Dynamic Behaviour of Materials
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Lecture No 1
Introduction to Dynamic Behaviour of Materials - I

Hello everyone. This course, Dynamic Behaviour of Materials, is offered by IIT Guwahati. My name is Prasenjit Khanikar and I am the instructor of this course.

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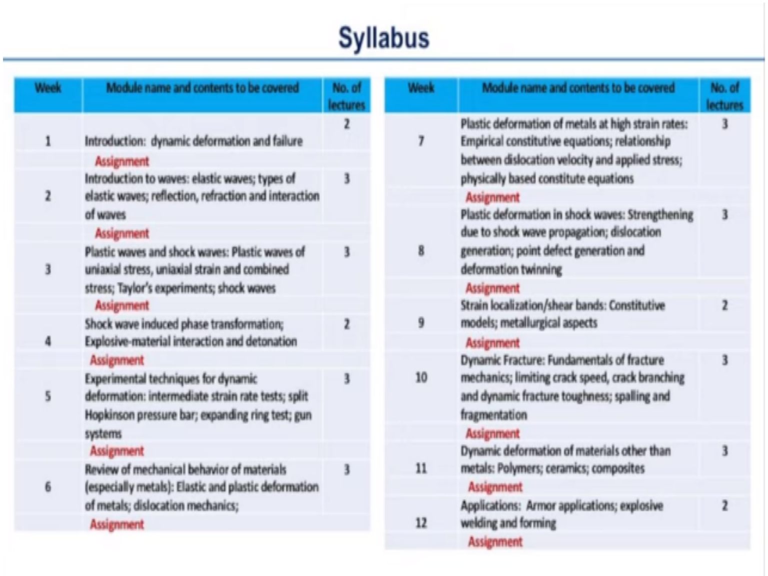

Syllabus

Week	Module name and contents to be covered	No. of lectures
1	Introduction: dynamic deformation and failure Assignment	2
2	Introduction to waves: elastic waves; types of elastic waves; reflection, refraction and interaction of waves Assignment	3
3	Plastic waves and shock waves: Plastic waves of uniaxial stress, uniaxial strain and combined stress; Taylor's experiments; shock waves Assignment	3
4	Shock wave induced phase transformation; Explosive-material interaction and detonation Assignment	2
5	Experimental techniques for dynamic deformation: intermediate strain rate tests; split Hopkinson pressure bar; expanding ring test; gun systems Assignment	3
6	Review of mechanical behavior of materials (especially metals): Elastic and plastic deformation of metals; dislocation mechanics; Assignment	3
7	Plastic deformation of metals at high strain rates: Empirical constitutive equations; relationship between dislocation velocity and applied stress; physically based constitute equations Assignment	3
8	Plastic deformation in shock waves: Strengthening due to shock wave propagation; dislocation generation; point defect generation and deformation twinning Assignment	3
9	Strain localization/shear bands: Constitutive models; metallurgical aspects Assignment	2
10	Dynamic Fracture: Fundamentals of fracture mechanics; limiting crack speed, crack branching and dynamic fracture toughness; spalling and fragmentation Assignment	3
11	Dynamic deformation of materials other than metals: Polymers; ceramics; composites Assignment	3
12	Applications: Armor applications; explosive welding and forming Assignment	2

So, this is the syllabus, this is basically, we divided into 8 modules and this is just a tentative schedule. We will have assignment after each module and the assignment will have equal weightage. So, we will discuss about this syllabus little later.

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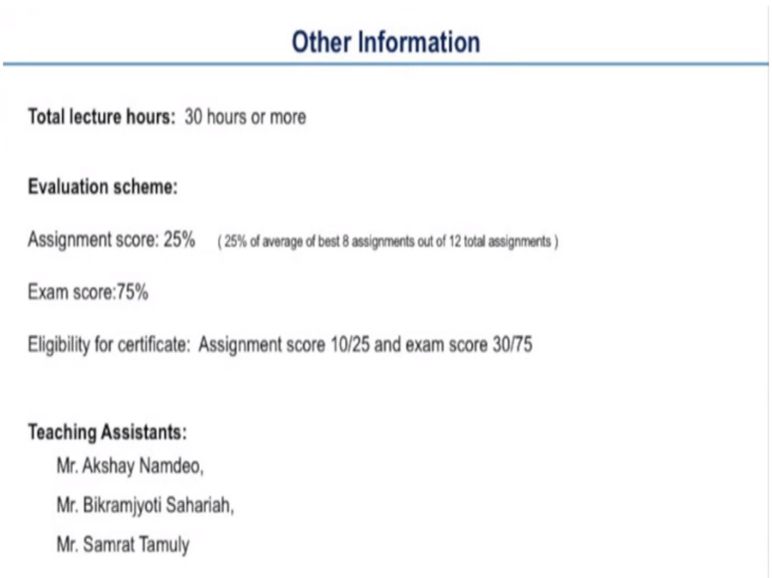

