**Engineering Fracture Mechanics**

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**Module No. # 04**

**Lecture No. # 18**

**Relation between K I and G I**

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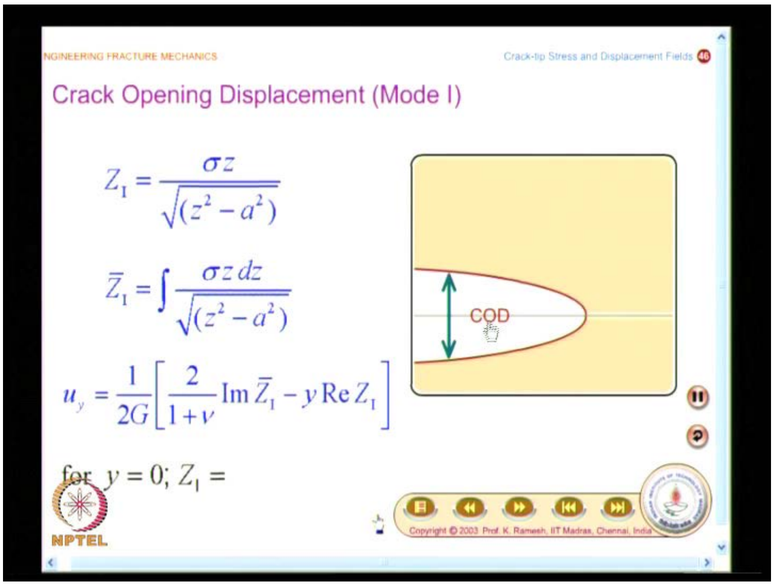


In the last class, we have looked at the very near tip displacement field equations, and I also said while developing the displacement equations, we have kept the stress function in two different ways - we could find out keeping the origin at the crack-tip, find out the displacement and also find out the displacement keeping the origin at the center of the crack. Then we moved on to finding out what is crack opening displacement, and when you want to get the crack opening displacement, what we define is when you have the crack has opened, this you call it as COD, and for you to calculate that you need to evaluate what is Z 1 and what is Z 1 bar and we would use the stress function referred with respect to the center of the crack and what we are going to have? We have to essentially find out, what is the displacement u y and that is given as 1 by 2 G into 2 by 1 plus nu imaginary part of Z 1 bar minus y real part of Z 1.

And you know one of the students came and asked me yesterday after the class was over, that you have said y equal to 0 and how are you getting COD. Because the confusion was the y equal to 0 specifies the complete crack axis within the crack as well as outside the crack. But what is implicitly assumed in our development is, we will confine our attention only for the crack length from minus a to plus a; you have to keep that in mind while we develop these steps.

So, if that information is given, then you can be clear that we are really finding out the COD, that is a crack opening displacement nothing but the displacement u y which had to be multiplied by 2, because you will find out on one side, the bottom is also the same value of u y will be there; so it is actually twice u y.

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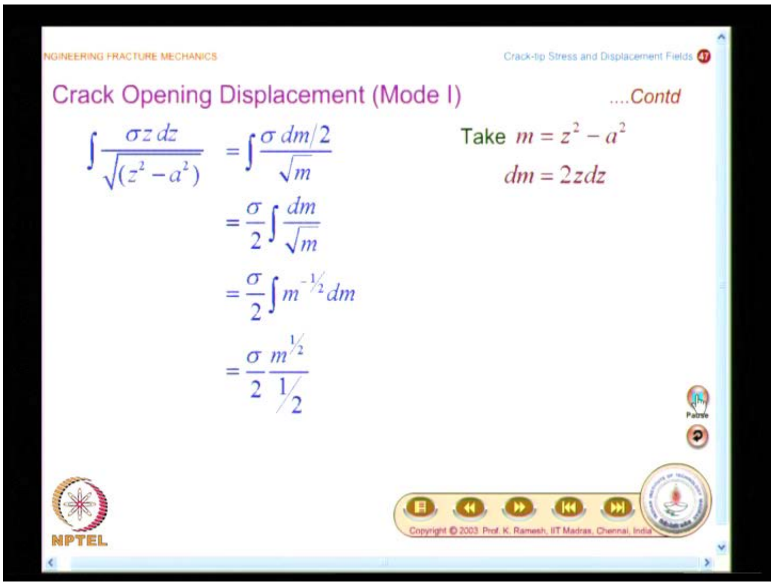


Let us see how we get this. We have to essentially get the integral sigma z d z divided by root of z squared minus a squared. In-fact, in the last class, I had told you that, you have to brush-up the table of integrals and also look at, by substituting the variable how you will evaluate the integral, and I will start giving you clues, then we can proceed.

So, when I have to evaluate the integral of this, you could substitute by a another variable; you could define m equal to z squared minus a square; once, I define m like this, you could find out what is d m, that is nothing but 2 z dz, then you can substitute it in this and comfortably evaluate the integral value. I think there should not be any difficulty in that; I want the class to think for a minute and then reflect up on it. It is not difficult, I want you to do it on your own and then, verify the result from my slide. You know in this class, I plan to take about three derivations and in a normal course, I would cover only a half of them, because it is being recorded; for providing continuity, I would be covering about three derivations and for each of them, there is a conceptual step and then mathematical derivation and for observing the concept, students need to have some time to reflect upon what is said.

So, in the process, you will have quite a few pauses in between that is essential and needed for learning the course. So, if I start pumping in information one after another, you would only copy them, rather than observing it. So, there would be healthy pauses even for the people who are going to use the course by downloading the video.

So, I would appreciate even those students to think and try to answer and then, verify the answer from what is given in the slides; so think along with the course. So, I would like to know having given this clue, have you been able to solve the integral? It is fairly simple; the only thing is you might have lost touch that is all.

