Basic Construction Materials
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Lecture-09
Materials Engineering Concepts-Part 6
(Mechanical Properties (Cont'd))

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Now another phenomena is a fatigue failure. What is fatigue? It is a type of failure that occurs in structures subjected to dynamic fluctuating stresses. It means the stress might change from tension to compression or compression to tension. So, these kind of fluctuations might happen in the stresses and that leads to a failure phenomenon called fatigue failure and this is widely observed in metal structures. About 90% of the failure of metallic materials is due to fatigue. It is an important phenomena when we look at metal structures.

In case of civil engineering, there are steel bridges and steel structures. But the steel bridges are more prone to fatigue failure because bridges are used by vehicles and you have moving loads on the bridges like vehicles when they pass. Vibrations are induced onto the bridge structure and that can lead to this kind of fluctuating stresses which lead to eventual failure.

So, here are some examples showing demonstrations on fatigue related distresses on the bridges. You can see here on the top left, this is the bridge, you can see the steel truss over here and this figure is the top view of the same bridge. It is Minnesota i-35 bridge, which collapsed due to fatigue related failure and also some people say there were lack of redundancy in the structural part.

Let us focus here on that fatigue because there are reports which says it is due to fatigue failure. Another example where there is a 7 foot long crack on a bridge you can see here, it is the steel girder. Another example where there is a crack on here also you can see another crack on the steel members and here is another crack which you can see on the steel member.

So, there are many steel bridges which are vulnerable to fatigue failure. Other industry when we look at aircraft's machine components and all those also have experience severe fatigue related distresses.

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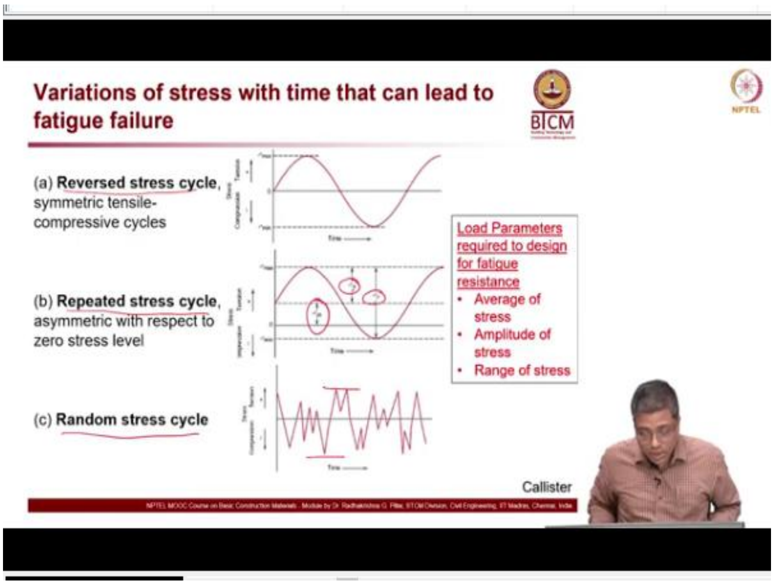

Now what are these loads where we just talked about variation in the stress from compression to tension, tension to compression? In general we can classify them as 3 type of cyclic loading. One is reversed stress cycle, where you can see the first graph on the top where it is symmetric in nature along the axis. That means this height (above) is same as this height here (below).

The amplitude is same, both for compression and tension, you can see the above the graph it is tension and then here it is compression. Now for the next case, repeated stress cycle, here it is not necessarily symmetric like the above case, you can see the graph center line is here or the zero stress line is here and then you have compression here and tension.

So, you have more tension in this particular case than the compression. So, that is another case and the third case is random stress cycle, which is probably the most common in case of civil engineering structures. Because most of our loads are not well defined, if you are talking about a bridge, you cannot really define the type of load, the actual load which is coming on to this particular truss element.