So total lecture hours will be 30 hours, we may need a few more hours to finish this syllabus. I will have teaching assistant for this course, three of my Phd students will help me in this course. They are; Mr. Akshay Namdeo, Mr. Bikramjyoti Sahariah, and Mr. Samrat Tamuly. So, they will be happy to help you out during this course.

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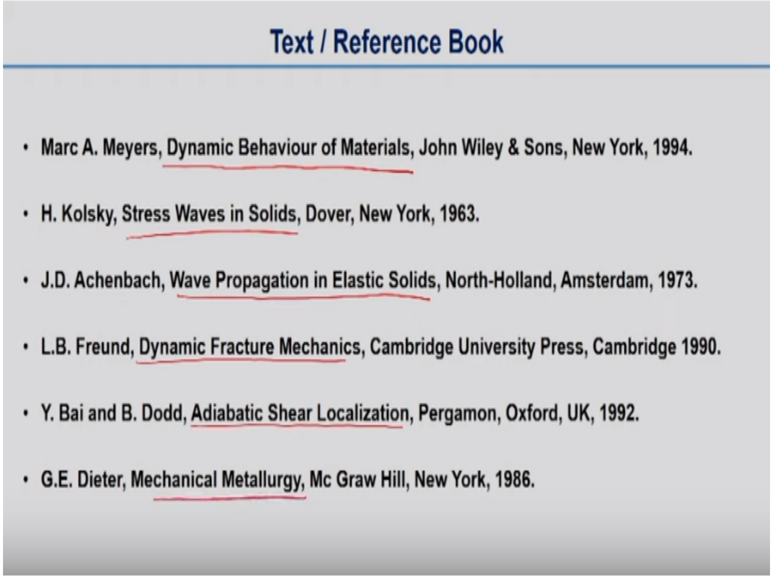

So we will be using these books for, as a text book or reference book. Dynamic behaviour of Materials by Marc Meyers, we will consider that as a text book. Marc Meyers is a professor in the University of California, San Diego. For Stress Waves, the Stress Waves in Solids by H. Kolsky and then Wave Propagation in Elastic Solids by J.D. Achenbach are some of the references.

Similarly for Dynamic Fracture, the book by L.B. Freund and for Adiabatic Shear Localization, the book by Y. Bai and B. Dodd we can keep it as reference and for review of the mechanical deformation of metals, we can use the classic book on Mechanical Metallurgy by G.E. Dieter. So, let us discuss a why we need to study this course behavior of materials under dynamic loading, that is high speed loading, is very different than behavior of materials under quasit-static loading, that is slow loading.

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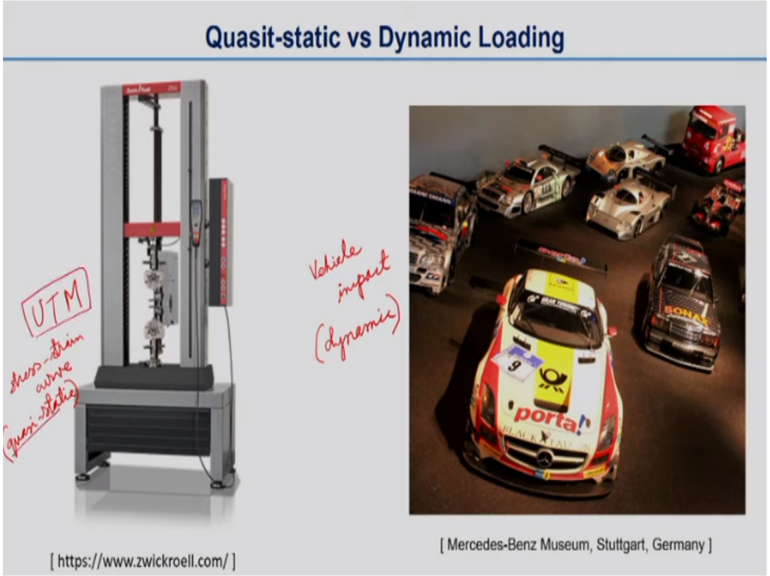

That means we need to consider the material properties or material parameters to predict the behavior of material under dynamic loading. These material parameters are different than what we obtain from our quasit-static tests. So, however, the material parameters under the dynamic loading are not easily available, which is like our quasit-static material parameters. Also, the deformation mechanism and failure mechanisms under dynamic loading are more complicated as compared to our quasit-static loading.

