Engineering Fracture Mechanics
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Module No. # 06
Lecture No. # 31
Fracture Toughness Testing

See, we have looked at variation of plastic zone over the thickness of the specimen, as well as, what happens when the crack proceeds along the length of the specimen, how the situation takes place. We will again have a brief look at that.

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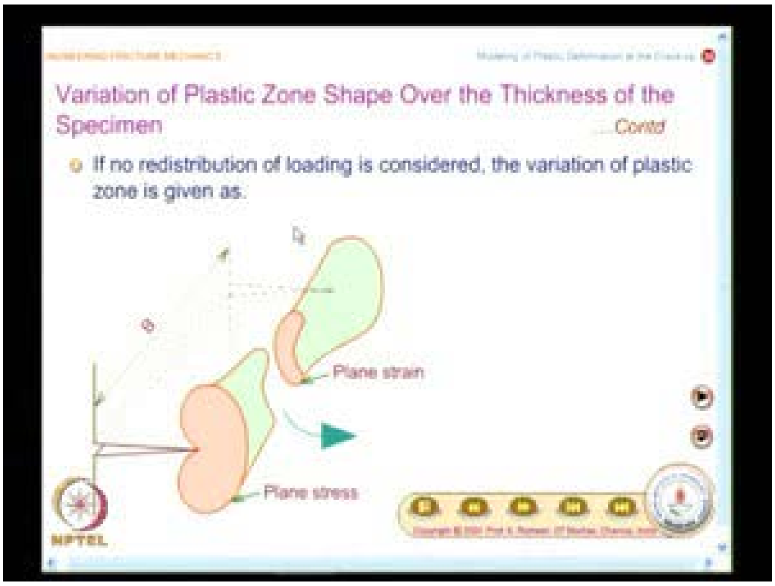

I had mentioned that, if no redistribution of loading is considered, the variation of plastic zone over the thickness of the specimen is given as follows. And we have already noted, in the case of fracture mechanics, for thick specimens, the surfaces are considered to be in plane stress and the interior portion is considered to be in plane strain, from the point of view of convenience in analysis. The definition is not strictly correct from applied mechanics point of view.

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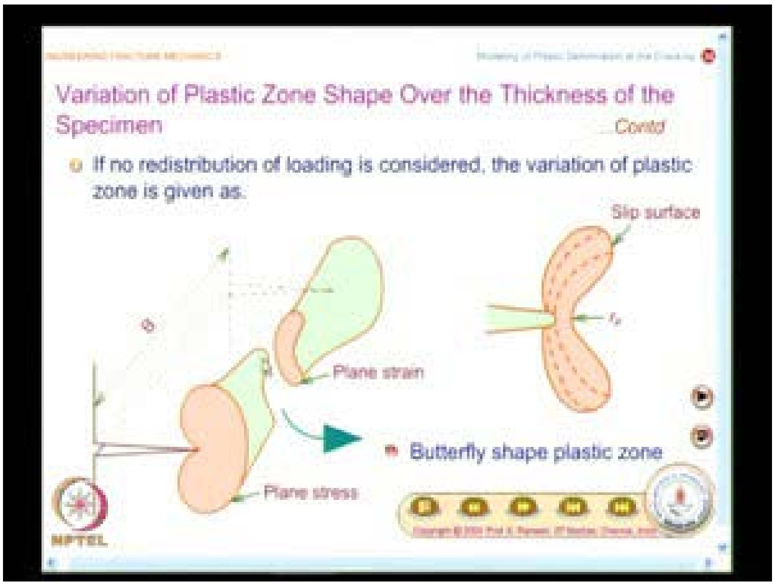

Nevertheless, this is very useful. And what we had noted was, in the interior of the specimen, you see the plastic zone in this form, which is also referred as butterfly shape plastic zone.

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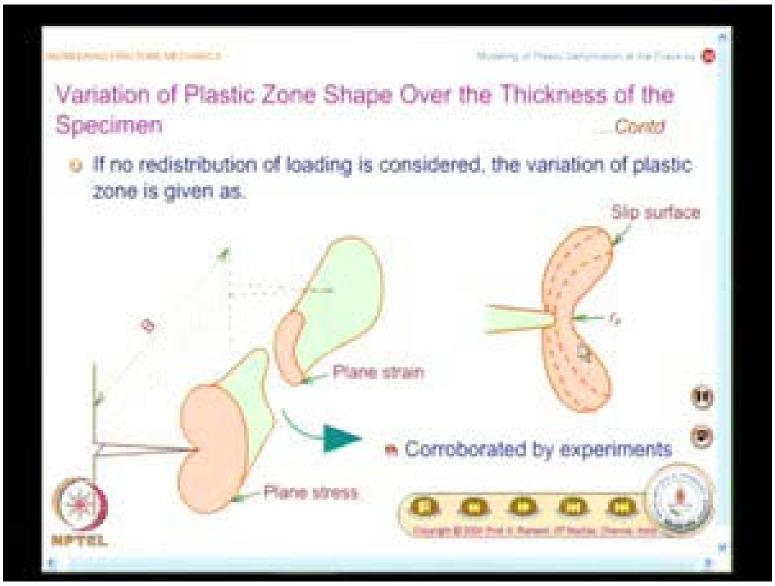

And this type of plastic zone is corroborated by experiments. Since we have been looking at photo elastic fringe patterns also, what you could notice is, the shape is very similar to photo elastic fringes.

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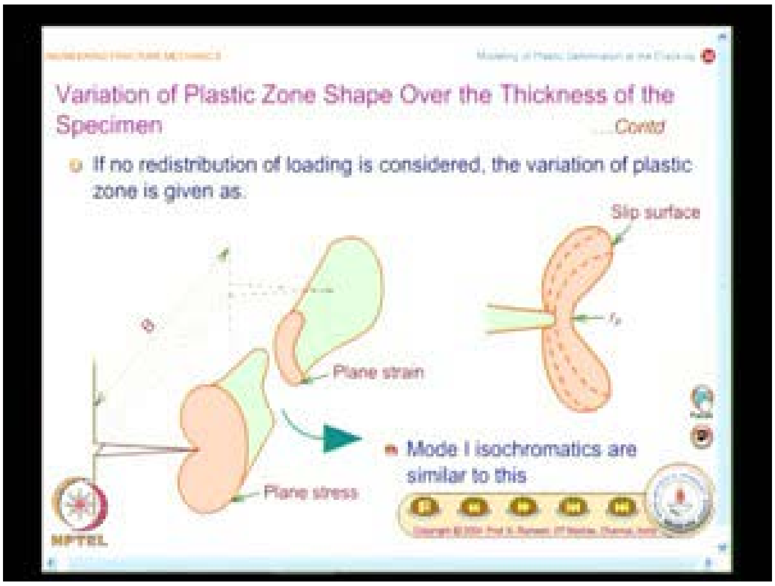

The difference is, you will not have a gap in the photo elastic fringes there. There the fringes would merge at the crack-tip. From the approximate model, what is given in the surfaces marked here. The idea is to give a visual picture that the plastic zone shape would change over the thickness of the specimen. That is the way you have to take this result. Suppose, I consider, even the redistribution, how does this shape varies? What happens is, what happens on the surface shrinks and at the interior, the zone slightly expands, which you could carefully watch in the animation.

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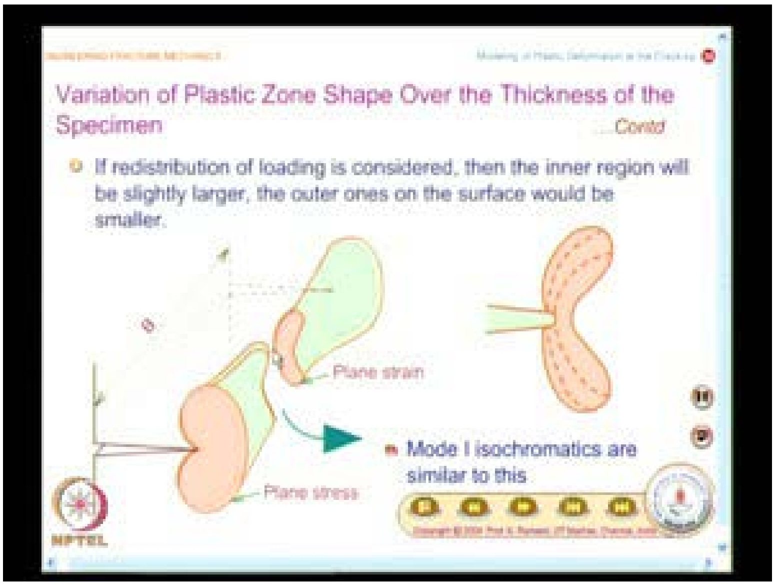

You could see that this expands and this shrinks by a small amount.

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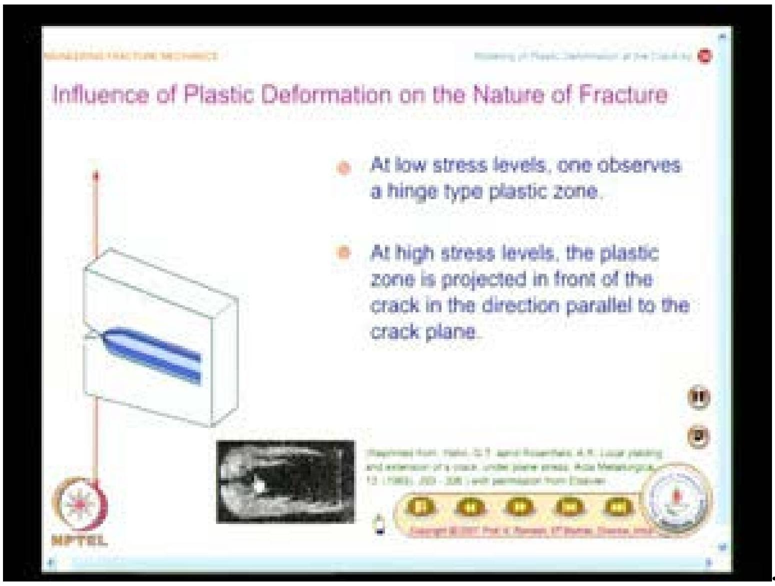

Next, what we will look at is, along the length of the specimen, how does this plastic zone changes? And this is observed and corroborated by experiments. We have already seen in the case of Hahn and Rosenfield.

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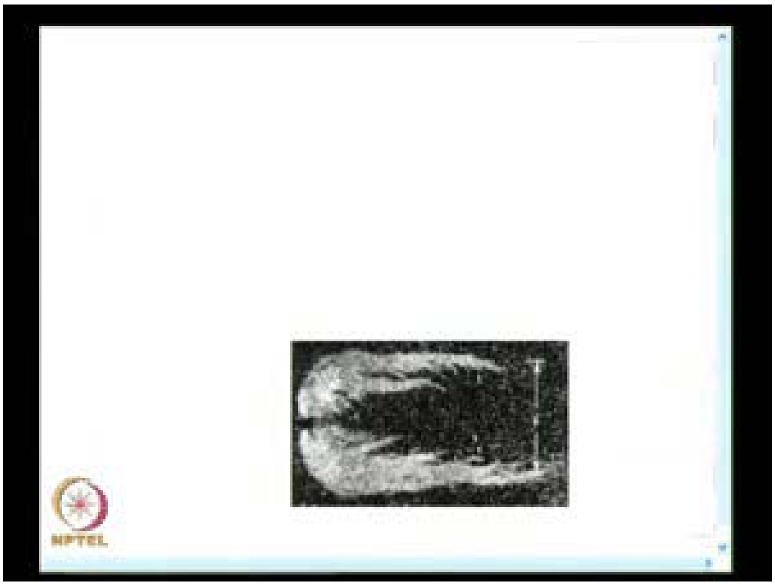

The plastic zone shape is given in this fashion. So, we are going to look at, what is the mechanism of fracture in this place and how does it change, as we look at, a little distance away?

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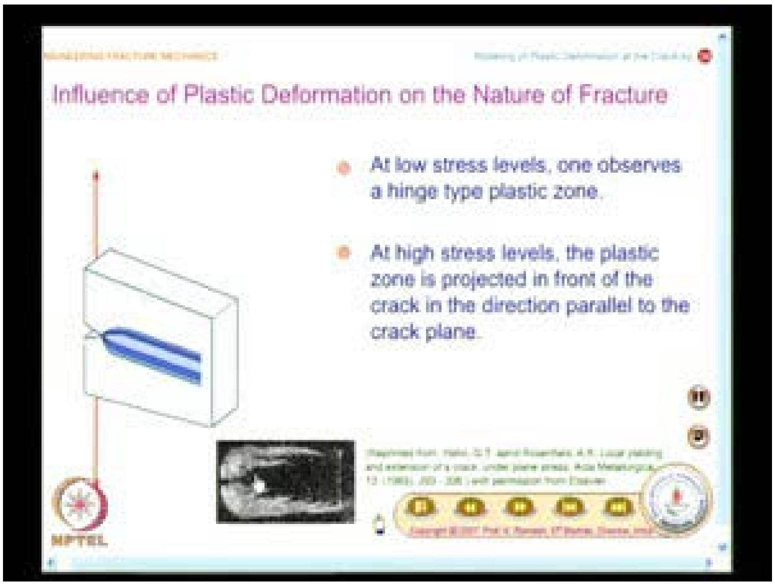

And what is summarized here is, at low stress levels one observes a hinge type plastic zone. So, that is what happens near the crack-tip. At high stress levels, the plastic zone is projected in front of the crack in the direction parallel to the crack plane. The mechanisms, of identifying the maximum shear stress differs in this place, as well as, at distance away from it.

