Mechanical Behavior of Materials
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Module No # 12
Lecture No # 58
Fracture Mechanics – X

Hello I am professor S.Sankaran in the department of Metallurgical and materials engineering.

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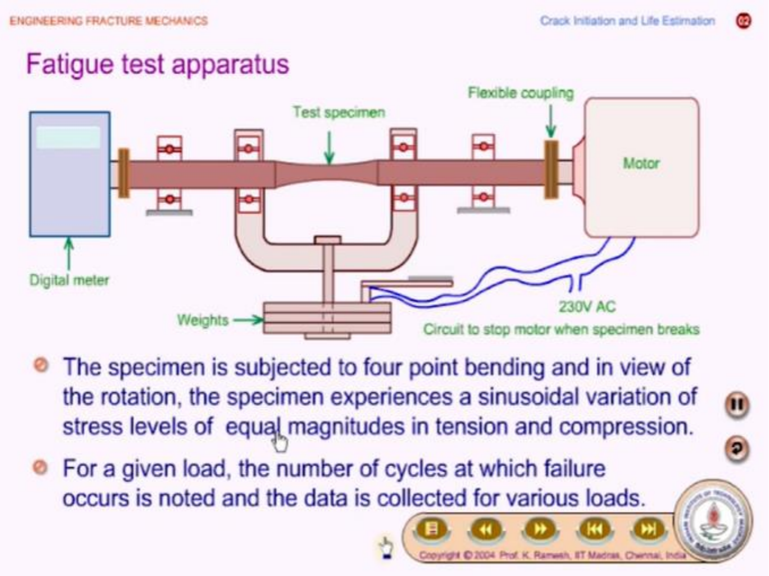

Rotations and this specimen is being you know held by the crips as well as the load, lot of weights depending upon test conditions. The specimen is subjected to four points bending and in view of the rotation the specimen experiences a sinusoidal variation of stress level of equal magnitudes in tension and compression. So, you have to remember in fatigue loading since it is called the cyclic loading.

So, the load given in one direction tension will be completely reversed to the other direction that is why it is given this tyπcal you know fatigue test is done by tension compression mode. For a given load the number of cycles at which the failure occurs is noted and the data is collected for various loads.

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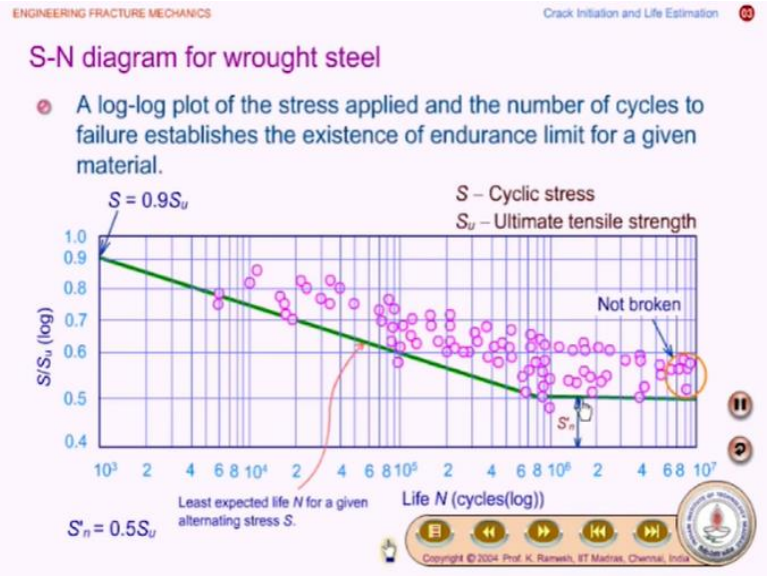

So that is one very basic way of recording the fatigue data, a log plot of the stress applied and the number of cycles of failure establishes the existence of endurance limit for a given material. So, this is a stress versus number of cycles of failure which is plotted in a log-log plot and here you see that the material after certain stress levels the material does not fail. So this stress is called the endurance limit of the material.

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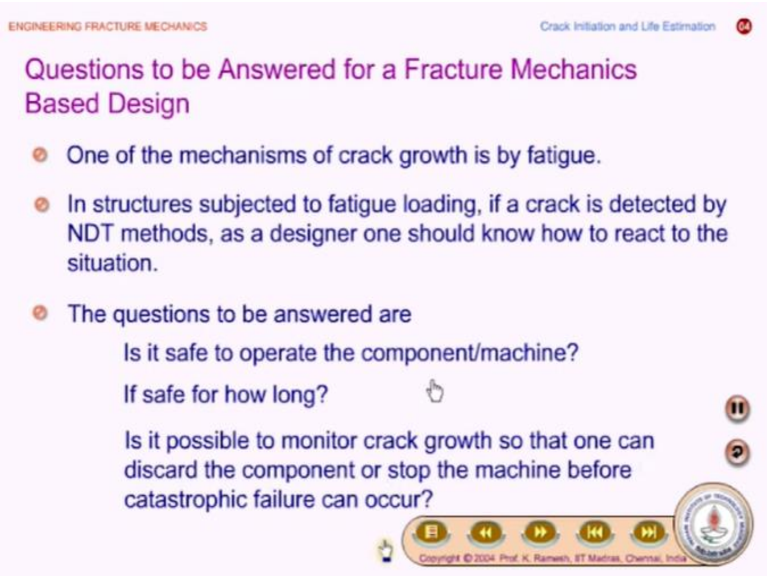

We will look at that aspect little in the next chapter in much more details but here we will connect to only fracture mechanics. Question to be answered for a fracture mechanics-based design one of the mechanisms of crack growth is by fatigue. In structures subjected to fatigue loading if a crack is detected by NDT methods as a designer one should know how to react the situation.

The questions to the answered are is it safe to operate the component or machine if the safe is saved for how long. Is it possible to monitor the crack growth so that one can discard the component or stop the machine before catastrophic failure can occur.

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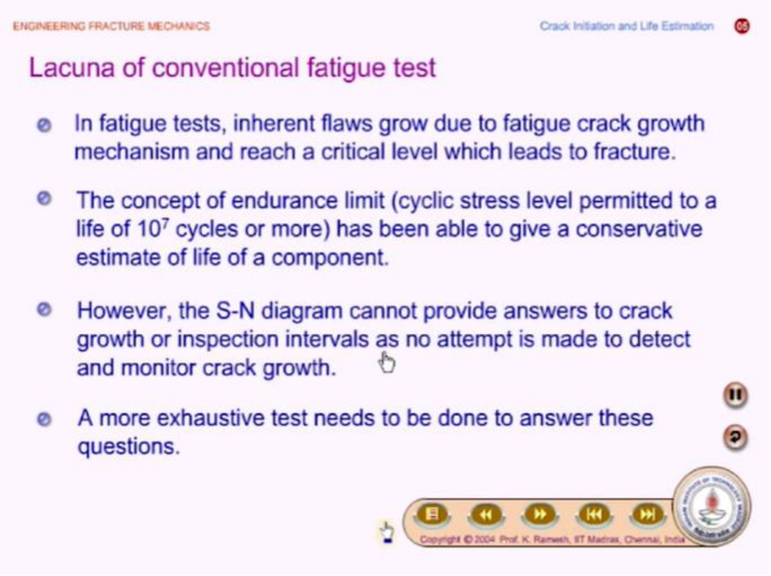

So, these are all crucial questions and what are the limitations in fatigue test inherent flaws grow due to fatigue growth mechanism and reach a critical level which leads to fracture. The concept of endurance limit cyclic stress level permitted to a life of 10^7 cycles or more has been able to give a conservative estimate of life of component. So, any component which subjected a cyclic stress which can endorse this kind of this many numbers of cycles than that is a bench mark so far but modern designs do not take this value which his much more stringent value but still this was one stage it was considered as a endurances limit life. However, the S-N diagram cannot provide answers to crack growth or inspection intervals as no attempt is made to detect or monitor the criteria. A more exhaustive test methods I mean test needs to be done to answer these difficult questions.

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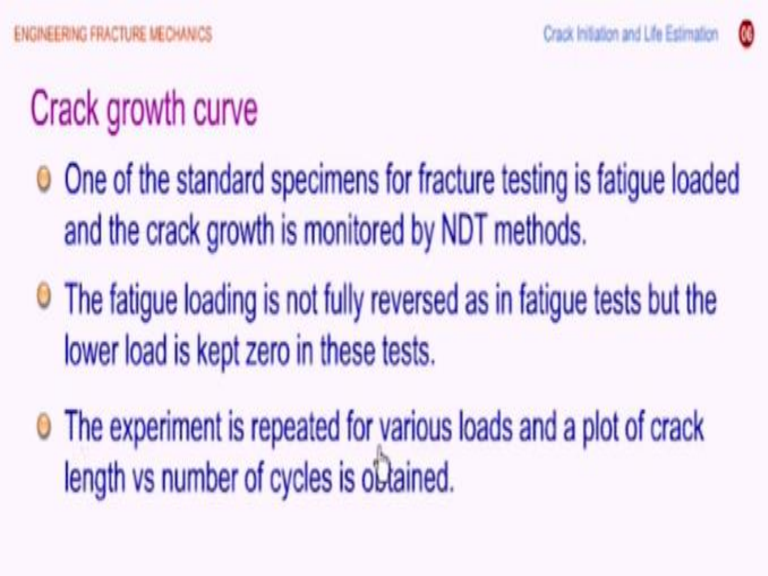

One of the standard specimens for fracture testing is fatigue loaded and the crack growth is monitored by NDT methods. The fatigue loading is not fully reversed as in fatigue test but the lower load is kept 0 in these tests. We are now talking about a crack growth curve how it is normally done? The experiment is repeated for various loads and a plot of crack length versus number of cycles is obtained.