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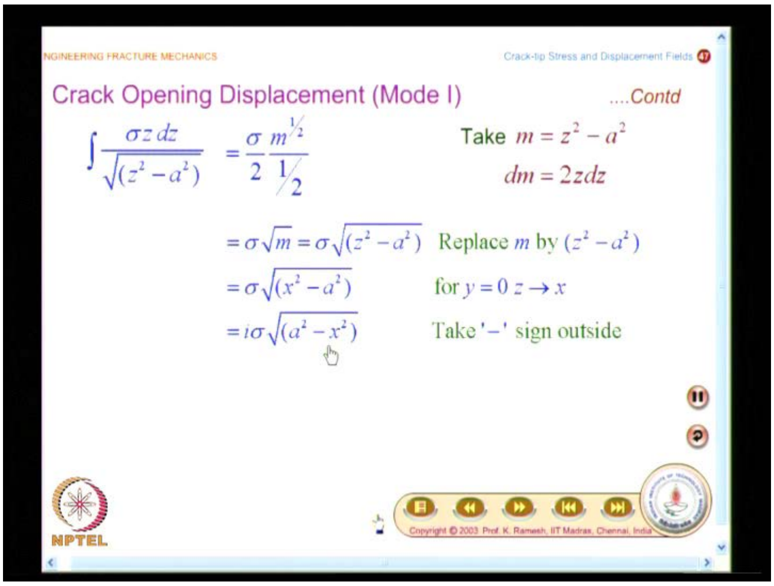


So, I could substitute here; so this turns out to be sigma into d m by 2 divided by root of m which could be recast like this and once you have the final expression like this, the integral value is very simple to find out. So, you have final value is given like this is nothing but sigma root of m.

And we have already defined m as z square minus a square; so this is nothing but sigma root of z square minus a square. You have to consider that, you are doing it for the line y equal to 0 for any value of x, I get this as sigma root of x square minus a square and here again, you will have to keep in mind, that we are really looking at the crack so that means, we are not talking of any value of x; we are talking between minus a and plus a.

So, if you are looking at like that, this expression also can be recast conveniently for our use. Because what you will find is, you will find, if you write it in this fashion- I sigma root of a square minus x square, this will always remain positive in the domain. When x changes from minus a to plus a and what you find here is the integral of this is nothing but i of sigma root of a square minus x square; I mean this is deliberately done, because when you are looking at the displacement field equation, I am having imaginary part of Z 1 bar.

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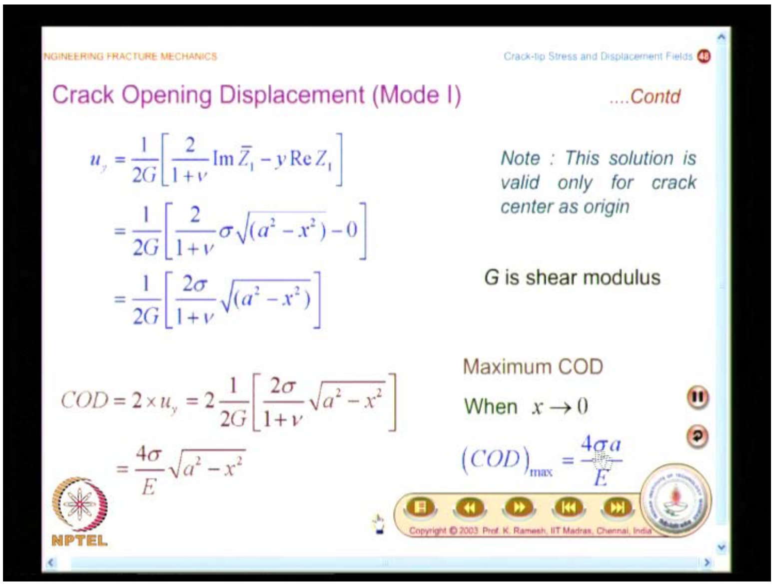


So, when I say imaginary part of Z 1 bar, I already have this; I will have to simply say this as sigma root of a squared minus x square and for your convenience, the expression for u y is given again I have this as 1 by 2 G multiplied by 2 by 1 plus nu imaginary part of Z 1 bar. Now, I can substitute the imaginary part very comfortably; I do not have to worry about the real part of Z 1, because I am considering the line y equal to 0.

So, the second term gets knocked off; so I have the expression like this; I have u y finally turns out to be 1 by 2 G 2 sigma divided by 1 plus nu root of a square minus x square. You know when you have this kind of an expression, you should always remember that this solution is valid only for crack center as origin; otherwise, it will not carry the meaning. And from our earlier figure, we have already understood that the crack opening displacement is nothing but 2 times u y.

When I substitute this, I get COD equal to 4 sigma divided by E root of a squared minus x squared what does this equation convey to you? Getting a COD as 4 sigma divided by E root of a square minus x square we have achieved. From your knowledge of mathematics, does it try to convey another very interesting information can the equation be recast in some other form to comment on that? That is also you have to look at, because you know I have been saying in all my animations I have taken carefully the crack opening as an ellipse. Is that information contained in this equation? It is definitely solved; when you look at this, this is nothing but the y displacement. So, I can replace this in terms of x square by a square plus y square by b square equal to 1 that is the general equation of your ellipse. When you refer it with respect to the major and minor axis, ellipse equation would be like that.

So, what you get by looking at the crack opening displacement is, you get a justification, that crack opens like an ellipse that is the information number one. And another one is you would also like to know what is the value of maximum crack opening displacement; you read this as when x equal to 0, we do not have to take it as tends to 0; read it as x equal to 0. The maximum crack opening displacement is nothing but 4 sigma times a divided by x modulus.

So, it is a very useful information; you know starting from Westergaard stress function, we have been able to find out the very near strip stress field as well as the displacement field, then we moved one step further and found out how the crack opens up. Now, what we will have to do is, we have already developed what is energy release rate based on the energy approach. Now based on the stress approach, we have developed what is stress intensity factor; they cannot be really different, you know there could be some kind of an interrelation ship possible.

Since we have the stress field as far as the displacement field, can we use the information what we have currently derived in a useful manner for you to find out the interrelation ship? Let us see how we can do it. I am going to discuss two methods, in each of the methods there is a conceptual step; once you understand the concept it is subtle, then it will be followed by a mathematical development; for the mathematical development again you have go to table of integrals; you know these are all you must have studied in the first year or second year of your engineering; you know if you do not use them, you tend to forget some of them.

