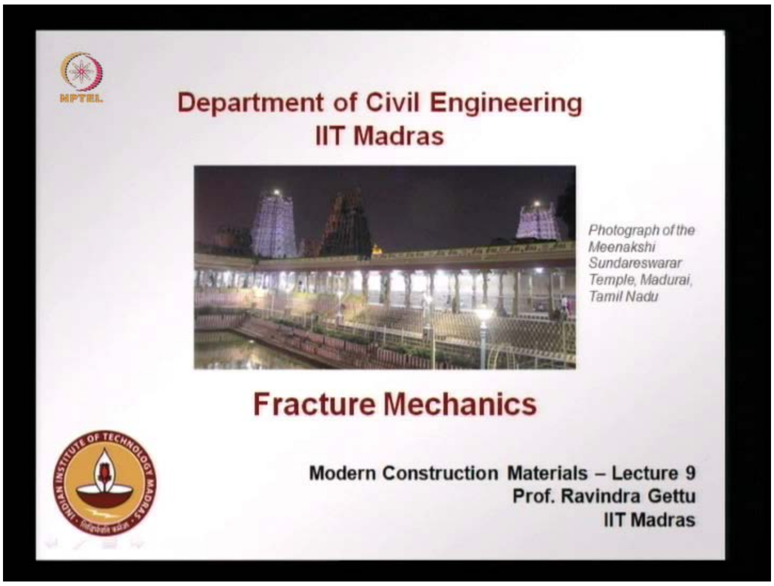
Modern Construction Materials
Prof. Ravindra Gettu
Department of Civil Engineering
Indian Institute of Technology, Madras

Module - 03
Lecture - 09
Fracture Mechanics

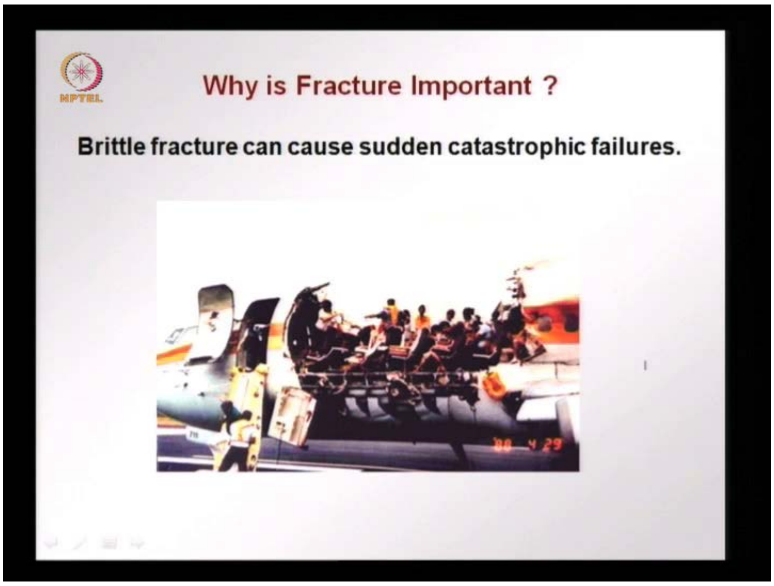
Welcome to lecture number nine of modern construction materials. Today we are going to talk about fracture mechanics, and fracture mechanics is important because lot of materials fail in brittle manner. And when defects occur in them then things get worst, these decade defects propagate into cracks and you have sudden catastrophic failure.

(Refer Slide Time: 00:40)



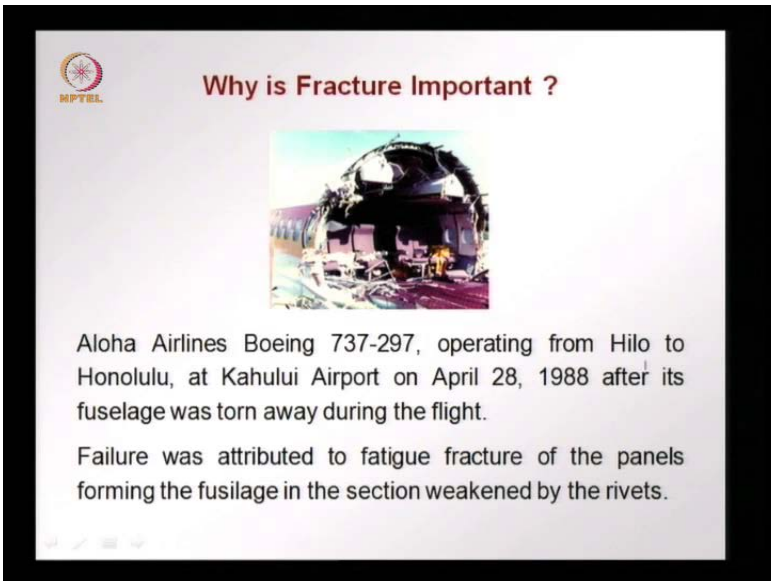
I start with this picture of the Meenakshi Sundareswarar temple in Madurai, which is about 600 to 800 years old and that most of it is made out of granite. And around this temple tank we have many, many, many columns of stone some of the stone column have started to crack, and they are being replaced and this cracking is due to settlement of the ground around pan and many other environmental factors.

(Refer Slide Time: 01:12)



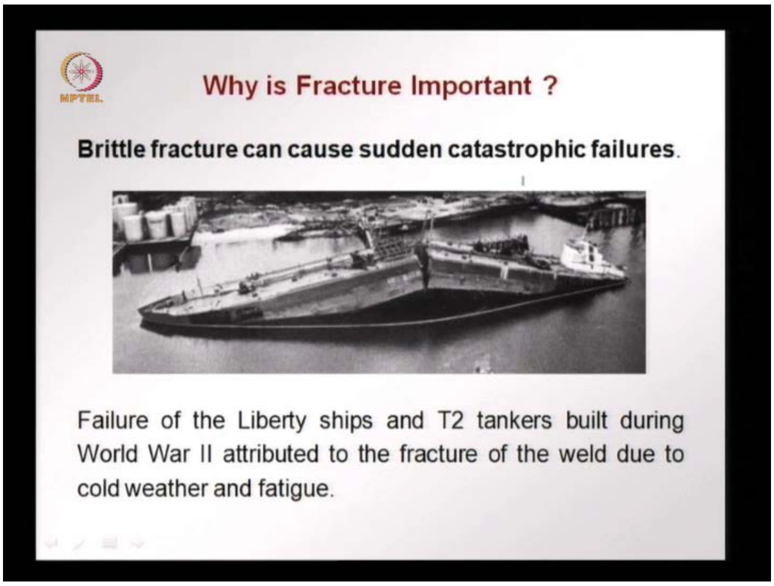
What else can fracture cause? Brittle fracture can cause sudden failure as we see in this picture. The cracks occurred in the fusilage of this plane, while it was being, while it was in flight and part of the fusilage ((Refer Time: 01:32)), most of the people surprising the survived, because they had the seat belts on.

(Refer Slide Time: 01:40)



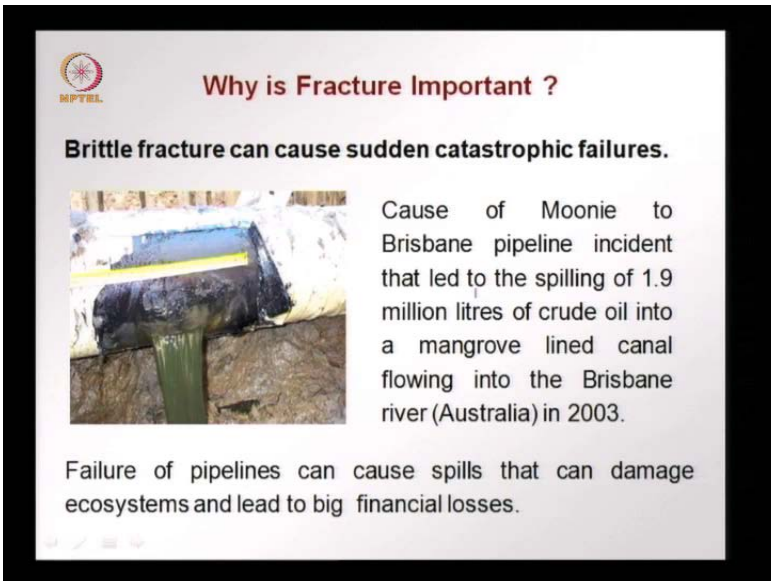
What happens was in this Boeing 737-297 that was flaying in Hawaii was that a crack propagated along the section that was riveted. After many flights due to fatigue loading defects had started to propagate along the circumference of the fuselage, where it was riveted. A crack suddenly developed and the fusilage was stone away unfortunately some people were killed during this accident.

