Dynamic Behaviour of Materials
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Lecture-33
Experimental Techniques for Dynamic Deformation 2

Hello everyone, so we were discussing about the experimental techniques, in the last lecture. So we actually did not start anything any techniques in the last lecture but we discussed about the basics of strain rate sensitivity and related things, so what we will do is today we will discuss some of the experimental techniques.

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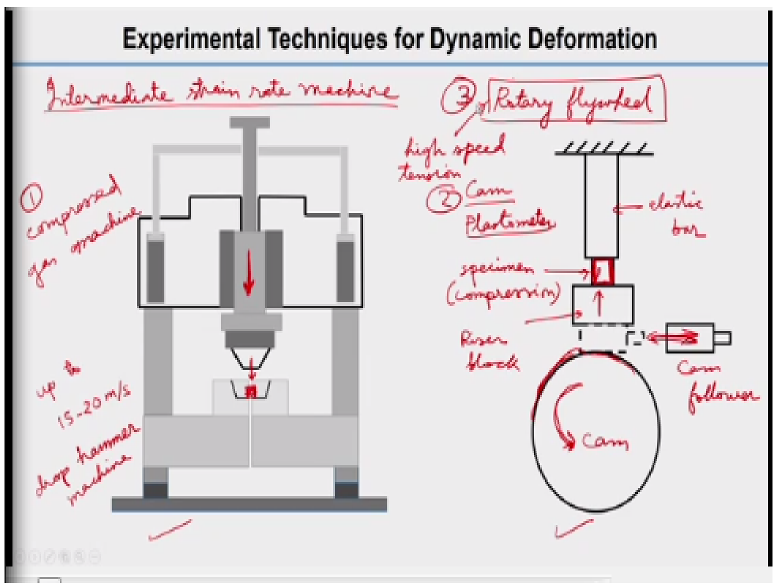

So we will now talk about the intermediate strain rate machines intermediate anyways these terms are very relative. So intermediate strain rates probably you can define as like which are not like in the very slow strain rate like quasi static rates**.** And which is also not very high strain rate like you know an explosive test was similar high strain rate experiments.

So these intermediate strain rate machines, so we can include this first machine that is compressed in gas machine. So mostly it is a it is kind of machines pneumatic machines and then what you can do is you can put your specimen here and you can compress from the on the top side. So it has mostly it is pneumatic and maybe some hydraulic controls can also be there.

So what will happen this will compress the specimen, so this can be used up to 15, 20 meter per second speed of that impact. And also there are simpler version of these machines are called drop hammer machines so drop hammer test. So similarly one more we use is drop weight test and in this in the right hand side diagram, so this in the right hand side diagram it is called the cam plastometer.

So we have the specimen here, this is the specimen and this is the cam and this is the cam follower. So it is like it is a bit little like this, so this cam follower it is not exactly circular shape due to the movement of the this cam follower the specimen which is mounted here. So this is a specimen is in compression, so this is called a just a riser block.

So what happen is due to the movement of the cam, so by the way I did not show it here that the cam will rotate like this and the cam follower will have a these type of motion. And then this will compress the specimen, this is an elastic bar. So we are not going to discuss about these methods in details but these are some the methods just to name them and also there is another one rotary flywheel.

So that with the help of this rotary flywheel let us say generally we use for tension high speed tension this machines are used. So what we discussed here is there are 3 types of machines let us a compressed gas machine the compression machine here using the compressed gas. And then the second was is the cam plastometer, and the third one is the rotary flywheel.

