Basics of Materials Engineering
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Lecture – 46
Fatigue Failure of Materials (Features of Fatigue Failure; Factor of Safety in Life and Stress)

In the last module, we have looked at how to create an estimated S-N diagram taking into account the correction factors. We have seen the importance of application of correction factors to calculate the fatigue strength of the material. When a component is subjected to a certain kind of stress amplitude, the presence of correction factors is very important, and we have seen an example wherein a material subjected to a particular stress amplitude turns out to be safe when there are no correction factors and turns out to be unsafe when there are correction factors.

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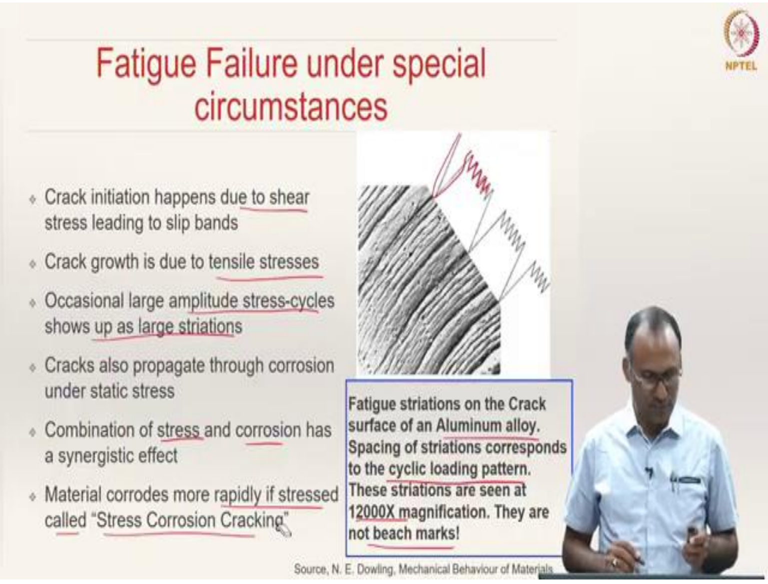

We will now look at fatigue failure scenarios under some special circumstances. This is a micrograph which shows the striations on a surface and please note that these are fatigue striations on the crack surface of an aluminum alloy. There is a distinct spacing that one can observe in these striations that correspond to the cyclic loading pattern of the system.

These striations are shown at 12000X magnification and they are not the beach marks that we have seen before. They are just the striations on the surface. They give you the signature of the kind of loading that we are having on the system. We know that the crack initiation happens due to shear stress that leads to slip bands and of course, the crack growth happens due to tensile stress. The occasional large amplitude stress cycle shows up as large striations.

So, you can see this large striation; they are occasional increase in the stress amplitude and this small striation are oscillations around that stress amplitude. The occasional stress jumps are shown as the signatures of large striations. This is one scenario that you would observe when you are looking at the failure surfaces. Another important factor that one needs to be worried about, particularly when regarding fatigue crack growth is the combination of stress and corrosion.

They have a synergistic effect. A material corrodes more rapidly if stressed. If you keep a material under a corrosive environment and if you apply a load on that, then the material corrosion get accelerated and such a phenomenon is called stress-corrosion cracking.

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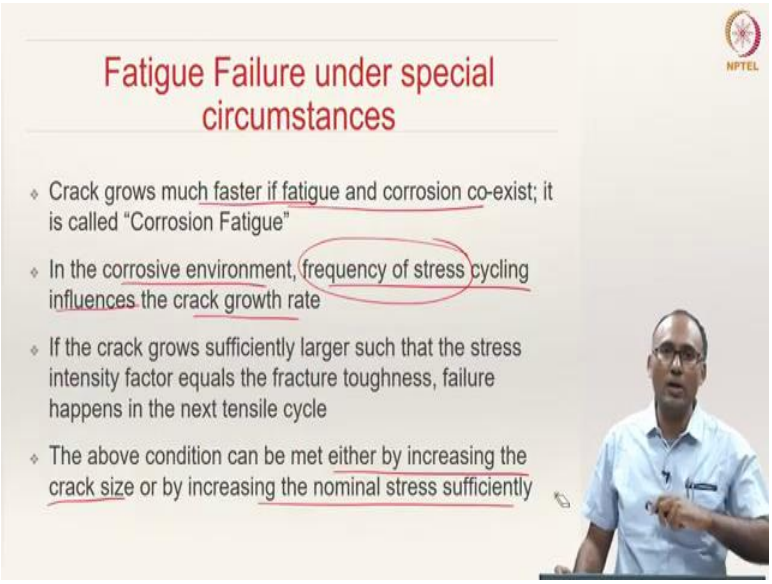