(Refer Slide Time: 02:18)



Another case that we already discussed is that of the failure of the liberty ships and some t two tankers that were built in world war two and similar behavior also happen in the titanic and what they say happened to the titanic when it sank here the wild that was used due to the cold weather and fatigue became brittle and a crack propagated this is what was seen in one of the ships in boston harbor crack developed suddenly this ship broken to two.

(Refer Slide Time: 02:59)

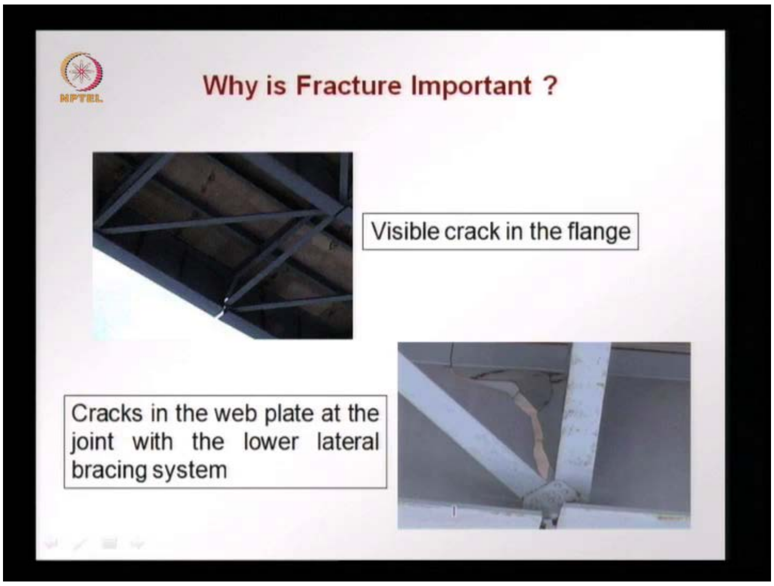


Brittle fracture can occur in smaller levels smaller scales, but with disasters consequences, but like in this case of a pipeline failing in australia with select to the spilling of about two million liters of crude oil causing a ecosystem damage in the mangrove lined canals flowing into the brisbane river in two thousand three huge financial loss and huge the ecological loss.

(Refer Slide Time: 03:29)

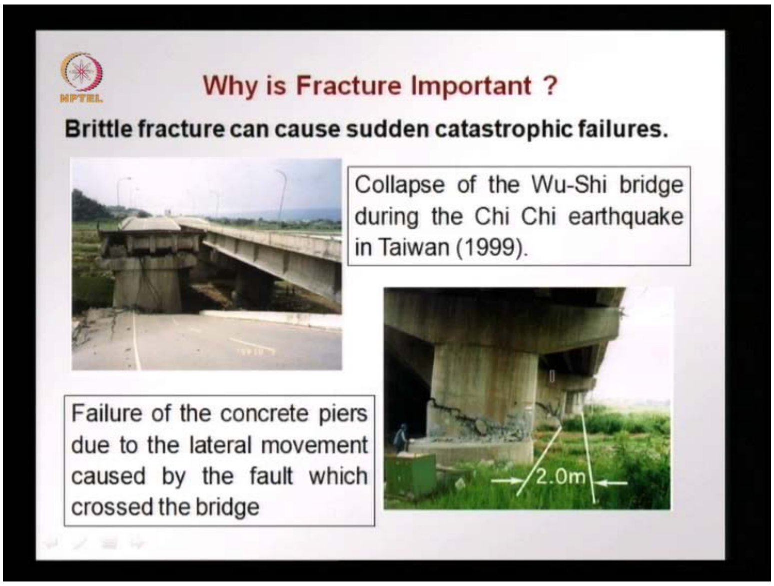
Another very interesting case of catastrophic failure occurred in two of the three steel griders of the hoan bridge in milwaukee the u s in the year two thousand and here generally ductile materials such as steel due to the triaxial constraint that was brought about by the the bracing system led to brittle crack propagation instead of ductile failure which was consigned. So, much it was constraint. So, much that the material could not yield, but failed due to.

(Refer Slide Time: 04:06)



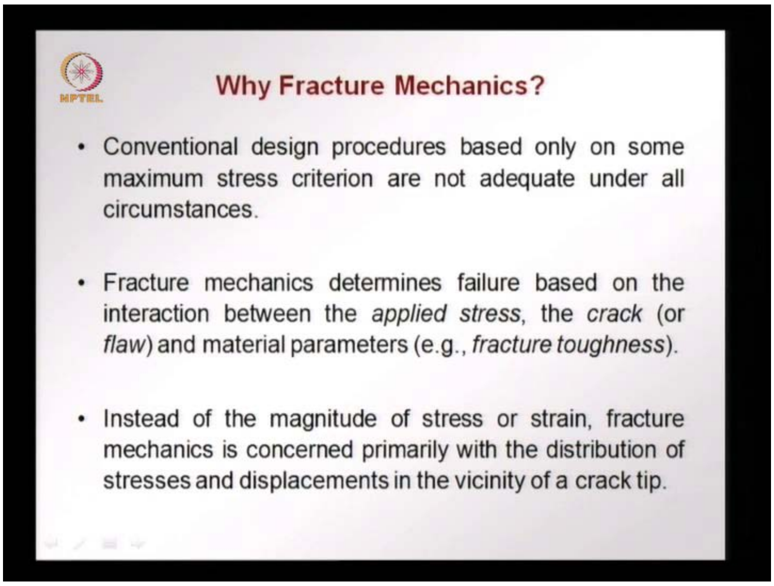
Brittle crack and these are some of the cracks that you see in the flange and in the plate this occurred over a period of a few hours and the bridge was then made unserviceable.

(Refer Slide Time: 04:21)



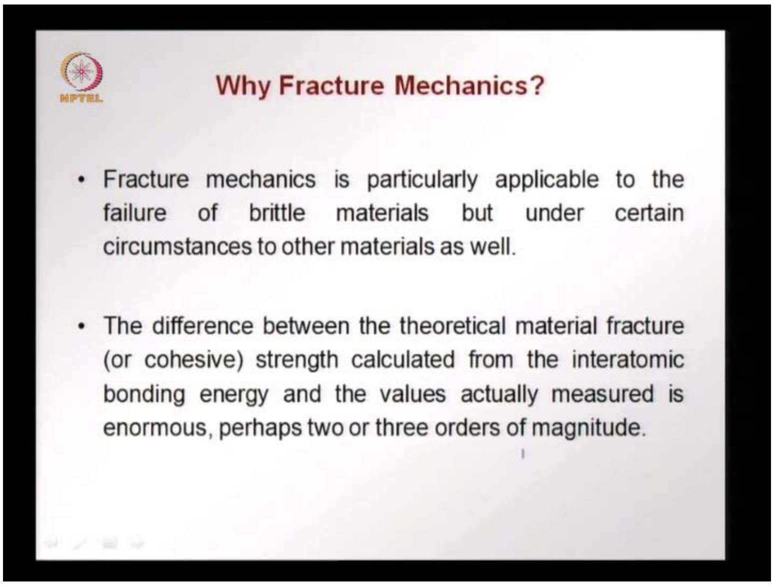
More brittle materials are more proven to fracture these are pictures of the wu-shi bridge during the chi chi earthquakes in taiwan in nineteen ninety nine where they there was the fault very near the bridge and the bridge and a lot of lateral loads resulting in severs cracking of the superiors of the large movements about two meters that this was not designed for and the concrete though it was reinforced fail by cracking. So, why fracture mechanics.