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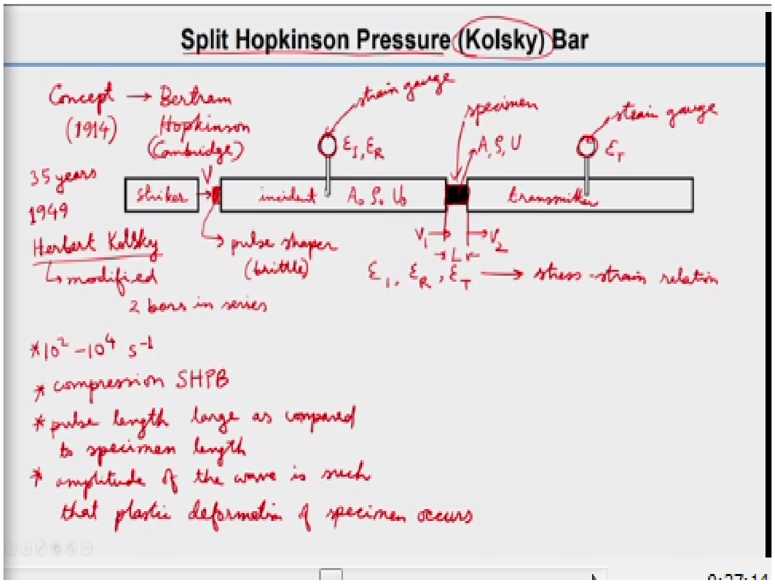

So after that, so we will come to our very common experiment the split Hopkinson pressure bar. We have already discussed several times about the speed Hopkinson pressure bar which is probably the most widely used for dynamic material property evaluation. So I am not going to explain everything in details because you already know about this.

So what is happening here is, this is the striker bar, striker bar will hit the incident bar this is the incident bar and then this is the specimen. So the specimen is here and you have this transmitter bar**,** so now this is your strain gauge and the another strain gauge is here. We have a little impact velocity V of the striker bar and the area of cross section of the bar incident bar and then density rho0 and particle velocity let us say U0 here.

So similarly for the specimen we have let us say the area is A, density is rho and the specimen sorry the particle velocity is U. So what will happen as we know this set up is called split Hopkinson pressure bar and also it is known as Kolsky bar some of you already know probably **I** I did not mention about much about this why it is also call Kolsky bar.

Because the first concept was proposed by from Bertram Hopkinson that is in 1914 more than 100 years ago. And then Bertram Hopkinson is was a professor in the University of Cambridge, so he is from Cambridge. So unfortunately he died in 1918 just 4 years after that and he was a while flying a aeroplane he was the pilot and then he died. And then again after 35 years in 1949, so Kolsky his enemies a Herbert Kolsky.

So he is also one British he is also from United Kingdom and then he studied in Imperial College of London. But most of his career he was in Brown University United States. So Herbert Kolsky modified the initial concept of the Hopkinson, Hopkinson what he did is he measured the stress falls in a metal bar. Now what Kolsky did is he modified into 2 bars in series to get the stress strain data of a material.

So this Hopkinson bar is generally used for as you probably already know from 100 to 10000 strain rate it is used for that strain rate. And what we were showing is a compression, so split Hopkinson pressure bar I will write SHPB from now onwards. So this is the compression on there can be some other Hopkinson bar we will show that. So also the pulse length is large as compared to specimen length, that we already discussed earlier.

And then amplitude of the wave is such that the plastic deformation of the specimen does not occur of the sorry what I told this does not cover that should be at it is plastic deformation of the specimen occurs but wave we will discuss that later. So the amplitude of the wave is such that the plastic deformation of specimen occurs, so we know these will are plastically deform the specimen.

We have these strain gauges, so in these strain gauges what we can do is we can get the strain related to incident we when the reflected wave in this strain gauge and the other strain gauge we can get epsilon related to the transmitted waves. So from these epsilon i epsilon R epsilon T, so we can get the stress strain data as we already know that this is considered as a uniaxial case in this uniaxial stress case in split Hopkinson pressure bar.

