Fracture, Fatigue and Failure of Materials

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Lecture 12

Plane Strain-Plane Stress Fracture Toughness Testing

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Hello everyone, and here is the twelfth lecture of the series Fracture Fatigue and Failure of Materials. In the last lecture, we have seen how plane strain fracture toughness is being determined. And in the present lecture, we will continue with that and we will then move slowly towards the next step towards plane stress fracture toughness testing.

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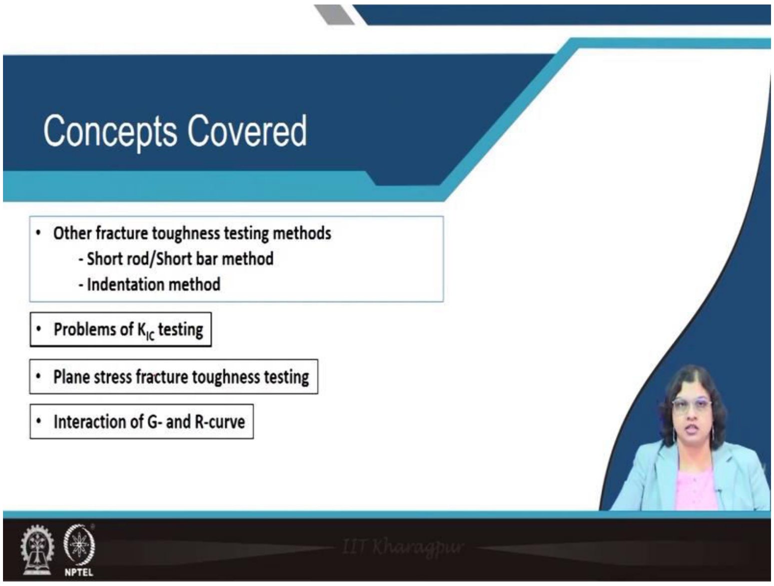

So, following are the concepts that will be covered in this lecture, apart from the typical method that we have discussed in the last class, we will also show that other fracture toughness testing method particularly for brittle materials, such as short rod or short bar method or indentation method. And, we will also discuss about the difficulties with K_{IC} testing, and then we will move on to the plane stress methods or fracture toughness testing. And for this we will see the interaction between the G and the R curve.

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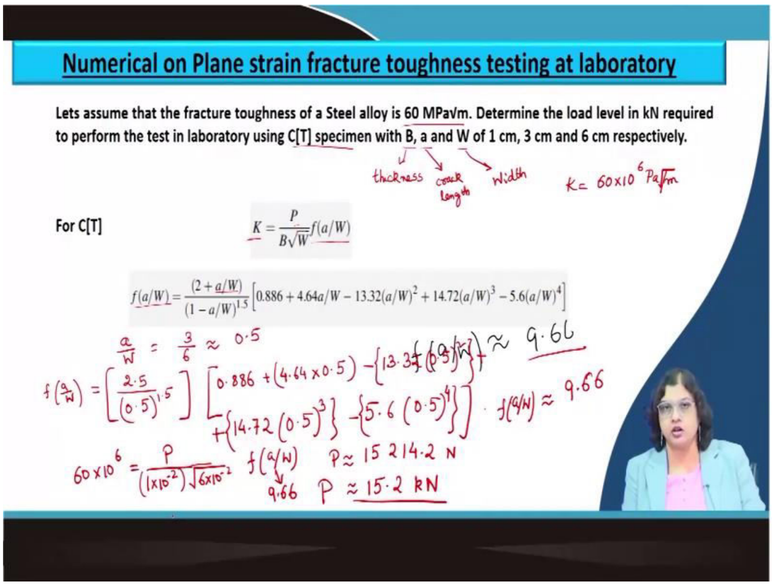

So, before we proceed further to continue from the last lecture, let us solve a numerical on the plane strain fracture toughness testing what we do in the laboratory. So, here is a problem statement which says that there is a steel alloy which is having fracture toughness value of 60 MPa√m, we need to test the fracture toughness of this material in a lab scale machine and we are using a compact tension specimen which is having the thickness crack length and width of 1 cm, 3 cm and 6 cm respectively.