Because that depends on the type of vehicles, the weight on the vehicle and many other factors play a role on that. But, still for design purposes we try to design by using 3 parameters which are mainly the average of the stress, then amplitude of the stress and the range of stress. So, these 3 parameters we consider for design purposes and by approximation of the loads which are coming.

So, this will give me the range of the load here and then maybe I am able to model if I can model this load pattern and then try to fit it to some kind of equation and model it nicely and then, it can be used and the corresponding 3 terms like the average and the amplitude and the range of stress can be used. So, here in the second case I will show you what is the average?

So, this is the average line here and this is the amplitude for the compression and then you have this is the total range of the maximum compression and maximum tension. So, all these parameters can be used to design the structures.

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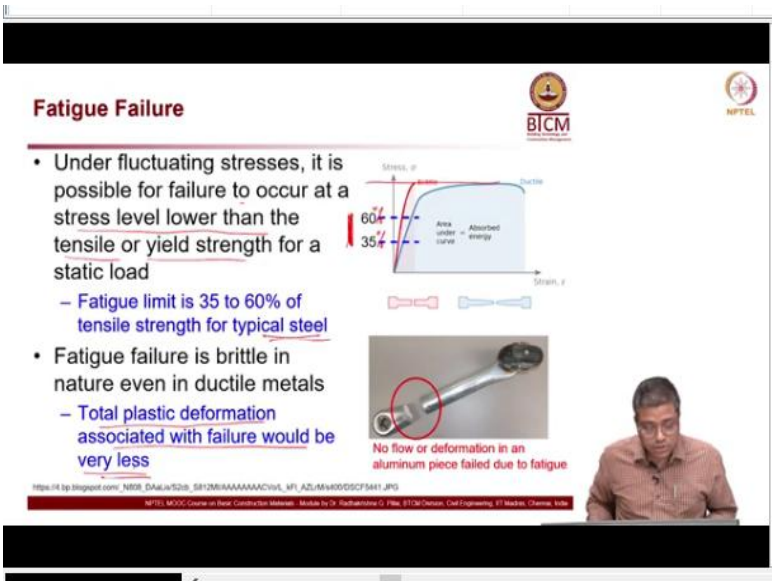

Now let us see what is the mechanism which is happening when you talk about fatigue failure? So, you can see on the top right, I replotted the same graph which we used earlier.

So, assume that this is the stress strain graph and then fatigue failure can happen at a lower stress level than the actual ultimate tensile strength or compressive strength of the material. Now you can see here, under fluctuating stresses it is possible for a failure to occur at a stress level lower than the tensile or yield strength for the static load.

We are focusing here tensile strength here. So, this can happen at this condition here. That means this even if the stress is much below the ultimate, the ultimate is somewhere here. So, only 35 to 60% of the load if it is there, there is a possibility of fatigue failure to occur, especially in case of typical steel. Now fatigue failure is brittle in nature and steel you can say it is a ductile material.

But still when it fails it can fail in a brittle nature. Here, I am showing an example of an aluminium piece which is highly ductile as compared to steel. But still, aluminium piece which is broken by fatigue mode, you can see that there is no really flow of the material here and it just broke into 2 pieces without really deforming like in usual case, as the necking that is not happening here.

If the same aluminium piece is pulled in a tensile strength test, you might probably see necking and then cup and cone failure, but here you are not seeing that. This is because it is a fatigue induced failure**.** So, the total plastic deformation associated with the failure would be very, very less even if the material is ductile in nature.