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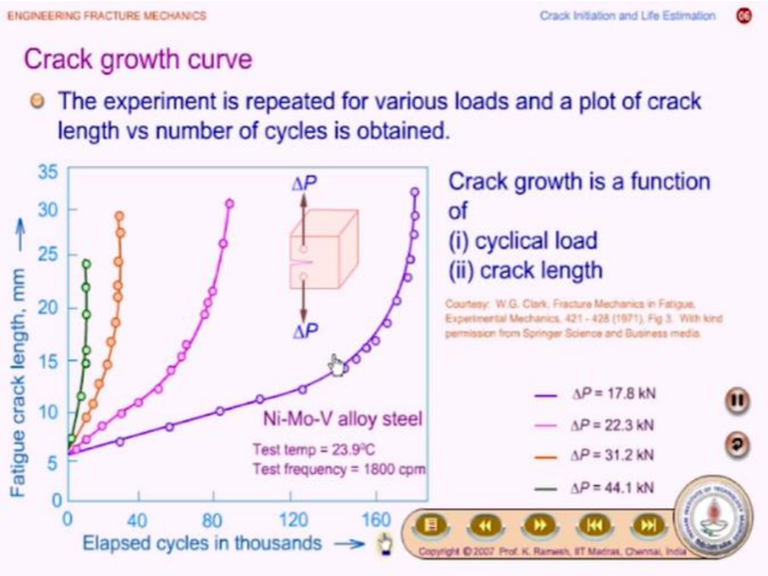

and the plot looks like this a fatigue crack length in mm versus elapsed cycles in thousands. So, you can see that such a, very less number of cycle the specimen failed that means you can see the load Δ P is very high load 44.1 kilo Newton. So, as you keep on you know reducing the load, the life also keep on increasing. And this is tyπcally for a Ni-Mo-V alloy steel, tested at 23.9° centigrade test frequency is 1800 cycle per minute.

And the crack growth is a function of cyclical load and a crack length so this is what it is a tyπcal curve. The point is as we keep on changing the load you will get n number of curves for a given material. So this is something we have to think about it.

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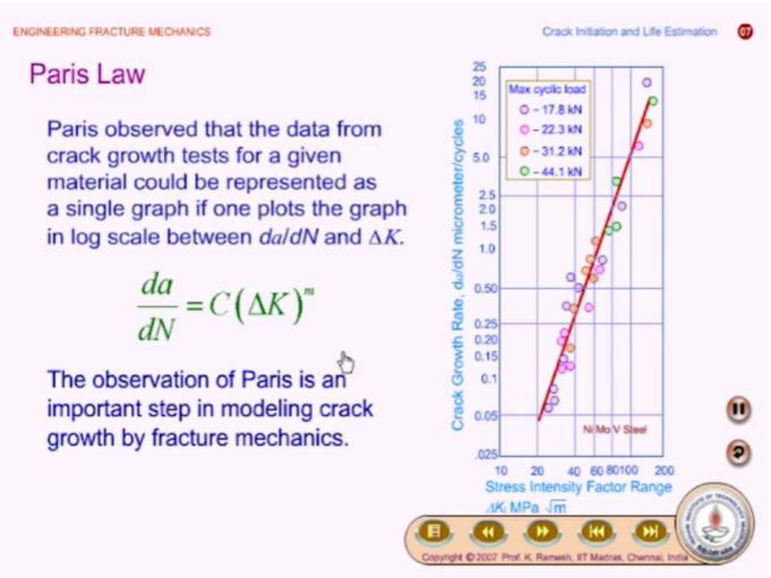

So what Paris has done? Paris observed that the data from the crack growth test for a given material could be represented as a single graph, if one plots the graph in log scale between da/d N between ΔK. So, what you see here in this plot is crack growth rate da/d N that is a micrometer per cycles and versus the stress intensity factor range that is the ΔK MPa√m it is a straight line. So, this is for again different loads and this the $da/dN = C(\Delta K)^m$. So, this is equation is called a Paris law the observation of Paris in an important step in modeling crack growth by fractional. So, it is a huge jump to understand the crack growth behavior that is quite obvious. Because if you look at the previous slide for a given material you can generate n numbers of crack growth curves. So, it will be then you know too difficult to handle such a huge data for a given material and it will be very difficult for designer to engage them. So, the Paris law gives a very important step in modeling the crack growth behavior that way.

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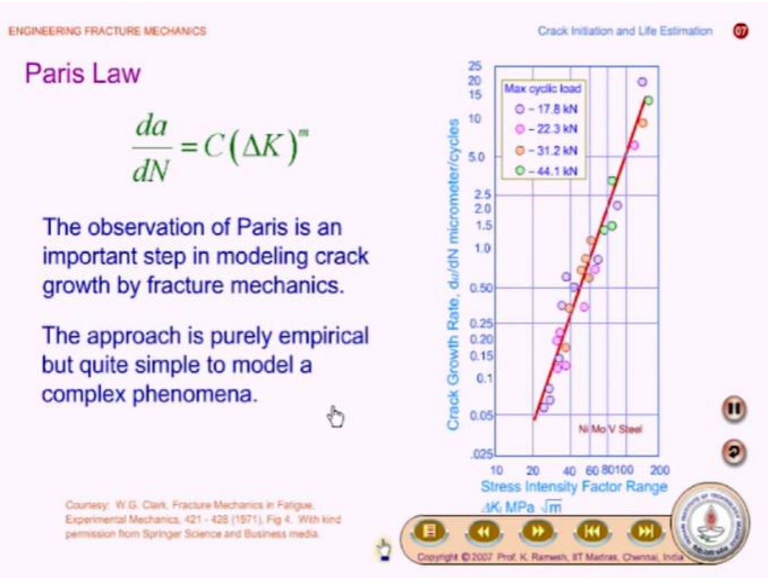

So now let us look at the details the approach is purely emπrical because it is a curve fatigue but then it is very intelligently done. But quite simple to model a complex phenomenon, very complex.

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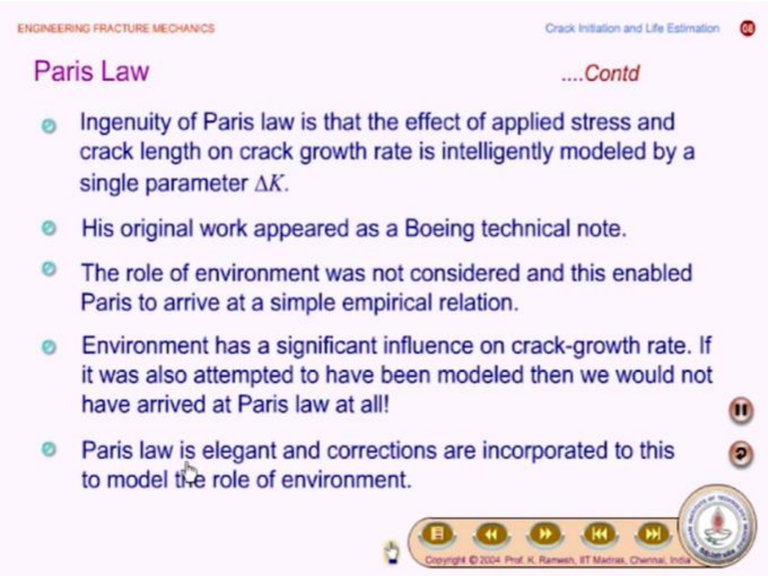

And the ingenuity of a Paris law is that the effect of applied stress and crack length on crack growth rate is intelligently modeled by a single parameter ΔK, that is very important point to note. This original work appeared as a Boeing technical note. The role of environmental was not considered and this enable Paris to arrive at a simple emπrical relation. Environmental had got a significant influence on a crack growth rate. If it was also attempted to have been modeled then you would not have arrived at Paris law at all because that kind of significant the environment has Paris law is elegant and connections are incorporated to this model the role of environment later.

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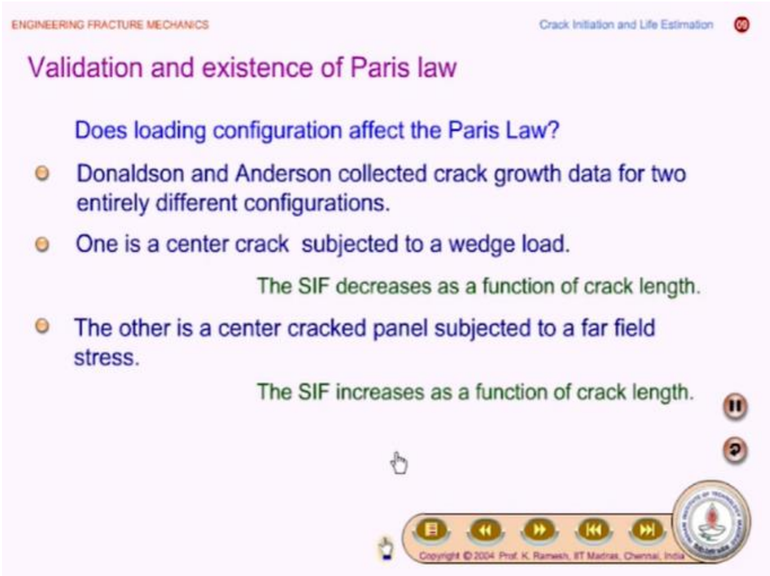

That was developed of Paris law. How was this Paris law validated because people raised a lot of questions before they applied to use this in a design aspect and then there are some verifications does loading configurations affect the Paris law that is the question. How do we that this how do we test? Donaldson and Anderson collected crack growth data for two entirely different configuration one is a center crack subjected to a ridge load where the stress intensity factor decreases as a function of crack length and the other is a central crack panel subjected to a far field stress where the stress intensity factor increases as a function of crack length. So, there are two extreme cases then they have applied this.