It is also known that the crack grows much faster, if the fatigue and corrosion coexist; that is called corrosion fatigue. The fatigue is also accelerated in the presence of a corrosive environment. In a corrosive environment, the frequency of stress cycling influences the crack growth rate; that is very important to know. So far, we are only focusing on the stress amplitude, but what happens to the frequency? Does the frequency influence the life of the component or the failure phenomena?

Turns out that in a corrosive environment, the frequency of stress cycling plays a critical role in influencing the crack growth rate. And if the crack grows sufficiently larger, such that the stress intensity factor at that particular crack length equals the fracture toughness, then the failure happens in the next tensile cycle.

So, you are applying a cyclic load on the material. At a particular cycle, the crack length reaches a critical length. Then, in the next tensile cycle, the stress intensity factor ahead of the crack tip has become equal to the fracture toughness and suddenly the material will fail. Such a condition is met either by increasing the crack size or by increasing the nominal stress sufficiently.

The crack size is the same, but suddenly you have increased the nominal stress. As you have seen, the large striations in the previous graph correspond to an increase in the nominal stress. That can also lead to increase in the local stress intensity factor. Although the crack length did not change, just by the virtue of increasing the nominal stress, the crack might actually become critical.

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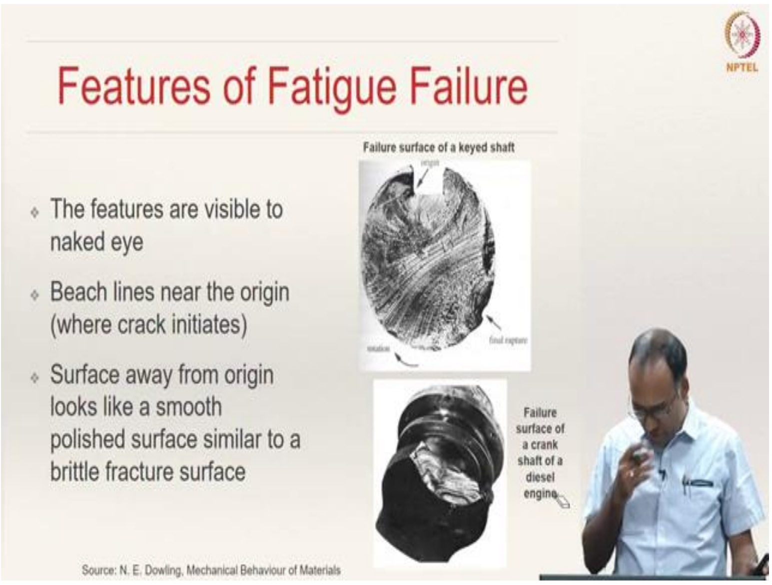

These are the features that we have already seen before; how a failed specimen under fatigue looks like. In this figure, you can clearly see that the crack is initiating here and you can see the beach line marks and this area is very smooth and then that represents the final failure.

Similarly, in this figure, you can see the crack initiation here and these are your beach line marks and then suddenly crack zips through and then breaks. These are the typical features that one would observe in the case of a component that fails under fatigue. Usually, these features are visible to naked eye. You do not have to look under microscope.

