Basics of Materials Engineering
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Lecture – 42
Fatigue Failure of Materials (S-N Diagram, Types of Time Varying Loads)

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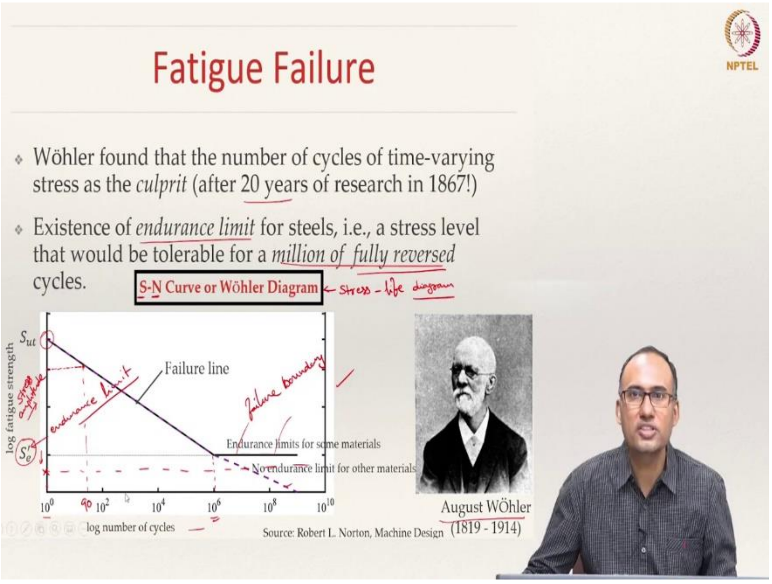

Welcome back. In the last class, we have looked at various events in the history, where most of the failures are associated with the fatigue in general and we have seen how the fatigue caused failures in the case of rail axle joints or trains or airplanes and so on. We have also looked at how fatigue failure in general, can be assessed in a material.

In today's class, we will look at how fatigue loads can be classified into different types and different kinds of fatigue analysis procedures. Most of the fatigue failure data for the first time was published by August Wohler from Germany.

He did experiments on rail wheel axles for several years. About 12 to 15 years of his work is only to do experiments on these rail wheel axles under repeated loading. He collated all that data of his work, conducted over a period of 20 years research and then he found out that the number of cycles of time varying stress is the culprit for the premature failure of these rail wheel axles.

He also identified that there is something called an endurance limit for materials like steels, that is, this limit is the stress level below which you will never have failure; that means, the material is going to give you infinite life. If you are loading the material over number of cycles, it will not fail if the applied load is below this particular level called endurance limit.

Instead of calling it as an infinite life, the general convention is that, if the stress level below which the material is guaranteed to give a million of fully reversed cycles (we will see what we mean by fully reversed in a moment), then such stress limit is called endurance limit.

Here we are showing the schematic of S-N diagram i.e., the stress-life diagram, where S stands for stress, N for number of cycles, which is the outcome of Wohler's research. On the y-axis, he has plotted stress amplitude, versus the number of cycles (on x-axis) and he has plotted this on a log scale. On the normal scale it is not a straight line, but on a log-log plot it is a straight line.

Here you can see the 10^0 cycles, meaning actually one cycle. It is not really a time varying stress. Whenever we are talking about fatigue failure, we are actually talking about fracture, right? Since we are talking about fracture, the material under static load is known to fracture at ultimate tensile strength

That is the maximum load that the material can take. The ultimate strength of the material is here at 10^0 cycles i.e., at 10^0 cycles, the material fails at a stress amplitude equal to ultimate strength. We will discuss what do we mean by stress amplitude in a minute.

Suppose that you reduce the applied stress amplitude on a material, let us say somewhere here, then you see that, the material will fail in say 90 cycles; it is a log scale, so it is not linear, please keep that in mind. So, it fails in 90 cycles, when you have your stress amplitude little less than S_{ut}; that means, up to 90 cycles it will be fine, after 90 cycles, it will actually fail.

