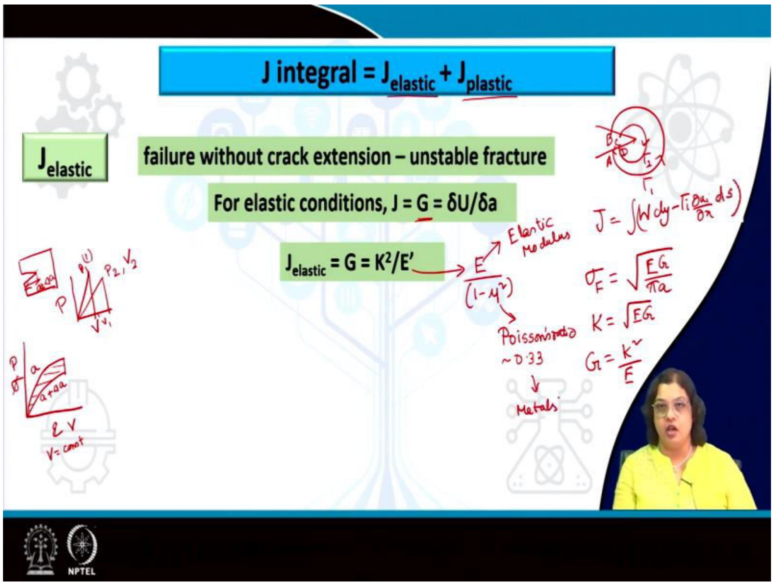
Fracture, Fatigue and Failure of Materials
Professor Indrani Sen
Department of Metallurgical and Material Engineering
Indian Institute of Technology, Kharagpur
Lecture 15
Experimental Determination of J 1C

(Refer Slide Time: 0:28)

Hello everyone, welcome to the 15th lecture of this course Fracture Fatigue and Failure of Materials. In this lecture, we will be talking about some more facts on the J integral. And the concept that will be covered in this lecture is primarily the physical basis of J integral and J_{IC} as well as how to determine that experimentally.

(Refer Slide Time: 0:52)



So, in the last lecture, we have seen that J integral is basically obtained for any contour and let us say we have a crack tip and we are talking about a contour in the immediate vicinity of this crack tip such that this is Γ_1 and starting from the point A and moving to B and then C with another contour, the direction of which, the direction of motion being opposite to that of the Γ_1. And finally, the surface segment D A is closing it.

So, we have seen that for every point of this our relation is valid, which is given by

$$J = \int \left(W dy - \Gamma_i \frac{\partial u_i}{\partial x} ds \right)$$

this entire relation is valid for each of the points and then this is integrated over the entire contour or the segments and then we are eventually getting the overall J integral value for this. And physically what it means is, if we have a stress-strain curve for a certain component let us say a C[T] specimen or even a SENB specimen and there is a certain crack length of length a, so, it forms a stress-strain curve or a load displacement curve for that matter.

So, load versus displacement curve will be something like this since it is having a plastic deformation, which is inevitable in case of J integral determination. So, if this is the one for the crack length a and then since the crack is growing or we are doing the experiment on another specimen with a slightly different crack length of a plus δa there will be a fall in the load and that should be something like this. If the displacement is constant, so, eventually we are getting this zone as the difference in the area which is signifying the energy that is required for the crack to grow from a to a + δa.

So, this also looks familiar to what we have seen in the concept of G the strain energy release rate. J integral also signifies the total amount of pseudopotential energy that is being released as the crack is growing or per unit growth of the crack length. So, that leads us to the very important concept of J integral is that consisting of two major parts, the elastic part, as well as the plastic component.

So, elastic part actually signifies the brittle fracture or the unstable fracture in which there is no crack extension once the crack starts to grow, let us say from here or there, it immediately leads to fracture, so that is the elastic or the unstable fracture mode and that is given by G. So, that is the same as that explained for G that we have seen for the elastic part of this curve. We have seen that it follows a straight line for the P versus V or the load versus displacement curve for a condition one, let us say it gets a point of P_1 and V_1, while if it is growing by a plus δa term for the elastic part, it will have a drop in the load and an enhancement in the displacement.

