Fracture, Fatigue and Failure of Materials

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Lecture 48
Fatigue in Materials

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Hello everyone, we are at the 48th lecture of this course Fracture, Fatigue and Failure of Materials and in this lecture we will be talking about the influence of cyclic overload. So we have seen that how if we are applying variable amplitude loading that can influence the high cycle and the low cycle fatigue significantly. So let us see how this influences the fatigue crack growth behavior and on that basis we will be also estimating the lifetime in case of a variable loading. We will also like to see how the fatigue crack propagation occurs in case of ceramics as well as composites.

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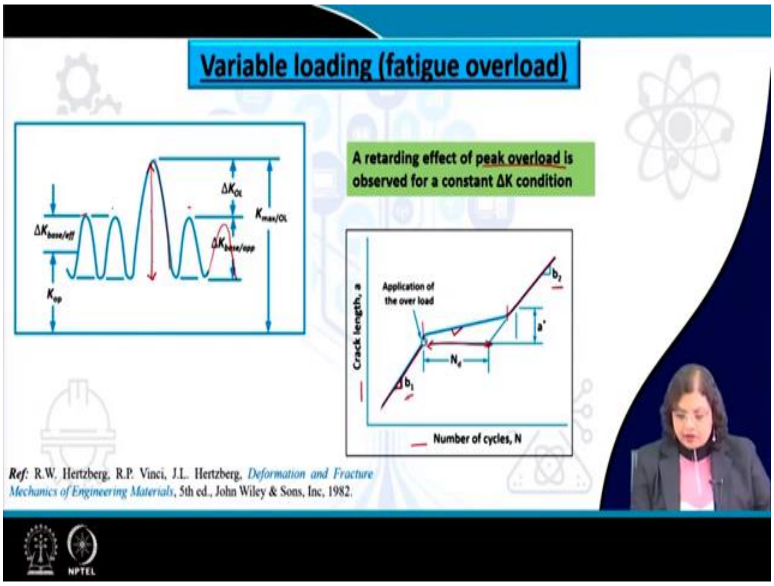

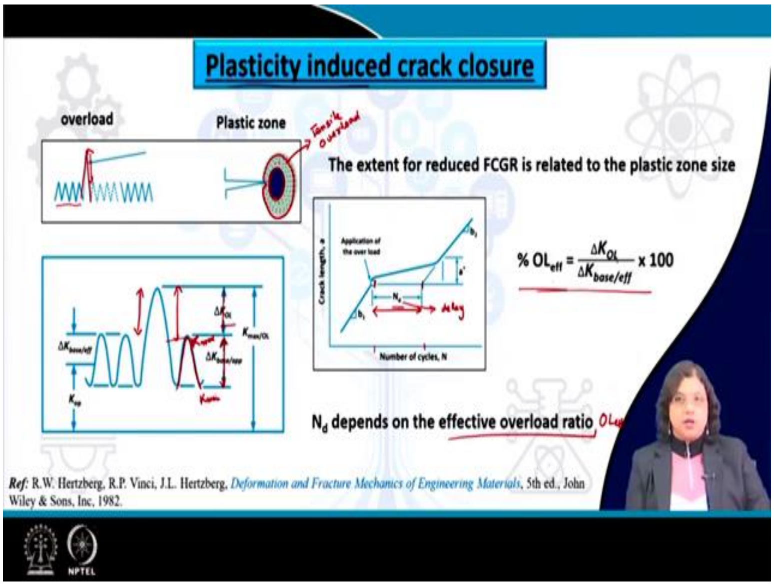

So let us talk about variable amplitude loading, particularly when we are having an overload just one cycle of overload. So what we are seeing here is that there is a regular fatigue cycle that has been applied with particular values of ΔK at every cycle and then suddenly there is an overload and once the overload is gone then again it is resuming back to the previous cyclic mode with the same values and all.

How should that influence the fatigue crack growth behavior, at the very first instance we have the tendency to think that in case there is an overload that may lead to an extent of the crack growth in a faster way because we are talking about a tensile overload, so this is all the positive stress that we are applying and this one is pretty much higher compared to the neighboring one on both the sides.

So obviously higher stress level should lead to increased fatigue crack growth that is what our typical expectation is. However, in actual practice what we see is a retarding effect so in case there is a peak overload that actually leads to a retardation or delay in the crack growth rate in comparison to the constant delta condition.

So what we are seeing here is the variation of crack length with the number of cycles and this is the regular value of cyclic loading that we are applying and this is how the crack length is increasing following a particular slope of b_1. Now in case there is a tensile overload for just one cycle that leads to a delay in the growth rate of the crack which means that the crack growth rate decreases, so you can see that from the slope here; the slope is quite reduced for this section compared to the previous section of b_1.

And once this overload period is over or the delay in the crack growth rate is completed finally the crack again resumes back its previous growth rate of b_2, which is more or less the same as that of the previous one only difference is that now it is having a higher crack length. So obviously that may lead to some modification in the crack growth rate, but overall we see that apart from this delay period the initial one and the final one more or less tell us but because of this tensile overload we are having a restriction in the crack growth rate that we can see here.