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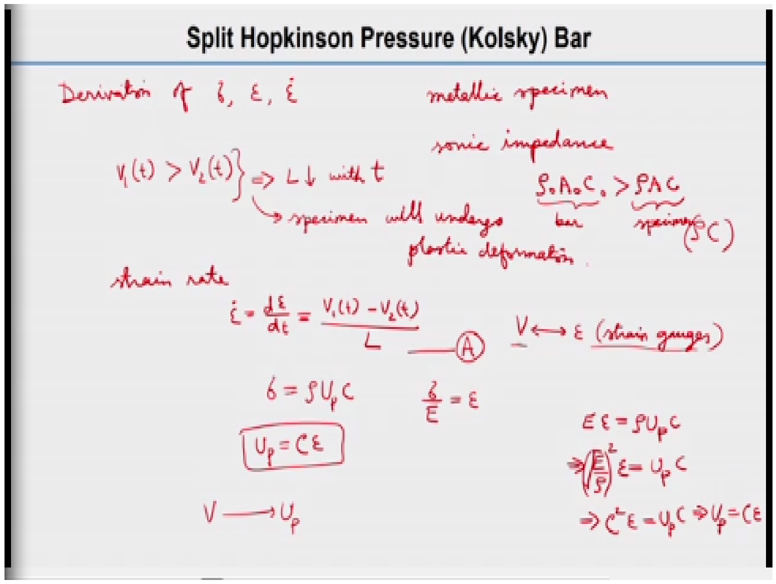

So we can get the stress strain relation here the derivation of sigma stress epsilon strain and epsilon dot the strain rate. Let us assume that we have a metallic specimen and we will assume that the sonic impedance of the bar that will be rho0, A0, C0 will be greater than the sonic impedance of the specimen. As you know the sonic impedance has also the area term sometimes we discussed earlier that only rho and C0 we earlier discussed as rho **C** C.

But we have the area as well this area because the area of the bar incident bar and the specimen are not equal here. So the sonic impedance of this is the bar, bar means incident bar or even transmitter bar is also will have the probably same area. When this rho A C of specimen, this is the condition here. And now if you see here again in the earlier diagram, so we have the velocity of the interface, interface between incident bar and the specimen, so that is we call it as V1.

And the velocity and the other interface and the specimen and the transmitter bar is V2, so here V1 which is a function of time will be greater than V2. And this means that the L that is actually length of the specimen, here we can write L like this. So length of the specimen will decrease with time why because V1 is greater than V2 and also the specimen and will undergo plastic deformation**.**

So what we will do is, now we will try to write this strain rate expression, so which is epsilon dot d epsilon by dt that you already know and then V1 t - V2 t divided by L, so that is the specimen length. So now we want to express these velocities in terms of strains, strain means strains in the strain gauges, so that we want to do. So for that we already know in our earlier classes the sigma = rho U p the particle velocity multiplied by C the elastic wave velocity.

And also we know from the Hooks law is sigma divided by Young's modulus is epsilon. And then this 2 will give us, so suppose if you write it like this E epsilon from these 2 what we can write is we can write like this. And from there if you write E by rho if you get the rho from the right hand side and if you again give a square root and again whole thing square epsilon U p C I hope you understood this.

And then that will give us this epsilon U p C this will give us U p = C epsilon, so here we got the particle velocity = elastic wave velocity multiplied by strain. So we will use this relation as we earlier told that so we will get the interphase velocity from strain gauges. So interphase velocity V is nothing but the particle velocity at the interfaces.

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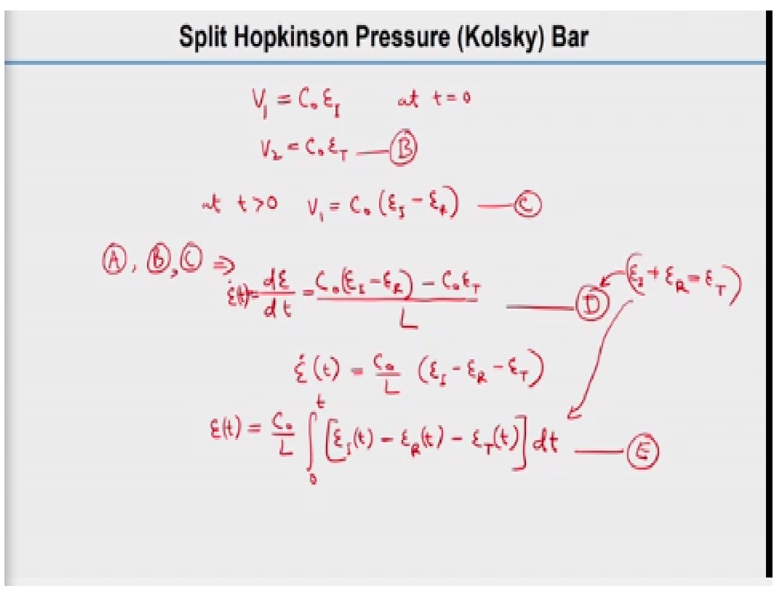