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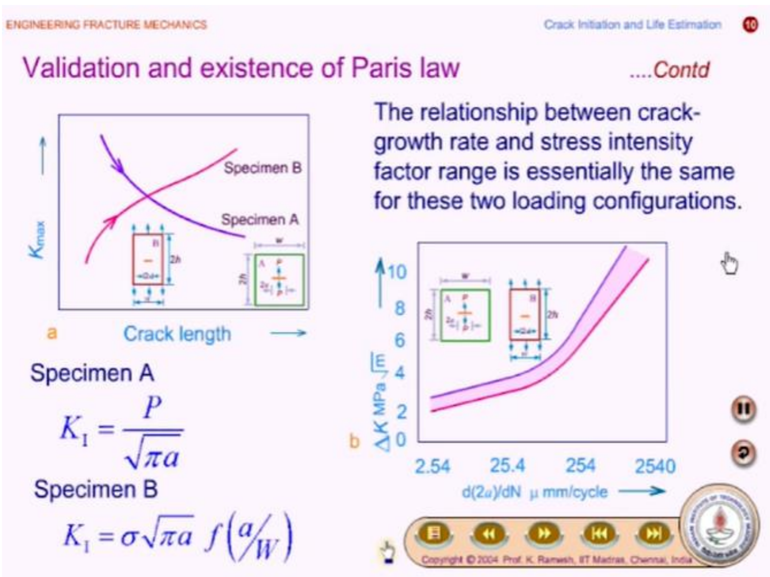

They have applied this Paris law to their experiment and then see what they get it too so that they can validate it. So, for a specimen they have taken K_{max} versus crack length which is given by this K $_1$ = P/√πa, it goes like this. And specimen B is K $_1$ = σ √π a f(a/w), which is goes like this. So, in one case just K_{max} decreases in other case K_{max} increases. But both of them, both the data is now for these two different specimens are plotted in this fashion ΔK versus da/dN. The relationship between the crack growth rate and the stress intensity factor range is essentially the same for these two loading configurations. So, that means these two different specimen configurations what you see here is the almost a similar time. So that means the Paris law is valid even for different the specimen loading card history.

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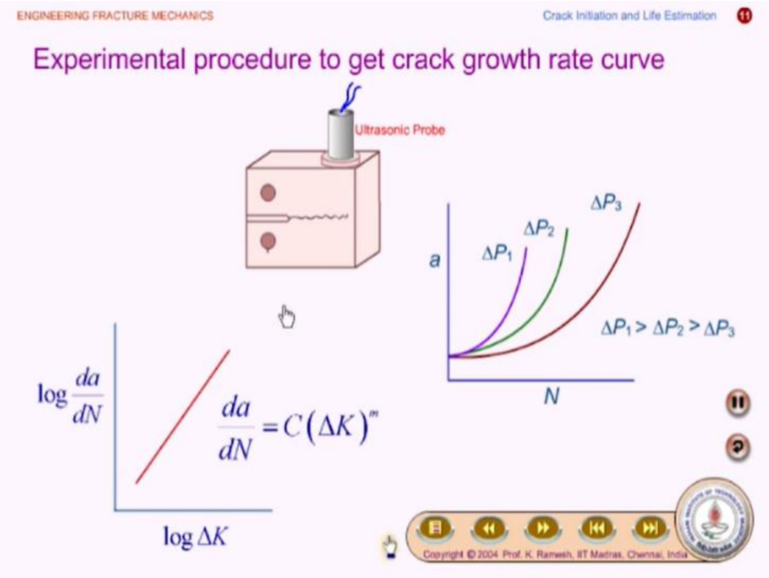

So how to get the experimental procedure to get the crack growth rate curve. So, this is a CT specimen and then this is and NDT probe which will monitor the growing crack and then a versus end plot are regenerated and for different loads and then you plot the log da/d N versus log K then you get a straight line. So that is then you obtain the material constant C and m.

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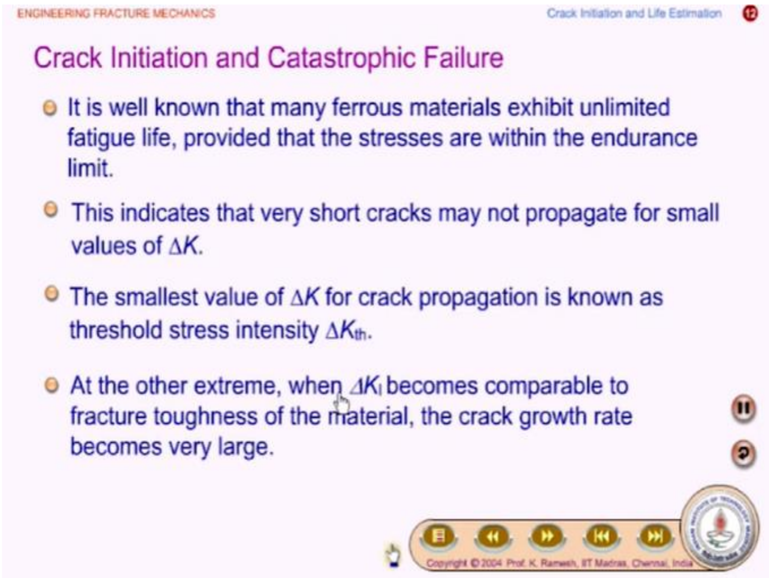

So this is how different it is well known many famous materials exhibit unlimited fatigue life provided that the stresses are within the endurance limit. This indicates that very short cracks may not propagate for small values of ΔK the smallest value of ΔK for a crack propagation is known as threshold stress intensity factor very important parameter in a fracture mechanism as well as fatigue. It is a characteristic of material, and it has got lot of influence on the fatigue behavior as well as the fracture behavior. We will look at that in detail coming slides at the other extreme when ΔK, becomes comparable to the fracture toughness of the material the crack growth rate becomes very large. So, this is also we will see in the crack growth curve characterization.

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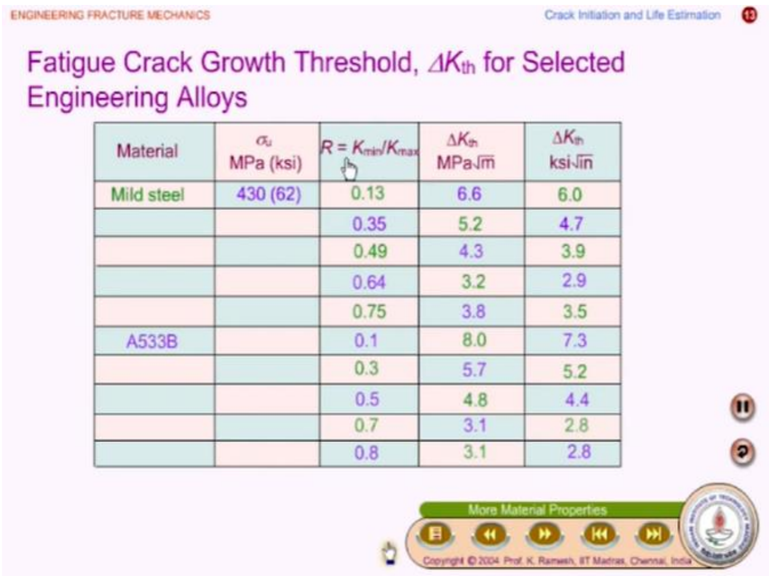

Material	σ_u MPa (ksi)	$R = K_{min}/K_{max}$	ΔK_{th} MPa$\sqrt{m}$	ΔK_{th} ksi$\sqrt{in}$
Mild steel	430 (62)	0.13	6.6	6.0
		0.35	5.2	4.7
		0.49	4.3	3.9
		0.64	3.2	2.9
		0.75	3.8	3.5
A533B		0.1	8.0	7.3
		0.3	5.7	5.2
		0.5	4.8	4.4
		0.7	3.1	2.8
		0.8	3.1	2.8

Fatigue crack growth threshold ΔKth for selected engineering alloys you can see that mild steel and this is aluminum alloy you can see that delta K threshold is 6.6 MPa mild steel and this is for other alloys given. This is an R value this is a K_{min}/K_{max}, this R is different from what we have seen in resistance in fracture mechanics

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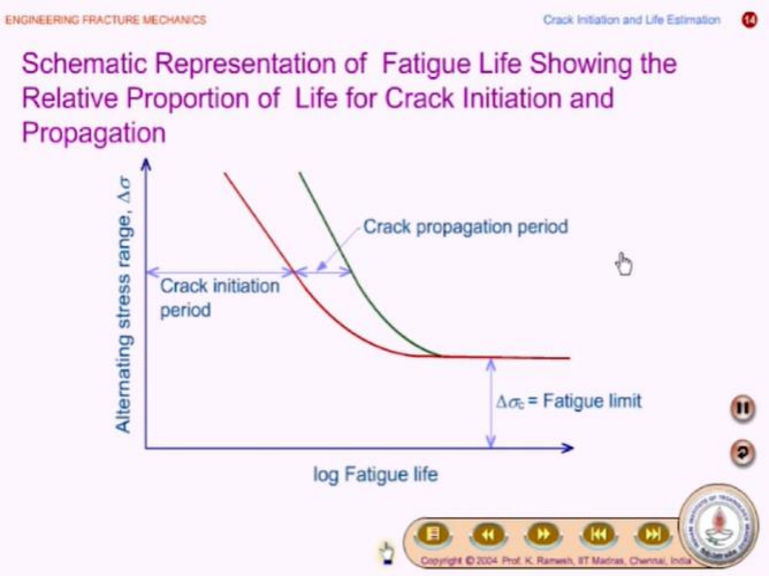

And now what we will is schematic representation of fatigue life as show in the relative proportion of life for a crack initiation and propagation. This plot I showed in the introduction slide, I mean in the introduction chapter, where you know the stress-versus life is plotted, the crack initiation period is much larger as compared to crack propagation period. First all we have to recognize that there are two stages are two components to the life one is the initiation period and another is propagation period. So this is very important this is fatigue limit.