(Refer Slide Time: 04:58)



What is different about fracture mechanics conventional design procedures that are based on maximum stress criterion are not always adequate failures theories and concepts that we discussed in the previous two lectures always considered a material free of defects and free of discontinuities fracture mechanics now determines failure based not only on the applied stress, but also on the crack or flow that is presence and brings in new material parameters like fracture toughness and instead of just the stress or the strain limits instead of the magnitude of the stresses strain which are very difficult to determine or very high values in many cases near the crack tip fracture mechanics is concerned primarily with the distribution of stresses the stress feels and the displacement feels in the vicinity of the crack tip.

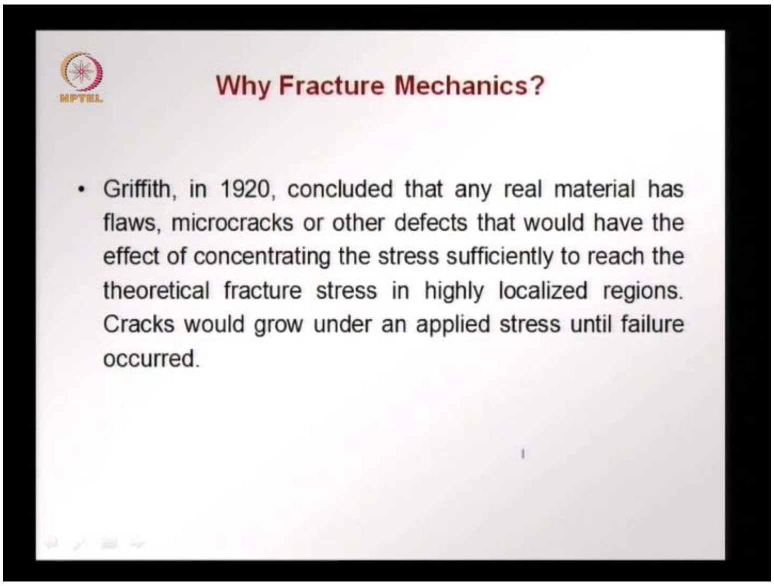
(Refer Slide Time: 06:04)



This is particularly applicable to brittle materials like concrete rock glass ceramics and. So, on, but and a certain circumstances are the materials also fail in a brittle manner like we saw in of the examples of the pipes and the grades fracture mechanics also helps us understand why there is such a larger difference between the theoretical material fracture strength that we can calculate from the bound energy in other maybe look at the quantum most diagram linking the energy with the entire atomic distance there was a bonding energy and we could also see what happens to the is bonding energy has the distance between the atoms changes. So, if we are to calculate the strength of the material from those values a bond energy we would find that that is much much higher than what is actually measured in the lab on a material rockabilly two to three orders of magnitude higher. So, there is a big difference between the actual strength and the.

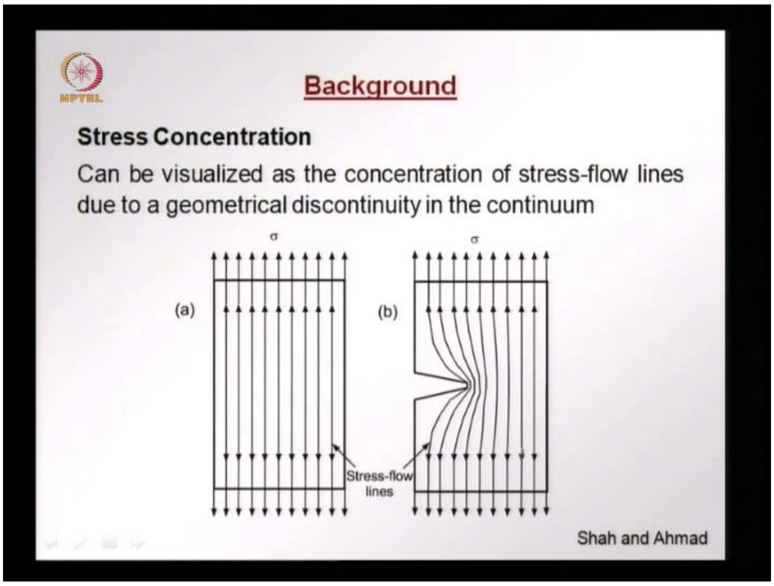
Theoretical strength the actual strength being much lower than the theoretical strength.

(Refer Slide Time: 07:19)



The reason for there is was categorically state and by griffith in nineteen twenty when you concluded that any material any real material is flaws micro cracks or some other defects and these defects concentrate the stress. So, much that the theoretical fractures stress is reached in small points small locations in small areas localized around these defects. So, has the theoretical fractures stress is reached at those points the cracked start to propagate even though the applied stress is less than the theoretical fractures stress and finally, fracture occurs.

(Refer Slide Time: 08:10)

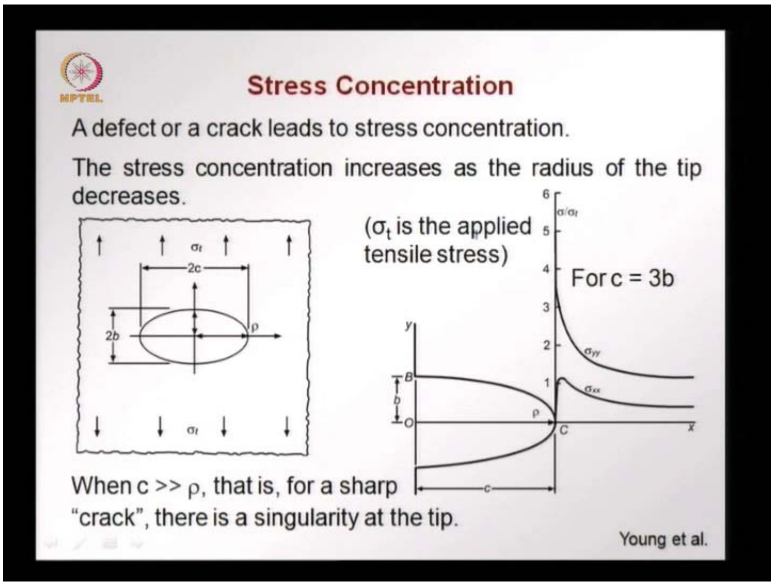


Now, let us try to visualize how stress concentration is induce and for this we look at simple diagram on the left we have a panel subjected to tensile load. So, these are applied stresses sigma outside the panel now imaging the channel with water flowing it.

so these lines would then be the streamlines water is flow similarly we can visualize in the case of a panel under stress that these would be the stress flow lines the stress as to go from one hand to other through the body. So, these are can be called the stress flow lines going back to the channel with water flowing example think of what will happen if you put your hand at one of the adjust you put table and into the flowing water and what would happen you would have know water moving faster along the edge of your hand because you have blocked a part of the flow and you'll find some currency recurrence forming around the edges. So, there is concentration of flow there is a faster flow occurring at the edge of your hand because your blog part of the channel now coming back to a stress example a similar thing happens suppose i have this panel and i make a continuum. So, i decrease the section i forces the flow of stress to go around this cut that i made or a that i have made. So, here you have zone of stress concentration. So, this stress concentration

occurs at here and we find that the stress here can be actually much higher than the stress applied for a way from this defects of power feel stress this stress now can reach at a small area that the theoretical fractures stress even though the stress applied or away for much less and this causes the propagation of the crack next things was higher stress concentration and the failure continuum. So, stress concentration can be visualized as a concentration of stress flow lines due to some geometrical discontinuity in the continuum so.

