Engineering Fracture Mechanics

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Lecture No # 30

Dugdale Model

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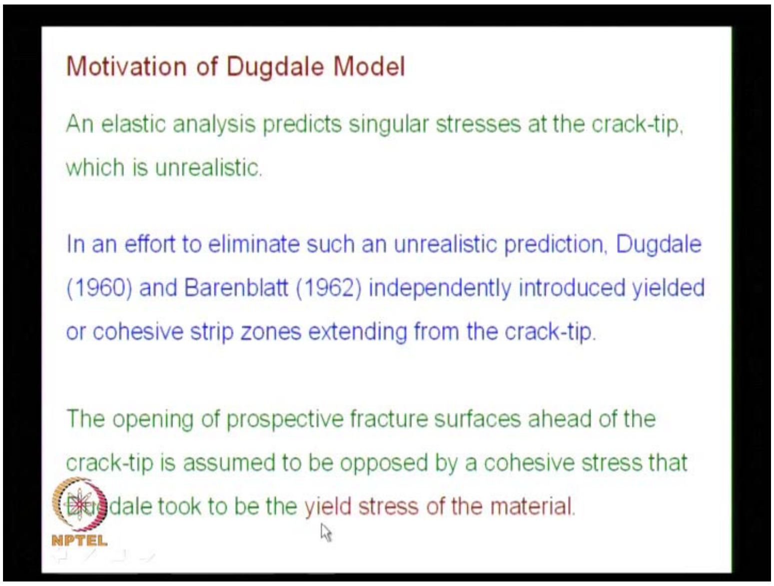

See, in the last class we have looked at what is the motivation of Dugdale model; we will have a brief look at that and proceed further.

An elastic analysis predicts singular stresses at the crack-tip, which is unrealistic. In an effort to eliminate such an unrealistic prediction, Dugdale in 1960 and Barenblatt 1962 independently introduced yielded or cohesive strip zones extending from the crack-tip.

So, you will have to keep in mind these are all models. People were attempting to solve a very complex problem, so they have proposed from their understanding, which way to go about. The opening of prospective fracture surfaces ahead of the crack-tip is assumed to be opposed by a cohesive stress, and what did Dugdale do? Dugdale took that stress to be the yield stress of the material, so it is an assumption. Essentially, he has taken this kind of an assumption and proceeded with the model.

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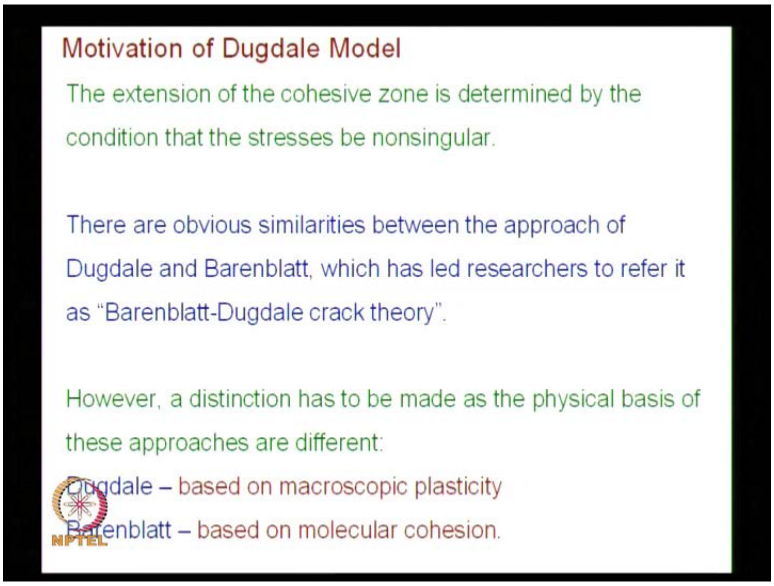

The next step is to find out the cohesive zone length and how this is determined? It is determined by the condition, that the stresses be nonsingular. When you look at the mathematical development, this statement would become quite clear and you will also have to note, that there are obvious similarities between the approach of Dugdale and Barenblatt, which has led researchers to refer it as Barenblatt-Dugdale crack theory.

But you will also have to note, that these have different physical basis. In fact, all of this we had discussed towards the end of last class, this is only for recapitulation.

The physical basis of Dugdale's model is macroscopic plasticity; on the other hand, Barenblatt theory is based on molecular cohesion.

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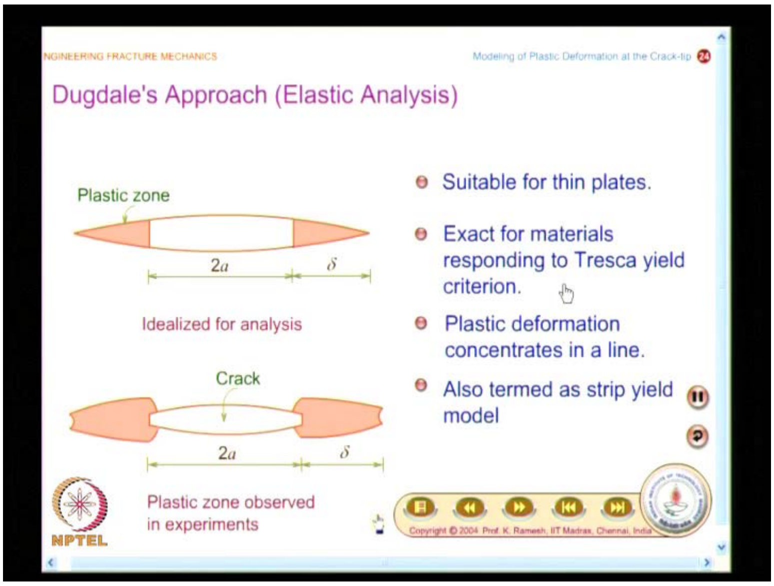

Now, we will take up the mathematical development of Dugdale's approach and you need to make neat sketches of this, and one is an idealization of the crack, other one is an actual crack with the plastic zone developed.

So, what you find here is, you have a crack of length 2a; there is an extent of plastic zone, which is depicted as delta. And you would also see the experimental result and reconvince our self, that this kind of picturization is what is seen in the actual experimentation. A figure like this is taken up for mathematical analysis and you will have to keep in mind, that the Dugdale's approach is suitable for thin plates. This is the restriction number 1 and the theory also assumes, that the materials respond to Tresca yield criterion. So, only for those materials the results will be exact.

And Dugdale also made another assumption. You know, we had earlier looked at what is the shape of the plastic zone near the vicinity of the crack-tip, we had seen a finite shape in front of the crack-tip for the Dugdale's model. He assumed that plastic deformation concentrates in a line. See, this goes with the other two assumptions. When you have a thin plate and the material respond to Tresca yield criterion, this is also valid.

In fact, we would see later, when Dugdale reported the results people did not accept it immediately, people were waiting for the experimental result of Hahn and Rosenfield;

we will see that also. And because you have plastic deformation concentrates in a line, the model is also termed as strip yield model.

So, what you have is, you have an extension of plastic zone, that distance is given as delta and we will have to find out how to get the extension of length delta.

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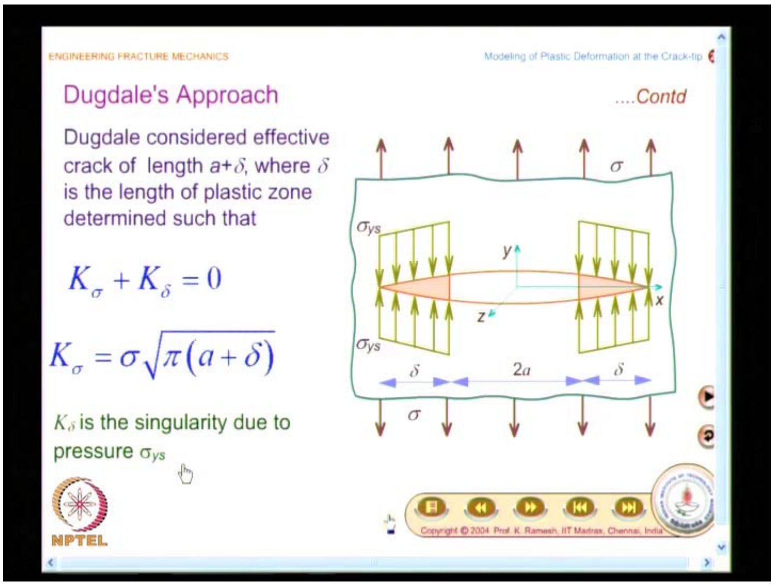

And make a neat sketch of this, you have a center crack in an infinite strip and what you have here is, the length of the crack is 2a and for this zone, which is plastically deformed. The stress level is taken as sigma ys, this is an assumption made by Dugdale in developing the model. And what is the effective crack length now becomes? It becomes a plus delta.

