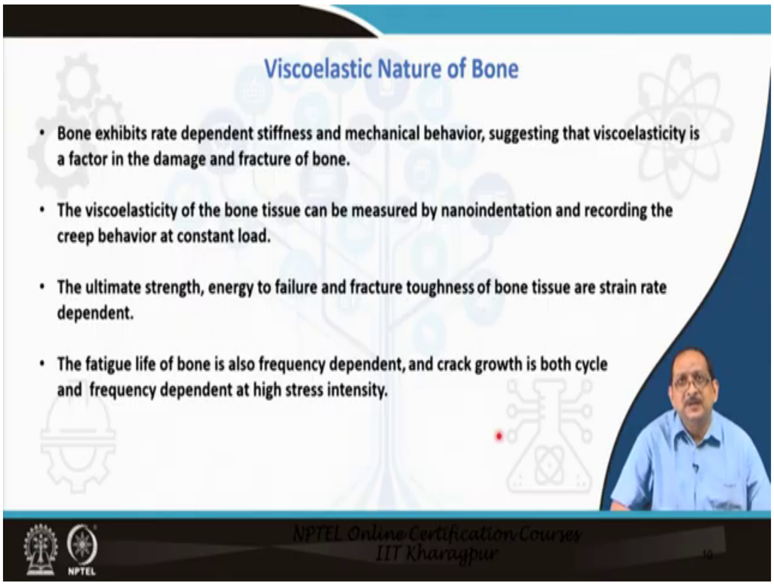

Let us come to the second topic of this lecture, the viscoelastic property of the bone. Bone exhibits rate dependent stiffness and mechanical behavior, suggesting that viscoelasticity is a factor in the damage and fracture of bone. The viscoelasticity of bone tissue can be measured by nanoindentation and recording the creep behavior at constant load. The ultimate strength, energy to failure, and facture toughness of bone tissues are strain rate dependent.

The fatigue life of bone is frequency dependent, and crack growth is both cycle and frequency dependent at high stress intensity.

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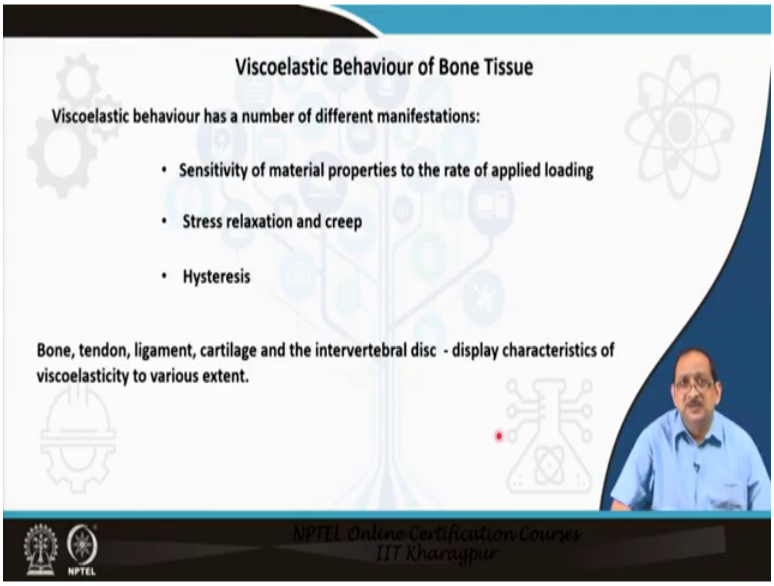

Now, let us look into the viscoelastic behavior of bone tissue. The viscoelastic behavior has a number of different manifestations: The sensitivity of material properties to rate of applied loading; Stress relaxation and creep; Hysteresis. It may be noted here with that bone, tendon, ligament, cartilage and the intervertable disc, all display characteristics of viscoelasticity to various extent.

