Basics of Materials Engineering
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Lecture - 43
Fatigue Failure of Materials (High Cycle Fatigue, Low Cycle Fatigue, Stress Ratio, Amplitude Ratio)

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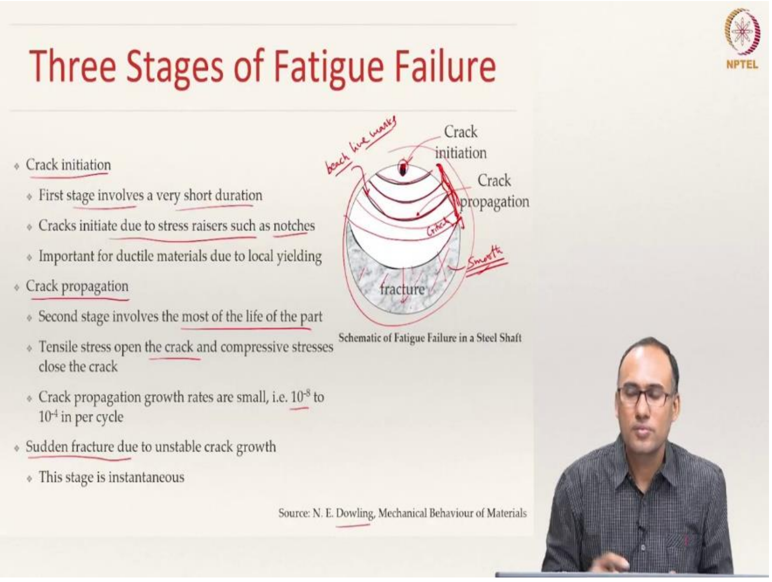

Let us now look at another important aspect in understanding the mechanism of fatigue failure. How does a component fail, when it is under fatigue loading? The fatigue failure in general can be classified into three stages.

The first stage is what we call crack initiation stage, followed by crack propagation stage and followed by sudden fracture. First you have to have an initiation of the crack and that initiated crack needs to become a critical crack. Only when it becomes a critical crack, that means a crack of critical length, there is going to be a sudden fracture of the component; until then the component is safe, because the crack is not yet critical.

From the initiation stage to the stage where it becomes critical, the crack needs to change its length; that means there is a crack propagation stage, during which time the material is under service. And once the crack reaches its critical length or the crack becomes critical, that is when the sudden failure of the component happens.

These are the three stages that one would see in the case of a fatigue failure. If you would look at a fatigue failure specimen here, I have only shown you a schematic; but you can look into the textbook of Norman E Dowling or Robert L Norton. There you can see the micrographs of the components which failed under fatigue, which show similar features as shown in the schematic.

Let us say here you have a crack initiation in this region. Once you have a crack initiation that is basically the first stage, which is a very short duration; because you may have a stress riser, even within very few cycles, the feature that is responsible for rise of stress or due to the stress concentration, might actually initiate a crack.

So, the crack initiates due to stress risers such as notches, key holes, etc. It is extremely important to pay attention to them even for ductile materials; because in the case of ductile materials what might happen is, the material may get into plastic deformation because of the stress riser. It may yield locally and that might actually cause the initiation of the small crack.

So, the small crack gets initiated and then you have crack propagation. When you see under microscope, you will see these lines called as beach line marks. Why they are called beach line marks?

If you would go to a beach, you know that the water comes and goes back and as a result, on the sand surface, you will see these lines. Because these lines are looking similar to the beach line sand marks, they are called beach line marks and this is a typical feature of a fatigue failure.

So, you have a small crack initiation, from there you will see these lines; they are actually representing the propagation, that is what is your propagation stage. So, that is the second stage that involves most of the life of the part; because from here up to here, the crack is propagating, because this is the length that is actually critical length for this component. Up to here, the crack may propagate, but the component is safe.

Most of the time is spent in this stage crack propagation stage. We know that the tensile stresses open the crack and compressive stresses close the crack and that is the reason why when we are looking at different types of loading, we are primarily focusing on the tensile regime, because that is where the crack propagates. But if you have a compressive regime, it is actually good for inhibiting fatigue crack propagation.

Usually in the propagation regime, the growth rates are typically in the order of $10^{-8} - 10^{-4}$ inch per cycle; so that means, it will take several cycles for a crack to grow to a critical length. For the crack to grow up to half an inch, it is going to take significantly large number of cycles.

