Engineering Fracture Mechanics
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Module No. # 09

Lecture No. # 41

Discussion Session-II

See, this is the discussion session two and students can ask the questions. Before you ask the questions, please raise your hand and then ask your question. In the case of a shallow elliptical edge crack, the stress intensity factor at the tip of the minor axis is higher than the stress intensity factor at the tip of the major axis. This is contradictory to our intuition. Can this be explained on the basis of physics? See first of all you have to understand what intuition is. Intuition is immediate apprehension by the mind or by a sense or it is an immediate insight. So that means, how your mind is conditioned, is the way you are going to react. You have always been seeing through the thickness crack.

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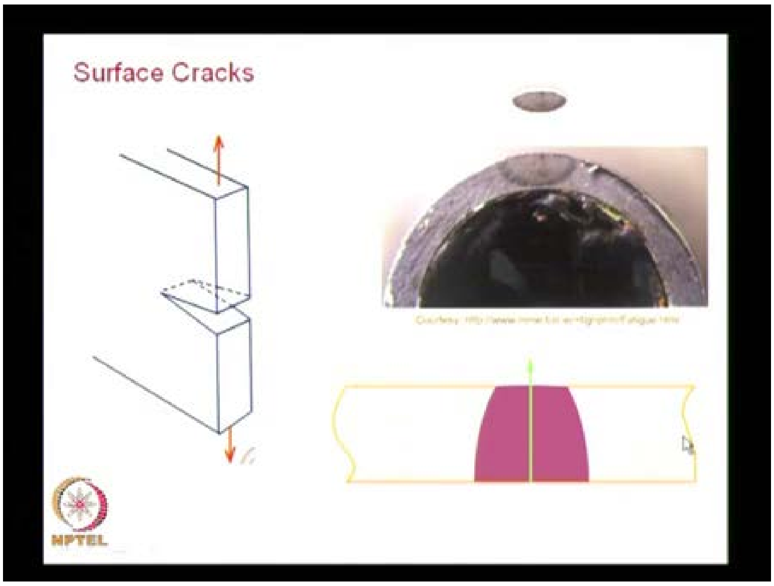

So, when you see through the thickness crack, you have seen the crack has extended like this and you have a crack front because it is a through the thickness crack and the crack front advances.

So, what happens in the case of a surface crack? The crack originates on the surface and penetrates into the specimen and we have seen that it could be modeled as a semi ellipse and so on. And if you look at the leak before break criterion, you have a surface crack like this. Imagine that this depth is not this high, but this is still very small, you will only have a scratch on the surface.

So, if you have a scratch, when you are having a the tip of the major axis; that is you are concentrating on tip of the major axis, there is no depth in that site. It is as good as a simple scratch. In fact, crack should not extend in a direction. Then even scratches will become very dangerous when you have a scratch because of corrosion products, the crack penetrates into the material.

So, you have to look at what is the crack front. That is very very important. So, when I have a surface crack this becomes a crack front and what we have seen the crack advances and it touches the other boundary, then you have a crack front on the side ways and this crack front moves on either side. Because wherever intuition fails, you know your mathematics has to come and rescue yourself. In fact, if you look at the history know the person who determine the benzene ring, he had a dream that snake was biting its tail then he coined how the benzene structure should be and later in his idea was verified by other observations.

People start with some intuition; whether intuition helps or not we will have to see. It depends on the conditioning of your mind and new idea strike only for a person who whose mind is prepared. And if you look at another example, you have the Tacoma Bridge which was a suspension bridge. People built it based on what were the design methodologies that they had at that point in time. But it violently vibrated and collapsed. People did not know that resonance can cause this kind of an effect.

So, what we will have to look at is, from physics point of view, I have looked at when you are having the major axis it is only a scratch. There is no crack front as such. Crack front penetrates into the model and if our idea is not working with what we are actually measuring, then we will have to go back and modify your idea.

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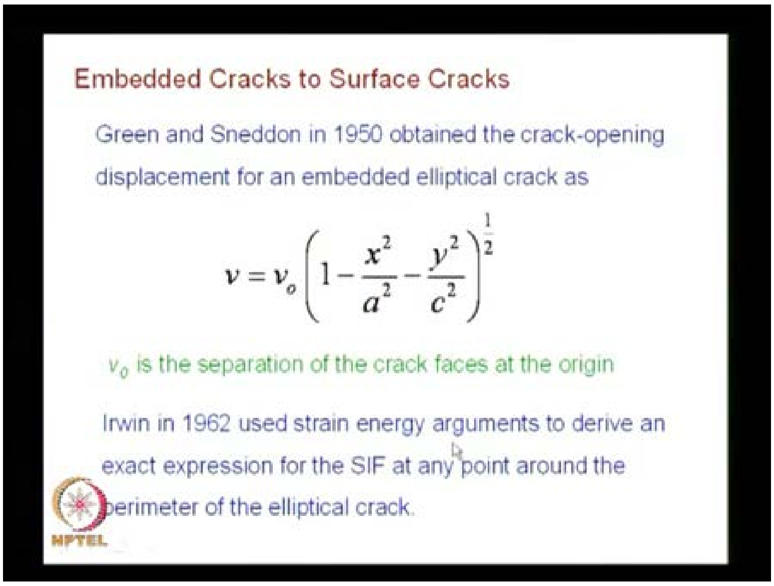

And let us look at again how we developed the stress intensity factor variation for the case of a surface crack. There was a substantive mathematical development and we have already looked at that there is no harm and looking at it again. So, you find the Green and Sneddon in 1950 obtained the crack opening displacement for an embedded elliptical crack.

So, I got this expression as v equal to v naught multiplied by 1 minus x square by a square minus y square by c square whole power half.

So, based on this expression, mind you this was reported in 1950; in 1962 Irwin used strain energy arguments to derive an exact expression for the stress intensity factor at any point around the perimeter of the elliptical crack.

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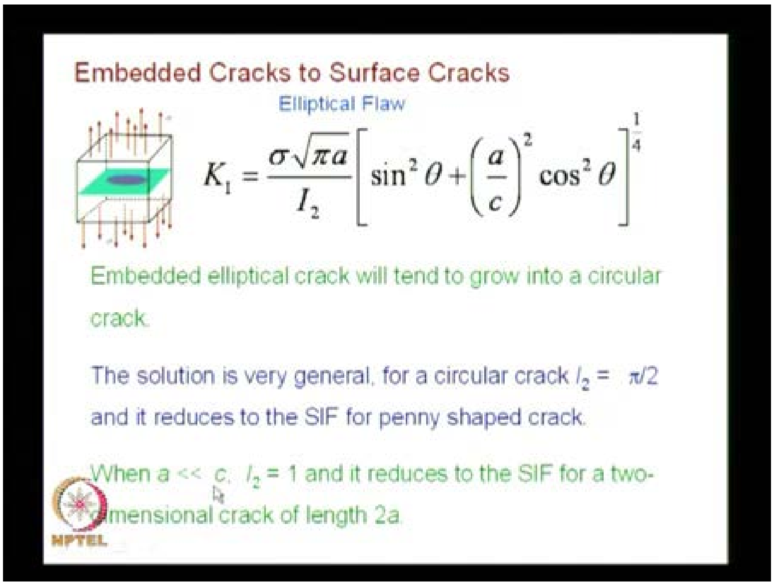

So, first result was for a embedded elliptical crack and what is that they found? Along the crack front, the stress intensity factor varies. Earlier the result was for a circular flaw; circular flaw the stress intensity factor remains constant.

So, in the case of a through the thickness crack stress intensity factor remain constant. So, this was the first instance when they found if the flaw is elliptical in nature, you have an expression for stress intensity factor as a function of theta.

So, it varies from point to point and we had also looked at that an elliptical crack will tend to grow into a circular crack and people looked at this solution very carefully and when you say I 2 equal to pi by 2, whatever the expression that you have got has reduced to the SIF for a penny shaped crack.

So, you have a generic solution. You simplify it, it reduces to a particular solution. They have looked at it for an elliptical, from an elliptical crack to a circular crack. They have also looked at when a is much less than c I 2 becomes 1 and it reduces to the SIF for a two-dimensional crack of length 2 a.

So, what does this show? Whatever the result that we have got is internally consistent. You are not done any serious mathematical error which is also supported by experimental observation.

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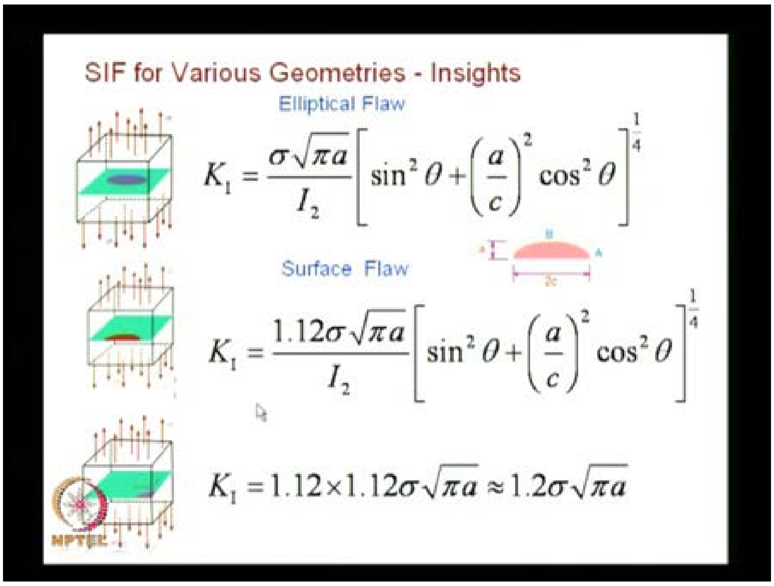

And we have also looked at stress intensity factor for various geometries the insights. We started with elliptical flaw embedded, we have also look at the definition of how to locate the point theta on the boundary of the ellipse. From this, we have graduated to a surface crack where in you compare it with an edge crack.