Now this appears to be quite surprising at the very first instance and to understand that we have to look into the plasticity induced closure mechanism. We have seen earlier also that how the crack tip plasticity can lead to tip blunting and that in turn can lead to reduction in the crack growth rate, so exactly the same thing is happening here. When we are having a typical cycle like this and there is a regular plastic zone that is forming, but in case there is a sudden overload and that in the tensile mode that means that there is an enhanced plastic zone also.

Now this is related to the tensile overload and more is the plastic zone, we know that that will influence the crack growth behavior further it will make the crack tip blunter and the crack growth rate will be delayed. So this is what we are seeing here the extent of this fatigue crack growth rate also is related to the plastic zone size, the plastic zone size in turn is related to the degree of overload. So how much this plastic zone size would be and how effective that will be to reduce the crack growth rate, what would be the duration of the crack growth rate that can be all determined based on the magnitude of this tensile overload.

So this period here where the crack growth rate is reducing because of this tensile overload is known as the delay, number of cycles that are involved in this are N_d where d stands for delay in the crack growth and this extend over which N_d is extended in the number of cycles mode is related to the tensile overload magnitude.

So how this magnitude of tensile overload is determined and this is based on the effective overload ratio, what is meant by effective overload ratio is a relation like this where ΔK_{OL} which is nothing but this much extent, so over which it is different from the base level so this one is the base level here. The initial ΔK level so that means the stress intensity factor range considering the K_{max} and K_{min} and whatever is the difference between K_{max} and K_{min} is nothing but the ΔK applied or considered here as a ΔK_{base}.

Now from this base level there is an enhancement in the tensile loading period and that is signified by the delta K_{OL}, OL stands for the overload and that overload level divided by the base level is multiplied by 100 terms as the percentage of overload or this is known as the effective overload ratio. So higher is this overload ratio obviously more will be the plastic zone size and that can delay the fatigue crack growth rate further which means that N_d will be extended as well.

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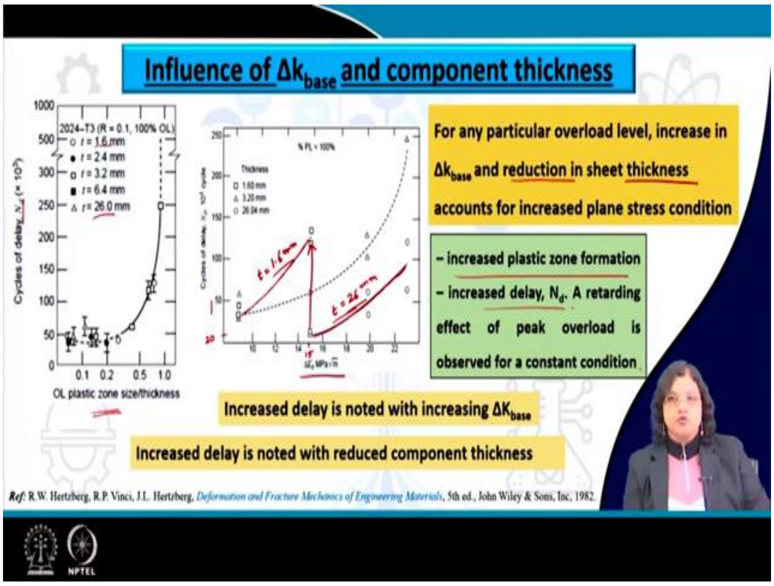

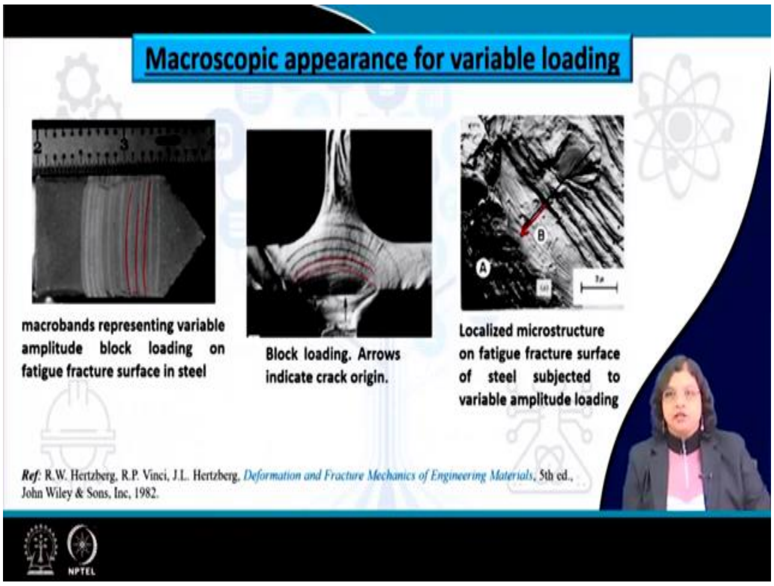

Now let us see what are the influence of ΔK_{base}, of course we have understood that how ΔK_{OL} is controlling that and more and more is the overload the extent of delay will be higher and higher, but how ΔK_{base} is also controlling that is important to note. Now for any particular overload level if you are considering that ΔK_{OL} is fixed then increase in the ΔK_{base} can lead to increase in the plane stress condition further and along with that we are also talking about the thickness of the component that also plays a significant role, because it is all related to the plastic zone size formation.

So apart from the ΔK_{base} the other factor that can control the plastic zone formation is the thickness of the component. In case we are having a reduced thickness that may lead to the plane stress condition and eventually plane stress means higher plastic zone size and higher plastic zone size means higher extent of the N_d.