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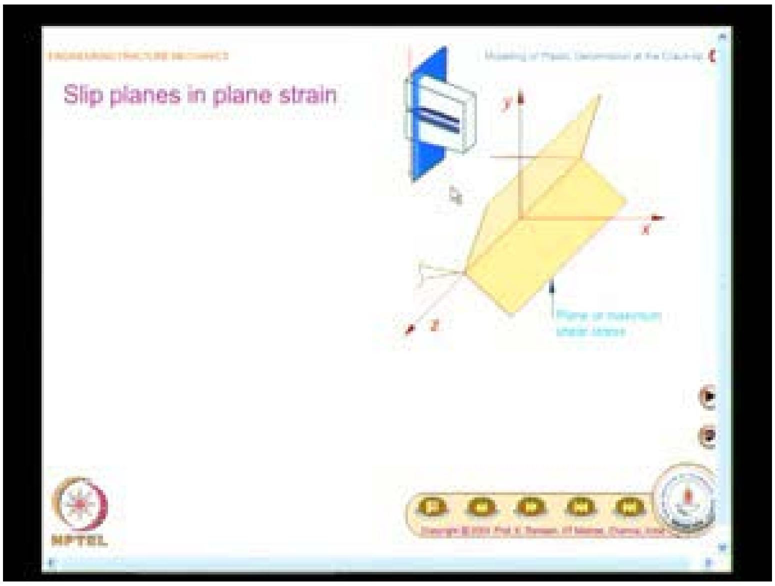

So, we will pass a plane close to the crack-tip, and look at what is the kind of idealizations that we are making. What you will have to note is, this is in a state of plane strain and in the case of plane strain, the maximum shear stress plane is in the plane of x and y; and the planes are shown like this. And you have to recognize the planes of maximum shear stress would be different, when you go to plane stress. This really matters. This dictates, what is the mechanism, that precipitates propagation of crack. So, initially, it will propagate by tearing action; later on you will see a shear lip.

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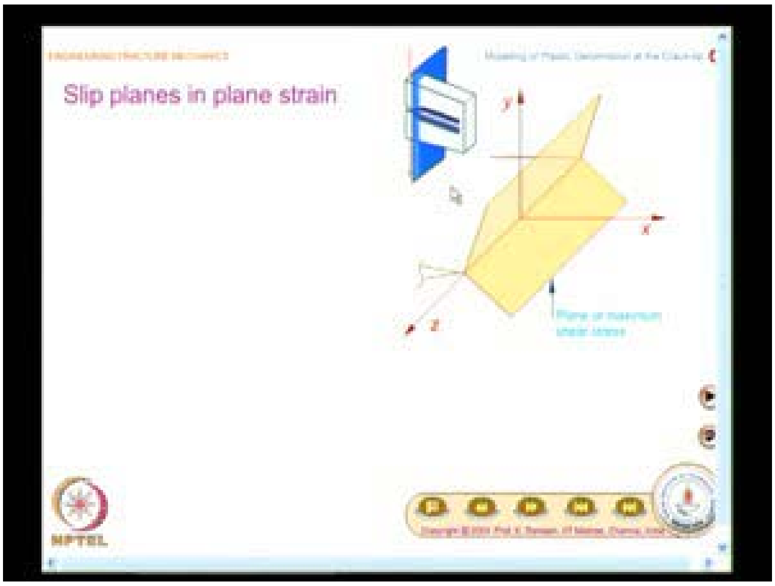

And since, you have the maximum shear stress plane oriented like this, you could also see, how the slipping of planes happens, in the case of a specimen.

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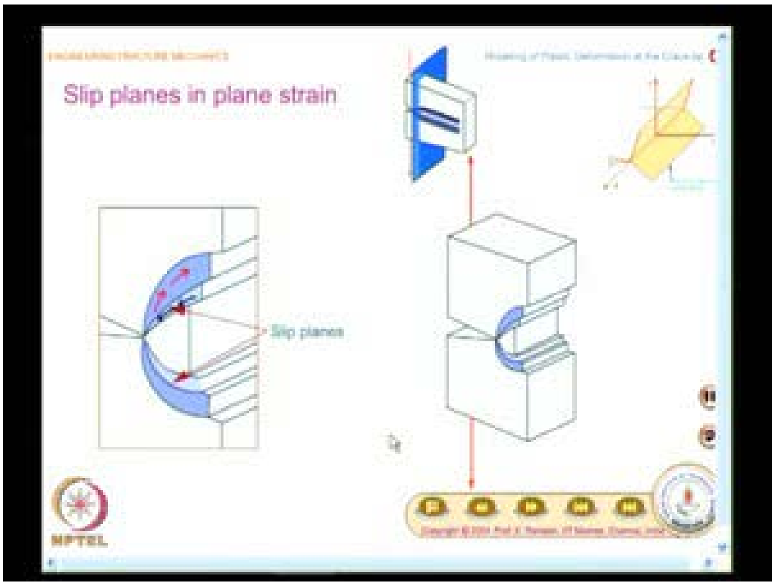

So, what is shown is, you have a thick specimen. I have a crack here and because the maximum shear stress plane is like this, you will have material slipping like this. And this is a highly exaggerated picture, for visualization purpose. And this is further exaggerated by a small portion here, that also you will see. So, what you find is, the planes are oriented like this, very similar to what you see here. And you will have slipping of these planes will occur. Try to make a sketch, as closely as possible. You may not be able to capture all aspects, but definitely you could identify the maximum shear stress plane and once you get into the material, several other factors dictate. So, the planes would be like this; the material would slip.

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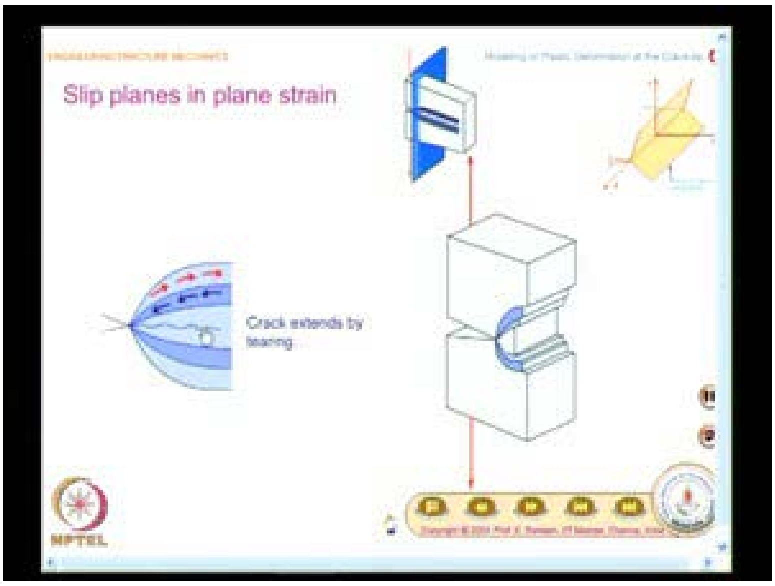

And that is indicated by opposite arrows and a two dimensional picture is also shown. So, because of slipping, initially the crack extends by theory. So, what happens here is, the idealization as plane strain and that recognition, that maximum shear stress plane is oriented in a particular fashion, dictates how the planes are; it is like this; the planes are like this. And the crack extends by tearing. At least, you make a neat sketch of this two dimensional representation. If you are in a position to extrapolate your skills in drawing, you could also sketch this as closely as possible. And the moment you go to plane stress, the situation is quite different.

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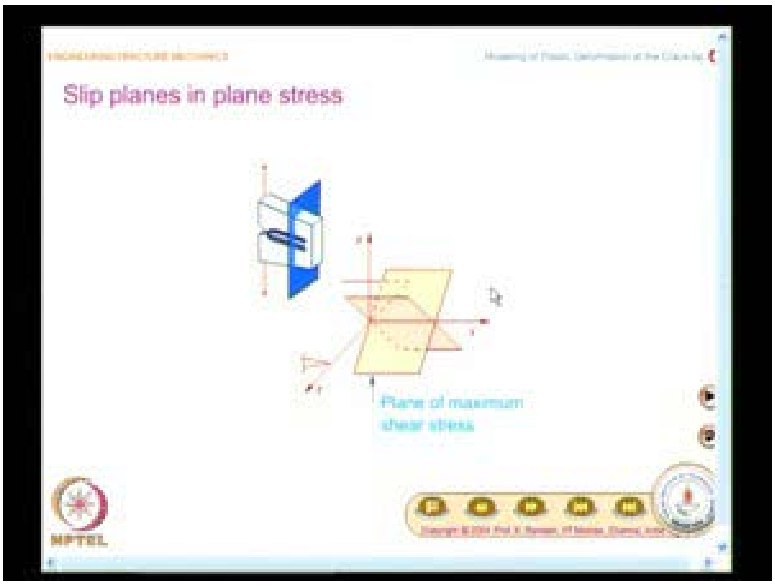

And what we are looking at is, we are looking at a plane ahead of the crack. And what you see here, the planes of maximum shear stress, is oriented like this. It is really out of plane of the x y plane. And this is what I had mentioned; everything is not plane in the case of plane stress. We have looked at the stress tensor as well as the strain tensor, and you have to recognize, the maximum shear stress plane is out of place; it is like this. So, if you have the crack, it will be like this.

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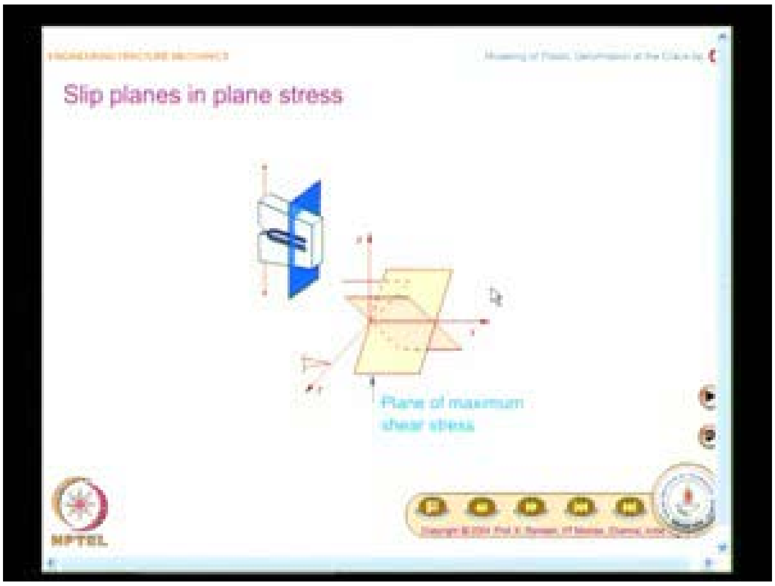

So, that dictates, how the slipping action would occur and that is depicted in the animation.

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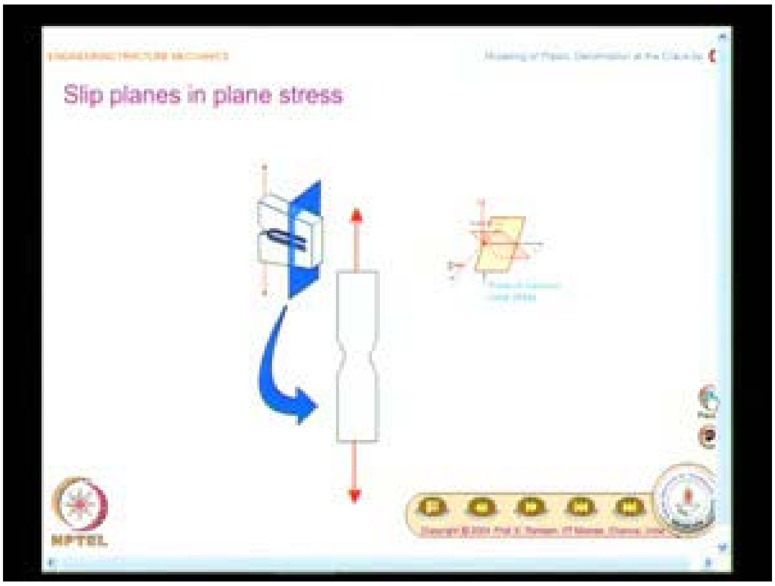

Initially a two dimensional sketch is put.