So, this will lead to P_2 and displacement of V_2. So, that leads to a change in the energy that is being released, which can be determined from the difference in this potential energy and eventually we can get the factor G. We can also explain this in a simplified form with respect to its relation with K and that has been first introduced by Irwin while Griffith criterion has been modified when we have seen that the sigma F which is nothing but the fracture strength determined by Griffith criterion and that is equivalent to

$$\sigma_F = \sqrt{\frac{EG}{\pi a}}$$

or we can rearrange this relation

$$K = \sigma_F \sqrt{\pi a}$$

$$= \sqrt{EG}$$

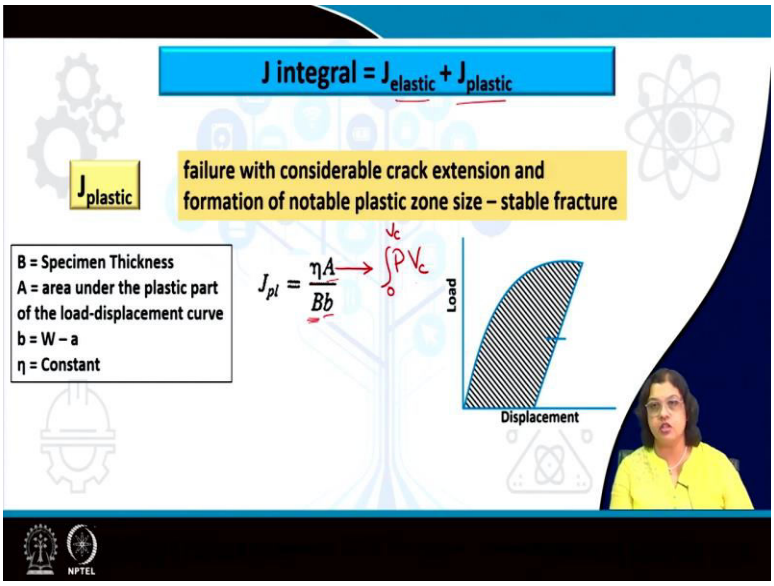
$$G = K^2 / E$$

So, that means that for the elastic part of this J integral J elastic is actually given by G or K^2/E, but it is not only E rather it is E' because we are talking about the plane stress condition now, and we have to consider the poison's ratio or the contraction in the perpendicular direction to this. So, that is actually given by

$$E' = \frac{E}{(1 - \mu^2)}$$

where μ is the poisons ratio E is the elastic modulus, typically, the value of μ for metallic materials is around 0.33. So, this is for metals it can have a different values for different kinds of material. So, that is what we have seen for the J elastic.

(Refer Slide Time: 7:20)



And now, moving on to J plastic, J plastic actually signifies some amount of crack extension due to the presence of notable plastic zone size which is which cannot be ignored anymore. And that leads to a stable fracture, means the crack propagation is slow unlike the unstable one that we have seen for the elastic component. So, in this case, the J plastic is actually is dependent on several factors such as η which is a constant and it depends on the specimen configuration and A, A is the area under the load displacement curve.

So, that can be obtained from a relation like this if we know the load and the displacement then up to the critical displacement at which fracture occurs, we can integrate this entire zone from 0 to Vc and eventually we can find out this entire area. This hatched section here which signifies the plastic area particularly.