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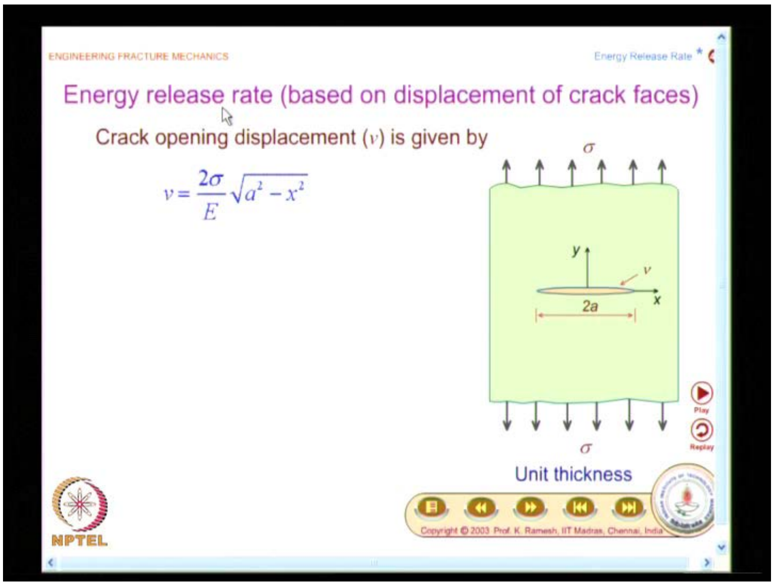


So, we will find out what is energy release rate based on displacement of crack faces. What is the information that I know? I have a nice animation which shows when the load is gradually increased to sigma, the crack opens up and mind you, this is a highly exaggerated figure; this is for visualization. And from whatever we have developed, what is say that we know? Before developing the Westergaard stress function and looking at the displacement field, we had no knowledge how the the crack face would displace. Now, we have that information. From the C O D development, we know the v displacement is nothing but 2 sigma divided by E root of a squared minus x square.

So, we are better half now; we are one step further, while developing energy release rate, we had nothing; we simply took up an analogy and then said the proportionality constant is something like pi by 2, and then you calculated the energy and you carried on with it; the justification was this is how it is reported in advance studies.

So, it tally's with that and we discuss the utility of energy release rate. Now, let me take up a problem of a center crack in an infinite plate and mind you, we are using the equation for a biaxial stress field for uniaxial loading situation and we have seen some kind of justifications for that. And in the first methodology, we would confine our attention only to the plate of an infinite plate with a central crack; we will confine our attention to only to a typical problem for which we know everything. You know, we have said for this problem K is sigma root by a and you also know what is your energy release rate.

So, I can directly write what is the relationship between G and E based on the solution itself; we will not do like that, we will try to look at from a different fashion. The additional information what you have got right now is when the loads are applied, the crack will open up and we need to know how to utilize this additional information for developing energy release rate. I want to you think about it. And the clue what I want to give is, you know we are looking at reversible systems, there are no energy loss.

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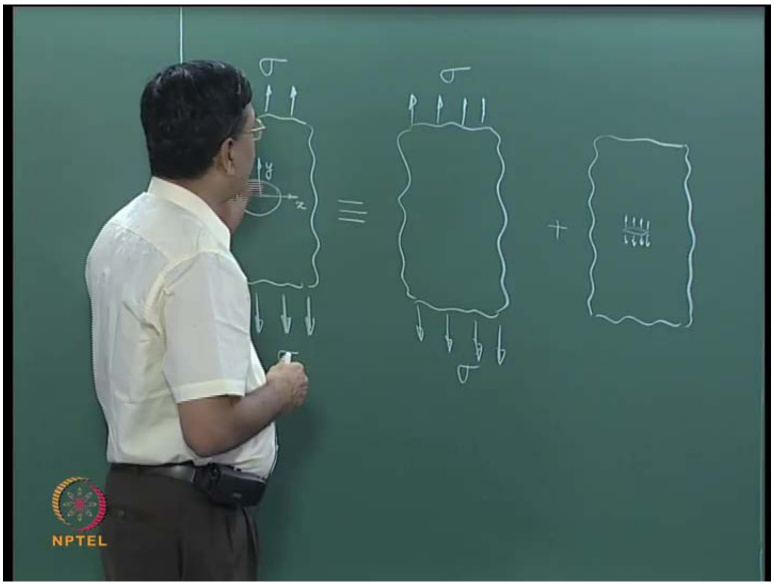

Suppose I require some energy to open the face or if I have some energy to close the face, that would be the energy required for formation of two new surfaces. So that is the way you have to look at it. Now, what you will have to think is by invoking principle of superposition, can you find out a simpler representation of this problem as some of two sub problems? If you think from that direction, it is possible for you to use the expression for v to calculate the energy release rate. Please think about it.

Problem like this, the actual problem is I have a crack is subjected to root sigma and the crack opens up, can I identify two sub problems to go into this? One way of doing it, I can imagine a problem wherein I have a plate without a crack plus I have the similar plate and I have the crack that is opened up by some load on either side.

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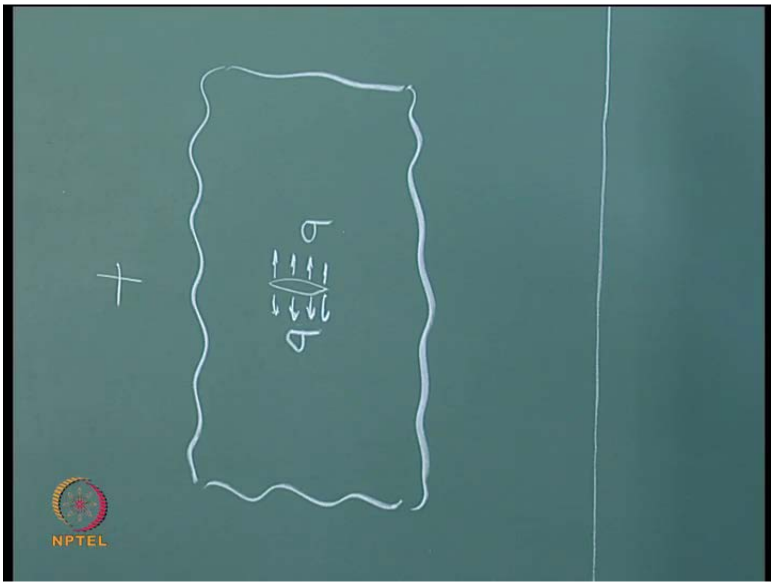


Can you agree to this kind of an explanation? This is the problem that I have; this could be thought of as solution of this problem plus solution of a problem like this. And from our knowledge of developing stress intensity factor, whatever the stress intensity factor I get out of this problem should be same as what I get in this problem. I Here I have a crack and I need know what should be the load, that is also needed; the crack needs to get opened up and it should be opened up to the extent that what we have already got as your crack opening displacement. So, if I maintain the crack is opened up by a suitable force system that would automatically specify, what is the singularity in this crack-tip; it will model the crack behavior and when you add these two problems, this problem is possible. And from such consideration that stress intensity factor is same for this problem and the final problem, this force or the load is nothing but sigma; it is like you supply an internal pressure and then the crack opens up.