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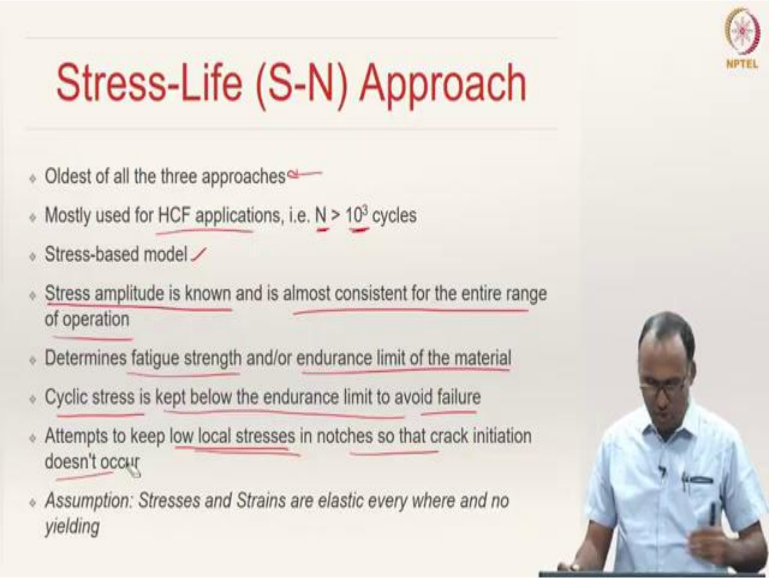

Let me summarize the stress-life approach that we have discussed so far. As we have already mentioned, this is the oldest of all the three approaches. What are the other two approaches? The strain-life approach and LEFM approach for crack growth. The stress-life approach is mostly used for HCF applications i.e., when the number of cycles for failure are usually expected to be more than 1000 cycles.

It is a stress-based model and for the entire range of operation, we know consistently the stress amplitude. In this approach, the idea is to determine the fatigue strength or endurance limit of the material. We will be able to find out this property.

Usually, the cyclic stress in this approach is kept below the endurance limit to avoid failure; that is the key. If you want to avoid failure, you want to make sure that the cyclic stress is below the endurance limit, because any stress level below the endurance limit is going to give you infinite life. Lastly, the attempts to keep low local stresses in notches, so that the crack initiation does not occur.

You should ensure that your design should be such that even if you have notches, you should be able to ensure that the stresses near the notches are lower than the endurance limit, so that the crack initiation does not occur. You may also keep the stresses not below the endurance limit, but to a very low value so that, there is no local crack initiation starting at those positions. The stress-life approach is based on the assumption that the strains are elastic everywhere and no plasticity is present in the material.

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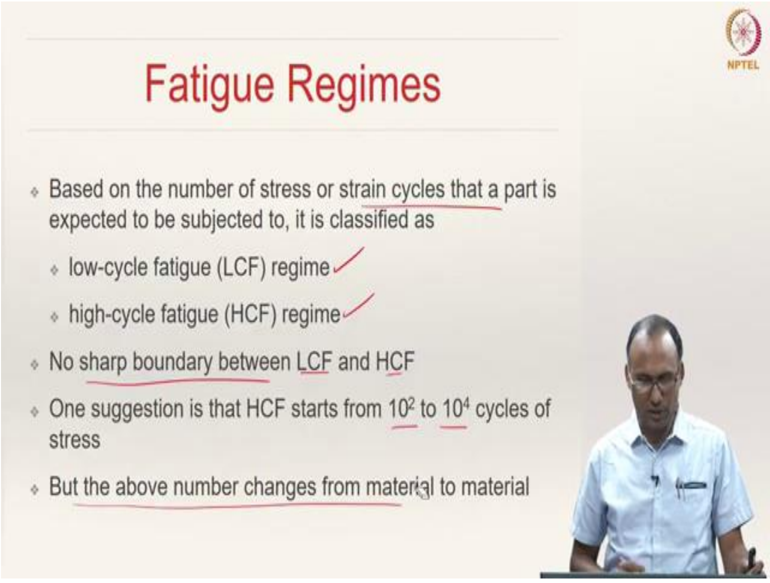

We have also discussed these fatigue regimes. Once again, I am summarizing. Based on the number of stress or strain cycles that a part is expected to be subjected to, it is classified as a low-cycle fatigue regime or high-cycle fatigue regime. We have already discussed that there is no sharp boundary between LCF and HCF although we are saying 10^3 cycles.

It is only a convenience, but usually it can span between $10^2 - 10^4$ cycles; that is why we have taken the midpoint between 10^2 and 10^4 cycles, on a log scale i.e., 10^3 cycles. However, the above number changes from material to material.

