Fracture, Fatigue and Failure of Materials
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Lecture 30
Introduction to Fatigue

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Hello, everyone. We are here in the 30th lecture of this course, Fracture, Fatigue and Failure of Materials. And today, we are starting the next module, the second module of this course, which is the part, Fatigue.

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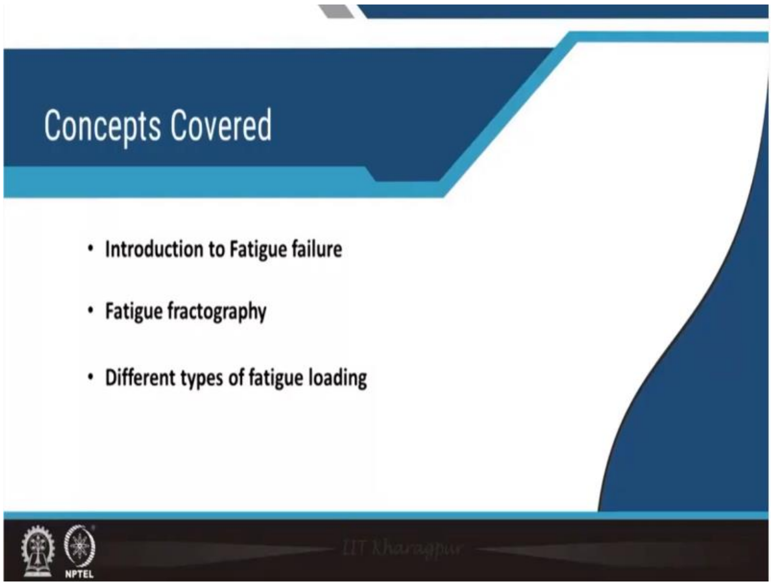

So, in this class, we will be having a basic idea about fatigue and how does that lead to failure. So, we will have some general introduction about fatigue. And next, we will move on to the fractography, which means, how the failure surface looks like and how from there we can understand whether the component or the structure has undergone fatigue loading or not. And finally, we will see what are the different kinds by which fatigue loading can be applied to a component and we will be mostly discussing the cyclic stress control fatigue.

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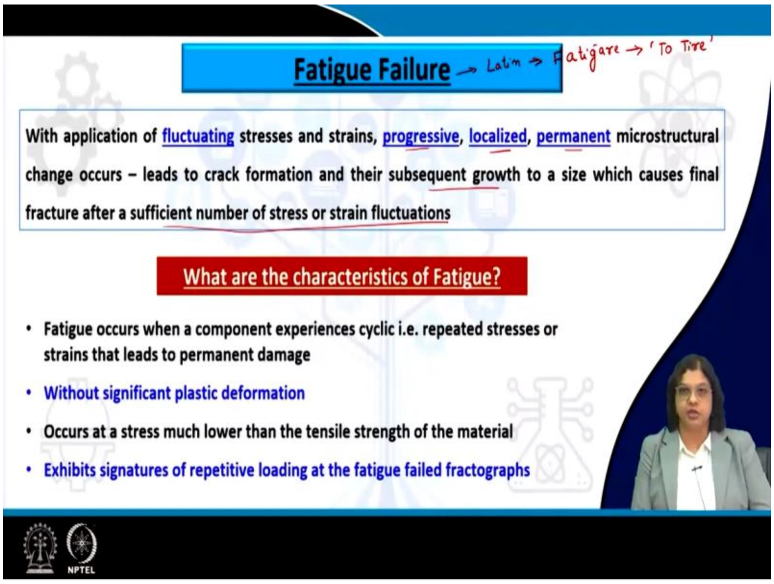