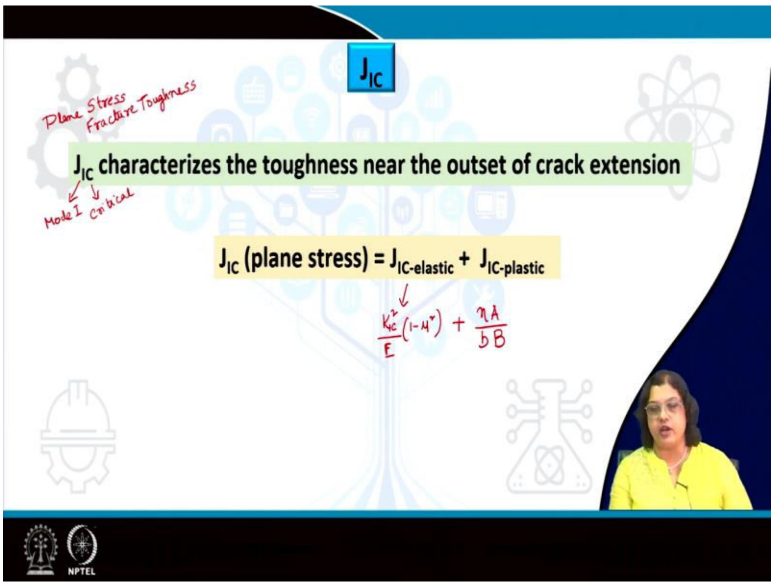
So, if we can do that, we can get the value of A and B capital B is the specimen thickness and small b is the ligament length which is dictated by the difference between the width of the component and the crack length of the component. So, this is the zone this is the region where all the plastic deformation starts or particularly happens within this area, so that is what is of significance and that is why we consider the small b term very clearly.

Also we can also see that the J plastic term is particularly dependent on the thickness which and that to inversely related to the thickness which means more is the thickness, as the specimen is getting thicker and thicker, the J component the plastic component of J is actually decreasing. Lower the value of B which means that thinner the component is J plastic increases.

So, that is what we have seen earlier also that how the plane stress fracture toughness is dependent on the thickness and not only that, thinner the specimen gets more and more the fracture toughness increases on the plane stress condition or in vice versa as the specimen or the component of the structure gets thicker and thicker fracture toughness values reduce until it reaches the plane strain condition when it is sufficiently thick, so that it encompasses the plastic zone well in within such type of plastic zone is almost one tenth of the thickness and then we can achieve the plane strain condition and the fracture toughness value is not changing any farther.

But we are well aware that one of the major disadvantage of plane stress fracture toughness is that it always varies and we have to consider this very carefully. So, that means that eventually if we want to find out this J integral, we have to compute both the elastic and the plastic components of this and the summation of this both these components will give us the overall J integral value.

(Refer Slide Time: 10:36)



And from there we can calculate not only J integral, but more specifically J_{IC}. So, J_{IC} characterizes the toughness and crack tip at near the outset of crack extension. So, this once again as we have seen this for the plane strain fracture toughness, which is termed as K_{IC} here the J_{IC} typically signifies the plane stress fracture toughness. So, let me just write it down here.

So, J_{IC} represents the plane stress fracture toughness and obviously, that means that the critical value of J integral at which fracture occurs that critical value is termed as J_{IC}, so C stands for this critical and once again as we have seen this for K_{IC} that 1 actually stands for mode one or the crack opening mode, when loading direction is perpendicular to the crack tip direction, and that makes it the worst possible scenario and we always want to predict the fracture toughness in the worst possible condition, so that in service it may not have this kind of worse situation and we can have a higher value of the fracture toughness.

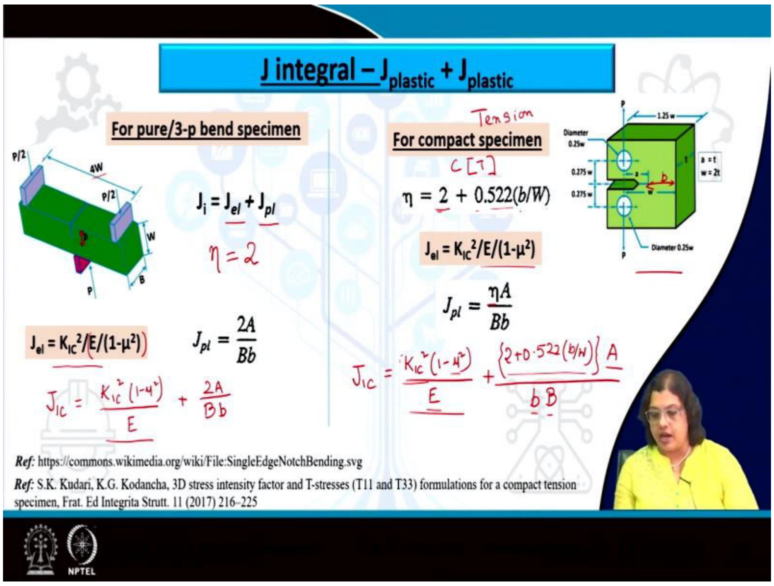
So, eventually that means, that J_{IC} can be obtained if we can obtain the critical value for the elastic and plastic component. Since, J_{IC} elastic is given by this relation here. So, this is given by