Once the crack becomes critical, it suddenly zips through as we have studied in the module on fracture mechanics. Then you will see, the fracture surface to be relatively smooth; that means until now you have these beach line marks and suddenly you do not see the beach line marks.

If you see features like that in a failed component, there is a point from which these beach lines are coming; that means that is the crack initiation site. After certain distance, these lines disappear and suddenly you will have a dimpled surface. That actually gives you an indication that it has actually failed in fatigue; because all these three stages would have passed through before the component completely failed.

The final stage is sort of instantaneous. Once the crack becomes a critical crack, the material fails almost instantaneously. That is why you should ensure that you never reach this position when your component is in service.

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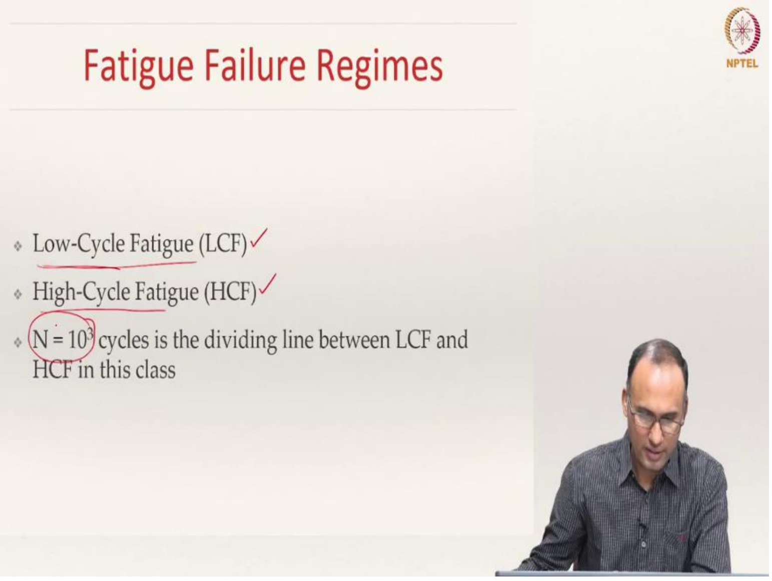

This is the fatigue failure mechanism that was proposed and we have also seen the different types of dynamic loads. Now, let us say your component is subjected to a repeated loading, i.e., multiple cycles of loading.

Depending upon the nature of loading and the number of cycles that it takes for the material to fail, there are different approaches that can be used in order to assess their fatigue response. In order to assess the fatigue response or fatigue behaviour of a material, primarily we are going to deal with two different approaches. One is called low-cycle fatigue and another one is high-cycle fatigue.

What do we mean by low-cycle fatigue? Low-cycle fatigue, from the name, implies that the component fails by operating at a higher stress amplitude, but lower number of cycles; that means it will actually fail in fewer number of cycles. The number of cycles that the component is going to be serving us will be low and that is why it is called low-cycle fatigue. If the number of cycles that the component is giving is large, then such a fatigue is called high-cycle fatigue scenario.

But what do we mean by low and high? It is always a relative term, right? So, how do we distinguish how many cycles is the boundary that I can mark below which it is low-cycle fatigue and above which it is high-cycle fatigue? It is very difficult to draw this sharp boundary. However, for convention, people have chosen about 1000 cycles as a reasonable thumb rule to distinguish between low-cycle fatigue and high-cycle fatigue.

If a component is designed to last for less than or equal to 1000 cycles, then you can say that the component is designed for low-cycle fatigue. If the component is designed to last for more than 1000 cycles, then you can say that the component is designed for high-cycle fatigue.

Please note that, this 10^3 is not really a very sharp boundary. For certain materials, it can be $\pm$ 100 or 1000 cycles, it is not necessarily exactly 10^3 cycles.

But in this class, for the sake of uniformity what we will do is, we will assume 10^3 cycles as the boundary; but for different materials there are guidelines in the literature, where you can actually look at the design principles and see the number that is suggested as the boundary between low-cycle fatigue and high-cycle fatigue.

Sometimes it is not a sharp boundary, you have a diffused boundary; that means you can say 1000 to 5000 cycles, it may be low-cycle fatigue and cycles higher than 5000 it can be said as high-cycle fatigue and so on.