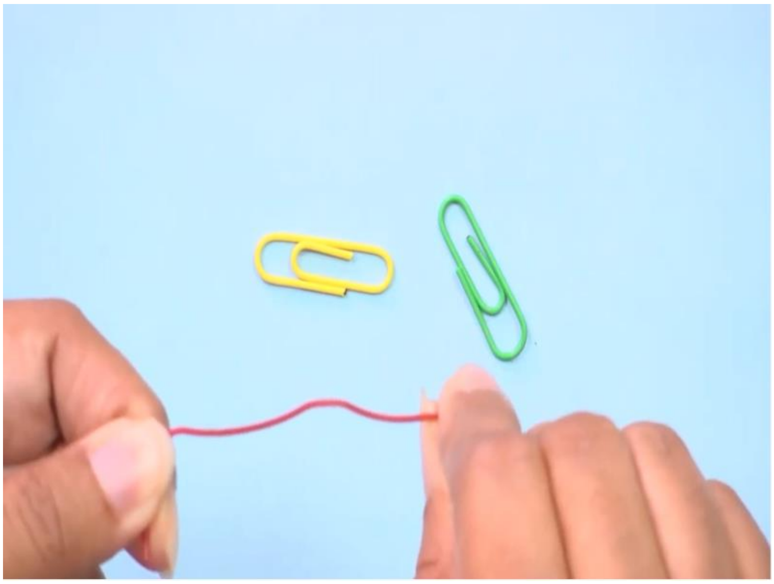

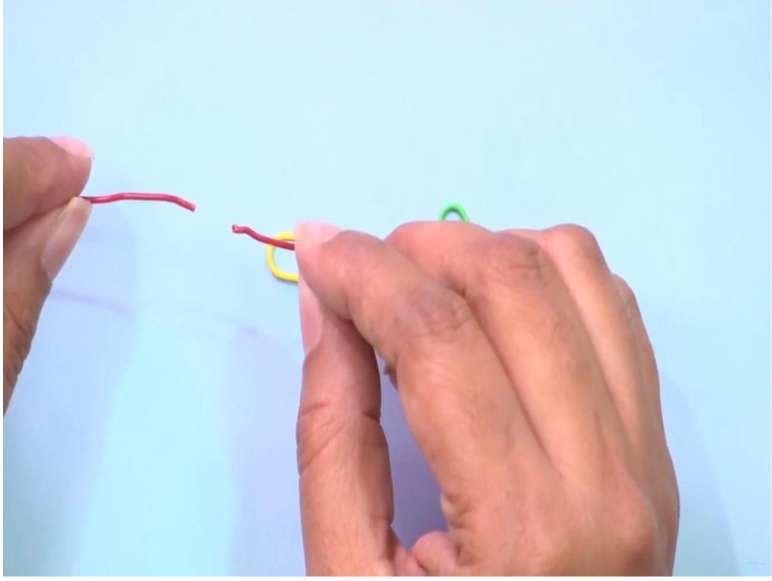

So, when it comes to fatigue, fatigue, the word fatigue has actually been derived from the Latin expression, Fatigare, which means literally to tire. We often use the word fatigued even in our daily life when we are tired or something. So, the same thing goes for the engineering world also, when something is overworked or worked repeatedly, then that material that component or that system overall gets fatigued. So, let us see metallurgically, what does the term fatigue signifies?

So, what it means is that with the application of stresses and strains which are fluctuating in nature, which means which are repeated in nature, which are not continuously increasing one rather they are continuously being changed to something or the other. So, that is the way a fluctuating stress or strain can be imposed on a system and because of that, there leads to a progressive and localized and permanent micro structural change.

So, I have highlighted this in blue signifying that all those key words have the particular meaning in terms of the fatigue failure. Progresses means that there is a continuous enhancement in whatever micro structural change or whatever micro structural defects are arising because of the fluctuating loading that is being done in a continuously increasing manner.

Secondly, this fatigue defects or fatigue failure is very much localized phenomena. So, the thing is happening at a very particular specific location while the rest of the behavior may not be following the same kind of attitude to the loading scenario. So, it is a localized behavior but whatever change is happening on the microstructure that is a permanent one which means that it cannot be reverted back to its original form.

As a result, whatever this permanent defects are forming, or this change in the microstructure that is happening, that leads to at some point when it reaches the sufficient energy to break the bond, it leads to formation of crack. And finally, if we keep on repeating the load, then it leads to the growth of the crack and finally, when it reaches the size which is critical and that can lead to the fracture of the material that leads to the final failure, but that can only happen after a sufficient number of cycles. So, after a sufficient number of stress or strain fluctuations, only the failure can be obtained.

So, let me demonstrate this with a very simple example that we can show you. Let us see that I have some gems clip here. So, what we know is that this material is quite hard or tough both ways and it is very difficult to tear it into two as such, if I try to pull it from both the sides so, if I apply the tensile stress, it will be really very difficult to break it into two but at the same time, if I am doing this repeated loading on both the directions, simply doing it for a certain number of times and you can see that there are some cracks being developed here.

You can try this yourself and you can look into how it is being changed. You can figure out that where exactly the damage is being localized and leads to the initiation of the crack, if I am able to do this for a sufficient number of times. And now we are able to fracture it into two. And there is a metal wire inside, which makes it a little bit more difficult to fracture and we had to do this many number of times to fracture but it is still possible.

And it is completely impossible if I want to just simply tear it to fracture, applying a tensile stress. So, that means that what the significance of fatigue is that it requires certain number of cyclic loading and that leads to some permanent damage leading to the crack formation and finally, the growth of the crack leading to the final failure.

Particularly, there is no significant plastic deformation that is evident on the material or the component, which means that there is no indication that a material or a component or structure is going to fail. And that makes it really, really difficult and challenging to understand or to control fatigue at the very first place.

And the most significant point here is that as we have seen for the gems clip, that it occurs at a stress much lower than the tensile strength of the material. We have seen that it was completely impossible to apply the tensile strength with our hands and to break the gems clip, but if we are repeatedly doing this, it is possible because we are not applying that much amount of stress to it.