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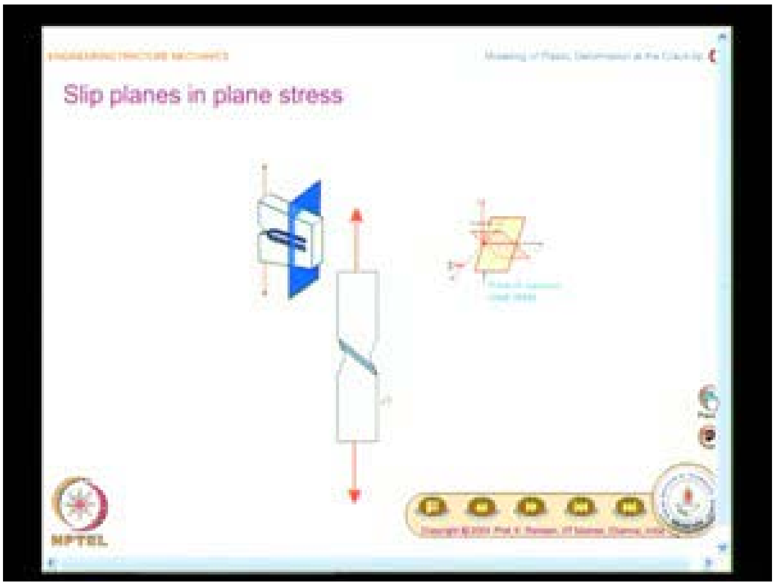

So, you could see that slipping occurs like this.

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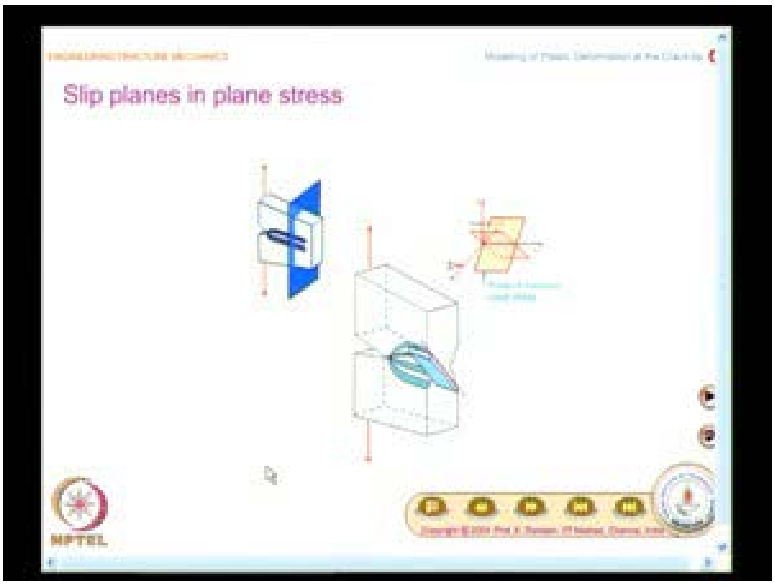

The slipping plane is quite different from what you had seen in the case of plane strain. So, you could see the slipping action and this diagram is difficult to draw. But we need, also need to have an evidence whether slipping action takes in this fashion. And we need to see the experimental result and re-convince ourself this is what happens. So, what I would do is, I would repeat the animation for this. We are looking at a plane ahead of the crack. I said the planes of maximum shear stress, is different. This dictates how the slipping will take place. And this picture is easier to draw. I would appreciate that you draw this rather than a three dimensional picture. So, I have slipping action taking place like this and it is highly exaggerated.

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And you will not see real steps in the case of actual specimen.

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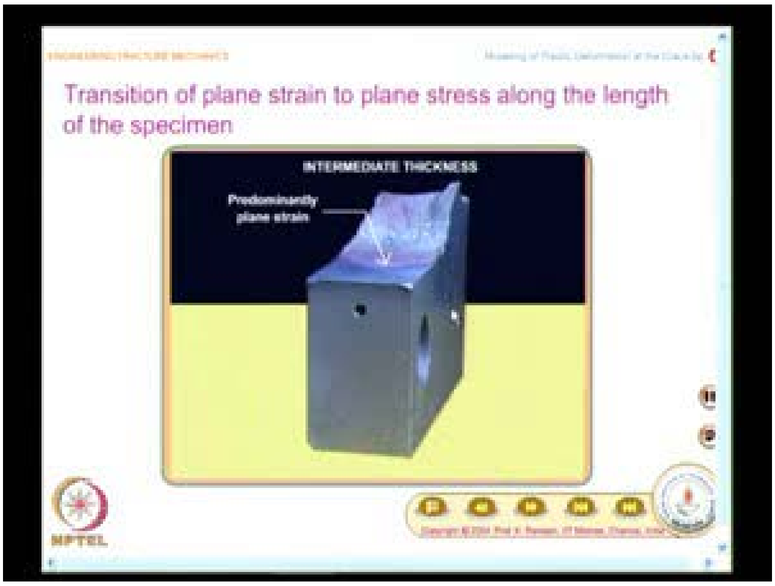

And when you actually see a fractured specimen, whatever we have discussed, is seen in that.

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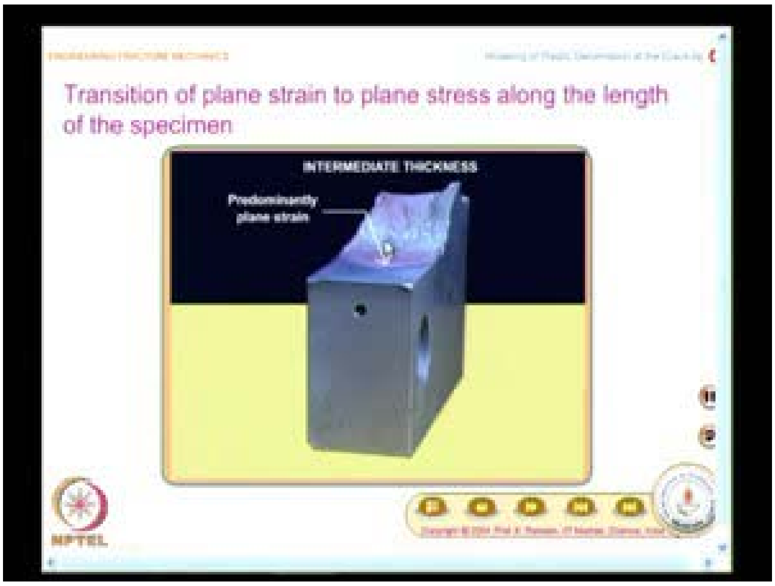

Initial stages crack propagates by tearing, predominantly plane strain. Ahead of the crack, what you find is, you have a shear lip. So, you have an experimental evidence.

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And there is also a very nice set of results reported by Rosenfield and his co-workers. In fact, the plastic zone on the surface, over the thickness and the rear surface were bundled as a three dimensional picture by my students and they have nicely provided this animation. And you indeed see, ahead of the crack slipping takes place at 45 degrees.

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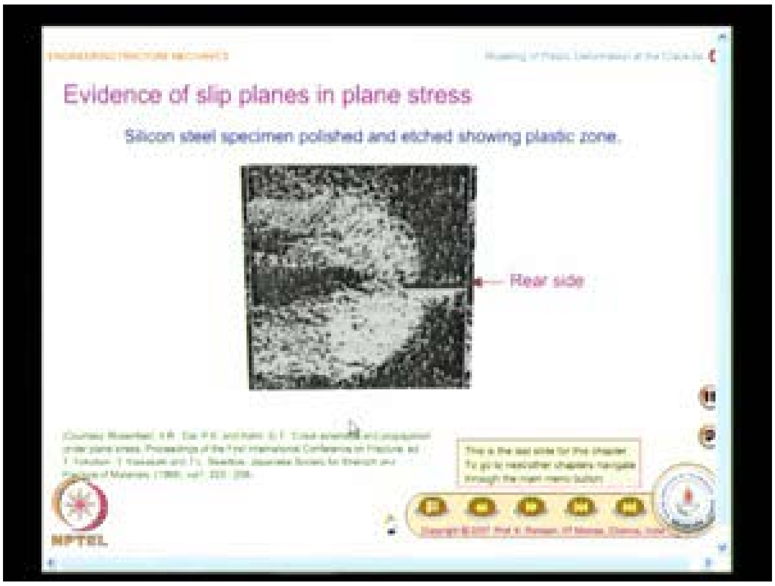

So, whatever we have discussed, was not just a conjecture. It is indeed observed in experiments. And this is a very nice piece of a representation. And this gives a realistic feeling, how the plastic zone varies over the thickness, as well as along the crack length. These are the two issues we have looked at.

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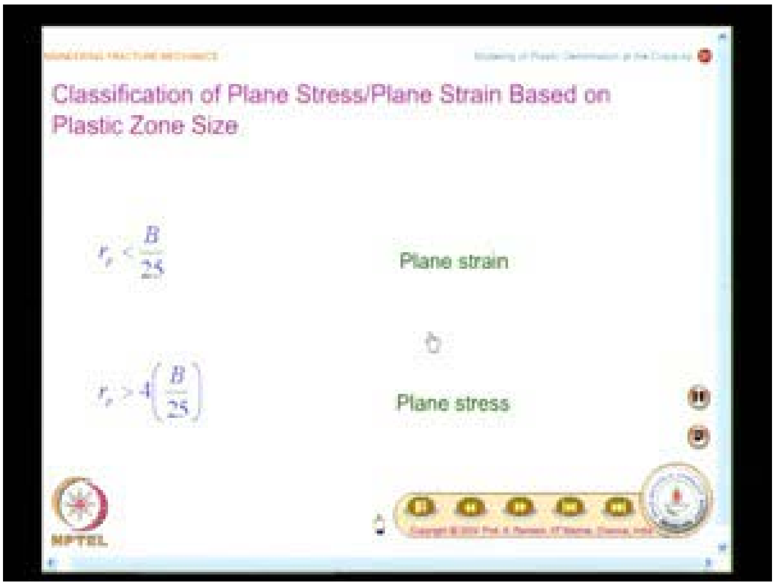

Now, what we will look at is, another aspect that we understand, from looking at the size of the plastic zone. We have looked at, how to get the value of r p, that is a size of the plastic zone. If the size of the plastic zone is less than B by 25, where B is the thickness of the specimen, the plastic zone size is very small. You could idealize that, you have a plane strain situation exists. Suppose, you have the plastic zone size is greater than 4 times B by 25, you could idealize that, the situation is plane stress. You know, these are different ways of looking at, how to model it as plane stress, or, as well as plane strain. Because, in fracture mechanics, we tend to have looser definitions of plane stress and plane strain. The problem is very complex.

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And what is important is, from the understanding of plastic zone size, it is also possible for us, to estimate a minimum thickness of fracture toughness test specimen. So, that is a very important aspect, which is outcome of modeling of plastic deformation at the crack-tip.

What we will have to do? For an experimental determination of K 1C, you have to maintain plane strain condition. And how do you asses that plane strain condition exists? This is by appropriately taking the specimen thickness, such that the plastic zone size is very very small. And what is recommended is, the specimen thickness should be more than 25 times of the plastic zone size. And in an expression form, it turns out to be, B is greater than or equal to 25 into 1 by 3 pi multiplied by K1C by sigma y s whole squared. If you recall, this was the plastic zone size in plane strain by Irwin's model. And if you simplify, I can simply write this as 2.5 times. Because 3 pi, I can take it as 10. So, I would write it as B should be greater than or equal to 2.5 times K1C divided by sigma ys whole squared. You know, this is a very very important and significant result. In fact, people have tested several specimens; from testing experience, they have arrived at the size of the specimen thickness should be, 25 times the plastic zone size. From mechanics point of view also, you could get this.

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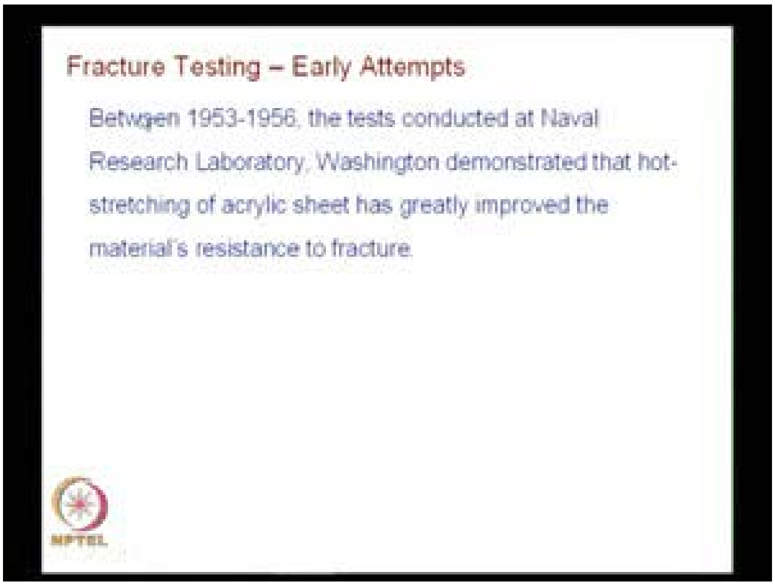

You know, the next topic that we would take up is fracture testing. In fact, once you go to testing, it is a very dry area of the course; because you need to look at codes and then satisfy conditions, and those conditions are very detailed. So, what I will do is, I will try to make, this part of the course as interesting as possible. And it is desirable that, we look at early attempts; and if you look at, between 1953 and 1956, the tests conducted at Naval Research Laboratory, Washington demonstrated that, hot-stretching of acrylic sheet has greatly improved the materials resistance to fracture. So, if you look at, fracture testing was done first on acrylic sheet; and this is way back in 1953 and 1956; and they measured the fracture toughness.