So this is exactly what is being seen here basically increased plastic zone formation leads to increment in the delay period or N_d, so this is exactly what we are seeing here are the experimental results for the cyclic delay N_d on the y axis and on the x axis we are having the plastic zone size divided by the thickness. So plastic zone size which is normalized by the thickness of the component and this is what we are seeing that as this ratio, plastic zone size to the thickness increases there is an enhancement in the delay also.

So you can see that the thickness has been increased from 1.6 to 26 mm which is quite a large value and based on that we can see that as the thickness is actually reducing that is more effective in generating the higher plastic zone size value and that can lead to an enhancement in the extension of the delay period. At the same point if we are looking for the ΔK_{base} condition, so you can see here the x axis now represents the ΔK_{base} and the y axis once again is the cycles of delay and what we can see here is that for the lower thickness so this one here is for thickness of 1.6 mm.

For any particular cycles of delay we can see that as the thickness is being increased so this one here is the highest thickness of 26 mm and obviously what we can see here is that the for a particular N_d value as the thickness increases, ΔK_{base} increases, in other word we can say that for any particular ΔK_{base} value we can see that as the thickness reduces the extent of the delay actually increases.

So you can see that from 26 to 1.6 mm thickness if we are keeping the ΔK_{base} value of something like around 15 MPa√m we can see that there is pretty high extent of the N_d value that is increasing. In the former case for the thicker plate of 26 mm it has the N_d value of around 20 number of cycles, whereas that increases to more than 100 if we are decreasing the thickness to 1.6 mm, so obviously the span over which this reduction in the fatigue crack growth is continuing increases if we are decreasing the thickness of the component.

So once again we can play around with the overload ratio as well as the base value of the ΔK as well as the thickness of the component to have a required amount of crack growth rate delay that we can use in actual service. So increased delay is noted with increasing ΔK_{base} as well as increased delay is also noted with reduced component thickness, these are the two findings that we observed in this slide here.

Now if we are looking into the fracture surface of the component once again we should be able to find out that there has been an overload or not? So this is also helpful for the post mortem failure analysis where we can just look into the fracture surface of the fractographs and we can figure out that there has been variable amplitude loading not only that there had been a tensile overload.

Now this you can see the bands here very clearly which signifies this kind of variable amplitude loading and in this case also you can see the circular loops and in case there is a sudden overload period you can see the stretch of the band for just one or a few cycles and you can understand that this is related to the overload zone.

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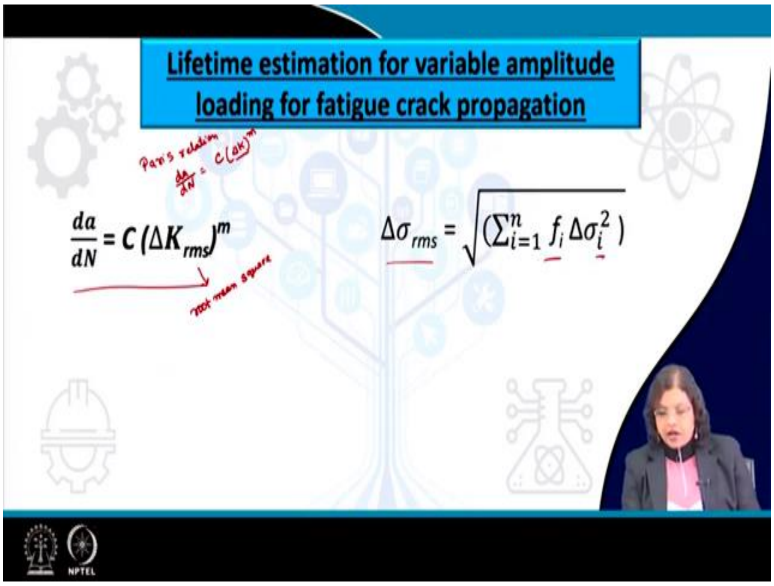

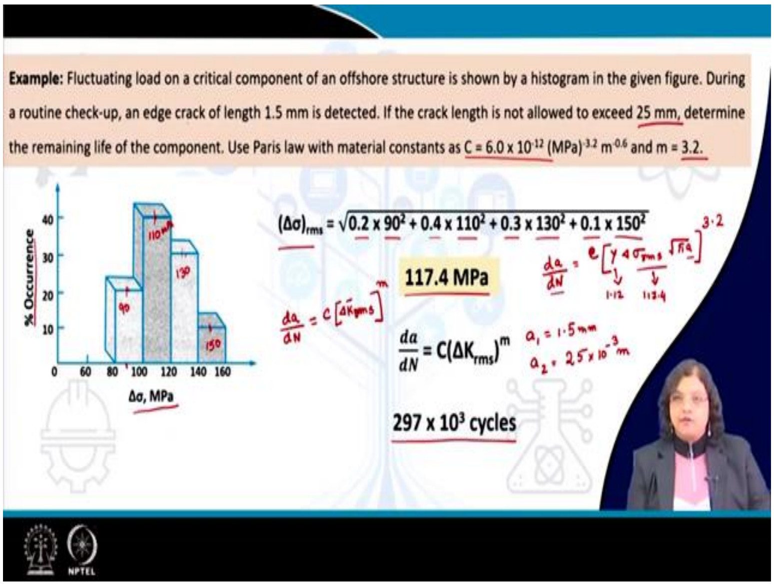

Now if we want to determine the life cycle in such cases when there is already an overload we have to consider the values of the ΔK for each of this condition or for that matter not only the overload for any kind of variable amplitude loading this would be useful to determine the life.