And from the discussion we have done earlier, what we are really looking at is, we want to see K sigma plus K delta should go to 0. You have a center crack in an infinite strip, because of the applied stress sigma you will have a singularity developed. And what Dugdale assumed is, ahead of the crack-tip, there would be a plastic zone and the associated stress level, he had taken that as yield. The strength of the material sigma ys, this will also introduce stress singularity. And we have to find out the length delta in such a fashion, the summation of these two goes to 0. And what is K sigma? K sigma is sigma square root of pi into a plus delta.

We are taking a fictitious extent of crack length by a distance delta and based on that only you have to calculate the stress intensity factor K sigma. And as I mentioned earlier, K delta is a singularity due to pressure sigma ys.

See, the singularity, because of the applied stress, is given in a very simple fashion and can you find some similarity here to find out how to evaluate the stress intensity factor in the presence of the sigma ys? The crack phases are symmetrically loaded, that you can recognize and in fact, we have done evaluation of stress intensity factor for symmetric concentrated load acting on the crack surface. Earlier, in fact, you could invoke that and write an expression.

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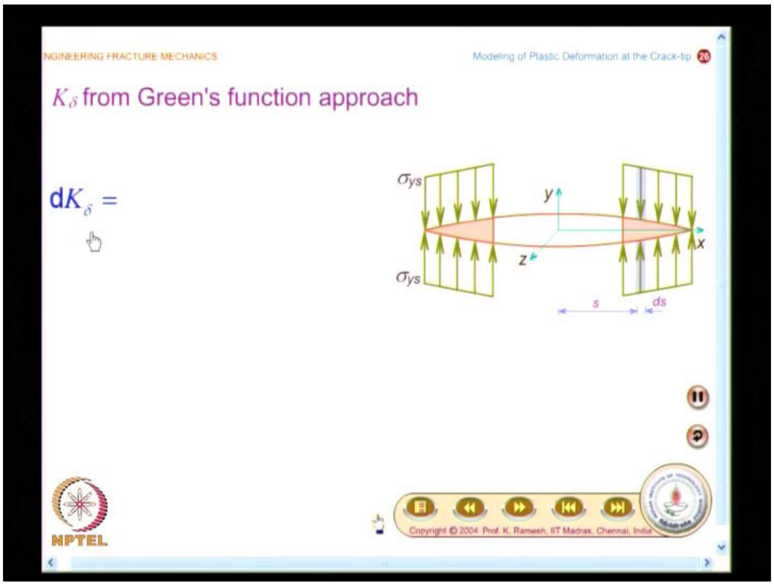

The difference is you are having a distributed loading where we had looked at a concentrated loading. So, I can take a distance s from the center of the crack and look at an incremental distance, ds. Please make a neat sketch of this graph, the crack loaded with stresses. I can also look at simultaneously on the negative x-axis at distance s, another strip of load.

And what we are going to write is we will write dK delta. We would just invoke the expressions that we have developed for a symmetric load and write this for an incremental value of stress intensity factor. Then, you integrate for the extent of the load sigma ys applied; you will be able to calculate the stress intensity factor.

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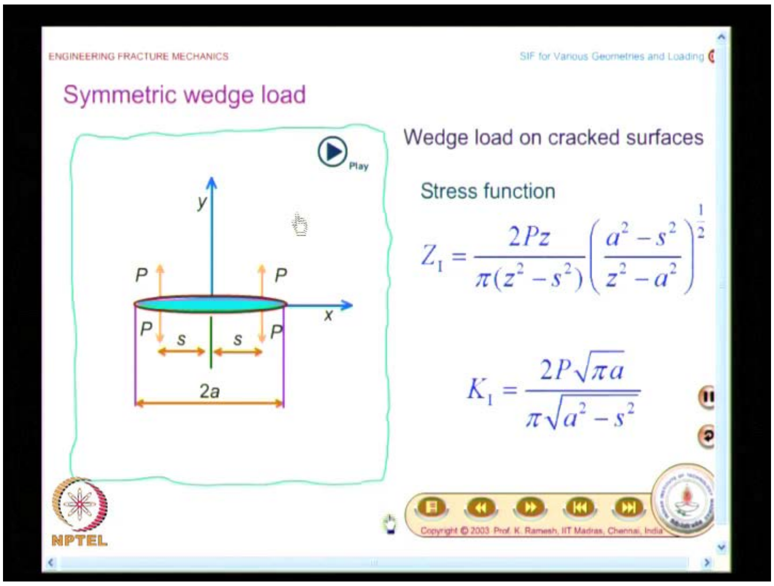

So, if you look at the form of the stress intensity factor for a symmetric wedge load, you have this load P per unit length, you have this as 2 by pi P into root of pi a divided by root of a squared minus s squared. So, I can invoke this and write the incremental value of stress intensity factor in the current problem.

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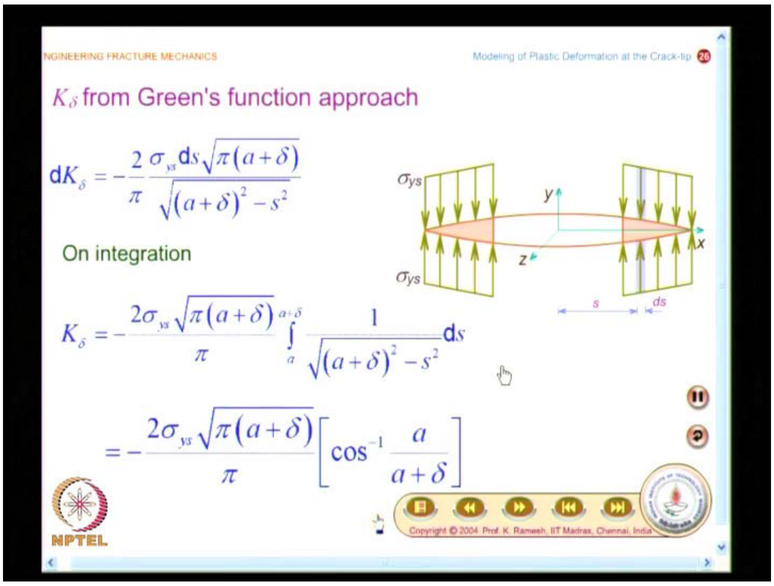

So, you have dK delta equal to minus 2 by pi. That expression was for a load trying to pull the crack surface; here, the load is trying to close the crack surface. So, I have a minus sign here and the stress level is known, this is given as sigma ys and incremental distance is ds. So, sigma ys ds denotes the load P and root of pi a and pi a is taken as pi into a plus delta and you have divided by square root of a plus delta squared minus s squared. And rest of it is simple mathematics, you know, we have been handling integration of such quantities and we would get those expressions.

So, what I have here is, it becomes K delta equal to minus 2 sigma ys multiplied by pi into a plus delta divided by pi between the limits. You integrate a to a plus delta 1 by square root of a plus delta square minus s squared into ds.

You know, we have solved such expressions earlier; you can look at your notes a few pages back and then, see, what would be the integrated value? You are essentially using the table of integrals, so you can easily find out what would be the integrated value, then apply the limits. In fact, I am going to skip that step; I will apply the limits and write the final expression. The intermediate step, I would like you to do it, we have already seen it earlier while discussing evaluation of stress intensity factors, so you can use that part of the notes. So, I am skipping the intermediate step of putting the limits.

After putting the limits, whatever the expression I get, could be simplified to cos inverse a by a plus delta and this is pre multiplied by minus 2 sigma ys square root of pi a plus delta divided by pi.

So, what we have done? We have used our knowledge of stress intensity factor for symmetric load acting on the crack phase, extended it for finding out the stress intensity factor when I have sigma ys on either side of the crack-tip, and we have got the expression for K delta. What we have to do next? We have to write the expression K sigma plus K delta equal to 0, that is what I am going to do.

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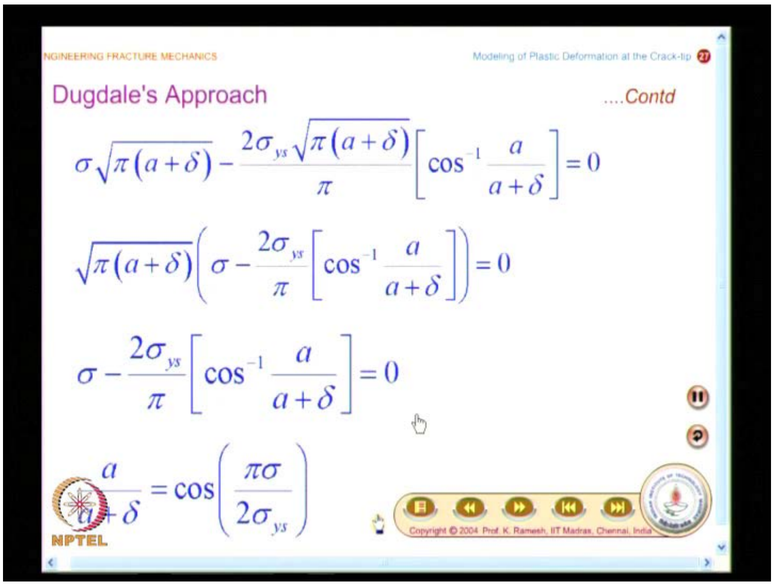

And that is what is written here. So, what I have here is, sigma square root of pi a plus delta, this is the K sigma expression and K delta expression we have recently calculated, that is, minus 2 sigma ys square root of pi a plus delta divided by pi multiplied by cos inverse a by a plus delta equal to 0.