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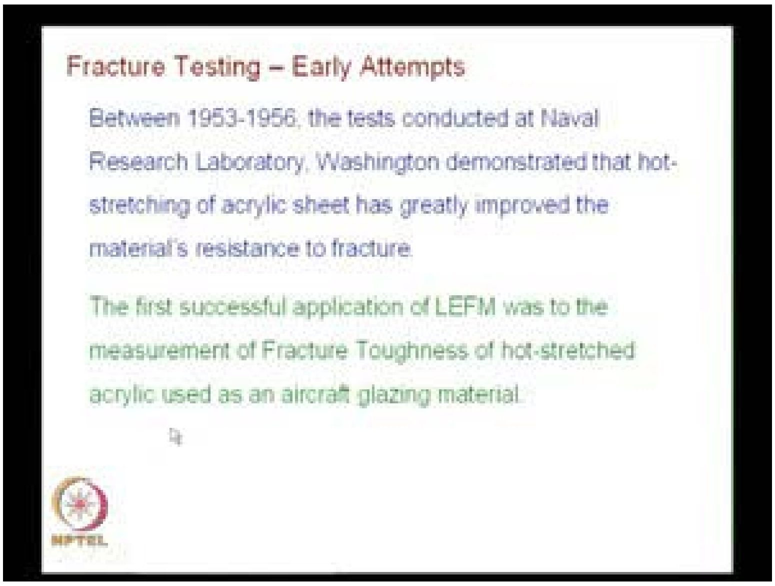

So, the first successful application of linear elastic fracture mechanics was to the measurement of fracture toughness of hot-stretched acrylic, used as an aircraft glazing material. And if you also look at, any development in science, whether you like it or not, many developments were focused on military applications. So, you will have a first specification and standards, discussed in the military circles; once they find this could be used for civilian application, it will come out in open literature; the same thing happened for this kind of test also.

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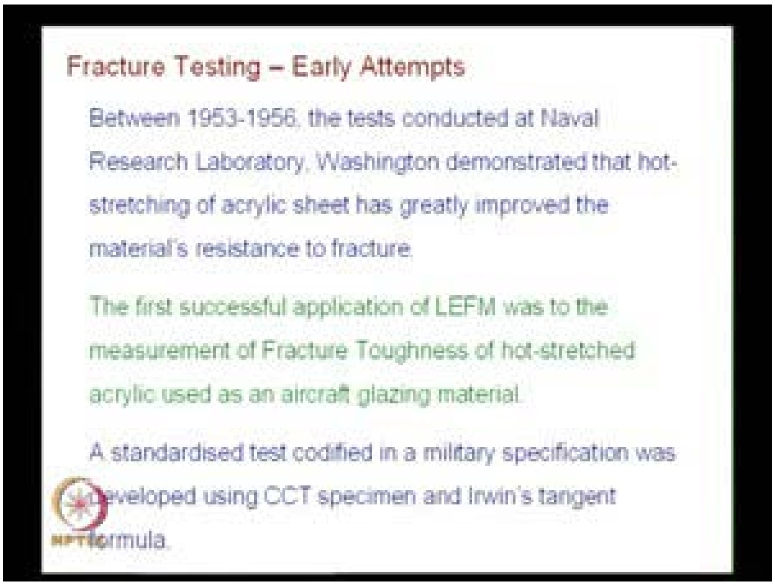

So, you have to be very conscious, to be useful to the society, but scientists are also asked, to provide support to the military. So, we have to keep this in mind. So, a standardized test, codified in a military specification was developed. And mind you, this was in 1953 and 1956. And I had mentioned, when we were discussing the stress intensity factor for variety of specimens, the center cracked tension specimen was used for fracture toughness testing. I also mentioned, that Irwin's tangent formula was used, to theoretically calculate the stress intensity factor. And this was used to find the fracture toughness for the acrylic sheet. So, this is how people proceeded, but now, you have very sophisticated specimen geometry and also boundary collocation solution, which gives you precise values of stress intensity factors.

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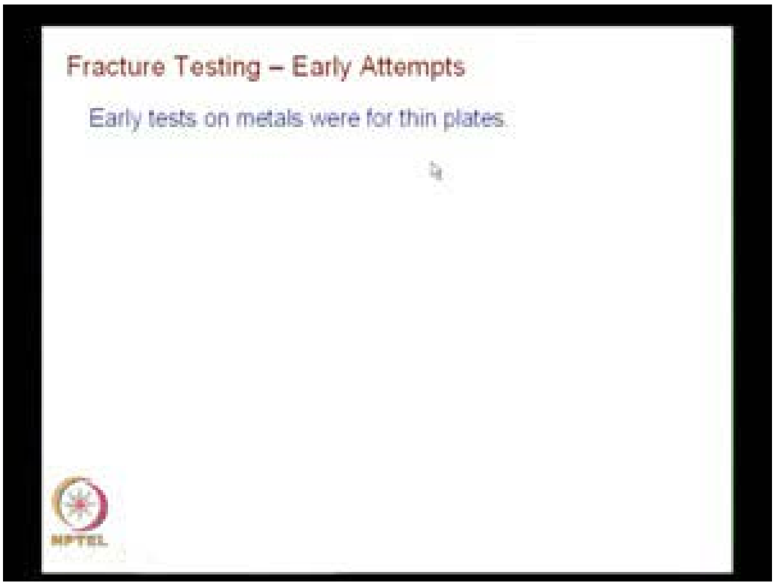

And you should also note, after the tests on acrylic sheets, the scientific community did tests on metals, that were for thin plates. They had not really tested thick plates; though we had discussed, as an extrapolation of modeling of plastic zone, to maintain plane strain condition, I need to have a appropriate specimen thickness; this knowledge was not aware, not available; this evolved, based on experience.

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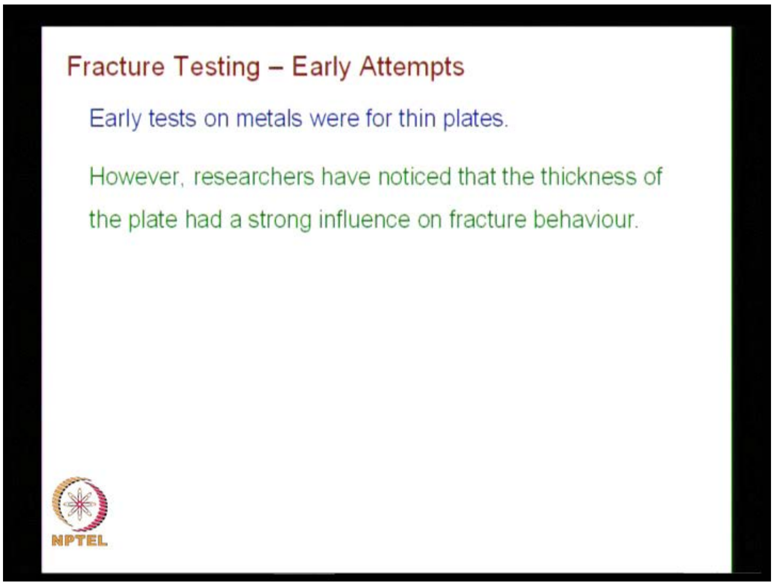

As I had mentioned, initially the tests were on thin plates; however, researchers have noticed that, the thickness of the plate had a strong influence on fracture behavior.

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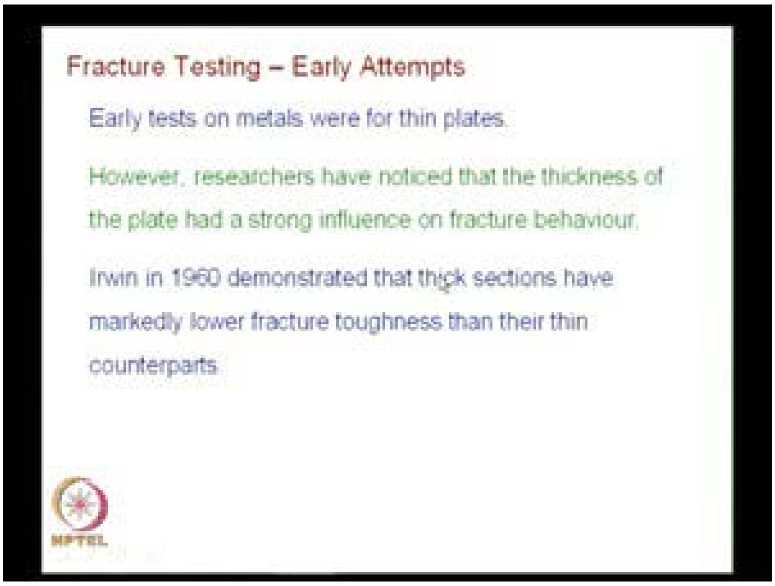

In 1960, Irwin demonstrated that, thick sections have markedly lower fracture toughness than their thin counterparts. Now, this is a standard knowledge, for anyone who does a course in fracture mechanics, he knows fracture toughness is function of a thickness of the specimen. But if you look at the early stages, they arrived at this result, based on experience; and intuitively they tried to propose, why this happens. When you say something is a material property, it should behave like a material property. What they found was, it behaves like a material property, only when plane strain conditions were satisfied.

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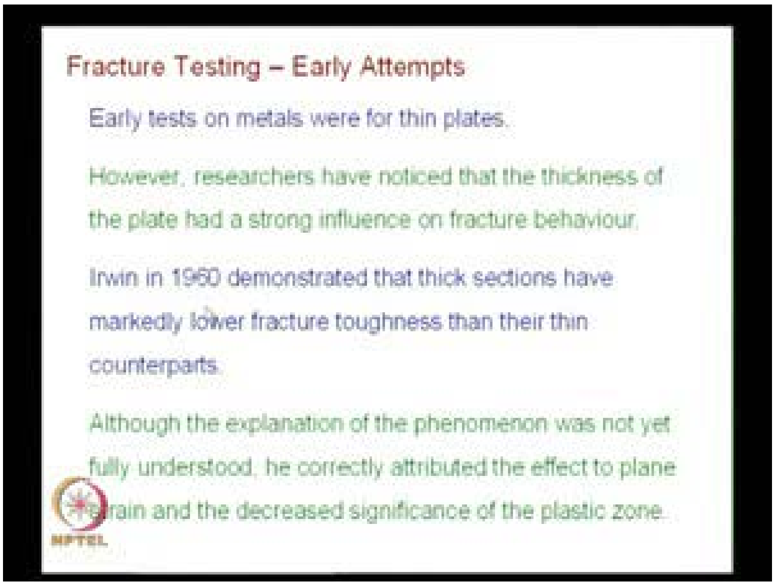

And, this is also recorded that, earlier, there was no explanation of the phenomenon, was not available; however, Irwin correctly attributed the effect, to plane strain and the decreased significance of the plastic zone. See, in the earlier discussion, I had mentioned, plastic zone is a friend for fracture mechanics, that is what, I said. In the case of plane stress, now, you know, the size of the plastic zone is much larger than in plane strain. So, the experiments revealed, the fracture toughness in the case of plane strain is far below what you have in plane stress. The intuitive understanding was provided by Irwin. Later on, his result was corroborated by further experiments and discussions.

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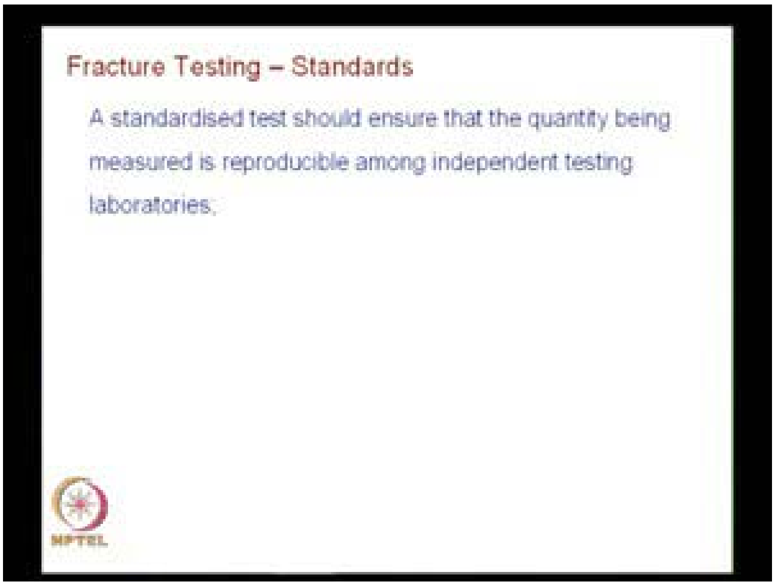

Once you have looked at this, we have to go for standards. It is a philosophical question. What is the purpose of a standard? And we will have to see, whether this purpose is satisfied in fracture testing. And what are the different standards exist? And if you look at, what is the purpose of a standard, a standardized test should ensure that, the quantity being measured is reproducible among independent testing laboratories.