Now it uses the same kind of relation as we have seen for the Paris relation which says that da/dN is C $(\Delta K)^m$, where m is the Paris exponent and C is a materials constant in this case instead of ΔK we are using rms which stands for root mean square and that means that if we are having different values of ΔK or for that matter Δσ actually we can determine the root mean square of that and consider that as the ΔK value that can be applied to this Paris relation and then from there we can figure out the number of cycles by solving the relation in the same manner as we have seen earlier.

And this root mean square is determined based on the number of cycles for each loading block and based on that so that signifies the f as the frequency of the number of cycles as well as $\Delta\sigma_i$ where i varies from 1 to n in this case for n number of blocks we can figure this out. So let us solve a numerical to have a better understanding of this.

So, this is an example which says that a fluctuating load on a critical component of an offshore structure is shown by this histogram and during a routine checkup an edge crack of length 1.5 mm is detected. Now before that let us focus on the loading condition here what we can see here the y axis is percentage of occurrence frequency wise how often this is being applied and what we are seeing is that $\Delta\sigma$ on the x axis which says that for up to initial 20 % stress level of 90 MPa has been applied.

So, this is what is 90 MPa that we can see for the first block and next for if we consider the total number of cycles as 100 %, so out of that 40 % is used for applying a load of 110 MPa and then there is 30 % for a load of 130 MPa. This is just we are obtaining from the histogram itself and the remaining 10 % is for a stress level of 150 MPa, so that the total extent of this is 100 % you can see that 20, and 40, and 30 as well as 10.

So first of all we need to find out the root mean square for the $\Delta\sigma$ that has been applied here and this can be done by using this relation here as 0.2 since this is 20 %, so 20 divided by 100 is 0.2×90^2, so that is the the relation for the root mean square and 0.4×110^2, 0.3×130^2 and 0.1×150^2.

$$(\Delta\sigma_{rms}) = \sqrt{0.2 \times 90^2 + 0.4 \times 110^2 + 0.3 \times 130^2 + 0.1 \times 150^2}$$

If we solve this we get the $\Delta\sigma_{rms}$ as 117.4 MPa, I suggest that you should also do this simultaneously to come to this number.

And once we get this $\Delta\sigma$ we already know how $\Delta\sigma$ and ΔK are related. So we can very well find out the ΔK from there or use this relation and we can find out the number of cycle, let us just write the Paris relation once again, so da/dN is C $(\Delta K_{rms})^m$ and this can be written as da/dN equals to C instead of ΔK_{rms} we can write Y $\Delta\sigma_{rms}$ and $\sqrt{\pi a}$, the value of m is provided here as 3.2, the value of C is also provided so we can plug in the values here also it is an edge crack so that means the value of Y should be 1.12 $\Delta\sigma$ already we have obtained the value as 117.4 and a is what that we need to figure out and we have seen that how this da and dN term should be used to integrate these values and in this case we have the a_1 the initial value of the crack that has been detected is 1.5 mm. So that means 1.5×10^{-3} m as well as the final crack length in this case is 25 mm the crack is not allowed to exceed 25 millimeter means that this is the limiting value that the crack can grow up to.

So a_2 in this case is 25×10^{-3} m and if we plug this value we should be able to figure out the number of cycles which comes around 297×10^{-3} numbers of cycles. So you can solve similar kind of numericals for a better understanding of how to find out the remaining life of a component which is already having a notch of certain length as well as when a variable amplitude loading is being applied on this.

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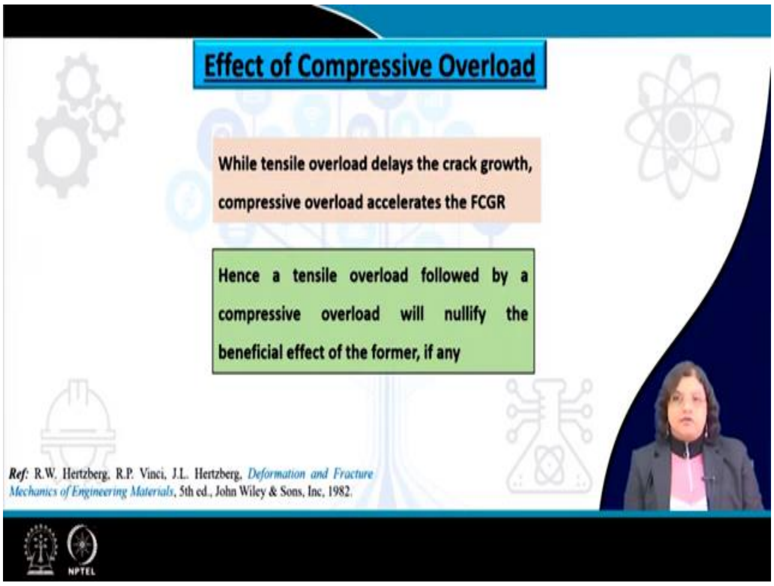