(Refer Slide Time: 10:47)

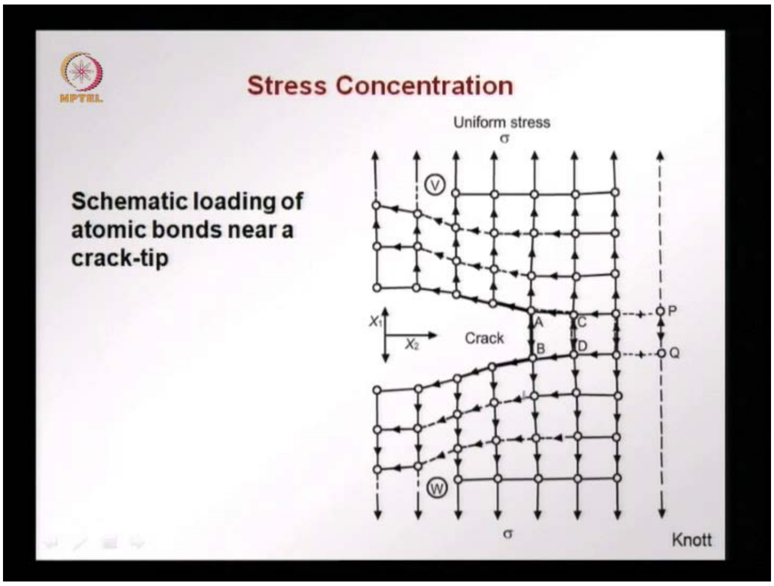


There are lot of the equations with described the stresses that form around defects we can look at the case of an elliptical defect or wide in a plate say and infinite plate subjected to a tensile stress sigma's of t you have now it defect or a crack insight and this defect is now we are assume in the form of net often ellipse defined by a length of two c a width of two b the radius at the end is rho. So, let us see what happens to the stresses in the vicinity of the crack tip. So, we go here this is now the.

Crack tip with semi length of case semi length of e this is as i told you the radius of the crack tip and if we considered a case of c equals three b as solution given in young we find that the stress in this direction in the direction of the pole caused by the applied stresses we find that at the crack tip this stress is almost five times the stress applied the x axis here we have sigma which is the stress at any point divided by the applied stresses sigma of t this is the sigma y y and this is sigma x axis this direction. So, we find the sigma y y is amplified almost five times at the vicinity of this defect tip sigma x x of also is quite high in for away sigma x axis and

sigma y y will becomes smaller near the crack tip you have very high values and what we see is that if the defect become sharper and sharper is that these c becomes very large compared to rho the radius that is for a defect that is very sharp tending to be a crack this stress now reaches infinity in the theoretical stress that is there is the singularity of stress in the cutinuum the crack tip stresses become singular

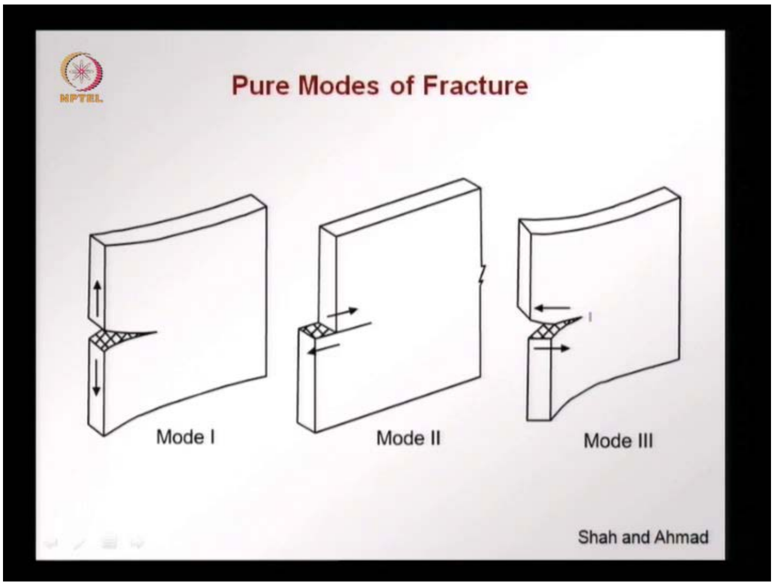
(Refer Slide Time: 13:22)



So, this can also be understood by looking at the lattice or that atomic bonds near the crack tip we have the far stress that is sigma that is applied for way from the defect are crack now the stress you have to go around the crack tip like we saw in this stress flow diagrams and it will happen is that the bond which is nearest to the crack tip of forms the crack tip will be very highly stressed lot of stress goes through here the stress here now is much more than sigma and this reaches point of failure. So, this bond breaks and then the crack now as advanced by one lattice plane and next the stress will.

Be taken by this bond c d and. So, on. So, this crock now keeps propagating through the body this is the reason why even though when you have a stress that is applied which is smaller than the theoretical fractures stress failures stress you have failure because the bond that are near the defect tip take very high stresses and start failures one by one.

(Refer Slide Time: 14:34)

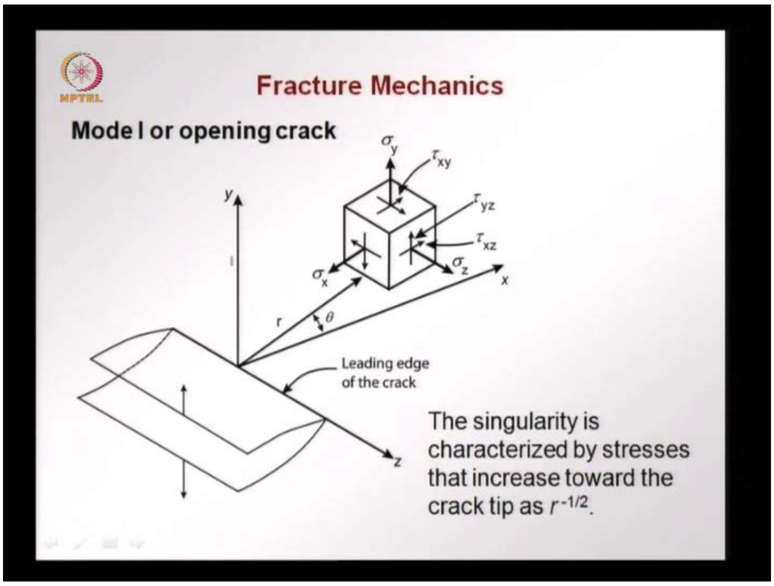


There are different ways that are fractures can occur and the three pure modes into which all the other modes can be put into or mode one where we have tension or opening mode this is called the opening mode wherever you have a crack cheese propagating due to tensile stresses. So, something is opening this your pooling on either side and the crack open this is the most common mode of failure of most materials due to tension

crack develops when the perpendicular to the applied tension and you have failures now than this is the sharing mode way you have in plane shear we have a case where we are propagating a crack by shear this is not wearing common one example what you would have seen in a direct shear stress in your soil lap when you did at a test on a rock joined or in over soil where two size of the material or slept to with respect to each other which are shear and a crack forms here along the shear plane without much opening. So, this is called in plane shear this as applications the earthquake engineering where there has slipping of joints mode three is called that tarring mode this is out of plane shear where you have something tearing when you tear piece of paper material now covers and you have sharing occurring out of plane. So, there is some torsion here occurring. So, these are the three principle the modes is most common is mode one most of.

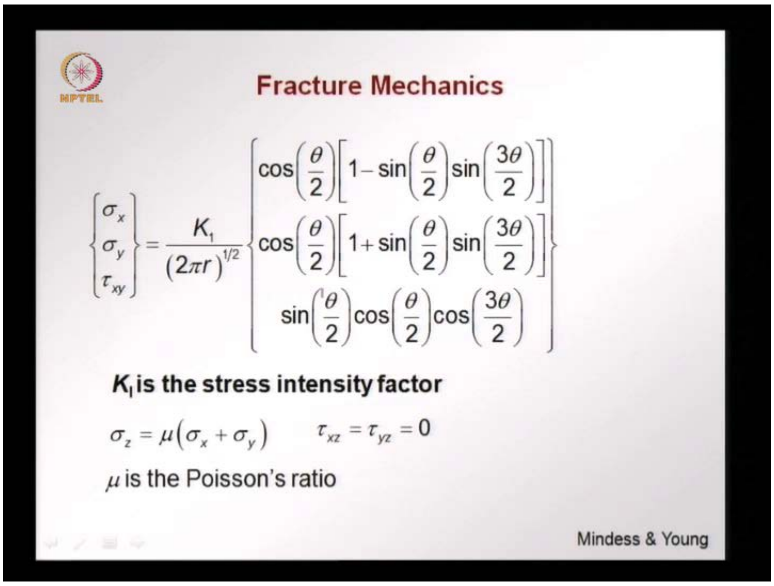
Materials that we consider failing in mode one of the tensile mode with an opening crack let us look.