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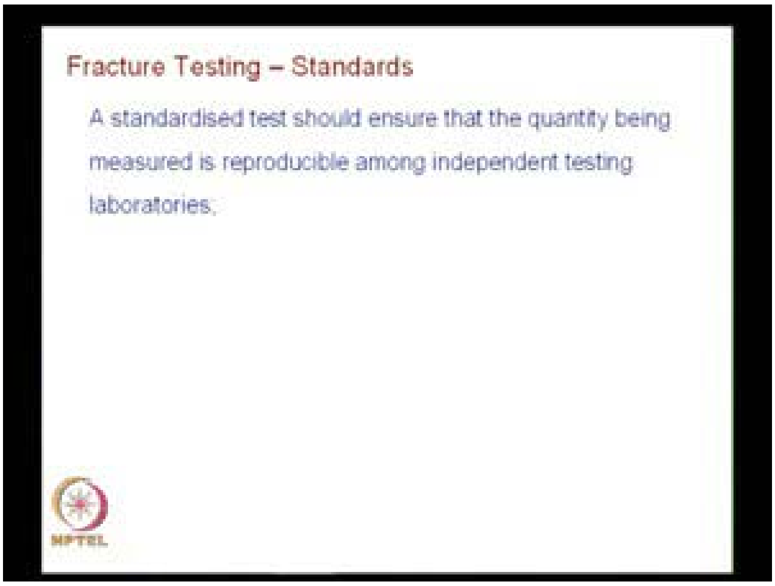

This is very important. You could have many parameters. To some acceptable degree of precision, the results of the test be independent of the test operator, the laboratory performing the test and the specific brand of test equipment used. You know, this is also very important. You cannot say, if you have to do fracture test, you have to buy machine only from one source; you cannot have a monopoly. So, when I develop a standard, the procedure should be well established; it accounts for all these minor variations, yet give the final result, with a certain level of precision.

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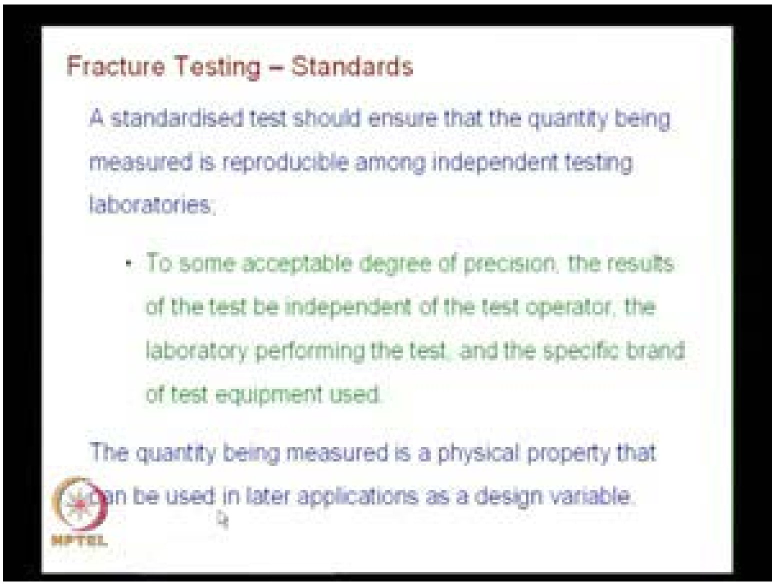

So, this is one aspect of, what is the purpose of a standard. The other, more demanding criterion is, the quantity being measured is a physical property that can be used in later applications as a design variable. In fact, this is very well satisfied by fracture mechanics standards, because we are going to measure fracture toughness and that is what, is depicted here. The quantity measured has a physical interpretation, independent of the standard used to measure it, that can be used in other physics applications. So, we all understand, when you have to investigate whether fracture instability will occur or not, we can use the parameter, fracture toughness.

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So, if you really look at the standards in fracture mechanics, the fracture toughness testing generated by American Society of Testing Materials does meet the more demanding criterion, that the parameter should be used for other physics applications.

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And, if you look at how people have proceeded in evolving the standard for ASTM special committee on fracture testing of high strength sheet materials, because these were used for aerospace applications. It was commissioned by the federal government, that is the government in USA, in 1959, to investigate a series of metal failures of national significance. The idea is, find out the cost and mitigate, whether they could prevent such failures. So, you need to have a standard and adhere to the standard in all the practices.

And if you look at the history, ASTM committee E-24, which is now designated as E-08, is an outgrowth of ASTM special committee, which was instituted in 1959 and in any development, knowing the history is very important.

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And if you look at the literature, Barsoum, in 1987 has provided a succinct history of the fracture research, that led to the initial series of standards. You know, people have main iterative atomics; based on their experience, they have come to the standards and if you really look at the standards history, standards may be withdrawn, standards may be reapproved, standards will be modified. So, there is a life attached to it. It is not, once a standard is announced, it becomes a, remains a standard for any length of time. People, as more and more experience pour in, those understandings are incorporated, if necessary, even the standard is withdrawn. So, you have to keep that in mind.

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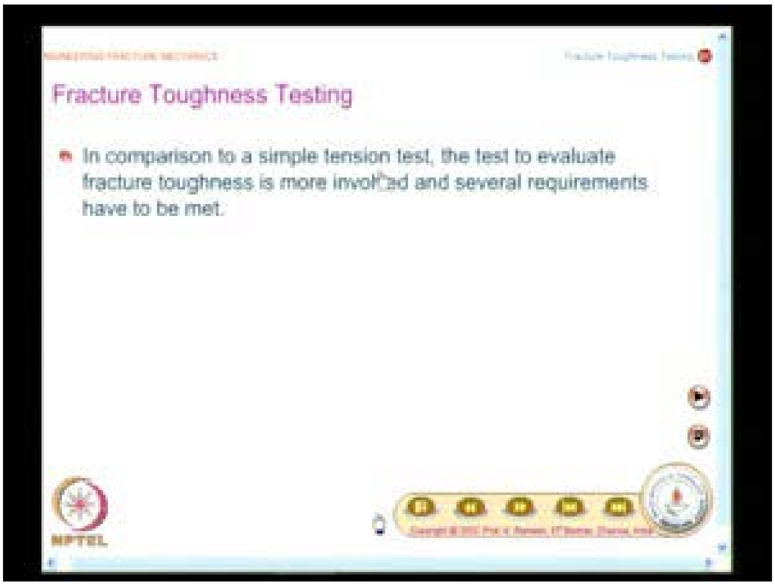

And if you look at, in comparison to a simple tension test, the test to evaluate fracture toughness is more involved and several requirements have to be met. This is the fundamental difference.

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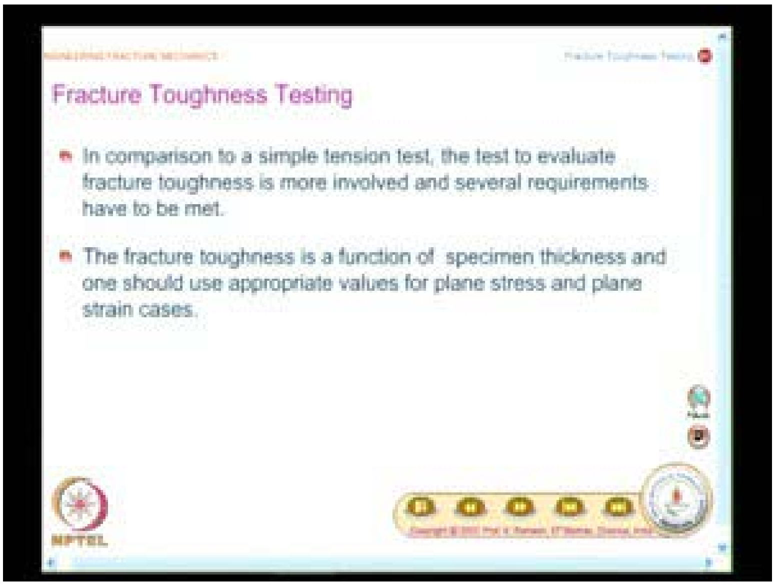

And we have already noted that, fracture toughness is a function of specimen thickness and one should use appropriate values for plane stress and plane strain cases. So, once you recognize it is a function of thickness, if I am having a structure which is primarily in plane stress, I should use only the fracture toughness applicable for plane stress situation. If I use the one which is meant for plane strain, then I would be having a lot of cushion, that I would be over designing my structure. So, you have to be careful about that.

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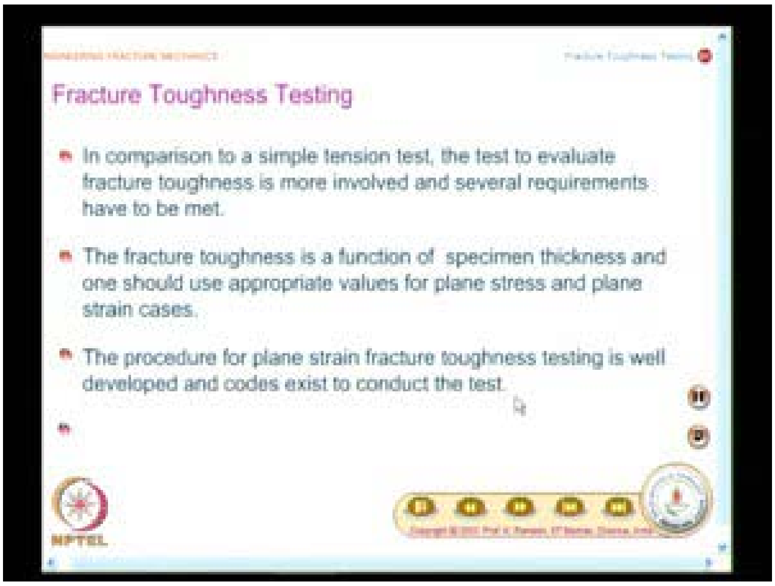

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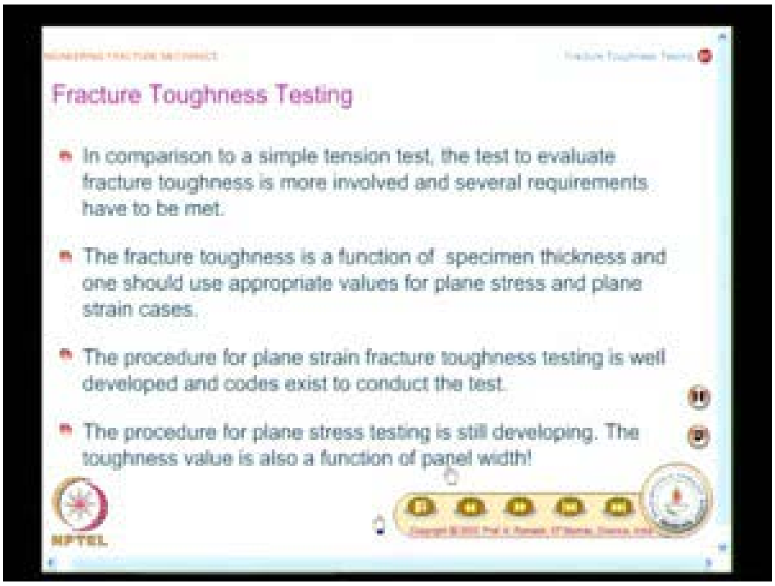

Having said that, you should also be able to measure fracture toughness in plane strain as well as fracture toughness in plane stress. And if you look at, the procedure for plane strain fracture toughness testing is well developed and codes exist to conduct the test. And, that is what we would cover in major part of this chapter. The procedure for plane stress testing is still developing. And you have to note a funny information, the toughness value is also a function of panel width. That too many parameters come into the picture. If I use panels of different widths, fracture toughness also changes. So, this you have to keep in mind. So, this makes your testing also a bit difficult.

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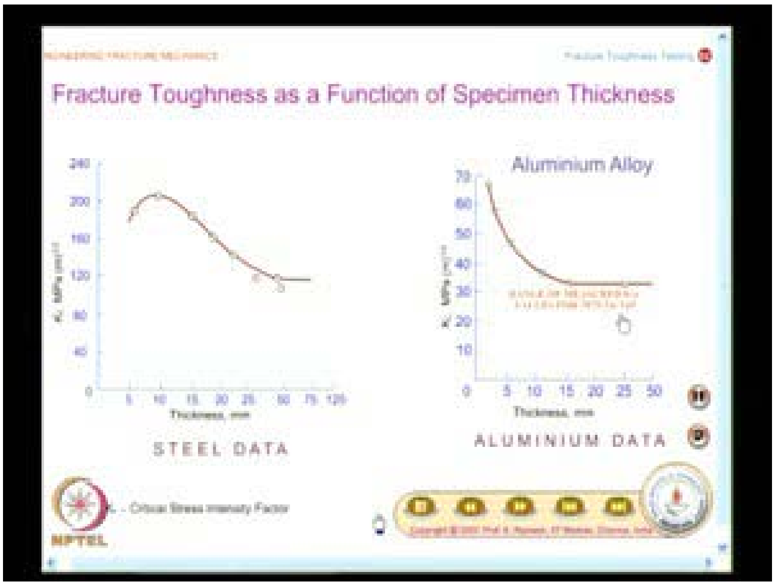

And you could see, fracture toughness as a function of specimen thickness. On the x axis, you have the thickness in millimeters. On the y axis, it is just put as K c. See, the understanding is, if we put as K c, it is a critical stress intensity factor. We are omitting that mode 1, because mode 1 is the predominant one people have analyzed; and you have the variation like this.

