Dynamic Behaviour of Materials
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Lecture - 25
Shock Wave Attenuation, Interaction and Reflection - II

Hello everyone. So we have been discussing about shock wave attenuation, interaction, and reflection. So what we discussed in the last class is last lecture is that the impact of a projectile of thickness d naught on a semi infinite target. So and we have shown that time and distance plot and then I have shown the pressure distance profile as well. So now we will continue this discussion.

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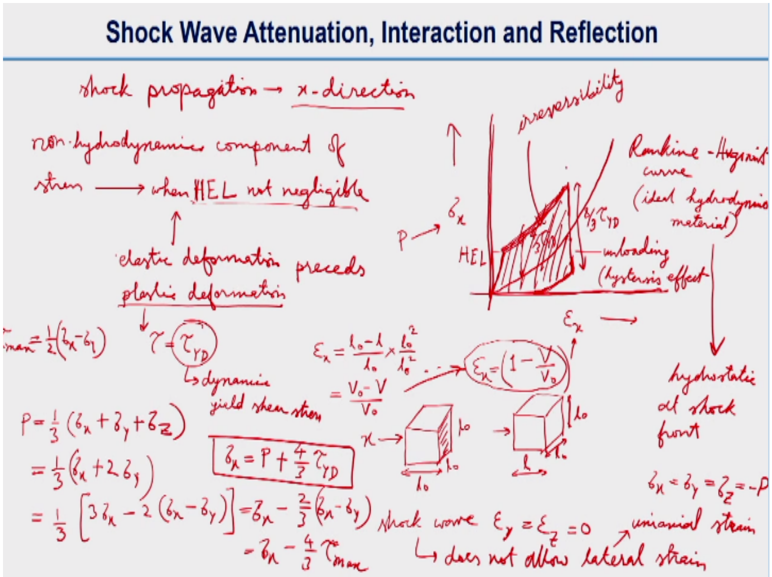

And so, we know that the Rankine-Hugoniot curve for a ideal, for an ideal hydrodynamic case, that the ideal hydrodynamic material. So we will draw that, this is a plot of stress sigma x and the strain epsilon x which is the shock wave is going in this direction and the x direction shock propagation direction is x direction, in x direction. That is why we are using sigma x and epsilon x.

This is basically now what we did is we are replacing the pressure P with sigma x and we are substituting epsilon x for one minus volume, the current volume divided by this initial volume. So this is basically the Rankine-Hugoniot curve for an ideal hydrodynamic material. So where this is can write ideal hydrodynamic material okay.

So this means basically that hydrostatic stress at shock front, so that means sigma x, sigma y, sigma z, which is equal to –P.

So only hydrostatic stress exist here. We will see how first we get this epsilon x equal to 1 - V by V naught. So what happens we are assuming only the shock propagation in the x direction. Let us say we have a volume here, something like this. So this in the x direction, the shock wave propagation direction. So we have, let us say the size of this element, here l naught, l naught, and l naught.

So after the shock wave will propagate this it will compress the material to something like this. Now so in this case, as we know for shock wave along x direction, what we can assume is strain in the y direction and strain in the z direction will equal to zero because shock wave does not allow lateral strain assumed to be the lateral strains or assume to be zero.

And that means it is a uniaxial strain case. That we already discussed, that shock wave is uniaxial strain case. So this is the assumption uniaxial strain. And so now coming to this, so if it is the shock wave direction in this direction, so this will be compressed to l, now the current this l naught compressed, this l naught would be now l, but the other two direction there is no lateral strain, the other two direction l naught will remain same.

So what we can do from this we can calculate this epsilon x, which is equal to l naught minus l divided by l naught. And then if we multiply this with the area, this l naught square, let us say we took l naught square by l naught square here. And that will give you V naught minus V the volume divided by V naught and which is nothing but this one. So this is the same.

So now what we talked about this again coming to this diagram, thus the plot of Rankine-Hugoniot curve. So non-hydrodynamic component of stress can come into picture, can come into picture when that HEL that Hugoniot elastic limit is not negligible when HEL is not negligible.

And that means HEL is not negligible that means that elastic deformation precedes plastic deformation and as you know this plastic deformation happens when the shear stress tau is equal to y, tau YD that means dynamic yield shear stress, dynamic yield that is shear stress not the normal stress, the dynamic yield shear stress. Coming to this pressure to sigma x conversion.

So what we know that the pressure is that hydrostatic component can be we can find out as this one. So that we already know and that means this is uniaxial strain case along the shock wave direction is along x. So sigma y and sigma z will be equal to equal and that will give us sigma or we can write this twice of sigma y. And that will give us one third of thrice sigma x minus twice sigma x.

