

Engineering Fracture Mechanics
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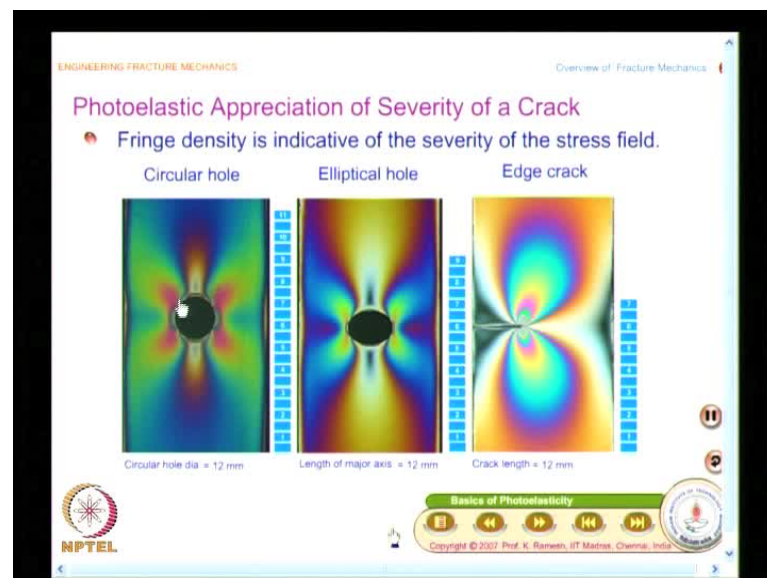
Module No. # 01

Lecture No. # 04

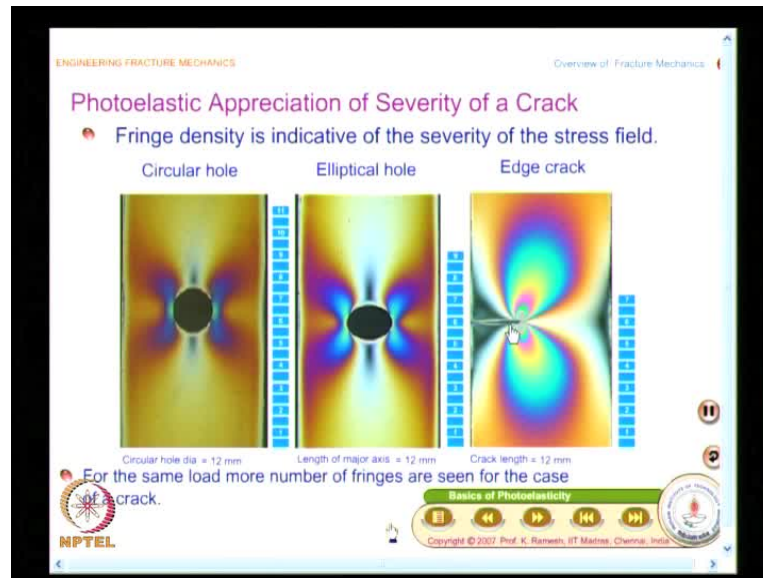
LEFM and EPM

In the last class, we had a brief introduction to Photoelasticity. And, I introduced Photoelasticity by taking an example of a beam **under** four point bending. The focus was to show that the photoelastic fringes indeed, represent contours of $\sigma_1 - \sigma_2$. So, what is the advantage? If you have the stress field equations, you would be in a position to calculate analytically $\sigma_1 - \sigma_2$ and plot it and see, whether it compares with whatever that is obtained in the experiments. And, in order to emphasize that, crack is more dangerous than a circular hole or an elliptical hole; we also saw the fringe patterns. We will see those fringe patterns again.

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You have a plate with a circular hole, you have a plate with an elliptical hole and you have a plate with a crack. And, if I maintain the load as 7 in plate with the circular hole, as well as 7 in the elliptical hole, the mere comparison shows, the number of fringes you come across in a crack is much higher than what you see in an elliptical hole or a circular hole.

So, the one way, what we could take advantage of this is, we are going to develop stress field equations in the vicinity of a crack. And, we need to verify whether those equations are correct.

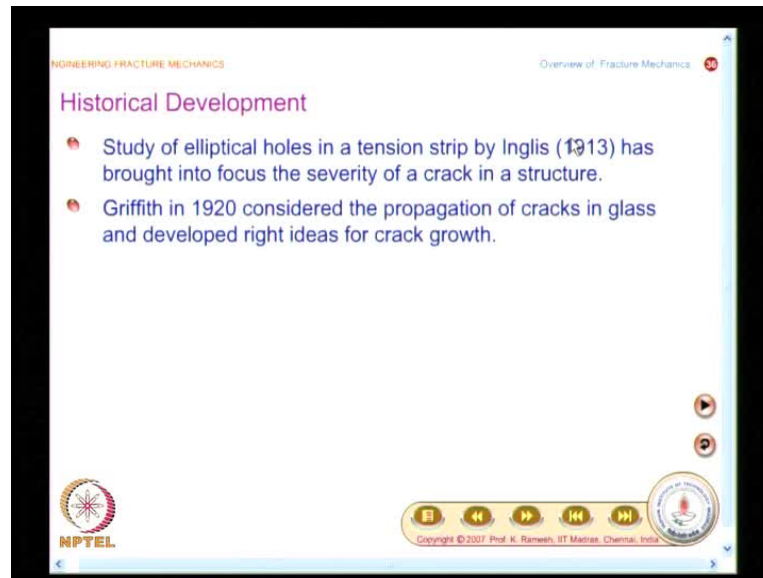
So, what we could do is, from the analytical equation, get σ_1 minus σ_2 and plot them and compare with the experimental result and ensure, whether our solution is correct. That is the reason why I said, I would be using extensively photoelastic method for developing the concepts in Fracture Mechanics.

If you really look at the history, the stress field equations have been improved by looking at the geometric features of the photoelastic fringe. And, I have also asked you to look at the special features of the fringe in the vicinity of the crack.

Let us, look at the features of the fringe. This is the crack and we will take this as a reference axis. About this axis, the fringes in the top and at the bottom are symmetrical. The other striking feature is the fringes in the top are tilted forward. Keep this geometric

feature in your mind. As soon as, we develop the stress field equations, we would plot contours of σ_1 minus σ_2 . And, compare with the fringe patterns and see, what we obtain? Let us, wait till such a moment.