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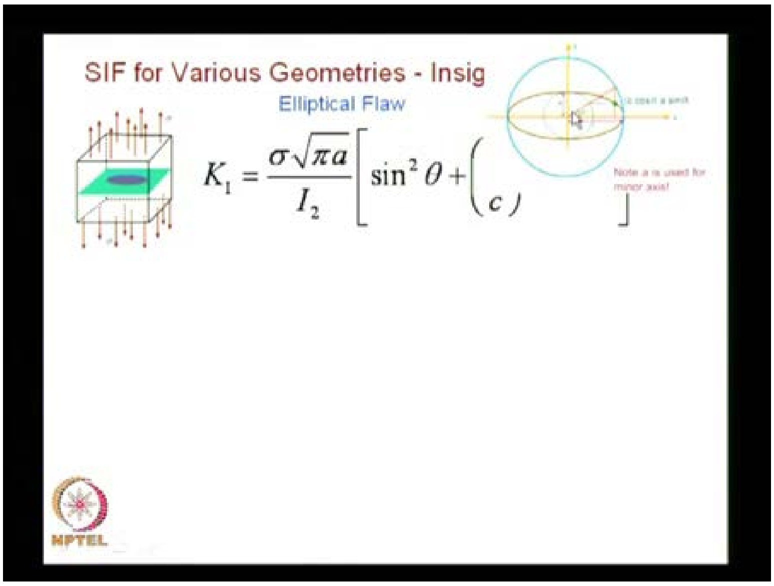

So, you have a factor 1.12 coming into the (( )). Then what we looked at we have also looked at a corner crack. So, from this starting point, people have arrived at solution for various other cracks geometries and whatever the conclusion that they have arrived is supported by experimental observation and there was also parallel numerical effort.

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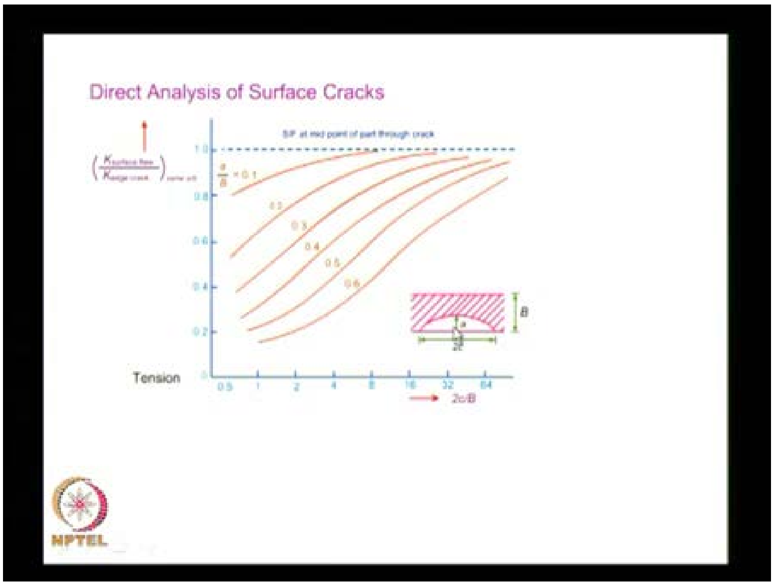

And what is the numerical effort? We saw direct analysis of surface cracks and how do you interpret this figure? You have a crack which is having a depth a and length 2 c and you also have a ratio A by B and A by B is increasing here and what does this graph show. When the depth of the crack in the specimen increases for the stress intensity factor at this point to reach the edge crack value, you need to have a very long surface length. Only then it will become this is the line where you have the SIF for the part through crack and you have the edge crack value is the ratio is 1 here. So, for it to attain this, you need to have a long surface length.

So, you have evidence from experiment and when you reduce the solution to particular cases you got this and you also have a numerical result which says you need to have a long surface length for you to have the stress intensity factor matching with the edge crack. All this result show the crack will penetrate only into the specimen. It will not go like this. There is no crack front it is only a surface scratch that you see.Yes sir.

The plastic zone size obtain through Irwin’s model is quite large in comparison to the one obtain through the yield criteria applied to the elastic field. Why.

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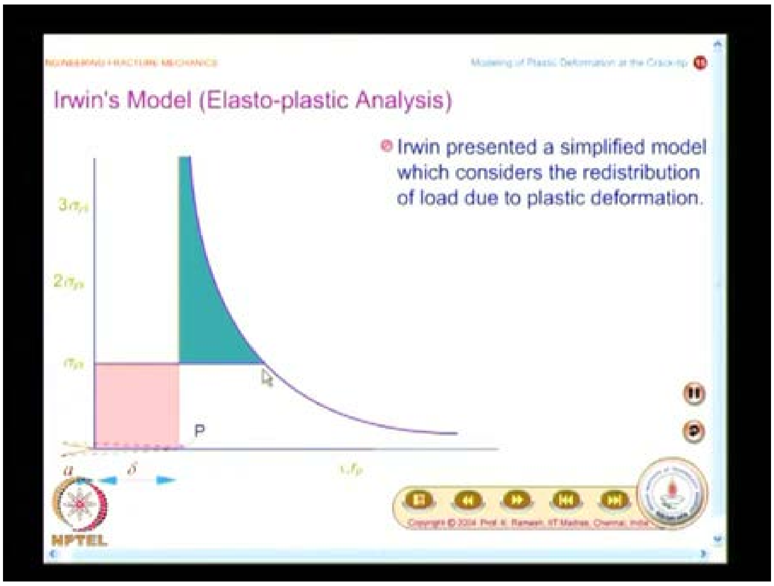

I think we will go back and then see how the Irwin's model was developed. And what we have said at that time was Irwin presented a simplified model which considers the redistribution of load due to plastic deformation and what I have it done in the simplistic case, you have the crack-tip and you have the stress field as given by your Westergaard solution.

The value of sigma y is plotted here. And the simplistic model was what we did? We simply cut off this line when it reaches the yield condition. If you apply Tresca yield criterion, it happens that sigma y s and when you do this, you have this point located and we said that this should be the length of plastic zone length ahead of the crack.

What happens to this load. The solution says it was original supporting so much load. And you say, in actual practice because the material cannot sustain load beyond the yield strength, simply cutting this curve at that position will not be the right approach.

So, what Irwin argued was you have to have redistribution of this loading. This would essentially amount to extension of plastic zone length and this he has done along the crack axis and how this area A 2 was obtained? It was obtain such that whatever is the unbalance load, this area and this area matches.

So, now you can ask a question. The plastic zone length is much longer than the simplistic analysis.

Now, we will have to look at was Irwin was the only person who calculated the extension of plastic zone length. Because these are all models these are very difficult problem that you are handling and you have to find out whether the results obtain by Irwin compares reasonably with other solutions in the literature. You also had another approach.

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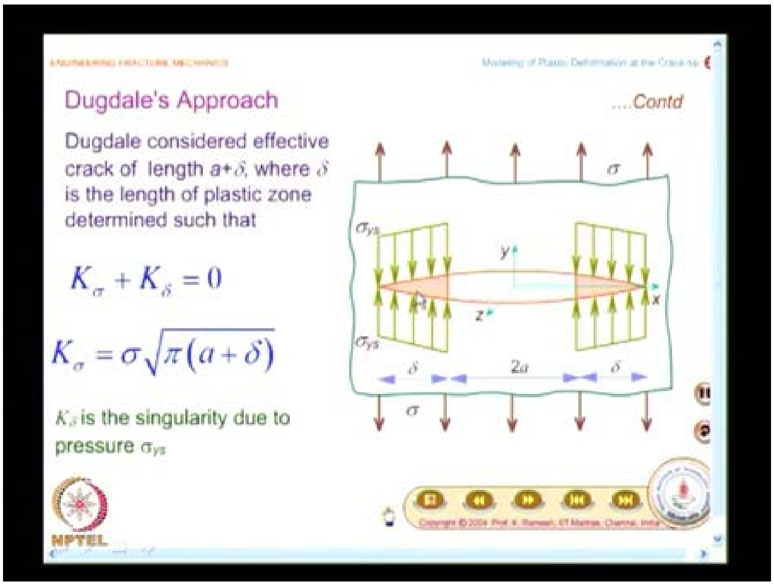

And this was done by Dugdale who coined a different problem. He imagined that there is plastic zone ahead of the crack-tip and here re-coin in the problem such a manner that whatever is a stress intensity factor because of the applied loads which is K sigma and he imagined that you have a cohesive zone which is compressed by the yield strength. This stress intensity factor the addition of these two should go to 0.

So, he fundamentally took a different approach to estimation of plastic zone length. He identified superposition of two problems and he obtained the plastic zone length.

The K sigma what you have taken is nothing but the original crack length a plus the assumed plastic zone length delta. The procedure is totally different and what is the result that he has got. Can we compare with the plastic zone length from Dugdale's model and Irwin's model? Are they far different or close enough from an engineering perspective point of view.

Based on Dugdale's model, you get the length of the plastic zone as pi by 8 K1 by sigma y s whole square and if you really calculate the value of pi by 8 it reduces to 0.393 multiplied by k 1 by sigma y s whole square.

Based on Irwin's model, it is 1 by pi K 1 by sigma y s whole square and when you will really calculate1 by pi the factor is 0.318 where as from Dug dale's models it is 0.393.

So, there is definitely a comparison. Though the plastic zone given by Irwin's model is longer than the simplistic approach, whatever the result that we have got by another methodology is no way of. But definitely the simplistic model is not correct. You cannot simply cut a curve out of your convenience.

Sir my question is regarding a fracture toughness testing sir. Why the dimension for fracture dimension is for a specimen in plane strain is based on material toughness testing toughness K 1 c sir.

I think your question is why are the dimensions of the specimen for plane strain K 1c test based on material toughness K 1 c.