So we are just trying to get one expression which is we will see from here now. So this is equal to sigma x minus 2 by 3 sigma x minus sigma y and which we can write as sigma x minus 4 by 3 tau maximum. That you know that maximum shear stress tau maximum I will write in above tau maximum is equal to half of sigma x minus sigma y. So we wrote it here and that tau max is in this case nothing but this tau YD.

This tau max is that tau YD here. So that means P we can write it and although it is very messed up now so but I will write it here P equal to sigma x minus 4 by 3 tau YD and the other way what we can write is we can write the other way and then we can write it as sigma x is equal to P plus this. Earlier we wrote P equal to sigma x by this. So this is the relation.

So from here what we can do is we need to as you can understand that if HEL is not negligible, if HEL is not negligible non hydrodynamic component of stress that not only the hydrostatic component the other component of stress are also need to be accounted for and in that case so we have the HEL. We need to be shown here in this plot. So HEL is this is corresponding to HEL and then we will have a parallel curve like this.

So after elastic deformation we have a plastic deformation. And if you measure this, that we understood that this is the pressure and that will be equal to our 4 by 3 tau YD and if you want to draw the unloading curve it will look something like this the unloading curve will come here and there will be a parallel line, parallel curve which will come like this.

So this does not look parallel or otherwise we need to make this curve little better here okay. Yes. So now this is the Rankine-Hugoniot curve, the first curve was the Rankine-Hugoniot curve for a ideal hydrodynamic material. But if we consider the that HEL is not negligible and non hydrodynamic component of stress, then the actual real curve will look like this. And if you do unloading, this is unloading.

And this curve will come and goes like returns back like this and this portion, is the hatched area actually, this shows the irreversibility of this process, irreversibility of the process. That means, that curb does not come back on the same way. So it has a reversibility and that is because of the elastoplastic effect. So have elastic deformation and then plastic deformation and that contributes to the rapid decay of the shock wave because the shock wave will dissipate energy because of this irreversibility.

And this is also called the unloading. We have we call this is hysteresis effect. So this and this distance as I told this is 4 by 3 tau YD and the entire distance will be actually 8 by 3 tau YD the dynamic shear yield stress. What we discussed about is that the Rankine-Hugoniot curve may not be always looked what it look like for ideal hydrodynamic material.

So if you consider the Hugoniot elastic limit that curve will can give us the irreversibility that is due to elastoplastic deformation. Let us discuss about the attenuation of the shock wave so that we did not discuss much earlier. So what is attenuation?

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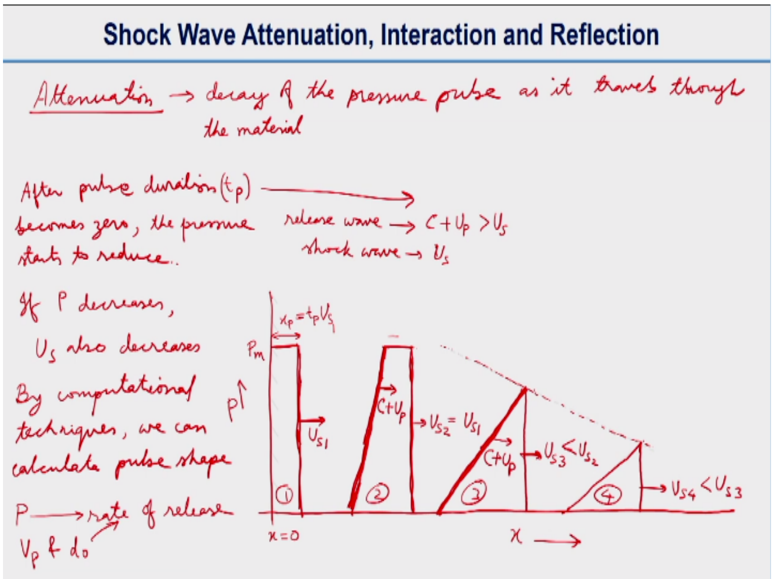

Attenuation of the pressure pulse, so that attenuation means the decay of the pressure pulse as it travels through the material or the target, through the material. So what happens even we discussed earlier so we will draw this. We have pressure versus distance. Distance means the distance into the target plate or you know the projectile will hit the target. And so we are measuring this distance into the target.

Suppose from the left hand side the projectile hits and we will see the pressure pulses here into the target. And this suppose, if x equal to zero, you can assume at that point x equal to zero is the impact interface. So initially, this shock pulse will look like this. So this is the maximum pressure, the peak pressure, peak pressure. I can write P m as a peak pressure.