See, there is a subtle difference in the development of the expressions itself. See, if we have looked at what way we developed Irwin's model, we had a plastic zone, the plastic zone length was given as r p, but the value of delta to modify the crack length is taken as 1 half of r p that was taken as delta. But here, in the development itself, we always take the complete length of the plastic zone as a correction required for the crack length. This is seen at every step of Dugdale's development, so keep a note of this.

So, the next simplification is, if I take out square root of pi a plus delta, the expression turns out to be sigma minus 2 sigma ys divided by pi multiplied by cos inverse a by a plus delta equal to 0. At every stage you are correcting the crack length with the expression delta.

So, finally, when we look at the plastic zone length and there correction necessary for crack length, we have to handle it carefully in Dugdale's model as well as Irwin's model, there is a subtle difference between the two.

And I can take this to right hand side, I can knock off this. So, essentially, I get sigma minus 2 sigma ys divided by pi multiplied by cos inverse a by a plus delta equal to 0. So, this will help me to get an expression for delta. Let us see what we get? So, I get a by a plus delta. On simplification you can take it on the right hand side and you will get this as pi sigma 2 sigma ys, so you get this a by a plus delta as cos of pi sigma divided by 2 sigma ys. We have to solve this further.

See, whenever we have an expression like this, as engineers we have to bring in certain approximations. Only by bringing certain approximations you would be able to get a simplified expression and what is approximation we will do? When you have sigma and sigma ys appearing here in most of the fracture problems, the value of sigma will be far below the value of yield strength of the material. See, that was the worry; structures were failing as stress is far below the yield strength value.

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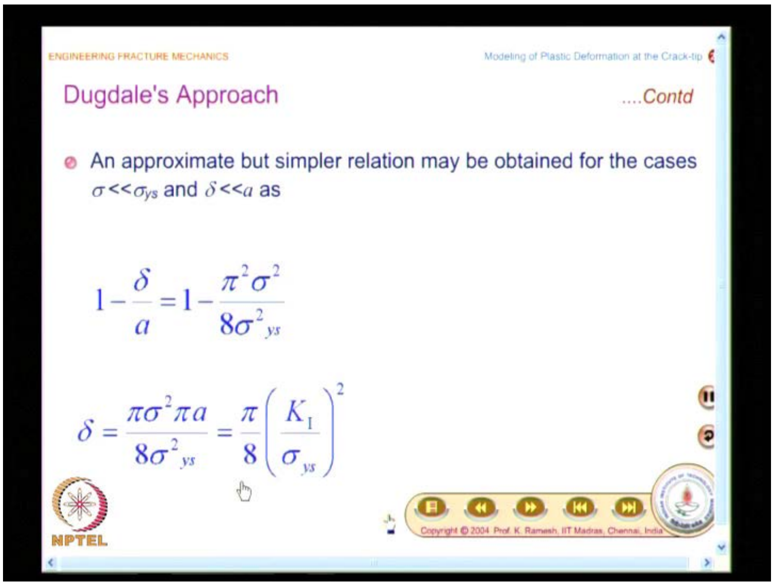

So, I can invoke this kind of simplification by saying sigma is far below sigma ys and also make another observation, that the extension of plastic zone is much smaller compared to the crack length. You know, these are very important, only when you make approximations like this we would be able to simplify and proceed further.

So, what you have is 1 minus delta by a equal to 1 minus pi square sigma square divided by 8 sigma squared ys. So, from this I would be able to calculate what is the expression for delta and delta turns out to be pi sigma squared pi a divided by 8 sigma squared ys. Since we are handling a center crack in an infinite plate, I can bundle this and write this as pi by 8 K 1 by sigma ys whole squared. In fact, in all problems dealing with plastic zone length you will have an expression K 1 by sigma ys whole square. It will be pre multiplied by a factor here. If the factor is pi by 8, we will also have a summary of these quantities and see how this can be utilized.

What is the kind of comparisons that we can make from simplistic model, Irwin's model and Dugdale's model? See, you will have to note, when Dugdale developed his model, he has got the extent of plastic zone length. In fact, in his original paper, he had just compared from certain experiments, what is the value of this extent of plastic zone experimentally, as well as predicted by his theory this matched quite well, but what he had not done is, he had not provided the pictorial support for his observations. We will also have to note that.

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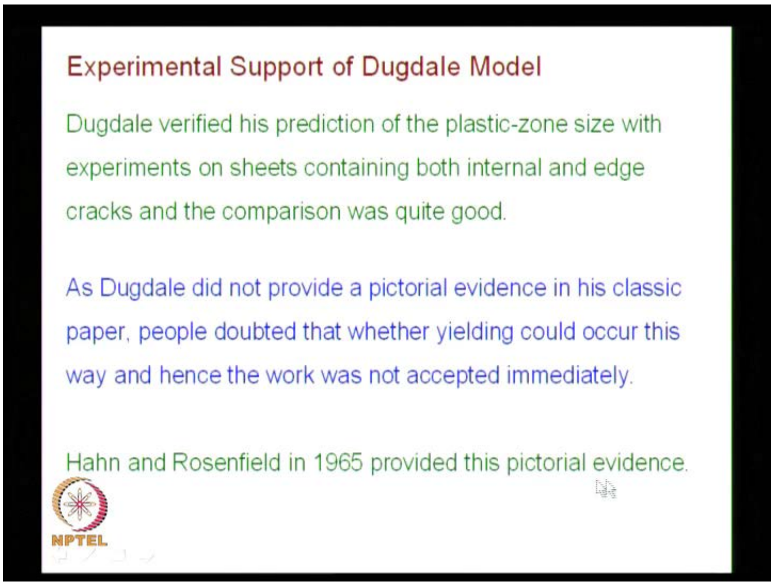

So, Dugdale verified his prediction of the plastic zone size with experiments on sheets. So, he was working on thin specimens containing both, internal and edge cracks, and the comparison was quite good because it is only a model. See, you are charting a difficult problem and you have to idealize it, so that you get some useful result for you to proceed further. So, his idea was, there would be a plastic zone, it will be in the form of a strip and he was also able to verify his prediction based on experiments.

As Dugdale did not provide pictorial evidence in his classic paper, people doubted that whether yielding could occur this way and hence, the work was not accepted immediately. See, we will have to keep it in mind, you know, we had done a circus to find out, approximately, what is a shape of the plastic zone near the crack-tip. I said, only in the case of mode three situation, you have, this plastic zone is like a circle, in all other cases it has some shape. And someone comes and says, in the case of thin plate you have this as a strip, you know, people just could not digest his contributions. So, people are doubting, is there anything wrong in his approach?

Actually, if you look at the result, that he had quoted in the paper, the experimental and theoretical prediction, the comparison was quite good, he had not provided the pictorial representation. This was done by Hahn and Rosenfield in 1965, who provided this pictorial evidence, then people started believing, yes Dugdale's model is a valid approach for evaluating the plastic zone length.

You know, this is very important, like, as students you get doubts scientists also got those doubts in those days, so it had to be verified by experiments. So, whatever the theory, that you develop, the predictions have to be substantiated by experimental observation only, then the theoretical approach can be taken on its face value. It is very important.

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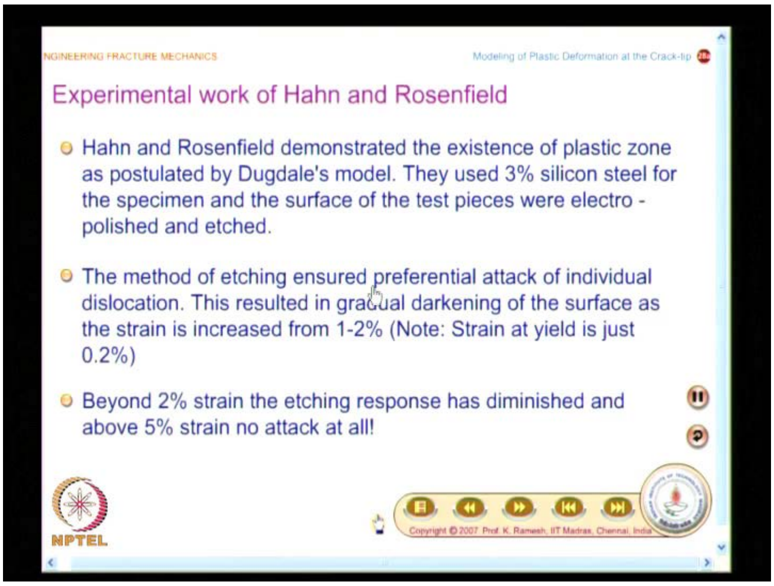

So, what is the experimental work of Hahn and Rosenfield? They demonstrated the existence of plastic zone as postulated by Dugdale's model. And what they did was, they used 3 percent silicon steel for the specimen and the surface of the test pieces were electro-polished and etched, and this etching is a very special process. This has helped to reveal the shape of the plastic zone and essentially, they were metallurgists, they were handling these kinds of issues earlier, so they had used this for crack problem.