So, for clarity, let me also write it one more time that B corresponds to thickness, a is the crack length and W is the width of the C[T] specimen which are respectively given as 1, 3 and 6 cm. Now, for C[T] specimen the relationship between P and K and f(a/W) function f(a/W) has also been provided. So, what we see here is that this f(a/W) stands on this ratio of a/W, so, let us figure this out first. So, a/W is actually nothing but 3/6 cm which makes it 0.5. So, if we simply plug in the values of 0.5 to this relation, let me just write it down for convenience. So, this f(a/W) comes around. So, this is

$$f(a/W) = \left[\frac{2.5}{(0.5)^{1.5}}\right]\left[0.886 + 4.64 \times 0.5 - 13.32 \times (0.5)^2 + 14.72 \times (0.5)^3 - 5.6 \times (0.5)^4\right]$$

So, if we simply solve this, this comes around 9.6. I am not doing the calculation here but you can simply use a calculator and find this out quite straightforward. So, it is coming around 9.66, let me write it down a little bit clearly.

So f(a/W) is 9.66, if such is the case, the let us see the P value. So, another thing we have to be carefully considered here are the units. So, the fracture toughness of this material or K or K_{IC} for that matter is given as 60 MPa√m. So, since we are talking about the relation between load and fracture toughness, so, the typical unit of load that is being used is Newton and if we are talking about MPa then that is equivalent to 10^6 N/m^2.

So, we better should write down K as 60×10^6 √m. So, if we write that we simply can use this relation as 60×10^6 that is given by P/B, B is the thickness which is 1×10^{-2} everything in for the dimension of length should be in meter and W is 6. So, that is root over 6×10^{-2} and then the f(a/W) which is 9.66.

$$K = \frac{P}{B\sqrt{W}} f(a/W)$$

$$60 \times 10^{6} = \frac{P}{1 \times 10-2 \sqrt{6 \times 10^{-2}}} \times 9.66$$

So, if we just solve this let me do the denominator first. So, P comes around 15214.2 N and for convenience we should better represent this as 15.2 kN. So, that is what is required we require the load capacity of 15.2 kN machine this is very important often we need to determine that what is the maximum load level that will be used and with that we can figure out that whatever load capacity machines we are having whether that will be sufficient or not.

This also varies if we are changing the specimen type for example, instead of compact tension specimen if we are using a center cracked tension specimen CCT or an SENB specimen single edge notch beam and having these different parameters by knowing this relation between K and P and the function f(a/W) which as I mentioned in the last lecture are provided the either the ASTM handbooks are also in the appendix of any of the mechanical behavior books or fracture mechanics book you can easily get that and based on that we can determine.

Now, this is very important since this course is not only on the theoretical concept, but we have to use it for practical experimental part to determine the failure mode and often the whether the fracture toughness values has been met by the component or structure the failed one we need to often do these kinds of analogies.

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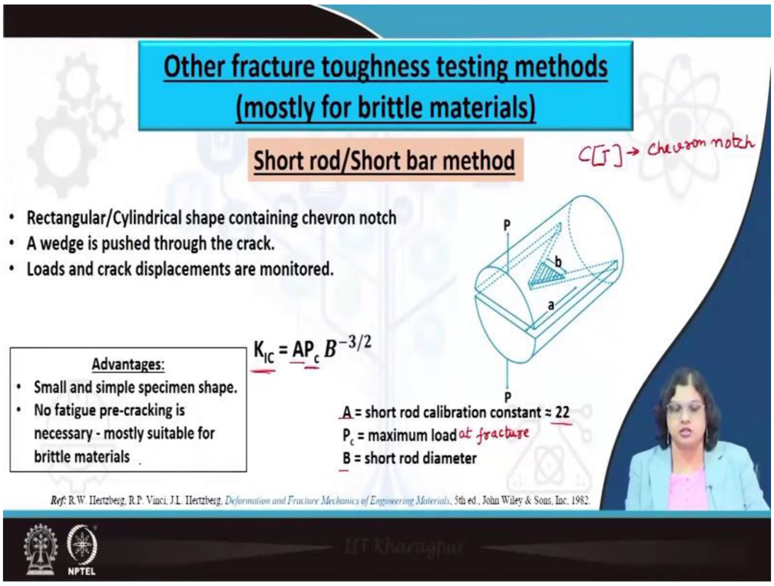