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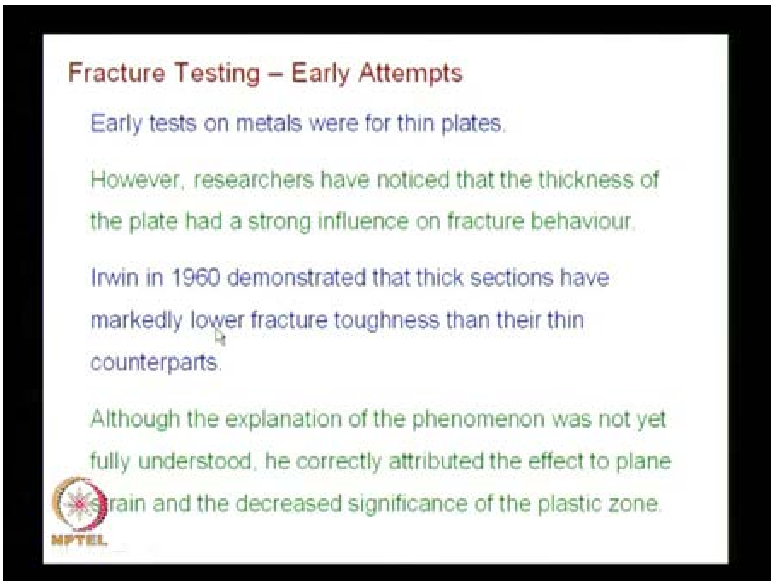

Now, what we will have to do is we will have to go back and see, how fracture testing evolved. You have to look at what are the early attempts and early tests on metals were for thin plates. However researches have noticed that the thickness of the plate had a strong influence on fracture behavior.

See right now from fracture books you all know that if we have to do fracture toughness testing, you have to maintain plane strain condition at the crack-tip which demands a particular thickness for the specimen. If you look at the early attempts on fracture testing, initially they worked on thin plates, then they notice that the thickness of the plate had a strong influence on fracture behavior and Irwin in 1960, mind you this is one of the early stages of fracture mechanics development. He demonstrated that thick sections have markedly lower fracture toughness than their thin counterparts.

So, at that time they did know what the reason is. See when you are doing a design, you will have to take a value which is a property of the material and when does become a property of the material? Only under plane strain condition that we know. But Irwin based on intuitive argument, he attributed the effect of plane strain and the decreased significance of the plastic zone for the SIF the fracture toughness values for the thick sections have markedly lower value. That is the way he looked at it. Later on it was supported by experimental result.

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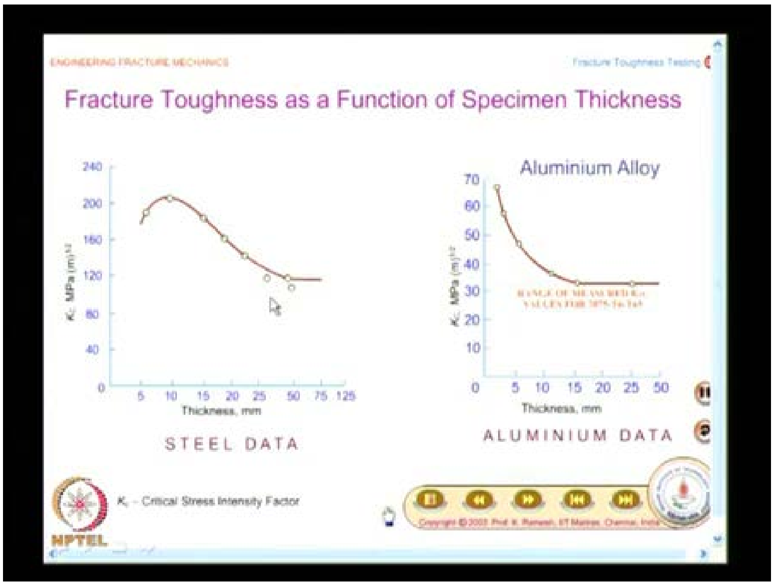

And you also looked at these graphs. When you look at steel the fracture toughness varies like this and it becomes a constant only after a particular thickness and if you go and investigate, this was really ensuring plane strain condition at the crack-tip. So, this is the reason why people go in for maintaining plane strain condition. So, that you get a material property which could be use for all your design calculations. So, initially to start with, they did not have an idea that it is a function of thickness. Once they understood it is a function of thickness, then you have to have a rationalization, how you should arrive at the thickness of the specimen.

Sir what is the relation between plastic zone size and the fracture toughness?

See let it put it this way, when you have to do the fracture toughness testing; we wanted to identify what should be the size of the specimen. For the specimen thickness calculation, we have utilized the plastic zone length.

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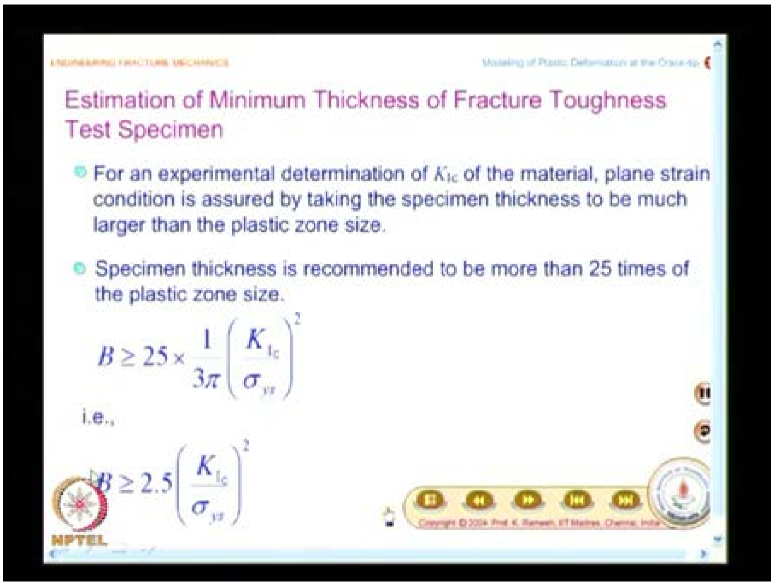

How we have utilized the plastic zone length? We have looked at in plane strain situation Irwin has obtained the plastic zone length as 1 by 3 pi multiplied by K 1c divided by sigma y s whole square. And based on experimental observation, people found that the specimen thickness should be at least 25 times of this plastic zone size.

So, when you multiply 25 into 1 by 3 pi, this has been approximated as 2.5 times K 1c divided by sigma y s whole square.

So, you determine the thickness B based on the plastic zone length. It stops there. There is no other correction between plastic zone length and fracture toughness.

People have look at it from experiments they found that it should be of such an such a thickness. Later on they work back work and found a relationship between plastic zone lengths in plane strain multiplied by 25 times gives to the thickness. So, that is the way the relationship comes. By knowing the plastic zone length you cannot estimate fracture toughness. But you can determine what should be the size of the specimen that you want for fracture toughness testing.

Sir if we uses specimen with large dimension to find K 1c, the accuracy of experimental results is high. But in experiments to determine SIF, specimen with large lateral dimensions is not employed. What is the reason for that.

See the answer is there in the question itself. Say when you are really looking at material toughness, there are recommendations what should be the thickness of the specimen that you want. And we have seen fracture toughness is a function of thickness. So, when you do K 1c determination for fracture toughness calculations, you use the thickness recommended by the codes.

Now, the question is for your given application, whether that fracture toughness is useful or not. You will have to decide. If you are working in the plane stress domain then calculate the plane stress fracture toughness rather than plane strain fracture toughness.

You know just because you are not applying your mind to find out what fracture toughness to use for your application, you cannot raise that the accuracy is higher when you are having a larger thickness and we are not using that for our specific application.

So, for plane stress situation, we have also seen a plane stress fracture toughness testing. So, take the data from that kind of curve for you to apply it for your specific application.

Is the compact tension specimen really compact?

Yeah

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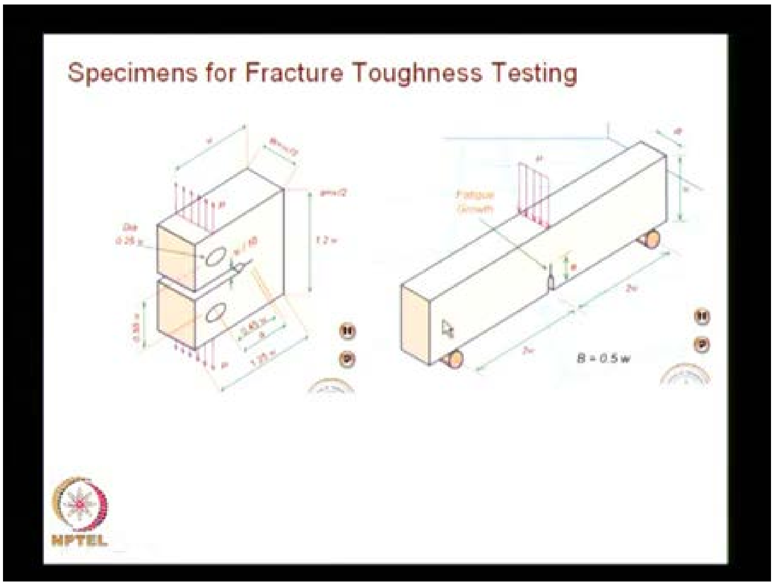

What are the specimens that we have looked at for fracture toughness testing? We have seen a compact tension specimen. We have also seen a three point bend specimen and I had mentioned three point bend specimen is the simplest to one to fabricate. Even the loading fixtures are much simpler. On the other hand, the compact tension specimen loading fixtures have to be little more sophisticated.

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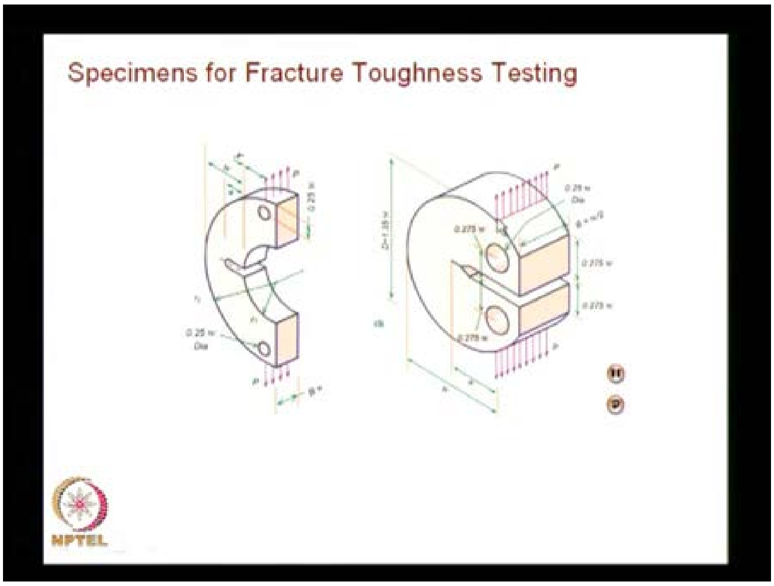

And we had also seen a C specimen and also a disk specimen and we have seen that this is for tubes and this disk is meant for shafts and so on.

