Mechanical Behavior of Materials

Prof. S. Sankaran
Department of Metallurgical and Material Engineering
Indian Institute of Technology – Madras

Lecture No 49
Fracture Mechanics - I

Hello I am Professor S. Sankaran in the Department of Metallurgical And Materials Engineering. Hello, everyone welcome to this course and today we are going to turn our attention to the next chapter of fracture mechanics. For this particular subject I am going to follow this book E-book what you are seeing on the screen written by Professor K. Ramesh of Applied Mechanics Department in our institute.

And professor Ramesh himself is offering a full-fledged course on fracture mechanics in the NPTEL platform and it has been now running for many years and I urge all the students to do that course as well if you have a complete knowledge of fracture mechanics which is almost 50 55 hours of lectures almost a four credit course. And I decided to follow this book because this book is designed very specially with a lot of animations what you are seeing on the screen here by sir Ramesh who has done a commendable job.

And he is also my teacher and this is published by IIT Madras itself. So, I thought you know I will use this book for taking the fracture mechanics course in our department as well because the all these animations not only are beautiful and they also motivate the students to you know look at them and it creates a lot of awareness about the concepts and is very interesting.

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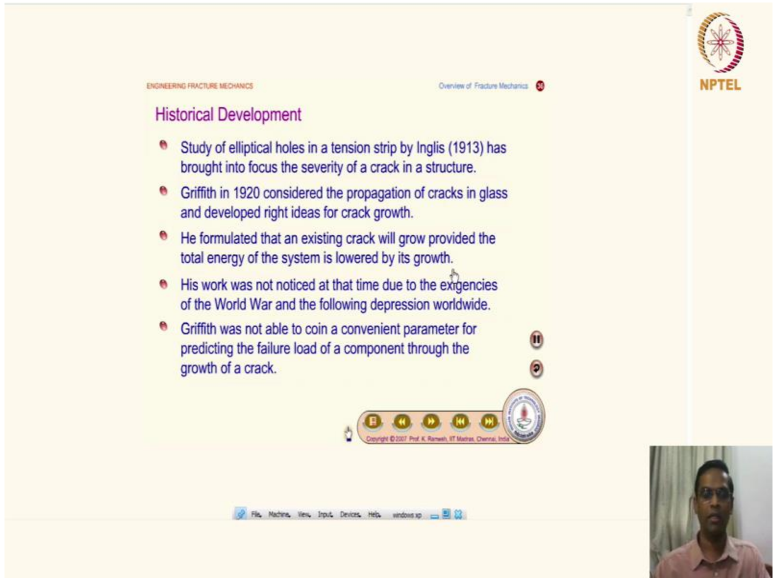

So, we will start this chapter by just looking at historical development. Study of elliptical holes in a tension strip by Inglis (1913) has brought into focus the severity of a crack in a structure. We are going to see the details of this what Inglis has proposed and but this is a one first event which is you know triggered the idea of severity of the crack. Then followed by Griffith in 1920 who considered the propagation of cracks in glass and developed right ideas for a crack growth.

So, this is again very important ok, after several years Griffith has you know developed some ideas for the crack growth. So, this is just a second event and he also formulated that an existing crack will grow provided the total energy of the system is lowered by its growth. So, this is something like what we do in thermodynamics like lowering the energy of the system but he coined right parameters to capture this idea. We will see how it is very interesting theory.

But 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. So, this is some of the initial struggle.

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But what happens is he did provide a good theory than before I mean and he coined that parameters for brittle materials like glass. So, what you are now seeing is a concept called healing of crack. What is healing of crack? You see this material shown in this animation, which is a non-metallic material which is being you know pushed by a ballpoint pen. So, what do you see there is an edge crack from the outer surface and then the moment the ballpoint pen hits on the plate and what do you see there is a crack growth or crack extension towards the inside of the plate. The moment that load is removed what you see again the crack is closing this is very important.

So, he Griffith's ideas were you know rightly captured in this kind of you know material he proposed a very nice balance theory for crack growth and crack closure as well. So, we will see how these ideas are developed. And this animation clearly shows you know it is a very simple a day-to-day kind of an activity in your workplace and then you know we do not bother how this crack is growing and all that but then if you pay an attention it is quite interesting to appreciate what the science behind it.