So, with this let us move on to some other methods by which fracture toughness is measured particularly for brittle materials. Now, the problem that we cannot use the method that we have discussed in the last lecture is that in case of brittle material, it is very difficult to machine a notch or certain configuration. So, that is why we go for a little bit simpler method where the specimen preparation is not that difficult to go ahead with the fracture toughness testing.

And in this case, the short rod or bar method what we use is either a cylinder or a rectangular specimens and we can see that there is a notch also, a chevron notch here which can be machined the way it can be machined in a brittle material, and then what we do is we push a wedge this triangular piece here, so, that the fracture happens and in turn the loads and the crack displacements are monitored.

So, in turn we can calculate the fracture toughness values as simply as this we need a calibration constant A. So, typically for the short rod configuration, this constant is around 22 and also the rest of the thing Pc is the critical load at the point of fracture, so, it is a maximum load at fracture, we can get this from the instrument and B is the short rod diameter. So, when we are machine, so when we are having this specimen we already know the diameter. So, in this case please be sure that this is not the thickness that we are talking about B here represents the short rod diameter, you can use the symbol B also if that is convenient.

And if we have these values particularly if we have the Pc value, which is the load at the point of fracture we should be able to figure out the K_{IC} values also quite well. The major advantages of this kind of technique is that we need a small and quite simpler specimen we do not need much of like a bigger specimen which is difficult to machine and there is no need for any fatigue pre-cracking and particularly suitable for brittle materials.

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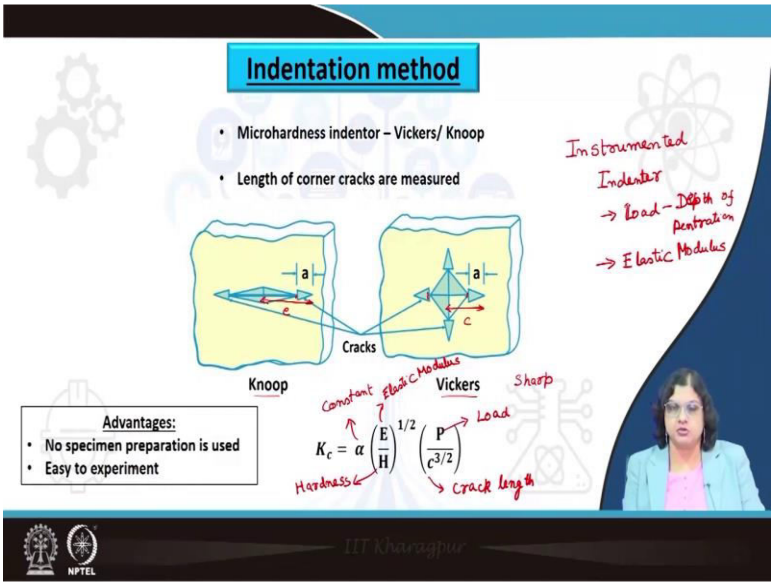

So, apart from that there is another method known as the indentation method or indentation fracture toughness which is also very much relevant and very much conveniently used for estimating the fracture toughness of brittle materials. Now, this is quite straightforward and simple and we actually do not need much of a material just a small piece which is well polished is enough what we need here is to have a specimen which is perfectly flat, both the planes are flat and it is plane parallel which means that there should not be any slant surfaces, this is particularly required because when we are indenting we are developing we are providing the force at a particular point and if there is any change in the topology that will lead to erroneous results.

So, we should take a flat and a very well polished sample, smooth sample surface. And we can indent this with either Knoop indenter or Vickers indenter. So, both of these are sharp indenters, sharp means which has a very pointed indenter tip. In case of metallic materials it will simply indent and it will leave us a impression metallic or ductile materials and from which we can determine their hardness as well as sometimes elastic modulus in case of brittle material this is not so straightforward rather it cracks, from the edges, from this corners of the indent impression it typically cracks and we can determine this crack length from the center to the edge of this crack this is termed as c from the center of the impression till the edge of the impression.