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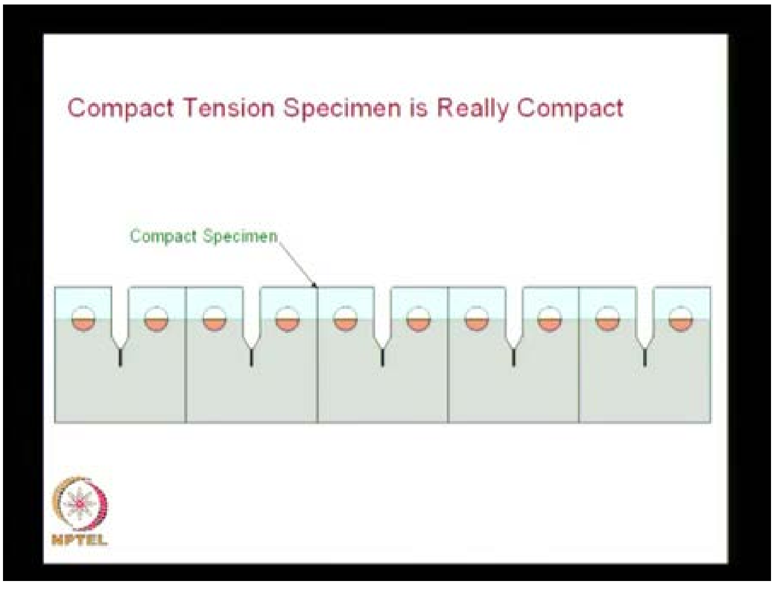

I had also mentioned in the case of nuclear installations, even though you have the containment made of very high tough materials because of neutron bombardment, over a period of time the material degrades. It becomes brittle. So, one of the techniques that people employ is, they stack several specimens in the reactor and take the specimen periodically out and test it to find out the material toughness. How it has degraded as a function of life of the reactor.

So, you need to stack as many specimens as possible in a given area. So, people are ready to pay an extra price for testing a compact tension specimen and if you really compare the relative sizes of three point bend specimen and a compact tension specimen, it is like this.

It is only a fraction of your three point bend specimen; you can make a compact tension specimen. So, it is going to occupy less space and you can also take them a periodically and all this operations have to be done by robots. Because it is all radioactive and people have developed robots only for this purpose and this is done in the nuclear industry from safety point of view. And you can also see you can actually pack as many as five specimens for one three point bend specimen. So, this really shows compact specimen is really compact. How can we determine the material constants C and m in Paris law, whether C and m is independent of stress ratio R. Now, will go back and see what was the test that we need to do to calculate C and m.

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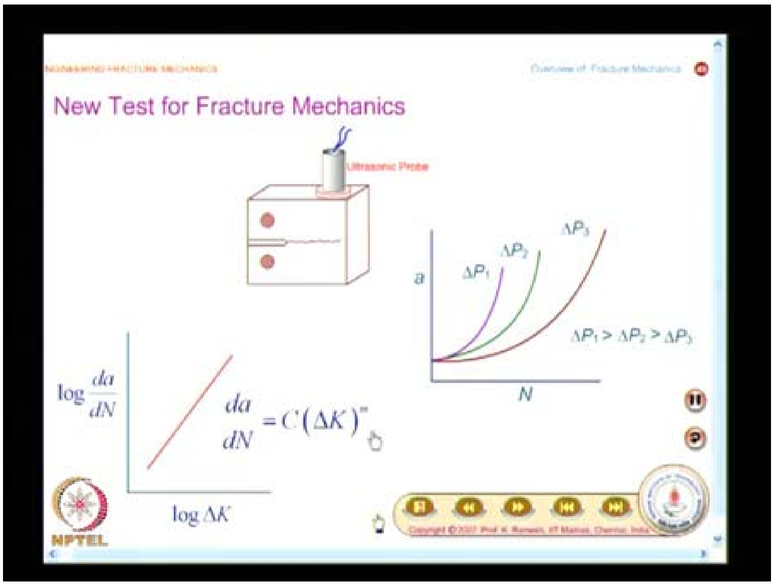

And I had said that you have to monitor the crack growth while applying the fatigue loading. You have the fatigue loading in the specimen you have to monitor it and I think I will replay the animation again. You have to apply the fatigue load as the crack advances by some mechanism either you do by MDT method or put a crack mouth opening displacement gauge and develop a versus N graph. So, from this graph you collect the data and get a graph between log of delta K versus log d a by d N and from this graph you can find out the intercept as well as the slope.

So, that is how you find out the C and m. And mind you, when you are looking at Paris law it gives only the straight portion. That is a reason why you find in advanced codes; they do not use Paris law as such, a modification of Paris law which also explains what happens when failure is going to take place. So, that is why people use Forman law where K 1c is embedded in the equation. As such Paris law does not tell you when the crack becomes critical.

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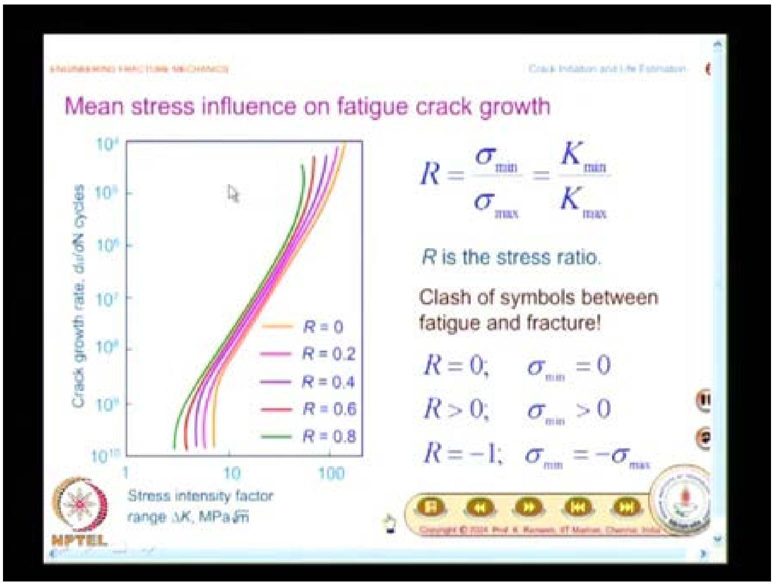

Now, the question is when the stress ratio changes, how the graph looks like. We have seen as a function of stress ratio the graph get shifted to the left. So, your threshold value keeps decreasing for crack initiation.

So that means, the C value changes, intercept changes, slope remains more or less constant. So, the only way what I can say is, you have to look at how the data is reported. You know if people have given some empirical relation, if you find out from one R ratio whether it could be extrapolated for other r ratios.

We will have to look at from that point of view otherwise you will have to repeat the test for different R ratios. There is no other way; either you should have an empirical relation which helps to you get from one R ratio to other R ratios; otherwise you have to do exhaustive test.

So, any success in fracture analysis goes with exhaustive material testing. Without exhaustive material testing, you cannot employ fracture mechanics and R ratio is a factor, but from this graph it shows that the slope remains same, but C changes that is what we find. But you will have to look at that data handbook how they reported this.

Sir could you please explain why in the case of short cracks or very long cracks, the LEFM criteria are no longer valid, even for relatively brittle materials.

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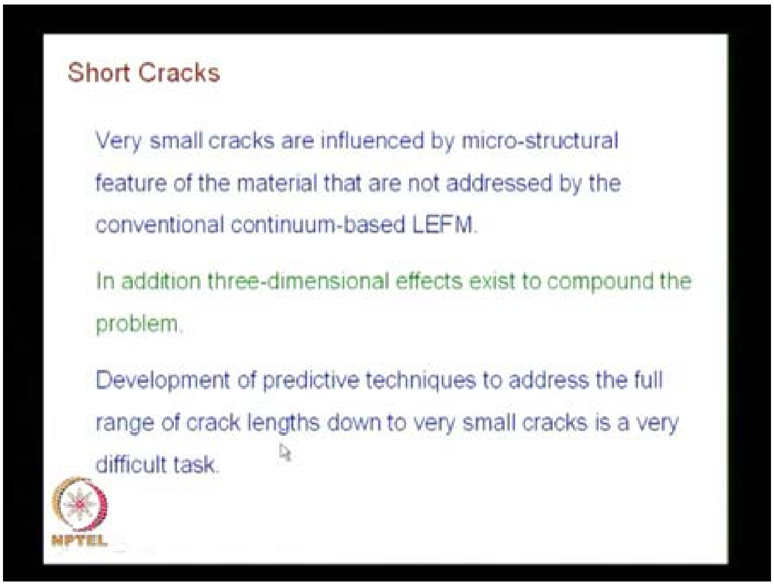

Yeah will get into the problem of short cracks and you have to understand how they influence. Very small cracks are influenced by micro-structural feature of the material that is not addressed by the conventional continuum-based LEFM. Because it depends on the scale. See in cosmology, what we find is, you have the mass distributed uniformly in the universe whereas, you find there is a large gap between earth and moon and also earth and sun. You have interstellar spaces where nothing is present. When you are looking at a very long scale in cosmology, you can use it as a continuum and play with it. The moment you go to short crack you have at the tip of the crack there is a plastic zone. The plastic zone size is comparable to length of the crack. So, when plastic zone sizes comparable length of the crack what we will have to do? LEFM will not do. Only EPFM will help.