(Refer Slide Time: 16:50)



|More in detail in what happens in mode one or for an opening crack what we can imagine in now we have a crack a sharp crack and let us see what happens in front of this crack. So, this crack is the advancing this way and if we look at the stress state of point tired of the crack tip defined by the distance from the crack tip or an a angled theta we would find that the stresses become infinite as it approaches as we approach the crack tip and this increases the stress is defined by the factors r to the power of minus one half. So, there is a singularity the stresses the stresses increase as r to the power of minus one half increases. So, when r become zero the stresses become infinite that is why it is called a singular stresses and.

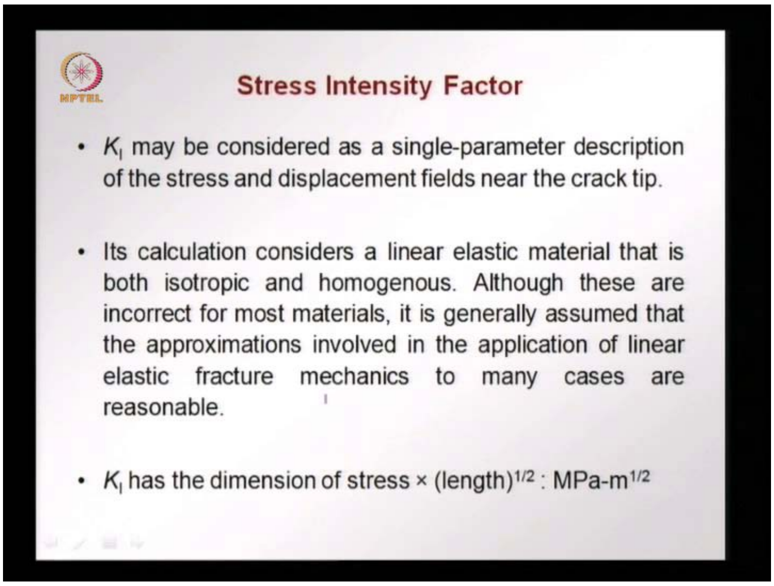
(Refer Slide Time: 17:56)



The equations for this r given here by we are sigma x sigma y and tau x y stresses i head of the crack tip the point that.

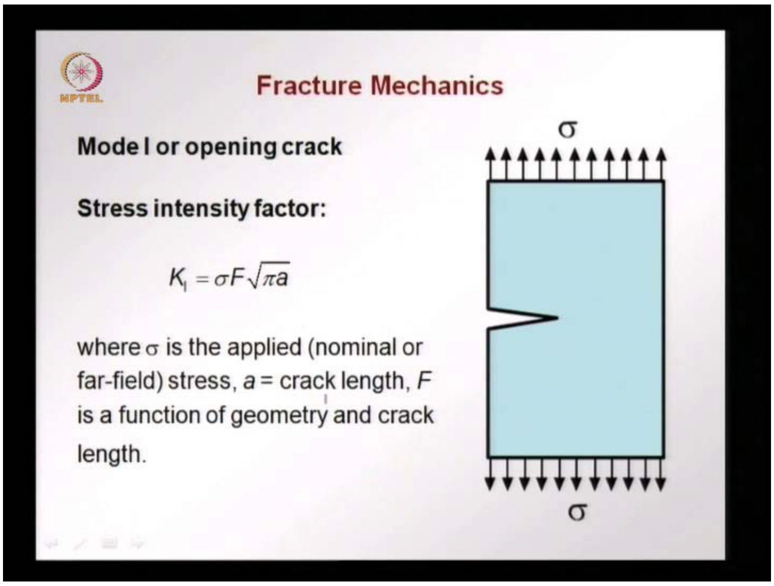
We are discussing is defined in terms of r being the distance from the crack tip to that point theta being the angle from the crack plane and what we find here there is we have a term here which is K 1 K 1 being the stress intensity factor divided by two pi r to the power of one r and here you see the term r to the power of minus n one half coming in for the stress singularity has r becomes smaller as we approach the crack tip these values become larger and larger and then r becomes zero these stresses become infinite the other stresses in this case would be tau x tau y is equal to zero and sigma z the stress perpendicular to the plane would be nu time sigma x plus sigma y nu being the stress what is important here is that we have introduced the term K 1 K 1 for the mode one which is the stress intensity factors this is one of the terms that we will continue to give a importance as we discuss fracture mechanics.

(Refer Slide Time: 19:28)



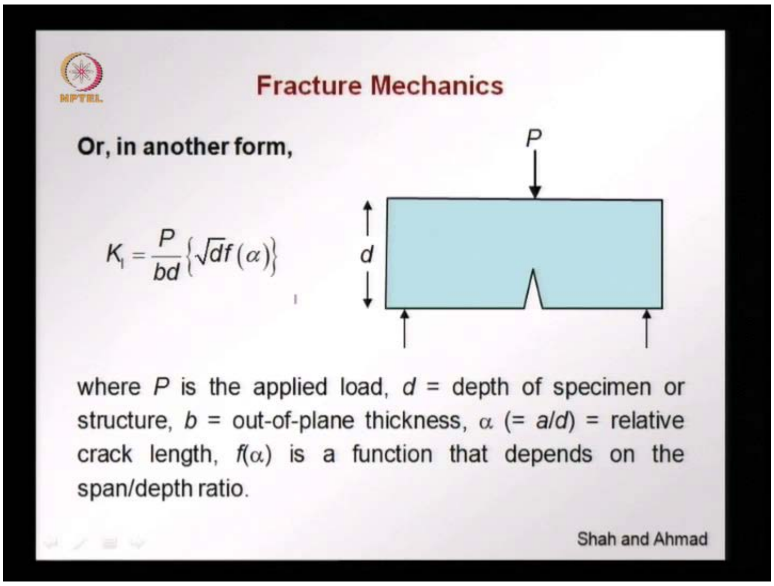
K 1 can be considered as a single-parameters describing the stress and the displacement feels near the crack tip. To calculated, we generally consider the material to be linear elastic and both isotropic and homogeneous that is the properties or uniform and the material is behaving in a linear elastic manner, even though it is fracturing. This has limitation in it can be incorrect for many materials, but generally we assume that the approximations involved in the application of linear elastic fracture mechanics is reasonable, we get reasonable values, and we can use these values and modified them later to bring in other nonlinearities. K 1 has the dimensions of stress time the square root of length such as megapascal square root of meter.

(Refer Slide Time: 20:24)



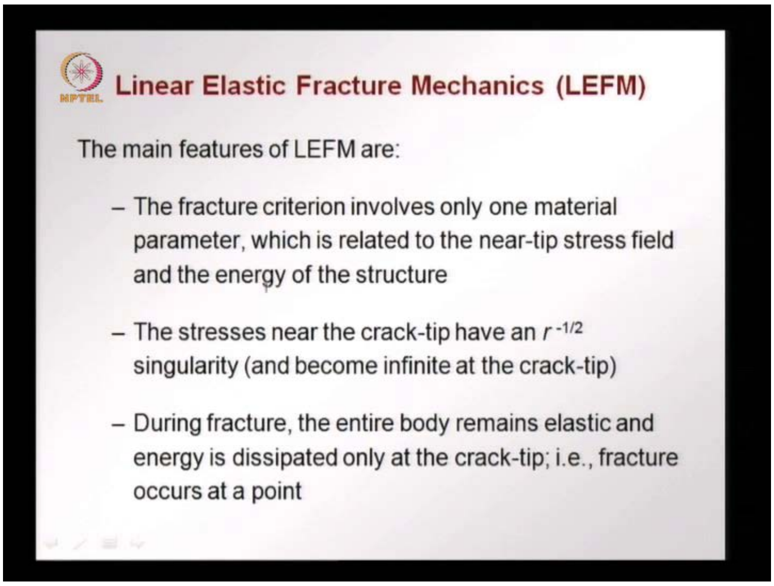
How we can apply or calculate K 1, say we have panel here with a certain crack of a length a, and we have a far-field stress applied a sigma. K 1 will then be is equal to sigma, which is they applied stress times F which is the function of the geometry, say the ratio between width and the length and crack length times square root of pi a; a again being the crack length. Through test of this type of element, we can get K 1, we can find out when failure occurs that would be the critical value of the K 1. And if we know this, we can calculate K 1 for any applied sigma and a.