So, this is termed as c and if we know that we also need to know the elastic modulus, we can either use the literature values from references as the elastic modulus or in case the indentation is an instrumented one, instrumented one, instrumented indentation means where we can get the load versus displacement curve.

In case we are using an instrumented indenter which gives a load displacement or depth of penetration actually depth of penetration curve if we are obtaining that we should be able to figure out the elastic modulus also for the same material at the same load level. So, that will be more relevant to use, but in case we are using macro vickers or micro vickers, which is not having this instrument and indentation facility, then we can typically use the elastic modulus of the material from any standard reference journals.

Also H is the hardness which we can get from the indentation test itself So, these two values typically are generated from the indentation test itself, P is the load level which again we can record from the instrument during the experiment and c as I mentioned is the crack length. So, we can put it in such relations and we should be able to find out the Kc. α is once again a constant and typical values of α is something like 0.16. So, these are also some of the other methods which are used for estimating the fracture toughness. The main advantages of this are as follows There is no specimen preparation is required and it is quite easy to handle the specimen as well as to perform the experiment.

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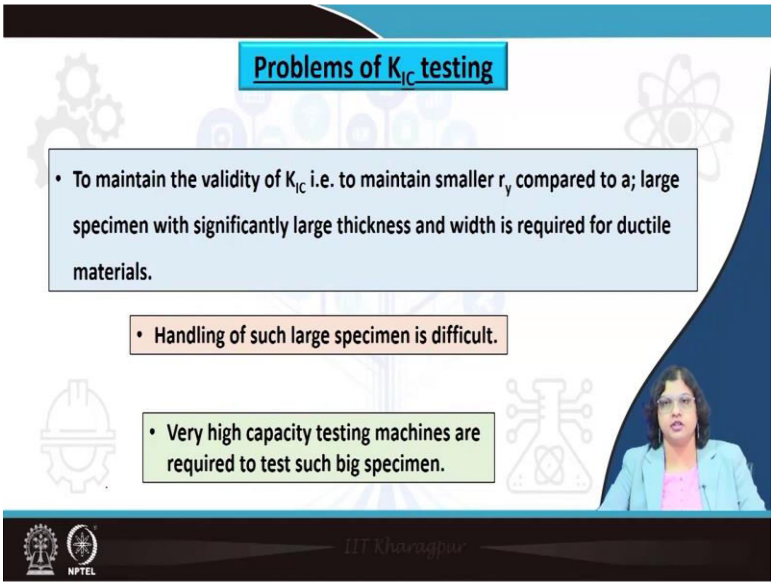

Now, coming back to the very Basic and the typical K_{IC} testing that are particularly used for a wide variant of materials, we should be also aware of what are the main disadvantages of K_{IC} testing, we already know about the advantages in the sense that plane strain fracture toughness testing gives us the lowest value and the constant value which is not bound to change and we can quote that as a materials property, but, at the same time, we should be also aware of the disadvantages of this testing.

First of all, the major disadvantage is that to maintain the validity of the K_{IC} that that is to make the r_y typically very, very small, actually 158 times the thickness of the specimen that is what we have seen in the last lecture. So, for that we need to have very, very large specimen with very large thickness, especially, the more ductile the material is larger will be the plastic deformation at a certain load and that will make us use even thicker specimen to get the valid plane strain condition to be active.

So, that means that more ductile the material is we will need more and more bigger specimen. So, that is sometimes quite difficult to get considering the kind of material that we are talking about considering the material being expensive and difficult to machine as well as to handle that also makes it quite difficult.

And not only that, we have also seen in this numerical that we have solved in this class that we need a certain high load capacity for testing of course, this is in comparison to the plane stress condition or have we use a thinner specimen, but if you are using a thinner specimen may need a lower load capacity machine, but then the plane strain condition will not be achieved.