V1 will be equal to C0 epsilon I, related to incident wave that is that time T = 0, so we will get to know what will have happen after time t = 0. And then V2 will be equal to C0 epsilon related to the transmitted wave. So from here we will try to find out these stress and strain. So as I told so at time t equal to greater than 0, the V1 will be changed because a reflected wave will also contribute to it, that will give like epsilon I - epsilon R.

So now we got several equations from earlier let us say this expression relation we write is A and then we have this as B and this as C. So if we combine these from these relations A, B and C what we can get is d epsilon dt that means your strain rate will be equal to strain is a function of t you can write it that way. And that will be equal to C0 epsilon I - epsilon R - C0 epsilon subscript T divided by L.

So this you can write in this way C0 L we would write all epsilon together and epsilon T here. So if we want to get the strain out, so strain we need to integrate as the earlier expression was the strain rate. So what we will get is if you want to integrate from 0 to T, so that will give us epsilon I which is all are function of time. So this is t - epsilon T t dt.

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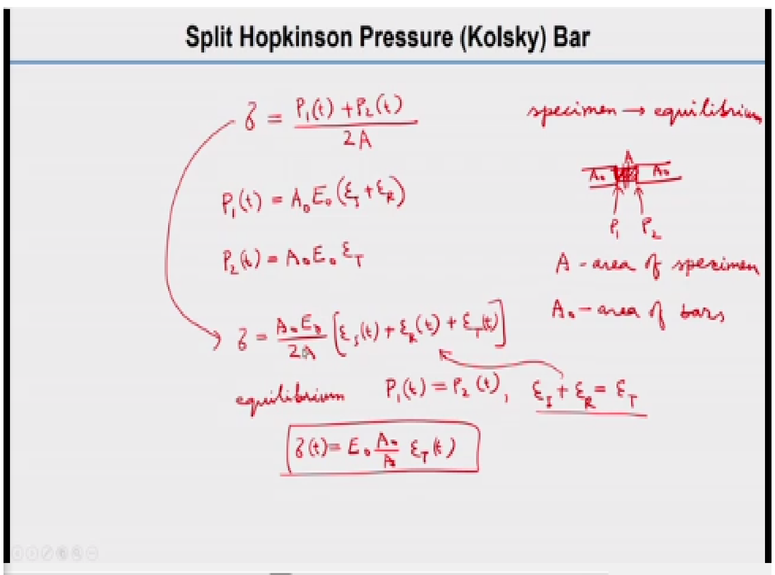

So now we will try to get the stress out, so what will be the stress as we know the specimen is in equilibrium**.** That means you have a specimen and these are the bars and this is the specimen. If you take any section in the specimen that you will get the same stress and that will lead you to the average force divided by area will be equal to stress.

So the force will be P1 t + P2 t divided by 2, that is the average force the P1, P2 are the forces at these interfaces P1 and P2. And so this is the average force what I wrote here and divided by the area, A is the area of the bars in both the incident bar and a transmitter bar, so this is the force now. And these forces if you want to get the expression for these forces let us say P1t that will be nothing but your area A0 of the bars what I wrote here is this is first one is the A, it should be the area of the specimen sorry about that.

And then this A0 will be the area of the bars both the bars let us say, so the A0 here and in this specimen this will be A. So A0 is the area and we will write what is stress that is the stiffness young's modulus multiplied by the strain. So E I sorry epsilon I epsilon R that will give us the P1 on the first interface on the left side interface of the specimen.

And then P2 t which will give us A0 E0 epsilon t and then if you want to get the again stress from the earlier expression. So what we can do is we can combine that to get twice A epsilon I, epsilon R and epsilon t. So this is the expression for stress but if you again consider that we know that this is in equilibrium. So for equilibrium actually we need to have on the both the interfaces the stresses the force should be equal.