So, we will have to look at what is the kind of difficulties. You will also have three-dimensional effects at that scale which also makes the problem difficult to handle. And development of predictive techniques to address the full range of crack lengths down to very small cracks is a very difficult task. You have to understand that. You know you develop linear elastic fracture mechanics so that we have a comfort zone we understand reasonably long cracks how do they behave; we are able to solve certain class of problems. So, that is only limited knowledge.

Any predictive technique to address the full range of crack lengths is very very difficult. And what we could do is possibly below the LEFM regime, but above the micro-scale heterogeneity which can influence the crack growth process EPFM would be effective. This is because the essence of the problem is the presence of plastic deformation.

So, from LEFM if you go to EPFM analysis, you could analyze still smaller cracks, but it does not start from 0. Then you have this micro-scale heterogeneity and so on.

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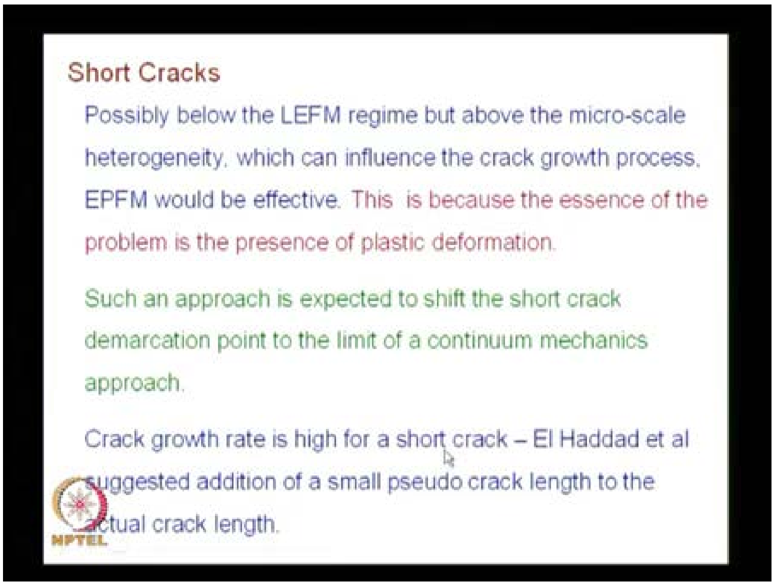

So, the use of EPFM is expected to shift the short crack demarcation point to the limit of a continuum mechanics approach.

Crack growth rate is high for a short crack. So, it is well documented in the literature. People have found whatever the fracture theories that fatigue crack growth theories which you have develop, they are not applicable to short crack because they have a higher growth rate and you know people are accustom to do certain things in LEFM. They extended similar ideas in handling the situation also. We have looked at there is plastic zone ahead of the crack-tip. How did we handle plastic zone in LEFM? You consider the crack length is longer than the actual physical length. Such an approach was proposed by Haded et al. So, they suggested addition of a small pseudo crack length to the actual crack lengths.

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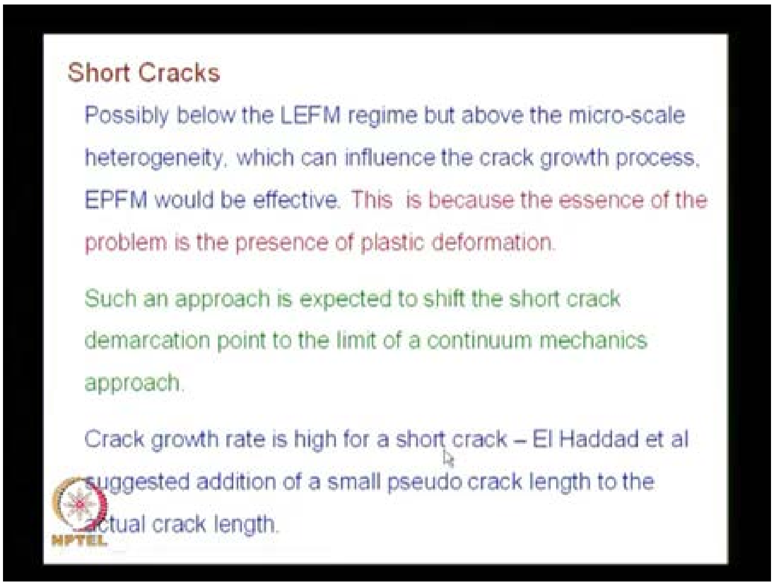

You know when somebody proposes people will not accept it on the face of it. Such an approach has been questioned in the fracture literature and people are now paying attention on use of an inclined strip yield model and elastic-plastic finite element models are being worked at to handle the short cracks. And you can note down this reference. This is by Leis, Kanninen, Hopper, Ahmad and Broek- A critical review of the short crack problem in fatigue. Mechanics of fatigue is AAS EAMD volume appear in 1981 that discuss of various methodologies.

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Now, let us see what we have to do. You have to understand the LEFM analysis gives no warning when it becomes invalid. Because your question is LEFM is not valid for short cracks as well as for long cracks. That is well understood because the LEFM methodology as such does not give warning. It is a user who has to be intelligent enough to assess the role of plastic deformation. The user must know whether or not plasticity effects need to be considered.

The safest approach is to adopt an analysis that spans the entire range from linear elastic to fully plastic behavior. So, keeping this issue in mind only I have discuss rudiments of failure assessment diagram and that is also summarized here. So, to take care of the issues that you have raised, the use of failure assessment diagram is recommended.

And will also how this diagram originated. You know people had looked at when you have very small load ratios; essentially it is in the domain of linear elastic fracture mechanics. I think you need to make a sketch of this it is a different figure that what we had seen earlier. And this gives you an appreciation how people have approached in fracture mechanics and you always borrow some of these ideas from what we know in conventional design analysis.

We have seen in conventional design analysis, you have sigma y s which is the yield strength from a tension test is used for failure of combine loading. In mixed-mode fracture we have found the K 1c value was used. Only when people went into empirical relations they also brought in K1c as well as K 1c or K 3c as the case may be.

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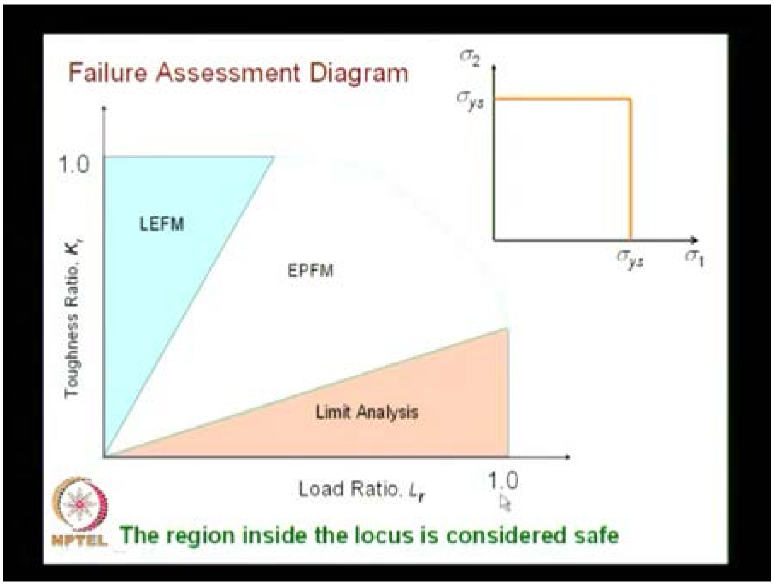

So, what people initially looked at was, when the loading on the specimen is about 30 percent, it is essentially dominated by LEFM. You will have a brittle fracture. If the loading is very close to the yield strength of the material, it is essentially dictated by plastic collapse. So, between the regions of LEFM and limit analysis, you have a region dictated by elasto plastic fracture mechanics. So, in this region you have to depend on elasto plastic fracture analysis and will also look at what is the variation. See what does this graph says is I cannot have a straight line and another straight line meet in here.

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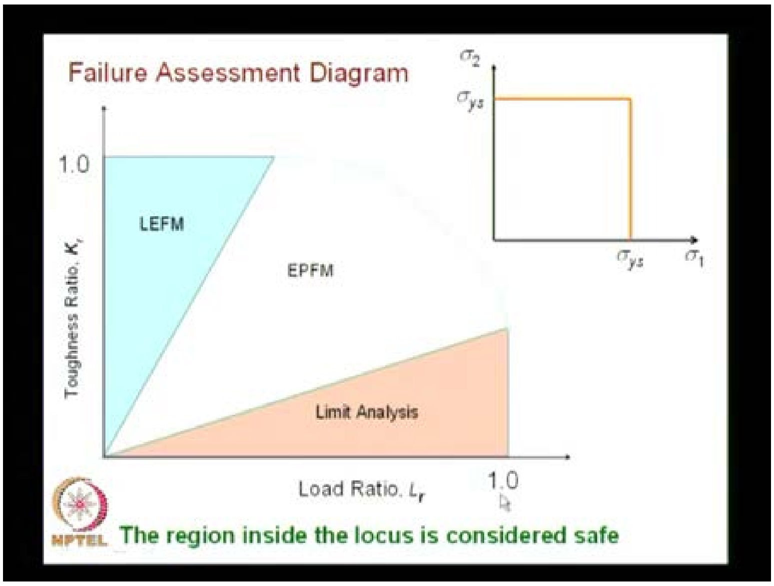

In conventional design what is that you have done? You had combine loading of sigma 1 and sigma 2 and you will see yielding occurs when sigma1 equal to sigma y s or yielding occurs when sigma 2 equal to sigma y s and this is the yield locus you get from your Tresca yield criterion.

It is like a square whereas, once you come to the failure in LEFM and plastic collapse, you cannot have a square zone. This is dictated by a curve. It is lower than that. This is the warning signal. You know what people have found is suppose you take a structure, analyze whether it satisfies brittle fracture. Suppose it satisfies the brittle fracture independently analyzed whether it satisfies plastic collapse. You find it satisfies plastic collapse. Even then if you use failure assessment diagram the point may lie outside this boundary. The region inside the locus is considered safe.

So, that is where the success of failure assessment diagrams. It really brings out when your LEFM analysis as well as plastic collapse fails. You cannot apply them individually. So, the recommendation is do not go and apply LEFM blindly. You always fall up on failure assessment diagram because it encompasses LEFM, EPFM as well as limit analysis. And initially, people did not worry about strain hardening because this was bailed in yield strip model. It stopped at the yield strength value. Whatever is the flow stress or the kind of limiting stress in plastic collapse, it is stopped at that.