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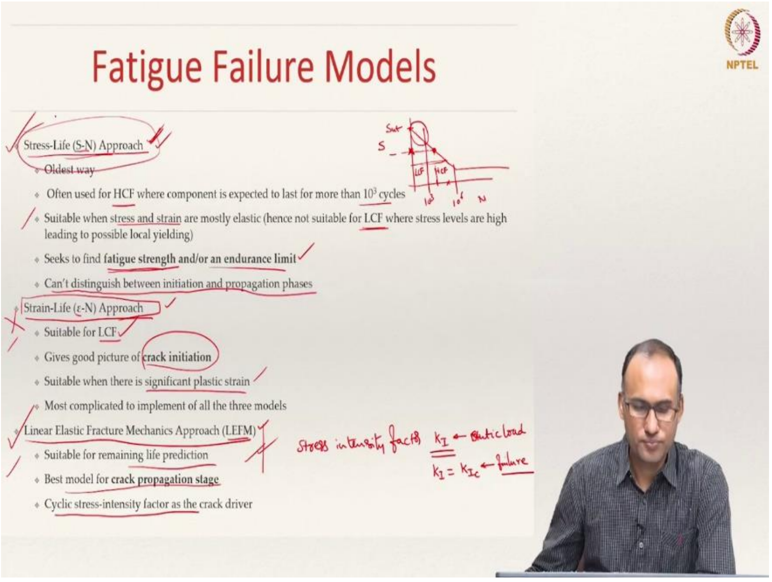

What are the things that we have discussed? We have discussed what are the different types of loading scenarios i.e., fully reversed loading, repeated loading, fluctuating loading; that is the nature of the load.

And then, we have discussed something called high-cycle fatigue and low-cycle fatigue; meaning the design philosophy that you would use in order to design a component which is expected to give a life of less than 1000 cycles is low-cycle fatigue. And the component that is going to give a life beyond 1000 cycles, then such a component is known to be or is considered to be subjected to high-cycle fatigue.

In order to understand or in order to design these components, what are the models that we need to use? What kind of a failure model one needs to adopt in order to design components based on different kinds of loading?

Here, we are going to talk about three approaches: stress-life approach, strain-life approach and linear elastic fracture mechanics approach or LEFM approach. So, we are going to talk about these three approaches here. And in this class, we will study in detail the stress-life approach and linear LEFM approach, and we will not study the strain-life approach.

What do we mean by stress-life approach? The stress-life approach is actually the oldest approach; this S-N diagram is actually from the stress-life approach. This is usually used for high-cycle fatigue; that means if a component is to last beyond thousand cycles, that is when you use stress-life approach.

It is mostly suitable when the stresses and strain are within the elastic regime, and as a consequence, it is not suitable for low-cycle fatigue; the stress-life approach is not suitable for low-cycle fatigue. Why? If you look at the S-N diagram; so, let us say this is 10^3 cycles and this is 10^6 cycles. In the case of LCF, this is the low-cycle fatigue regime and this is the HCF high-cycle fatigue regime, because this is10^3 cycles.

Now, in this regime, the stress amplitude is usually very close to the ultimate strength; that means the magnitude of the stress that is experienced by components under low-cycle fatigue regime is usually very high. As a result, there is a higher probability for these components to experience plastic deformation. Hence, the stress-life approach is not suitable, because the stress-life approach assumes elastic deformations or stresses being elastic, when we are doing the analysis. Consequently, the stress-life approach is not suitable for LCF i.e., low-cycle fatigue. In the stress-life approach, we try to find out the fatigue strength or endurance limit. For the materials that have endurance limit, we will say endurance limit; otherwise, the general the name is fatigue strength.

That means if the load applied is this much, then this is the failure. So, that is your fatigue strength, at this number of cycles the fatigue strength of the material is this much and at these number of cycles, the fatigue strength of the material is this much and so on.

One important issue here with the stress-life approach is that, it cannot distinguish between initiation and propagation stages. Because everything is elastic in nature here, we are not really focusing on initiation stage, mainly we will be spending time on propagation stage, because it is extremely difficult to distinguish these two stages.

And then we will talk about strain-life approach, which is perfectly suitable for LCF; because you are dealing with strain, you can explicitly figure out what is the plastic strain induced in the material. Based on the plastic strain, we will be able to do the analysis and hence it is very much well suited for low-cycle fatigue.

Since you can incorporate the plastic deformation into your model, it gives a very good picture of crack initiation stage. As we are saying we are dealing with strain, then this model is particularly suitable when you have significant plastic deformation or plastic strains in the material.

Because you are bringing in plastic deformation as well, of the three approaches that we are discussing here, the strain-life approach is the most complicated of all. The last approach is linear elastic fracture mechanics, and this is suitable for remaining life prediction.