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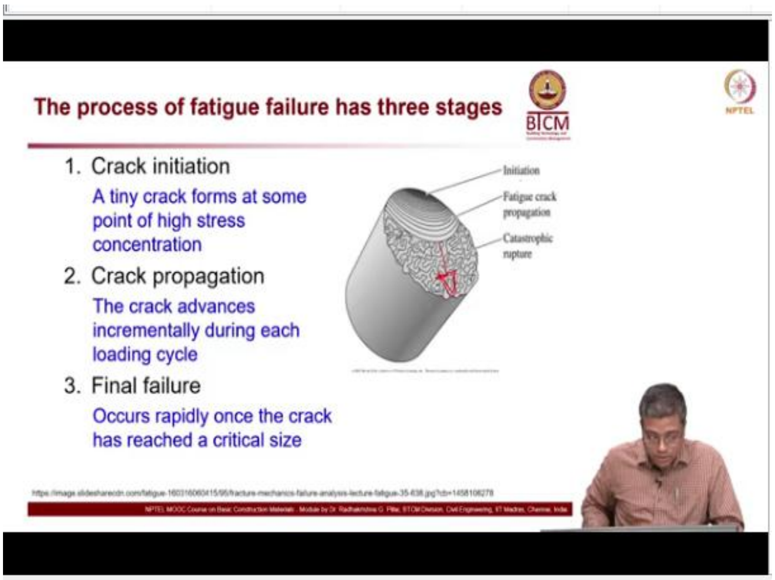

Now how the fatigue failure would happen? There are 3 stages for this, stage one is crack initiation, it happens right here and then stage two is crack propagation, which happens up to this much distance and then the remaining portion is stage 3 or the final failure. Now if you look at the time taken for all these, initiation of course it just happens when there is a small crack or something which is happening.

But the crack propagation period, that will be very long as compared to both the first and third case. You will have several cycles to undergo before I mean all these lines over here indicates one by one cycles, cyclic loading which could be in millions. Here it is easily demonstrated to see as lines, but there could be millions of cycles or millions of those crack propagation steps.

Once it reaches some threshold level, then the remaining material fails all of a sudden (very quickly). That is the final failure, the third step.

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Here is an example for that, you can say this initial crack happened here and then you have the propagation phase and then from here, it is all of a sudden the final phase. So, here the smooth region you can see on the top is the initiation region and then the propagation region and then this is the third face here, the darker colour region.

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Now if you look through a microscope, you can see the same pattern and also you can see striations depending on the microstructure and the type of loading which the material is experiencing. All these narrow and small lines indicate different loading cycles or a small failure propagation of the failure under each loading cycle**.**

They also call it as beach marks or clamshell marks, because it looks something similar to that**.** In microscope, when you look, you can probably see that millions of cycles shows the evidence that it does not happen in just few cycles of loading.

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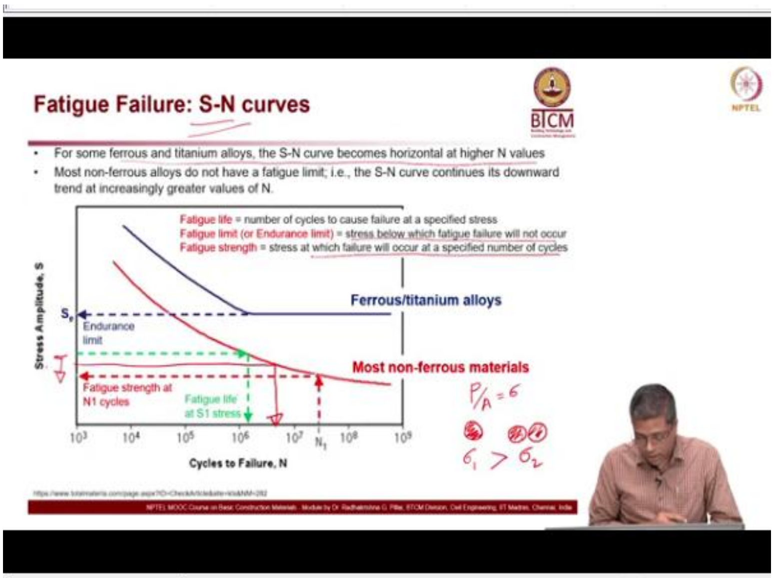

Now, how do we take care of this problem in our design? When we design structural systems knowing that there will be cyclic loading how do we handle that? So, there are something called S-N curve. S stands for the stress amplitude and the N stands for the number of cycles until failure. Now, you can see 2 curves here, one is a red curve and another one is a blue curve.