Here you see something called $S_e{}'$ and if you look at it, the number of cycles to failure is 10^6 i.e., one million cycles and this S_e' is what we call endurance limit of the material or endurance strength of the material.

We are only focusing on black line, that is typically for steel materials or steel kind of materials, which show endurance limit; that means, if your applied stress amplitude is less than $S_e{}'$, then the material will not fail. So, you can think of this black line as a failure boundary. If you take any stress state somewhere below S_e' i.e., your endurance limit, you see that it never touches your failure surface; that means, it is never going to fail.

So, it has infinite life in that sense. So, that is why the endurance limit S_e' is an important material property, below which the material is going to give infinite life. However, note that not all materials show this behavior of endurance limit, there are certain materials which do not show any endurance limit; that means, there is no infinite life that you can expect from these materials. And such materials are called no endurance limit materials. Typically, aluminum alloys do not show this endurance limit; that means, the fatigue strength is actually changing. Hence this curve will not flatten out at S_e', and it continues to go down. As a result, if you are reducing the stress amplitude you are going to get a larger life, but not infinite life as in the case of the steel materials.

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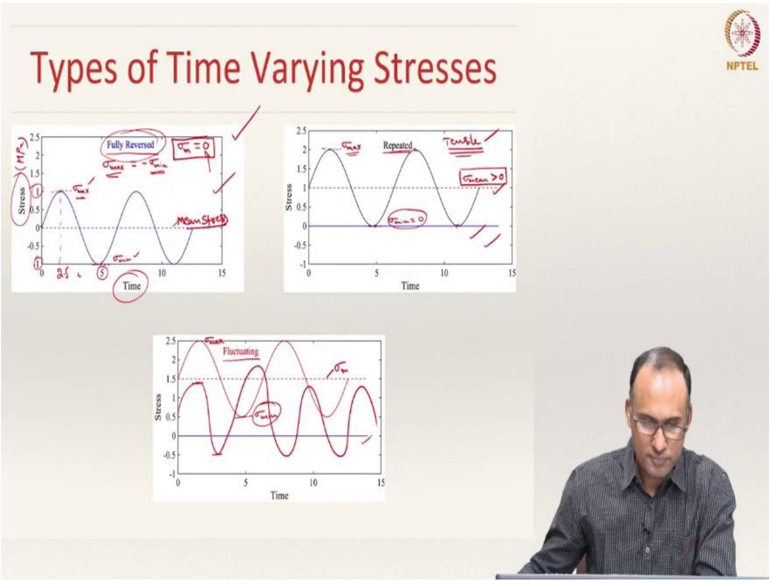

We have discussed this is something called stress amplitude. Fatigue loading is nothing but, a time varying load; that means, if you take any point in a material, at that point the stress state is going to change as a function of time.

When we have looked at static failure theories, there what we said was, the stress state at a point is time invariant; that means, it does not change with respect to time, but now we are saying that the stress state is going to change with respect to the time at that particular point.

When we say the stress state at a particular point is going to change as a function of time, we need to also say, how is it going to change as a function of time? What is the nature in which it is going to change as a function of time? Depending upon the nature in which the stress state is going to change as a function of time, the stress state can be classified primarily into three classes. So, that means, the nature of this change can actually be classified into three primary classes.

The first one is called fully reversed loading, then we have repeated loading and finally fluctuating loading. What do we mean by fully reversed loading? In the plots shown here, on the y-axis you have stress, on the x-axis you have time.

These numbers are only representative; do not pay much attention to these numbers as these numbers can be different. I have chosen to plot between certain numbers, but the idea is to see the nature of the variation of the stress. Here, in this particular loading scenario, the maximum stress is 1, i.e., $\sigma_{\text{max}} = 1$ and the minimum stress $\sigma_{\text{min}} = -1$.

Here $\sigma_{\text{max}} = -\sigma_{\text{min}}$. Their magnitudes are the same, but their signs are different; that means, if the maximum stress is tensile, the minimum stress is compressive.

Such a loading scenario where $|\sigma_{\text{max}}| = |\sigma_{\text{min}}|$ is called fully reversed loading. Why are we calling it as fully reversed? In one situation a material point is experiencing maximum tensile stress and the same material point after sometime experiences maximum compressive stress. Let us say, you are starting here, at time $t = 0$.