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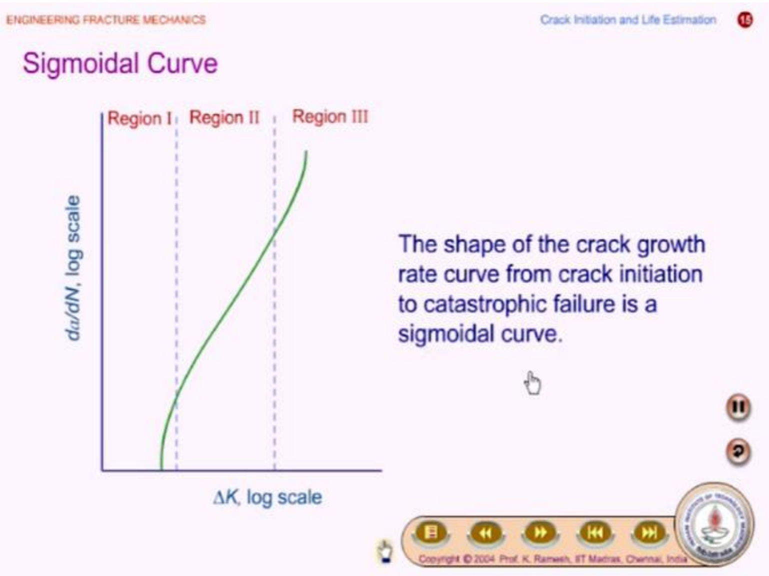

Sigmoid curve so this is typical fatigue crack growth curve and d a/d N versus ΔK and log scale you can see. This curve is being you know divided into three regions for it is geometry you can see that. This is ΔK threshold and this is the region 1 and the region 2 is kind of a straight line this is a crack growth region 2 and region 3. The shape of the crack growth rate curve from the crack initiation to catastrophic failure is a sigmoidal curve very important curve for engineering and design.

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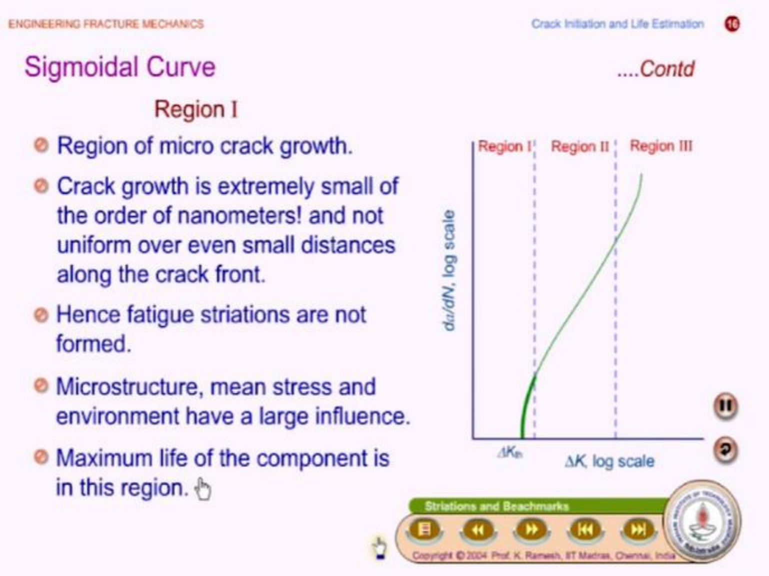

So, the region 1 is characteristic of the following, this is a region for a micro crack growth or you can always see that this threshold, that means this crack initiation phase. So, all the cracks will be in the micron level crack growth is extremely small of the order of nanometer and not uniform over even small distances along the crack front. Hence the fatigue striations are not formed. Microstructure, means stress and environment have large influence in this region, very important point to note. Maximum life of the component is in this region, so the maximum life is in the crack initiation. That is what we have seen in the couple of slides back. So maximum life of the component is spent to reach the ΔK threshold that is important point to note.

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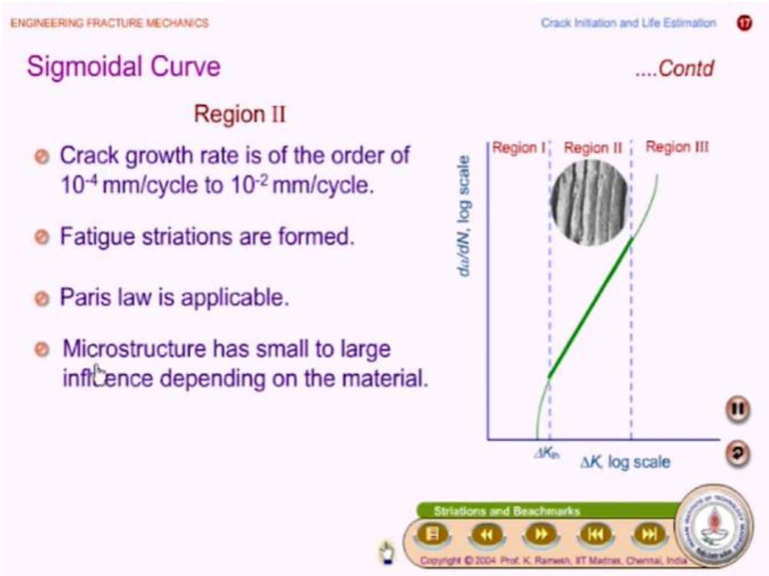

And now the region 2 is so called the Paris region, crack growth region rate is of the order of 10^{-4} mm/cycle to 10^{-2} mm/cycle, this is a rate and Fatigue striations are formed in this stage so it is shown here you can see that fatigue striations. Paris law is applicable only in this region because that is straight line. Microstructure has small to large influence depending upon the material. So, you cannot say that it is not having any, I mean micro structure do not have any role to play we cannot say that but depending upon the material either it as a small or a large influence that is what we have to understand.

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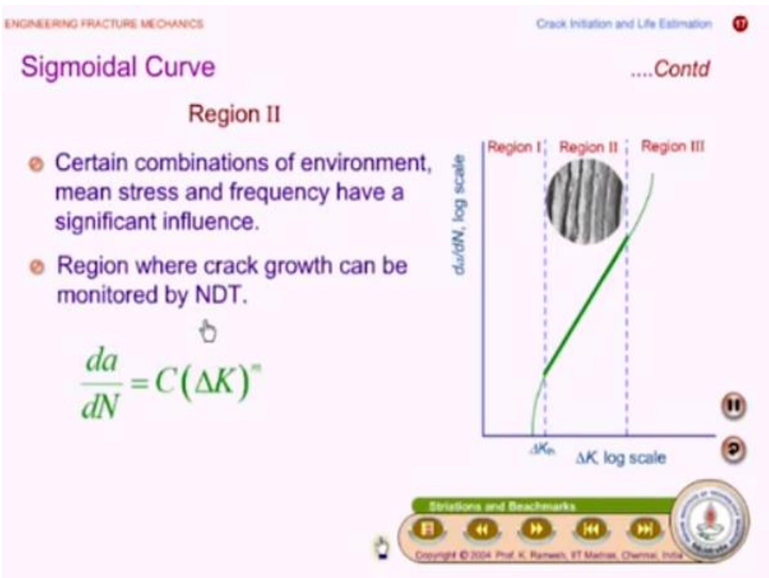

Certain combinations of environment mean stress and frequency have a significant influence and this region where the crack rate can be monitored by NDT because it is a steady state growth so it can follow the Paris law and then it can be nicely monitored by an NDT technique.