The red curve is for the most non ferrous materials and the blue one or dark blue for the ferrous or titanium alloys. Let us first discuss the ferrous or titanium alloys and then we will go to the non-ferrous material. Some ferrous and titanium alloys becomes horizontal at higher N values or more the cycle it becomes horizontal. You can see this in graph over here, it is more or less horizontal after about 10^6 cycles.

Now that is a very good property which the ferrous or titanium alloys have. That limit or the corresponding stress value S_e or endurance limit or the fatigue limit. It is a stress below which failure due to fatigue will not occur. So, it is a good thing because, if the stress level acting on the material is going to be less than S_e for that material, then you do not have to worry about fatigue failure.

Because no matter how many cycles you have, it is still going to be flat, this curve is going to go like this. So, there is no fatigue failure if the applied stress is going to be below the endurance limit. Now let us talk about the non-ferrous materials. Here there is nothing like endurance limit or fatigue limit. Let us look at the red dash arrows there.

So I am going to start from N_1 and go upward and hit the red curve, let us say some non-ferrous material and now I go leftward and I reach here. That is the fatigue strength, which is the stress at which failure will occur at a specified number of cycles. Specified number of cycle in this case right now I am discussing is N_1 and that means the material will fail when the stress is here.

So, let us say this point I am going to call S_0 and now look at the grid. This is the case where I am in a design stage and knows, the number of load cycles which the structure is supposed to experience or withstand.

That is N_1, and S_1 is the stress corresponding to N_1. Now, what I have to do as a designer is that the stress which is going to be experienced by the material should be kept below S_1. As long as I do that the system will survive for N_1 cycles that is the idea. So, applied load has to be less than S_1. This is the design stage.

Now let us say you are talking about a bridge or any structure which is already built and you want to see maybe there is an increase in the load or something, so you want to assess the remaining life of the structure. So, what do you do? You know the stress which is applied, that is known in the green case here, and look at the change in the direction of the arrows.

So, you go from here to the right and hit the curve and then come down. That is about 10^6 cycles. Now what we have to do is, if this is the load which is supplied, let us say stress which is applied is S_1, it comes here to the green text here, saying fatigue life at S_1 stress.

So, that fatigue life is 10^6 or about that. Now, I can say how many cycles the structure has already experienced and what is remaining cycle, because I know that if the current load is being applied, it will not stand beyond 10^6 or approximately that. So, as a person who is in charge, if the life of the structure need to be extended, you have to reduce the S_1.

And probably start somewhere here and then go further and then make sure that it gets more life. So, this is the use of this kind of graphs, as we can design the structure to resist fatigue load and also we can design or retrofitting strategies to ensure that the structure really meets the new demand. So, you might sometimes want to increase the size of the column. Let us say there is a column which is originally of this size and now you have to reduce the stress a little bit, what you do, you put additional column.

So, that the entire load which is coming is going to be half of that, because the total load P is same. Now P/A is the stress. So, stress in case 1 and stress in this case 2 stress, 1 meaning only one of this column and then stress in case 2 will be 2 columns. Now when you double the area, definitely the stress in case 2 is going to be less. So, that means we can actually increase the life by reducing the stress applied. So, this is the whole idea.