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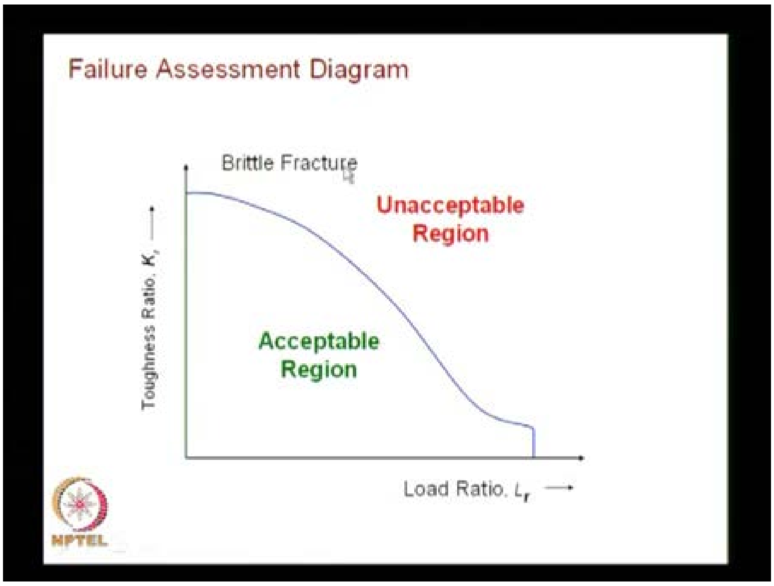

But later on, people extended this by considering strain hardening and the curve was also different and we had seen the curve is dictated by various parameters and various ways you can get it. It is not simply a straight line from LEFM and straight line from plastic collapse. And this curve you have to find out for a given application. It demarcates what is the acceptable region and what is an unacceptable region.

So, the best way to go about and apply fracture mechanics is always fall up on failure assessment diagram. Do not do LEFM because you have learnt LEFM. We have learnt exhaustively LEFM analysis. We have also looked at rudiments of EPFM. We have also looked at failure assessment diagram. So, when you apply fracture mechanics concept to actual structure you should do the analysis from LEFM to plastic collapse and then only decide whether you on the right zone of your application of concepts. Otherwise fracture mechanics concepts cannot be applied to actual designs. Short cracks is a well known problem well documented in the literature.

So, look at the current literature and find out what ways you can improve your understanding and take the appropriate theory for analysis. That is what you have to look at it.

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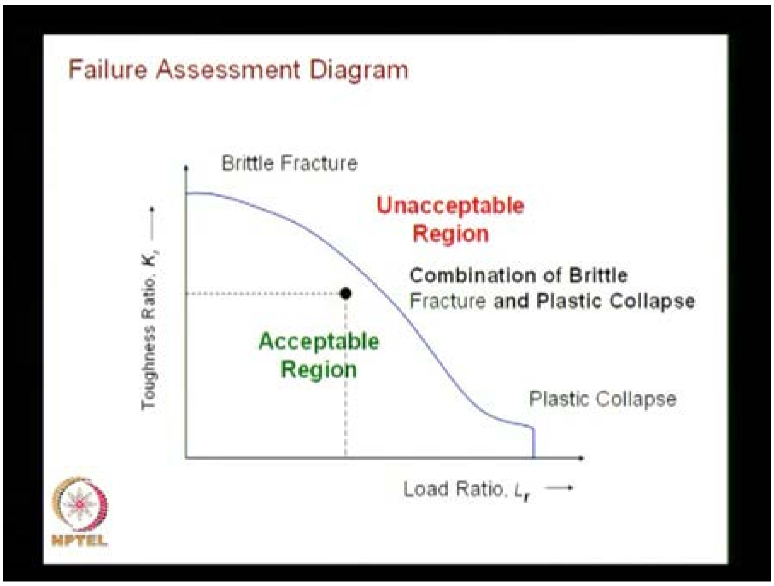

And you can also look at for again recapitalization. So, the initial zone is covered by brittle fracture, the intermediate zone is covered by brittle fracture and plastic collapse and the final zone when the load is very close to the flow stress it is dictated by plastic collapse and you have the data point. So, this data point has to be seen in the fair diagram. So, the recommendation is do not do these analysis separately. Look at the fair diagram. People have shown examples where it satisfies LEFM independently. It satisfies plastic collapse independently, but still the structure is not safe because the point was lying outside the factor. So, such examples people have demonstrated and you have to take knowledge from that.

Is fracture behavior different in composite materials? Yeah definitely. So, fracture behavior in composite material is very very complex. There are multiple failure modes and what you will have to look at is, look at the literature like you have fiber pull out, d lamination, fiber breakage matrix breakage or so many aspects.

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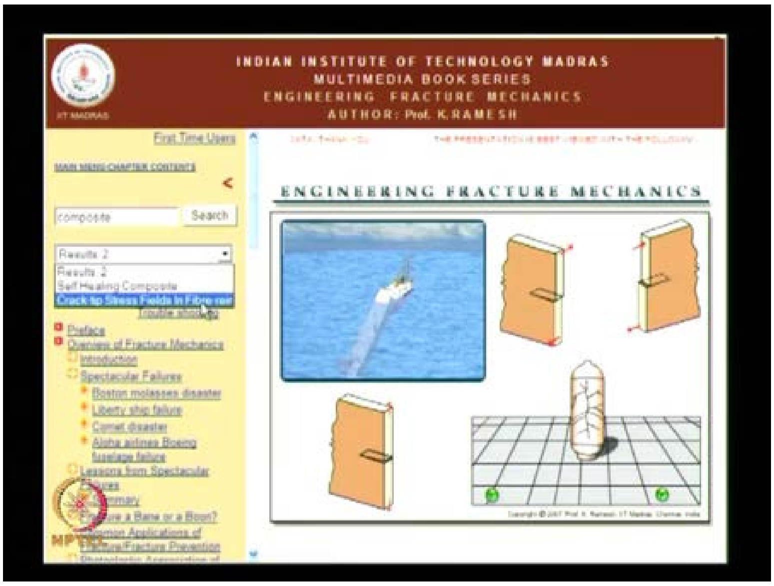

But nevertheless you know, people have utilized photo elastic analysis for analyzing stress field in composites and that is what am going to show.

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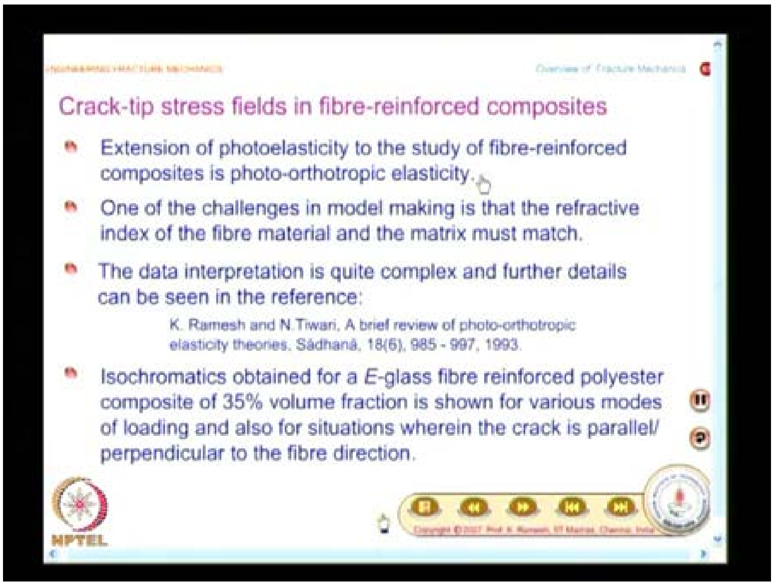

So, you have like photo elasticity you also have photo-orthotropic elasticity. For restricted flaws of problems you have the results. When you have a matrix reinforced by fibers, how do they fail? And one of the challengers in this is how to make a model which is transparent enough. You know my students have developed you have this glass fiber embedded in epoxy resin or polyester resin by appropriately matching the refractive indexes of these two, you could make transparent composite and two problems have been studied. If I have a crack parallel to the fiber or perpendicular to the fiber how the crack grows and what is the kind of stress field which you could see, what is the kind of isochromatics that you can obtained and this has been done for a E-glass fiber reinforced polyester composite of 35 percent volume fraction. In fact, if it look at composite literature, preparing a composite which is transparent with 35 percent volume, fraction is a challenge. This has been achieved and the various photo-orthotropic theories have appeared as a paper in Sadhana in 1993. You can have a look at it. The mathematical analysis is quite complex, you know even the material stress fringe value have to determine in the l direction, t direction also l p direction and so on.

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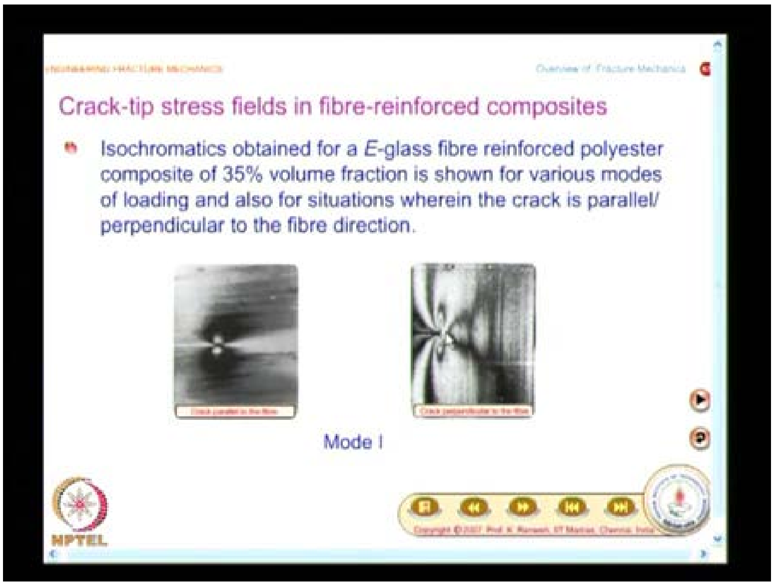

But I will show you some of the fringe pattern that we have obtained and you have these are the fringe patterns obtained. This is for the mode one loading for two situations when crack is parallel to the fiber and crack is perpendicular to the fiber. I think I could enlarge this and show you see the fringes are stretched in the fiber direction and obviously, when you have a crack, the crack will propagate not straight, but it will propagate along the fiber and you could also see how the crack looks when you have a… crack is parallel to the fiber fringe patterns are like this and these were obtained for the first time in the literature for composites.