So, we will see one by one the next item is crack growth speed. It is a shadow photograph of a crack branching process in a plate of glass. So, I play this animation. So, what you see this is a crack is growing and then stopped here and then it started branching. But if you look at this animation carefully the crack comes with the speed and then it accelerates and then it stops and then grows. Note that increase in the crack speed beyond a crack speed is bad beyond the crack speed it branches.

So, that means at what stage a crack tend to branch this is again a very important question and Griffith has provided a very nice solution for us. We will see later you know the elaborate photoelastic analysis has predicted a crack cannot grow beyond a rayleigh wave speed. So, beyond that what happens and then why it branches and what is the science behind it, these are also some curiosity I mean it also a curiosity level questions.

So, we will be able to answer it during the course of the time. So now if you look at the branch fracture mechanics is a broad area covering several discipline like I mentioned in the beginning I know. This branch is being you know applied in different disciplines like Mechanical Engineering, Applied Mechanics, Engineering Design, Aerospace, Civil, Materials and so on.

But if you look at the in a nutshell which is connected to you know Material Science, NDT and the Stress Analysis and Design. How they are connected? So, if you look at the Material Science aspect then these this branch takes care of are the studies a fracture, fracture process and fracture toughness. So, these are all you know elaborately focused in this subject domain but what is this NDT do? That is non-destructive testing.

NDT takes care of crack detection. It is a how to find out the flaw size you know, how to identify the flaw and then the flaw size and then crack growth monitoring. You can also monitor as a function of time by NDT schedule and then important most important thing is again the stress field evaluation which is done by the other branches engineering branches.

And then damage tolerant design. What is damage tolerant design? you have inherent flaw all the structures will have an inherent flaw you measure them and then predict the life. How long this, what is the critical size of the flaw, how long the remaining I mean remaining life of the component or how long that will take to fracture something like that. So, that is called damage tolerant design. In that you have a safe like design or fail-safe design. So, there are two concepts we will see all of them.

In a fail-safe concept has different aspects again a multiple load path, design for crack arrest and then leak before break. So, we are talking about the you know design for a crack arrest, we are talking about there is a design you can do where the crack we are just seeing the crack closure, we can also see that some aspects which can give the crack arrest. And the next one is very important leak before break that means before the fracture your system should give a sufficient warning.

See if you like if you take a simple tensile test, say before the fracture happens you have enormous amount of yielding it goes through yield point and UTS and then fracture something like that. You have you know it is very important for the nuclear or power plant applications, you know without that these are all going to be very difficult. So, this is these kind of designs are useful and which is provided by this subject that is what we are going to see.

So, fracture mechanics attempts to account for existence of inherent flaws and structures and thus is closer to reality Modeling engineering problems. That is what I just said 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. You see the stress analysis comes out with a parameter called stress intensity factor we will see it is called K. Ok

So, all these stress intensity factors is evaluated by the stress analysis and the material science as I mentioned takes care of the fracture toughness measurements NDT initial process. Design for a given safe life is possible if the above mentioned three inputs are available. So, all these three are forming a primary basis for the design. LEFM and EPFM. What is LEFM? Linear Elastic Fracture Mechanics and Elasto-Plastic Fracture Mechanics.

We are going to see them also. What are they? Structures made of ductile high strength alloys failing in a brittle fashion prompted the birth of fracture mechanics. This is the bottom line why fracture mechanics becomes so important because people believe that a ductile high strength alloys which you cannot people never imagine that it will fail in a ductile fashion. So, then people started looking at them seriously.

So, linear elastic fracture mechanics which deals with extension of Griffith's ideas or ductile solids to ductile sorry, ideas for brittle solids to ductile high strength materials was done by Irwin in 1948. Though Griffith gives ideas for only brittle solids, Irwin extended those to high strength materials, you have to understand it is just only for high strength materials. The main focus of Irwin's theory is on the crack tip rather than the crack by moving the analysis to the crack-tip.

We will see why we are talking about a crack-tip here because initially the crack was you know crack length was measured and then the analysis started from the center of the crack. The moment the attention shifted from the center of the crack to the crack-tip that were quite you know the scenario was quite different, that is why it is mentioned like a crack-tip. Irwin devised a workable parameters like stress intensity factor and energy release rate very important.