So that means that if we are figuring out the tensile strength of the material by the monotonic tests like the tensile test of a specimen or a material, but if that material or that structure undergoes cyclic loading in service then, it may fail at a stress much lower. than the expected tensile strength of the material.

And whatever it does, if we are looking at the fracture surfaces of the fatigue failed specimen we should be able to look at some signature features and looking into that we can understand that the component might have undergone fatigue failure, might have been cyclic loading to it. So, this gets very, very important if we try to find out the actual reason, because that is necessary especially when we are doing the failure analysis and we want to avoid such kind of failure in future.

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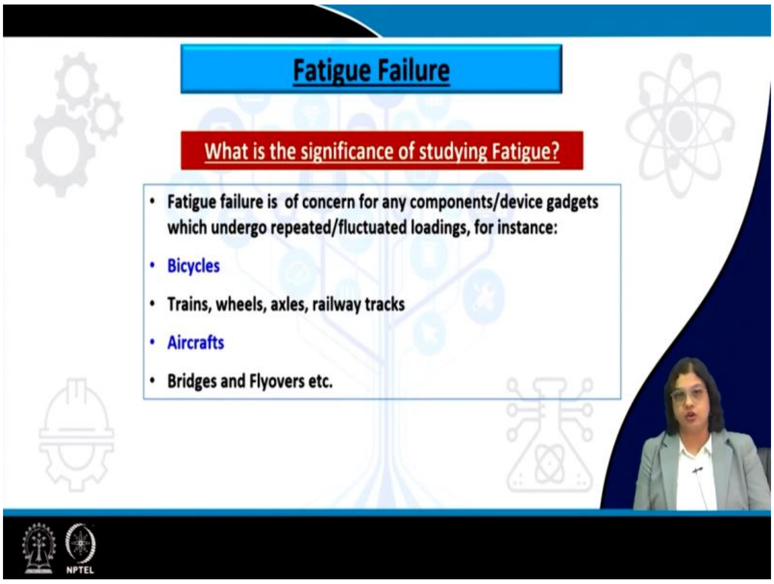

So, what is the significance, why should we study fatigue at the first place? Fatigue failure is of concern for any components, device, gadgets, whatever you can think on which undergo repeated fluctuated loadings. For instance, if we are talking about the bicycles, we use the bikes for our regular conveyance and not only the wheels or the axles but also every part of this bicycles while it is moving and while we are applying the stresses in regular fashion, every part of it is actually getting fatigued.

So, it is often, it has been seen that some parts especially the chains and all which undergoes repeated cyclic loading fails even if we have not, it has not encountered any particular stress level or sudden stress hike but still it fails just because of this repeated number of cyclic loadings.

Similarly, fatigue is also of very much relevance for the trains, the wheels axles, railway tracks all this through which the train passes. This undergoes repeated cyclic loading and there is some term known as rolling contact fatigue, which is of significance for such cases. These are just some of the examples which I thought of bringing but you can think of anything which undergoes repeated motion can lead to fatigue failure at a stress much lower than the expected strength of the material.

Aircraft, fatigue is of much concern for this particularly, several parts for example, the engines, as well as the wings of the aircraft which has to encounter the resistance and the frictional forces of the wings at several frequencies at several speed. The wings are constantly in motion and fatigue failure is of significant concern there. Not only that the fuselage of the aircraft when it undergoes repeated pressurization and depressurization, when the aircraft is flying at certain altitude it has to maintain the pressure and it has to maintain it in the inside, just for the comfort of the passengers.

So, that means that it has to match with the environmental pressure versus the pressure that has to be maintained to a constant value or more or less particular value inside the chamber so, that the passengers should not feel any discomfort and for doing that it has to continuously pressurize and depressurize, to maintain that level. And for that the fuselage the skin of the aircraft often gets fatigued. So, any kind of defect if already present there, that can trigger the formation of the crack, fatigue crack and the growth of the crack and that can lead to the early failure of such structure.

Bridges and flyovers, these are again very, very significant where fatigue is of concern, particularly if we are talking about the railway bridges or even flyovers through which several kinds of vehicles passes. So, we can understand that when there are heavy vehicles loaded trucks versus when there are the bikes, there is a fluctuation in the level of load also and then at certain period of time particularly maybe during the daytime there are a lot of traffic, while at night the traffic's are less. So, there is a change in the loading frequency also.

So, all this along with the repeated number of vehicles that are passing through those bridges lead to fatigue failure. And we will see later on in the case studies that how that can lead to the crack initiation and formation and failure of the entire bridges. So, we need to be extra careful for such structures but it does not mean that we should be only careful about the aircraft or the bridges, fatigue is what we can see even with the components or with the kind of devices that we use for our daily usage.