Let us say this is about 2.5 seconds. The material point is experiencing a maximum tensile stress of 1 MPa here and by the time, you reach time 5 seconds, the same material point is experiencing a compressive stress of 1 MPa.

So, it is experiencing the same value magnitude-wise, but at one particular time, the maximum value is actually a tensile state of stress and at another point of time the maximum value is compressive state of stress; that means, the nature of the stress is completely reversed. Hence it is called fully reversed loading.

The way to characterize fully reversed loading is to see $\sigma_{\max}$ and $\sigma_{\min}$. Please pay attention to this dashed blue line; that is what we call mean stress. Typically, we designate that with σ_{m} and you can clearly see that, when you are dealing with fully reversed loading, the mean stress will become 0. That is one of the key parameters that we are going to use during the analysis of fatigue failure. So, when the mean stress is 0, then you can actually say that it is fully reversed loading. Now, let us come to repeated loading.

In the case of repeated loading, you see this is your maximum stress and that is your minimum stress. Here the entire stress state is in the tensile regime, right? At no time, the material point is experiencing compressive stress.

All the time it is only experiencing a tensile state of stress. However, in general, when we are defining repeated loading, it can be either completely in tensile regime or completely in the compressive regime. But we are not going to look at compressive regime, because we know that, the fatigue failure is due to extension of crack; that is what we have discussed when we were dealing with the fracture mechanics module.

We know that a crack propagates when the local state of stress is subjection to tensile state of stress. Under compressive state of stress, the cracks do not open up and rather close. Hence, we are not showing compressive stress. But the definition of repeated loading need not be confined only to the tensile regime.

In the case of repeated loading, the minimum stress is 0 and maximum stress is some positive value, and as a result $\sigma_m > 0$, when you are working in the tensile regime. Note that $\sigma_{\min} = 0$ for repeated loading.

That means, from 0, you are actually repeating the applied load. The applied load oscillated between 0 and a maximum value. Please note that here we are plotting the evolution of stress state at a point as a function of time.

If you look at different points in the material, each of these points may be undergoing different cycling or different nature of variation of the stresses, but here we are only focusing at one point. When you are talking about design, you typically look at the most critical point. You know the material point that is expected to be most critical point and then you try to assess the nature of variation of stresses as a function of time at that particular point.

This is about repeated loading. Here, we are talking about fluctuating loading, wherein the minimum stress is not equal to 0. You have $\sigma_{\max}$, this is $\sigma_{\min}$ and this is σ_m. We have shown that this is completely in the tensile regime. However, it is possible that the minimum stress may lie in the negative regime.

You can have something like this; this is also a feasible definition for fluctuating loading. The fluctuating loading basically means that $\sigma_{\min} \neq 0$ and $|\sigma_{\max}| \neq |\sigma_{\min}|$.

You can have any sort of fluctuation. You can have the maximum stress to be positive, minimum stress to be negative; that means, your crack or your material point is experiencing, for some time tensile state of stress, for some time compressive state of stress, but the compressive state of stress that it is experiencing is not necessarily equal to the tensile state of stress. If it is equal, then you would have called it as fully reversed loading, but since it is not equal, then you are calling it as fluctuating loading.

These are the three different kinds of loading scenarios that one would come across, when dealing with the fatigue loading or dynamic loading of materials. In the first module, we will be primarily focusing on fully reversed loading, where mean stress is equal to 0. And once we have understood how to analyze problems, where mean stress is equal to 0, then we will move on to the looking at situations when you have finite mean stress. What do we need to do, when you have finite mean stress?

What is the effect of having a non-zero mean stress on the material is something that we will look at, once we understood the situation of designing components subjected to fully reversed loading.