So the shock wave velocity U s 1 let us say at this position that shock wave velocity U s 1. Then after some time, this as we know that is the shock front right and this line is we call the shock front. The here also the shock front will be the same, maintaining the same peak pressure that is the peak pressure P m. So we have, let us assume the velocity is U s 2, which is nothing but the same as U s 1now.

And then this behind portion will not be a straight vertical line, it will be inclined line. It will be a straight line, but it will be inclined line. This is as you know this comes from the interaction of this release wave. Release wave means the reflected wave that comes back from the back surface of the projectile. So this is the release wave portion.

So we can have this velocity of the release wave which is we earlier had that C + U p. C is the sound wave velocity at a particular pressure P and U p is the particle velocity. However, after some time what will happen is that this plateau or the flat top will disappear and then the pulse will look like this after some time, after some distance, it will look like this and then pressure the peak pressure will decrease, the peak pressure earlier was here and then it will decrease.

And also if you see the back side this curve release part where the pressure returns back to zero value from the peak pressure to the zero value that also have now the slope is less now earlier the slope was high. In this point the slope was high. Here now slope is less. And then let us see, let us say this is U s 3 the shock wave velocity which is lower than U s 2 okay, lower than U s 2.

Again if we draw it here one most step ahead some distance ahead. So it will look like this. So this will be pressure will be again reduced, pressure will be reduced. And let us say the shock wave velocity U s 4 which is even lower than U s 3. So now what is happening here, so we shall see this what is happening here. So the release, as the wave progresses, as the wave progresses, the release wave overtakes the shock wave.

So you have this shock wave and this we have the release wave. So what happen the release wave is also traveling in this direction and the shock wave is also traveling in this direction. The velocity here is U s or different times we are writing U s 1, U s 2 like that. And then the other case the release wave, which is reflected back from the back surface of the projectile, so it has almost a constant value and this C + U p is higher than the U s.

So that is why the release wave will overtake at some point of time, the overtake the shock wave. So here if you see the in the suppose this is case 1, case 2, case 3, case 4. So in case 2 still the release wave is behind the shock wave and but in case 3 what happened is that released wave overtake already overtook the shock wave and that is why this peak pressure that was earlier P m now it is got reduced and similarly for the number 4 case also it even reduced much to a lower value.

This duration of the pulse we call this is the duration of the pulse that is we can write as X p which is nothing but the time duration is t p; t p multiplied by U s or in this case U s 1 will give the pulse duration and that distance the pulse travels. This will be reduced, reduced as it travels, the shock wave travels through the material and then when it the release wave overtakes the shock wave, that pulse duration will be zero, and then after that it will the pressure will be reduced.

So after pulse, I will write it here, after pulse duration becomes zero. Pulse duration is nothing but the t p becomes zero the pressure starts to reduce, the peak pressure. Also you can see if, if the peak pressure got reduced, if P decreases, the peak pressure decreases U s also decreases. That is we have not discussed this much, but it happens if you can see this experimental values also this with the pressure that shock wave velocity decreases.

So that is why you can see that U s 2 and U s 1 are equal because the peak pressure is same. But U s 3is less than U s 2 and U s 4 is less than U s 3. That you can see from this plot. And by appropriate computational techniques, by computational techniques now we can calculate the pulse shape. We can calculate pulse shape. So by computational techniques we can calculate the pulse shape based on the velocities of shock wave and the velocities of release wave.

The rate of release also very much dependent on pressure P and that is why even impact velocity and the flyer plate velocity can change the release rate. So I will write it here. So pressure, pressure P can change if the pressure is changed then rate of release that rate of release as you know the release means the from the peak pressure or if you can see this from the peak pressure, the pressure returns to zero pressure.

That rate of release depends on the pressure and also if it depends on the pressure then also V p the impact velocity of the projectile and also the thickness of the projectile that is d naught that can also change the rate of the release. So the rate of release depends on these factors.