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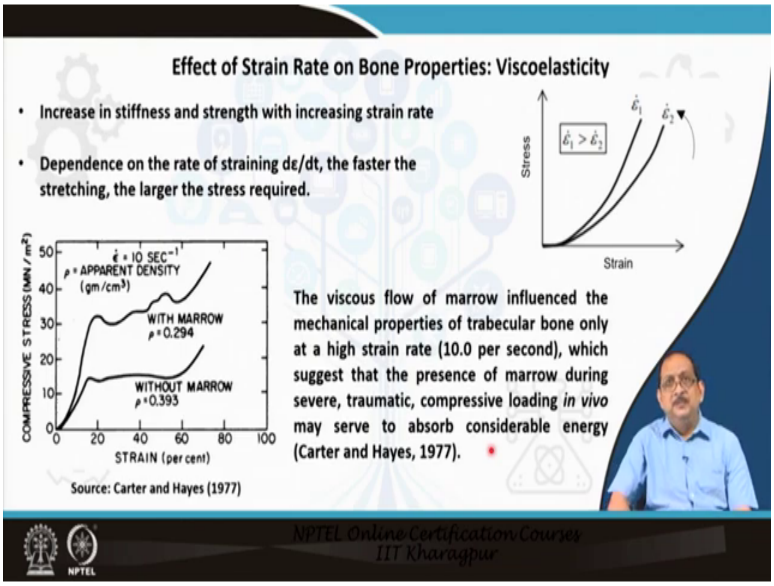

Let us now look into the effect of strain rate on bone properties. An increase in stiffness and strength occurs with increasing strain rate as indicated in the figure. The higher the strain rate, the higher is the stiffness and strength. Dependence on the rate of straining can be explained in a way the faster the stretching; the larger is the stress required.

Now, let us look into the experimental data of Carter and Hayes which investigated the influence of the marrow. So, the two curves that are presented here are the mechanical behavior, stress-strain behavior with marrow and without marrow. And the strain rate recorded for the bone for the mechanical behavior is 10 per second.

So, it can be concluded that the viscous flow of marrow influence the mechanical properties of trabecular bone only at high strain rate (10 per second), which suggests that the presence of the marrow during severe traumatic and compressive loading in vivo may serve to absorb considerable energy.

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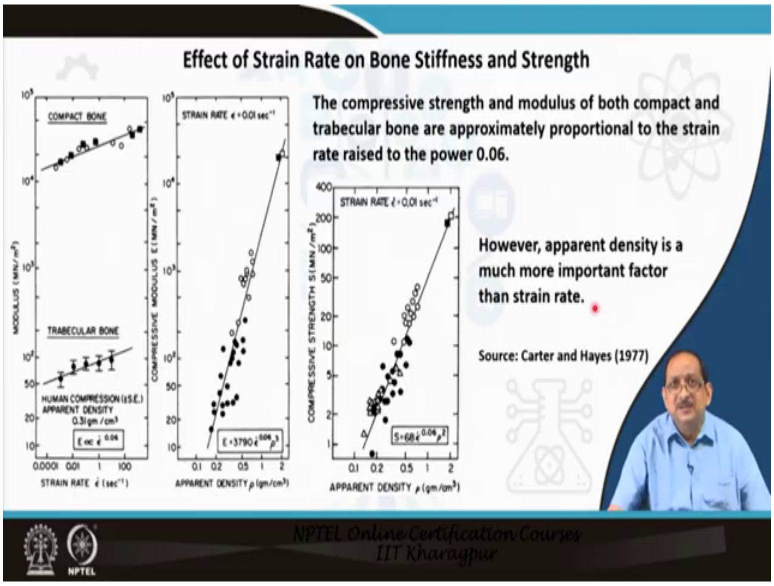

The effect of the strain rate on bone stiffness and strength is presented in this slide and these are experimental data from Carter and Hayes. As you can see in the slide, the compressive strength and modulus of both compact and trabecular bone are approximately proportional to the strain rate raised to the power of 0.06. However, apparent density is a much more important factor than the strain rate as per as the bone mechanical properties are concerned.