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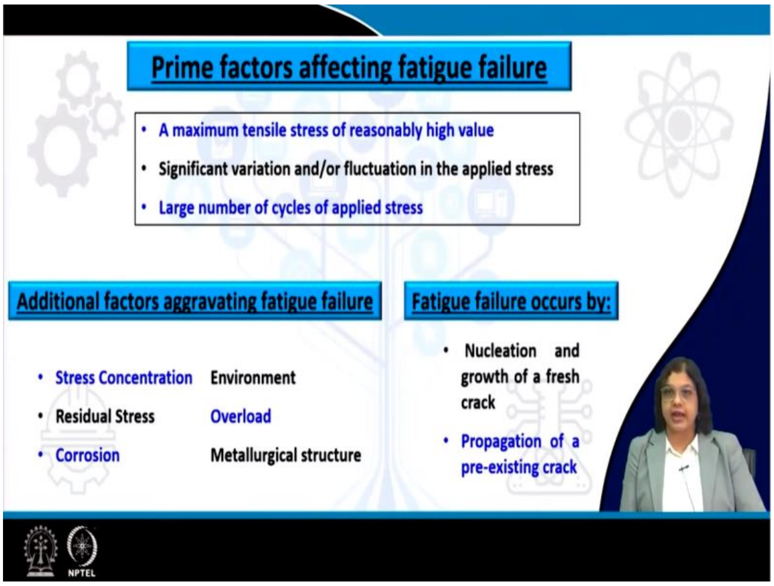

So, let us see what are the prime factors which affect the fatigue failure. When we are talking about fatigue of course, there has to be a tensile stress. As I mentioned that there should be a fluctuating stress, but it should have a tensile component of the stress, the mode of the stress should be tensile, and that should be of reasonably high value that should not be as high as the tensile strength of the material, but it should be sufficiently high so, that that can trigger the initiation of the crack.

And once again, even if it is a fluctuating loading and we may have both the tensile and the compressive component of this, tensile one is the most dangerous one, the detrimental one because that leads to the crack opening mode. So, we need to have a sufficient or the component if it is encountered with sufficiently high tensile stresses repeatedly, that can trigger the fatigue failure.

And whatever this magnitude of the stress is, that has to be varied significantly for a certain number of cycles. So, large number of cycles are typically necessary, it is not just only one or two cycles that can lead to fatigue failure, but it has to be for a certain number of time so, that the fatigue failure can be obtained.

So, the additional factors which are aggravating fatigue failure are the following stress concentration. So, if there is any animali or any kind of non-uniformity in the structure that may lead to stress concentration, if there is any cracks or notches or even the corners that can lead to stress concentration that are the locations which are very much prone for the fatigue crack to initiate. So, any such stress concentration actually makes the early initiation of the fatigue crack and lead to early onset of fracture.

Residual stress is also another thing which is clubbed with the applied stress can bring to the stress intensity factor to a very high value and that can lead to early onset of the crack initiation at the first place. Of course, corrosion as we have seen in the last lecture, that corrosion and the environment, different kinds of environment, even temperatures, all this can lead to early onset of crack initiation, and once the crack initiates, if we have the repeated kind of loading and that too, there is some tensile component of the loading, that can certainly bring the fatigue failure into picture.

And often we have also seen that there are overloads. So, there are fluctuations and there is certainly an overload or maybe there is a continuous load, there is no fluctuations, but certainly there is an overload following which it is coming back to its normal rhythm. So, that may also lead to fatigue fracture to occur.

And last but not the least, metallurgical structure is very, very important and practically for any kind of mechanical behavior, structure is something which is controlling the properties to a large extent and that is nonetheless for fatigue also metallurgical structure is of very, very significance and we will see that how we can modify the structure to achieve better performance, improved fatigue strength of the material.

So, typically if we are talking about the different stages of fatigue, there are particularly two, first of all, there is a nucleation and growth of a fresh crack it can occur, in case that there is no dominant notch or crack present there, then the crack has to be initiated. And once it gets initiated, if the fluctuation, load fluctuations are being continued, then that can lead to the growth of the crack and subsequent failure. That is one way of having fatigue failure.

And the other way is when there is already some kind of crack or notch or even the stress concentration region are already present. So, that leads to crack initiation even at the point of very early number of cycles, very low number of cycles and that means the propagation time only for this preexisting crack to have the final failure.