So, to make it to our advantage, what we do typically is to use specimens like the compact tension specimen, we have already seen that compact tension specimen has a higher value of Y, the geometrical parameter being as high as around 4 to 5. So, that makes the usage of the load quite less, but still in case of plane strain fracture toughness testing and in case the material is quite ductile, then we need very large specimen and that will require very high load capacity machine. So, for that, we have to go ahead with the plane stress kind of testing.

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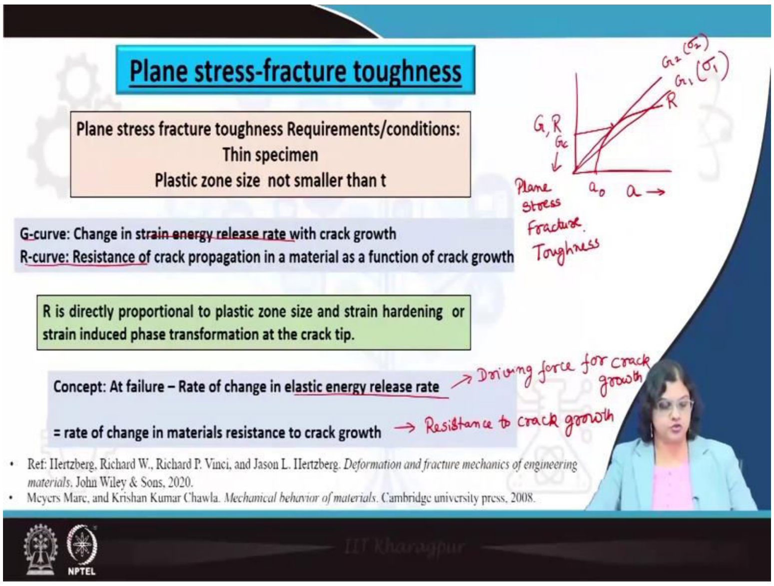

And again, for the case of plane stress fracture toughness testing, first of all we require thin specimen and particularly this is valid or this is to be done for materials or for the failure mode in which the plastic zone size is not smaller than the thickness it is actually it almost equivalent even it could be bigger than the thickness of the specimen then the plane strain condition is not valid anymore and we have to look for plane stress fracture toughness testing.

So, way to use this or to employ this concept is by using the G curve and the R curve let me elaborate on the G curve. So, G, the term G is the strain energy release rate, we are already familiar with this term. According to Irwin's modification, we have seen that how G is related to both γ_s and γ_p which means that it is already taking care of the plastic deformation part itself.

So, at least for those materials, where there is certain amount of ductility, so, G actually is considered as the driving force for crack growth. On the other hand, there is something known as that R curve. So, R stands for the resistance to crack propagation as a function of crack growth.

So, if we plot this, both G and R curve together, we should be able to figure out the point at which the G and R is equivalent, that is actually the fracture point. So, R is directly proportional to the plastic zone size R is a resistance to crack growth more is the plastic zone, actually the crack is being stopped being hindered by this plastic zone. So, plastic zone avoids the growth of the crack. So, in that sense plastic zone is beneficial, we always prefer to have some amount of plastic deformation prior to fracture that means, that ductile fracture is preferred to brittle fracture.

Now, R being the resistance to crack growth, more is the plastic zone more is the R or in other words, we can also say that if a is increased the crack length is increasing, higher crack length will lead to higher plastic deformation zone also that means, r is also increasing on the other hand G which is the strain energy release rate, which acts as the driving force for the crack growth. So, that also increases as we are increasing the σ value or the applied stress value. So, we have to tally this.

What happens at the point of fracture is that, at this failure the rate of change in the elastic energy release rate or the strain energy release rate which acts as the driving force for crack growth and on the other hand R acts as the resistance to crack growth. So, this too has to be tallied. And, at the point of failure, these two are getting equal values and then only fracture can come.

So, we have seen that at the point of failure, this G and, which acts as the driving force for the crack growth gets equal to the resistance to crack growth. So, if we want to draw that, we will have a graph something like this where the Y axis is either G or R and let us say X axis is the crack length.