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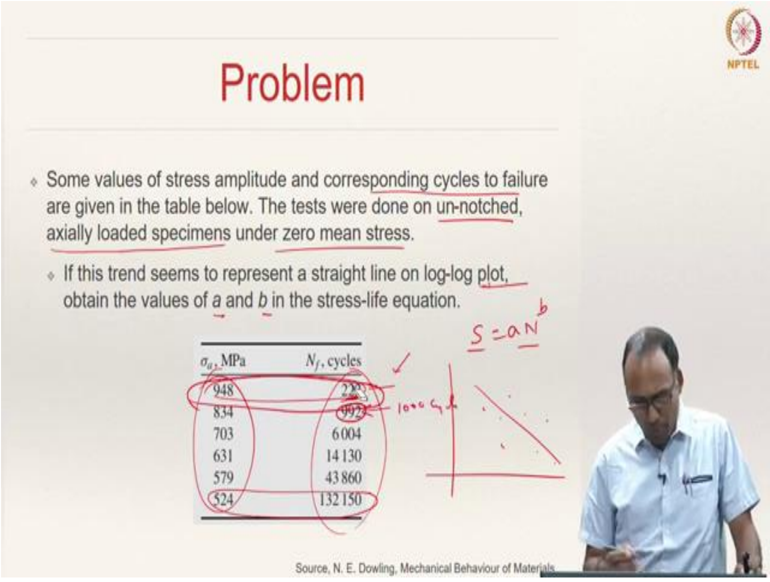

Let us look at a more generic situation. This problem gives a more generic situation wherein you are given the experimental data of stress amplitude and the corresponding number of cycles to failure. How do you go about constructing an S-N diagram for that? So, some values of stress amplitude and corresponding cycles to failure are given in the table here and the tests were done on un-notched axially loaded specimens. The specimen is axially loaded under zero mean stress i.e., fully reversed bending.

If this trend seems to represent a straight line on log-log plot given by $S = aN^b$, obtain the values of a and b; that is the question. Here, you have this data and these are number of cycles. But if you would plot this data on a log-log plot, you would see that the data is not exactly following on a straight line, it will be something like that.

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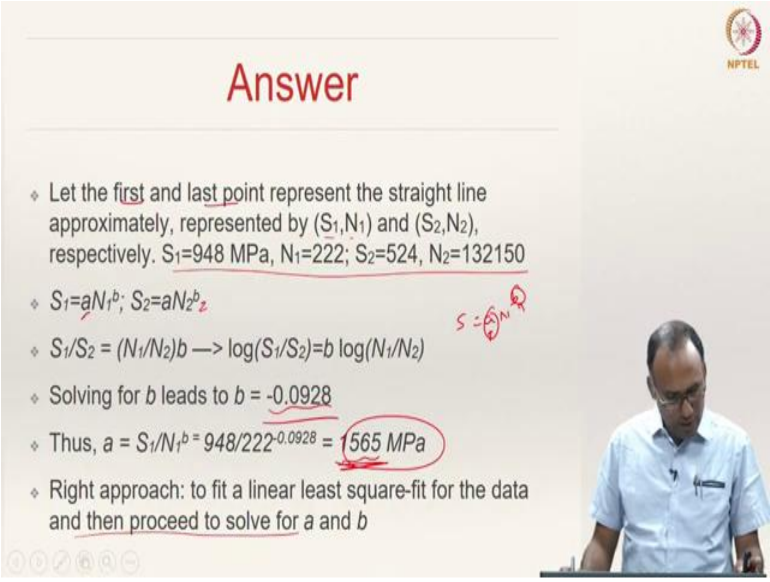

As a first-hand approximation, what we can do is let the first point and the last point of this data -- this point and this point are on that straight line, $S = aN^b$ and then go about finding the values of a and b. So, (S_1, N_1) and (S_2, N_2) are the first and last points, and then you have identified these values.

Upon solving, we get $a = 1565\,\text{MPa}$ and $b = -0.0928$. This is a first-hand approximation. However, the right approach is to fit a linear least square fit for the data and then proceed to solve for a and b.

You have to do a regression curve fitting for the data that is provided and then figure out what is the value of a and b. You can take this data and then do a power law fit for $S = aN^b$ and then find a and b. These values of a and b are not going to be what you have found here.

It is going to be little different. However, this is a reasonable estimation when you are using pen and paper rather than solving using a computer to fit the data. That way you can calculate a and b for any given data, assuming that, the data is fairly represented by a straight line on log-log plot of stress and life diagram.