So, from the energy release point of view, whatever the work done I do to open it, is the energy that is required for me to form the two new surfaces. See mind you this is a thought experiment; you will have to visualize is mentally. Now, with this information when I have sigma, when I have the displacement v which is already determine from crack opening displacement, can you write the expression for energy? And you know we have taken this as unit thickness we have taken the specimen as unit thickness, then the whole job is done; this is the conceptual step. The conceptual step is you have to visualize this as superposition of two sub problems.

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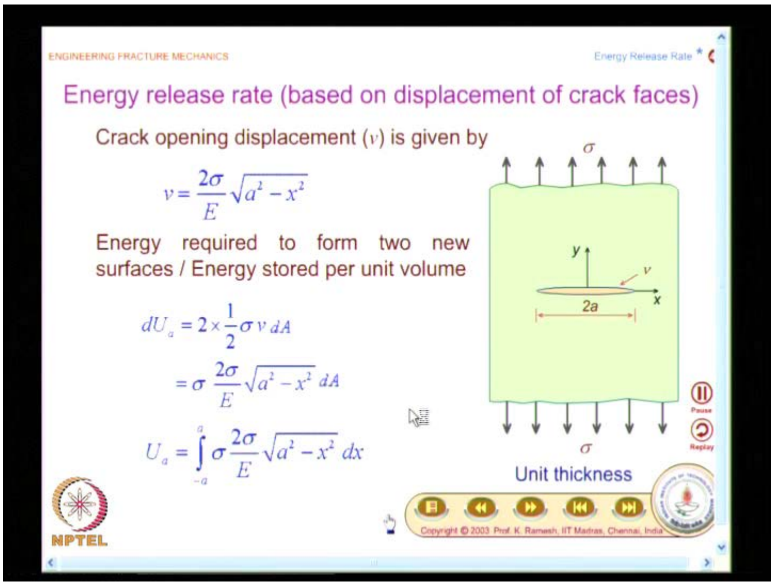


So, let me write the expression for energy, because we have always been looking energy expression as, if you have sigma into strain you always have volume; you think and write. I have already questioned you whatever that is coming on the slide not necessarily be correct. If you say that whatever I have written is right, then you are not applying your mind, you are blindly copying it. See you have to distinguish here, when I am writing this energy expression, I have the stress; so if I have to find out the force, I have to multiply by area, but I am not multiplying by the strain; I am multiplying by the displacement.

So, essentially this equation should reduce to sigma v into d A not d v. So, that is what you have to be very careful about it. And we have looked at a thought experiment to justify that the force acting on the crack faces is sigma, you know this is the conceptual step. The conceptual step is we have got the crack opening displacement. When I have to find out the energy, I need to find out what is the force and displacement.

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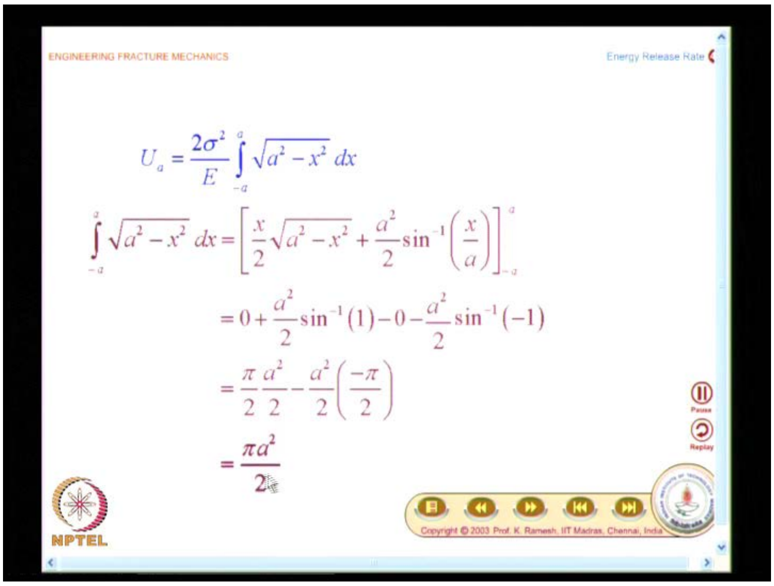


And it is subtle, I am telling you it is quite subtle; to reconvene yourself that you have to apply sigma to open the face is very subtle. If you catch that, then you can write the expression for energy, then it is only in an exercise in mathematics. So, I have this energy, because of crack is integral minus a to a sigma into 2 sigma divided by E into root of a squared minus x squared, because you have already multiplied by 2 1 for the top surface and bottom surface, so the crack surface is taken as minus a to plus a.

So, the important conceptual step is to write this equation and to visualize, you have to take the force as sigma into d A. And we are having a unit thickness so that is why d A becomes d x into 1. Say if I have a plate of thickness b, I would here have capital B, because that is how we have defined the thickness in fracture mechanics.

Now, it is an exercise in mathematics, which also I said that you should come prepared; I hope you have looked at the table of integrals and let us see how to get this. I will give a minute for you, now this is necessary once I have given this, even for the listeners were going to use this course later, please try to write the integral in your own way, then verify it with the result shown in the slide; if the slides are shown successively, there is very little time that you have for thinking. So, apply your mind, make mistakes, do not be afraid of making mistakes, then you remember better.

I think I can show the I have given you sometime, so I can show you what way the expressions look like.

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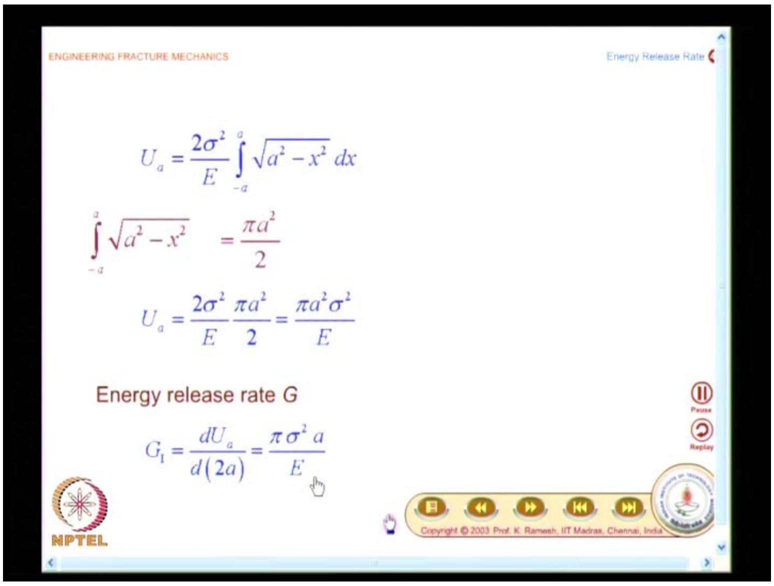


(Refer Slide Time: 25:07) So, if you look at the table of integrals, you have this expression available root of a square minus x square d x can be simply written as x by 2 root of a square minus x square plus a square by 2 sign inverse x by a in the limits minus a to plus a; this you simplify. You all know when you have sign inverse 1, what is it that you have to substitute. So, when you substitute, you will get that magical number, because in the earlier derivation of the analogy approach, we simply took the proportionality constant in a manner which is consistent with the final result. Now, what we are doing is, we are evaluating the final result; you have looked at the crack opening displacement, and then, we have found out what is the force, and when you do the energy calculation for the integral portion, this happens to be pi by 2.