(Refer Slide Time: 21:11)



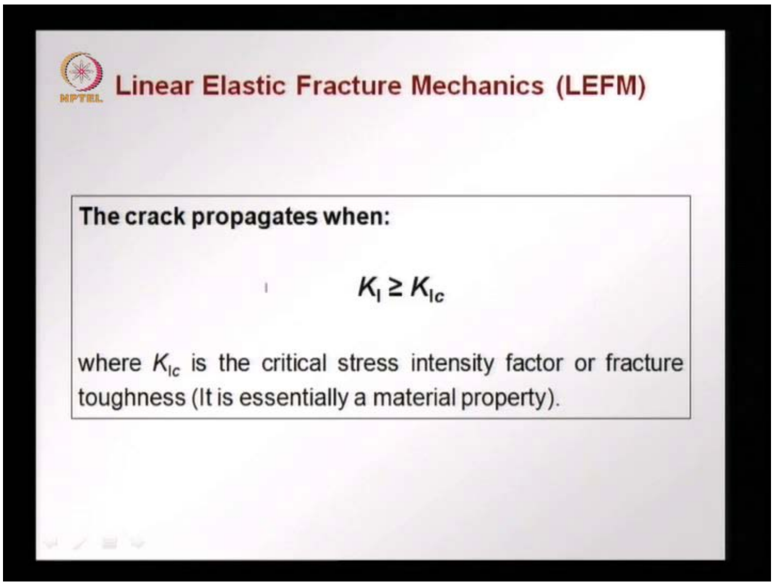
In another form, suppose you have beam, we can put K 1 in form of load P is the applied load, again we have a beam now with a certain depth, and a certain width - b is the width of the beam - the thickness of the beam, d is the depth of the beams. And K 1 could be put in the form of P divided by bd times the square root of f alpha. Alpha being the a by d ratio or the relative crack tip depth ratio, this is a, this is now a and a divided by d is alpha; f alpha is a function that depends on the span depth ratio. This is now this span, this span depth ratio defines this function f alpha and this can be calculated from numerical analysis not otherwise. So, K 1 can be determine depending on the geometry of the element and the defect length of the crack length.

(Refer Slide Time: 22:19)



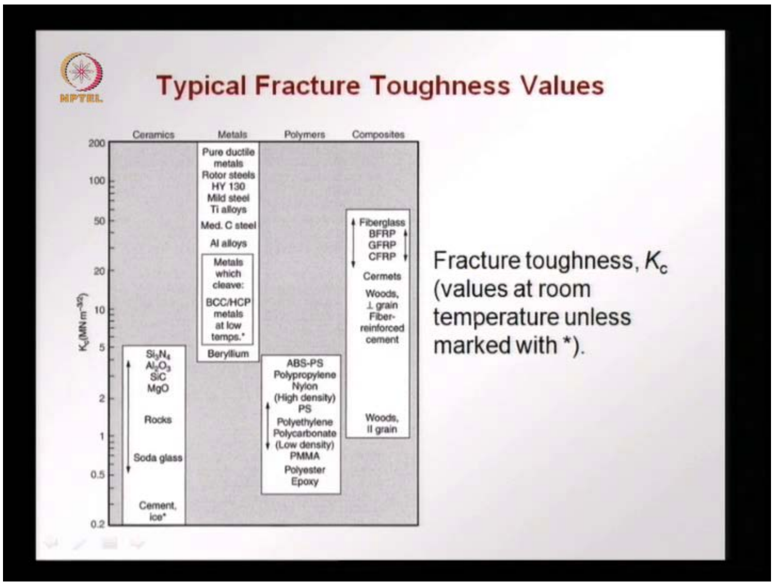
Until now, what we will discussed is called linear elastic fracture mechanics or a LEFM. The main features to summarize are that the fractures criterion involves only one material parameter, which is related to the near tip stress field and the energy of the structure. The stresses near the crack tip have an r to the power of minus one-half singularity and become infinite at the crack tip. During fracture, we assume that the entire body remains elastic and whatever energy is dissipated during fracture occurs only at the crack tip that is fracture occurs at a point, which is the crack tip. These are the main features of linear elastic fracture mechanics. These are limitations cannot be applied all materials and all situations.

(Refer Slide Time: 23:17)



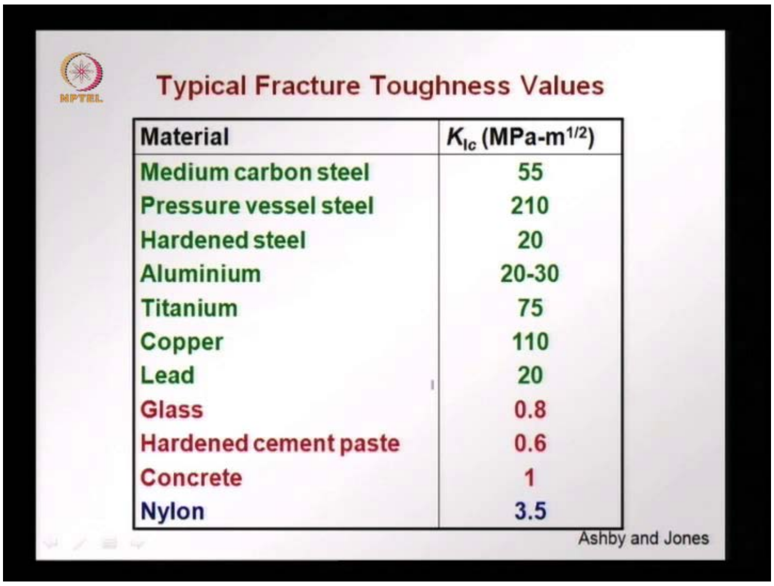
In this framework, when do we considered the crack to propagate. Crack propagation according to linear elastic fracture mechanics occurs when K 1 is greater than r equal to K 1 c. So, this is the fracture criterion. K 1 if you remember comes from the geometry of the element, the stress applied or load applied and the defect. K 1 c is the material properties; it is a material parameters called the critical stress intensity factor or fracture toughness, it is a material property. So, on the right side, you have a material property; and the left you have a parameter which depends on the load that you applied, the type of the structure and the defect that it has when K 1 increases and reaches the value of K 1 c or surpasses the value of K 1 c, the crack starts propagating. So, this is the failure criterion according to linear elastic fracture mechanics.

(Refer Slide Time: 24:27)



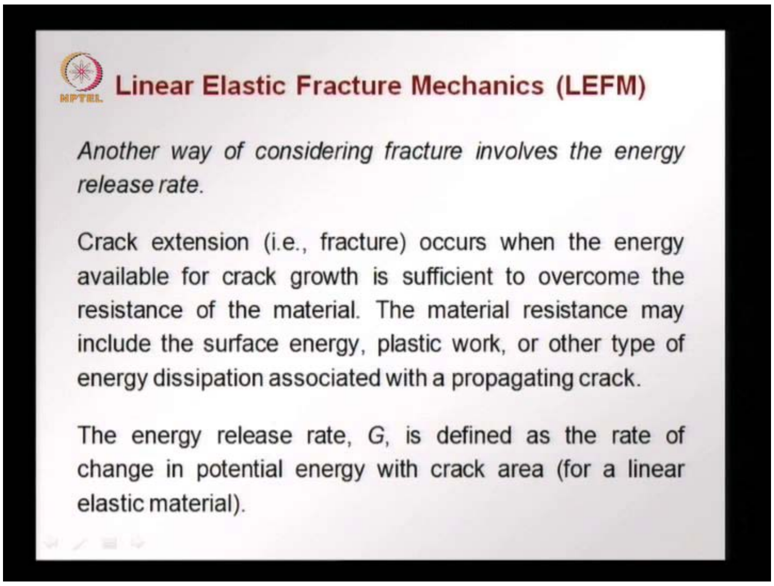
We can look at a tabular values of fracture toughness, we see that the values of materials that we always think of as brittle like glass, cement, ices, rocks, other ceramics are lower the fracture toughness is low, so that is why these material crack rather than yield. On the other hand, we have metals, ductile metals, the pure metals the most ductile right of the top, where the fracture toughness so high that these materials always yield, and they do not crack or rupture. Again and the bottom, we have materials like epoxy, which are very brittle; slightly higher of would be other polymers which are not so brittle like polypropylene and nylon. In the middle, we have composites and wood. Wood again parallel to grain, cracks more easily that is the grain separate we look at the this again when we talk about timber. Perpendicular to the grain there is higher crack resistance the fracture toughness is higher composite’s which are polymers reinforced different types of fiber or more at the top moron fiberglas fibers carbon fiber reinforced polymers.