And also we earlier discussed about these the strain will be in equilibrium. So that will give us our sigma = E0 A0 by A, this by this, so how you got this expression. Because as you know you put this expression of strain in here and then you will end up with this.

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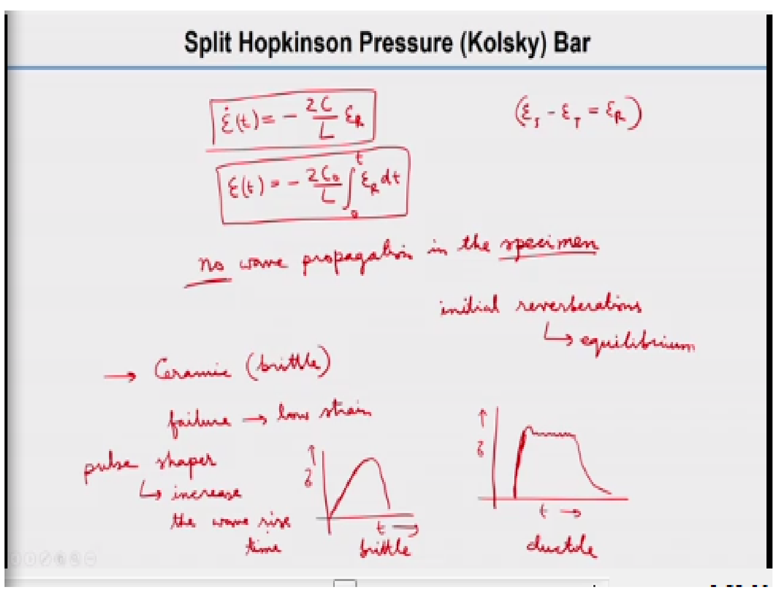

So this is the stress, so we need to know about strain as well, so this is strain rate and I will write strain as well. So from where we will get these 2 expressions, so here the first one let us say we call it as D and this one is let us say we call it as E. From D if you use that relation again I am showing it here itself epsilon I epsilon R = epsilon T, if you use this relation in T and even you can use that in relation E as well.

So that will give you - twice C L epsilon R and here also - twice C0 L integration 0 to t epsilon R dt. So you know why the - sign came here you can see from here the - is already there ok, so what as you understood what we use these epsilon I - epsilon T = epsilon R. So using that we got the strain rate and we got the strain, so earlier we got the stress. So we now finally got what we wanted to derive.

So now as you understand we do not consider the wave propagation in the specimen, no wave propagation in the specimen, specimen is very small. So we are not considering any wave propagation in the specimen although there are some initial reverberation that means the fluctuations we get in the specimen. But that will after let us say t reverberations that will reach to a equilibrium and it will damp out.

So what we should understand that there will be no wave propagation in the specimen, the velocity will propagate through the bars incident bars but not in the specimen. And if you want to test a ceramic which is a brittle material, so if you want to test a brittle material. So there is some issue here failure will occur at a very low strain that you know that. And we know that this rise time of the wave is very small very early classes we discussed about that.

So what we discussed is if you are talking about the stress false is very steep and then it will have some fluctuation it will come down. So this rise time is very steep but now this is actually for the ductile material, so rise time we saying that this is stress and this is time. So for ceramic material what we need to do is because of the very steep rise time at a very lowest strain it will happen.

So that is why we generally what we do is we need to keep a pulse shaper here which is made up of copper material softer material it is called pulse shaper used only for brittle material. So this was for ductile material and for brittle material if you want to get the pulse shape. So we use the pulse shaper and then the rise time will increase the rise of the way will the time will increase and then it will go down. So the pulse shape is use to increase the wave rise time otherwise you not get a proper signal output.