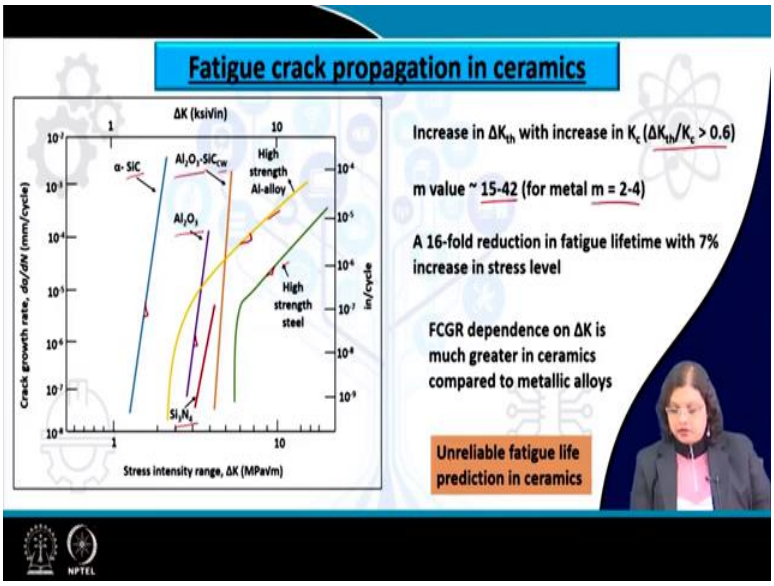

Now so far we have mostly talked about the tensile overload, of course there can be compressive overload because in service there can be actually fluctuating load of several different magnitudes and in case of compressive overload, however, there is an opposite effect which means that compressive overload actually leads to an enhancement in the fatigue crack growth rate.

So unlike the tensile overload compressive overload is not a good news, so this is also very much important to note that while so far we have always talked about how compressive loading could be beneficial in case there is an existing notch particularly because compressive loading can lead to crack closure, but in case of this overload that may not be the case because in case of compressive overload there can be a reduced size of the plastic zone and that may lead to an enhanced crack growth rate.

Not only can that if tensile overload is followed by a compressive overload then the beneficial effect of the tensile overload be nullified by the destructive effect of the compressive overload. So we also have to be careful that while the tensile overload is good in terms of restricting the crack growth rate a compressive overload may not be.

Now particularly tensile overload is often seen for the case of the aircraft even the wings which has been through some harsh atmospheres and vibration loading and that actually can lead to higher delay in the fatigue crack growth and lead to an enhanced life in general. So let us now move on to the different kind of material and see how the fatigue crack propagation was active in case of the ceramics.

Now, in case of ceramics actually increase in ΔK_{th} or the threshold value is typically seen with increment in the value of Kc, which means higher the fracture toughness of the ceramic component, higher will be the initiation point for the crack growth and this is particularly active when the ΔK_{th} by ΔK_c value is greater than 0.6.

The other important factor that we should keep in mind while talking about ceramics is that the m value which is the Paris exponent the value is quite high for the case of ceramics, the value is within 15 to 42 while for the case of metals we have seen this value lies within 2 to 4. Now such a high value of m will certainly have a dominant influence on the fatigue crack growth behavior and the overall fatigue performance of the material. So this has a significant influence in particularly the variability of the fatigue crack growth behavior and this is seen for example a 16 fold reduction in the fatigue lifetime is observed with just 7 percent increase in the stress level.

So you can imagine that if there is a certain variation in the fatigue loading condition that may lead to a significant change in the fatigue crack growth rate as well as the overall lifetime, and this FCGR, the fatigue crack growth rate dependence on ΔK is also very much higher for the case of ceramics and this is in comparison to metallic alloys which leads to a significant variability in the value of the fatigue crack growth rate as well as the fatigue lifetime which makes the fatigue life prediction in ceramics very unpredictable or unreliable.

You can see this is the da/dN versus ΔK curve for some of the ceramics and in comparison some metals are also shown, for example this yellow one is for the aluminium alloy and this one is for high strength steel where we can see this distinct regimes as 1 and 2 here and what we can see for the ceramics is that one for all we can see that first of all there is no such distinct regimes, so there are several components or several materials that has been shown like silicon carbide and alumina as well as some composites of ceramic in which the silicon carbide whiskers are there in the alumina matrix as well as Si_3N_4 and for all the cases what we see is just a straight line with a quite higher slope.

In each case you can see the slope is quite higher compared to what we are seeing for the metallic system like aluminium or even high strength steel. So this signifies that any variation in ΔK will lead to a pronounced effect on the variation in the crack growth rate and that will make the behavior quite unreliable or the prediction will be not very much accurate.