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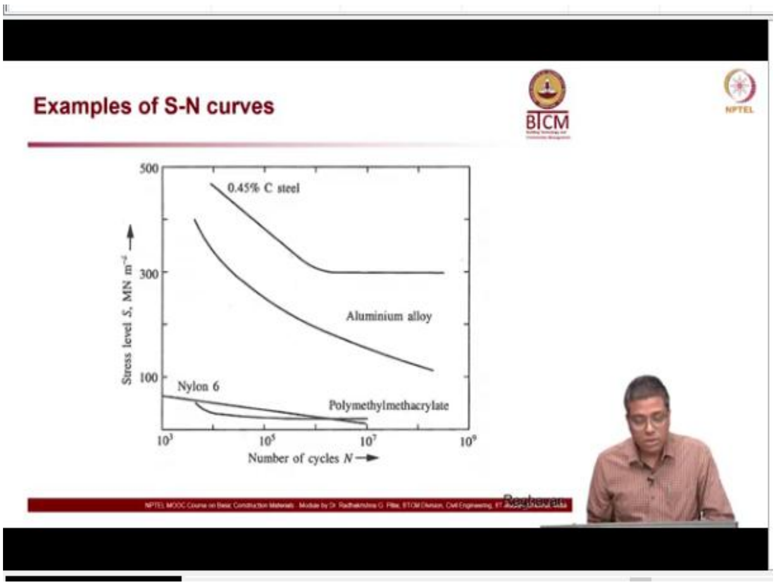

Now these are some examples of S-N curves, this is for steel, you can see this flat region here and then you have alloy which is going down like this and you have nylon which is also going down. So, looking at these curves we can decide and can use these curves both for design purpose and for analysis purpose, analysis and life extension purposes.

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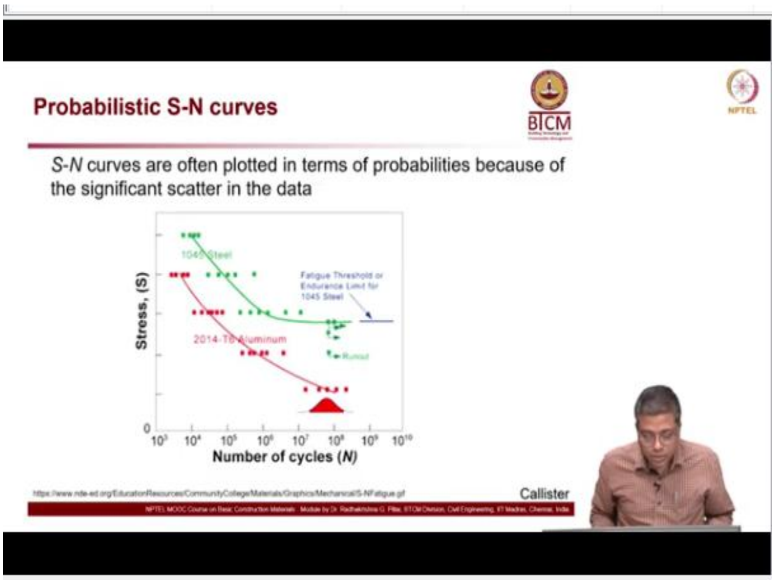

We just discussed very simple graphs, but when in reality when we actually do this test on various materials, there is lot of probability which comes into the picture. As you see on these graphs you can see here in the green and red one's there will be a lot of variations.

How do we handle these variability in the test results? We can look at the variation at every point and then draw some probability based curves. So, I am going to show you that in the next slide on probability base curve. So, for example, here I can say that this is probably the mean value and then the graph is moving like this. There is a mean value associated with the data and then also the probability or the scatter.

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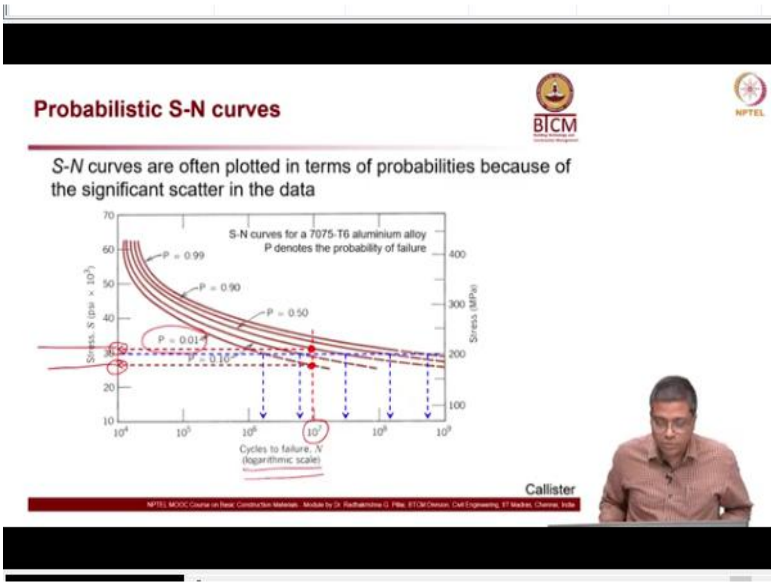