Please note here that you can also do a little bit better job saying that, does it make sense to actually consider the first point? We know that the stress-life approach is a best description in the HCF regime and for HCF regime, we said the number of cycles to failure is at least 1000 cycles. But here it is only 222 cycles, it is definitely in LCF regime.

The stress-life approach is not really the right approach. Hence, you should use this probably as it is close to 1000 cycles. Hence instead of using$(948, 222)$, probably it is better to use $(834, 992)$ as (S_1, N_1) in the work that you have done here. Instead of these two, you might want to use the next data point that actually is at 1000 cycles.

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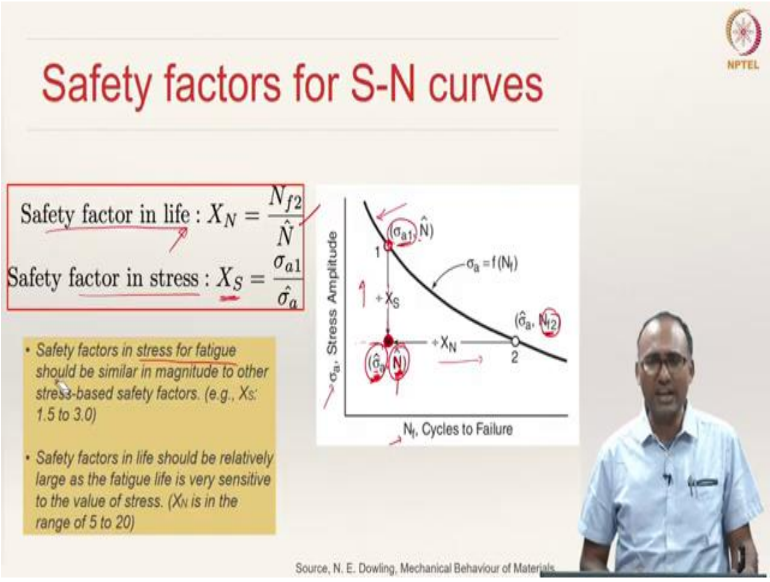

Now, we are going to define the factors of safety for S-N curves and here, this is the stress amplitude and the number of cycles to failure. Let us say you are designing a component which is expected to experience a stress amplitude of $\widehat{\sigma_a}$ and it is expected to give a design life of $\widehat{N}$, and let us say the material has an S-N diagram like this. We define two factors of safety. One is what we call say safety factor in life another one is what is called safety factor in stress.

Safety factor in stress is something that we have already done during the static failure theories. When we are doing the fatigue failure theory, another safety factor comes in, that is safety factor in life. Along the x axis you have life, along y axis you have stress. Let us say at that particular stress amplitude, the number of cycles to failure is N_{f2}. So, factor of safety in life is $\frac{N_{f2}}{\widehat{N}}$.

If you want to talk about factor of safety in stress, we know that the component is designed for $\widehat{N}$ cycles, but obviously, it is not failing at the corresponding stress $\widehat{\sigma_a}$. Now, what is the stress amplitude which corresponds to the failure cycles of $\widehat{N}$? That is, if you go vertically, σ_{a1} is the stress amplitude. If the material is subjected to that stress amplitude, it fails in $\widehat{N}$ cycles, this number of cycles.

Now, the factor of safety in stress is $\frac{\sigma_{a1}}{\widehat{\sigma_a}}$, because at $\widehat{\sigma_a}$, at that number of cycles the material will not fail, but at a different stress for the same number of cycles i.e., that stress is σ_{a1}, the material will fail. That means, the stress can be increased up to σ_{a1} at the same number of cycles and still the material will not fail.

Hence, in order to give the factor of safety in stress, it is $\frac{\sigma_{a1}}{\widehat{\sigma_a}}$. A caution is that the safety factors in stress for fatigue should be in the same range as the static failure theories which is about 1.5 to 3, whereas, factors of safety in life are expected to be relatively large numbers. X_N is the factor of safety in life, X_S is the factor of safety in stress.

They are anywhere between 5 to 20 or more than that; sometimes it can be much larger than that. Usually, the factors of safety in life are known to be larger numbers compared to stress. That is also expected because the fatigue life is very sensitive to the value of stress because of the power law that we have for stress-life relations.