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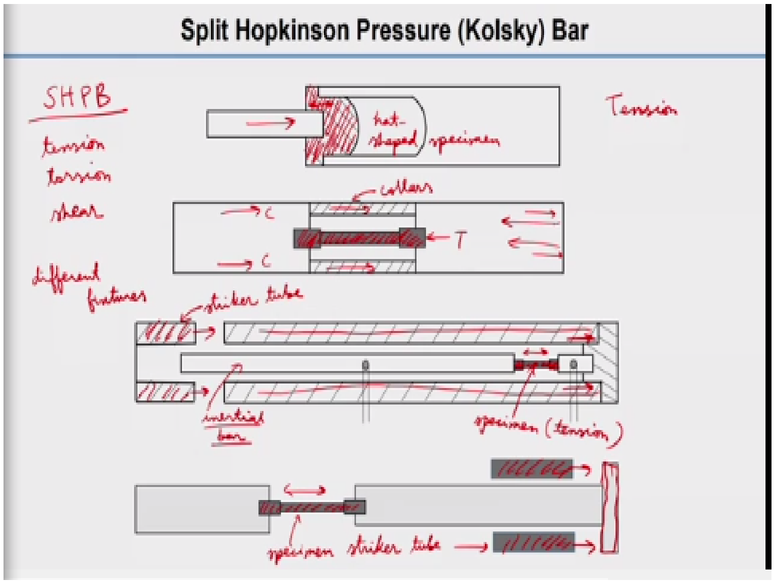

So now we will discuss a little bit very quickly on other forms of split Hopkinson pressure bar. So for split Hopkinson pressure bar what we discussed earlier was in compression bar, now you can get some tension or let us say torsion and shear loading as well with different fixtures, fixtures are different or sometimes the entire the system look very different. So here what is happening mostly these 4 are showing all tension little maybe difficult to understand.

But we will go quickly if you are interested more you can read the book or you know other sources. So this whatever I am making it red color, so this part is the specimen it is a hat shaped specimen. So if you propagate some compressive wave compressive loading here then the specimen will in this portion if you can imagine, so this will elongate. So that is sometimes I will loading, so this is called hat shape kind of specimen.

And then similarly in the second case, so you can see the specimen is this one, so in this there is a system where you have the compression waves that bypasses and goes through the collars. So these are the collars and then it is system is such that it does not go through the specimen and then these the compressive wave will go and reflect back and then have some tensile wave.

So these wave compressive wave and it will come back at a tensile wave to the specimen let us say so and produce tension in the specimen. In the third case, so this is our striker this is the striker you know that this is a like tubular shape striker tube and this is called inertial bar that is at rest inertial bar you can see that this is the specimen. So an entire this is a tube you can see that this is a tube.

So this striker you will hit it and then you can see that the this portion will move in the right hand direction and so produce a tension here in the specimen, specimen will be intension. As this inertial bar will stay at the same place and then there will be a tension producing in the specimen. Similarly a fourth case, so the striker tube is this one, so this is we can write striker tube, you understand I guess.

So this the tube will move in this direction hitting this arrangement and then producing attention in the specimen, so this is the specimen. So these are different kinds of tension system that split Hopkinson and pressure bar or Kolsky bar tension system, so there are maybe several others developed by people.

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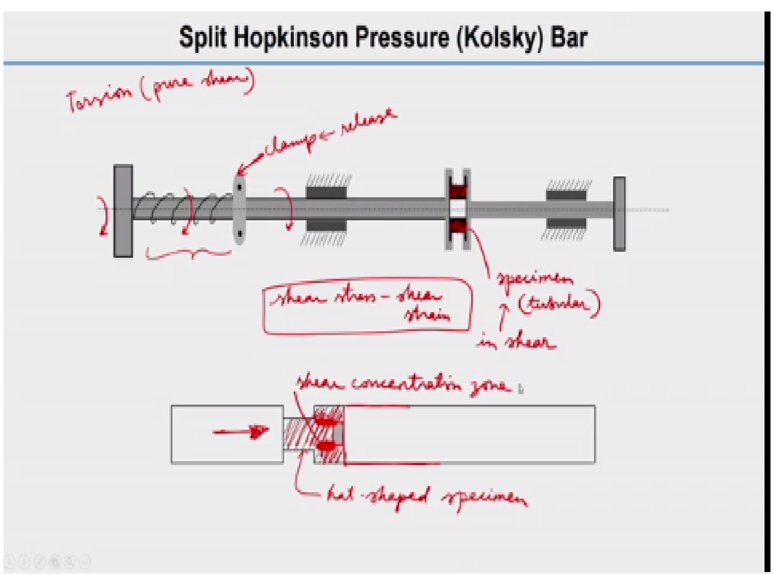