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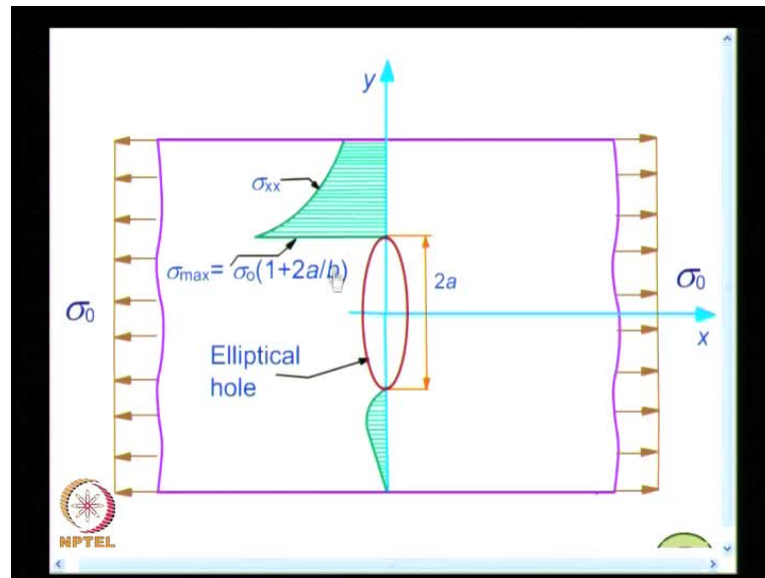


Now, let us go and look back the historical development. And, if you look at study of elliptical holes in a tension strip by Inglis, was done in 1913. And, what was the important emphasis from his work? If you look at the History, the first problem leading to stress concentration was solved by Kirsch. It was in 1898. He solved the problem of an infinite plate with a small circular hole. This was possible because you had the development of polar coordinates, as well as Cartesian rectangular coordinates. So, the **hole** can be modeled from a polar coordinate. You can easily identify the boundary condition on the hole. You can easily specify the boundary condition on the **hole**.

So, the first problem was solved by Kirsch, for the case of a circular hole in a tension strip. And, it took almost fifteen years for Inglis to go and repeat the same for an elliptical hole.

So, the moment you go to an elliptical hole, you need to specify the boundary conditions on the boundary of the hole. And, they had to develop an elliptical coordinate system to conveniently handle the problem. And, that alerted the importance of a crack.

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Let us, look **at** very closely. And, I would like you to make a neat sketch of this. I am showing it in a finite screen. So, imagine that this is an infinite plate with a small elliptical hole. But, it is shown big for clarity and also, there is also a small **pixilation** error here. The figure is magnified. So, you find that, there is a shift in this. You imagine that, this as a straight line.

So, what you have here is, in a tension strip you have an elliptical hole. And, this shows the typical variation of the stresses on this axis. And, you have the variation of sigma x x and Inglis found that, this is related to the **far** field stress by a factor 1 plus 2 a by b. This, you might have heard in a course in strength of materials.

The moment when b tends to 0, the multiplication factor goes to infinity. What is the meaning of that? One meaning is the stresses go very high. Other meaning is the methodology of stress concentration to **ascribe to a crack**, no longer is valid. You need improved mathematical approaches to handle the problem of a crack. And, what is the advantage of an elliptical hole? You can verify, whether the solution is correct by changing the **minor axis**.

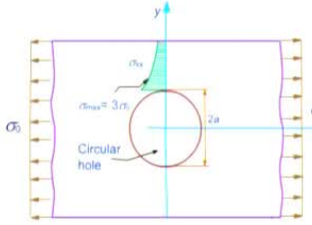
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ENGINEERING FRACTURE MECHANICS

Stress field in a plate with circular/elliptical hole

Extremum Cases of the Elliptical Hole

- For $a = b$ (a circular hole), the maximum value of σ_{yij} is $3\sigma_0$, which agrees with the results given by Kirsch.



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If I make the minor **axis** equal to the major **axis**, I would get the problem of a plate with a circular hole. And, if you make b equal to a , this goes to 3. And, this is, what was obtained by Kirsch, way back in 1898. And, you find, when you have a circular hole, the maximum stress is three times the far field stress.

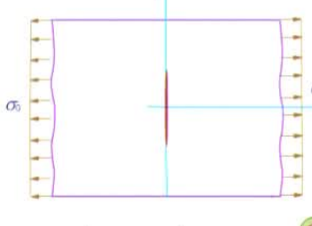
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ENGINEERING FRACTURE MECHANICS

Stress field in a plate with circular/elliptical hole

Extremum Cases of the Elliptical Hole

- For $a = b$ (a circular hole), the maximum value of σ_{yij} is $3\sigma_0$, which agrees with the results given by Kirsch.
- The maximum value of σ_{yij} increases without bound as $b/a \rightarrow 0$, that is, as the semi-minor axis b becomes smaller and smaller relative to a .
- Ellipse becomes a crack in that case and one requires newer approaches to handle such a problem.



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So, you all know stress concentration factor is 3. And, for an elliptical hole, you can calculate the stress concentration factor. The moment when you make b tends to 0; you

have the modeling of a crack. And, what is summarized here is, one requires newer approaches to handle such a problem.

Now, let us come back. Suppose, I have a plate with the hole; you will have only stress concentration, until the stresses reaches the maximum values failure will not happen. On the other hand, when I have a crack, what does it show? The values go to infinity.

In reality, nothing can go into infinity. At the most, the stresses can reach the plastic condition. This is what you can anticipate. The direct interpretation of Inglis will only alarm you that nothing can remain in solid form, if I have a crack; because even, for a very small load, you will have an infinite stress; it may eventually break into pieces, but that is not the way you come across. In reality, you have structures, they have embedded crack, but they do not make the structure as a powder. That is what Inglis result shows, if you look at it on the face of it.

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ENGINEERING FRACTURE MECHANICS Overview of Fracture Mechanics 30

Historical Development

- Study of elliptical holes in a tension strip by Inglis (1913) has brought into focus the severity of a crack in a structure.
- Griffith in 1920 considered the propagation of cracks in glass and developed right ideas for crack growth.
- He formulated that an existing crack will grow provided the total energy of the system is lowered by its growth.
- His work was not noticed at that time due to the exigencies of the World War and the following depression worldwide.
- Griffith was not able to coin a convenient parameter for predicting the failure load of a component through the growth of a crack.

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In order to explain, why structures remain with cracks, Griffith was able to come out with a theory that, you need energy for the crack to grow. That was a contribution by Griffith in 1920.