Let us say there is a starting the initial crack length of something like a_0. And in this case, the resistance to crack growth will be like this. So, that is the R curve. On the other hand, for the G curve, we are getting straight linear curve something like this, let us say this is for G, we named as G_1 for a stress value of σ_1, if we increase the stress value, we are getting a different G curve with different slope and the point at which it touches the R curve, that is the point of failure. So, let us name this as G_2 for a stress value of σ_2. So, this particular one here is termed as Gc or we can count this as plane stress fracture toughness. So, that is the point when the crack will grow to fracture.

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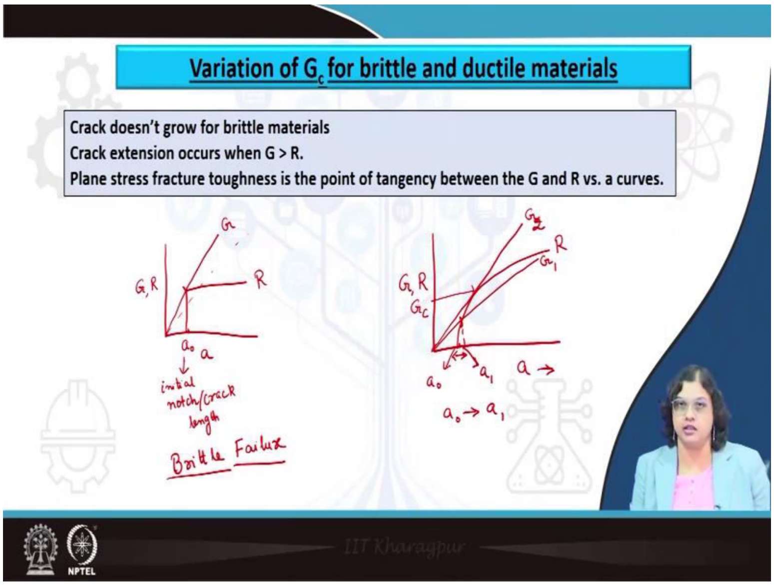

Now, in case of brittle materials, however, the crack is not supposed to grow, so, there should not be any growth of the crack on the other hand, in case the G value exceeds the R value, so, the amount of energy that is being released exceeds the resistance to crack growth, then there will be some growth in the crack and plane stress fracture toughness is just at the point of this tangency.

So, if we want to see this, how it looks different for the brittle and the ductile material, we will see that this is for brittle material, once again we have the G and the R on the Y axis and a on the X axis and let us say we have a starting notch of a_0. So, that is the initial notch length, notch or crack length.

And, in case of brittle material, actually the resistance curve will look something like this. At this point, there will be no fracture until it reaches certain value of R and then once it reaches there will be a instantaneous fracture catastrophic one. However, the G, the G curve on the other hand at this point will be something like this and at this point there, they will be tangent and there will be fracture.

If we are applying lower load value, then the G could be somewhere here also, but since this is not exactly the tangential position, there will be no fracture. So, this is for a brittle material. On the other hand, if we are brittle failure, if we are talking about the ductile failure, it will be something like this once again, the G and the R on the Y axis a on the X axis and we are starting with certain value of a_0.

And in this case, this will be the R curve for the ductile material and G curve can have different values as I explained. Now, let us say we have a G something like this initially, and for that, this point of intersection at this point of intersection between G and R, the crack is supposed to grow. So, this was a_0, and let us name this as a_1 for G_1. So, this is the amount of crack length that will be grown. So, the crack will grow from a_0 to a_1, if we are applying a G value of G_1.

On the other hand, if we are still increasing the stress value and there is a tangent, so, that is typically let us name this as Gc or this particular value of G is known as Gc or this one should be G_2. So, this particular point where the tangent occurs between G and R curve is the Gc. So, that is how we can figure out the increase in the crack length, which however, was not there in case of the brittle failure.