So, I get this as pi by 2 a squared and when I want to find out the complete energy, it is nothing but 2 sigma squared divided by E into this integral value. So, when I substitute it here, I get this as pi sigma squared a squared divided by E; this was same as like what we have got earlier; at that time, we assume that as pi by 2, if you recall what way we have taken the value of lambda, now we have got that as part of the solution.

And what is the kind of problem that we have taken? We have taken a plate with a center crack and when I define G, whether I am talking about one crack-tip or two crack-tips that is also important and that is what is very clearly written here, G 1 equal to d U a divided by d of 2 a, because I am having a center crack with two crack-tips. So, when I differentiate this, I get G as pi sigma squared a divided by E.

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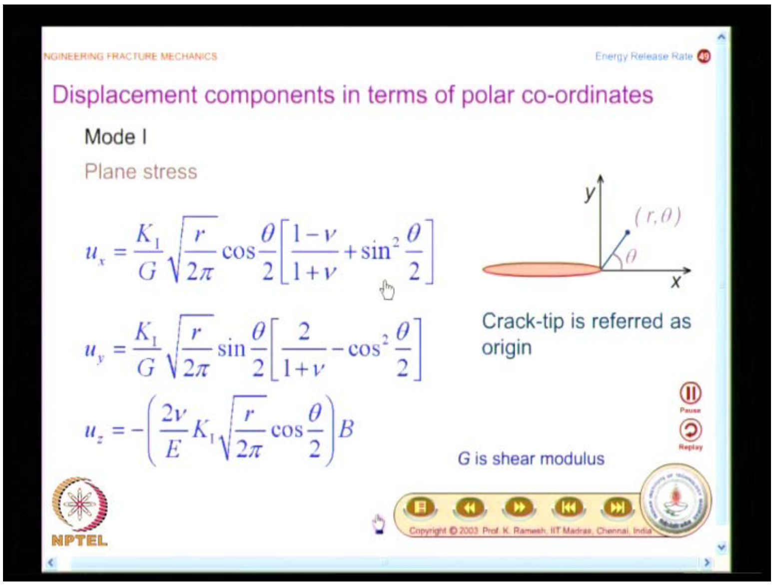


See for this specific problem, we also know analytical expression for K what is the analytical expression for K? It is sigma root pi a. Can you find out an interrelationship between G and K with this? G equal to K squared by E that is all, as simple as that, but we have done it for a specific problem here. See for a generic problem, you may not have an expression for K available to you; for a generic problem, you have to go from first principles, you have to retain that as K, and then find out a interrelationship between K and G. In-fact, for that development, we would use the stress field as well as the displacement field referred with respect to the crack-tip; there the visualization is lot more simpler and more convincing, than whatever the problem right now we have looked at. We have taken the problem of a plate with the central crack; now we will move for a generic problem. But before you go into that, we will also have a look at the displacement fields that we have got and what you will have to keep in mind is, we are concerned about the displacement y, that is the v displacement or u y displacement; we will have to develop it for plain stress followed by plane strain and what is the form of this expression have a look at it. I get this as K 1 by G root of r by 2 pi sin theta by 2 and we are going to concentrate on the crack axis.

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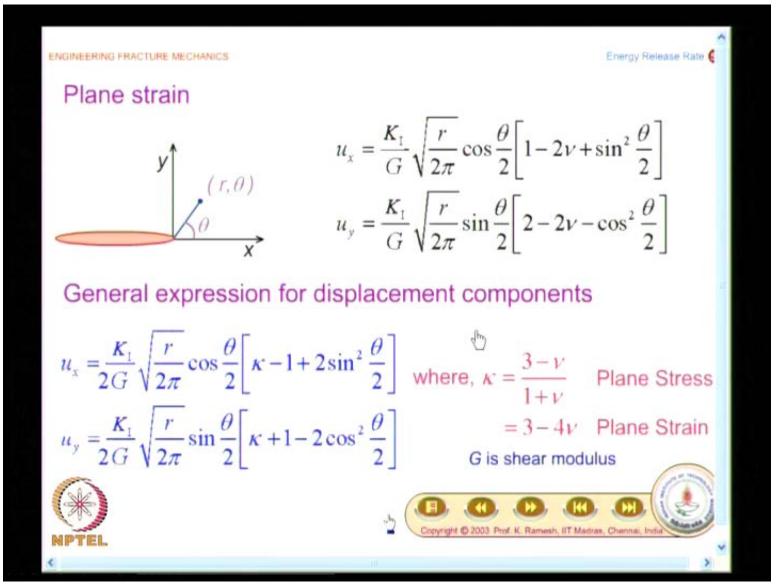


So, on the crack axis, how it will be? You have to be very careful about specifying theta and when you are looking at the polar co-ordinates; I am giving you all the clues and when I have the origin fixed at the crack-tip, how will you define the crack surface, what would be the value of theta, that you will have to substitute in this expression when I have to use this; so keep that in mind. Because that is plain stress, we also have expression for u z; once you have for plane stress, you can easily get it for plane strain also, we have developed them earlier. For plane strain situation also you have a look at how the expression looks like, I have this as a sin theta by 2 multiplied 2 minus 2 nu minus cos square theta by 2.