Therefore, scientists and engineers are still trying to understand many dynamic processes and dynamic mechanical behavior of various materials. Let us consider these two figures; the left hand side is a UTM, universal testing machine, made by Zwickroell company as most of us have performed the quasit-static test in UTM, so we know how to obtain a stress-strain curve out of these quasit-static tests.

On the right hand side, this is a representative image, I click this image in the Mercedes Benz Museum in Stuttgart, Germany. So, if we have this high speed curves, if we have vehicle impact between these high speed curves, the material deformation of this curve in these dynamic impact will be very different than what we found from the quasit-static test, of those material using the UTM.

Here in this case, the vehicle impact will be dynamic, is a dynamic deformation process. So, when these dynamic deformation happens, the material will behave in a very different than how the material behaves in a quasit-static test using the UTM, universal testing machine. So, before going to discuss, so what is the difference between the dynamic loading and quasit-static loading, I will like to remind you the simple physics.

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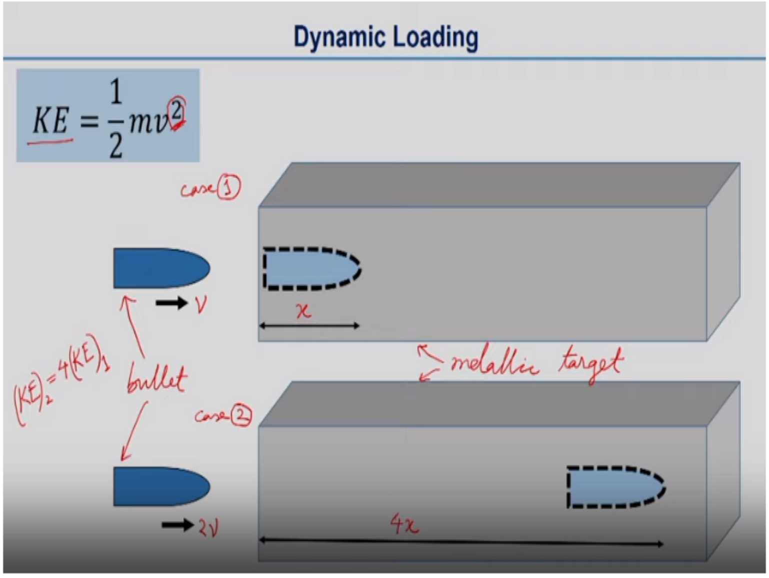

We know that kinetic energy increases with square of the velocity. So, here in this case, we are taking a high speed bullet hitting a metal target, it is a metallic target. There are two cases here as you can understand from the figure; case 1 and case 2. In the first case, the bullet is having a velocity v, and in the second case, the bullet travels much faster it has a velocity 2v. So, as you know that the kinetic energy increases with square of the velocity, so kinetic energy in the second case, will be four times that of first case.

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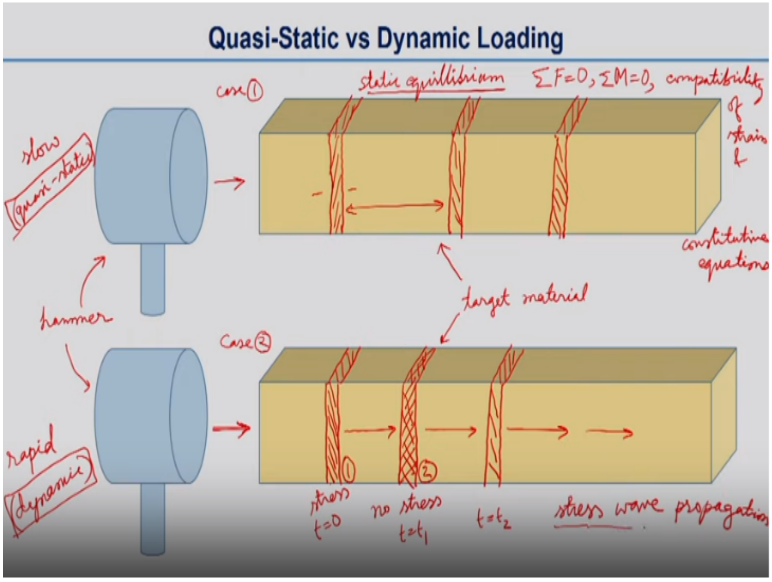