He was particularly interested in propagation of cracks in glass. And, he could develop right ideas for crack growth. This is very important. He was able to penetrate and say Inglis solution is very important. It alerted that crack is more dangerous. But, it provided

a logical explanation that you will have structures with crack. Just because it has a crack, you need not have to discard. The cracks will grow in surface, attain a critical dimension; only then, fracture will occur. And, we would see a large number of practical cases. When you do postmortem, you would see distinctly a crack growth region followed by fracture. So, the contribution of Griffith in 1920 was very important. And, as I mentioned, he formulated that an existing crack will grow; provided, the total energy of the system is lowered by its growth.

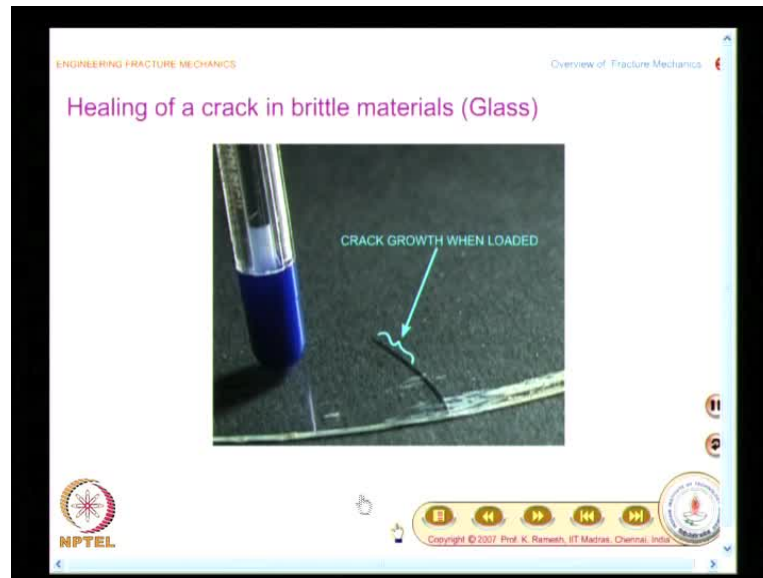
So, you have to appreciate **that** the existing crack will grow. And eventually, when it becomes critical, fracture will occur. So, it is not that, when you have a crack, when you apply even smallest load, **this** structure is going to fail. It is not so.

The contribution of Inglis, you have to appreciate. He was able to bring out analytically that crack is much more dangerous. Even though, Griffith was able to formulate his ideas, his work was not noticed at that time due to the exigencies of the world war. It happens. You know, somebody does scientific work. Only if, there is peace all around, people will notice **what contribution is this**. And, after the world war, there was also depression. So, people were worried with day to day living. So, they were not really worried about Science. So, it was not noticed.

And, there is also another **aspect**; see Griffith was not able to coin in a convenient parameter. See, for the development of any field of Science or Art, you would need to develop jargons. You know, jargons are very important. And, the moment you listen to the jargon, you immediately understand what it conveys.

So, you need to make a convenient parameter, until then fracture was not looked at by people. That contribution was done by Irwin and that came a **word** way back in 1948, so, 1920 or 22 Griffith with all these experiments. Only in 1948, Irwin extended this to ductile materials; whatever the work that was done by Griffith, was on glass. So, what you will have to appreciate is, the contribution of Inglis is also very important. The understanding of Griffith is good. He had right ideas for crack growth, but he was not able to express it in a convenient fashion.

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And, let us look at some of the interesting examples. Just, watch this animation and identify what this animation is trying to show. Now, you have seen it. Let me, ask the question. Do you see that there is a crack in this plate? And, what happens? This is actually a ball pen. You know you press it, you find, what happens to the crack.

The crack grows in length. **The moment** I remove the load, you find there is a **semblance** of healing of the crack. In fact, in brittle solids like Mica and Glass, Griffith observed when the loads are removed, the crack heals. See, this is very advantageous for us. Suppose, I want to go and do an energy method, it is easy for me to formulate the equations if I have a reversible process.

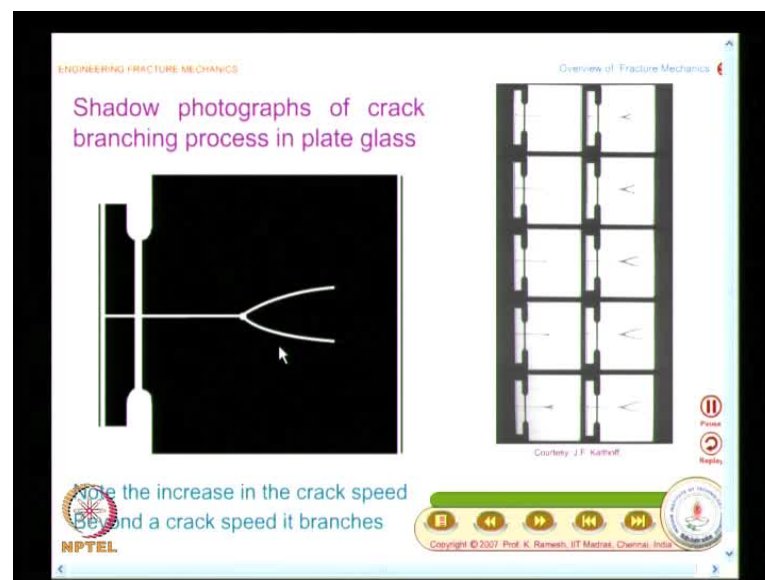
See, if you look at fracture, it is intrinsically non-reversible because in an actual solid, you will have plastic deformation. Energy is dissipated and you cannot come back to the original situation at all. In highly brittle solids, people have found that under suitable conditions the crack can heal. If you recall in the energy release rate, I said I want to find out, what is the energy required for the crack to grow? I said, I am going to close it, find out the energy required to close. I will use it for finding out what is the energy required for fracture growth.

So, in order to, go to that kind of a mathematical manipulation, this helps. In fact, this was an accident in our laboratory. And, I quickly got that recorded and included as part of the course material. And, let me take one more example. Here, I am showing a glass

plate, I have just thrown a stone in this place, it will **break**. And then, I use cellophane tape to put them together and bring it to the class.

What do you see here? By putting a stone, I have pumped in energy to this glass and glass has to dissipate the energy. **What** way **it has done**? You have some material removed **in** the core and you have several branches of crack. This is very important. If I develop a fracture theory, the fracture theory should be able to say how many cracks are there, in which direction it should develop and grow, we should have that kind of an answer.