$$J_{IC\text{-elastic}} = K^2 (1 - \mu^2)/ E$$

$$J_{IC\text{-plastic}} = \frac{\eta A}{bB}$$

So, at the point of fracture if we are able to find this out, so, this will be K_{IC} square then and we will be eventually able to find out the J_{IC}.

(Refer Slide Time: 12:45)



So, again as I mentioned that the η factor is dependent on the specimen dimensions and the specimen configuration. So, let us see this for the two most important configuration or most widely used specimen configurations which are used for J integral testing. One is the SENB A SINGLE EDGE NOTCH BEAM SPECIMEN which is used for three point bend specimen or the flexure test kind of, but in this case, we have a crack length which has this half-length of a and all the other dimensions are maintained as per the ASTM standard.

And what we see here is the span length which is the distance between the two loading points, they should be four times the width of the specimen and if such is the case, then once again Ji or the total J integral will be the summation of the elastic and the plastic component and for this plastic component, elastic component we already know that this is given by

$K_{IC}^2(1 - \mu^2)/E$ but for the plastic part, we have the η or the materials constant that is

equivalent to 2. So, that makes the plastic part as 2A/Bb. So, let me write down the total term here then, so, J_{IC} will be given by

$$J_{IC} = K_{IC}^2(1 - \mu^2)/E + \frac{2A}{bB}$$

On the other hand, there is another kind of specimen which is very much used for fracture toughness testing and that is the compact tension specimen also known as the compact specimen. Most particular term will be compact tension specimen and this is also denoted as C[T].

So, this is the geometry of the compact tension specimen again following the ASTM standard. And in this case, the elastic part is same as that we have seen for any other kinds of specimen, but the twist is that in this case η has a value of $\eta = 2 + 0.522(b/W)$

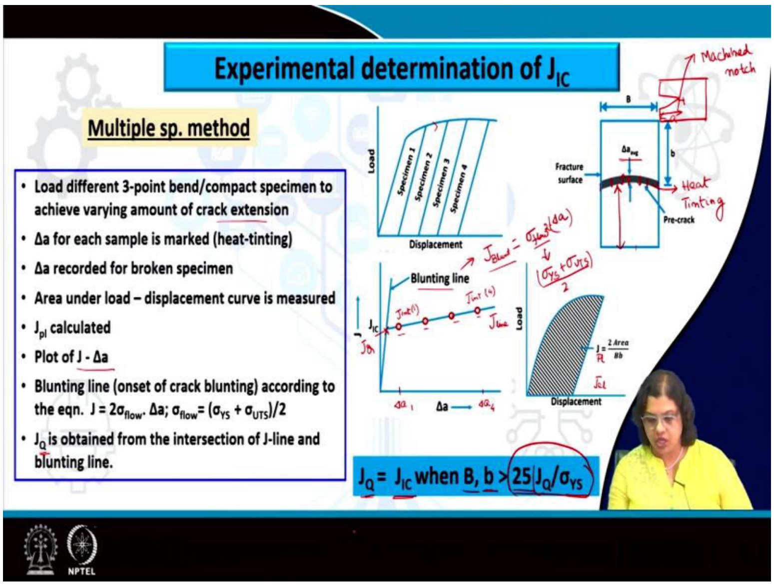
So, this b is the ligament length. So, essentially this is what is b here small b and the ratio of this multiplied by 0.522 and that added with these two terms will give us the overall η, so that makes J_{IC}.