And then if all other condition remains same, the penetration will also be four times. That is in the first case if the penetration is x, then in the second case the penetration will be 4x. So, now, let us again discuss about the difference of deformation mechanism between quasit-static and dynamic loading. Here, we have two hammers hitting a target. Basically, there are two cases here; the case 1 and case 2. We have this, a hammer, both the cases and we have the target material.

So, in the first case, we are hitting the target at a very slow speed and in the second case, the loading is rapid, that is we are hitting the target with a high speed. So, in the first case, this is slow, that is why we can call it as a quasit-static and in the second case, that is an example of dynamic deformation. So, if we take a section out in the first case, we will get to know that, this thin section will be in static equilibrium with it is surrounding parts.

If you go to the left side or right side, this section will be in equilibrium with the surrounding and if you take another section, you will see that the similar stresses or actually the uniform stresses present in both the cases. So, in both cases, you will get uniform stress at a given time the entire target material is uniformly stressed due to the quasit-static loading. So, all the thin sections will have the same stress.

But now in the case of dynamic case, if we take a thin section, so when you hit the material with the hammer so the stress experience in this thin section will be different than the other sections. So, probably in this second section, this is, let us say, we have section second, section number 2 and then there is the first section.

So, in the second section, there will be no stress at that moment and the first section there will be stress, but after some time the section 2 also will experience the stress and similarly, let us say, this is time t equal to 0, this is let us say, time t equal to t1, here let us say, time t equal to t2, so you will get stresses here.

So that means, the stresses or the disturbances produced by the dynamic loading, it will advance with time, the stress will propagate. So, that is why we call it as a stress as a wave and that is stress wave propagation.

So, that means for a quasit-static loading, we have static equilibrium state of static equilibrium and with your well known equations of mechanics of material we can, for example, summation of force equal to zero summation of movement equal to zero compatibility of strains and constitutive equations. These are the set of equations, we require to solve the problem in the quasit-static loading case.

In the dynamic loading case, however, we have additional consideration. We need to consider the stress wave propagation, okay.

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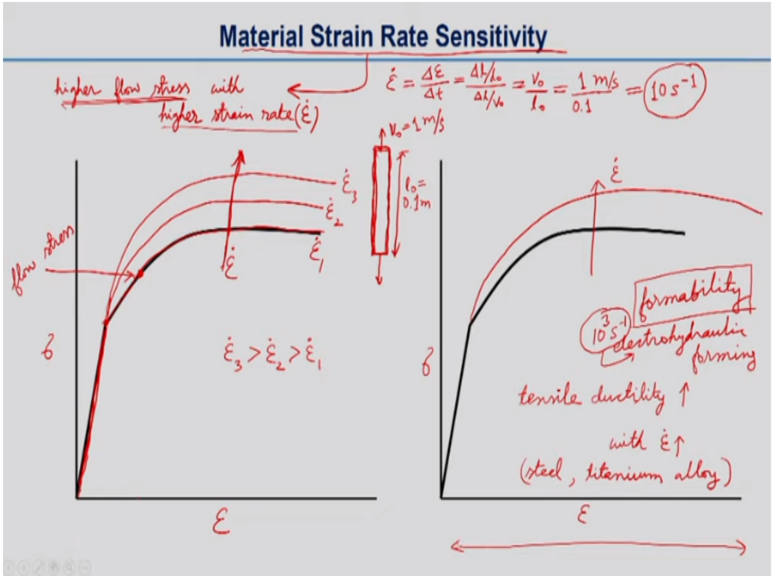

So, let us discuss another aspect of dynamic loading. So, the materials strain rate sensitivity. So, let us discuss what is this material strain rate sensitivity. The flow stress of a material increases with strain rate, that is called strain rate sensitivity. Flow stress means, the instantaneous stress in the plastic deformation part of the, you know, stress-strain curve.

That means, this is as you know, this is the, so this is actually the strain and the stress. So, as you know, this is the elastic part, the straight line part, this is elastic. After the yield strength, this is the plastic part. So, flow stress means instantaneous stress in the plastic region corresponding to any particular, you know, strain.