The method of etching ensured preferential attack of individual dislocation. So, whatever is the plastic zone, it is because of dislocation pile up and the etching process ensures, that there is a preferential attack and it makes the plastic zone reveal in some form. The etching has resulted in gradual darkening of the surface as the strain is increased from 1 to 2 percent.

See, you will have to note down, in the context of strain, 1 to 2 percent is very high because if you really look at material testing, the offset strain, that you take when the yield strength is not sharply defined, you take that as 0.2 percent offset. So, 0.2 percent itself is sufficient for the material to yield. So, when you have 1 to 2 percent, the material has definitely deformed plastically.

Beyond 2 percent strain the etching response has diminished and above 5 percent strain, no attack at all. These are certain minor details on how the experiment was done. What is important to us is by the process of etching, because of preferential attack, you are in a position to obtain the shape of the plastic zone that is what you have to look at. You are in a position to get the shape of the plastic zone by a particular procedure adopted in the experiment.

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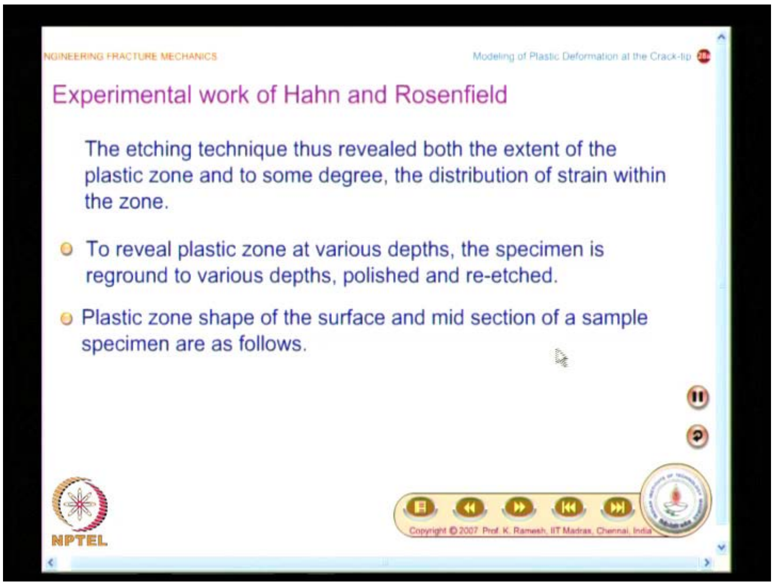

The etching technique thus revealed both, the extent of the plastic zone and to some degree the distribution of strain within the zone because I have already mentioned, that 1 to 2 percent, it is able to do well; beyond 5 percent, there is nothing has happened. So, you also get some crude values on what is a level of strain, shape is very interesting; level of strain is additional information, though it is crude, it provides some such additional data.

And what they had done was to reveal plastic zone at various depths, the specimen is reground to various depths, polished and re-etched. So, you have a via media, whether the plastic zone remained constant over the thickness of the sheet of the specimen, all that you have to investigate because we are going to see, how the plastic zone changes across the thickness. And we will also see, how the plastic zone, say, changes as the crack propagates, both we will have to look at it.

So, whatever the experimental method of Hahn and Rosenfield, also ensured, not only you see the plastic zone on the surface of the specimen, but also at various depths, you have that kind of an advantage. And you have a sample of the plastic zone shape of the surface and mid-section of a sample and that is given as follows.

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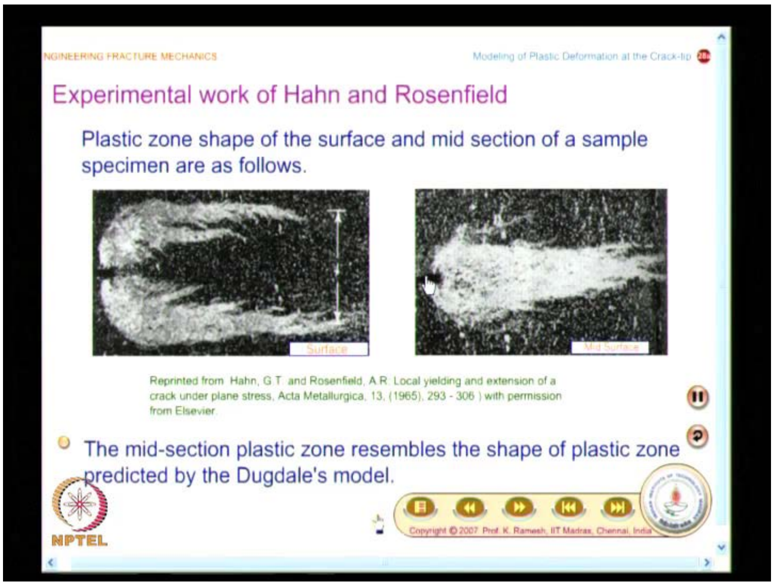

On the surface the plastic zone is like this, at a mid-section the plastic zone is like this. See, this is a very highly magnified picture, you can for all practical purposes consult this as a line.

So, this happens on a surface, I would like you to make a sketch of this, you know, you need to have, these are all very valuable information and only after seeing such a plastic zone people believe Dugdale's model. So, from that point of view this is very important result, and make a neat sketch of this. This happens on the surface and we would also spend sufficient time on this a few slides later, so make a neat sketch.

So, this is from Hahn and Rosenfield from the paper on local yielding and extension of a crack under plane stress, published in Acta Metallurgica and what you have to notice is the mid-section plastic zone resembles the shape of plastic zone predicted by the Dugdale's model. So, this provided a comfort in accepting Dugdale's model as a valid approach.

And really, what is the use of finding out the plastic zone? See, we have seen earlier when we looked at SSY approximation. You have to take the effective crack length as a plus the extent of plastic zone in Dugdale's model. In the case of Irwin's model, it was a plus 1 half of plastic zone; that is what we had looked at. And we will also have to find out what is the resulting stress intensity factor that would be useful information because we want to graduate from high strength alloys behave in a brittle fashion to alloys, which also have some small trace of plastic zone. You could apply fracture mechanics to that, so you have a simple via media of modifying the crack length.

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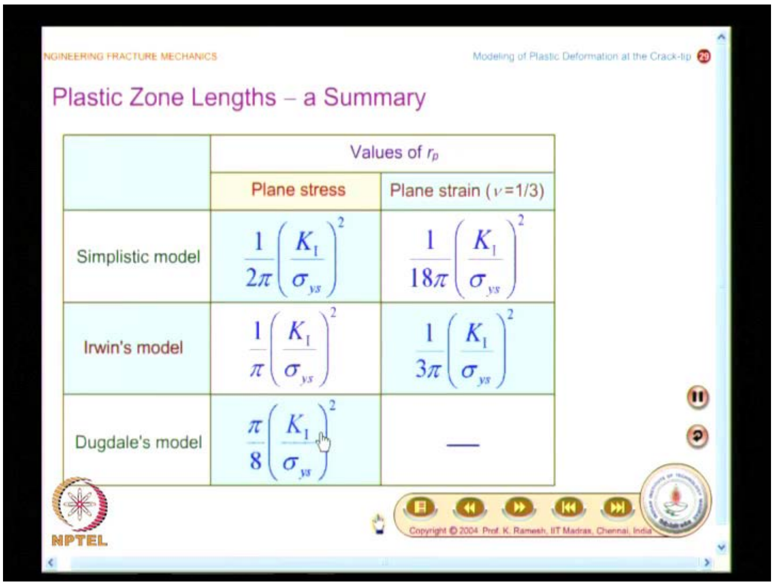

And before we proceed to the calculation of stress intensity factor, we would have a look at the plastic zone length that we have calculated by various methods. We will also look at what way the results of plane stress and how the results change for plane strain. You had the simplistic model, where you did not consider redistribution of load, the plastic zone length is 1 by 2 pi K 1 by sigma ys whole square and in the case of plane strain this is much smaller, you have this as 1 by 18 pi K 1 by sigma ys whole square.

Then, you have the Irwin's model, for plane stress it is 1 by pi K 1 by sigma ys whole square and when you go to plane strain, it is 1 by 3 pi multiplied by K 1 by sigma ys whole squared; see, this is a very important value. Later on, we are going to study what should be the selection of the specimen thickness for fracture toughness testing; there you would see the use of such expressions.