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A common man **will only say the glass is broken**, replace the glass. A scientist has to go and see how the energy has been dissipated, how many crack branches have come about and how to deal with this. I will show one more example. Again, you just watch the animation.

This is again in a sheet of glass. I will repeat the animation again. It conveys a very important message. What you have is, I had one crack, which was having a particular speed and then suddenly, it will branch out as two cracks. I will repeat the animation. You just observe it.

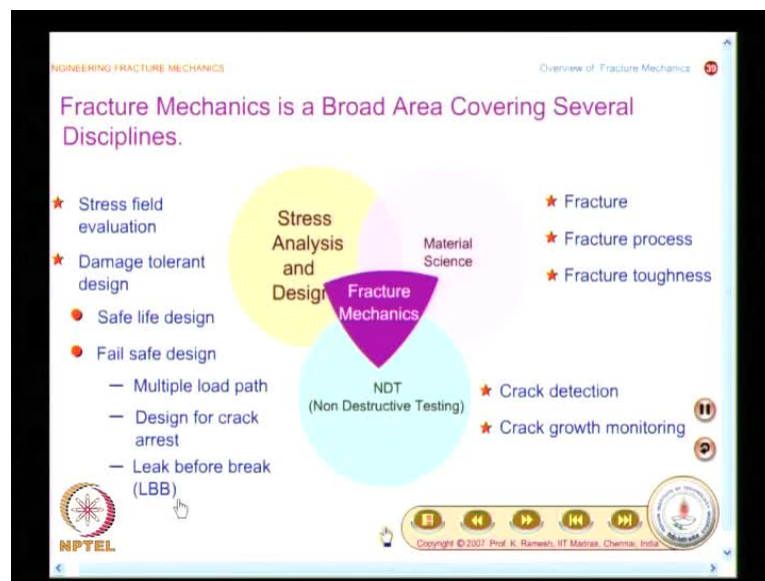
The crack speed increases, suddenly it becomes two. So, from Fracture Mechanics point of view, what you will have to look at? **?** If I develop a fracture theory, the fracture theory

should be able to say why a crack branches out. In fact, if you have closely looked at the animation, the crack speed was increasing.

So, when the kinetic energy was more, then what it is? The speed was increasing and it has been established by photoelastic analysis; using, Dynamic photoelasticity that the crack can take only the Rayleigh wave speed. It cannot go faster than that. So, more energy cannot be dissipated. So, if more energy has to be dissipated, the crack has to branch out. So, that is why I said, photoelasticity is very closely linked to development of Fracture Mechanics.

So, there is an upper limit with which a crack can grow in a material; that is, decided by the Rayleigh wave speed. And, this was first brought into focus by **Kathoff**. He had done a series of experiments, using the method of caustics. These are the caustic shadow that you get in an experiment by caustics. And, you can again look at the animation. The animation shows that, crack speed increases and it branches out.

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In this, we have already noticed that Fracture Mechanics is a broad area covering several disciplines. And, you have Material science, Nondestructive testing, Stress analysis and design. And, we would see one after another, what **you** will learn in each of these aspects?

The Material Science covers fracture. Whether, it is a cleavage fracture or a ductile fracture, the fracture process and also measurement of fracture toughness. These three aspects come under the topic of Material Science.

In Nondestructive testing, you will have to find out, how to detect a crack and also how to monitor the crack. What should be your periodic interval to go and monitor the crack?

And, finally we come to stress analysis and design. In this, you have several issues. We would develop the stress field. Using that as an information and also the information on fracture toughness, we could go for improved design methodologies. And, we had already seen, Fracture Mechanics has to help us to have damaged tolerant design approach. So, in this, you have two main categories.

One is a Safe life design. See, in conventional analysis, when people were thinking about fatigue, they wanted to have infinite life. Infinite life is not possible. What we are saying here is, within the life that is anticipated, the structure is safe. This is the way we are looking at. So, this is a different approach. Another way of looking at is, when you are having difficult installations like nuclear power, where any accident can lead to catastrophe, you would like to invoke, what is known as Fail safe design.

One is the multiple load path. You do not want to have a structure to fail, if one member fails. A good example is, suppose you make a castle out of the playing cards; people have such competitions. You just go and blow or remove one card, the whole structure will collapse. And, you do not want to have your structural systems to collapse like that. You need to have multiple load path. And I used to mention, if you look at your own human body, God has given you with two kidneys. If one kidney fails, you can still survive. Another kidney can help you. So, you find even in natural systems, there is some kind of essential redundancies, in built. So, by looking at optimization, do not stretch optimization beyond a limit.

So, you need to have multiple load path. Suppose I have a crack, I must also have the design to arrest the crack. We must have methodologies to arrest the crack. And, finally there must be some kind of a warning, before the structure is about to fail.

So, you have, what is known as Leak Before Break, which is abbreviated as L B B. And, L B B criterion is very important in Nuclear Technology. Unless the components go

through L B B criterion, they do not permit those components to be utilized in nuclear power installation. So, you can feel safe. So, science is used.

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ENGINEERING FRACTURE MECHANICS Overview of Fracture Mechanics

Fracture Mechanics is a Broad Area Covering Several Disciplines

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- Fracture mechanics attempts to account for the existence of inherent flaws in structures and thus is closer to reality in modeling engineering problems.
- It uses stress analysis to determine the stress intensity factors, material science to determine the fracture toughness and NDT to determine the initial flaw size.

Design for a given safe life is possible if the above mentioned three inputs are available.

Stress Analysis and Design, Material Science, Fracture Mechanics, NDT (Non Destructive Testing)

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So, this is what, we have been emphasizing all along. Fracture Mechanics attempts to account for the existence of inherent flaws in structures. And, thus is closer to reality in Modeling Engineering problems. And, how does this do? It uses stress analysis to determine the stress intensity factors. You have still not looked at what are stress intensity factors. You would develop the concept and uses Material Science to determine the fracture toughness and nondestructive testing to determine the initial flaw size. So, this is very important.

So, what we will go about is, when you say a nondestructive testing, we will see that what the minimum size it can detect. So, that would be the assumption on what is the initial crack size. And, we would do theoretical calculation. So, if you have a better nondestructive testing, even our fracture calculation would be much better. So, N D T development is also equally important. With all that information, it is possible to design a structure to give a safe life.