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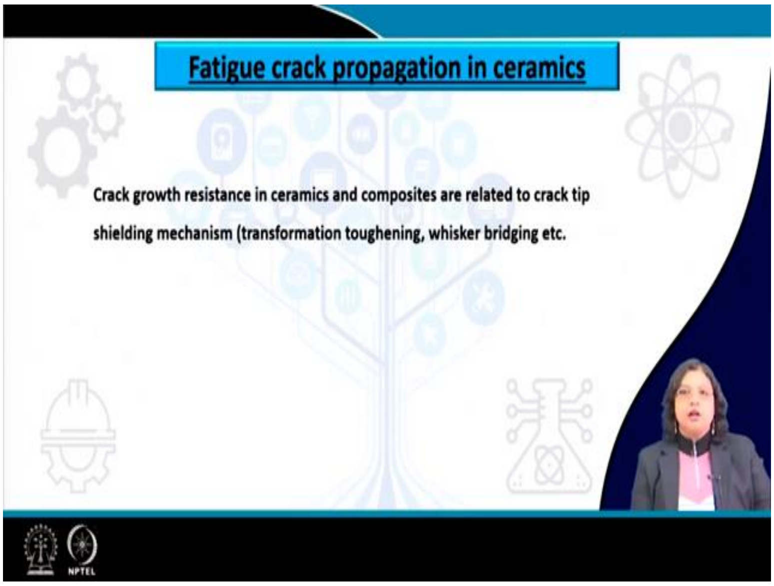

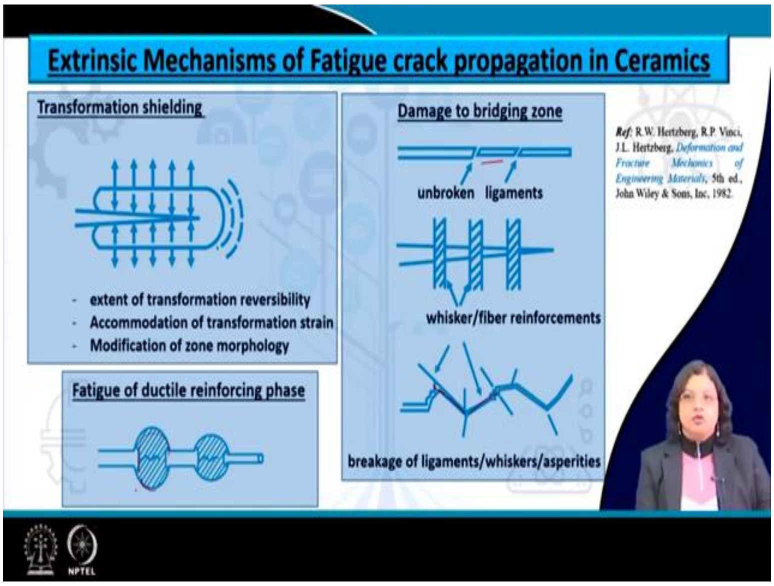

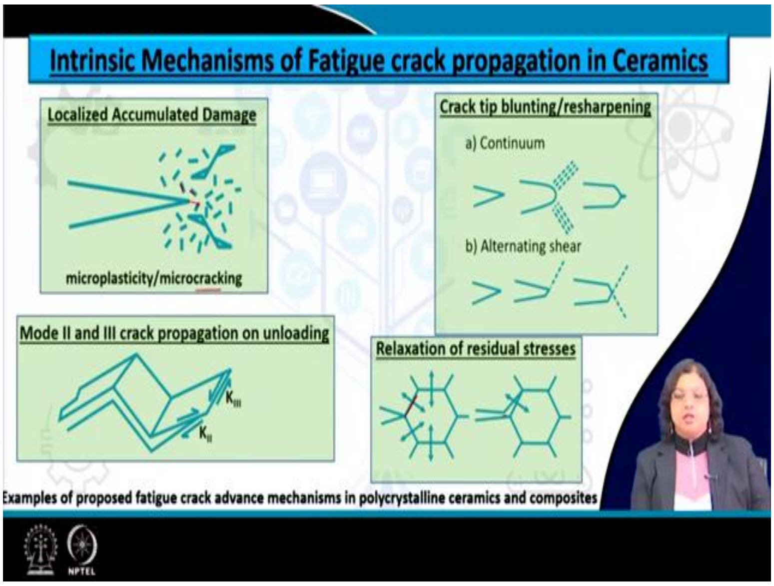

Now crack growth resistance in ceramics when we are talking about the fatigue crack growth under cyclic loading, we need to understand that in case of the ceramics or the ceramics matrix composites this crack growth is related to the crack tip shielding mechanism. The restriction to the crack growth is only through the shielding mechanism such as a transformation, toughening, whisker bridging, etc, but more or less the plasticity induced crack closure is not much seen in case of ceramics considering that this is a brittle material inherently. So these are some of the mechanisms by which the crack growth is being arrested and that dictates the fatigue crack growth rate.

The first one or the very important one is the transformation shielding which is often used for enhancing the toughness or reducing the fatigue crack growth rate for ceramic based on the composites. In this case what happens is because of the phase transformation at the tip or near to the crack weight because of the applied stress level this phase transformation uses up some of the energy for undergoing the changes from one phase to the another.

And there is often some volume change that is associated with this transformation that leads to a residual compressive stresses and which acts in enhancing the fracture toughness in general, but if you are talking about cyclic loading this also acts in closing the crack in each cycles and that will lead to an reduction in the fatigue crack growth rate.

There could be a damage to the bridging zone as well and this is particularly relevant for ceramics composites in which these fibers or whiskers can act as the restriction of the crack growth and it needs to be either broken or even there could be aspiratives which needs to be broken during the path of the crack growth and that will delay the crack growth further.

Now in case there is the reinforcing phase being ductile that may lead to some amount of plasticity ahead of the crack tip and that can lead to for the reduction in the crack growth onto the plasticity induced closure, but this is active only when we have the second phase or the reinforcing phase as a plastic material.