Then, finally, we had seen the Dugdale's model and we will have to keep in mind this is applicable only for a plane stress situation. He had taken only thin specimens, essentially thin plates; he had not calculated the plastic zone size for plane strain situation. And in

Dugdale's model, the plane stress plastic zone length is pi by 8 multiplied by K 1 by sigma ys whole squared.

And we had noted that Irwin's model is an elasto-plastic analysis and this, we have set this as an elastic analysis. He had considered redistribution of load, whereas Dugdale considered a strip of plastic zone. You have no singularity because of that, on that premise he was able to calculate the plastic zone length.

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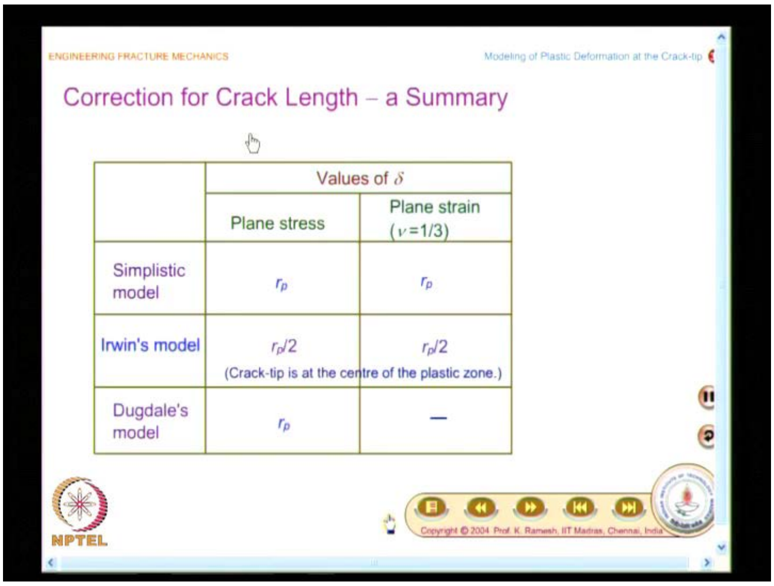

And we will also look at what is a correction that we have to do for crack lengths.

In the case of simplistic model, you take that as, length as r p for plane stress; for plane strain, you know, the calculations we have done for nu equal to 1 by 3, you take that as r p. However, when you go to Irwin's model, you take that length as r p by 2 because only on this basis, you know, Irwin has arrived at even the estimation of the plastic zone length, it is embedded in the development of the equation itself. Finally, when you come to Dugdale's model, you take the total length of the plastic zone as the correction for crack length.

You know, these are all subtle differences. When people handle complex problems, they do by different approaches. So, when you go to actual application, if you find it satisfies your experimental observation, you carry on with it.

Now, with the corrected crack length we should also improve the value of stress intensity factor because the whole idea is to get the stress intensity factor. When you have small amounts of plastic zone, an intermediate step is, consider the crack as slightly longer than the actual crack length; that is physics here.

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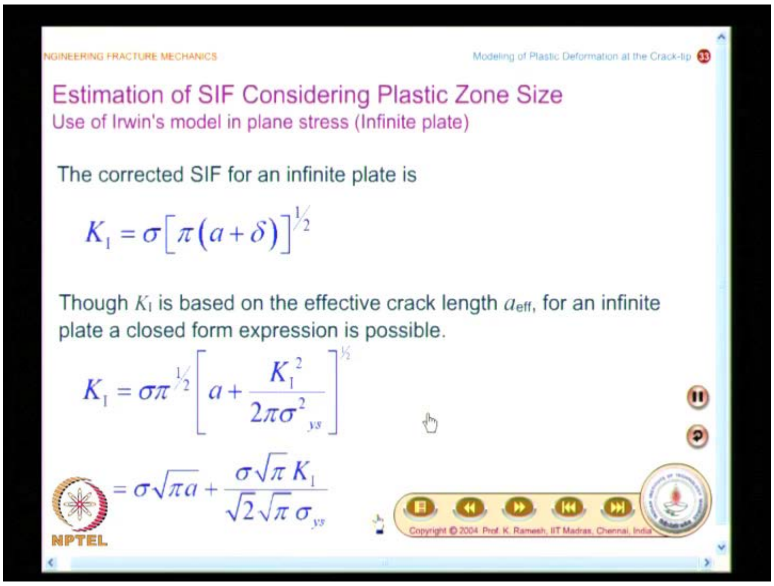

What we will do is we will calculate the stress intensity factor for an infinite plate considering the plastic zone size.

K 1 is sigma into pi into a plus delta whole power half. See, you have to note, that delta is dependent on K, but because the problem is simple, I do not have to do iteration, I can find out an expression for K 1. For this specific example, a closed form expression is possible.

So, I will substitute the expression for delta from Irwin's model. I have this as sigma pi power half multiplied by a plus K 1 squared divided by 2 pi sigma squared ys whole power half. And this could be further simplified as sigma root pi a plus sigma root pi K 1 divided by root of 2 multiplied by root of pi sigma ys, these are all intermediate steps.

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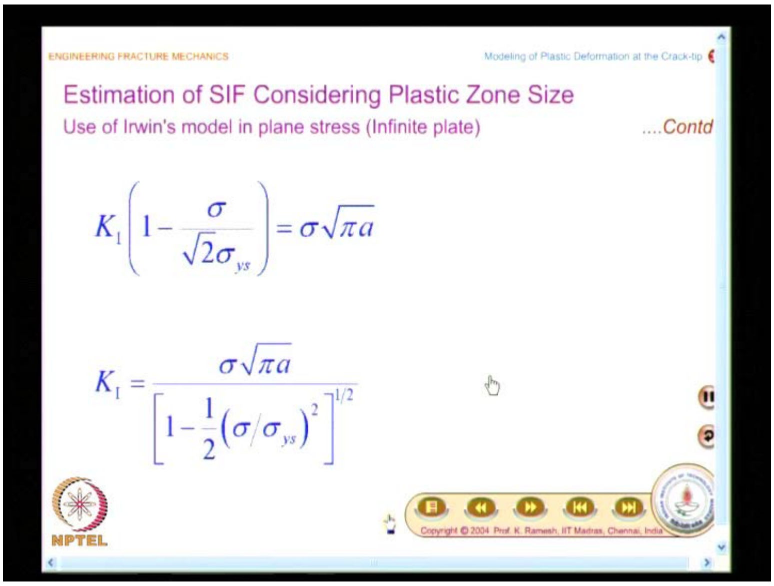

And we would finally get the expression for K 1 as, in this fashion, K 1 equal to sigma root of pi a divided by 1 minus 1 by 2 sigma by sigma ys whole square whole power half.

See, you note down, the ratio sigma by sigma ys appears in all these calculations. So, we can also comment, when the stress levels are far below the sigma ys, the correction is almost negligible. We can also estimate, when sigma is closer to sigma ys, to what extent the values of K 1 can change. We would see that also in the case of an infinite plate with a center crack.

If you consider the plastic zone, the K 1 becomes an expression, other than sigma root pi a you have a denominator, which will be less than 1. So, this value will be eventually higher.

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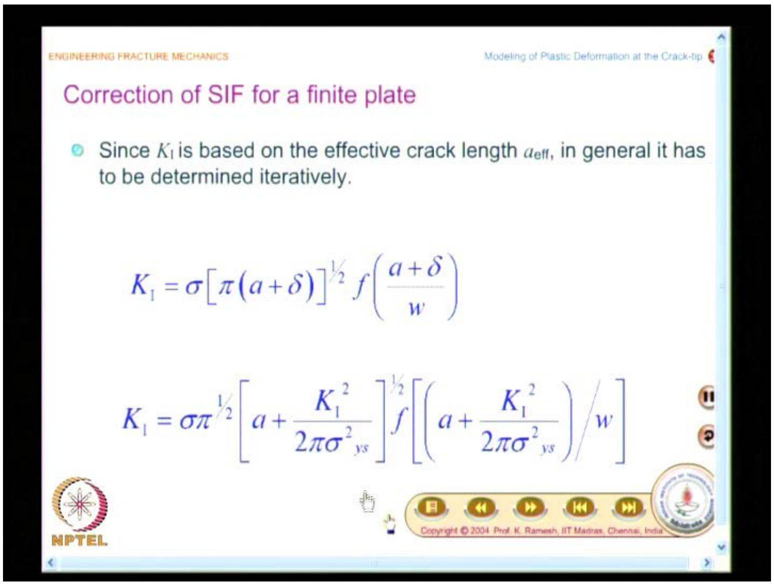

And you can also extend this kind of a correction for a finite plate. The moment you go to your finite plate you cannot avoid iteration; in general, it has to be determined iteratively, there is no other go. So, I would write this expression as K 1 equal to sigma multiplied by pi a plus delta whole power half and a function of a plus delta by w. So, this function also will change when you do the iterative process and it is possible to write software to do this job.