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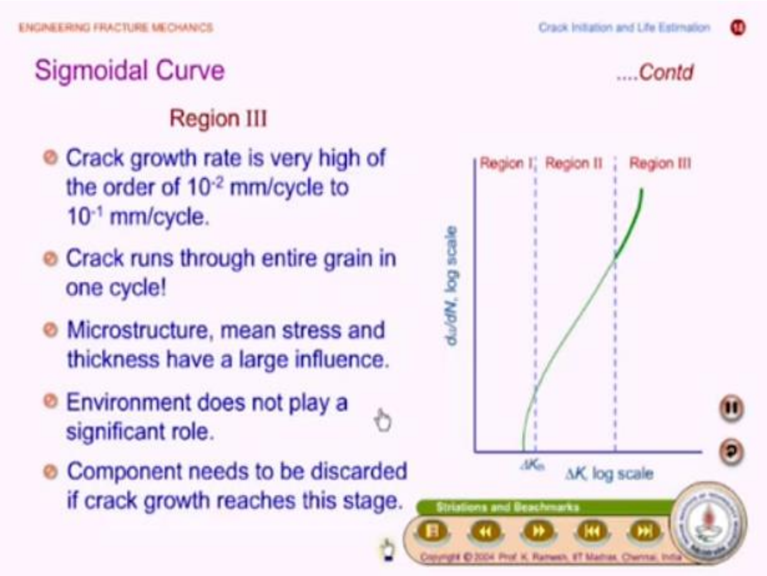

Region 3 the crack growth rate is very high of the order of 10^{-2} mm/cycle to 10^{-1} mm/cycle. Crack runs through entire grain 1 cycle. Microstructure, means stress and thickness have large influence and environment does not play a significant role in this region as compared the region 1 this is completely opposite. Component needs to be discarded if the crack growth reaches this stage. So, it is almost dangerous situation so that is the where you have to decide.

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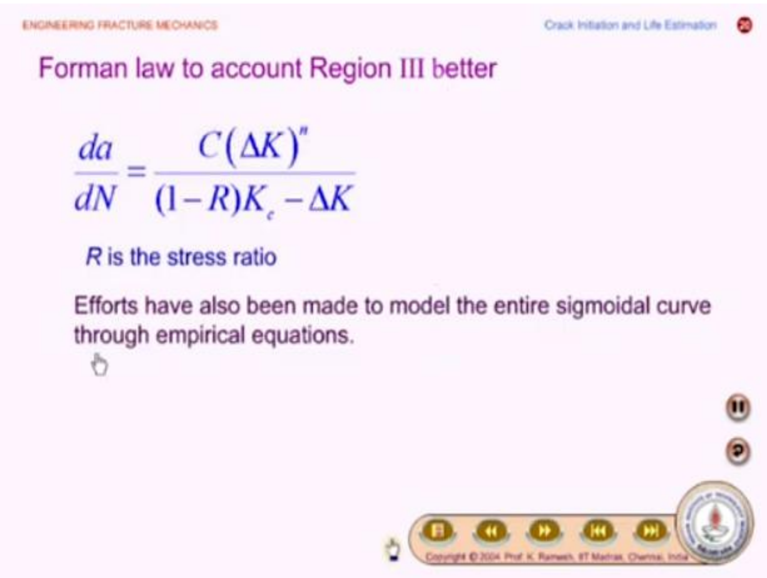

So, there are several other models to improve upon the Paris region proposed by several researchers some of them I am just giving the just for the information sake not to get into the detail and similarly there are if you look at the region that was the region 1 and this is given by other scientist Forman Law for the region 3, d a / d N is given.

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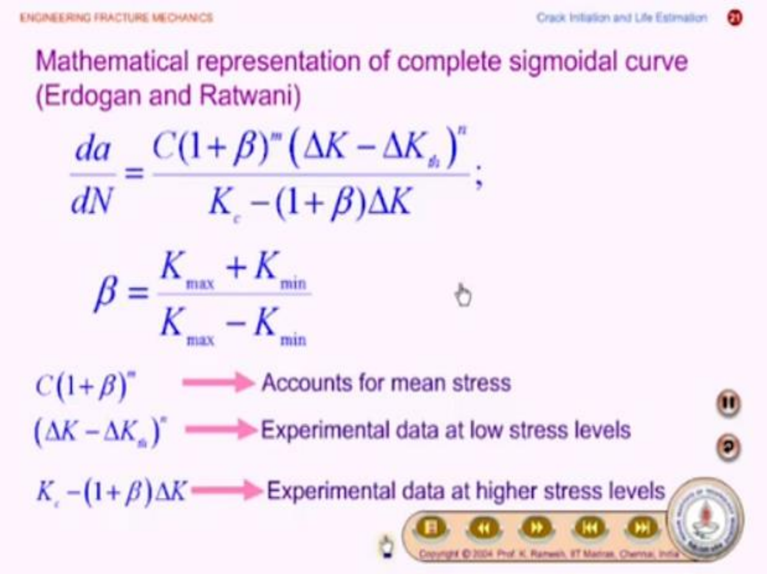

And then later you will see that entire sigmoidal curve is given by other people for this kind of an expression. And we are not going to discuss all of them, I will just give you an expression that the Paris law has been developed and then modified and then they have been used at different, I mean they have been used effectively to monitor the crack growth behavior. That is the information I want to convey.

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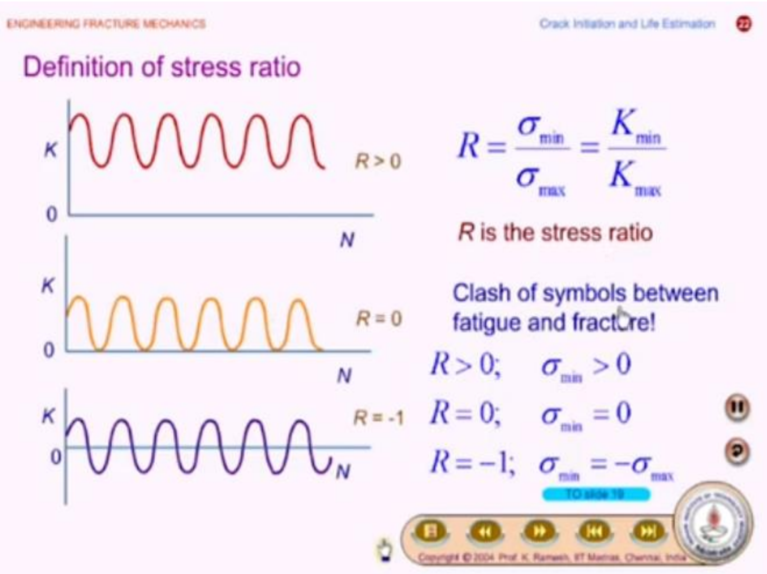

So the next important topic we are going to is stress ratio that is R. I showed in the table K_{min}/K_{max} that is called a stress ratio, K versus number of cycles. So normally a fatigue loading is in this cycle, in this particular case R is greater than 0. R is defined as $\sigma_{minimum} / \sigma_{max}$ which is $K_{minimum} / K_{max}$. R is called stress ratio and then you have the second type of scenario where R = 0, where the cycle K versus N plot will look like this.

There is another scenario R = -1 then the positive and negative values of A will go through in the cycle as a function of number of cycle and clash of cycles between the fatigue and fracture. So that is what I just mentioned or in a fracture is resistance here it is a stress ratio and this is for R >0, R = 0 and R = – 1, under which they are fatigue testing can be done with the different stress ratio values.

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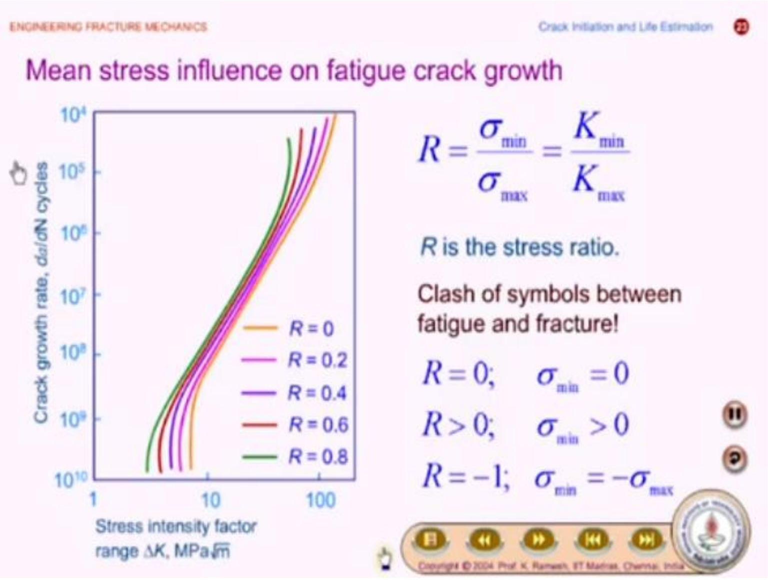

The mean stress influence on fatigue crack growth is given in this plot. So, you keep just changing the value of R then you are essentially looking at the mean stress influence and what you will see here is? The curve keep on moving to the left hand side but not significantly important in this Paris region but it has got some influence again on the rigidity. So, what we can see here is the mean stress influence is significantly happening in the region one of the sigmoidal curve under region 3. That is how you should take it.