So, if you have a crack and you know what is the cyclic loading, then can you predict how many cycles of life is still remaining? How many more cycles can I run this component for before actually replacing it? This is a very important information for engineers particularly.

When you are having a component with a known crack size to begin with, as soon as you see a crack, you are not immediately required to change the component, provided you know the information that how many cycles can I run this component before this crack becomes critical crack and that is something that is provided by LEFM approach.

The LEFM is the best model for crack propagation stage. You know that the stress state is changing as a function of time; that means the stress is cycling between two values. When we were talking about linear elastic fracture mechanics in the previous module, we have introduced a very important concept called stress intensity factor, K_I.

In that module, we had a static loading; but now you have a cyclic loading, and hence when we are studying this LEFM approach for crack propagation under dynamic loading, you have to deal with something called cyclic stress intensity factor, that is the crack driver.

In fracture mechanics, we have learnt that, when $K_I = K_{Ic}$, that is when failure happens; that means crack propagates. Here what we need to look at something called cyclic stress intensity factor, because your stress is cycling between two stress states.

The summary of this discussion is, we have three fatigue failure models and of the three; the first one is stress-life approach, second one is strain-life approach, and the third one is LEFM approach. In this class, we are only going to discuss about stress-life approach and

LEFM approach and we are not going to discuss strain-life approach. We will spend most of our time on stress-life approach.

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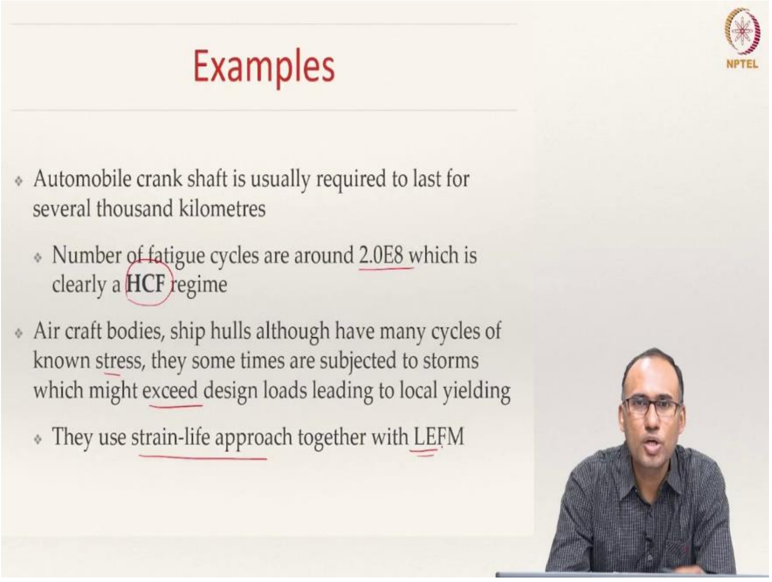

We have discussed the stress-life approach and strain-life approach and we said that stress-life approach is best suited for HCF, high-cycle fatigue regime and strain-life approach is best suited for low-cycle fatigue regime, right? But what are the different engineering components that actually need to be designed for one of these scenarios; whether I need to design a component for high-cycle fatigue or low-cycle fatigue?

For instance, if you take an automobile crankshaft, you would expect it to last for several years, right? You do not want to change it every one thousand cycles or ten thousand cycles; you want it to last for few hundred million cycles. Ideally, you do not want the crankshaft to break down at all even before you discard your car; that is the kind of expectation that you have. That means you are expecting extremely large number of cycles of life for this crankshaft.

Since you are expecting extremely large number of cycles, you have to ensure that the stress amplitude that you are applying on this component is relatively low. As a result, the automobile crankshaft qualifies to be a component that is designed for high-cycle fatigue, right? Typically, the number of cycles that you would expect is about two hundred million cycles for a crankshaft and that is why it is designed as a high-cycle fatigue component.

On the other hand, you have certain other critical components like aircraft bodies and ship hulls. They are having so many cycles of known stress; but sometimes these components are subjected to unknown stresses of large magnitude. For instance, it is highly possible that an aircraft may encounter turbulence during the flight. Same is the case with ships; they may be experiencing severe storms while sailing.

These are the stress levels which are not usually within the operating stress levels of these components. The loads that are coming on to the structures may exceed the design loads, causing local yielding. Hence, you should not design these components for high cycle fatigue, you should usually design them for low cycle fatigue.

For the design of these components, you may use strain-life approach together with LEFM or fracture mechanics. Strain-life approach together with fracture mechanics can be used to design the components such as aircraft bodies, ship hulls or nuclear reactor components, which are critical and known to be subjected to very high stress levels.