So there can be some shear system or torsion for pure shear actually this is I would write torsion for pure shear. So the first one is kind of not very difficult to understand I think this is a clamp. We rotate this part and then that produces torsion in this part of the bar. And then you have the clamp here, so whenever it is required you can release that clamp and that will your specimen is tubular in this case this specimen is a tube not kind of a bar, so tubular specimen.

So what will happen because of these torsion, so it will be specimen will be in shear that will be in shear loading. So from that you can obtain shear stress versus shear strain plots or data from this. Similarly in this next arrangement this entire hats part is a specimen this is we can call a hats spaced specimen. So we are heating or the loading or compressive wave will propagate from this direction.

And then what will happen this is a fixed structure with the this other bar this bar and so when we hit it from the left hand side, so there will be some shear zone, shear concentration zone in these locations. So these are I would write shear concentration zone, so this is also a way to produce shear loading share concentration zones.

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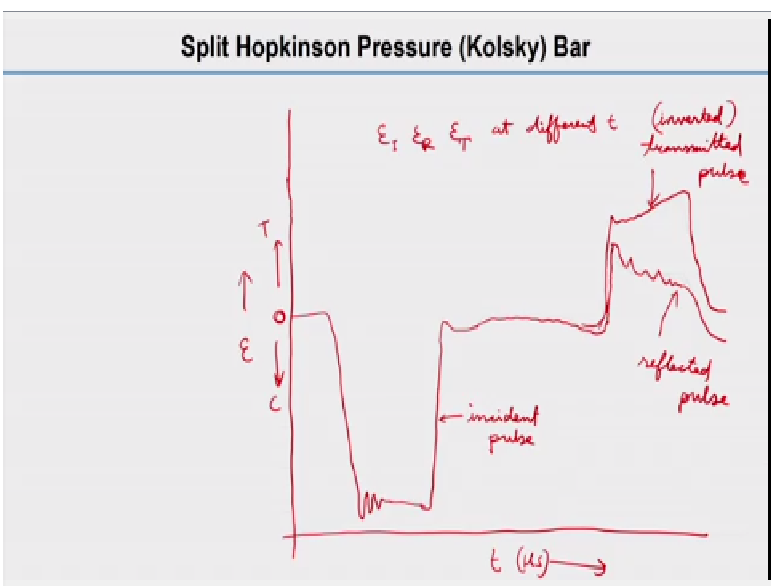

We probably have not discussed much about the data we get the plot we get from split Hopkinson pressure bar. So I will just quickly show how this look like, so this is let us say time in microsecond in the x axis. So let us see in the y axis this is epsilon strain, so what will happen is this is a strain is 0 and then we can draw the first incident pulse, incident pulse will fluctuate like this as we told that the reverberation.

The fluctuation is because of a release waves from the surface of the bar, so this will something look like this. And then the reflected wave will be something like this, so this will also produce some fluctuation. And if we draw the transmitted wave, so it will look like something like this actually transmitted wave this is an inverted transmitted wave.

So I will just let you know this is incident pulse which should be compressive as you know this is the 0, so this is compressive on this side and tensile on this side when you are talking about strain or stress. So this is incident wave and our reflected pulse is tensile that you can understand because we are having the bar with a higher impedance then our the specimen.

And then other plot is curve is for transmitted pulse transmitted pulse and as you know transmitted pulse is inverted, inverted means it should be we expected it to be compressive. But in this plot we are showing it a on the positive side, so this is inverted. And then from here we can actually calculate these from the strain gauges whatever value we will get epsilon I epsilon R or epsilon T at different time t.

So let us say I will write t, so we can calculate the strain rate, we can calculate the stress, we can calculate the strain produced in the specimen.