So, we are now talking about parameters called stress intensity factor, I said that comes out of the stress analysis elaborate structure analysis. And also the new term, energy release rate this is another parameter which governs the crack growth, the energy for the crack to grow that describes, that description also we will follow now, which is all part of LEFM. LEFM accounts only for a small scale yielding near the crack-tip.

See Linear Elastic Fracture Mechanics does not consider the plasticity that is what it means right? So, it can only accommodate a small scale yielding which is close to the crack-tip. It cannot handle major plastic or yielding prominent then you have to go move on to Elasto-Plastic Fracture Mechanics. LEFM is quite useful for analyzing problems in the aerospace structures. So, far LEFM concepts only serving the full aerospace structures and if you look at Elasto-Plastic Fracture Mechanics what are the features.

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

If you see in the previous chapters we also looked at the polymer behaviour. We looked at the tensile deformation, we looked at creep deformation and how the visco plastic Models and all that we have talked about for polymers. So, here also you can see that LEFM can, I mean LEFM can be applied to this kind of polymeric material below TG and ceramics materials and ceramics composites and so on.

So, if you typical material for which EPFM or 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. So, it is quite obvious we have looked at all these parameters like we looked at room temperature deformation, we looked at high temperature deformation of where all these materials we in fact elaborately we also looked at the creep behaviour.

So, now you will have a nice background to appreciate whatever we are just mentioning here. So, what is the range of LEFM, EPFM? It is to be noted that fracture mechanics based engineering design looks at brittle failure of structures. The plastic zone is very small and highly localized and then how do you visualize this how do you visualize this plastic zone? So, if this is a nice schematic where the high strength material in a plane strained condition.

And you see the crack which is there and you can also see that high strength material in a plane stress condition. In these two scenario, LEFM is applicable where the plastic zone is very small and highly localized and you can see that I can just show it in a zoomed manner. So, you can see that very small plastic zone. Yeah, come back so and what is the next? More ductile material in a plane stress or plane strain condition.

And then you can see that the ductile material with the spread of plasticity, the plastics zone size is very big you can see that and in such a situation it is better to or the EPFM is highly useful. But in extreme cases for example you know the ductile material which is fully plastic that means the plastic zone is completely you know occupied the entire specimen then it is explained only by plastic perhaps.

None of these theories will be useful at that kind of a situation that is what it is. Now we look at Modes of loading. In fracture mechanics most of the analysis is done by three Modes. The Mode I is opening Mode, the schematic is nicely shown here where the; you can see that the crack surface, once it opens. Loading is normal to the crack surface and displacement of the crack surfaces are perpendicular to the plane of the crack.

So, one of the most common and dangerous loading for crack growth, so, we are trying to introduce what is more one basically or nothing more than that we will look at the details as we progress. We are only just introducing this. Mode II is called also called sliding Mode, loading is on the crack plate that is in-plane shear it is also called in-plane shear. Displacement of the crack surfaces in the plane of the crack and the perpendicular to the leading edge of the crack.

In many instances, the presence of Mode II loading is to alter the crack growth direction. So, we can also you know interfere the crack growth by adjusting the loading. So, this is one of the idea. So, the Mode II is also called Sliding Mode, Mode I is called opening Mode. So, what is the third one? Third one is tearing mode, Mode III or it is called a tearing mode. This mode is caused by out of plane shear. So, this is a shear stress direction and obviously the shear is out of plane.

So, you can see that and the displacement of the crack surfaces is in the plane of the crack and the parallel to the leading edge of the crack. Paper is usually separated by a tearing action see if you give a paper to somebody or if you want to tear a paper you intuitively you know you just tear it in the tearing Mode. We do not think fracture mechanics when we tear the, you know paper by naturally we do the tearing Mode.

So, that is what it is shown here. So if you look at the summary of all these three, it is Mode 1, Mode II, and Mode III. They are shown in this slide just to see the difference between the animations you can see that. So, like I mentioned the stress analysis will arrive at different stress intensity factors for all these Modes. And then the correspondingly in material science will evaluate a parameter called Fracture toughness K_{1c} that is critical stress intensity factor of Mode I or Mode I critical stress intensity factor.

Mode II critical stress intensity factor which is also called a fracture toughness in material science but yeah in a stress analysis we will term it as stress intensity factor to start with. So, this is a kind of introduction to Modes of failure. So, what the fracture mechanics should be able to answer? Fracture mechanics should be able to answer the following questions, what is the critical length of the crack?