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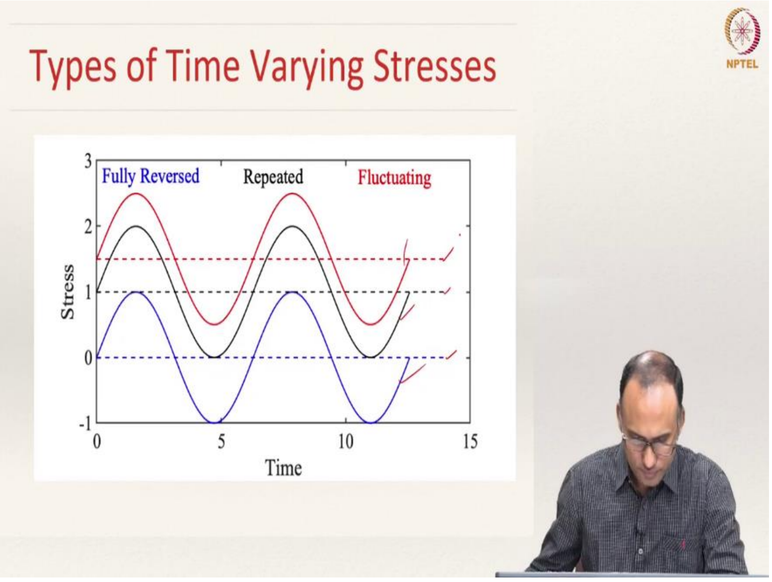

If I would plot all these three loading scenarios on the same graph, this is how it looks like. The blue curve is fully reversed loading, the black curve is repeated loading and the red curve is fluctuating loading. You can clearly see that, here you have zero mean stress and here, the repeated loading has some positive mean stress and the fluctuating loading in this particular scenario also has some positive mean stress.

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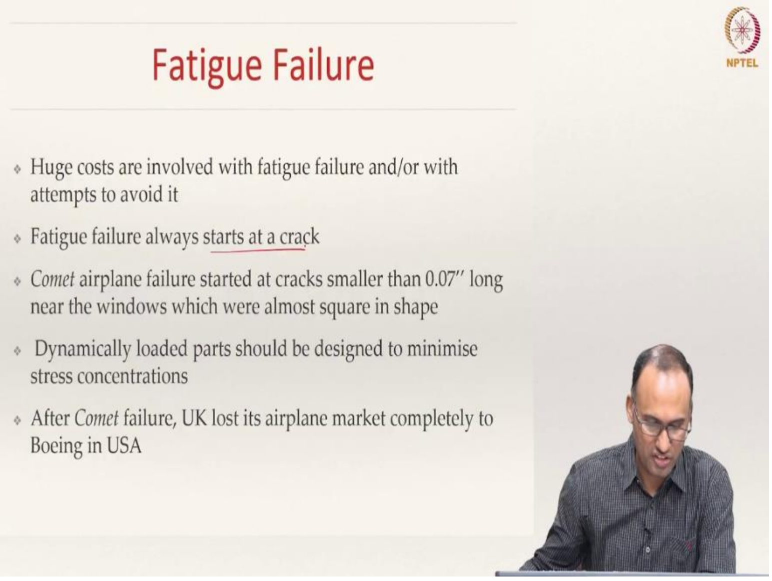

We have actually discussed this, when we were talking about various failures that were observed in the history. Most of them are associated with the fatigue failure. And we have also seen that, there are huge costs involved with fatigue failure. Even when there is failure and even if you want to avoid the fatigue failure, you need to put in lot of energy and understanding to develop / devise new methodologies to avoid fatigue failure.

That is actually an area, which involves a lot of efforts from scientific community which costs a lot of money. We have already seen that the fatigue failure always starts at a crack. So, you have a crack to begin with and then that acts as a driving scenario for eventual failure of the material under fatigue.

We have seen that in the situation of comet airplane case study, the small crack generated at the corner of a square shaped window of the airplane, acts as a stress concentration region and that small crack eventually led to the complete breakage of the component.

The key is that, you should not have stress concentration regimes in your design. Whenever a material is going to be subjected to dynamic loading, you should always ensure that you minimize the regions where you may have stress concentration. It may not be possible to remove these regions which have stress concentration altogether, but you can always try to reduce the effect of that stress concentration.