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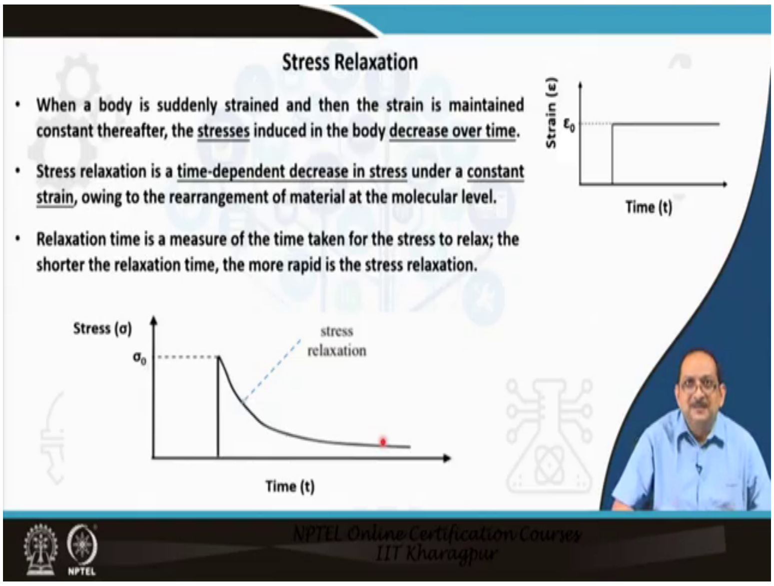

Now, let us discuss the basic of stress relaxation. When a body is suddenly strained, and then the strain is maintained constant thereafter, the stress induced in the body decreases over time.

Stress relaxation is a time dependent decrease in stress under a constant strain, owing to the rearrangement of the material at the molecular level. Relaxation time is a measure of the time taken for the stress to relax; the shorter the relaxation time, the more rapid is the stress relaxation.

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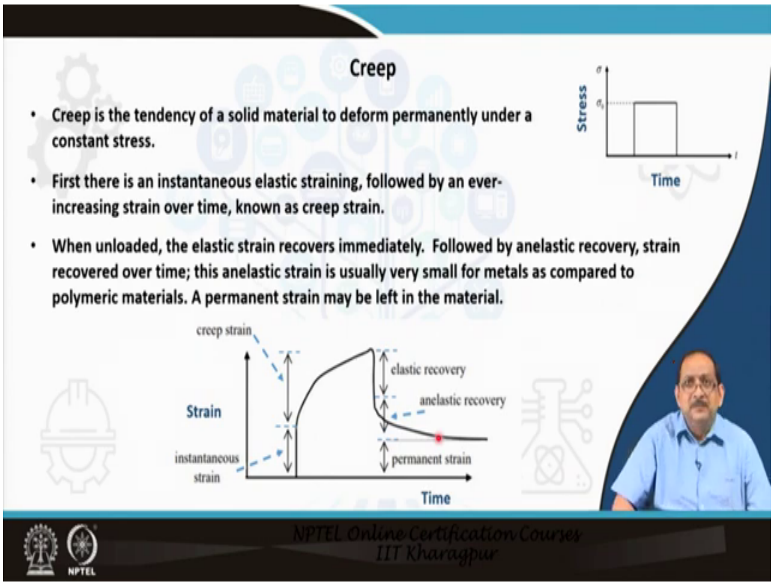

Now, creep is the tendency of a solid material to deform permanently under a constant stress. It is somewhat opposite property to stress relaxation. First there is an instantaneous elastic straining, followed by an ever increasing strain over time known as the creep strain. When we are unloading, the elastic strain recovers immediately followed by anelastic recovery that is strain recovered over time. This anelastic strain is usually very small for metals as compared to polymeric material. A permanent strain may be left in the material.