The elastic part being the same, but we have certain differences particularly for the η part and that makes a difference in the overall value. So, this multiplied by A and then we have b times B. So, if we look into this carefully look into this relation, we will see that the first part, the elastic part, for both the cases, we can determine even without doing the tests. For example, this K_{IC} which is the standard fracture toughness values, and since this is a constant value, which is not supposed to change any more and the lowest one we know now, that the plain strain fracture toughness value can be quoted as the standard fracture toughness value other materials property.

So, this K_{IC} for most of the materials are also available in the standard handbook. So, we can obtain the values from there. μ is also other poisons ratio for most of the materials are also known and same goes for the elastic modulus as well, we can get these values from the literature itself. So, we can eventually calculate the elastic component which is nothing but the G basically. So, based on all these parameters obtained from the literature values, we can calculate that even without doing the experiment.

Coming to the plastic part again this b and B, both the small and the capital B, which means the ligament length and the thickness this can be obtained from the specimen dimensions even before doing the experiment. So, and that goes for eta value also, at least for these two configurations of SENB and compact tension specimen. So, the only factor that we cannot determine without doing the experiment is the A, the area under the curve and that makes us do the experiment, so that we can precisely determine the plastic part and this also varies a lot if we are changing the material, if we are changing the dimensions overall and as a result, we are getting all the differences in the values.

(Refer Slide Time: 18:08)



So, let us see how experimentally J_{IC} is determined because after learning all the concepts as well as the physical significance as well as the formulas giving us J integral or the J_{IC} values, we finally need to implement this to perform an experiment, to get the values in for real material, so that we can use this value for the application scenario. So, we can do this using multiple specimens. Specimens have similar configurations, but they might have different crack length or we can load it, so that the crack grows up to different levels.

So, this is a multiple specimen method. And in this case, let us say we are using a three-point bend specimen or compact tension specimen, and we are loading different specimens to achieve varying amount of crack extension. So, we are loading it like this. So, this is for specimen 1, and it has some amount of plastic deformation and then we are not using that specimen anymore and we are coming back to another specimen of same configuration.

And this is the load versus displacement curve for specimen 2, this has been shifted from the origin to make this clear, but actually all these graphs should merge with one another, the elastic part will merge with one another and we will see some differences in the plastic part. So, four specimens has been shown here as an example, that how we can get the load versus displacement curve for the four different specimens which are for each of these cases. Actually, they are slightly varying or slightly different amount of total crack length or the load that has been applied is different which leads to different crack length.

Now, after we have done this specimen actually what we need to know is how much the crack has been extended. Initially, we have a specimen that has been machined with a notch. Let us say that we are giving an example of a C[T] specimen here. So, this is the notch, when we say that this is a, this is actually this notch is machine, and what we need to figure out is that how much it is extended as we are applying certain amount of load and this can be obtained if we are heat tinting. So, tinting means just the discoloration or giving it a different color.

So, what happens is that, if we are breaking the specimen or if we are simply hitting this and then breaking it, we will look into the fracture surface which will look like something like this. So, this part here is the machine notch which has been there right from the beginning. And because of the load variation or whatever load that we are applying this is the crack extension part, we can see here like a loop that we are getting an arch the crack extension. This actually, gets a different color if we are hitting it and that is why this is known as heat tinting. It is getting a different color because it is very interesting because this is nothing but a free surface, a crack is nothing but a free surface.

And when we are when or when the crack is growing, it is a freshly formed free surface, so very much reactive to anything. when we are heating, it is the free surface that is getting oxidized first, mostly happens for the case of steels or some other materials which are reactive to oxygen, most of the metallic systems are. And as a result of this there is a difference in the color between this crack, the newly formed crack length versus the machined one. And based on that, if we break up in that we can figure it out very distinctly and very clearly what is the crack extension part.

Now, this forms like an arch, so, we need to measure this also carefully and typically, it is measured at five different places near the edges and near the center and then two places which are in between the center and the edges. So, we measure this at five different places and then the average values taken. As you can see here, this is the delta A average value that is considered. So, once we have that, for all the broken specimen, we can record this value of delta A, we also know the corresponding load displacement curve for this particular specimen. So, we can determine this in this case for all the four specimens.