Now these are graphs made based on the type of data which is obtained previously and then you draw these different curves associated with different probability of failure 0.99, 0.9, 0.5, 0.1, and 0.01. So, I have 5 curves here indicating different probability of failures. Now focus on the blue dash lines, you can look at the horizontal blue line. Now I know corresponding stress is 200 mega pascal, the stress corresponding to the horizontal blue line.

Now I have to look at the number of cycles at which some probability of failure can be defined. For example, if the system reaches about a little bit more than 10^6 cycles when N is equal to about here, the probability of failure is 0.01. If the number of cycles is here, then probability of failure is 0.1.

Similarly, I can find the probability of failure corresponding to different number of cycles or load cycles. So, when it reaches that particular load cycle, I know that how seriously I should take care of the repair activities or other maintenance activities or retrofitting, so that I can still bring the probability of failure down.

Now look at the red dash lines where I am going the other way, where I am putting one cycle here 10^7. At that time I can find out at what load or the stress applied what is the corresponding probability of failure. So, if I want the probability of failure to be very low, I have to decide on what is that corresponding stress which I can allow**.** So, here you can say 10^7 and then corresponding point here.

And if I want the probability of failure to be very low at 0.01, then I have to keep my stress level at this value. If I am okay to have a probability of failure of let us say 0.5, which is not really a good case (but for the purpose of demonstration I am showing that here, the second the one above), then I can go for a stress value of that much**,** about 30. So, this is the use of this kind of probabilistic S-N curves. One thing to note is on the horizontal axis you have logarithmic scale**.**

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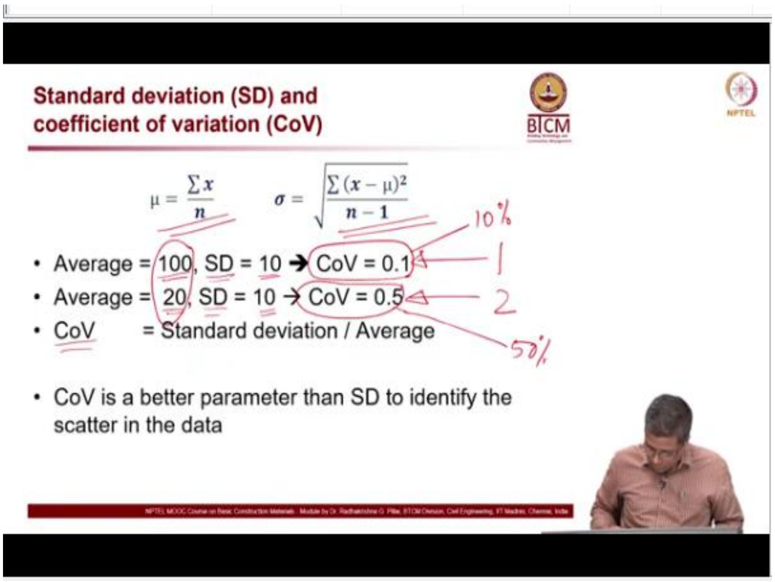

When you talk about this variability, I think it is also important to know the difference between standard deviation and coefficient of variation. Average is mu (μ) which is sum of all the values divided by the number of values and also standard deviation sigma (σ), now sigma or SD and CoV is the coefficient of variation.