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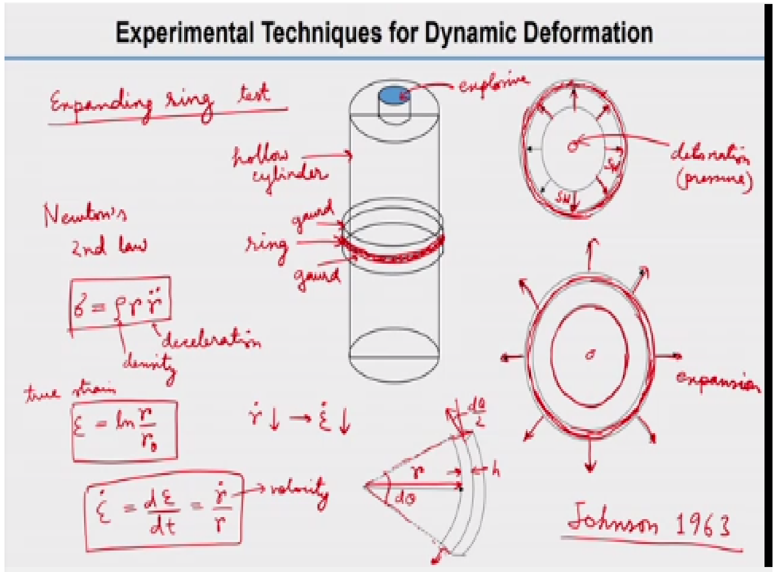

Another important test is expanding ring test or technique it is, so the ring is somewhere here 13 ring, this is the ring. And we have a hollow cylinder let us say it is a it is made up of steel and then we have explosive which you want to detonate to produce the deformation in ring. So there are 2 another rings up and down these are guard, so what will happen is these if you see the top view of this.

So this is the ring or I would write this way ok, so this is the ring and you have these shockwaves I will write SW for shockwave. So this is the shockwaves and detonation will be in the middle, detonation products I think you can understand this is the top view. And then you have pressure generated due to the detonation and the shock wave will act and then what will happen is the result will be a larger ring expanded, that is why it is called expanded ring technique.

So this will be a larger ring after detonation and then it is just these arrows are to show the expansion. So initially the ring let us say dimension was like this and then it is got expanded. Now how you do the calculations is, it is quite straightforward although we are not going to derive each and everything. So you take a portion ring and then what you do is you have let us say this is h the thickness of the ring, that is that means outer radius - inner radius.

And then you get the you know this force acting on this and then also the angle will be look something like d theta by 2. If we do all the calculations I am not going to do that but you can use just Newton's second law. And from Newton's second law what you can calculate is the sigma is will the expression of sigma will look like this, that is the R the radius of that ring.

And then R double dot you can understand that is the de-acceleration. So de-acceleration history and it is density will give us the stress, so you know the radius this is your density. So and then de-acceleration will give us the stresses and then if you want to get the true strain, so there will be epsilon = natural logarithm of r by r0, r0 is your the original ring radius and that will look something like this, and R is the current radius.

And then if you want to get the strain rate, d epsilon dt = r dot that means that will give you actually the velocity sorry this one is velocity divided by radius. So as we know the velocity of the ring will drop and that means the strain rate will drop. So r dot will drop we know that and then that means r strain it also drop, the here the velocity as you know the ring will kind of deform expand into like fly out.

So this is the expansion I will write here, so these are the relations we can get stress, strain and strain rate. So the ring is proposed by Johnson in 1963, so it is quite popular even now, what we discussed today is. So we discussed mostly about the split Hopkinson pressure bar, so we discussed about the compression arrangement which is the most common. And then we have shown also the how the tension or shear or torsion can also be test can be performed with the help of the same bar with different features or sometimes a totally different arrangement.

And we also discussed about the expanding ring test which is also popular and there are other intermediate test we just had a glimpse of it. Like the compressed gas machine and rotary flywheel and camp plastometer. So we will continue these discussions in the next lecture, we will talk about gas gun systems and some other techniques in the next lecture, thank you.