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ENGINEERING FRACTURE MECHANICS Overview of Fracture Mechanics

LEFM and EPFM

- Structures made of ductile high strength alloys failing in a brittle fashion prompted the birth of fracture mechanics.
- Linear Elastic Fracture Mechanics (LEFM)
 - Extension of Griffith's ideas for brittle solids to ductile high strength materials was done by Irwin in 1948.
 - The main focus of Irwin's theory is on the crack tip rather than the crack; by moving the analysis to the crack-tip, Irwin devised workable parameters like stress intensity factor and energy release rate.
 - LEFM accounts only for small scale yielding (SSY) near the crack-tip.
 - LEFM is quite useful for analysing problems in aerospace structures.

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And, once you come to Fracture Mechanics, there are two broad categories that you can think of. One is Linear Elastic Fracture Mechanics. Another one is Elastoplastic Fracture Mechanics. The whole of Fracture Mechanics focuses on structures made of ductile, high strength alloys. This is very important. You do not apply Fracture Mechanics to mild steel. Only for high strength alloys, Fracture Mechanics is applied. The high strength alloys fail in a brittle fashion has prompted the birth of Fracture Mechanics.

This is what I had mentioned earlier. Whatever the ideas generated by Griffith, for brittle solids was extended to ductile, high strength materials by Irwin in 1948. You would see how he has done.

When we look at the chapter on Energy release rate, we would be able to find out how conveniently he was able to extend the ideas of Griffith. And, what did Griffith do? See, when you look at Inglis solution, he alerted crack is very important.

So, people were thinking crack is important. And, they were trying to generate ideas, but they were missing a very important point; which was pointed out by Irwin. He shifted the focus from the crack to the crack-tip. Then, the whole of Fracture Mechanics became very simple.

So, what he did? By moving the analysis to the crack-tip, he devised workable parameters like stress intensity factor and energy release rate. So, that was the very

important contribution by Irwin. And even, in one of our earlier class, we have shown that when you have a crack, I showed that crack-tip is taken as the origin, crack axis is taken as the x axis.

So, all that comes from contribution by Irwin; just because he shifted the focus to the crack-tip, we were able to get convenient parameters. Relatively because if you look at the stress intensity factor, it has very funny units; leaving that apart, compare to what Griffith was trying to say, what Irwin said was easier for people to understand. And, we have already emphasized that the moment you have a crack, you will have very high level of stresses.

So, definitely there will be a plastic zone developed. And, if you look at L E F M, this accounts only for small scale yielding near the crack-tip. And, this abbreviation S S Y is also a very important abbreviation in Fracture Mechanics. So, when you come across S S Y, you should understand that it refers to Small Scale Yielding. You have plastic zone that is very highly localized. This is what; you have to appreciate because if you directly extend Inglis result, you would get confused. This structure would have become a powder, while it still remains as solid. That explanation was provided only by Griffith. Even though, you have very high stresses from a practical point of view, it cannot become infinity. If it is an elastoplastic material, it will either become plastic or it will have some work hardening. Some, such aspect will happen. You will not have infinite stresses there. But, the plastic zone is very highly localized. If it is very highly localized, then L E F M is applicable. If it is spread slightly, then you will have to go in for E P F M. We will classify L E F M as well as E P F M based on plastic zone also.

The use of L E F M is found in aerospace structures because you use essentially thin structures and by enlarge, it is more of a Thumb Rule. In some aerospace components, you will also require E P F M. But, by enlarge L E F M is applicable to aerospace structures.

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ENGINEERING FRACTURE MECHANICS Overview of Fracture Mechanics

LEFM and EPFM

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- Elasto-Plastic Fracture Mechanics (EPFM)
 - ★ Role of plastic deformation near the crack-tip is better accounted in EPFM.
 - ★ For situations where material behaviour is non-linear such as in nuclear applications, EPFM is essential.
- Typical materials for which LEFM is applicable (at room temperature) are
 - ★ High strength steel, precipitation hardened aluminum, polymers below glass transition temperature, ceramics, ceramic composites.

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As I mentioned, if the plastic deformation at the crack-tip is high, then E P F M is what you have to look for. For situations, where material behavior is non-linear such as in nuclear applications, E P F M is essential. You could also classify L E F M and E P F M, based on which material you are dealing with. And, I would like you to take down the notes of these slides. And, when you look at L E F M, if I use high strength steel, precipitation hardened aluminum, polymers below glass transition temperature, ceramics and ceramic composites; for all of these materials, you could comfortably go and attempt L E F M. If it fails, then go for E P F M.

These are all Thumb Rules; these are all not rigid rules. It depends on various factors. It depends on thickness of the specimen also. But, this is more like, when I have a high strength alloy, how do I go about and pick out. And, polymers are also becoming very important these days. When polymers are becoming very important, you will have to know until what condition you can analyze it, based on L E F M. And, we find polymers below glass transition temperature; you could invoke L E F M. If it is above glass transition temperature, then you will have to go for E P F M.

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The slide is titled "LEFM and EPFM" and is part of an "Overview of Fracture Mechanics" presentation. It lists typical materials for Linear Elastic Fracture Mechanics (LEFM) and Elastic-Plastic Fracture Mechanics (EPFM). The slide includes a navigation bar at the bottom with icons for home, back, forward, and search, along with the NPTEL logo and copyright information for Prof. K. Ramesh, IIT Madras, Chennai, India.

ENGINEERING FRACTURE MECHANICS Overview of Fracture Mechanics

LEFM and EPFM

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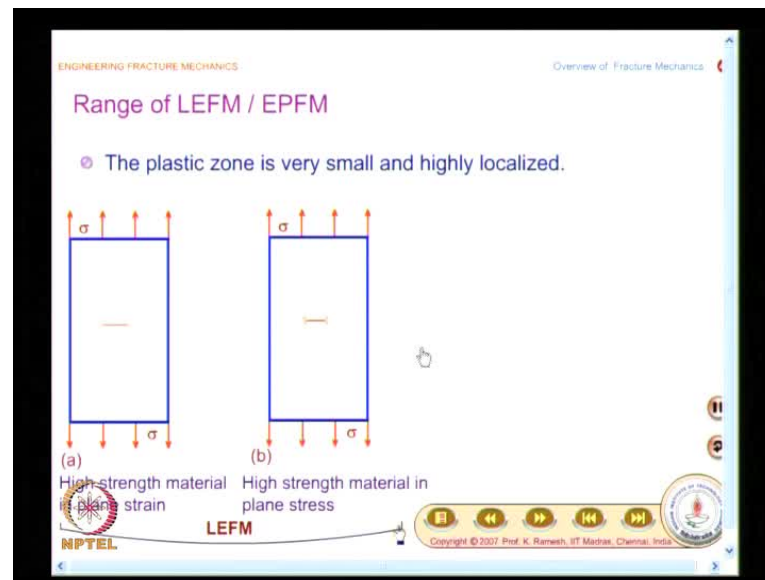
- Typical materials for which LEFM is applicable (at room temperature) are
 - ★ High strength steel, precipitation hardened aluminium, polymers below glass transition temperature, ceramics, ceramic composites.
- Typical materials for which EPFM/Non-linear Fracture Mechanics is applicable are
 - ★ Low and medium-strength steel, metals at high temperatures or high strain rates, polymers above glass transition temperature, ceramics at high temperatures.