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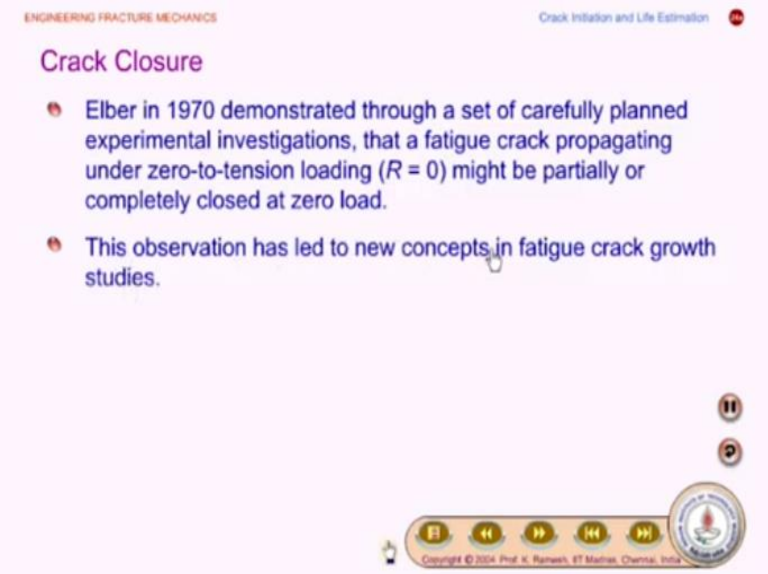

Now, very important aspect of fracture mechanics as well as fatigue is the crack closure so we have been talking about crack growth and its stability and where it reaches a catastrophic limit and all that. But we should also now talk about crack closure this is also very important idea which will influence on the fatigue life as well as fracture mechanics analysis. Elber in 1970 demonstrated through a set of carefully planned and experiment investigations that fatigue crack propagating under the 0 to tension loading that is R = 0 might be partially or completely closed at 0 load. This observation has led to a new concept in fatigue crack loads studies, very important idea.

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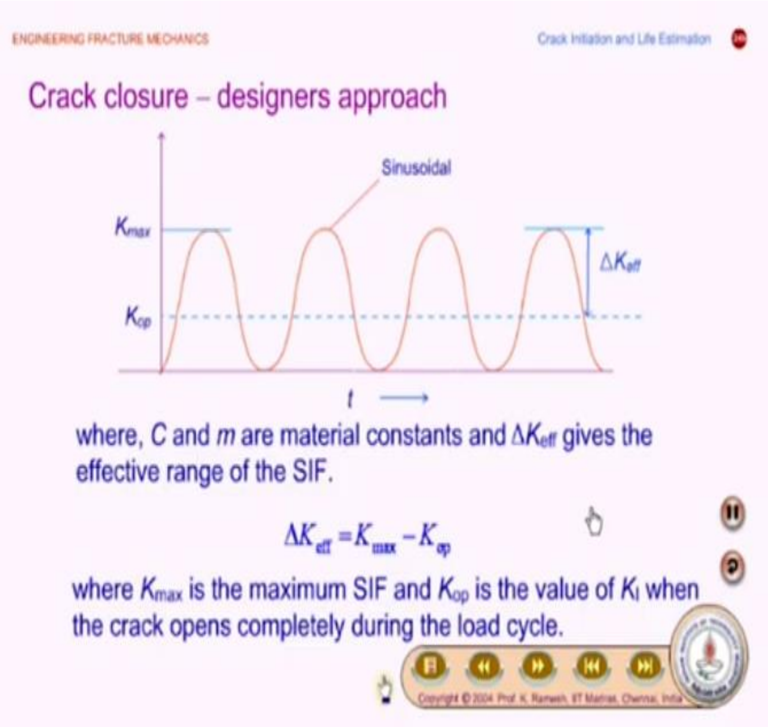

So, how do you understand this? to account for a crack closure designer employ a modified Paris law. Which is as follows, $da/dN = C(\Delta K_{effective})^m$, So ΔK is being now replaced by $\Delta K_{effective}$. So, how do we understand $\Delta K_{effective}$. Suppose, this is K versus T plot so this is a cycle sigmoidal cycle. So the moment you know the stress reaches this level that means the crack start opening then it close further and then it comes back. So, when it comes back again it will close right then it will open, reaches maximum close again it is opened reaches maximum close something like that. So, where C and m are material constants and $\Delta K_{effective}$ gives the effective range of stress intensity factor. So, $\Delta K_{effective}$ is $K_{max} - K_{opening}$, so this distance is the $\Delta K_{effective}$, where K_{max} is the maximum stress intensity factor and $K_{opening}$ is the value of K_1, when the crack opens completely during the load cycle. So, this is how we have to understand, this designers approach of crack closure.

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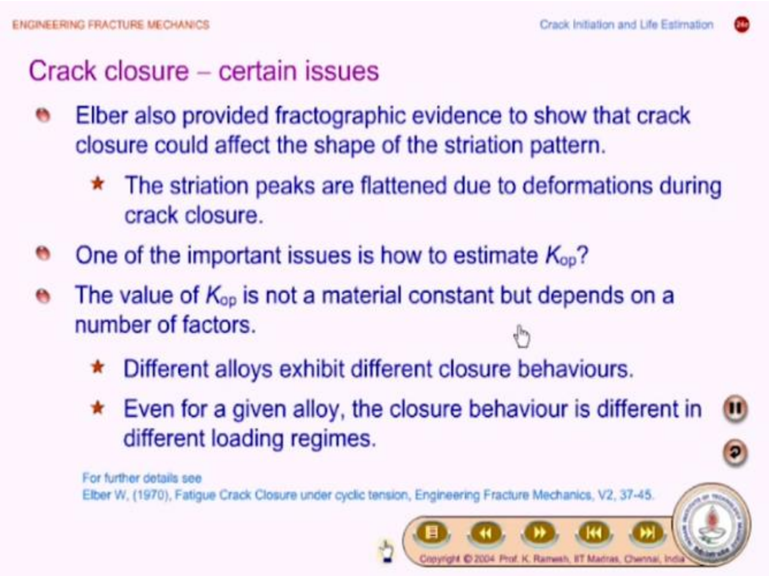

Elber also provided fractographic evidence to show that crack closure could affect the shape of the striation pattern. This striation speeds are pattered due to deformations during crack closure. One of the important issues is so how to estimate K_{open}. The value of $K_{opening}$ is not a material constant but depends on the number of factors, different alloy exhibit different emotional behaviors. Even for a given alloy the closest behavior is different at different loading regions. So, these are all some limitations for this proposals nevertheless it was practiced with some limited experimental conditions.

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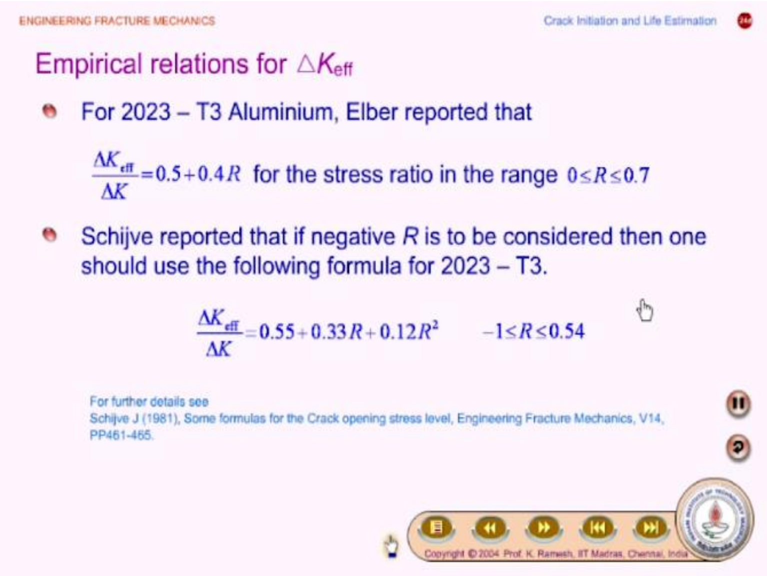

So there are some empirical relations given for engineering alloys for example T 3 aluminum, Elber reported that $\Delta K_{effective} / \Delta K = 0.5 + 0.4$ R for the stress ratio range of 0 to 0.7. The other people have also given similar empirical relations for the crack closure study.

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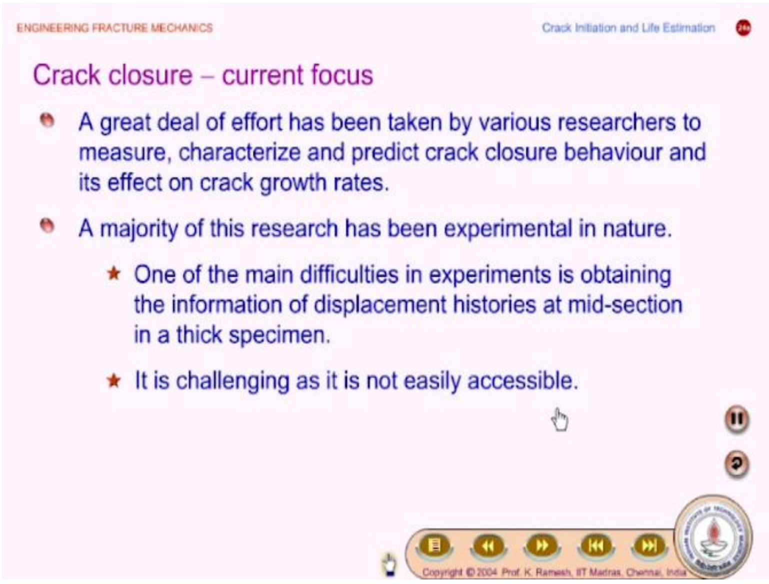

So let us look at what is that current focus a great deal of effect has been taken by various researches to measure characterize and predict crack closure behavior and it is effect on the crack growth rates. The majority of this research has been experimentally in nature one of the main difficulties in experiment is obtained the information of displacement histories at mid-section in a thick specimen. It is challenging as it is not easily acceptable, it is one problem.