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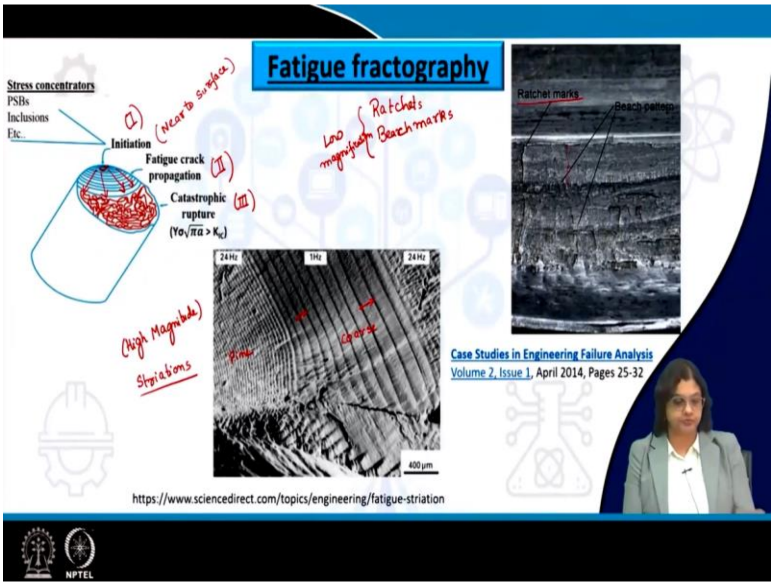

So, these are the micro structures or the fractographs. If we are looking into the structures of the fracture surface that is termed as the fractography. So, typical signatures of fatigue fracture can be seen from the fractographs. Particularly if we are looking on the whole component, fatigue typically has these three locations.

So, first of all, there is some initiation zone here, which most of the cases it is near to the surface, fatigue is very much prone to initiate from the surface defect. So, we have to be extra careful in making the surface very, very smooth and devoid of any such kind of non-uniformity that can lead to crack initiation. So, we see typically the crack initiation site and then we can see the crack propagation.

So, the crack propagation region is like the step two, which can be very well distinguished from the fractograph itself. If we are looking at through our naked eyes, or maybe very low magnification microscope or even just with the magnifying glass, we can figure out that this is the location on which the crack has been extended. So, this is the direction on which the crack has grown and we can understand that, that is the fatigue crack propagation regime.

So, this is crack initiation regime is regime one, then we have the crack propagation regime as regime two. And finally, this is the region here which leads to the catastrophic failure and that is the regime three. Now, if we are looking into more signatures of this we can see that, at a very low magnification, we can see some signature features such as ratchets. So, ratchets are nothing but it looks like the steps. So, it is like the staircase, it is like the steps which we can see that there are different altitudes.

So, there are some topographical contrast which is known as the ratchets. And there are other features like the beach markings. So, typically this kind of features such as ratchets and beach marks so, it look like the sand waves that we can see on the sea beaches. So, similar kinds of features can be seen for the fatigue field specimen and all this can be seen at quite low magnification and we can understand if we look into that, we can understand that fatigue failure might have occurred.

On the other hand, if we are looking at higher magnification if we are looking at under an SEM at a comparatively higher magnification we can see the striations. So, here are striations that we can see here, the striations width our also we can see that they are varying as we are varying the frequency levels also, here we can see very fine striations and with the width very less and here we can see quite coarse striations.

So, this striations however, cannot be seen with our naked eyes or with low magnification, we need very high magnification to look into the striations. And striations are certainly the signature of fatigue failures so, if we are able to see the striations on the fractured specimen, we should for sure know that that has undergone fatigue loading.

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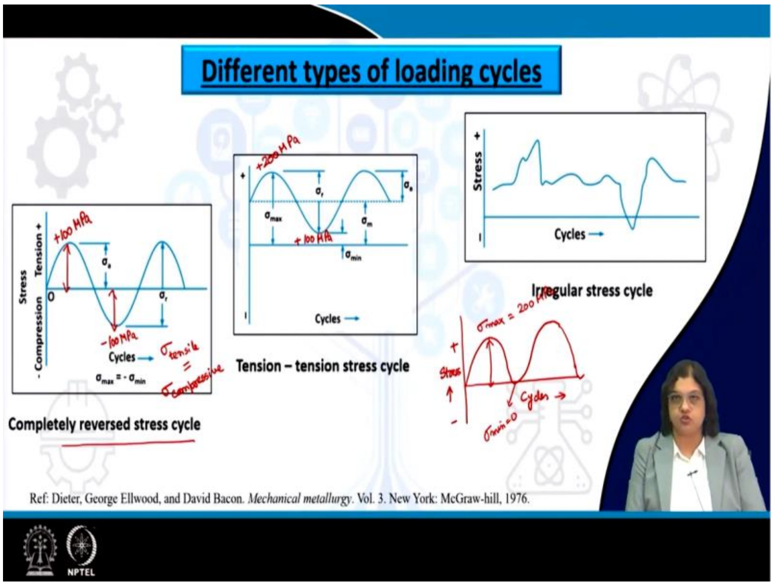

So, let us see what are the different types of loading cycles that can be employed, while we are doing especially a lab scale testing, the commonly used cycles that we can give to a specimen is the tension-compression. So, this one here is a completely reversed stress cycle, which means that the magnitude of the tensile stress that we are applying and the magnitude of the compression stress that we are applying are the same. So, it has been completely reversed.