The strain rate sensitivity means higher flow stress with higher strain rate. Basically, this is positive strain rate sensitivity, there can be sometimes negative strain rate sensitivity as well, but let us discuss what is strain rate. So, if you take a material, let us say, our one sample and then you were trying to load it in tensile loading in the UTM.

Then let us say your dimension of the material is 0.1 meter, let us say dimensions will write l 0 and let us say the velocity of the extension v 0 is equal to 1 meter per second that means, the material extension is at 1 meter per second, then the strain rate epsilon dot will be equal to delta epsilon divided by delta t, delta epsilon can be given as delta l divided by l 0 and delta l divided by v 0 which will give you v 0 by l 0 and that will be 1 meter per second divided by 0.1 equal to 10 per second

So, if you have a 10 centimeter long sample and you are doing a tensile test with velocity v 0 equal to 1 meter per second then your strain rate will be 10 and the unit of strain is second to the power -1.

So, now, let us come to the strain rate sensitivity as we talked about that, higher the flow stress with higher strain rate that is positive standard sensitivity. If you draw another stress-strain curve at higher strain rate, let us draw one more with even higher strain rate. So, that means, if you increase the strain rate, that means, let us say this is strain rate 1 epsilon dot 2, epsilon dot 3. So, basically this is in the order of strain rate, and you can see that the strength or the flow stress will increase with increase of strain rate.

So, let us consider the right hand side stress-strain curve, let us discuss another aspect on the right hand stress-strain curve. So, what we talked about earlier is higher flow stress with higher strain rate, but in this case, there is another phenomena we will discuss, the tensile ductility will increase with strain rate. So, this generally happens and for materials like steel, titanium alloy, and this happens.

So, what does it mean? So, if you have a higher strain rate, the ductility will be more that means at higher strain rate the ductility will be more, ductility means, the strain to which it will elongate will be more and that is why formability. That means, the ability to undergo forming of some materials are significantly enhanced by carrying out the forming operation at high strain rate for example, electro hydraulic forming, which is at a strain rate of 10 cube per second, electro hydraulic forming is performed at 10 cube per second.

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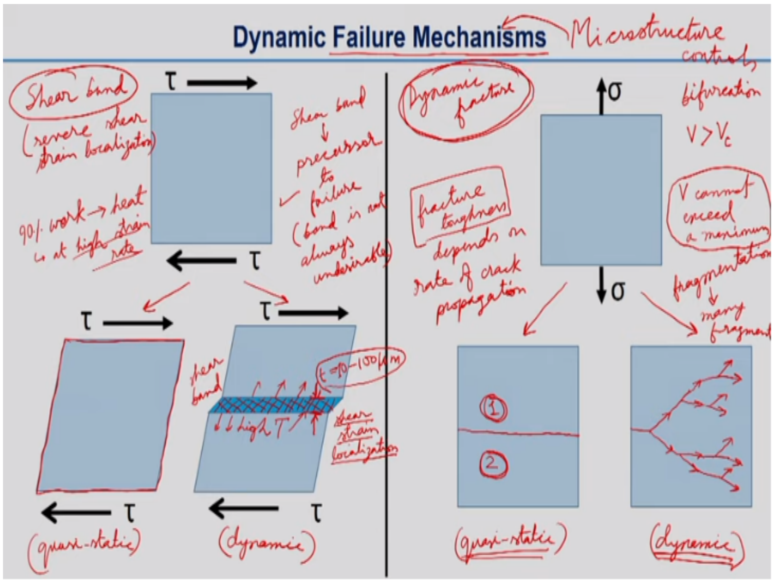

So, what we discussed so far is the dynamic deformation mechanisms. Now, we will talk about dynamic failure mechanisms. Though there are some failure mechanisms, which are unique to dynamic loading and they are not seen in quasit-static loading. In this case, here the first one is shear band or severe shear strain localization and the second one is dynamic fracture. So, in the shear band, at a high strain rate, the most part of the work, that is, almost 90% work done in plastic deformation is converted into heat. It happens in high strain rate.

So, in these two cases, so, basically this is the initial configuration and when you are sharing the material, there are two cases we are showing; the first one is slow loading, which is quasit-static case and second one is dynamic, which is high speed loading. So, this is a high strain rate. So, most of the work spent in plastic deformation converted to heat and due that heat the high temperature is generated at some local area and because of that, the material softens in that part and due to high rate of loading, there is not much time to defuse the heat away from this area.