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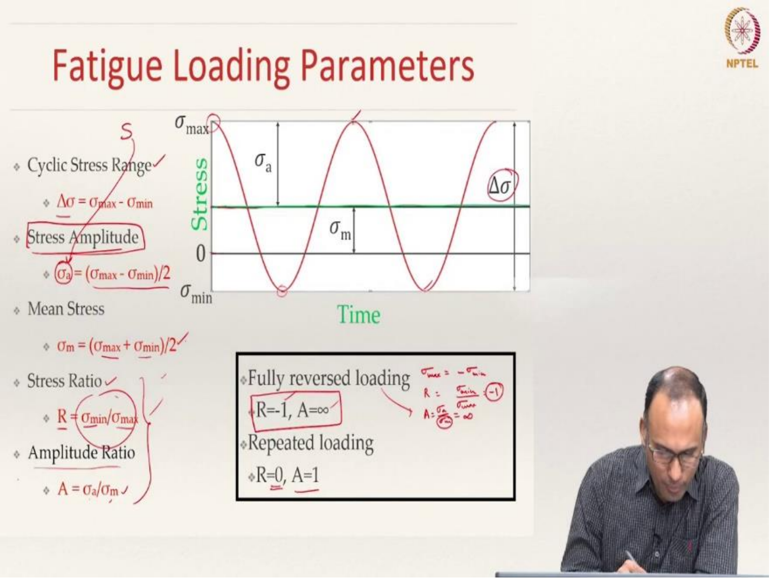

Before we move on, this is a very important slide where we need to understand the definition of various parameters when we are talking about fatigue loading. Here we are showing a fluctuating loading scenario. This is the most general loading scenario, wherein you have a minimum stress to be negative, you can see this is 0 and maximum stress to be positive.

That is what I discussed previously; a fluctuating loading scenario can actually have some part in tensile regime, some part in compressive regime. The green coloured line is the mean stress.

We define five important parameters; the first one is called cyclic stress range, that is basically the difference between the maximum stress and minimum stress. It is the distance between the peak and the valley. The cyclic stress range, designated by $\Delta\sigma$ is given by,

$$\Delta\sigma = \sigma_{\text{max}} - \sigma_{\text{min}}$$

Let us look at another important quantity called stress amplitude. What is stress amplitude? Stress amplitude is the distance between the mean stress to the maximum stress or mean stress to the minimum stress; because the mean stress is supposed to be halfway through maximum and minimum.

$$\sigma_a = \frac{(\sigma_{\text{max}} - \sigma_{\text{min}})}{2}$$

When we have drawn the S-N diagram, on the y-axis, what we have drawn is the stress amplitude; the S in S-N diagram is actually the stress amplitude. The mean stress is given as

$$\sigma_{\text{m}} = \frac{(\sigma_{\text{max}} + \sigma_{\text{min}})}{2}$$

When $\sigma_{\text{max}} = -\sigma_{\text{min}}$, i.e., for a fully reversal loading, the mean stress becomes 0, otherwise it will be non-zero.

Depending upon the magnitude of σ_{min} compared to σ_{max}, the mean stress could be positive or negative. If $|\sigma_{\text{min}}| > |\sigma_{\text{max}}|$, then the mean stress would be negative, otherwise it will be positive. If both of them are equal, then it becomes 0. Then we have something called stress ratio. Stress ratio R is defined as minimum stress to maximum stress.

$$R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}}$$

Then you also define something called amplitude ratio A.

$$A = \frac{\sigma_{\mathrm{a}}}{\sigma_{\mathrm{m}}}$$

By looking at the two parameters R and A, you can say which kind of a loading the material is subjected to i.e., the nature of the loading; whether it is fully reversed loading or a fluctuating loading or a repeated loading.

let us look at the case of a fully reversed loading. For the fully reversed loading,

$$\sigma_{\max} = -\,\sigma_{\min} \;\Rightarrow R = -1$$

When the stress ratio $R = -1$, it is a fully reversed loading scenario. What happens to the amplitude A. We know that mean stress in the case of fully reversible loading is 0, hence $A = \infty$. For a repeated loading

$$\sigma_{\min} = 0 \;\Rightarrow R = 0$$

Stress amplitude and mean stress are the same for repeated loading, and hence $A = 1$. So, by looking at the stress ratio and amplitude ratio, you can find out the nature of the loading for a given problem. These are very important to understand and remember as well.