The y axis here signifies the stress level and the x axis signifies the cycle. So, sometimes it is also represented with respect to time. So, we can see that the σ for the tensile part is same as σ of the compressive part, or σ_{max} equals to minus σ_{min}. So, same magnitude but opposite in sign or there could be tension-tension stress cycle also. So, tension-tension means we are applying maximum stress which is of higher magnitude and a minimum stress, which is a lower magnitude but still it is not in the compression side, it is still in the tension side itself.

So, we are applying higher stress and lower stress and highest stress and lower stress and so on. So, let me give you some numbers to appreciate this better. For example, the first case a completely reverse cycle. If we are applying a stress of let us say, plus 100 MPa and minus 100 MPa. So, that one is completely reverse one. In this case, however, we can apply a stress of let us say plus 200 MPa and the minimum stress of 100 MPa, it is still in the positive side.

We can also have tension and 0. So, if we are having the stress on the y axis and cycles on the x axis, and this is positive, this is negative, we can have the stress cycle something like this, such that we have σ_{max} here. Let us say σ_{max} is 200 MPa and σ_{min} in this case is just 0. So, there is no compression part as such. But in actual practice or in service, what we have is an irregular stress cycle something like this where the stress and the strain does not follow any regular pattern. So, that may also happen.

And other than doing the tests in the lab scale, if we know the kind of applications which will require not a very particular kind of stress fluctuations, we often need to employ such kind of irregular stress cycle also to appreciate the actual performance of the component.

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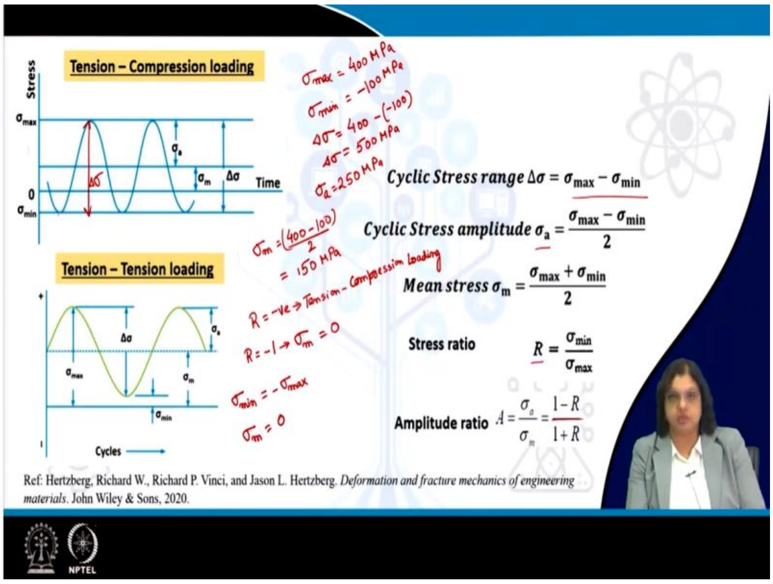

So, let us see the different parameters which are of interest when we are talking about the fatigue loading. First of all, any kind of stress cycles that we are considering whether it is a tension and compression, or tension and tension, whatever it is, if we try to figure out how the material will behave, we have to understand the following parameters, we have to quote the following parameters.

For example, the cyclic stress range, cyclic stress range is the difference between the maximum and the minimum stress ($\Delta\sigma = \sigma_{max} - \sigma_{min}$) . So, if this is the maximum and that is the minimum, this entire range is given by $\Delta\sigma$ or the cyclic stress range. So, you can see here that for the tensile tensile loading, the cyclic stress level is just a maximum minus minimum. So, let us use some numbers to have this idea a little bit better.

So, let us talk about σ_{max} being 400 MPa and σ_{min} being minus 100 MPa. So, $\Delta\sigma$ in this case is 400 minus of minus 100 so, that means 500 MPa. The other parameters which are derived from the cyclic stress range is first of all the stress amplitude, cyclic stress amplitude typically denoted as σ_a , which is the $\Delta\sigma$ / 2. So, it is $\sigma_a = (\sigma_{max} - \sigma_{min}) / 2$.

So, in this case, the stress amplitude then will be 250 MPa. You can see how the amplitude has been shown in this curves here for the tension-tension or tension-compression kind of loading, we can find out what is the stress amplitude. Mean stress (σ_m)on the other hand is the average of the σ_{max} and σ_{min}. So, in this case mean stress will be (400 – 100) / 2. So, that means, it should be 150 MPa.

So, we see that how the sign also should be considered to find out this effective parameters. Stress ratio now, this is also a very, very important parameter and we often define the entire cycle by following this or by mentioning this stress ratio. So, it is the ratio of the σ_{min} to the σ_{max} ($R = \sigma_{min} / \sigma_{max}$). Please be careful of using the minimum stress at the numerator.

So, if we say that stress ratio value of R is negative that means that we are talking about tension-compression cycle. So, this certainly mean that there is a compressive part in the loading and the compressive part actually leads to this negative sign of R. If we are saying that R is negative and it has a value of minus 1, that however means that σ_m equals to 0.