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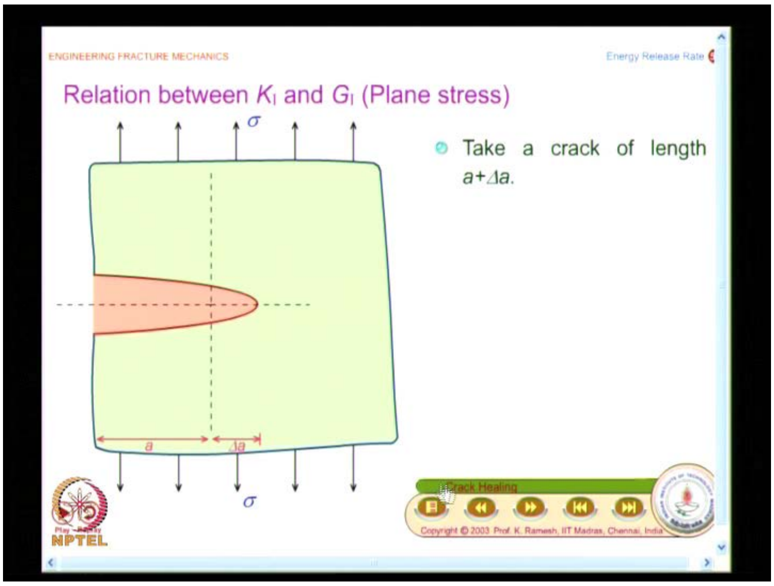


So, you need to have this information the back of your mind. Now, let us look at a generic problem, we will go step by step and I want to make a neat sketch of this. In fact, you make an overall sketch and make sub sketches what happens at the crack-tip. So, you need to make multiple sketches. And what we are doing is, we are taking a plate and then, we are applying a load sigma and I am considering one crack-tip. You know we have already said, whatever the energy required to close the crack-tip is energy required for formation of two new surfaces.

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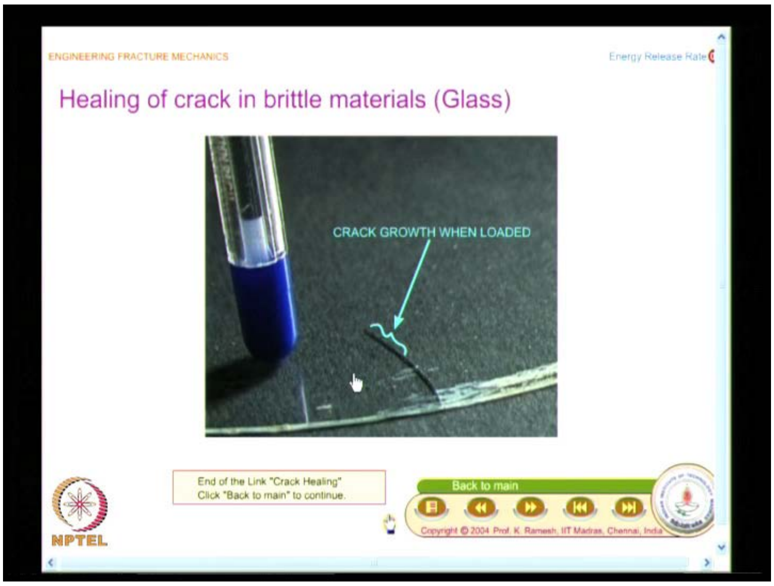

If I take a length as delta a, if I close it, whatever the energy require to close would be the energy required for the formation of two new surfaces and for which we have already looked at an experiment of glass breaking like this; it was an accident in the laboratory. So, you find the crack propagates, when the pen is removed, there is a healing scene. In the case of highly brittle materials, this has been recorded; recorded for mica, recorded for glass and mind you, when we are developing the energy based approach, we were only considering brittle solids; from brittle solids this was extended to ductile solids by Irwin and Orowan bringing in energy for plastic deformation. But while developing the theory, we would confine our attention to brittle solids; establish the relationship between K 1 and G 1 from fundamental principles.

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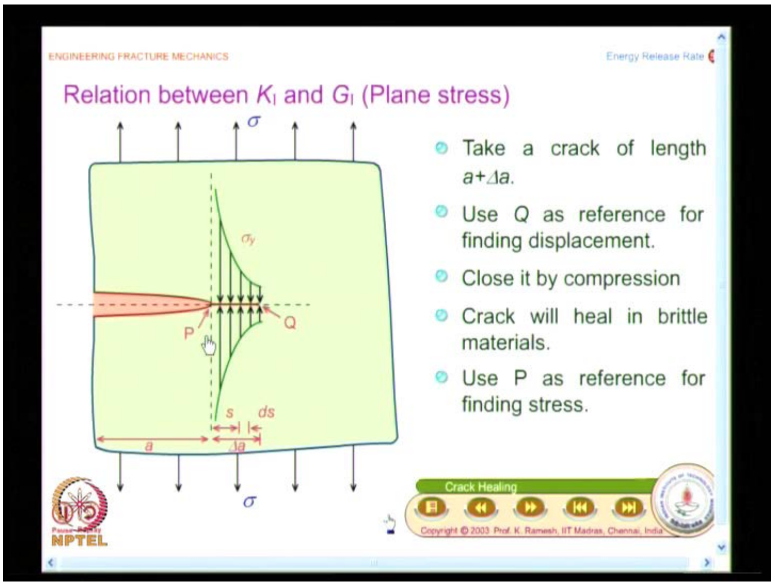


So, you have the plate with a crack of length a plus delta a and now we have spent time in developing the stress filed as well as displacement filed. I have this as the tip of the crack, what I am going to do is, I would try to close the crack for the length delta a. See mind you, here I am looking at what happens ahead of the crack-tip; I have to find out the displacement; for finding over the displacement, I would use a longer crack-tip as the origin; for finding out the stresses, I will look at the shorter crack-tip as the origin; you have to understand this and when you look at the animation, you will appreciate it better. And what is mentioned here is use Q as reference for finding displacement; when I have Q, I have to find out displacement on this; this is an exaggerated picture, it is actually a straight line here.

So, what would be the value of theta that you have to use? Theta is 0 or 90 or the 180 degrees; you have to visualize that this is 180 degrees, because I am talking behind the crack-tip. Now, what I am going to do is, I am going to close the crack by compression; I am stopping the animation in between. So, when I close it by compression, the crack faces heal, it is all thought experiment; physically you cannot go and do it like this; so mentally you can visualize this.

And I am writing the stress field. See this is very direct from whatever we have developed based on Westergaard's equations; this is what you will have to appreciate. I am taking a crack-tip, my interest is if the crack extends by a length delta a, what is the energy that is required is my ultimate interest. For which what I am doing? I am doing the reverse of it; I take a longer crack length, close a part of it by thought experiment and find out what is the energy required for close a and to do this, I take relevant expressions that we have already developed in the near vicinity of the crack-tip; such solution is available. When I complete this animation sequence, you find the crack would heal for brittle materials we have already seen it.