Now, once we do that, our next target is to find out the area under this load displacement curve. So, since we have, so this is from the specimen itself and now coming back to the load and displacement curve, we can determine the area under the curve with a similar way that we have discussed, the plastic part, and based on that we can calculate the plastic component of J as well. And the elastic part is simply dependent on the K and E as well as the μ value, so we can determine the elastic part also. So, eventually, so far, we can determine the δa and we can determine the elastic and the plastic component of J integral value, so that we can have the J as well as δa value for each of the specimen.

Now, once we have that, we plot the J versus δa curve this looks something like this. So, this is for the four specimens that we can see here, we can see the corresponding J_{IC} value or so far, this is actually the J value we will come to that and the J integral value. Now, let us name this as J integral for all the four specimens, so this is one and this is for specimen four and the corresponding del a values also we are getting for specimen 1, specimen 2, 3 and 4.

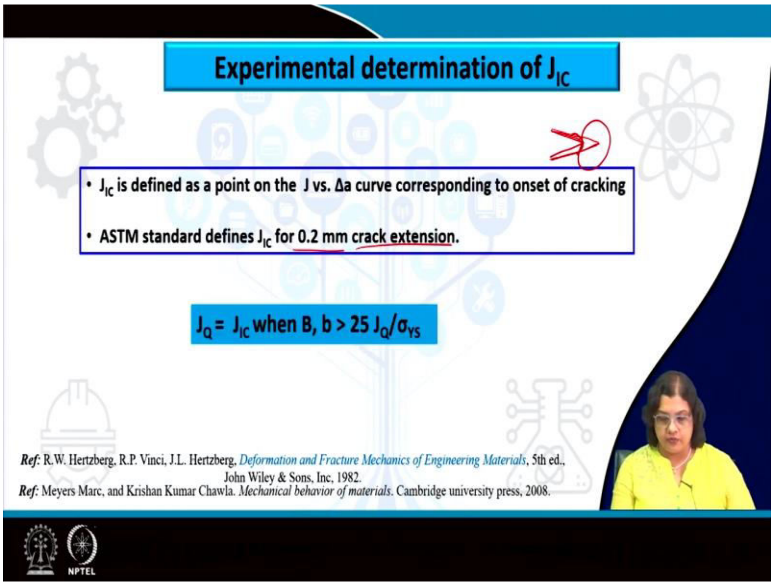
Now, that signifies the J value, but we are yet to find out that what is the critical value of J at which fracture occurs. How can we say that this is the amount of J that is required for the fracture to materialize, how can we come to that? So, for that we need the help of a blunting line. So, this signifies the relation between J, so, J blunt we can say and this is related to the flow stress and the crack growth twice, the crack growth actually. This flow stress is nothing but it is the average of the yield and ultimate tensile strength of the material.

So, this takes care of the any kind of work hardening, strain hardening, behavior of the material as well. So, that means that if we can figure so, that is taking care of the plastic deformation part. So, if we can get this blunting line itself and plot it here, it starts from the origin and you can see that it has a very steep slope and the point of interaction or wherever these two cuts out this is the point which is termed as J_Q, the intersection between the J line as well as the blunting line. So, this is the J line, that is the J_Q value.

Since, we are mentioning the term Q, you might be getting familiar with the concept of K_Q that we have been introduced during the determination, experimental determination of K_{IC} , which means that this is not yet a finalized value, we still need to validate this, and for validating this actually what we need is this concept of J_Q, equivalent to J_{IC} or we can term this as the plane stress fracture toughness only when it satisfies this criteria that the thickness as well as the ligament length is greater than 25 times this ratio.

So, if we are getting the value of J, we can plug this value of J here put it in this relation J_Q and the instrument of the material can be obtained from the literature or we can perform a tensile test and determine the instrument, this ratio multiplied by 25, if this factor is being less than the B both the B values which means the ligament value as well as the thickness, then we can safely say that J_Q is equivalent to J_{IC}.