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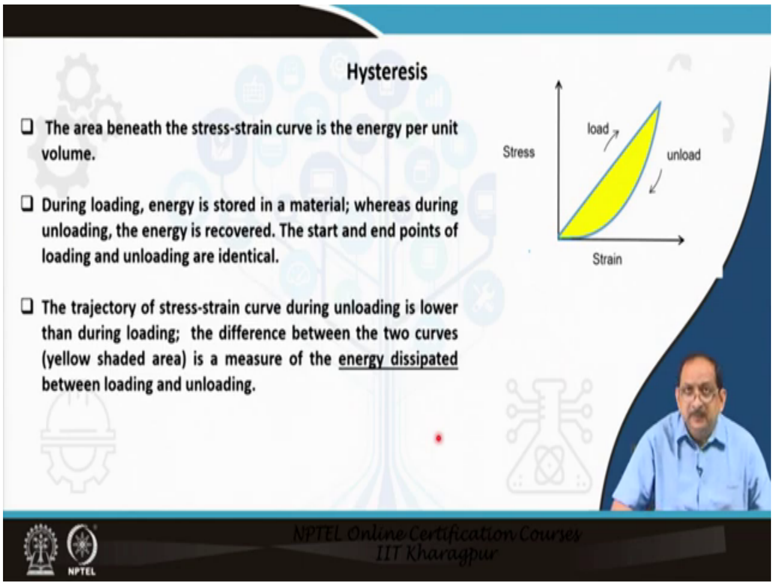

Let us discuss Hysteresis by the help of this stress-strain diagram, the loading and unloading of stress-strain. The area beneath stress-strain curve is the energy per unit volume. During loading, the energy is stored in a material, whereas the energy is recovered during unloading. However, the start and end points of the loading and unloading are identical.

The trajectory of the stress-strain curve during unloading is lower than during loading; the difference, as indicated by the yellow shaded area in the curve, between the two curves is a measure of the energy dissipated between loading and unloading.

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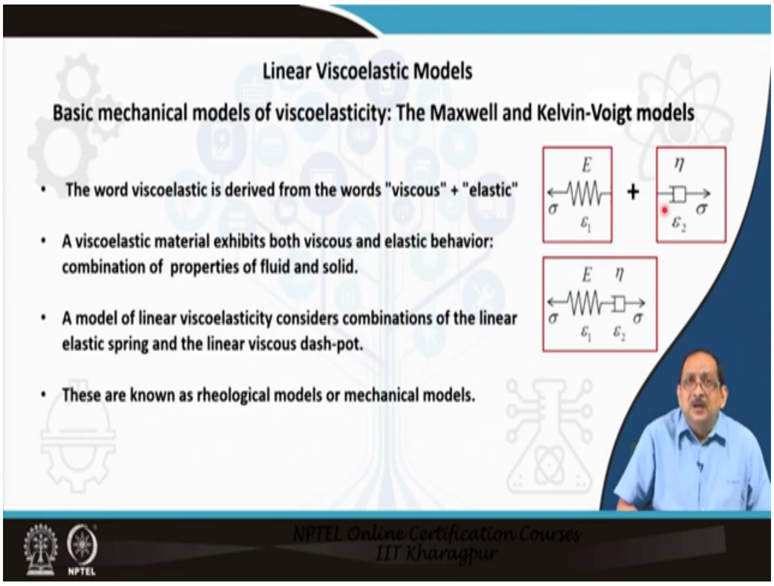

Let us now discuss more in details about basic models of viscoelasticity: the Maxwell and the Kelvin-Voigt models. The word viscoelasticity is derived from the words "viscous" and "elastic," the viscoelastic. A viscoelastic material exhibits both viscous and elastic behavior, a combination of fluid and solid properties. A model of linear viscoelasticity considers combinations of linear elastic spring and the linear viscous dash-pot. These are known as rheological models or mechanical models.