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So, you have some kind of a guideline. We will have to take this more as a guideline, rather than as rigid separation of the... Typical materials for which E P F M or Non-linear Fracture Mechanics is applicable are low and medium strength steel, metals at high temperatures or high strain rates; these are all becoming very important. High strain rate is becoming very important, when people want to find out safety of structures due to bomb blast. So, these are all happening at very high strain rates. So, you need to have proper modeling. Particularly, nuclear installations should be safe from a bomb attack.

Polymers above glass transition temperature, ceramics at high temperatures because in gas turbines, people want to improve the thermal efficiency. So, they want to push the operating temperature as high as possible. And, ceramics are being used. Ceramic is basically a brittle material, but if it is used in high temperature application, L E F M is not sufficient. You will have to invoke E P F M. This is again a guideline. So, you have to be very careful. Now, what we will look at is, we will classify L E F M and E P F M based on the plastic zone. And, certain ideas you will also get.

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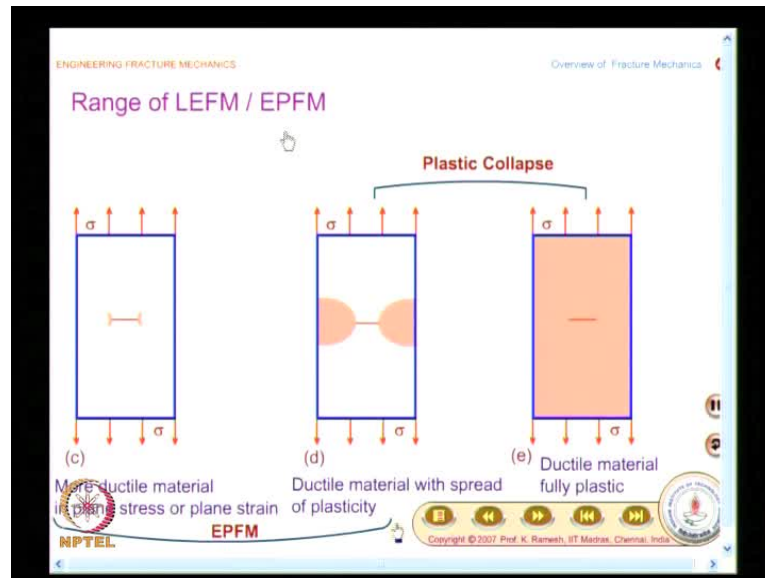


The plastic zone is very small and highly localized. And, this shows a small schematic of what **would** be the nature of the plastic zone. And, I have this for high strength material in plane strain, then I have high strength material in **plane** stress. If you watch it carefully, the plastic zone in the case of a **plane** strain is much smaller than, what you have in the case of a **plane** stress.

See, in conventional design, you say, if the material yields, you consider that as a failure. I have already said, before you define what failure is, you will have to understand your application. Depending on the application, you establish what **the meaning of a failure is**, then go on look at the design.

In the case of Fracture Mechanics, when I have a crack, you will invariably have plastic zone at the crack tip. The plastic zone is highly localized and in fact, if the plastic zone is slightly spread as in a **plane** stress condition, it is beneficial from Fracture Mechanics point of view. The structure as a **whole** will still remain as brittle only. When you apply the load, it will have elastic response; it will not have a plastic response. But, near the crack you will have a plastic zone. And, that plastic zone dictates how the crack is going to behave. And, in fact in Fracture Mechanics, if you have some plasticity near the crack-tip, it is beneficial. It prevents the crack to grow easier. So, it is good from the point of view of safety.

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Then, we have another set of material, which is more ductile in plane stress or plane strain. You have still higher plastic zone and you also have situations, where the plastic zone is visibly spread. I would like you to make a neat sketch of this. You know this brings out in a nut shell, the role of plasticity in fracture analysis.

So, if I have a ductile material with spread of plasticity, until a certain point you can apply E P F M, beyond a point you need to go for plastic collapse; because certain structures can fail by plastic collapse. So, you have to find out whether the failure is precipitated by fracture, that is, material separation or even before fracture occurs, plastic zone spreads on the entire structure. And, that is the reason, why you have failure assessment diagrams are used in fracture analysis. They want to find out, whether it comes in the category of plastic collapse or fracture.

So, this kind of approach is needed, when you have to handle practical problems. So, this gives an overall idea how plastic zone indirectly dictates, which type of theory you have to invoke as a first approximation to handle the problem.

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ENGINEERING FRACTURE MECHANICS

Modes of Loading

- Irwin observed that there are three independent ways in which the two crack faces can move with respect to each other.
- The corresponding modes are labeled as Mode I, Mode II and Mode III.
- The three modes describe all the possible modes of crack behaviour in the most general elastic state.
- A cracked body can be loaded in any one of these modes, or as a combination of two or three modes.

Displacement of the crack surfaces of a local element containing the crack front is shown.

Overview of Fracture Mechanics

Mode I
Opening Mode

Mode II
In-plane Shear Mode
Sliding Mode

Mode III
Out-of-Plane Shear Mode
Tearing Mode

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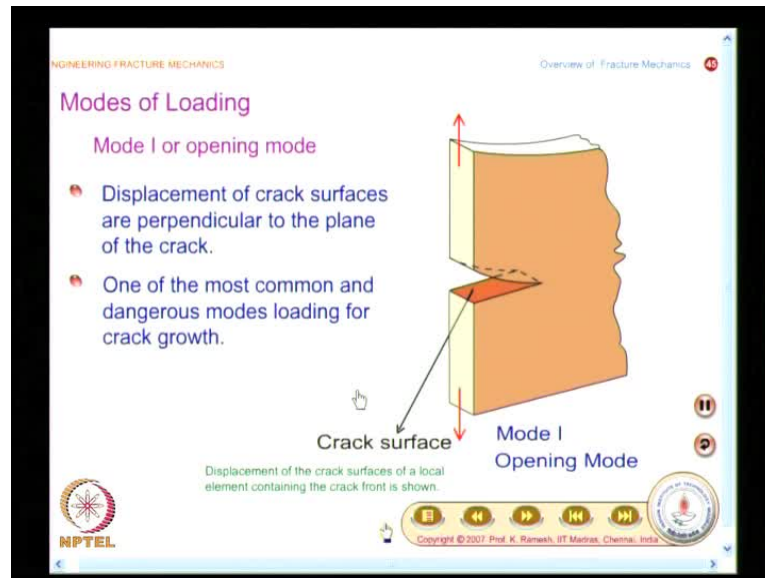
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Then, we move on to the important aspect that, what are the modes of loading near the crack-tip? This is again, the contribution by Irwin. And, he observed that there are three independent ways, in which the two crack **surfaces** can move with respect to each other. You do not have to write this animation currently. We would see each one of these modes. You write only these points