So, we were talking about NDT monitoring. So, what is the critical length of the crack? For a given length what is the residual strength? So, you know the critical crack length then how long this structure is going to last before it fracture that is again a question. What is the time that would take for a crack to grow? So, in a crack you have two phases, a growth phase and then fracture, that we will see it. So, what is the time that would take for a crack to grow and that is also very critical.

How is NDT schedule decided? What causes the crack to branch? Just we talked about it right? What are the energy dissipation mechanisms? Very interesting questions, all these questions will be addressed by this subject. So, new test for fracture mechanics basically just to monitor the crack you see that this animation clearly shows this is a compact tensioned specimen where the notch is made and you see that the crack is grown by fatigue loading, basically ΔP is the amplitude of the loading and this there is a probe which monitors the crack growth.

So, the crack length is measured as a function of number of cycles to failure and this is for a different different amplitude you see and from this you call out a data that is da/dN versus log ΔK will give you a straight line. So, this is a crack growth plot. This equation is called Paris law

$$da / dN = C(\Delta K)^m$$

We will look at the details of this Paris equation and materials implications in detail in the later part of this course.

So, we are now looking at the overview and what you are seeing is here you know the when we talk about fracture mechanics, fatigue by default comes and comes into the discussion because you see whatever the discussion we had in the previous chapter, mostly we dealt with the deformation and from this fracture mechanics onwards, we are talking about the fracture. So, if you recall in the beginning of the course, we just showed the whole subject mechanical behaviour of materials into two domains.

One is a deformation another is a fracture. Now we are talking about fracture and this fracture mechanics by default the crack is I mean the crack growth is discussed because the fatigue crack growth is a primarily a mode of method to grow the crack in the material and then study this. So, they are all interconnected. So, you cannot really separate them, it is a fatigue fracture and fracture mechanics study. So, that is one point I just wanted to derive, drive home in this slide.

So, what you are seeing is a schematic representation of fatigue life showing the relative proportion of life for a crack initiation and propagation. You see this is the plot of Alternating stress range $\Delta\sigma$ versus log fatigue life. What you are seeing here is a very interesting plot, you will understand this more in the later part of the course.

But the point we want to emphasis here is the crack growth is essentially involves crack initiation period and crack propagation period. So, very important, if you look at the you know the as the stress range comes down the crack initiation period is keep on increasing to the majority of the life, what is important to note is the majority of the life of the component is spent on the crack initiation period rather than the crack propagation period.

This is something very important. So, that is why it is brought here and this is $\Delta\sigma_C$ is called fatigue limit. We will see it what is the importance of this fatigue limit every material is characteristic of I mean every material will exhibit a characteristic fatigue limit, we will see them in the due course. And there is something called a residual strength diagram which comes out of all these crack growth experiments.

And you have the service load and then you have a design strength which is a reference and then you look at the crack size how it grows and then what is the maximum service load and what is the corresponding crack length, if you have this crack load plot you will be able to get this. So, a_p is a permissible crack length. So, you look at a_p, that is a crack length which is against the σ_{max}, a_c is a critical crack length which is given by I mean which is related to a_p by

$$a_p = \frac{a_c}{N_c}$$

where N_c is a crack length safety factor.

And we will also see that you know how the crack growth curve will look like as a function of time crack size and then there is a time plot which looks like this and then you can also take this data as a function of time t_1 t_2 how the crack is growing and then time available for inspection the total life. So, this kind of idea will enable us to schedule the NDT tests and so on. This is kind of you know a real time practice in engineering structures or structural monitoring health monitoring of the equipments and so on.

So, what professor Ramesh describes is you know fracture mechanics is a holistic methodology something like in a you know in a medicine field Homeopathy does not treat the symptoms but addresses the root cause of a disease through symptoms and likewise fracture mechanics starts with you know premise that any structure can have internal flaws and it attempts to account for them in design.

So, similar to homeopathy, in fracture mechanics one finds different recommendation for handling thin structures which is considered as a plain stress and thick structures as a plain strain. So, what professor Ramesh's view is that in fracture mechanics you have solutions for a case specific, for thin specimen particular type of recommendation, for a thick specimen particular type of recommendation is given as a solution for the crack problems.