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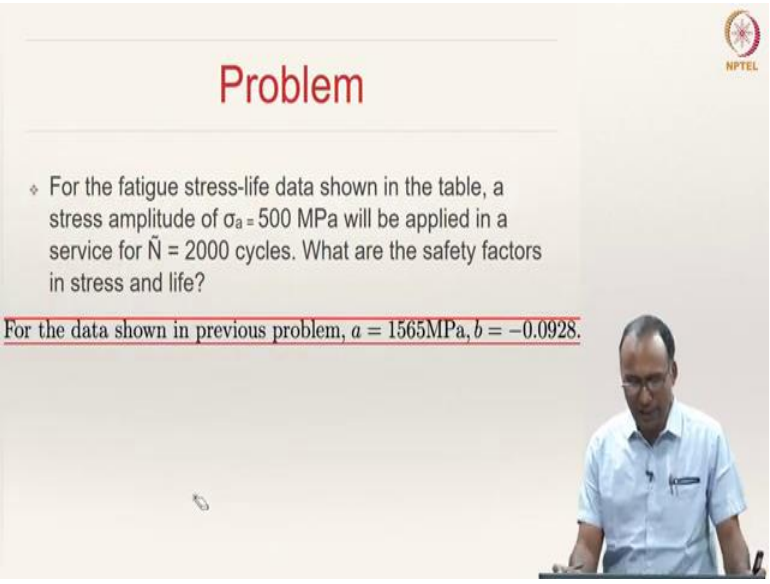

Let us now look at a problem. In the previous problem, we have found the values of a and b. For the fatigue stress-life data shown in the previous table, a stress amplitude 500 MPa is applied in a service life of 2000 cycles. So, that means, you are designing a component made of this material and that component is subjected to a stress amplitude of 500 MPa and the design life is 2000 cycles. You are telling your customer that you can apply a stress amplitude of 500 MPa and I am giving you a design life of 2000 cycles, i.e., the component will not fail before 2000 cycles; that is what you are telling your customer.

Now, you need to know the design safety factors for life and stress for this particular component. So, how do we go about doing that?

You need to calculate the number of cycles to failure at this stress amplitude and the value of stress at which the material fails at this number of cycles.

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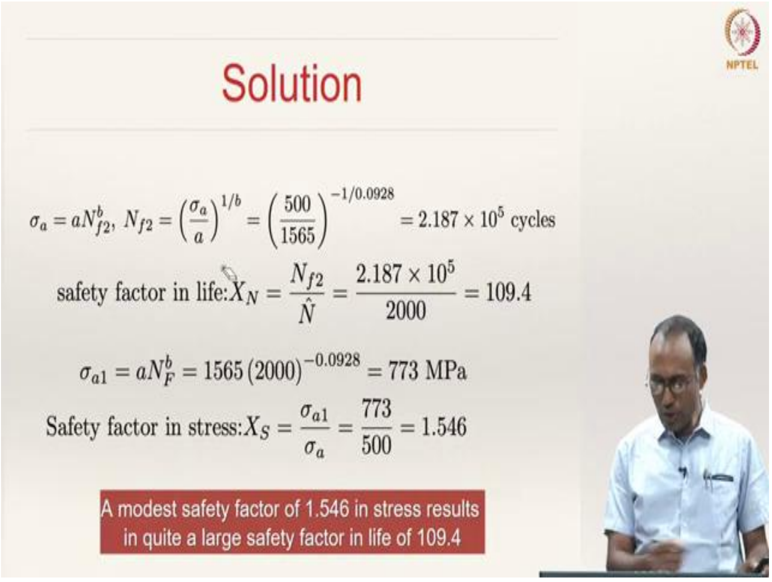

You can do that calculation by knowing a and b and then you will calculate that for 500 MPa, the material fails at 2.187×10^5 cycles. The factor of safety in life is $\frac{N_{f2}}{\hat{N}}$. $\hat{N}$ is the promising number of cycles that is 2000 and the factor of safety in life is 109.4; there is a huge factor of safety in life.

Now, let us calculate factor of safety in stress. The failure stress corresponding to 2000 cycles turns out to be 773 MPa. What is the operating stress amplitude? 500 MPa. So, the factor of safety in stress is 1.546, right? We have a modest factor of safety of 1.546, a reasonable factor of safety in stress. But you have a very large factor of safety in life, and that is typical when we are doing a fatigue design.