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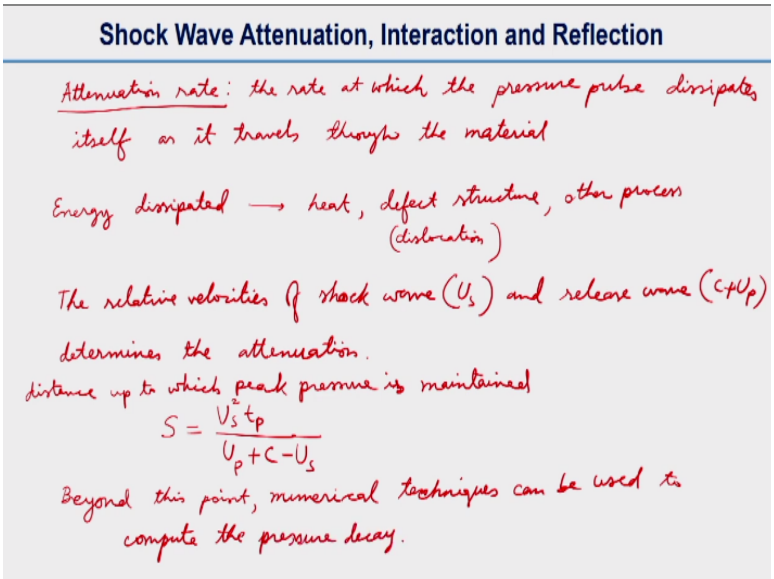

And attenuation rate, if we talk about attenuation rate that is the rate at which the pressure pulse dissipates itself as it travels through the material. So that is the decay rate of the pressure and then energy carried by the pressure pulse is dissipated as the pressure as you can see from the earlier plot the pressure will decrease. And that means the energy dissipated.

That can be converted as heat or defect structures. Defects structure means and also there may be some other processes. Defect structure means for example dislocation structure, dislocation is a crystal defect; dislocations or other defects. The attenuation is decided by the relative velocities of shock wave and the shock wave and the release wave the velocities of, so the relative velocities of shock wave U s and release wave C + U p determines the attenuation and the attenuation rate.

So the distance till what point the peak pressure will be maintained that can be calculated with some simple calculations. So that distance we write it as the distance can be I am just writing the expression. No derivation. So this will be U p + C – U s. You know all terms. I even discussed about t p as well. So this is the distance that peak pressure is maintained. Distance into the target material.

The distance up to which peak pressure is maintained, peak pressure is maintained. And as you know after this distance, the peak pressure will fall down. And then beyond this point, numerical, beyond this point, beyond that distance numerical techniques can be used. Can be used to compute the pressure decay. So this predictions of pressure pulse, so the prediction of pressure pulse using hydrodynamic theory is not very realistic.

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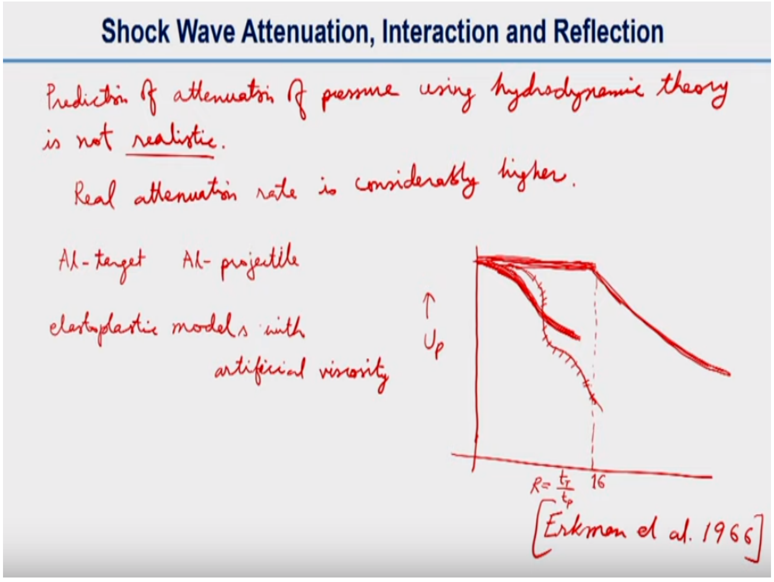

Prediction of the pressure pulse decay actually the attenuation, prediction of attenuation of pressure using hydrodynamic theory is not realistic. So actual attenuation rate is considerably higher. Real attenuation rate is considerably higher. There is one work by Erkman sorry this is a old work by Erkman and other workers and researchers. It is published in 1966.

He showed that if we plot particle velocity U p versus target thickness by plate thickness, let us say t by which is ratio R, t target by t target thickness by projectile thickness and that the flyer plate thickness. So what happen is if we use the hydrodynamic theory we can see that the peak pressure will maintain till a long distance.

That means, if it is around 16 the target thickness by the plate sorry that projectile thickness and then it will decay down. It will decay like this. But for experimental cases, experimental cases it looks something like this and even these are the some experiments did earlier. But now some sophisticated codes can be used which can give relatively better results and much better result actually.