The intrinsic mechanisms these were mostly the extrinsic way by which we can control the fatigue crack growth rate behavior of ceramics but there could be some intrinsic mechanisms also. For example, in case there are some micro crackings that occur, now this micro cracks are nothing but the free surfaces and every time the crack interacts with these micro cracks the energy is being released to some extent and that means the crack gets blunted also and it needs to regain its energy back to lead to further growth.

Crack tip blunting and re-sharpening could also be active now depending on the mode of loading as well as the particular material that we are talking about for which case crack tip blunting is a possibility and often this is seen that there is a change in the crack growth mode from mode 2 to 3 and that means in plane shear to the anti-plane shear and that because of the change in the direction as well as a growth mode that can lead to a reduction in the fatigue crack growth rate.

In any case if the residual stress that already exist here is being released by some interfaces that can also lead to a reduction in the crack growth rate. So this are the different kind of ways by which we can have a control on the fatigue crack growth rate of ceramic materials or the composites of ceramics and based on which the fatigue performance of the material can be altered as per the service requirement.

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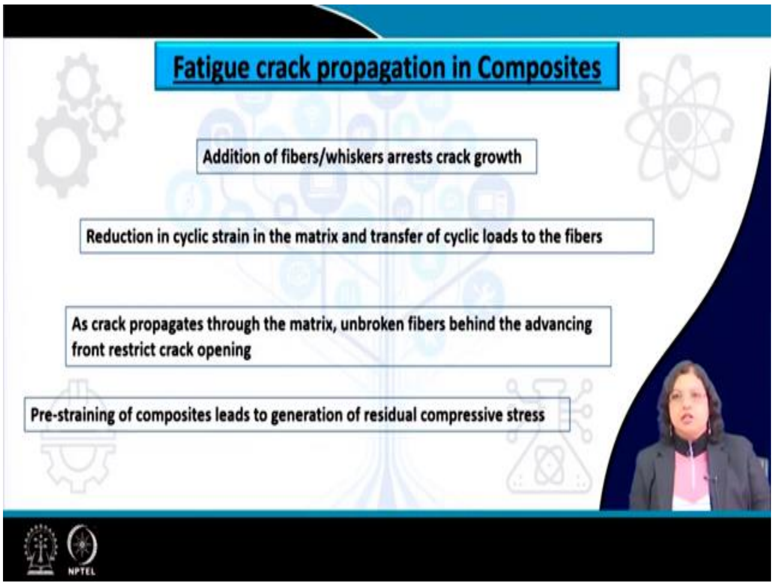

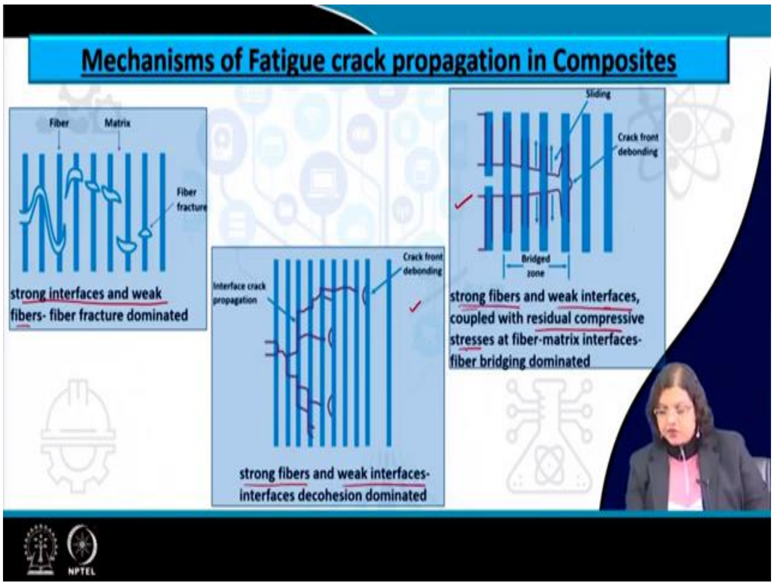

Now let us look on the fatigue crack growth propagation in case of the composite materials and in this case also as in the composites there is a matrix and a fiber phase, the second phase or the fiber or the whiskers those are actually arresting the crack growth. Reduction in cyclic strain particularly in the matrix that leads to a reduction in the transfer of the cyclic load to the fiber, so the extent of the load that is being transferred to the neighboring fibers that can get reduced if we somehow can reduce the strain that is generated in the matrix.

As the crack propagates through the matrix this unbroken fibers behind the advancing crack, so not only the fibers or the whiskers act in bridging but also the one which is left behind the crack front that also restrict the crack tip from reopening and that also acts in closing the crack or delaying the crack growth or reducing the fatigue crack growth rate in general.

Pre-straining of the composites is another mechanism that actually leads to generation of residual compressive stress and once again residual compressive stress is actually good news because it leads to closure of the crack and that can enhance the fatigue life in general and reduce the fatigue crack growth rate.

So, these are some of the mechanisms which are used for the case of composites to engineer the fatigue crack growth rate behavior. Particularly, the interface between the matrix and the fiber are very important and they played a lead role in controlling the fatigue crack growth rate behavior.