And now you have a recipe for me to calculate the quantities, I have to find out the force into displacement; I have to calculate the force based on P as the origin. So, when I have a crack of length a, whatever the stress field would be determined by the stress intensity factor for crack of length a and I have a small extension delta a and I have to find out the displacement. So, I have to find out from Q as the origin that would be decided by a stress intensity factor for a crack of length a plus delta a. See while developing the mathematics we will say we will take this, take that and so on, then we will bring an approximation; when you are handling small quantities, you know that is how we can develop mathematics; if you do not bring in suitable approximations, you will not be able to get the answers at all; so that is what we are going to do. Now, for your benefit, I would repeat this animation once more and if you carefully watch it, whatever that happens on this animation is synchronized with the points that appear on the right side. So, I would repeat the animation that would clarify what is that thought experiment that we will have to visualize. So, take a crack of length a plus delta a, I think I would show this animation again and just observe the animation.

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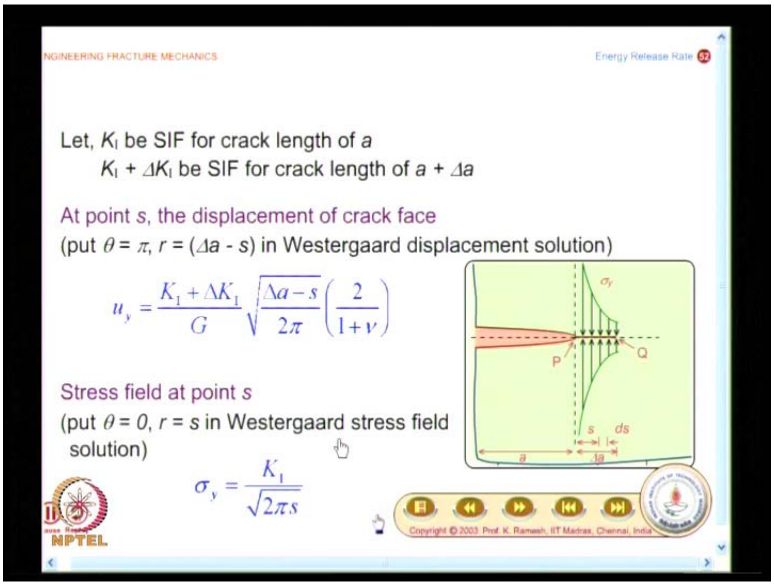


So, this gives you what is the thought experiment that we are doing it and if you want to find out the displacement field or stress filed, we have the expressions; we have to appropriately substitute the relevant quantities and then simply evaluate the energy, as simple as that. Conceptually this is more appealing, because I am really looking at a small extension of the crack. In the earlier case, we had a crack how it is opening, closing, how the crack was originally introduced all those question we did not want to answer.

Here you have a crack, the crack is extending; instead of extending, we are closing it. So, conceptually this is much more appealing; for everything we will depend on Westergaard solution, we will depend on the singular solution and then, arrive at the appropriate expressions. So, these are the two conditions that you have to think and write. I have already explained; I have also brought your attention how it should be done and I would show this as a magnified picture for your clarity. So, what I have here is, I have the distance marked as a, which is at the crack-tip, then I am looking at what happens in the distance delta a. I am looking at a position s from the first origin, that is P and I am taking a small distance delta s; so I can integrate from 0 to delta a, this is how I am going to proceed. I will write what happens at a distance s from P; I have to write the displacement as well as the force. See if I have not shown the animation earlier, you would not visualize that there was a displacement which was closed by the force.

When the force is applied fully, you will not have opening; it is closed. So, in order to visualize that aspect only the animation was done. So, now, you will have to visualize for writing Q; you will have to imagine that there was a longer crack like this and find out what is the displacement; writing P is very simple; this illustration is quite sufficient for you to write what is sigma y variation; only to recognize the displacement, you have to imagine that there was a longer crack and you should use the value of theta and r appropriately and get the expression.

So, now what I want you to do is, you tell me at point s to find the displacement of crack faces what is the value of r n theta, I should substitute. You know that is very important; that is the conceptual step; once you answer the conceptual step, rest is mathematics. See the conceptual step is the one which you will have to assimilate; I have provided you very clear explanation, you have to say what is the value of theta, I have already given you the clue and many of you also agreed that theta you will take it as pi; you should not take it as 0; you have to very careful; this where you know, your thinking has to be very clear and what is the value of the r for this case?

So, we will have a look at what I have in my notes. So, I have this as r as delta a minus s, because I am measuring it form Q, I have to find out this distance; whereas the stress field simply put that as theta equal to 0 and r equal to s. So, note this subtle difference in the way you write the stress field as well as the displacement field, because the origins are in different in both the cases. So, you have to recognize that, because of that your distance as well as the theta differs; if you write this, rest of it is very simple; there is absolutely no difficulty in absorbing the mathematics, because it is simple and straight forward.

Now, what you will have to remember is what is the expression for your displacement. I have already highlighted how it is because I am going to write only the final expression and just verify whether you have got the similar expression. Because I take a crack of length a plus delta a, I anticipate K should be written as K 1 plus delta K 1, there would be some small change; so divided by G multiplied by root of the value of r is written as delta a minus s divided by 2 pi and if you look at the other part of expression, it reduces to 2 by 1 plus nu, is it ok at this stage?

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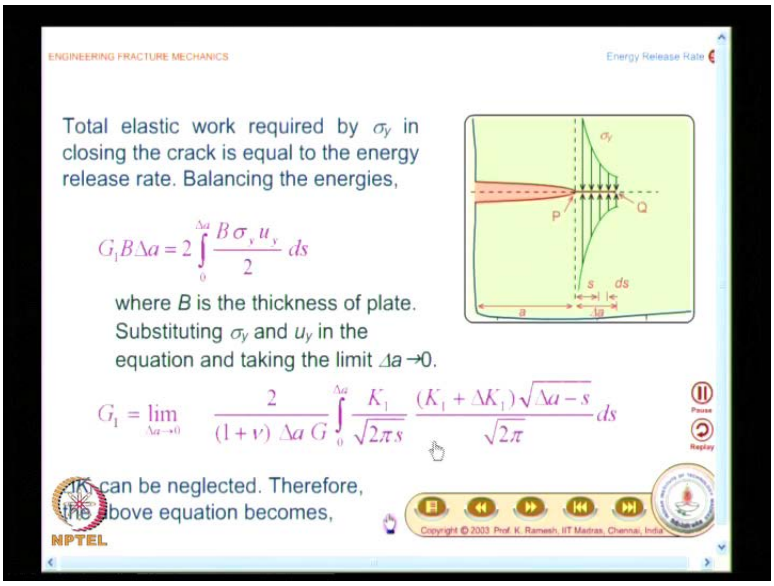


Now, we have got the expression for displacement; now you have to look at what is the force. You have to first write the value of sigma y, which is nothing but K 1 by root of 2 pi s that is very simple and straight forward that comes directly from your Westergaard solution. Now, I have to carefully write the energy expression and deliberately for this exercise, I have taken a plate of thickness B.