(Refer Slide Time: 26:01)



Some materials that we can deal with in civil engineering are listed here we have like we said before higher values of fracture toughness for metals pressure vessel steel two hundred and ten mega paschal square root of meters copper hundred and ten and. So, on. So, metals have relatively higher fracture toughness value and if you see here the more brittle materials as much lower almost two orders of magnitude load over glass cement peace concrete and very low fracture toughness value. So, the crack more easily and well and they go brittle failures nylon for reference here would be intermediates slightly higher than these brittle materials, but still not comparable to those of metals .

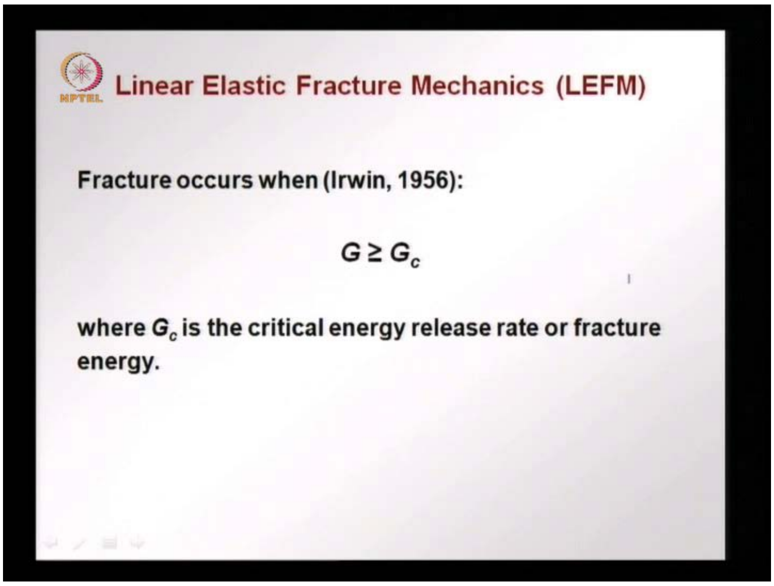
(Refer Slide Time: 27:03)



Another way of considering fracture involves the energy release rate instead of K 1 which is the stress intensity factors we can look at fractures mechanics in terms energy release rate whenever a new crack is form surfaces form and for this we required in energy. So, all crack tension requires energy to be available for the crack growth this energy should be

sufficient to overcome whatever resistance that comes from the materialist itself and this material distance can come from the use energy is going to be create plastic work for the work that was goes into the yielding and any other type of energy dissipation right heating nonsense on a that is some form of energy that accompanies a crack we define what is called the energy release rate is the rate of change potential energy crack area design what is the rate of the can change the potential energy for every unit crack area to be create this again for a linear elastic material.

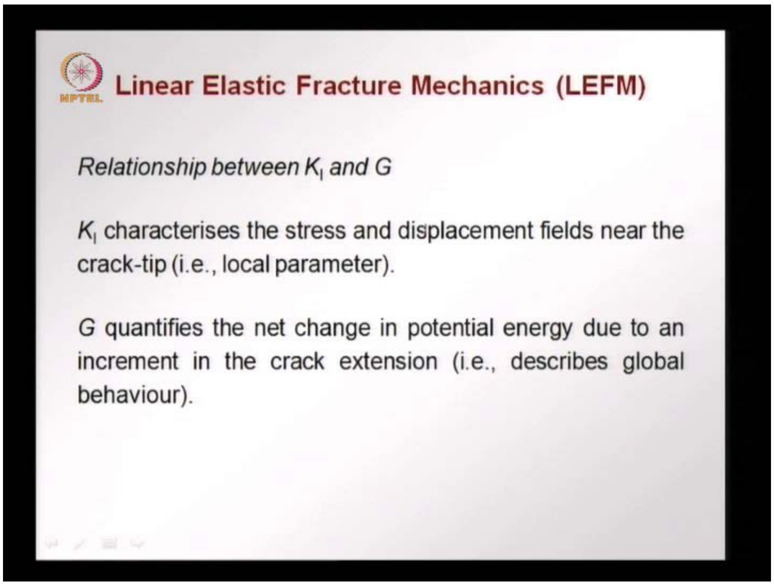
(Refer Slide Time: 28:22)



What even found in nineteen fifty six was the fractures criterion could be given in this form where g is the energy release rate this now depends on the stresses are load applied and the body the shape of the structure shape of the element and the defects this as to be a greater than or equal to a material parameters critical energy release rate are the fracture energy. So, this is also could be.

Ah failure criteria that these two failure criteria that you seen greater than one greater than eight is equal to K 1 g g greater than or equal to g c or not independent was found.

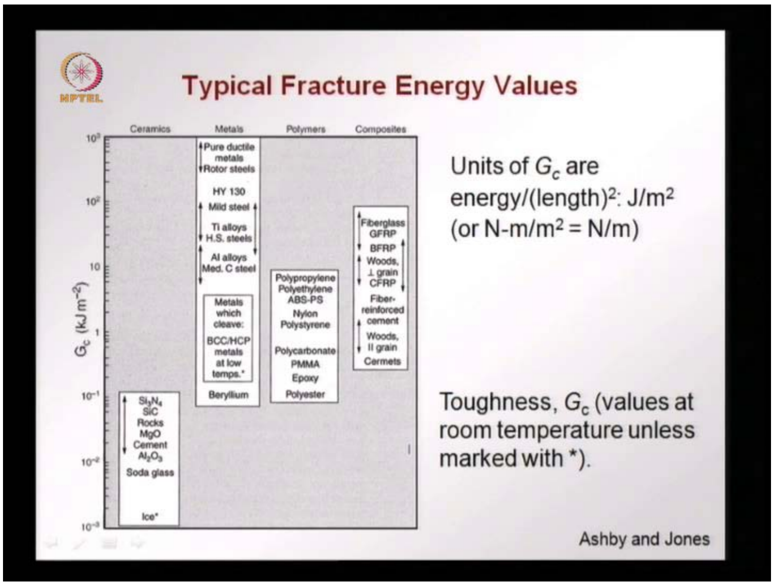
(Refer Slide Time: 29:08)



That K 1 characterizes the stress and displacement feels near the crack tip which is the local parameters we look at the what happens near the crack tip and g which quantifies the net change over the body how the potential energy change this due to this track extension which can be described as a global behavior are relating that k and g K 1 and g or relativity and in nineteen fifty seven to ensure that there is a unique relation between K 1 and g g is equal to K 1 is square over e prime. So, what we look at previously not two independent and failure criterion, but they are related and K 1 is parameter which is coming from the near tip stresses and displacements and g gives us the global change in energy e prime.