There is no magic to that, what I did is R equals to minus 1 means the value of the σ_{min} is exactly same as that of σ_{max} but only with a minus sign. So, obviously, σ_m or the average sigma in that case will be just 0 because σ_{min} and σ_{max} will cancel out.

Similarly, amplitude ratio is also defined as the stress amplitude divided by the mean stress, it is the ratio between the stress amplitude and the mean stress or also defined as

$$A = \sigma_a / \sigma_m = (1 - R) / (1 + R).$$

So, if we know all these parameters, we should be able to figure out that what kind of stress is being applied and what is the possibility of this component or structure to survive.

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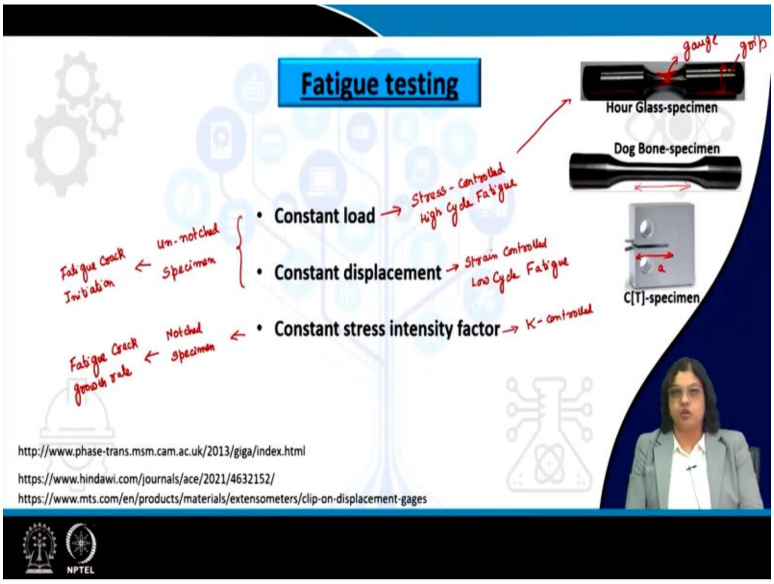

So, let us see that how we can test fatigue. Typically, there are different ways by which fatigue testing has been done. And we can do it in the following way. We can do it either in the constant load mode. So, basically what we do here is to control the stress. So, this is typically stress or load controlled mode. And then, we have the constant displacement. So, in this case, instead of the stress we control the strain.

And there is another way by which the stress intensity factor or K is typically controlled. So, that is K controlled. The stress intensity factor is the same thing that we have learnt for the fracture mechanics part. So, that if we are controlling the stress intensity factor while doing the experiment, while doing the tests that can lead to this K controlled test.

Now, why do we do this by controlling the different factors? The stress controlled and the strain controlled one are typically being done on unnotched specimen. So, we do use unnotched specimen. So, that means that there is no specific notch or crack on the specimen. And what is of interest here is to figure out the number of cycles for fatigue crack initiation. So, we need to figure that out from the unnotched fatigue and that can be done in the stress or strain control mode.

So, let us see what kind of specimen do we use for such kind of testing. So, for the stress controlled one, we typically use the hourglass specimen. You can see in this specimen mode that this looks like the hourglass, a typical sand glass that we use for measuring the time. So, similar kind of thing, there is no particular gauge length here, rather there is a narrow-gauge section at this point which has much lesser diameter compared to the grip part.

So, that is the gauge part and the grip part but, there is not much significant grip, the gauge length here. This part, the grip part is inserted into the instrument and then it is being continuously loaded, repeatedly loaded fluctuating load, so that we can figure out the number of cycles it can survive under such condition.

Strain controlled fatigue is, however, uses the actual kind of machine and it uses a dog bone kind of specimen. In this case, we also see that there is a gauge part and a grip part but we can see that the gauge part is quite pronounced here with a certain length and we have seen similar kind of specimen to be used for tensile testing also that should be used for the strain-controlled fatigue.

But both of these kinds of specimen do not have any typical notch there, they do have a gauge section which has a diameter less than the grip part, but there is no particular notch there and we are interested to find out the fatigue crack initiation. So, this typically, this stress controlled and the strain-controlled fatigue leads to high cycle fatigue and low cycle fatigue which we will discuss extensively in this course.

But for now, let me give you the basic idea of what kind of specimen we use and what kind of loading mode we use for different kinds of fatigue. So, there are typically different ways by which fatigue can be tested and the properties can be understood. And finally, when we are talking about the stress intensity factor control, as I mentioned that this K is nothing but what we have understand from the fracture mechanics part. So, that means that it also uses same kind of specimen that is used for fracture toughness testing.