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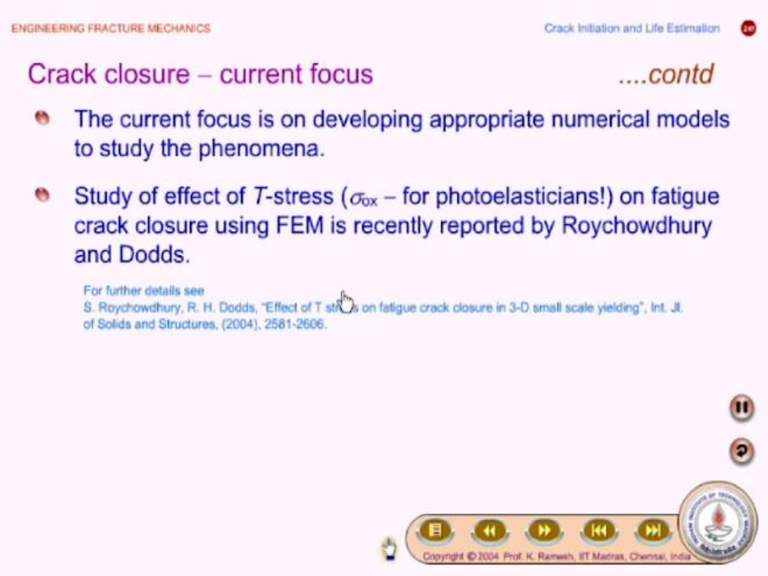

So the current focus in on appropriate numeric models to study the phenomenon. Study of effect of T-stress that is a σ o x for the this is a terminology for the photoelasticity. T- stress on fatigue crack closure using FEM is recently reported by Rouchowdhury and Dodds. So, this is something currently it is going on in the recent times.

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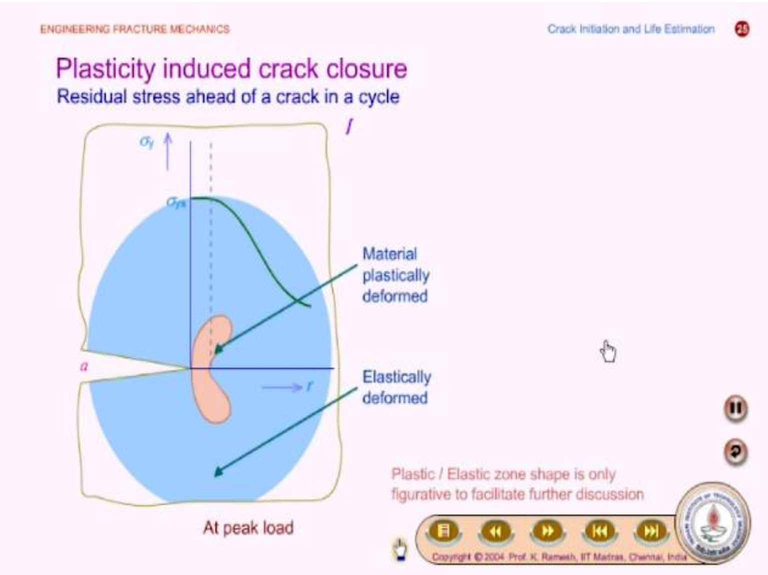

And then we will now look at types of crack closure. One important classification is plasticity induced crack closure, where you are going to look at the residual stress ahead of the crack in a cycle. So, what you are going to see here is you see the crack tip and there is a plastic zone. This is a material plastically deformed and surrounding region what is given is elastically deform because of this two, you know deferent zone is typically residual stress is generated in this region.

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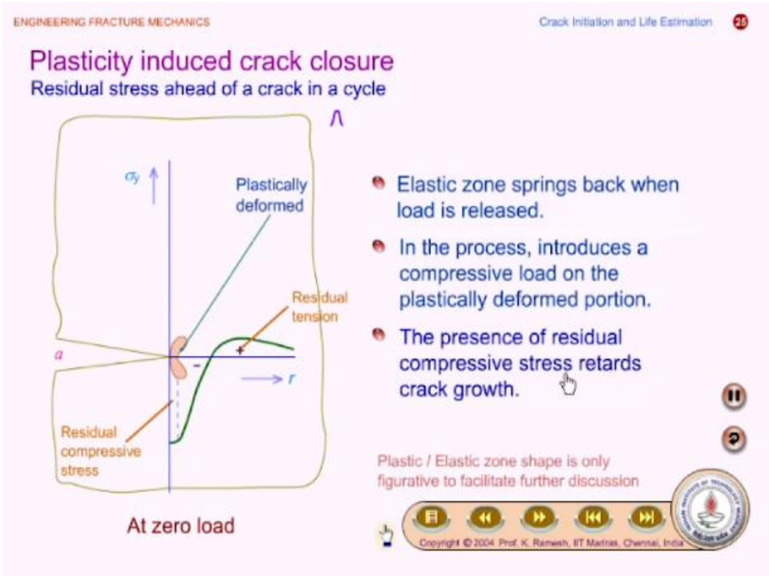

Elastic zone springs back when the load is released in the process introduces the compressive load on the plastically deformed portion. So, this is well understood and because of that you get you know this kind of a residual pattern generated. A residual compressive stress is here and this is a residual tension. So, you see that this kind of residual pattern and this, the presence of residual compressive stress retards the crack. So, this is the ultimate idea the sense the plastic zone ahead of the crack tip facilities is retarding the crack growt. So that is one very important idea so this also will you know will induce this plasticity also will induce the crack closure that is what we discuss here.

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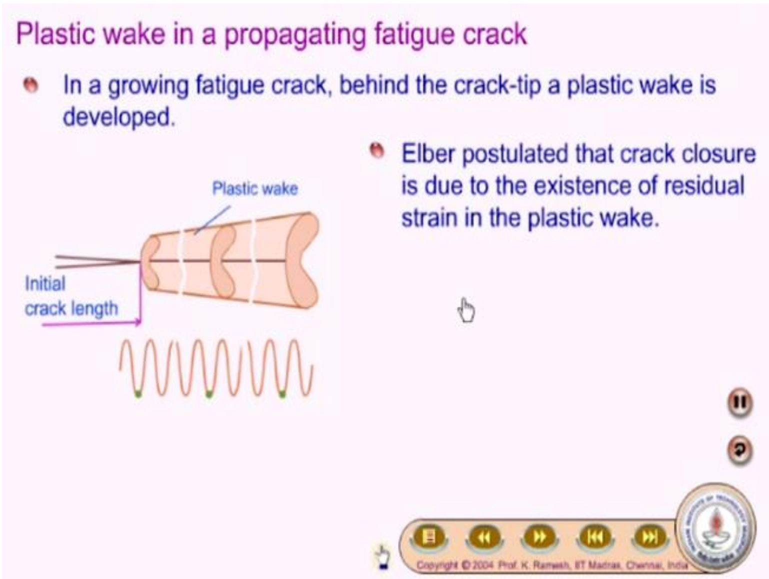

If you look into the details in a growing fatigue crack behind the attractive a plastic wake is developed. So how do we understand this? how it grows so this is an initial crack length and then this is a plastic zone if you look at the animation carefully so every time you know it completes number of cycle the plastic wake region is also getting increased. Elber postulated that crack closure is due to the existence of residual strain in the plastic way.

So there is a large amount of strain in the region of plastic wake so that residual strain okay which is responsible for crack closure that is proposed by Elber.

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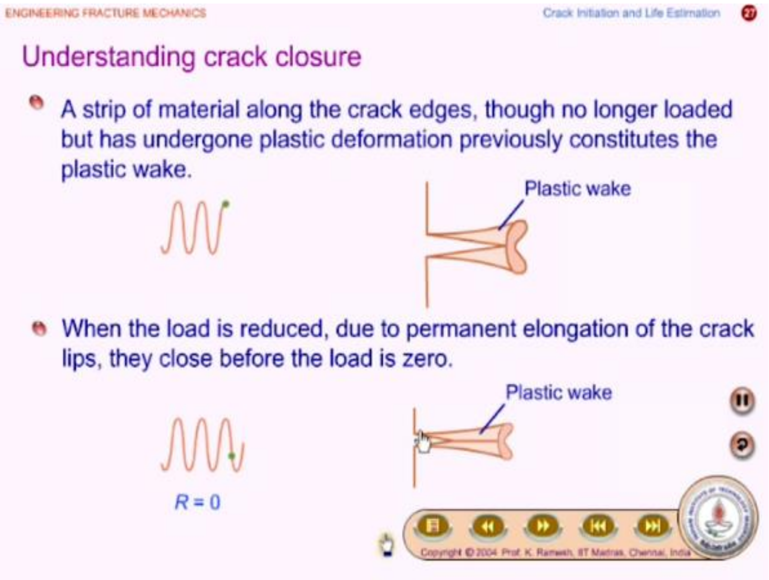

This is one model and another thing is, here is a crack and then around this crack you have the plastic wake and the plastic zone is formed here. So we can consider this as a strip of material along the crack edges, though no longer loaded but has undergone plastic deformation. Previously constitute the plastic wake, we can consider like this when the load is reduce to the permanent elongation of the cracked clips. They close before the load is 0 so this is one way of looking at it you can see that the load is not yet reached 0 but even before it is 0, you can look at this green bar here the crack is closed because of the plastic weight. So, this is one way of understanding how the plasticity induced crack closure happens.