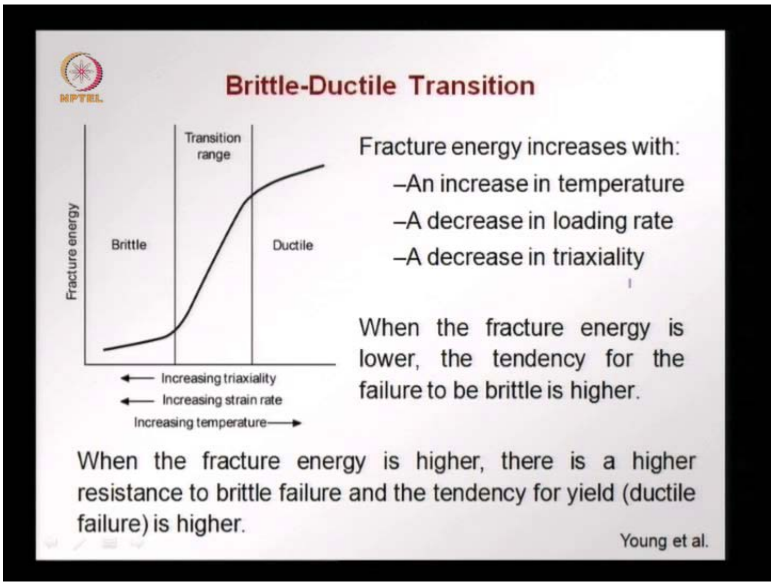
Here is given as e for plane stress and e divided by one minus nu square for plane strain nu being.

(Refer Slide Time: 30:17)



The concentration fracture energy can also been a determine and this is a chart again from ashby and jones showing typical fracture energy values we find again that the fracture energy for brittle materials like ceramics rocks cement glass are at the bottom we have here a group of brittle materials and that the top we have pure ductile materials and the alones that is all. So, again we find that these materials failure in a brittle manner these materials not falling in a brittle manner and in wood rather yield polymers and somewhere in the little in a epoxy at the bottom and less brittle polymers at the top leg poly properly and composite’s in the again in the middle the units of fracture energy or the critical energy release rate or joule per square meter are you can permit

(Refer Slide Time: 31:18)

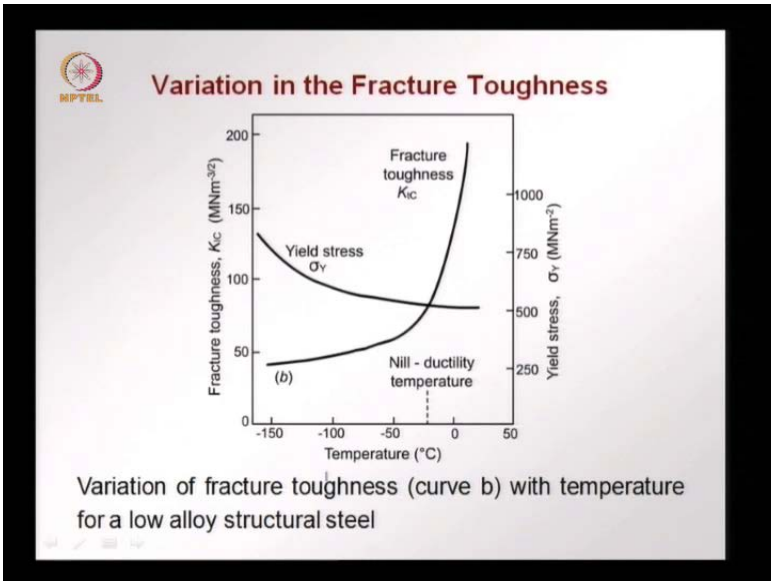


We are discussed brittle ductile transition that can also be now related with the fracture toughness and fracture energy we find like to see in the tough on the left the fracture energy increases with the increasing temperatures. So, fracture energy increases with than any increasing temperatures. So, a ductile metal when it is becomes colder will have a fractures energy that is decreasing and can become brittle an fail in a brittle fracture energy also increases then there is a decrease in loading rate that is as the loading rate increases a material will have a lower fracture energy can become brittle fracture energy increases as the loading rate decreases if loads slower the fracture energy is higher there is a less tendency for brittle failures when you load very very slowly when you load very fast it is that the you see a decrease in a fracture energy and a higher tendency for brittle failure to occur a third case which shows a increasing fracture energy is a decreasing

triaxiality triaxiality is the consignment in the degree of construct as you remove constraints fracture energy increases appose to when you have increasing in triaxiality the fracture energy decreases in you have brittle failures this was like in the case of the bridge that we saw from milwaukee where there was higher triaxiality giving to brittle type of failure even though the materialist characteristically duct. So, this is something interesting that you should remember what causes a brittle to ductile transition and how it can be related to the fracture energy whenever the fracture energy is lower the tendency of brittle failure is higher when the fracture energy is.

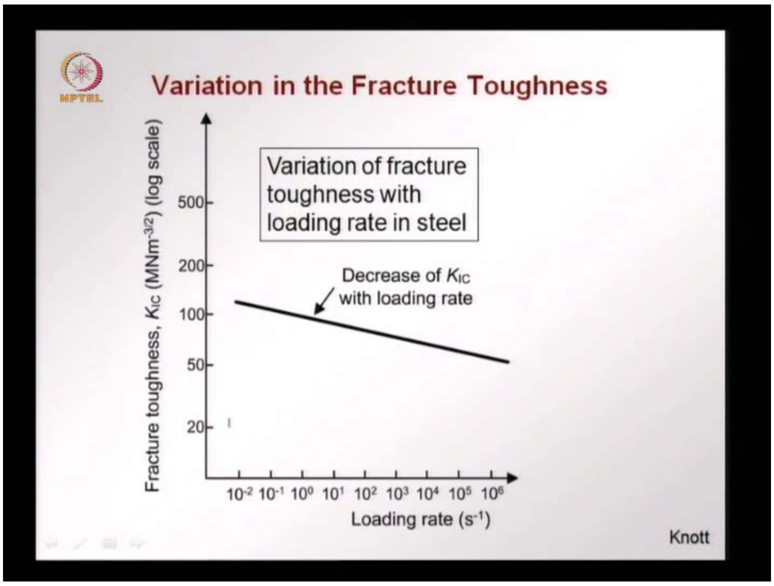
High you can have more of give type of failure ductile failure rather than brittle.

(Refer Slide Time: 33:36)



Here you see how the fractures toughness varies with temperatures for a low-lying structural steel in this curve you have on the y axis fracture toughness x axis you have temperatures and you find that as temperature decreases the fracture toughness decreases the material is becoming less ductile and more brittle as the temperature is decreases this is the corresponding trend for yield stress which keeps decreasing as we increase the depth yield stress increases as the temperature decreases whereas, the fracture toughness decreases as temperature decreases the material becomes little bit stronger, but more brittle as the temperature drops and this is what gave rise to the failures of steel elements in this case that we saw in very low temperatures

(Refer Slide Time: 34:33)



In terms of loading rate when the loading rate becomes faster here we have in the x axis the loading rate and y axis we have the fracture toughness of steel we find that has is load.

Fosters loading rate is higher where the fracture toughness decreases that is tendency for more brittle failure when the loading rate is faster and the failure would be more ductile when we slowly loaded this is the reason that we intuitively always try to break things very fast when we want them to crack we apply a very fast load when we want something to crack into two where we are intuitively decreasing the fracture toughness by increasing the loading rate. So, we will stop here with this part we introduced linear elastic fracture mechanics we looked at the concepts and very interestingly will see how at the tip of the crack we can have very high stress much higher than what is applied for away and in the case of linear elastic fracture mechanics the stress can become.

Singular on infinite at the crack tip with then went on to define failure criteria terms of the stress intensity factor K 1 and the energy release rate g and in both the cases rapture occurs when these parameters surpass or equal the corresponding material property fracture occurs when K 1 is equal to the greater than K 1 c K 1 c is now the fracture toughness of material parameters or alternatively we can see that fracture will occurs at crack propagation will occur when g the energy release rate is greater than r equal to g sub c which is the fracture toughness the critical strain energy release rate we also saw what happens to these fracture parameters under conditions of increasing temperature triaxiality and loading rate and we found that under these changing conditions they can be the applied to brittle transition or brittle to ductile transition and this could.

Change the way the material fails ductile material could enter failing little manner and vice versa in the second part of the lecture will go on to see how different material fails in fracture what happens in the crack tip what controls the crack resistance we look at metals we look at polymers we look at concrete and we look at some of the models which go behind just linear elastic fracture mechanics this could be called non-linear fracture models and will see some applications of these models and detained of the next lecture will also bring in the defect of probability the variations in the defects that we see in different materials and how the probability of the defect occurring can change the strength that we get when you have a brittle failure.

Thank you.