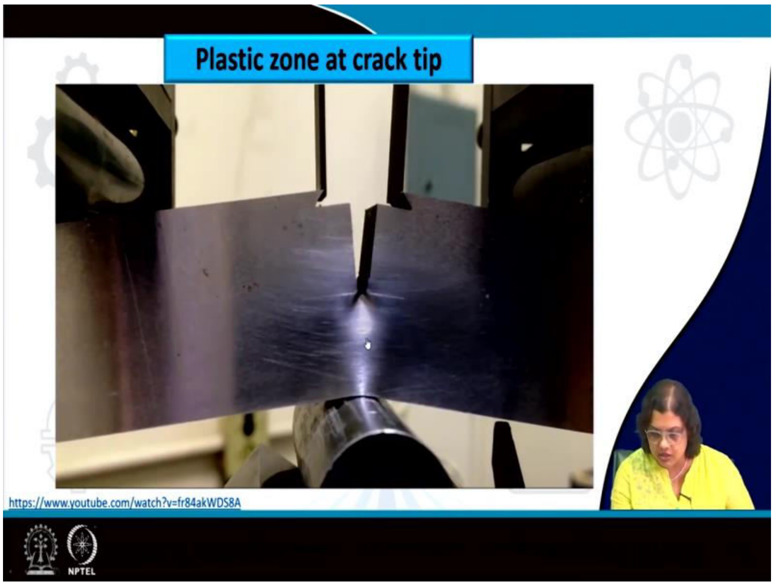
(Refer Slide Time: 27:28)



Now, this is not arbitrary, it is not or whim that we can see that we have to maintain this ratio, there might be some particular reason for this. And the reason is that, we have to appreciate this that in case of plane stress fracture toughness, whenever there is a crack and a plastic zoom ahead of the crack, we know that there is a effective crack length and eventually the crack is getting blunter. So, it is very difficult unlike the plane strain fracture toughness, it is very difficult to find out that at what point fracture is happening, how much deep blunting or how much extension of the crack can be considered as the critical value for the onset of the fracture and for that we need to validate through this relation.

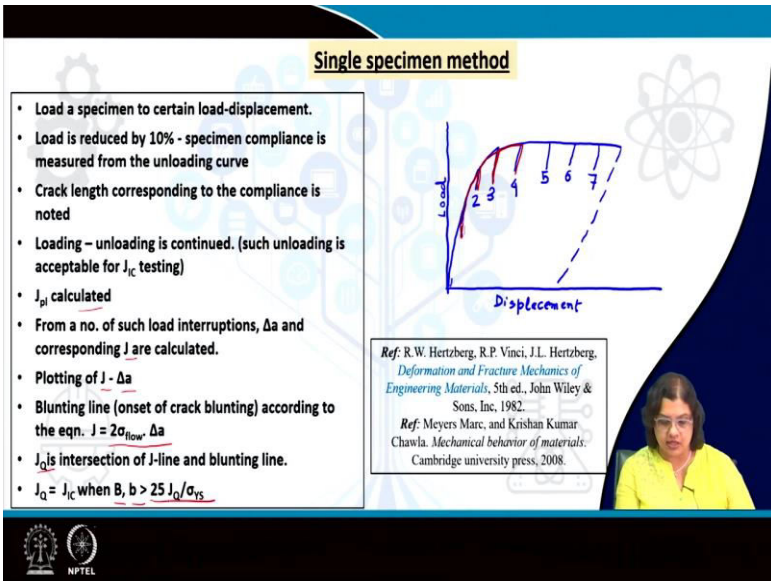
Like for the case of K_{IC}, we have used this secant line which has a slope less than 5 degree than the tangent line and that signifies that the crack is growing by 2 %. In this case, instead of 2 % we actually use a value. So, this relation 25 (J_Q/σ_{ys}) stands on the fact that there is a crack extension by 0.2 millimeter. So, there is a finite crack extension and that finite limit is 0.2 millimeter, then only we can say that J_Q whatever value of J_Q that we have obtained that is nothing but the J_{IC}, and that signifies the onset of cracking or the onset of fracture.