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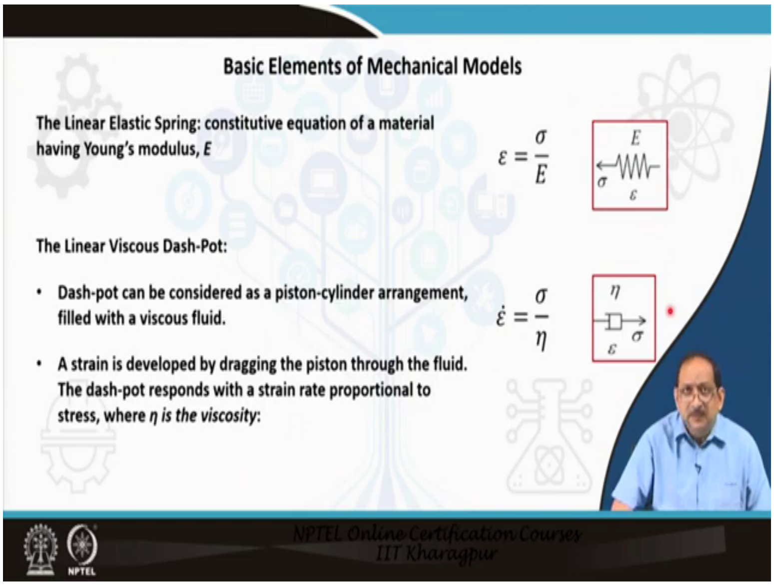

The basic elements of these mechanical models, as indicated in this figure, is a linear elastic spring wherein stress is related to strain through the Young's modulus. In the linear viscous dash-pot system, the dash-pot can be considered as a piston cylinder arrangement filled with a viscous fluid. A strain is developed by dragging the piston through the fluid. The dash-pot responds with a strain rate proportional to the stress, connected through the viscosity of the fluid.

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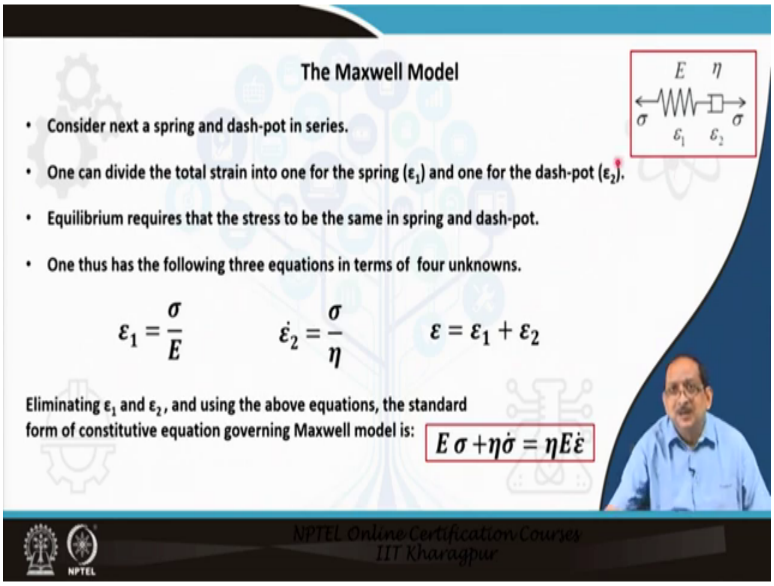

Let us look into the Maxwell model, in the Maxwell model; we considered a spring and the dash-pot in series as indicated in the figure. One can divide the total strain into one spring and one for the dash-pot. Equilibrium requires that the stress to be same in the spring and in the dash-pot. Therefore, we can actually write three equations in terms of four unknowns. Eliminating this individual strain and using the above equation, the standard form of constitutive equation governing the Maxwell model is presented in this slide.