So this goes some codes shown in this textbook, so this goes like this. So basically this is the experimental that I want to show you, this is the experimental one. And this is the using the this curve shows the hydrodynamic theory. So if you can see the pressure drop here for the experimental curve. Experimental curve is the rate of attenuation is considerably higher.

This experiment was done with aluminum target and aluminum projectile, both are same. The projectile and target are aluminum and so there are the advanced codes like what I showed you this curve, this curve. So these are based on some advanced models, which is let us say some models with elastoplastic model with some artificial viscosity term.

We are not going to discuss about these models, models with artificial viscosity consideration. Just to let you know that there are some advanced mathematical models that can predict these experiments very accurately at least much accurately and then the hydrodynamic theory which is you can see is very different from the experimental findings.

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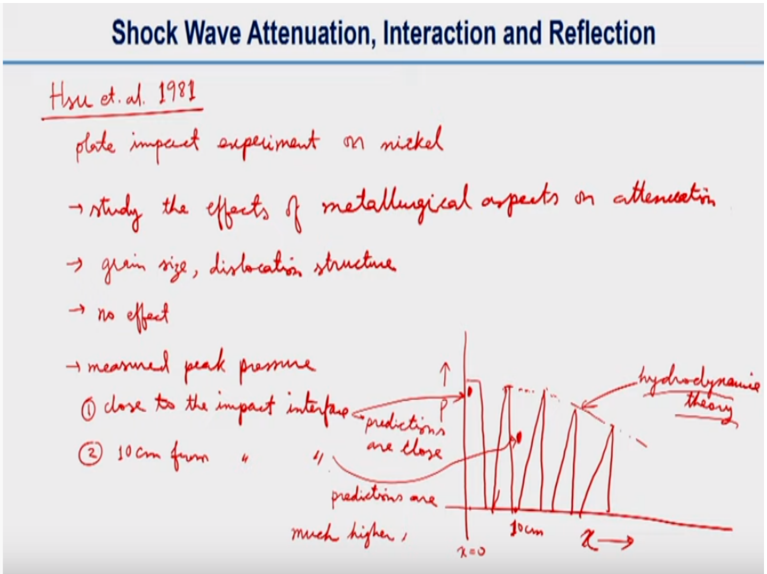

One more publication Hsu and his coworkers did in 1981. So this group actually did a plate impact experiment to study the metallurgical aspect that is they did it on nickel study the effect of metallurgical aspects on attenuation. So and what are this metallurgical aspects? This basically grain size and this location structures.

So we will discuss these things a little bit later, but I hope that you all know about what is grain and what is dislocations. This is basic material science, all of you have studied. So effect of grain size and dislocation structure. Dislocation structure, it may mean even the density and distribution of dislocations. Dislocation is the primary cause of the plastic deformation. Dislocation is nothing but a crystal defect.

So and they found out that there are no effects actually, no effects were found from their experiments. And they measured the peak pressure they measured peak pressure at two places, peak, one number 1 is close to the Impact interface that is the target, impact interface and they measured at a distance 10 centimeter from the from the impact interface. That means into the target.

So what they found is, so they found that even I will roughly draw a plot of pressure versus distance. Sorry this is x. So as you know the pressure pulse will first it will look like this. Then the pressure pulse, the back line will be little inclined and then this will be look like this. Then pressure will decrease, something like this, something like this.

So now what they did one point the experiments they did, one point they took the very close to the surface. This is the impact interfaces x equal to zero, very close to the surface they took and then pressure point they found it somewhere here, too close to the interface close to the interface. There they have they got good results. That means, the predictions were good. The predictions are close.

But at a distance of 10 centimeter, at the distance of 10 centimeter let us say. This is the 10 centimeter point. So here the pressure they got it something like this. So which is much lower than the peak pressure. But if you see the if you use the hydrodynamic theory, sorry I actually probably forgot to tell you this whatever plots we have this is from using hydrodynamic theory.

And they had two experiments. I mean, they have one experiment with two positions of measurement. So the second point is here at 10 centimeter from the surface, and here you can see this predictions are much higher. So that means the peak pressure prediction is higher. So the theory says it will be in this place. That means the attenuation is higher in real case. So attenuation is higher in real case.

In the previous slides we discussed about it and with hydrodynamic theory the attenuation is lower, attenuation rate is lower with if you do a real experiment attenuation you will find it as quite high. So we will close this today's lecture. So what we learnt here is about we are discussing about attenuation of shock waves. So what we will be even continuing with interaction and reflection of shock wave.

We will see how the shock waves interact when it transmits from one material to the other material and when it reflects back from a free surface or when two waves superimpose each other. So this discussion we are keeping it for the next lecture. Thank you.