You do not find these kinds of fringe patterns other than our results for a 35 percent volume fraction. This is done for mode two also and you have this as perpendicular fiber, this is parallel to the fiber you have the fringes and in fact, you could estimate the stress intensity factor by processing the fringe data.

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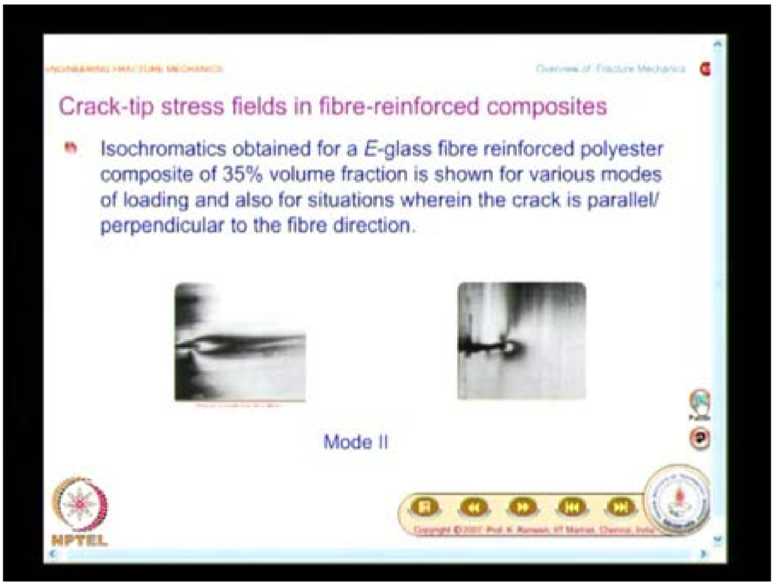

So, this is obtained for mode one, mode two as well as combination of mode one and mode two.

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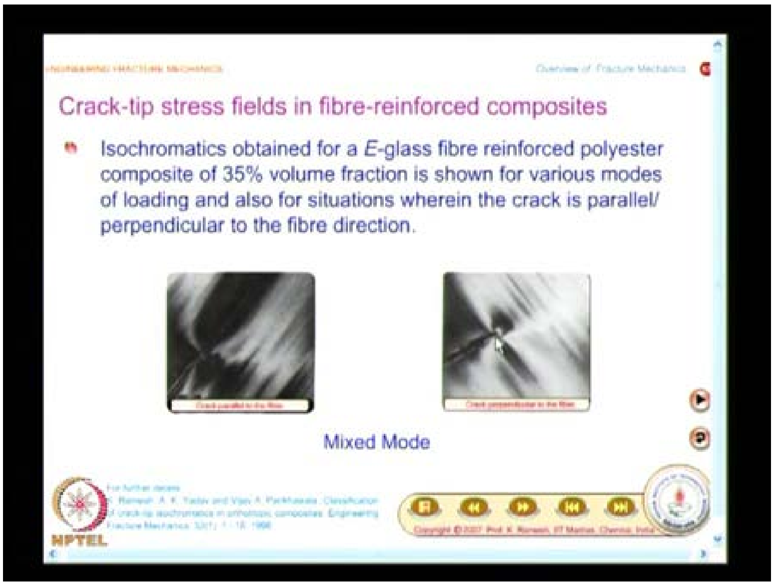

And these pictures are quite dramatic; we could see when the crack is perpendicular to the fiber, the fringes are pulled along the crack axis and this is when crack is parallel to the fiber and you could find some of the results in this paper.

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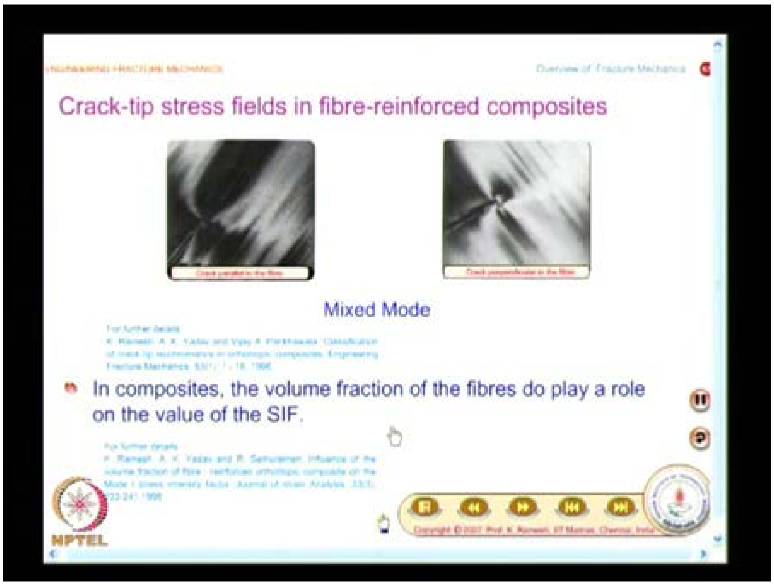

This is by myself A.K. Yadav, Vijay, A.Pankhawala which appear in engineering fracture mechanics in 1996 and there is also another important issue. See in the case of stress intensity factor determination, material parameters did not play a role in isotropic materials. What we have found was the material [car/can] properties do influence in the case of composites.

So, the volume fracture of the fibers does play a role on the value of SIF. What we have found is the influence is quite marginal. This also as appear as a paper in journal of strain analysis in 1998 and the authors were myself, Yadav and professor Sethuraman in machine design. So, what you have here is a flavor of how photo elasticity has been applied to composites for a restricted class of problem. See the moment you go to composites, the whole issue is different. People bring in concepts related to damage mechanics into studying fracture mechanics of composites.

So, you have to look at the relevant literature and then learned what I have shown is how photo elasticity can be applied to a class of problems in composites. It is not exhaustive, its only indicative and you see how the fringe patterns look like and how you can understand, what is the severity of the crack and so on and so forth. And we have also shown whatever the stress intensity factor developed for isotropic material could be used for composites analysis. Though volume fraction plays a role, its influence is small.

Can fracture mechanics explain the formation of first during (( )). You know it is a good question. You know the answer is I do not know. That is also an answer because you know I have seen that people have applied fracture mechanics to where problem. So, the best way to go about is you have powerful internet. Please search the literature and if you find a good paper related to this, try to read it on your own because I have provided you enough fundamentals in this course for you to look at application oriented areas. In case if you have difficulty in understanding, please bring the paper to me, I can sit with you, learn myself and teach you.

What is the approach of damage tolerance?

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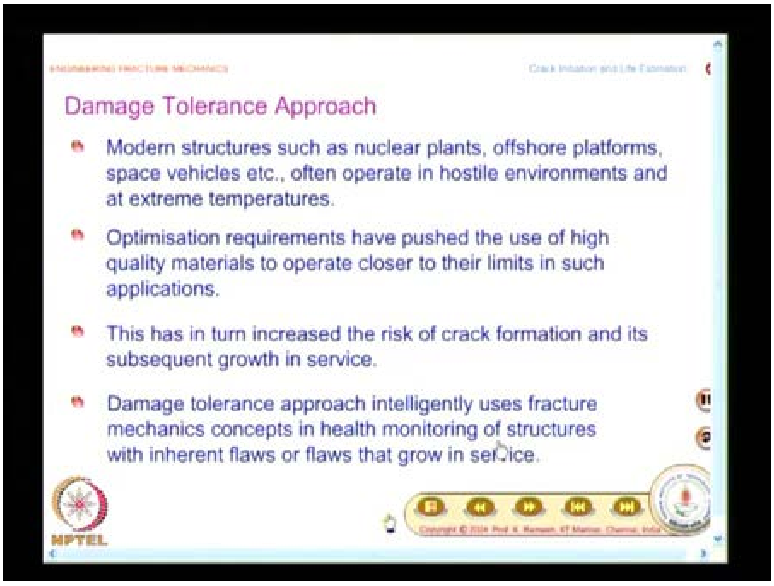

See we look at what is damage tolerance. You know if you want to apply fracture mechanics for field problems, now it is very common in industrial environment, they called this as d t. Once you join an industry the utility of fracture mechanics is only d t because we all know the structures have inherent flaws and how to implement fracture mechanics concepts for safety of structures. That is what damage tolerance approach encompasses. And if you really look at the modern structures such as nuclear plants, offshore platforms, space vehicles etcetera they often operate in hostile environments and at extreme temperatures. See such a necessity was not there in the earlier generations; particularly this generation, we are pushing too hard.

So, we are pushing the material also to the extreme operating conditions. We have to look at that optimization requirements have pushed the use of high quality materials to operate closer to their limits in such applications. This has in turn increased the risk of crack formation and its subsequent growth in service. So, the damage tolerance approach intelligently uses fracture mechanics concepts in health monitoring of structures with inherent flaws or flaws that grow in service. So, damage tolerance is nothing but practical utilization of fracture mechanics concepts in the field. How do you go about?