So, I will get K 1 equal to sigma pi power half multiplied by a plus K 1 square divided by 2 pi sigma squared ys. You are essentially replacing the delta in terms of Irwin’s result. I have the function rewritten as a plus K 1 squared divided by 2 pi sigma squared ys whole divided by w.

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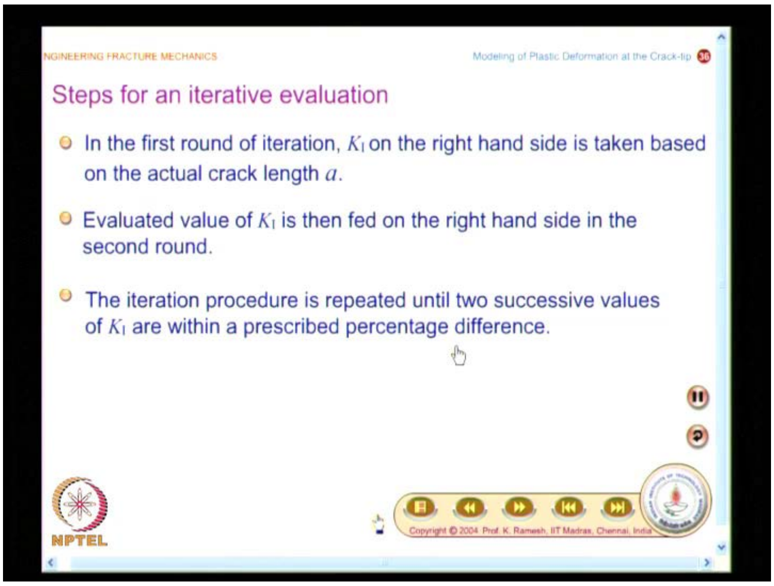

And what are the steps for an iterative evaluation? In the 1st round of iteration, K 1 on the right hand side is taken based on the actual crack length a.

Evaluated value of K 1 is then fed on the right hand side in the 2nd round. It is very simple; it is not complicated, straight forward.

The iteration procedure is repeated until two successive values of K 1 are within a prescribed percentage difference, then you stop.

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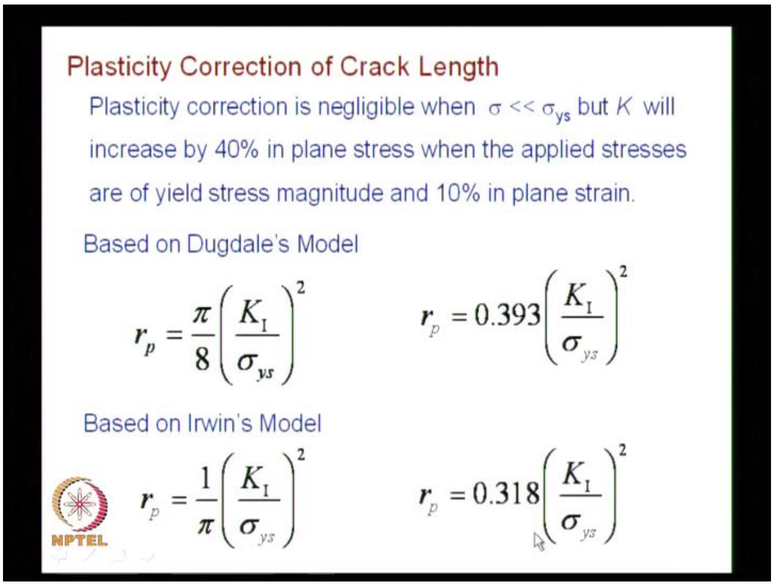

See, what is important at this stage is what is the influence of correction of crack length? I have already mentioned, when the applied stress is far below the yield strength of the material, plasticity correction is negligible because we have seen in all the expressions, a ratio of sigma by sigma ys was appearing.

Now, what we will have to know is what way K can change? If the value of applied stress is closer to sigma ys, K will increase by 40 percent in plane stress and 10 percent in plane strain, so that relative increase of K is significant. What happens in plane stress and what happens in plane strain? And it is also worthwhile to look at the expression for Dugdale's model written out in a different fashion. When you rewrite, you can write this as pi by 8 as 0.393. In the case of Irwin's model, the extension is given as 1 by pi K 1 divided by sigma ys whole square; this 1 by pi is actually 0.318.

So, if you compare, they are not really very different. Irwin has approached the problem from one methodology, Dugdale has approached in another methodology; both seem to have got the extension of plastic zone within limits. But the way how it is used in modifying in the crack length is slightly different in Irwin's model and Dugdale's model. And you have to keep in mind, you know, the problem is very complex, people wanted to proceed further, so they wanted to have simplifying assumptions and go ahead. From that point of view, the contribution of Irwin is very significant.

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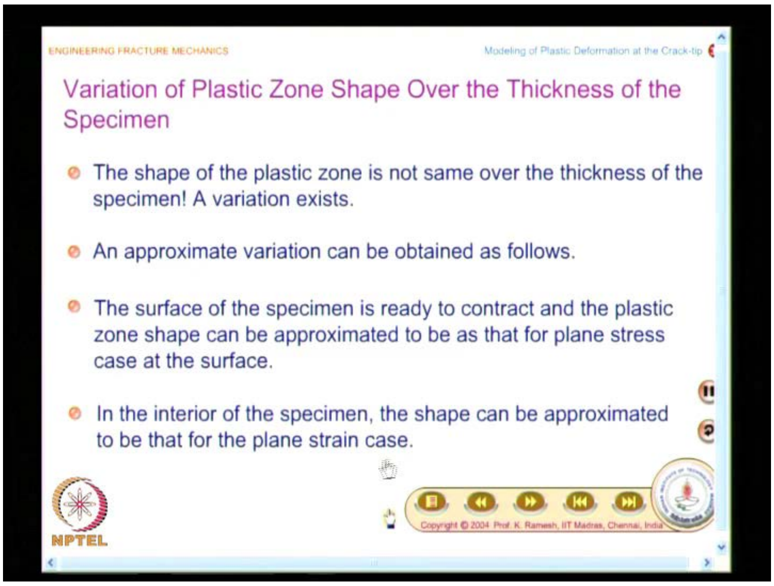

Now, having looked at all this, what we will look at is what is a variation of plastic zone shape over the thickness of the specimen? See, you have to look at the mathematical development. We try to proceed in a way as simple as possible, so you evaluate at approximate shape, but approximate shape is not the one, which is going to be seen in an experiment, that was for specimens of different thickness.

On the other hand, Dugdale came and said, for thin plates it is like a strip. That is other extreme, but for a specimen of given thickens, you have to know how the plastic zone actually is. So, whatever the discussion I am going to present is based on what is seen from finite elemental solution or from experiment. Whatever the discussion we had earlier was approximate analytical approaches and you have to keep in mind the shape of the plastic zone is not same over the thickness of the specimen, a variation exists.

You had that evidence even in your verification of Dugdale's approach. You had seen how the plastic zone was on the surface, how it was there in the middle, even for a thin plate. Now, if you are having a thickness specimen, you are going to have… And we also had a discussion, what way we call plane stress and plane strain in the case of fracture mechanics. If I have a thick specimen, I will consider the surface to behave like a plane stress and interior when you go, it behaves like a plane strain. So, that kind of an idea I would use in looking at the plastic zone shape also. So, what you will have to look at is the plastic zone shape differs over the depth of the specimen; so, that is what is summarized.

The surface of the specimen is ready to contract and the plastic zone shape can be approximated to be as that for plane stress case at the surface. And I have already mentioned the plane stress and plane strain are loosely defined in the case of fracture mechanics. So, on the surface, the shape is what is seen for plane stress case; in the interior of the specimen the shape can be approximated to be that for the plane strain case.

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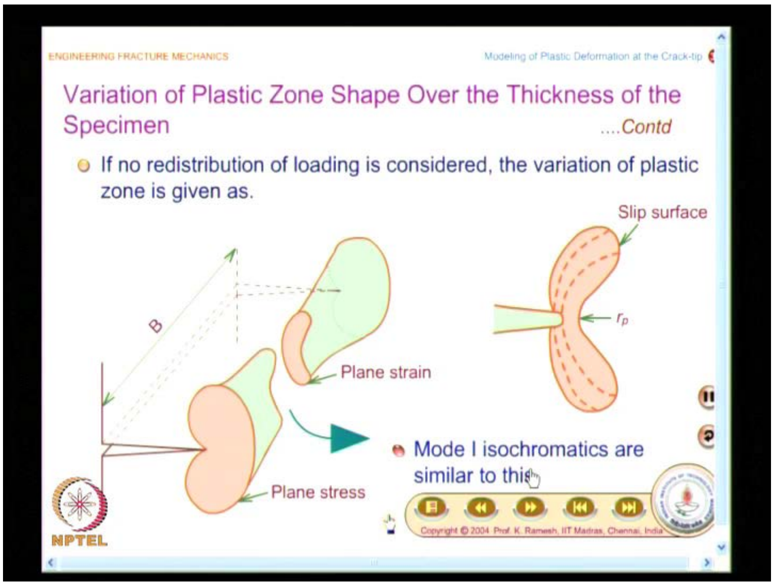

And what I would like you to do is make a reasonable sketch of this. So, the 1st set of result, what is presented here is if no redistribution of loading is considered, the variation of plastic zone is as follows. So, you have to note, that the crack is like this, you have a thickness of the specimen as B. On the surface, the shape is something like this; interior to the surface, the shape is like as a butterfly. I have this slipping takes place, I have this length of the plastic zone, along the crack axis is given as like this and whatever you see here, is similar to your mode one isochromatics.