Further the process induced anisotropy is accounted for in the fracture testing and design. This is also another aspect to look at it. This slide is very important slide and which describes the fracture parameters, yes summary. What are the fracture parameters? *G* that is energy release rate or crack driving force which is the energy-based parameter proposed by Griffith. So, the G is after the name of Griffith.

And the next parameter is *K* stress intensity factor which has got a unit of MPa square root meter we will spend some time on this unit how to understand this later which is stress based and which is proposed by Keis a collaborator of Irwin. So, it is known that you know the *K* is after the name Keis a collaborator of Irwin just to honour him. And the another parameter is J, which is measured in N/mm called *J*-Integral again an energy based parameter proposed by J. R. Rice.

And the last one is CTOD or COD Crack-tip Opening Displacement or Crack Opening Displacement which is measured in mm which is a displacement based proposed by Wells it is basically from UK and what you see here is the first two parameters are applicable for LEFM and the later ones are applicable for Elasto-Plastic Facture Mechanics. So, very important slide to remember we are going to look at one by one in the course.

Now I would like to just to show some of the typical failures initiated by the crack. This is a helicopter blade retaining the bolt hole fracture. So, what you see here is it is a very nice fractograph. So, you can see that crack growth has taken place. So, it is a growth phase and this is a fractured surface. So, there is as I just mentioned in the previous slides that every crack has got a two phase, one is a growth phase and another is a catastrophic fracture.

So this is a very important and this crack is originated at a corrosion pit here and this is a real time you know fracture surface. The other typical example is it is called you know typical failures initiated by the crack is shown here this is a what is this cross section? This is a cross section of a ray. So, this is a crack but what is interesting is the crack is not initiated from surface usually fatigue cracks or further pattern any other cracks normally initiated from the surface but this crack is just initiated below the surface.

So, what does it mean how do we describe this crack is described as kidney because of the shape kidney-shaped crack or a detailed crack has initiated fracture of a rail section this has been a topic of study for the at least 20 years usually the older rail sections are found to fade by this. So, what is the how do we understand this. So, rail failure means it is basically through the contact fatigue right it is not a surface.

So, any contact loading the fracture does not you know occurs on the surface it is just below the much below the surface. So, this also will be explained by fracture mechanics nicely. Why a crack you know occurs much below the surface when it is a contact loading. So, stress analysis clearly says that the stress concentration is not to the surface but much below this. So, we will also look at it later.

So, this is one example of very contact fatigue loading. So, the other one is a failure of a bolt due to hydrogen embrittlement, cracks have initiated due to stress corrosion cracking at two sides. So, this is a bolt. So, you are seeing a crack one which is grown here the other crack is here which is grown from this surface. So, there are two cracks they are all emanated because of the stress corrosion cracking.

In fatigue failure, normally the first or the second thread fails here the failure has occurred a few threads below due to stress corrosion cracking. So, it is not just a stress concentration alone it is also because of the chemical attack combined. So, called stress corrosion crack this also we will see it when we discuss the crack growth mechanisms. This is one of the crack growth mechanisms popularly known. This is another example of you know inherent flaw in the aircraft engine crank shaft.

So, the flaw shape could be modeled as an elliptical crack. So, this is a track which is you know shape up here is the elliptic ellipse. So, just to give a visual impression. So, this animation time. So, this is an example from the aircraft engine crank shaft. So, these are the crack propagation from a circumferential group of a shaft under torsion. So, we are now looking at a different type of failures this is under torsion.

You can see that how the crack propagated. The crack growth pattern in a shaft subjected to low amplitude Mode III cyclic stress intensity factors. The growth pattern in a shaft subjected to high amplitude Mode III cyclic stress intensity factor. So, all of them are characterized with the what type of you know mode of failure and then what type of stress intensity factor has been recommended for evaluating this kind of a failure.

So, this is one example another example I just wanted to show. So, this is a photoelastic visualization of crack-tip stress fields just to give what kind of a stress distribution in the crack-tip we were talking about crack-tip. So, anyway we are not going to discuss them in detail but this is just to give you an idea how photoelasticity visualizes the crack-tip stress fields. We will discuss about the stress fields but we will not get into the photoelasticities one.

But it gives you an overall you know very nice visual impression about this stress distribution around the crack-tip. So, I will stop here and we will continue the lecture in the or the overview lecture in the next class, thank you. **(Video End: 39:57)**