Typically, we use the CT specimen, the compact tension specimen that is used for fracture toughness testing also. So, you can see here that there is a very big machine notch, this notch is almost 50 % of the total width of the specimen, we have already seen that, we have also seen that thickness has a very strong role to play in case of fracture and the same goes here also. So, it basically uses the concepts of fracture mechanics here, so, that we can figure out the fatigue crack growth part here.

So, we know that there is an existing crack in this, we need to find out how fast or how slow the crack is growing. So, that can be understood by using a notched specimen. That is how all these three different fatigue modes are different from each other and based on our requirement to find out the crack initiation or the crack propagation rate, we can decide what kind of testing should be done.

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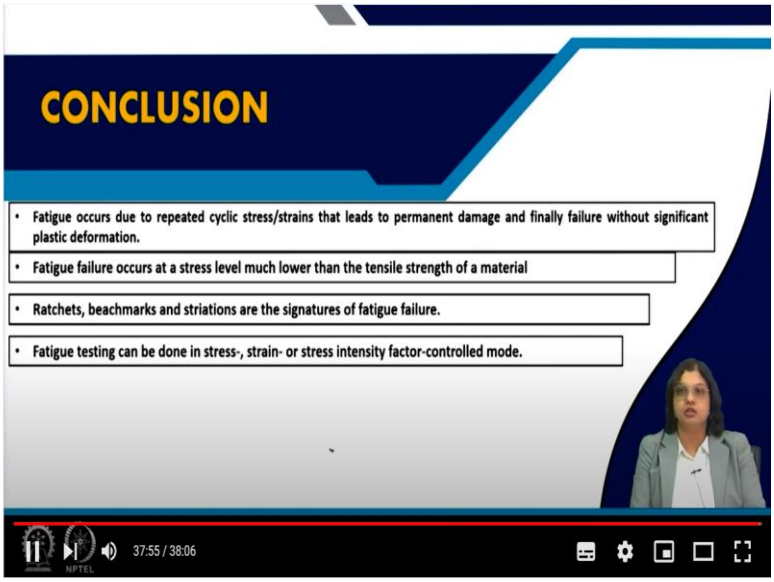

So, this leads to the conclusion for this lecture, that fatigue occurs due to repeated cyclic stress strains that leads to permanent damage. And finally, failure of the component without significant plastic deformation. And fatigue failure occurs at a stress levels much lower than the tensile strength of the material.

So, both of these factors make fatigue a concern, particularly because there is no indication that fatigue failure is about to happen, there is no plastic deformation and also because it fails at a much lower strength than compared to the tensile strength of the material. So, based on our testing results, we cannot obtain all the understanding about the fatigue performance of the material and we need to do the specific tests for that.

If we are looking at the fracture surfaces, there are some typical signature features such as ratchets and beach markings which can be seen at low magnification, whereas at higher magnification we can see the presence of striations which signify that the component has undergone fatigue loading.

Fatigue testing can be done in different kinds of mode, we have seen that it can be done in stress or strain or stress intensity factor-controlled mode. The former, the stress controlled one can be used for estimating the high cycle fatigue condition, the strain controlled one on the other hand is suitable for low cycle fatigue condition. But both of these, the stress or the strain control fatigue lead us to understand or assess the fatigue crack initiation life.

On the other hand, stress intensity factor control test is typically done on the compact tension specimen which is already having a notch, a big machine notch or crack existing in the system. So, what we tried to figure out from the stress intensity factor control mode is the crack growth rate to fatigue.

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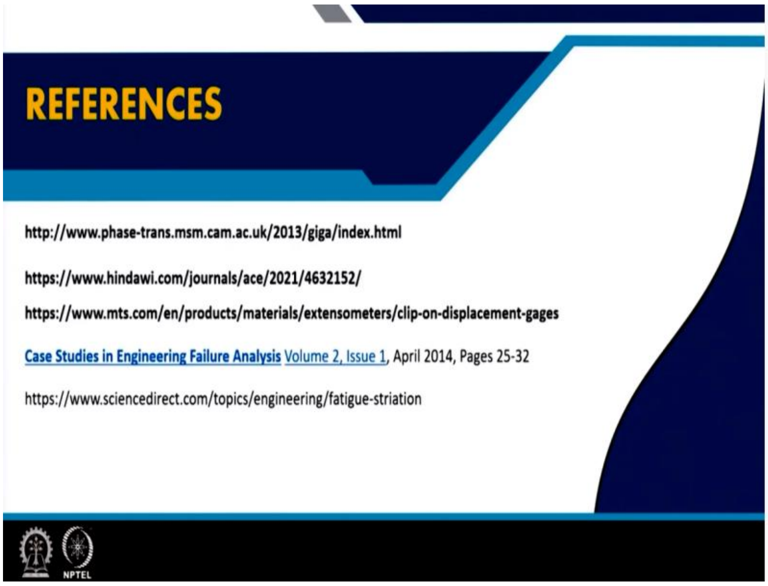

So, following other references that has been used for this lecture. Thank you very much.