See, people will have also done finite element calculation, including the second term, that is, t stress. They have plotted a very similar to this, so this gives you an understanding over the depth of the specimen. Over the thickness of the specimen the plastic zone varies and views the approximation, that surface behaves like a plane stress situation. On interior it acts like plane strain situation and this is very similar to your mode one isochromatics.

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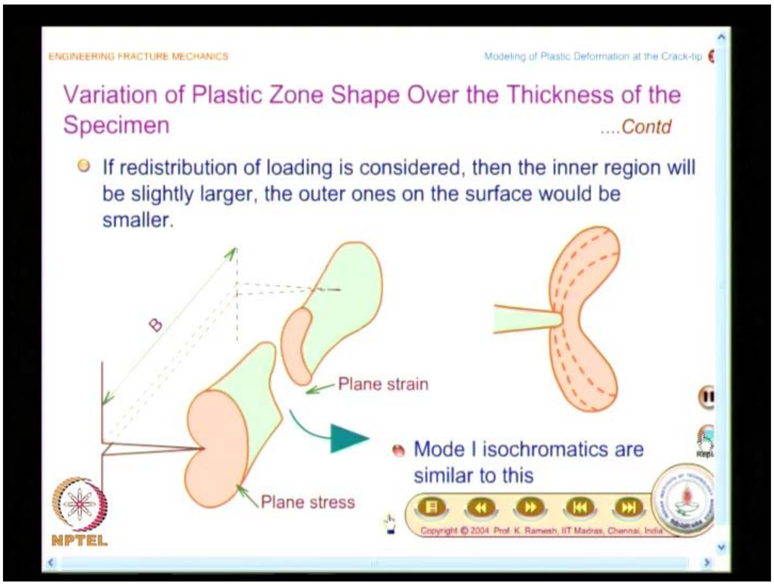

Suppose, I consider the redistribution, what way these zones change? You just observe this, then copy it. What happens is, the inner places, it increases and the surface shrinks. So, what I will do is, I will just redo the whole thing.

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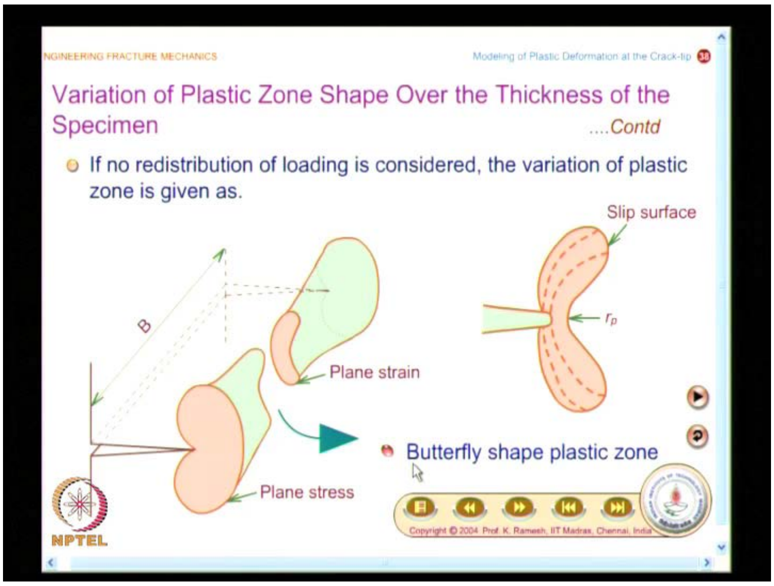

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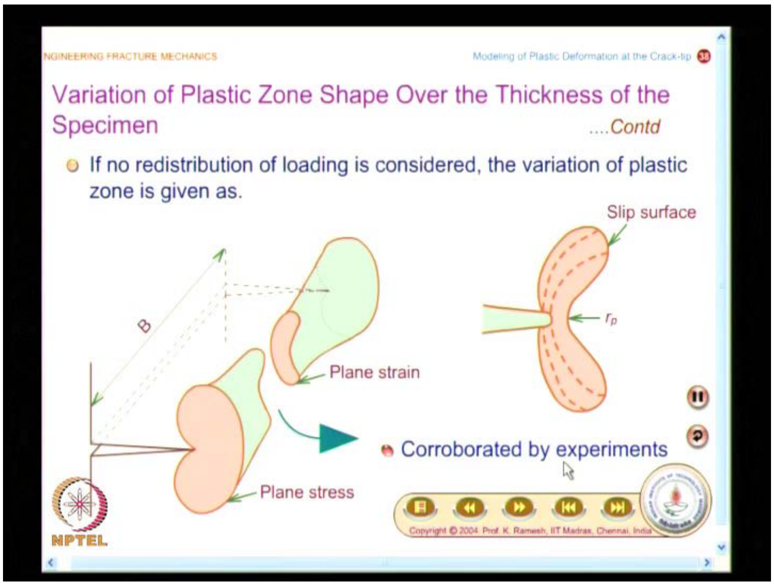

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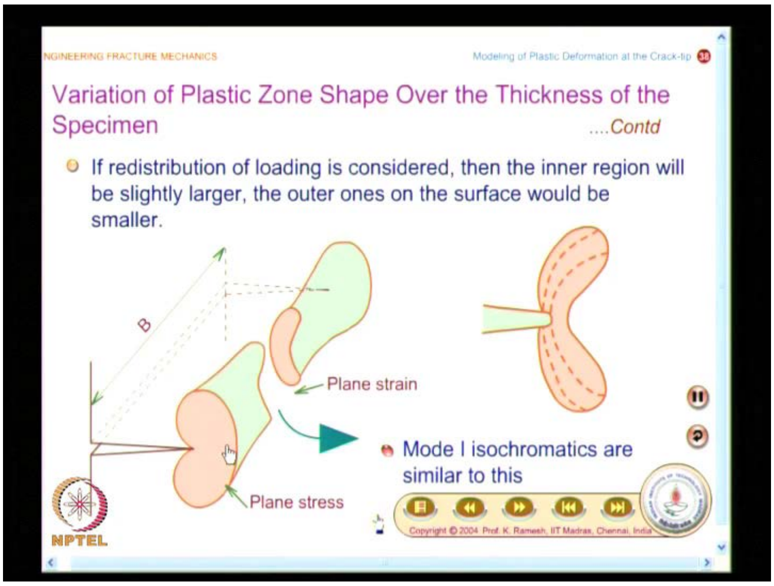

If no redistribution of loading is considered, you have this and this is what happens at the slip surface and you should also note, that these are known as butterfly shape plastic zone because it looks like this, corroborated by experiments, that is very important, similar to mode one isochromatics. And if you consider redistribution, just observe the animation, this will shrink and that will increase.

So, drawing it on your notes maybe quite difficult because the variation, it may not be easy for you to show, but nevertheless, you have seen, how this changes when you have redistribution. So, we have seen over the thickness of the specimen how the plastic zone changes, now we will have to see, when the crack propagates how does the plastic zone change? That is also people have studied.

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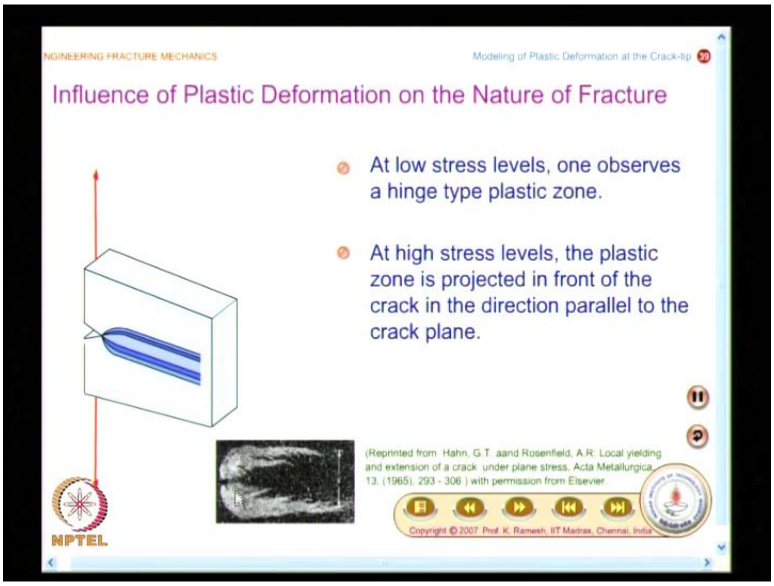

You know, in the case of Hahn and Rosenfield, we have seen the plastic zone in this shape. This people have given explanation, so we will have to go and see how the plastic zone is dictated near the crack-tip and how it is dictated at distances away. So, what I would appreciate is, you observe this animation today and in the next class, may be you can make a sketch.