So, it stabilizes around 120 M p a root meter, whereas it can go as high has around 200 M p a root meter for steel. And you also have a similar graph for an aluminum alloy; this is 7075t6t65. Here again, you find, the trend is from plane stress to plane strain, there is a drop in the value and it stabilizes; it is around 35 M p a root meter. It can be as high as 70 M p a root meter, in the case of plane stress. And if someone is alert, you would find, the thickness is different for an aluminum alloy and thickness is different for a steel data. You say it is plane strain, when it is about 50 millimeter thickness; whereas, here, even a 15 millimeter thickness is in a situation of plane strain condition. This is one of the important issues; that means, if somebody comes up with a new material, (()) you will not know, what is the minimum thickness that is necessary for conducting a plane strain fracture toughness test. You have to make a guess work. You will see all that. That is why, the test is more challenging than in the case of a simple tension test.

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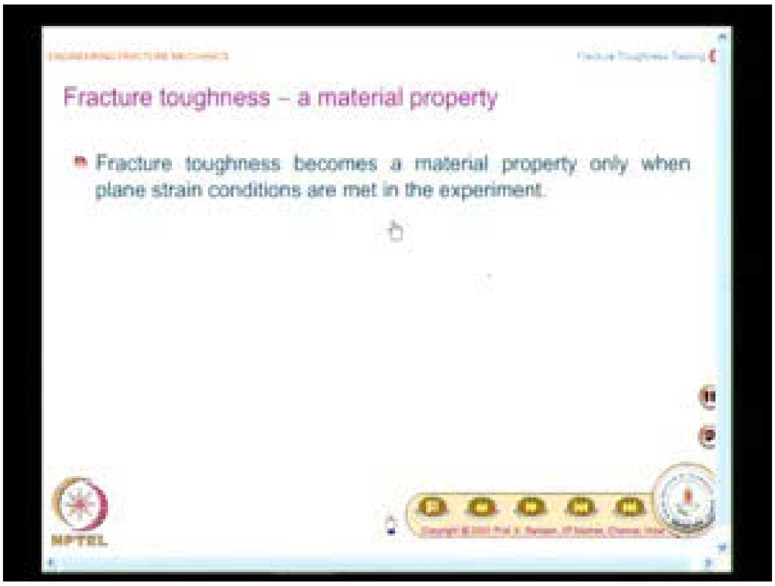

And obviously, if it is not a material property, people would not invest so much money, to evaluate fracture toughness. And, as I had mentioned and also shown in the form of graph, fracture toughness becomes a material property only when plane strain conditions are met in the experiment. So, you have to achieve this by various means. We have looked at, how to assess the specimen thickness is sufficient to provide a plane strain condition at the crack-tip.

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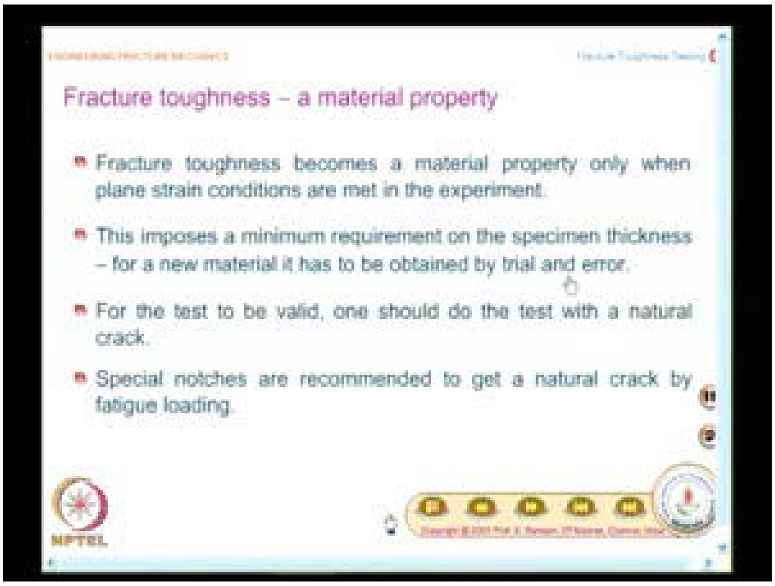

This imposes a minimum requirement on the specimen thickness; for a new material, it has to be obtained by trial and error. It is a very important aspect; that means you do the complete test. If the screening criteria is not satisfied, you have to scrap. Fracture toughness testing is more expensive, keep in mind. A tension test is very simple. Even the specimen preparation is far simpler in the case of a tension test. Once you come to fracture toughness testing, even specimen preparation is quite involved. And imagine, at the end of the test, if plane strain condition is not satisfied, you have to scrap the test. That is too expensive. We will see, how people have handled these scenarios.

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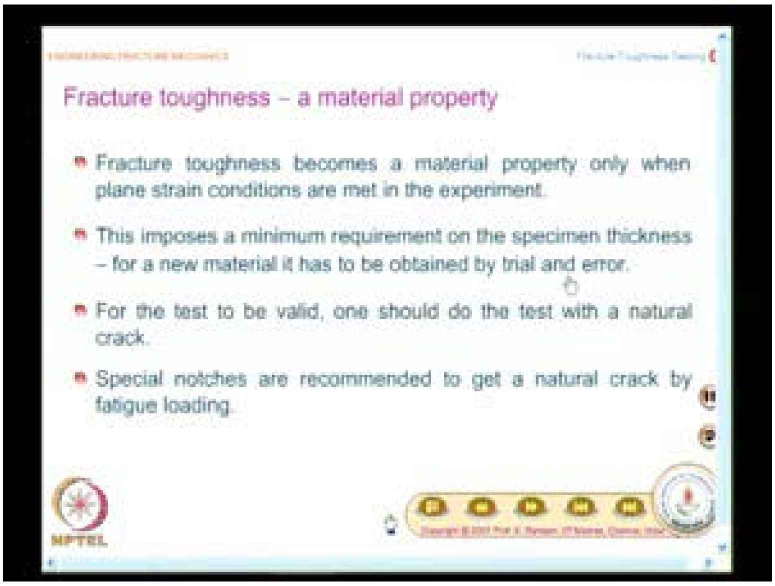

And another requirement is, for the test to be valid, one should do the test, with a natural crack. See, its very highly demanding. See, when you have a specimen and you want to have a natural crack at a particular location, at a particular way, it is not a simple task. You have a actual structure, because of several reasons, cracks are developed and you want to analyze how the structure is going to fail, that is a different issue. From testing point of view, you have to maintain plane strain condition; you will also have to have a natural crack. It is not that, you simply put a slit and then say, that you can do the test. You have to develop a natural crack. That is a arduous task. And what is done is, special notches are recommended to get a natural crack by fatigue loading. And you will find, there will also be restrictions on how fatigue loading has to be done. You should not do the loading in a manner, that you develop excessive plastic zone; you must select only appropriate range, so that, you get a natural crack. And we would see, by having special notches, you could control the plane in which the crack will propagate.

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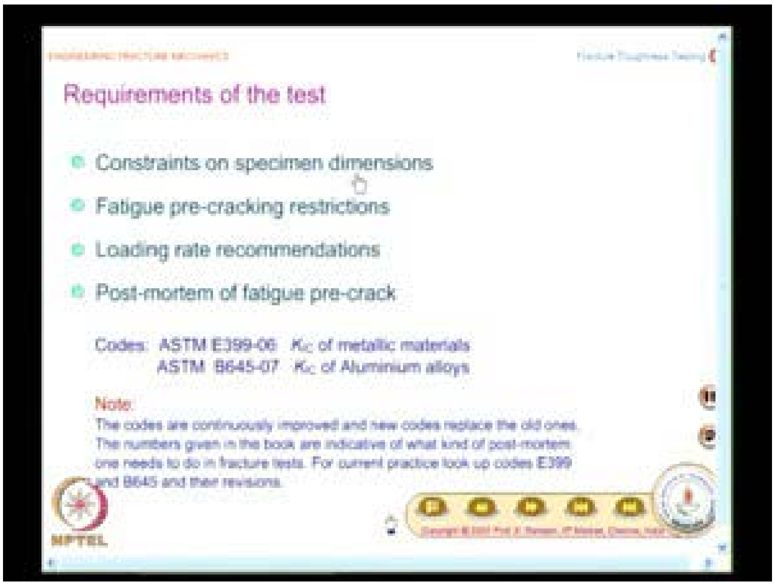

And, what are the requirements of the test? You have constraints on specimen dimensions. You all know that, we have to maintain plane strain condition; that is going to impose what should be the thickness. Once you decide the thickness, all other parameters would be decided. And I had already mentioned, you need a natural crack. This has to be done by fatigue loading. And you will have certain restrictions on, how this fatigue loading is applied. So, you have fatigue pre-cracking restrictions. Once you have a specimen with a natural crack, at what loading rate would you conduct the test? There are recommendations for that. Because, if you look at the fracture toughness testing, you have the specimen with a natural crack and then, simply apply monotonic load. You do the loading, until the specimen breaks. So, after a fracture toughness testing, the specimen has to be broken completely, by a monotonic loading.

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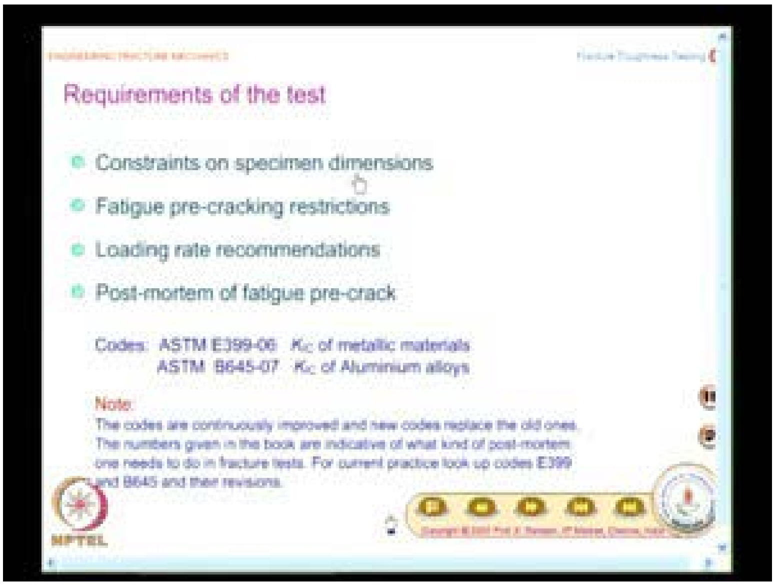

So, you have loading rate recommendations. After all this, you have to do postmortem of fatigue pre-crack. Because, that is going to decide whether the crack was in the way it should be, for you to accept the test. So, at this stage, if the crack is not alright, then you have to scrap the test; then you have to redo the test. And you have standards for that. You have ASTM E399-06, the 06 indicates the year in which it was approved or reapproved, because it has a life. It was developed way back in the 90s; several modifications have been incorporated. And the latest one is with the 2006. And this is K1C of metallic materials. And there is also a practice associated with this, where people make certain modifications and you have for aluminum alloys, a ASTM standard practice, B645 reported in 2007. And you have to keep in mind, I am going to give only a flavor of how these conditions are met. As I had already mentioned, the codes are continuously improved and new codes replace the old ones. So, the advice is, for current practice, look up codes E399 and B645 and their revisions. So, certain aspects of whatever we discuss, may get outdated or may remain; only time will say.

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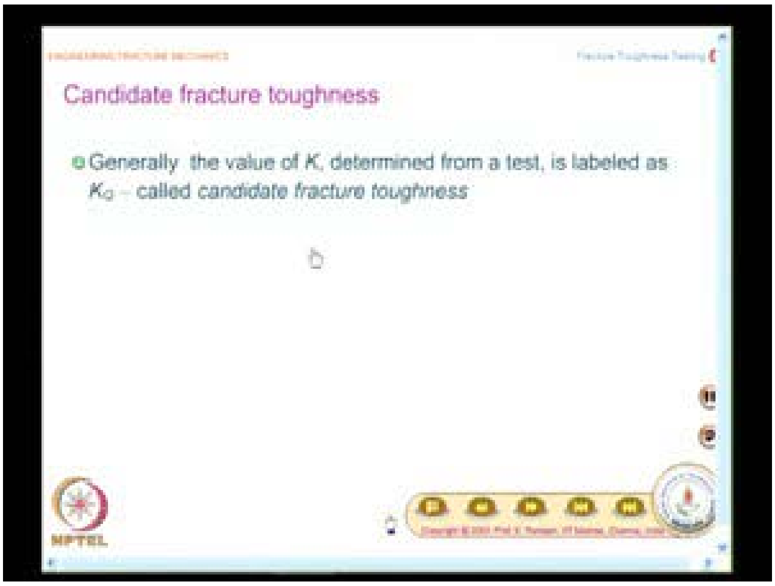

And, what you do is, you also have another concept called candidate fracture toughness. So, that means, when I perform a fracture toughness testing, at the end of the test, whatever I get is labeled as K Q; which is called candidate fracture toughness. Whether this candidate fracture toughness can be qualified as fracture toughness, you have to do the screening of whatever the way that you have conducted the test, and postmortem of your specimen at the end of the experiment. If it satisfies all the screening criteria, then you say K Q can be taken as K1C. Otherwise you have to reject the test, and redo the test. This is how the standard E399 operates.