So, when I take plate of thickness B, the delta a is B into delta a; so I have to evaluate G 1 B into delta a, you know which I have already mentioned in many of my subject development, for certain cases I will use it unit thickness; certain cases I will do it with constant thickness B so that you get familiar with different forms of expression, because if you take any book, they would have followed in a particular fashion; you should be able to quickly associate, whether it is developed for unit thickness or whether it is developed for a constant thickness B and so on and so forth this is very important.

So, now, we have the expression for energy. So, this is nothing but 0 to delta a; I am closing the top surface; I am closing the bottom surface; so I have a factor two coming into the picture, do not associate this 2 for 2 crack-tips; we are not doing in that way. You know if you listen it half way and then, simply extrapolate, do not do that; you have to listen carefully, understand the context in which we are doing it and write the expression carefully.

So, what I have here is, I need to find out the area; so I will have this as ds into B; so sigma y multiplied by ds into B gives the force and a displacement is u y half of that, because we always assume the loads are gradually applied. In all our development, unless it is explicitly stated as impact loading or dynamic loading, we always assume the loads are gradually rise that is why you have a factor of half of force into displacement, that is what we are writing it here.

And you know we will also have to bring in another important aspect that we want to take the limit delta tends to 0. So, I am going to simplify the expression; I will write what is the expression was sigma y and u y and there is scope for me to simplify the expression for u y. If I write the expression as such, it turns out to be limit delta a tends to 0 2 by 1 plus nu delta a into g, then you have the integral 0 to delta a K 1 divided by root of 2 pi s multiplied by K 1 plus delta K 1 multiplied by root of delta a minus s divided by root of 2 pi into ds.

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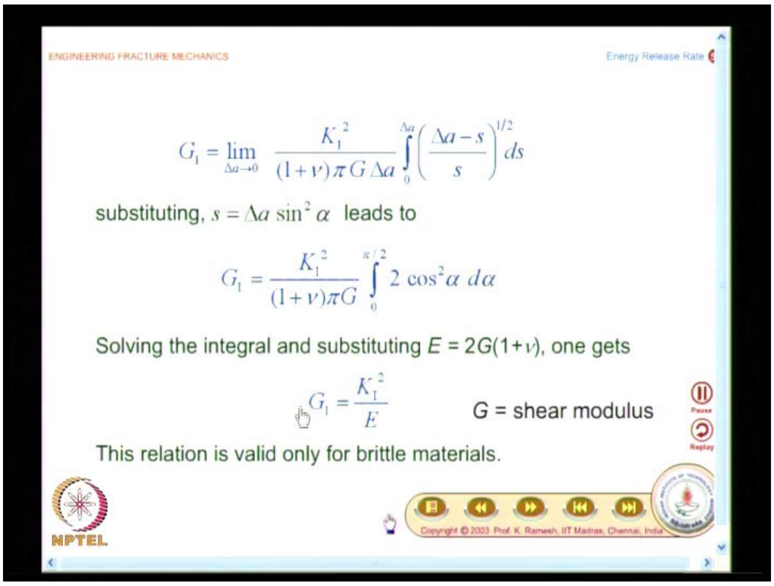


So, in the limit, when delta a tends to 0 what I can say? I can simply say delta K 1 would be very small; so I would simply take that as K 1. So, I will write this as K 1 square, that is what I am going to do and you could also do some simplification of product of this root of 2 pi and 2 pi, and then cancel at with this 2, and recast this complete expression; it is possible to do that, you make an attempt and then simplify it and we would see how the expression looks like.

So, the expression looks like this; I have G 1 equal to limit delta a tends to 0 K 1 squared divided by 1 plus nu pi into G delta a integral 0 to delta a delta a minus s divided by s whole power half, you know have to evaluate this integral and the usual procedure is substitution of variables. So, I can take this as s equal to delta a sin squared alpha; if I substitute this, it is possible for me to simplify this and evaluate the value of the integration, please take a minute and then try to do this. When I substitute for delta a sin squared alpha, the expression reduces to integral 0 to pi by 2, instead of 0 to delta a, it changes 0 to pi by 2 and the whole expression including this delta inside you will have this as 2 cos squared alpha d alpha.

So, this can be integrated and you can find the answer; absolutely there is no problem. So, when I do this, it will be nothing but 1 plus cos 2 alpha and then, substitute the limits it would be simply pi by 2 and when you do this simplification, I get a final expression G 1 equal to K 1 squared by E. So, this is a very generic expression in relating energy release rate and stress intensity factor and in fact, when this relationship was initially reported, they felt we have found a nice way of calculating G. Because K 1 squared is lot more simple to evaluate; it is the way people looked at it and then, you had pi as a nuisance in G evaluation; the pi is absorbed in the value of K. So, this is the way people have looked at it.

So, in this class what we have developed was, we had looked at crack opening displacement, then we moved on to finding out an interrelationship between energy release rate and stress intensity factor; we in fact saw two different approaches- in the first case, we utilized the crack opening displacement and performed the thought experiment to find out how to calculate the energy for the formation of two new surfaces. The exercise was confined to the problem of a center crack in a tension strip; in the next experiment, thought experiment we took the case of a single crack emanating from one of the edges and we wanted to close a small segment of the crack and evaluate what is the energy required for close in the crack. Because we are using brittle solids, the system is reversible; we equated that energy to the energy release rate and the final expression you have got is the very famous, very useful expression also G 1 equal to K 1 squared divided by E and this is developed for plane stress situation, keep that in mind you will always have one set of recommendation for plane stress, another set of calculations for plane strain in fracture mechanics. So, you have to keep tab of all these issues, whether we are talking about plain stress or plain strain whether with respect to crack-tip as the origin or crack center as the origin, keep this kind of issues in your mind always.

Thank you.