At low stress levels, one observes a hinge type plastic zone; that is what is seen here. At high stress levels, the plastic zone is projected in front of the crack in the direction parallel to the crack plane; that is what happens. And what you will have to now remember is the plane where the maximum shear stress occurs, is different in plane strain, as well as plane stress. See, this is very important, that influences.

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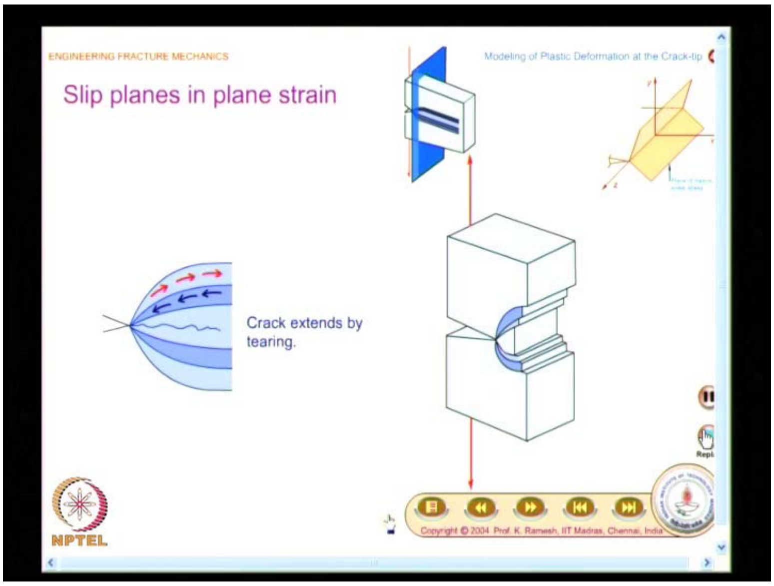

Now, I take a situation, which is very close to the crack-tip and this is the plane of maximum shear, it is different. And because of this, what happens is, you have a slip occurs like this, you have a slip occurs like this, you have planes like this, it occurs like this. So, you have the steps shown here and slip occurs between these planes and a tearing action can take place and the crack will propagate.

So, what I will do is, I will just repeat the animation sequence, you just observe. The plane is different, it is in the x-y plane itself and you will have slip occurring like this. This is magnified here, you have slip occurs here and because of this you will have crack propagation, crack extends by tearing.

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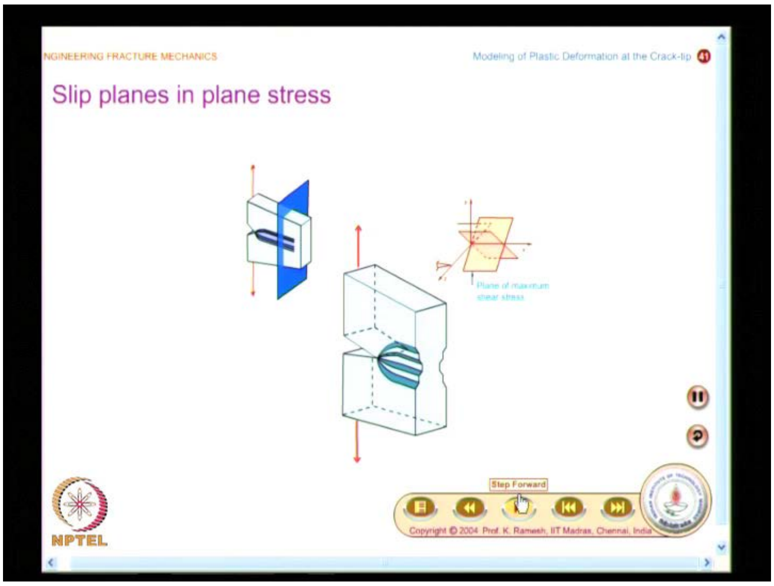

Now, let us see what happens at distances away. I am looking at a plane like this, where I have essentially plane stress. The plane of maximum shear is really out of plane. So, do not think when I say plane stress everything remains in the plane, it is not so. That is why we have looked at stress tenser as well as strain tenser.

And you can see the animation here and when you look at the side of the specimen, you have slip takes place at 45 degrees because this is the plane where you have the maximum shear stress and this is how you anticipate plastic zone to occur.

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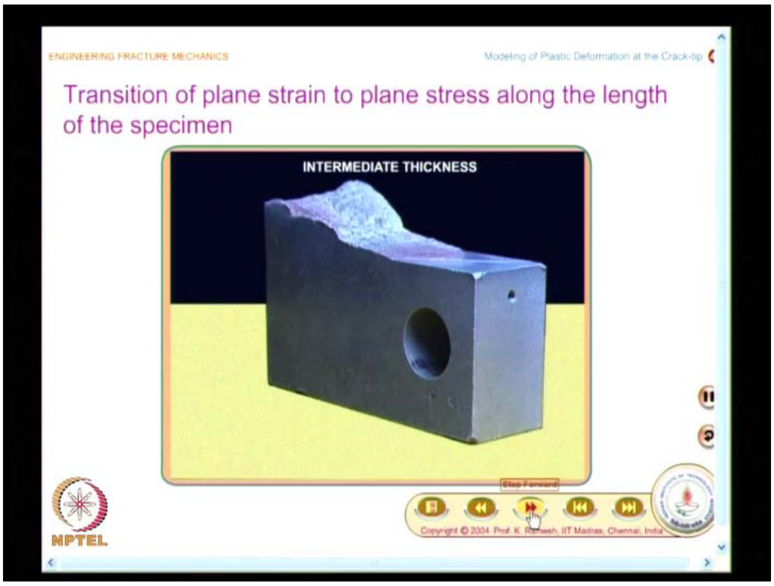

And in fact, if you go ahead and then see how the specimen looks like, this you had seen it earlier from the context of delineating, the crack surface and fracture surface. So, initially a crack propagates by tearing action, finally you have shear lip. Now, the question is, do we have an experimental evidence for this? I have to show, at the end of the specimen, you should have slip taking place at 45 degrees.

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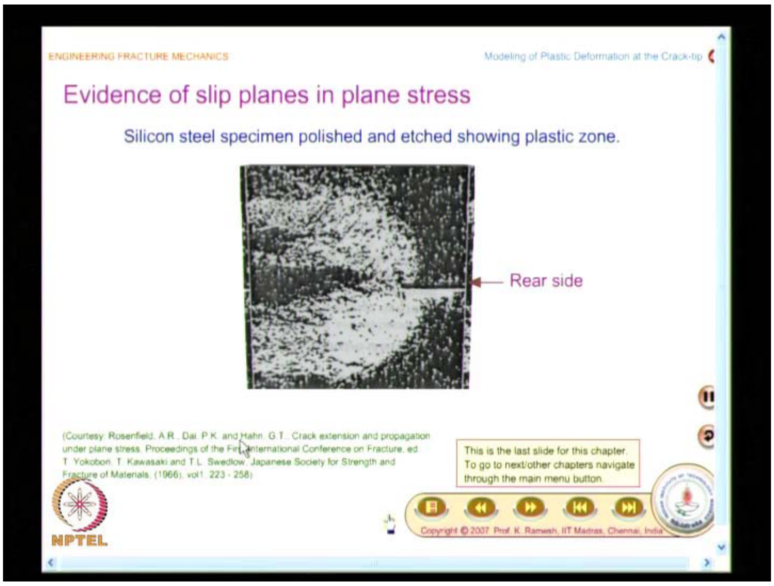

So, if you have that as an objective, you see the experimental result, you find, on the surface it is like this, close to the crack-tip. At the ends, you indeed see slip planes at 45 degrees. This was again, reported by Rosenfield, Dai and Hahn. So, very important result, you know, this gives you an understanding, that people have been able to find out what happens at the crack-tip.

So, in this class we have essentially looked at Dugdale's model followed by what is an extension of crack length you have to take. Then, we evaluated stress intensity factor with the modified crack-length, then we had looked at how does the plastic zone changes over the thickness of the specimen and as crack propagates, initially it is dictated by plane strain followed by plane stress.

The plane of maximum shear stress is different in plane stress and plane strain; that is a reason why, the plastic zone appears like this.

Thank you.