Now take case 1 and case 2. In case 1, let us say the average value is 100. I am going to show you here which is more important parameter for you to consider and why probably standard deviation is not a good parameter to consider always. So, let us say case 1 average is 100 and standard deviation is 10, what is coefficient of variation? It is 0.1 or let us say 10%**.**

Now in this case 2 average is 20**,** standard deviation is 10 and coefficient of variation is 0.5. So, I can call it 50%**.** Now you can see in both cases 1 and 2 standard deviation is 10, but coefficient of variation is 10 and 50. So, there is a huge difference in the coefficient of variation. So, it is very important to consider coefficient of variation when you want to compare or look at the error or scatter in the data or variability in the material properties etc. It is very important to consider coefficient of variation and not always the standard deviation.

You can look at standard deviation, if the mean values are also in the similar range. If the mean values like here, if they are widely separated values then coefficient of variation is probably a better parameter than the standard deviation**.**

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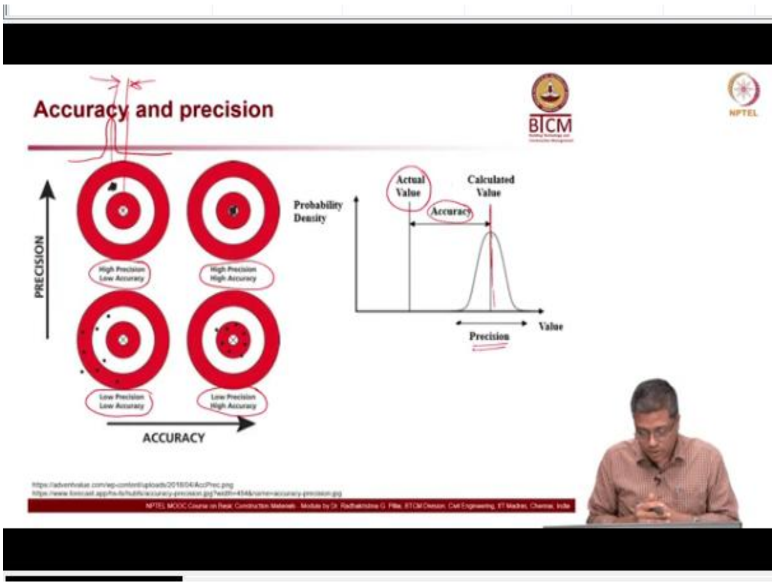

Another concept which is very important is difference between accuracy and precision**.** We sometimes get confused with these. So, here look at these 4 dot boards. You can see on the bottom left, it is of low precision and low accuracy, because all these black dots are all over the place and it is widely separated, nothing is close to the center point**.**

Now look at bottom right, we see low precision and high accuracy. All those black dots are very close to the center point but not necessarily right on the centre. There is still some variability involved in that. So, variability is not very good, but accuracy is very good.

Now in top left it is high precision and low accuracy. You see all the black dots are very close to each other**,** but none of them are close to the center point. So, that is the case of low accuracy but high precision, all are very close to each other. Now the fourth one, high precision and high accuracy as all the points are close to each other and also they are all very close to the center point. So, these are 4 different cases.

I think this is a very easy way of demonstrating the difference between accuracy and precision. Now in sketch a slightly different way, when I said precision I use the word variability, this is kind of the scatter in the data which is available. So, the more the width of this probability density function, it is going to be less precision i.e. less precision, the more width.

Now if you are talking about accuracy, it is how far the mean value of the calculated values are going to be from the true value or the actual value that is the distance between the mean and mean, like if you look at the one on the top left, the dot you can see here, the mean of that is very much away from the center point. It is widely separated, so it is not accurate but the precision is very good.

Because if I draw a graph like the pdf on this it will come something like this. So, the width of the pdf is narrow, but it is away from the true value. So, the true value is here and this is slightly away. So, you can relate the sketch on the left and right side.