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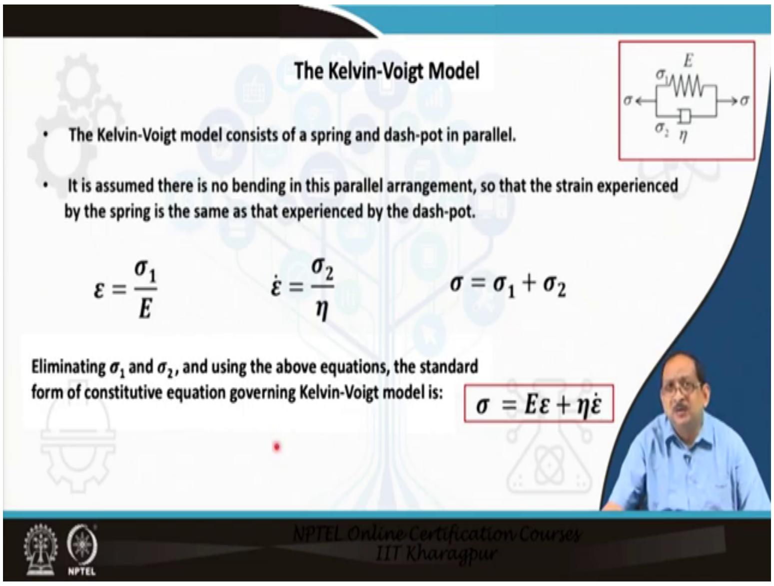

The Kelvin-Voigt model, in comparison, consist of a spring and dash-pot connected in parallel. It is assumed that there is no bending in this parallel arrangement so that the strain experienced by the spring is the same as that experienced by the dash-pot. Again so, mathematical relations are can be written and eliminating stresses and using the above equation, the standard form of the constitutive equation governing Kelvin-Voigt model can be written as shown in the slide.

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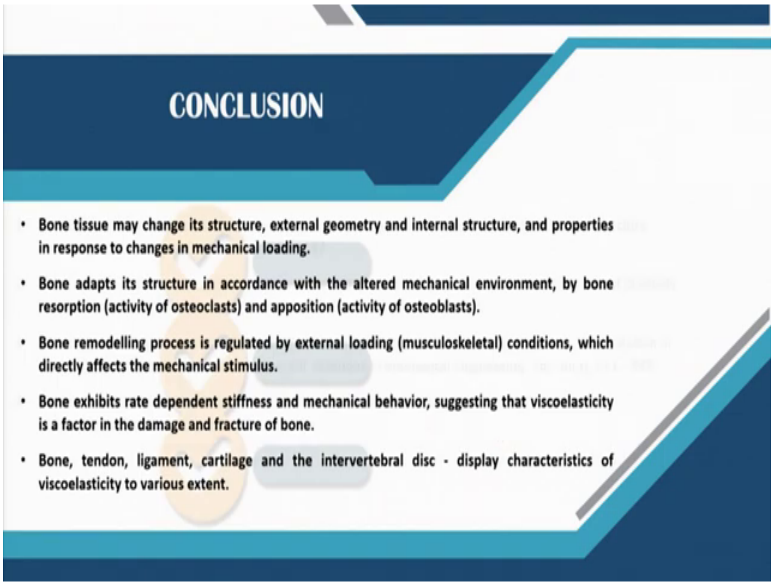

Let me summarize the conclusions of this lecture. Bone tissue may change its structure, external geometry and internal structure as well as the properties in response to changes in mechanical loading. Bone adapts its structure in accordance to the altered mechanical environment by bone resorption (activity of osteoclasts) and bone apposition, triggered by the activity of osteoblasts. Bone remodeling process is regulated by external loading which directly affects the mechanical stimulus.

Bone exhibits rate dependent stiffness and mechanical behavior, suggesting that viscoelasticity is an important factor in damage and fracture of bone. Bone, tendon, ligament, cartilage, and intervertabral disc, all display characteristics of viscoelasticity to various extents.