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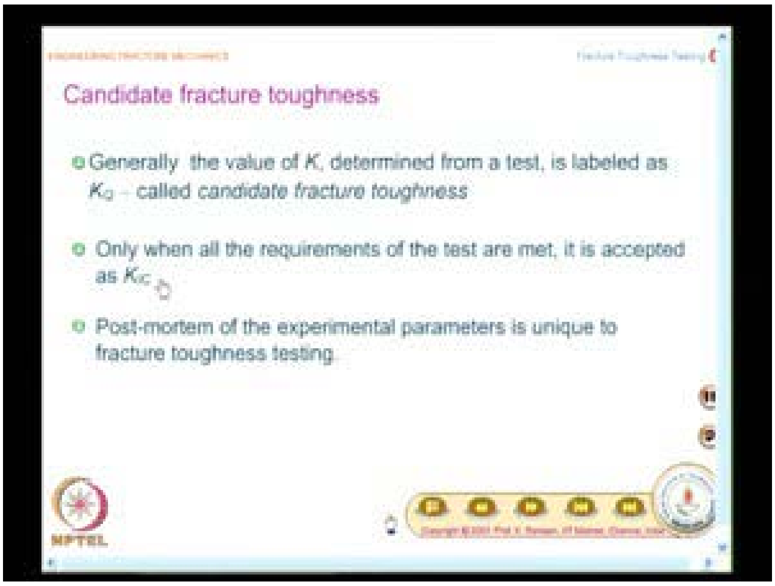

This is what is summarized. Only when all the requirements of the test are met, it is accepted as K1C. Post-mortem of the experimental parameters is unique to fracture toughness testing. You do not do any post-mortem in the case of a tension test; you take a specimen, go, break it and you find out, what is the yield strength. It is very well stream-lined and it is as simple as that; even that is expensive. If you come to fracture toughness testing is much more expensive.

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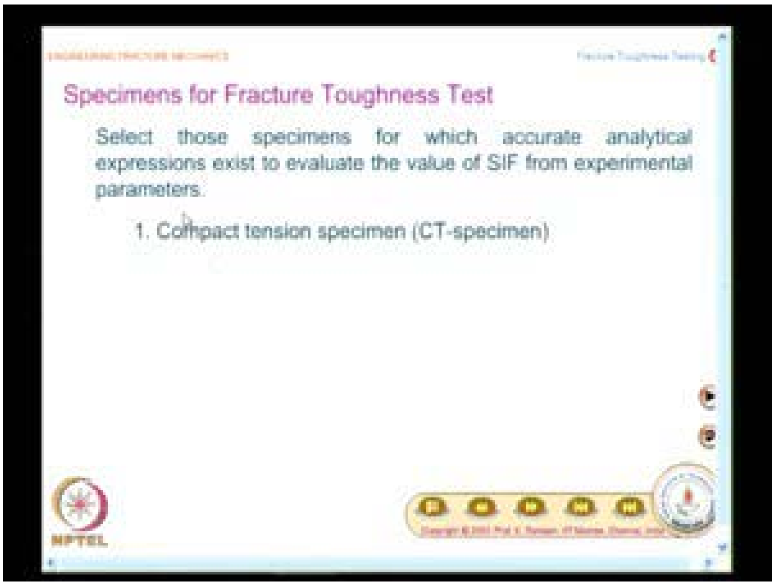

And what are the specimens that you could use for fracture toughness test? See, I had said, in the initial stages, they had used the CT-specimen, but now, you have, different specimens have been reported. But the basic philosophy is, select those specimens for which accurate analytical expressions exist, to evaluate the value of SIF from experimental parameters. Because, what you are going to do is, we are going to find out the load at which fracture occurs, for the test specimen; for that value of the load, for the given geometry of the specimen, you will find out, what is the stress intensity factor. That stress intensity factor, you will call it as K1C, fracture toughness.

So, you need to have accurate analytical expression. So, what people have done is, people have done the boundary collocation type of approach, numerically solved these standard geometries, and have arrived at empirical relations, to find out, what is the value of K within an error bank. All that, we will see. And you have compact tension specimen, which is known as CT-specimen. We will also see a standard and say, how these would be represented later and you have a 3 point bend specimen. It is a TPB-specimen. Then you have a C-specimen and a disc-shaped compact tension specimen. Each of the specimens is used for a particular kind of application.

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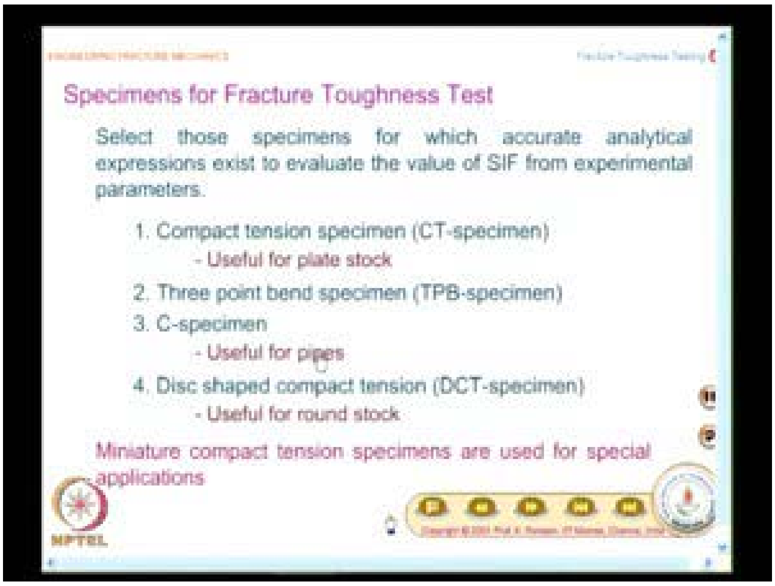

This is useful for plate stock. So, you go for CT-specimen, when you have a plate stock. When you have a pipe, go for a C-specimen. When you have a round stock, go for a disc shaped compact tension specimen. And what you will have to note is, you also have miniature compact tension specimens, reported for special applications. See, mind you, some of these exotic alloys are very expensive; you cannot have a big specimen and you would see the specimen size restrictions. People have also arrived at very small specimens. In fact, if possible I will bring it in the next class and show you how the specimens look like.

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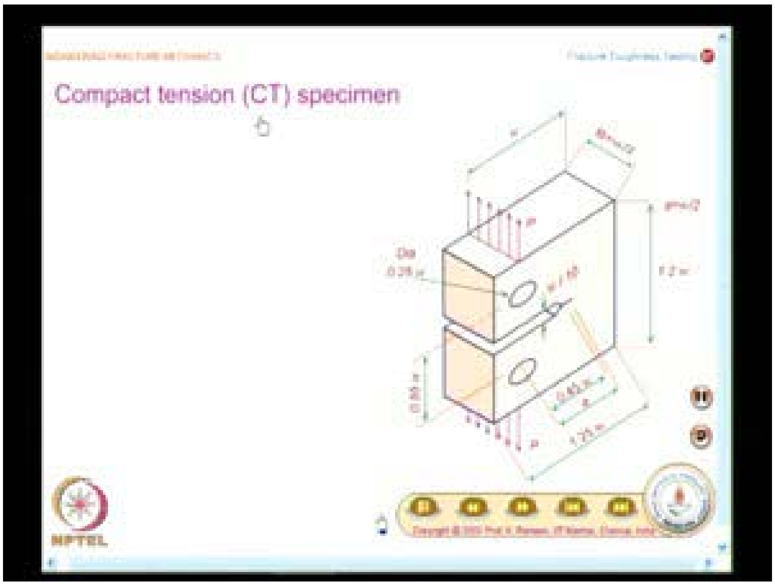

And this figure shows how a compact tension specimen looks like. You can make a 2 D sketch of this. And what you have here is, the thickness is given as w by 2, and if you look at, how the crack is measured, it is measured from the load application point to the end of the fatigue crack. And if you look at, for all the fracture toughness specimens, we would have the length of the crack is around 0.5 w, we would see that as one of the conditions.

So, you want to have a by w ratio is around 0.5. The crack is sufficiently long. And you have very strict nomenclature, what should be the distance of the holes, what should be the dia and what is the tolerance; these are not shown here. If you take up a standard, they would also give what should be the tolerance for each of these dimensions. And the important aspect is, ((apriory)) you do not know, what is the value of B, for a given material. This is where the challenge lies. So, you have to make a intelligent guess work and then prepare your specimen. I need to have a minimum specimen thickness to assure plane strain condition. If my guess work is wrong, you have to repeat the test.

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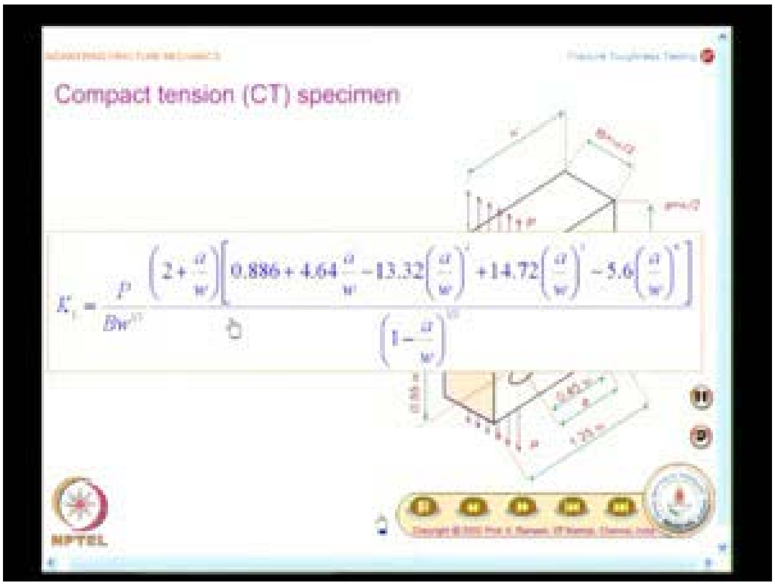

And you also have expressions for this. Please make a note on this in your notes. K 1 is given as P divided by B w power half, multiplied by two plus a by w multiplied by 0.886 plus 4.64 a by w minus 13.32 a by w whole squared plus 14.72 a by w whole cubed minus 5.6 a by w whole power 4 divided by 1 minus a by w whole power 3 by 2.

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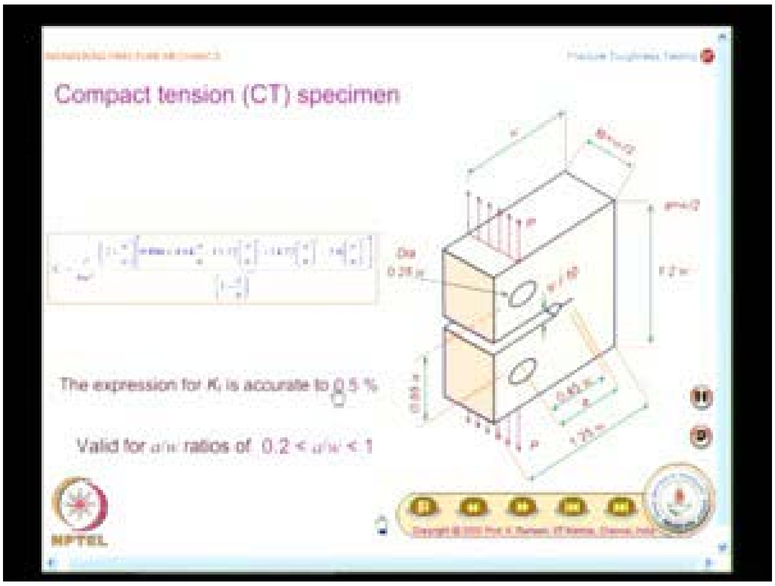

And the standard also gives, what is the accuracy. The value of K 1 is accurate up to 0.5 percent. This is valid for a by w ratios of 0.2 a by w and 1. a by w between 0.2 and 1. And I had said, you will have a by w hovering around 0.5; that is how all the specimens are mentioned in the case of fracture toughness testing. And you should also keep in mind, I had mentioned, in the case of nuclear installation, the material degrades because of exposure to radiation. So, the standard practice is, they stock fracture toughness specimens, inside the reactor and take them out periodically and find out the fracture toughness; and see how the fracture toughness changes, as a function of time; and for that purpose CT-specimen is recommended, because this is very compact. That is why it is called as compact tension specimen.