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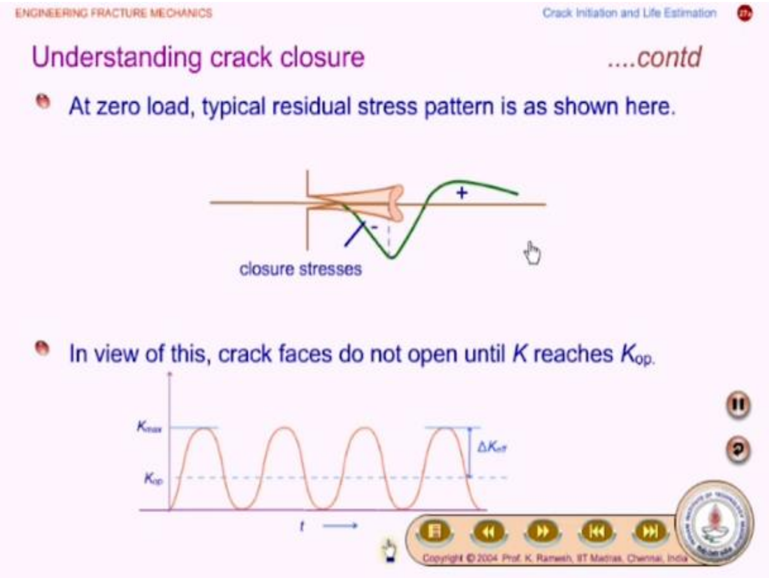

At 0 load typical residual stress pattern is shown here so here again you can see that the residual pattern is you know completely compressive here and this is a tension. So, this is in view of this crack faces do not open until K reaches K $_{open}$ so because of this residual stress development it does not open until reaches the stress K $_{open}$. So that way it is it is quite you now interested to note that plastic deformation helps in closing the crack.

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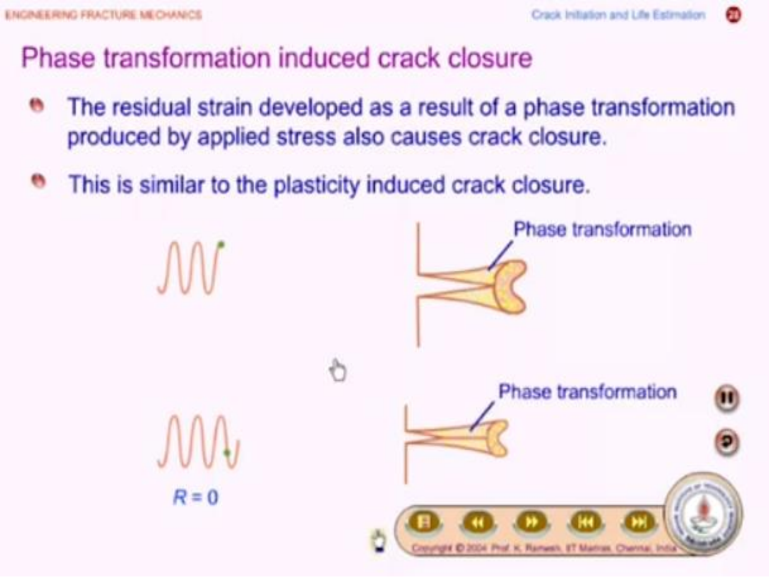

The next one is the phase transformation induced with crack closure. The residual strain developed as a function of as a result of phase transformation produced, by an applied stress also as correct closure. This is similar to the plasticity induced effect closure so you can see that the new phase which is formed around the crack tip, is a you know they will create a similar residual pattern like your plastic wake before even it reaches 0.

We try to close the crack so similarly any phase transformation also will cause this in material signs this is quite popular in improving the fracture toughness of ceramics, I will discuss that in the next chapter and I will bring this idea so here it is just discussed in the very generic manner, we will take up the specific example and then discuss this.

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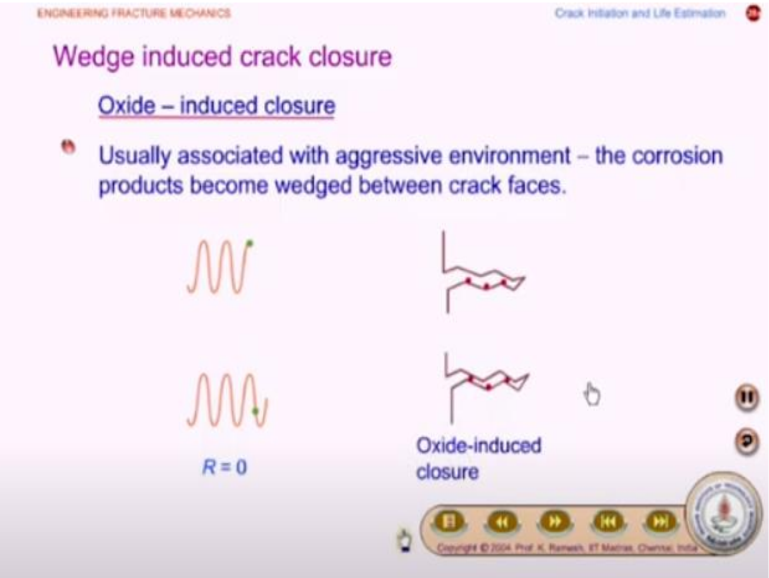

And wedge induced crack closure is the another mechanism which is also known as oxide induced crack closure. Usually associated with aggressive environment that quite obvious right, the oxide has to form and then that will facilitate the crack closure mission. So that means it is essentially happening in the aggressive environment, the corrosion products become wedged between the crack faces. This is very quite popular mechanism in the fatigue failure.

So, you see that they crack extension is shown like this and some of the corruption products are sitting like that. And they are all going to act as a wedge between these two crack faces before the load reaches to 0. They are going to kind of you know get wedged between these two crack faces. So, this is considered as an oxide induced crack closure.

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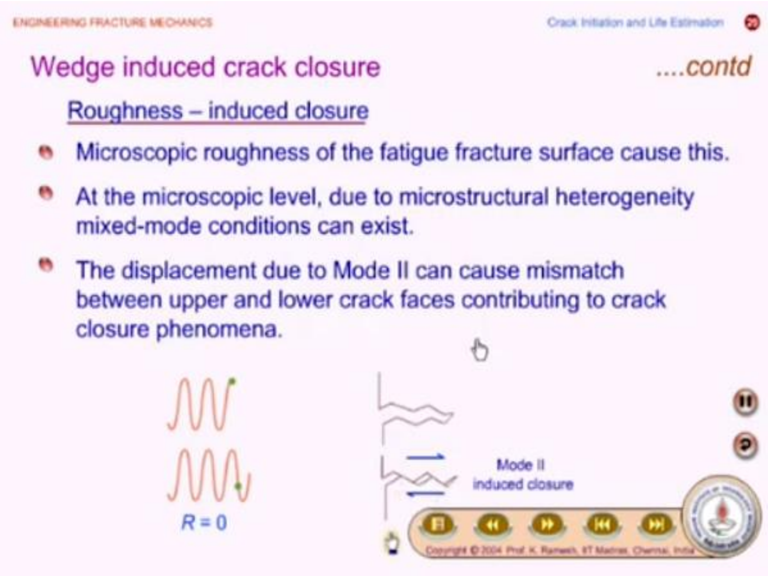

And in the similar way roughness induced crack closure is also quite popular microscopic roughness of the fatigue fracture surface causes at the microscopic level due to the microstructural heterogeneity mixed mode condition can exist. The displacement due to the mode 2 can cause dispatch between upper and lower crack faces, contributing the crack closure. So mode 2 is a sliding mode so obviously it will us to realize these kind of the crack closure mechanisms very straight forward idea..

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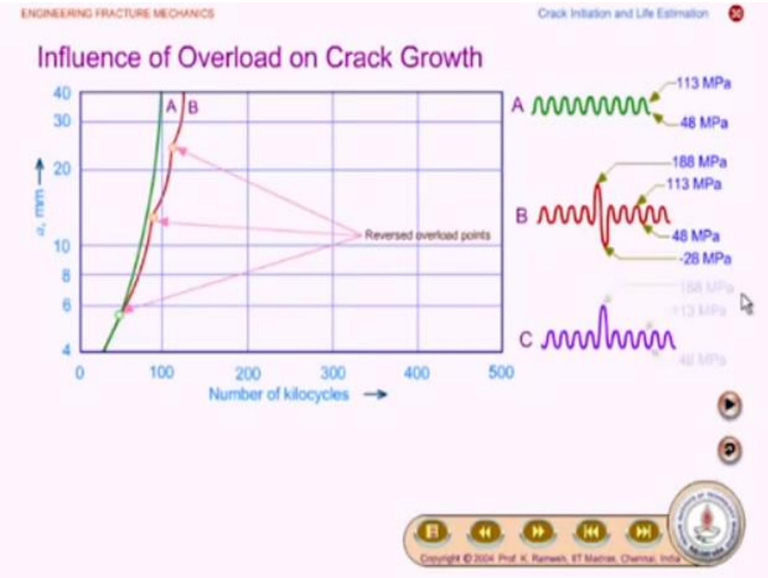

So now we will look at influence of overload on the crack growth and this is also very important mechanisms probably you will just discuss in the next class. Probably I will stop here, we will continue next class thank you.