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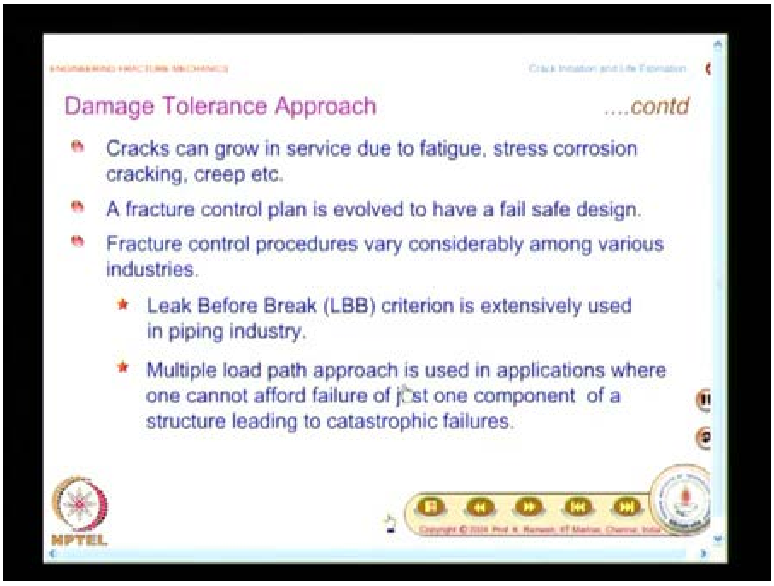

And we all know that cracks grow in service due to fatigue, stress corrosion cracking, creep, etcetera. So, you need to evolve a fracture control plan. What is the role of the fracture control plan? It is to have a fail safe design. See, earlier you had concepts like infinite life. People have understood that nothing like an infinite life. What we want is if the component is going in to fail, let it fail safely. So, that is the best that you can get out of it and that is what damage tolerance is all about. And how do you do fracture control? They vary considerably among various industries, if you look at nuclear instillations, leak before break criterion is extensively used in nuclear industry where you have heat exchangers. So, you can also extend it for piping industry where you have chemical processing plants and so on and so forth. And you also have another important concept- multiple load path approach is used in applications where one cannot afford failure of just one component of a structure leading to catastrophic failures. See you would have seen in T.V shows that they have a competition to build a castle out of your playing cards. You know they have to make the biggest castle as possible and you go and remove one card, the whole structure will collapse. How nature as looked at you. You are gifted with two kidneys, if one kidney fails other kidney will come to your rescue.

So, there is optimization necessary, but also essential redundancy is required. See you cannot design a structure that if one member fails the whole structure collapse. So, that is what this multiple load path approach is all about. And also in the case of fracture control, when you are having welded structures, provide deliberate crack arrestors.

So, if we have a reverted connection, the reverted connection itself serves as fracture control because you have holes. So, when the crack comes to a hole, the hole acts like a delay in rickrack initiation. Such a luxury is not available in the case of welded structures, but welded structures also have to be protected. So, you provide extra stiffeners at vantage locations so that you reduce the energy release rate and provide fracture control. If the crack originates, you do not say that it will propagate for its full length and then the component will separate into two and causing damage. You try to restrict the damage.

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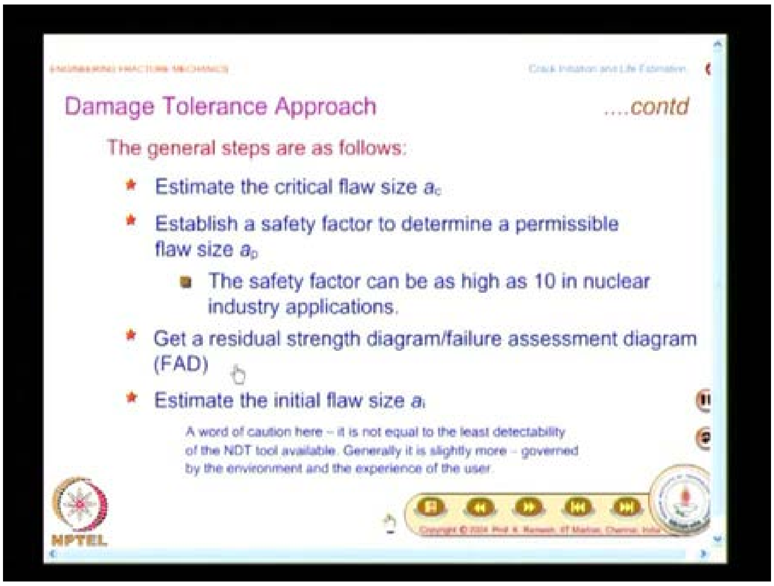

So, for all that you need to have calculations. If you have to do that you have to estimate the critical flaw size and here again you know the problem is so complex, though you do fracture mechanics do not conclude I do not have to have a safety factor because I have understood all about the structures. It is not so. There again you bring in a safety factor. You may have a critical crack-length, but you would allow only a permissible crack size a p and I had mentioned in conventional design for the case of cable rope ways, the factor of safety is about 10 because there if anything happens even rescue becomes very difficult.

So, people want to have a very high factor of safety. A similar factor of safety is also used in nuclear industry application even when you apply fracture mechanics. So, the safety factor is as high as ten. You know there is lot of discussion goes on about nuclear plant safety. Whatever the scientist have understood they have implemented. They never thought there would be a combination of earthquake and tsunami coming at the same time. Then you improve the design there is no other go I mean you have to learn through experiences and then do not repeat the same mistake again. That is where science can help. And you have to get a residual strength diagram. Now you are equipped with failure assessment diagram. So, you can do a better analysis. So, the warning is simply do not apply LEFM because that you have learn it thoroughly.

That is a starting point. This course open the door way for fracture mechanics. This is only a first level course you are learning certain rudiments. For you to apply this knowledge to practice, you have to read additional literature, look at safety regards and then extend the knowledge and with the background I am sure you would be able to do that. And you will also have to estimate the initial flaw size a i and there is also a word of caution mentioned. It is not equal to the least delectability of the NDT tool available. Generally it is slightly more governed by the environment and the experience of the user. Just the least count want do. If you do not use the least count properly, you will also have to look at the experience of the looser.

So, look at the realistic value of initial flaw size and I have already mentioned if you, look at Nasgro or Afgrow, they provide you recommended initial crack lengths for various applications; for space structure separately as YFM structures and so on.

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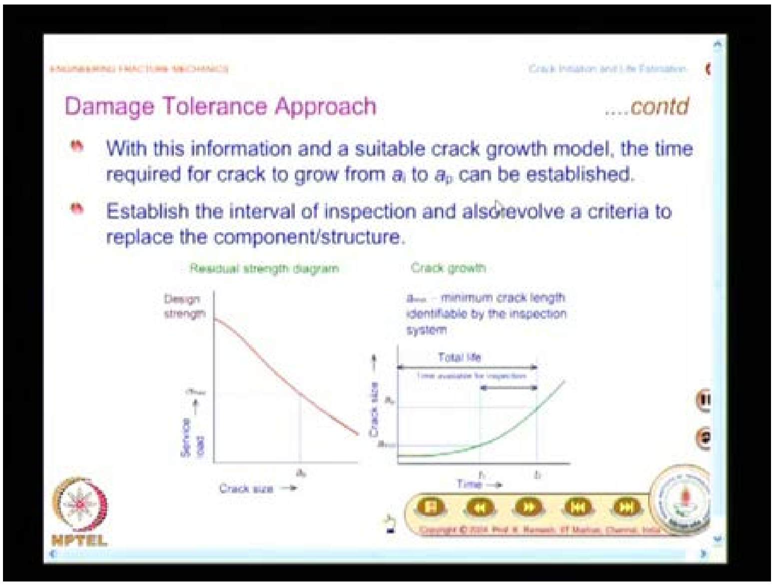

So, from that you can use a suitable crack growth model. You know it is very carefully don . We have seen several crack growth models. So, you have to identify a suitable crack growth model and from that determined the time required for crack to grow from a i to a t. Then you do the inspection intervals. See if you do these calculations wrongly, you go and inspire after the crack has become critical what is use.

So, the crack growth model has to be realistic. So, all that comes from practice .Your field experience it is definitely needed for developing and implementing damage tolerance approach. So, you can get residual strength diagram, similarly you get a FAD failure assessment diagram. You also look at crack growth data and then estimate the intervals appropriately. So, the crack growth model is very very important and we have already seen, if you are going to have random loading, one of the difficult task is even to assess realistically the type of loading acting on the structure.

So, all that requires careful data collection and analysis and then establish inspection intervals because the inspection intervals have to be realistic. If they are not realistic fracture mechanics is not going to help. You have to apply fracture mechanic concepts very very carefully.

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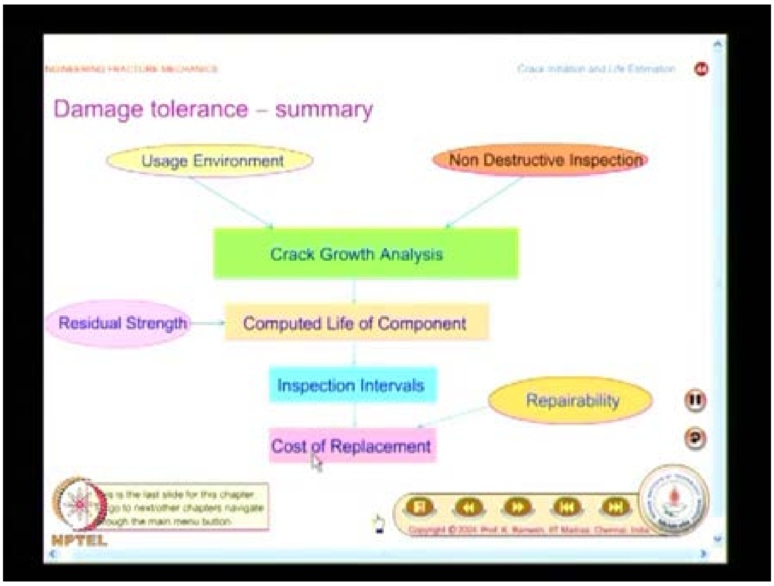

And this gives you the summary of steps and what you have is you have to do the crack growth analysis; the usage of environment comes as well as non destructive inspection. We have seen the Paris law was the carnal; it was not incorporating the environmental effects. The environmental effects were to be taken separately when you are doing d t that should be incorporated. Then you look at the residual strength as input, then find out the computed life of the component, establish inspection intervals and then you find out whether I can salvage it by repairing the component or replacing the component. So, by these procedures you ensure the structure would fail safely. So, that is the emphasis of d t and the whole purpose of fracture mechanics is to arrive at damage tolerance approach. Thank you.