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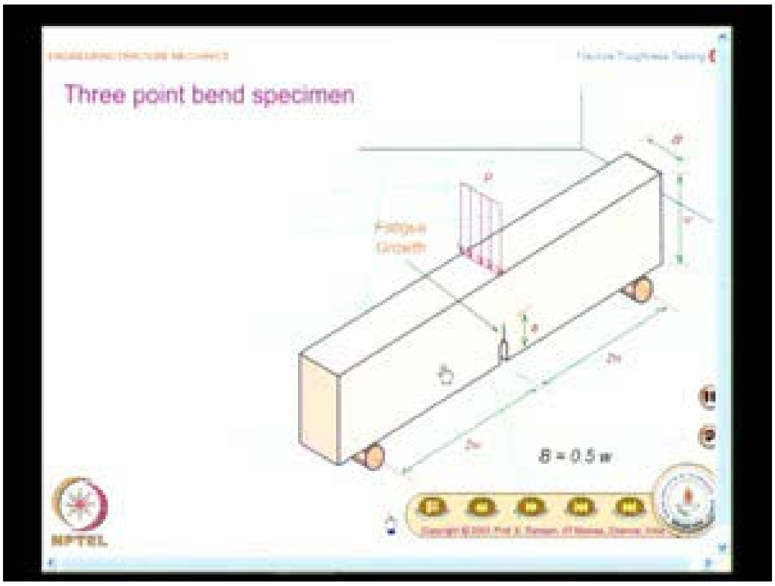

And the next specimen, which is popularly used, is the three point bend specimen. In fact, this specimen is much easier to manufacture than any of the other specimens. Not only this, even the loading fixtures, to load the three point bend specimen, is very simple. So, it is a very popular specimen from that perspective. That is why the standards give you, a variety. You make a two dimensional sketch. I have a nice three dimensional representation. You can always make it as two dimensional sketch.

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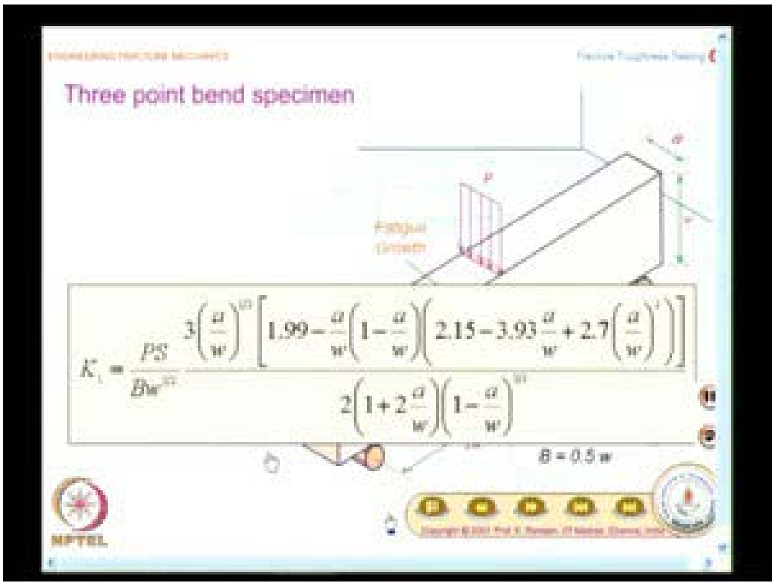

And we would also see, what is the expression for stress intensity factor. And this is given as, K 1equal to P into S divided by B w power 3 by 2, multiplied by 3 into a by w whole power half; this is multiplied by 1.99 minus a by w into 1 minus a by w into 2.15 minus 3.93 a by w plus 2.7 a by w whole squared divided by 2 into 1 plus 2 a by w multiplied by 1 minus a by w whole power 3 by 2. And you have to know, what is the value of S. That is mentioned here. S equal to 4 times the width of the specimen. This length is taken as S. And the expression for K 1 is accurate to 0.5 percent. And you know, you also have other specimens.

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We would see that in the next class.

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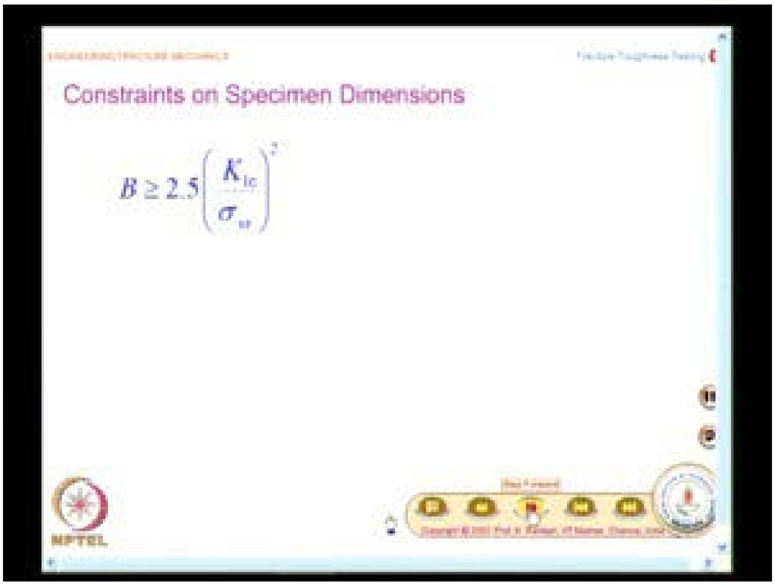

And we would look at two issues; what are the constraints on specimen dimensions, which we have already looked at. You need to have B to be greater than 2.5 five times K1C divided by sigma y s whole squared and we would also see some of this, in the next class.

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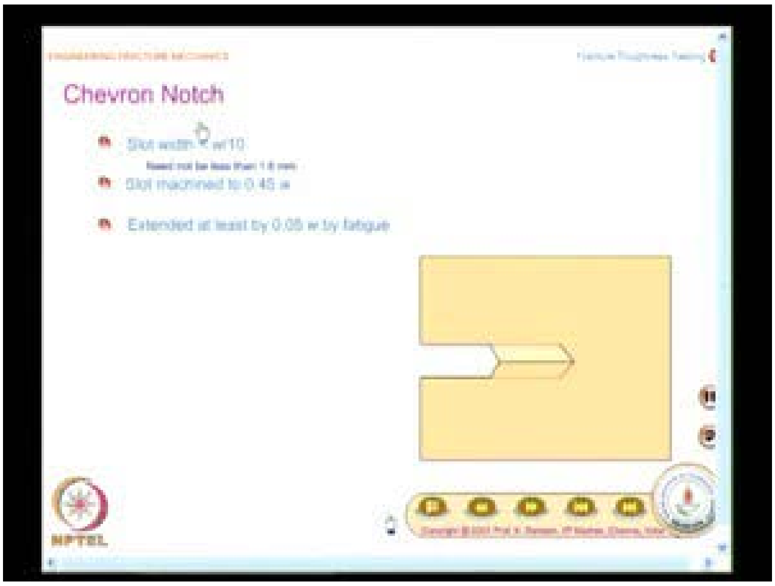

My interest is, to discuss what is a chevron notch? Because, I said you need to have a natural crack to conduct the fracture toughness testing. And we want the crack to be in a plane of our choice and it should propagate in a particular fashion. This is assured in a chevron notch. I am not going to give you the complete answer today. You have to make a sketch and from your experience in drawing, you should visualize, how a three dimensional representation of the notch would look like?

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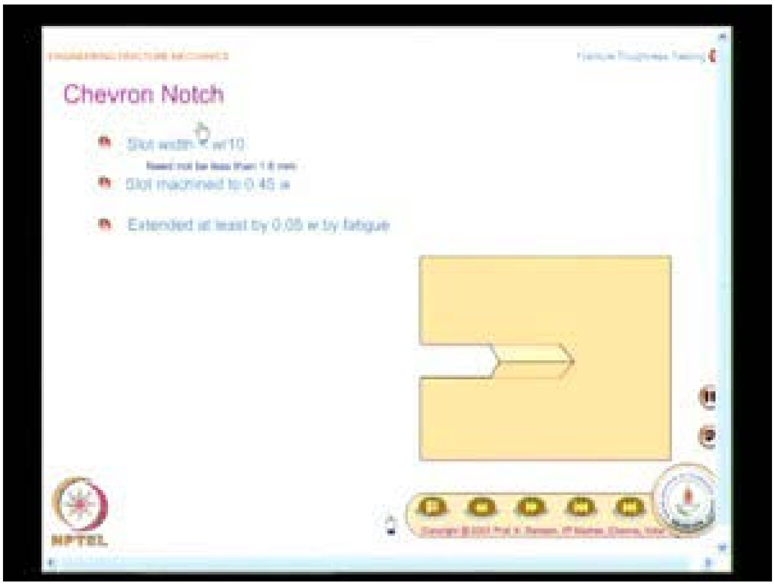

You make a sketch of this. I have lines like this, I have a line like this, I have a line like this, and this is the slot width. The slot width is given as less than w by 10 and the standard says, need not be less than 1.6 millimeter; all these you have to satisfy. When you actually do a problem, you will know how to do it. The slot is machined to 0.45 w. What is the length? It is extended at least by 0.05 w by fatigue. So, what you will have is, at the end of notch you will have a fatigue crack. Now, the question is, how the fatigue crack plane and its orientation has to be controlled. This depends on the design of the notch.

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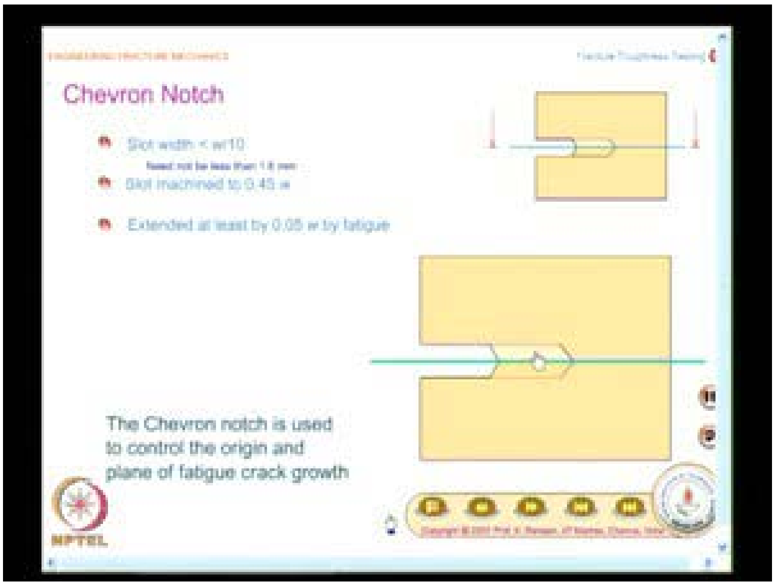

And, let me put a plane passing through this. The idea of the chevron notch is used to control the origin and plane of fatigue crack growth.

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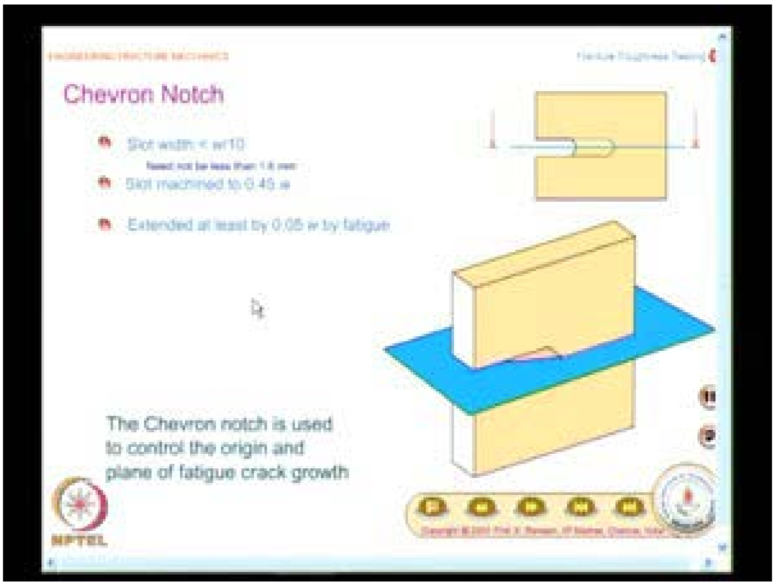

And you know, you have a clue, how the notch will look like. But I will put a plane over it, and the exercise for you is, from the knowledge of your drawing, when the specimen is cut like this, what would be the isometric view of the chevron notch? The focus is, it controls the origin of the crack and plane of the crack. Do this as an exercise and come to the next class.

So, in this class, what we have looked at was, how does the plastic zone changes over the thickness of the specimen; and also, along the length of the specimen, we have looked at, what are the slipping planes in the case of plane strain, and the slipping planes in the case of plane stress, which you have corroborated by experimental result of Rosenfield and his co-workers. Then we moved on to fracture toughness testing. We have looked at two specimen dimensions; we would see the other specimens in the next class. And the idea of, what is a need for chevron notch was explained. And I would like you to sketch a possible shape of a chevron notch, because this is difficult to make. You need special tooling to make this. Thank you.