So, basically, this part would be softened due to high temperatures and it will have severe shear strain localization. So, that is why you can see the deform shape is different than the what we have seen in the quasit-static case. Why we called it as a band? Why it is called as a sheer band because, as you can see, the thickness of this part very less, it can be the thickness of that part can be 10 to 100 micron.

But, it is not always the case, sometimes the shear strain localization may not form a very thin region or band, but some cases many materials show a very thin band, that means, the band is effectively two dimension, the third dimension is very small, that is why it is called a shear band and this shear band precursor to failure or fracture of the material. However, this band is not always undesirable. In some cases, it may have positive effect like in manufacturing processes, it is desirable or it has positive effect.

So, it is very important to understand the physics of shear band in most of the applications, most of the dynamic loading applications. Now, let us talk about dynamic fracture. Here also we have considered two cases this is we are having some tensile loading and we are considered these two cases. So, first one is quasit-static and second one is dynamic.

Now, if your loading is very slow, that is quasit-static, so, you will get a single crack and your material will break into two parts; part one and part two. But, in case of dynamic loading, the crack we bifurcate, similarly this crack will also bifurcate, we call crack branching, there are a lot of branching and there will be a lot of cracks will generate at different orientation from one single crack and after some time, we will see the material will fragment, that is called fragmentation, that means the material will break into many fragments.

So, basically, as you understood in the quasit-static case, there are only two broken parts, but in the case of dynamic case, the crack will branch out and to form multiple cracks in different orientation and these cracks will divide the material into many fragments and that is called fragmentation. Also this bifurcation, depends on, bifurcation happens at some velocity of the crack, the velocity like some threshold velocity is a critical velocity of cracks above which only that bifurcation happens and also fracture toughness of a material depends on rate of crack propagation.

So, that you understood like this happened mostly in dynamic cases, so the fracture toughness will, you know, increase or decrease with the rate of crack propagation and as you know, the fracture toughness, you might know that fracture toughness is the resistance of a material against fracture. The velocity of propagating crack has a limiting value and that means, the velocity of crack has a maximum value, it cannot be exceed a maximum value. So, that is called limiting value. So, that means, the crack propagation velocity will have a maximum value and it will not cross that maximum value.

And also one thing for these both; this shear band and dynamic fracture is very important that micro structure of the material controls the failure mechanisms, both the shear band and dynamic fracture. So, both of these failure mechanisms are controlled by the micro structure. Those details we will learn later, we will discuss that later.

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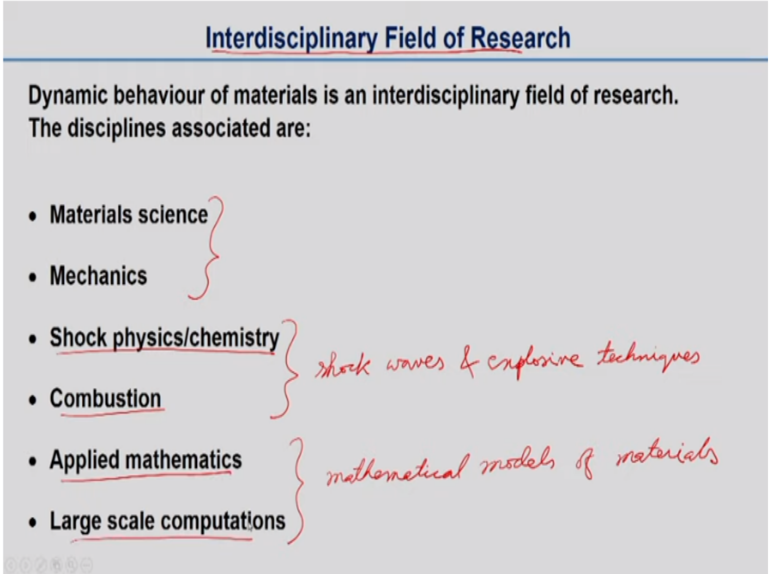

So, we have already discussed about deformation mechanism and failure mechanism under dynamic loading. Now, we should know that the dynamic behavior of materials is interdisciplinary field of research, let us see what are the disciplines associated with it as we know the knowledge of material science and mechanics is very important to study dynamic behavior of materials.

Also, we will discuss about shock waves, and explosive techniques of dynamic deformation. This will require our knowledge in shock physics or chemistry and combustion. Also, the mathematical models of materials need to be studied for predicting the material behavior and these knowledge can be required by applied mathematics and also it involves large scale computations.