So in this case we see a strong interface and weak fibers, so that means it is difficult for the interface to be debonded and that may affect the fatigue crack growth behavior in some way. On the other cases, in case we have the strong fibers as well as weak interfaces, in this case interfaces are very easy to be debonded whereas the fibers are really strong so the crack has to find an alternate mechanism to deviate the fiber or to cut off the fiber applying higher and higher amount of stress intensity factor to propagate the crack.

This one here shows again the strong fibers but in this case there are the weak interfaces, but with residual compressive stresses. So essentially this condition as well as the one here at the end is having the same kind of fiber and interface combination, but the third one is having the residual compressive stresses which acts as a beneficial mode in closing the crack and thereby reducing the fatigue crack growth rate.

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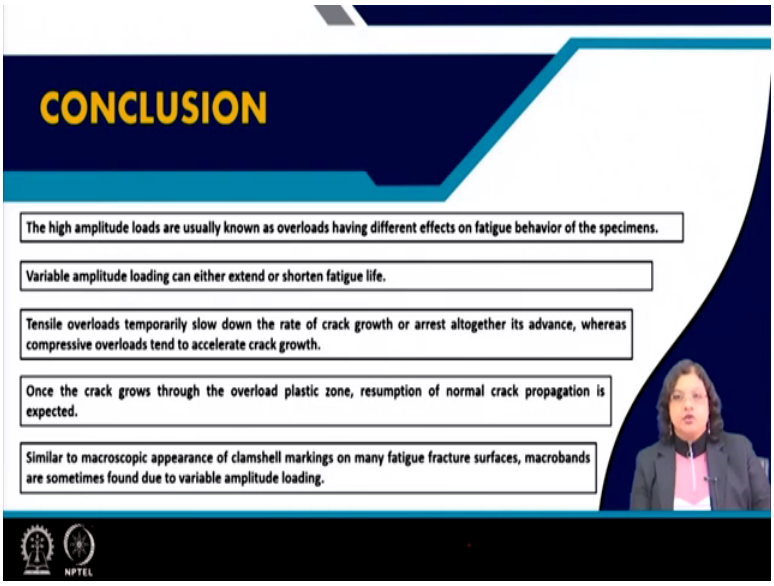

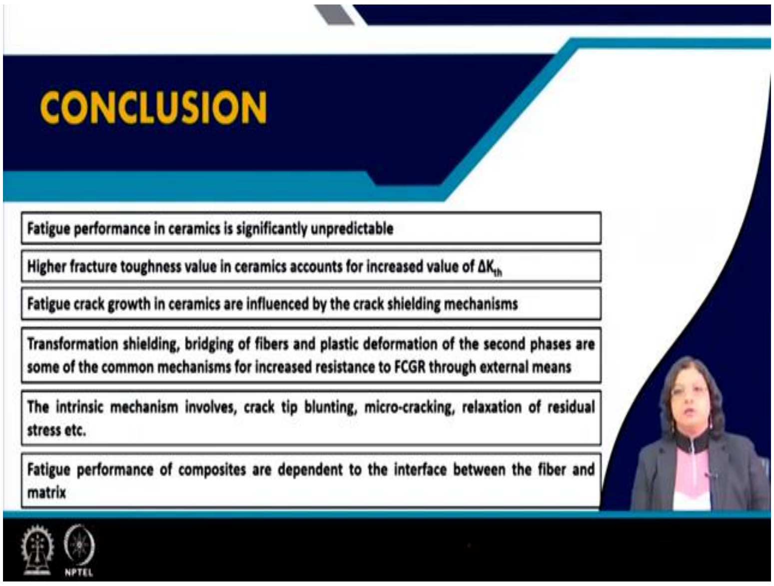

So in conclusion we can say that the high amplitude loads are usually known as overloads and they have different effects on the fatigue behavior of the specimen. Particularly, in case of variable amplitude loading can either extend or shorten the fatigue life particularly, if you are talking about the tensile overload then because of the presence of the plastic zone size of significant amount that can temporarily slow down the crack growth rate or it may arrest it altogether, whereas the compressive overload on the other hand tend to accelerate the crack growth.

Once the crack grows through the overload plastic zone then the normal crack growth rate will be resumed again and similar to the macroscopic appearance like a clamshell markings and such kind of loading patterns can be seen on the fracture surface itself like macrobands and in case there is an overload a stretch of this band can also be seen which signifies that there has been a certain extent of loading for a certain period of time.

Now, in case of ceramics we have seen that fatigue performance is significantly unpredictable or unreliable we can say and higher fracture toughness values in ceramics are related to higher ΔK_{th} value as well and fatigue crack growth in ceramics are influenced by several crack shielding mechanisms such as the transformation shielding, bridging of the fibers, plastic deformation of the second phase if that is an option.

Now these are the external means by which the fatigue crack growth rate or in case of ceramics can be influenced and in case of the intrinsic mechanism there are the crack tip blunting, because of micro cracking or relaxation or residual stresses are some of the ways by which the fatigue crack growth rate can be reduced in case of the ceramics.

For the case of composites fatigue performance are dependent particularly to the interface between the fiber and the matrix and depending on whether the fibers are strong or weak and particularly the interface is strong or weak that dictates the fatigue crack growth rate behavior and presence of the residual compressive stress is often found beneficial and that enhances the fatigue performance significantly in case of the composites. So following other references used for this lecture, thank you very much.