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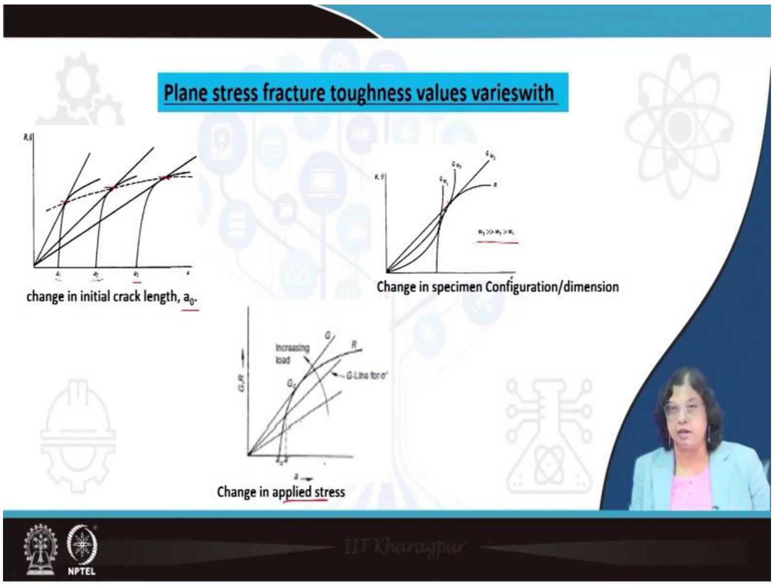

Now, not only that, plane stress fracture toughness also changes if we are changing the dimension of the component of the specimen, we have already seen that it is not a constant value. So, either if we are changing the initial crack length a_0, you can see that there are three different crack lengths that are being shown here, a_1, a_2 and a_3 and for each of these cases, the tangential value changes and that leads to slight alteration in the respective Gc values also, although not that prominent the major change in the Gc values will materialize, if we change the specimen dimension like the thickness of the specimen or the width of the specimen.

In this case, the width relation has been shown where width for the component 3 is much much greater than that of component 2 and 1 respectively. And what we see is that, this value is that the shape of the G curve also changes and that leads to a significant change in the value of the Gc, so Gc_1, Gc_2 and Gc_3 will be significantly different. And not to mention that whenever there is change in the applied stress, as we have seen that how the G curve changes, so, that will lead to a change in the tangential position also if we are changing the applied stress values.

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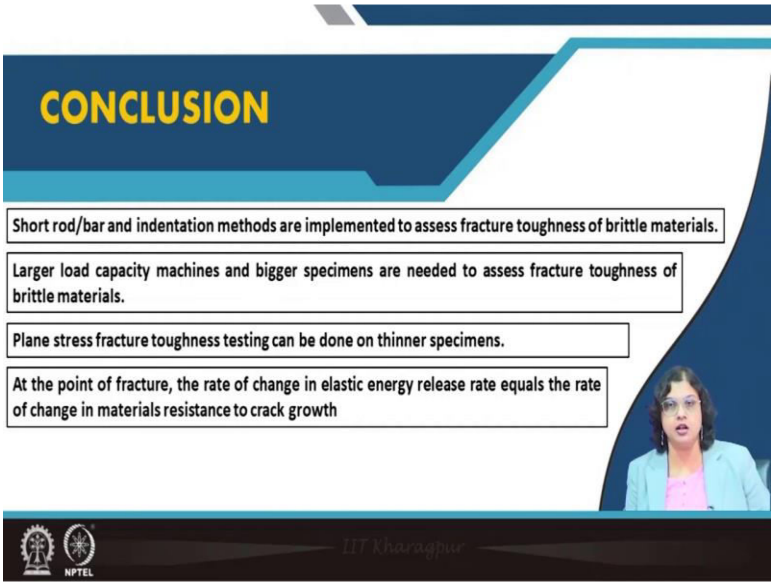

So, with this let us conclude this lecture. So, what we have understood here is that, the short rod or bar and indentation methods are some of the other ways by which we can estimate the fracture toughness particularly for brittle materials, these are advantages considering that we do not need a complicated specimen dimension or higher load capacity machine.

Typical plane strain fracture toughness testing in the lab scale, it does have some kind of disadvantages, which includes bigger specimen and as well as higher load capacity machine also, we have seen that for thinner specimen are the material which has significant ductile deformation we prefer plain stress fracture toughness testing and one of the ways to do that is by equating the rate in of change in the elastic energy release rate to the resistance to crack growth.

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So, these are some of the references used. And thank you very much