(Refer Slide Time: 29:10)



So, this is being maintained. And you can see here that there is the plastic zone which is forming at this point here. So, that signifies the plastic deformation and if you look that carefully, you can see that there is a crack tip blunting as well. So, initially the crack was even sharper and just in this clip itself, we can see that the crack tip is getting more and more blunt. So, basically the effective crack length is increasing.

(Refer Slide Time: 29:41)

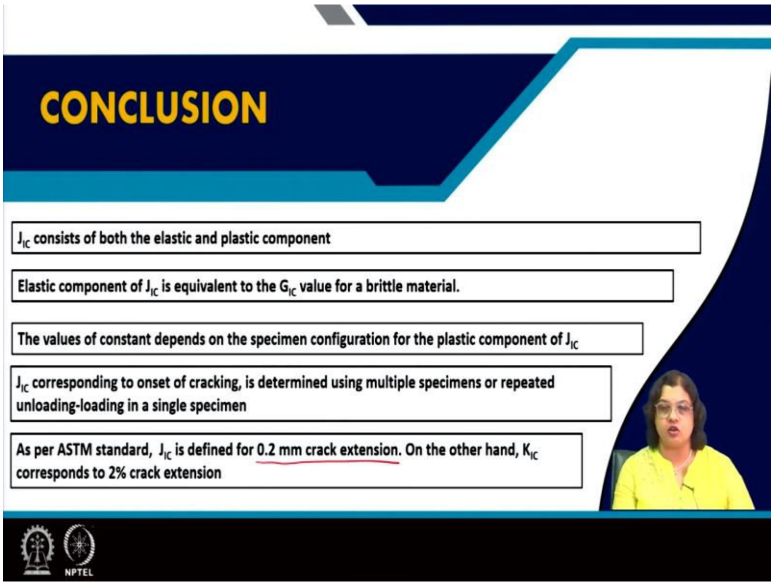


Now, in a similar way like we have seen this for the multiple specimen we can also determine the plane stress fracture toughness is based on a single specimen in which for each of the specimen we are repeatedly unloading this up to certain percentage like 10 % or so, we are unloading and then again we are loading it back and unloading and repeatedly unloading and loading. So, this is a way by which we can conserve material we can use just one specimen to determine the fracture toughness and in a similar fashion we get the load displacement curve and reduce it by around 10 % on the specimen compliance is measured from the unloading curve, from the compliance we can also measure the K value, the G value, etc.

And this loading unloading is continued and for each of this we can also calculate the J plastic and from a series of such kind of test ultimately the J values both the elastic and the plastic components are determined and some and finally, we also get the J versus δa curve. Again, by heat tinting or any other method we can distinctly see the steps in which the crack has been grown.

So, we can plot the J versus δa curve and once again using the blunting line and the intersection point on a similar fashion as we have seen for the multiple specimen method, we can determine the J_Q and in case this validates this relation that is the thickness as well as the ligament length is greater than 25 times J_Q/σ_{ys} we can safely say says say that that value is the J_{IC}.

(Refer Slide Time: 31:36)



So, coming to the conclusion, we have seen that J_{IC} consists of both the elastic and the plastic components. And the elastic component is nothing but this is exactly equivalent to the G value, do the G_{IC} value. Whereas, the plastic part is particularly dependent on the value on the factor eta which is dependent on the specimen configuration. So, η for SENB specimen or η for compact tension specimen are different and this is again one characteristics of plane stress fracture toughness that it depends on the not only the specimen dimensional, specimen configuration, and it changes as the value of thickness or any other parameters change.

J_{IC} correspond to the onset of cracking at that point it is termed as J_{IC} and it can be determined based on multiple specimens or repeated loading unloading, in case we have just a single specimen. And particularly, we determined J_{IC} on a considering the fact that there is a 0.2 mm of crack extension that has led to the fracture. So, that is the basis of validating the obtained J_Q value to J_{IC} values.

(Refer Slide Time: 32:53)

So, these are some of the references that has been used for this lecture. Thank you very much.