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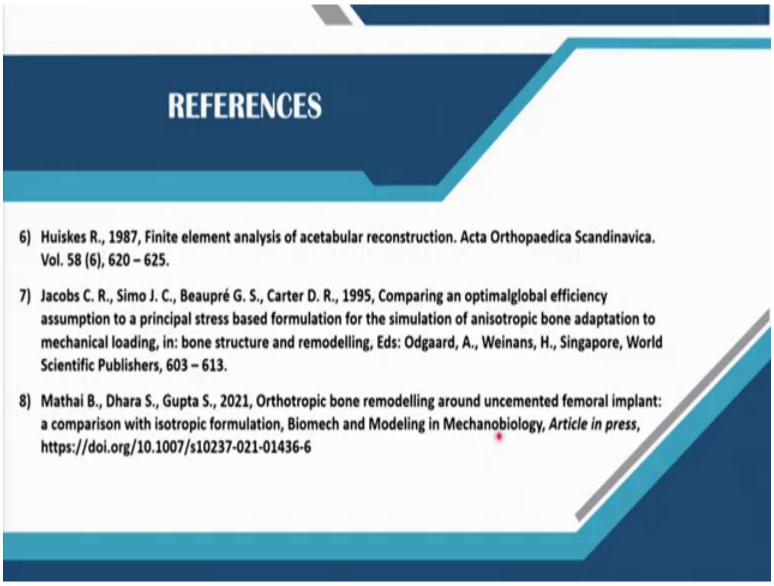

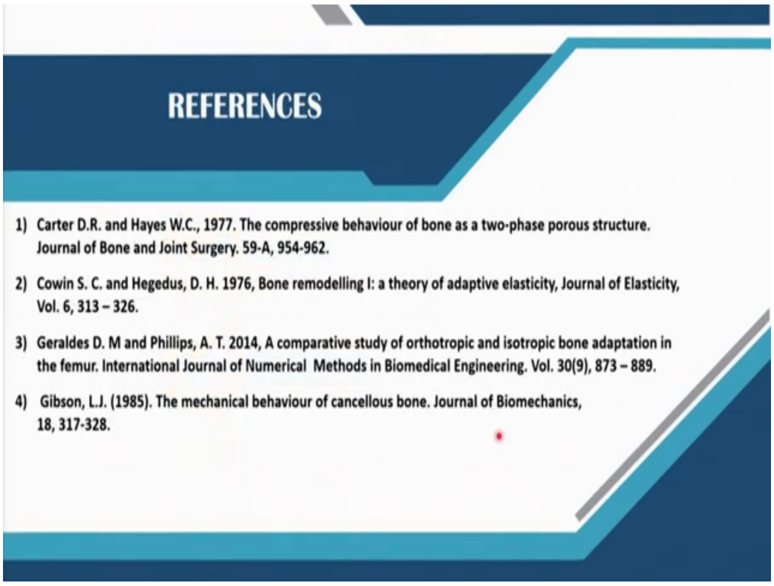

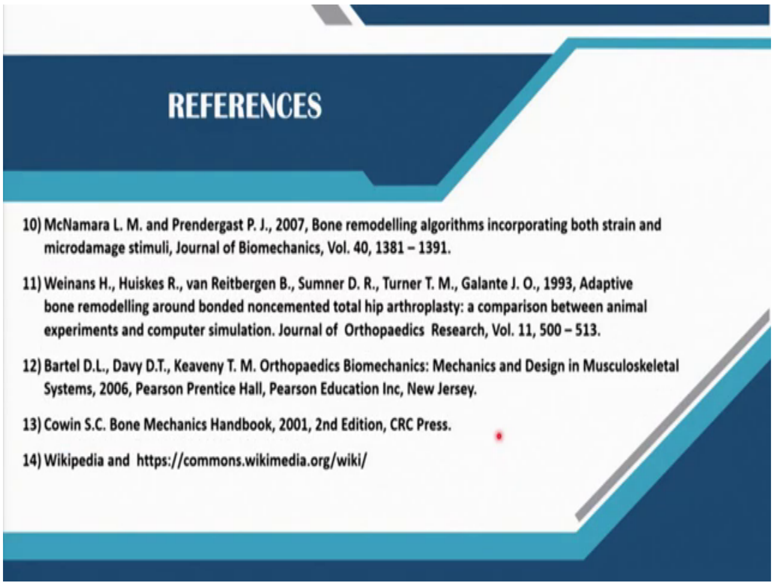

The references of this lecture are listed here; thank you for listening.