The corresponding modes are labeled as Mode I, Mode II and Mode III. There could be three independent ways in which the two crack **surfaces** can move. And, these are labeled as Mode I, Mode II and Mode III. And, what is the beauty of this concept is that the three modes describe all the possible modes of crack behavior in the most general **elastic** state.

So, you will have a combination of Mode I, Mode II and Mode III of various proportions in a generic problem.

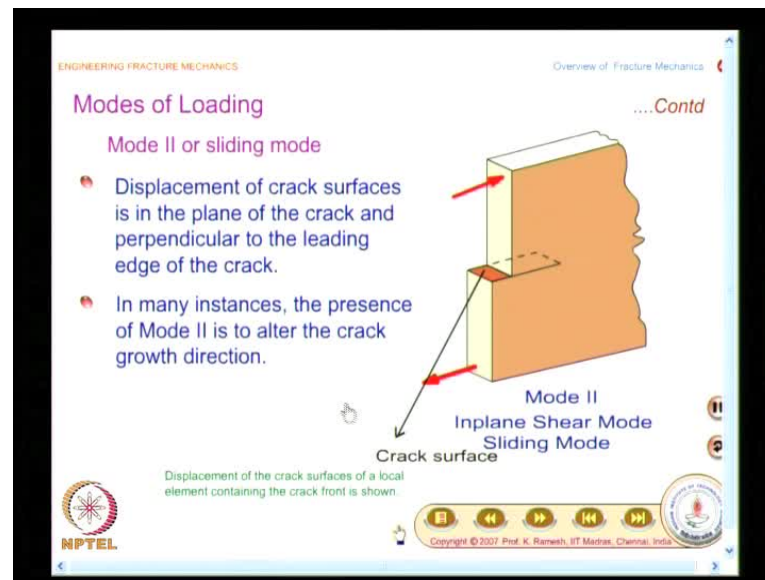
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It may be predominantly Mode I or predominantly Mode II or predominantly Mode II or a combination of this. And, what we would see now is, we would go and investigate and understand, what happens in each of these modes and how they are labeled and which one of them is more dangerous than the other, what way the other modes play in crack propagation. You make a neat sketch of this crack that is opening. This is very important. And, what is shown here is the crack **faces** open up like this. The displacement of crack **faces** is perpendicular to the plane of the crack.

This is labeled as Mode I. This is also called as Opening Mode. Mainly because you have the crack and the crack opens up like this. Because of the load, the crack opens up like this, this is one of the most common and dangerous modes of loading for crack growth. People have developed theories and showed that crack will eventually take a path such that, the loading is perpendicular to that.

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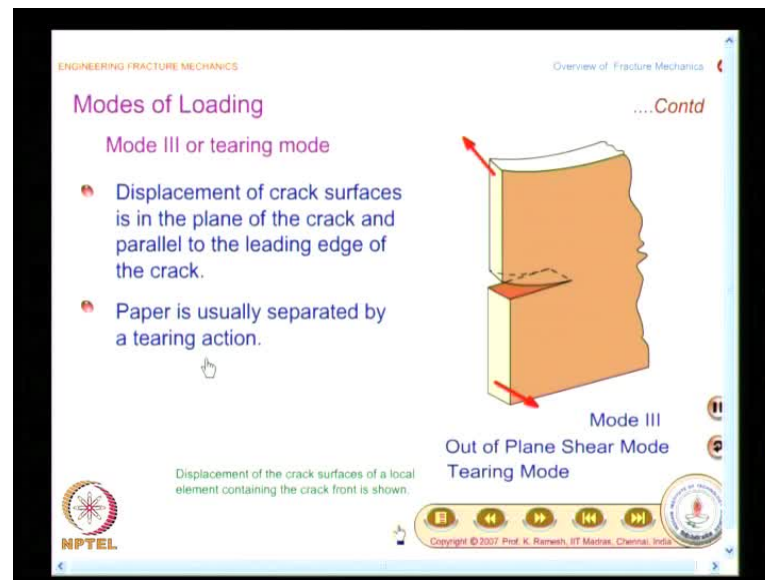


So, Mode I loading is the most dangerous. And even, when we want to find out the stress field equations, we would develop the stress field equations for mode I. Then, followed by Mode II and Mode III, I hope you have been able to make the sketch with reasonable accuracy.

Then, we move on to Mode II, which is also known as a Sliding Mode. And, you could see here in this animation, this is the crack. And, the crack surface slides. There is a sliding in the plane. And, you call this as Inplane Shear Mode or Sliding Mode. The displacement of crack **surfaces** **is** in the plane of the crack and perpendicular to the leading edge of the crack.

And, that is very clearly seen in the animation. And, if you have the crack, the crack **surfaces** are sliding. They are sliding like this. You have the opening mode, you have the sliding mode and the third mode is it is tearing like this. It is out of plane shear. That is what, we are going to see. I hope you are able to make a sketch of this. You can make a reasonable sketch and what is shown here is, displacement of the crack surfaces of a local element containing the crack front. We are not shown the entire object. The external loading may be anything. We **are** only looking at what happens in the vicinity of the crack.

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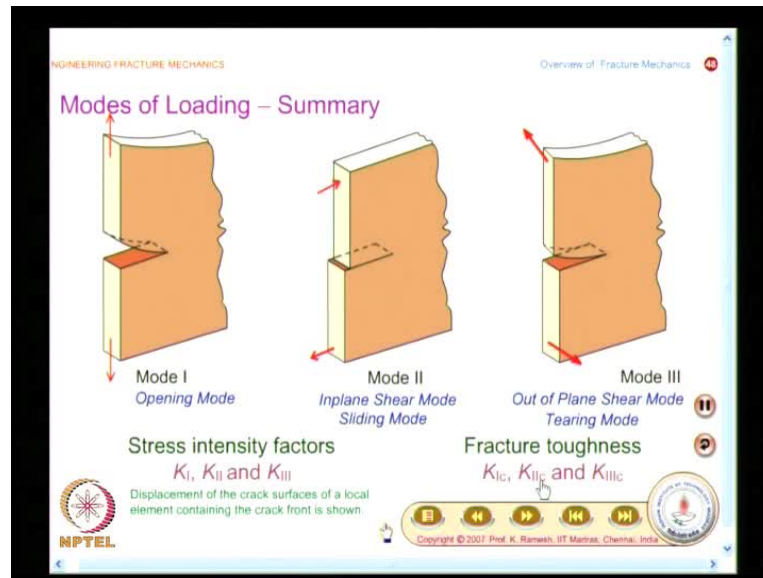


How the **faces** move, depending on that you label them as Mode I, Mode II or Mode III. In fact if you go for **bi-material** problems, apparently external opening mode can also cause a sliding of the crack **faces**. So, it depends on the problem. We are not looking at what is the external loading; we look at only in the near vicinity of the crack. This is the Tearing Mode also called as Mode III. And, you find the crack **faces** are like this. They move in this fashion. It is called as Out of plane shear mode. And, this is also called as Tearing Mode.

And, we have already seen, paper is usually separated by a tearing action. Because if somebody gives a sheet of paper and ask you to separate, you will not pull it like this. You will make a fold and tear it like this. And, that is much more convenient. And, paper fails easily by tearing action. And, one of the challenges in early understanding of Fracture Mechanics is, in a given problem of external loading. If you have a crack in that structure, what kind of loading exists near the crack **surfaces**, whether it is subjected to Mode I loading, Mode II loading and Mode III loading. In fact, one of your assignments gives a series of common design scenarios, where you have a structure with known type of loading with cracks located in various fashion.

You have to find out because of the external loading, whether the crack experiences a Mode I loading, Mode II loading or Mode III loading from Fracture Mechanics point of view. It is not trivial. You will have to **have** some kind of training.

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And, what is the summary? I said that you need to have, what is known as a stress intensity factor. Although, we may not define it now, you will know what it is. For each of these modes, similar to the stress concentration factor, you could identify what is known as a stress intensity factor, which dictates the strength of the stress field in the near vicinity. And, this is labeled as K_I . Do not read it as k_i . This is one of the common mistakes people do. You have to read this as K_I , read this as K_{II} and read this as K_{III} .

So, for a given loading, you find out what is the value of K_I , what **the value of K_{II} is** and what **the value of K_{III} is**. From a material test, you find out what is the fracture toughness for Mode I, Mode II and Mode III. And, they are labeled as K_{Ic} , K_{IIc} and K_{IIIc} ; the c denotes it is a critical value. And, this is considered as a material parameter. And, I had already noted. See, in the case of simple strength of materials, what did you do? when you had combined loading, you invented the concept of principle stresses.

And, you utilize the result from a simple tension test of the yield strength. And, you find out how the failure will occur in combined loading. You do only one test. So, similarly in Fracture Mechanics, when we go and look at fracture theories, even though we talk about K_{Ic} , K_{IIc} , K_{IIIc} , people find out K_{IC} and try to find out how well it can be utilized even to predict a combined mode failure. That is why; I said it **has** commonalities between your conventional strength of materials, as well as in Fracture Mechanics. Because we would like to practice, what we understand. And so, it should be simple

enough to practice. That is why we go in for it. We are not looking from a mathematical point of view that I need all these parameters, only then I will go and design. It is not the way design works. You have to find out a simpler procedure for you to implement it.

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ENGINEERING FRACTURE MECHANICS Overview of Fracture Mechanics

Fracture Mechanics should be Able to Answer the Following Questions:

- What is the critical length of a crack?
- For a given crack length what is the residual strength?
- What is the time that would take for a crack to grow?
- How is the NDT schedule decided?
- What causes the crack to branch?
- What are the energy dissipating mechanisms?

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So that, you are well within the limits and now we can ask, when I do a course in Fracture Mechanics, what are the answers that, I could get from Fracture Mechanics is the question that **when** ask. So, the first question is, “what is a critical length of a crack?” you cannot say, I will wait for the structures to fail and find out what is the critical length of the crack. You have to predict; that means you have to develop the fracture theory, you have to understand what way the crack will behave, you have to get the material parameter and you should be able to predict for a given type of loading and situation. For that structure, this crack is critical. And, there is another important point, which you **have** not noticed. See, when I had shown the modes of loading, I have taken only one crack. In the idealization what we said, in strength of materials you have idealize that, it is an elastic **continuum**, you found that there are no discontinuities or inclusions in the material. The moment, you have come to Fracture Mechanics, you recognize the role of inherent flaws.

When I say inherent flaws, I cannot consider only one. You will have many cracks in the structure. Later on as you develop the theory, you will realize, what we are really looking at is among these, whichever is the one, **which is critical, is a one**, which we look at in

our modeling. That is the way you can analyze it to start with. Now, you have studies, if I have multiple cracks how do they interact, which way you have to go about, what should be the reason for methodology, all those issues are being addressed to research.

So, the first question is, what is the critical length of a crack the second question is for a given crack length, what is the residual strength? Then, what is the time that would take for a crack to grow, and this is very important for you to answer the next question. The next question how is the NDT schedule decided? And, I already shown that, crack can branch. What causes the crack to branch. And, finally what are the energy dissipating mechanisms. So, this puts a focus, what you should be able to answer at the end of this course. If you are able to answer these questions, then you have reasonably understood what Fracture Mechanics is.

So, in this class, we started with severity of the crack indicated by Photoelasticity. I also mentioned, photoelastic contours are nothing but contours are σ_1 minus σ_2 . So, when we develop the crack stress field equations, it is possible for us to plot σ_1 minus σ_2 from analytical solution and compare it with the experiment and see whether our solution obtain is good enough. Or, do we have to take higher order terms. And, such questions have been answered by conducting experiments on Photoelasticity.

Then, we looked at historical development of what was the contribution of Inglis, what was the contribution of Griffith and how Irwin extended it. Then, we had a brief outline of how to classify LEFM and EPFM. And finally, we had seen some fractures in the case of glass and we raised certain questions that need to be answered as part of this course. Thank you.