Materials Science
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Lecture 32
Fracture

We were talking about the response of the material to the mechanically applied force and we have seen the temporary deformations and the permanent deformations but what is that happens if I continue to apply the force beyond deformation (())(1:18) a limit when the material what we say is failed is failure the material I also refer to as the fracture and that is what fracture in solids we shall look in the next topic.

You have done a tensile test and some of you have also tested a glass slides in the glass in bending, the aluminium specimen and the steel specimen which you tested they failed or rather separated in two pieces while the glass slide those of you have tested must have seen that breaks into number of pieces.

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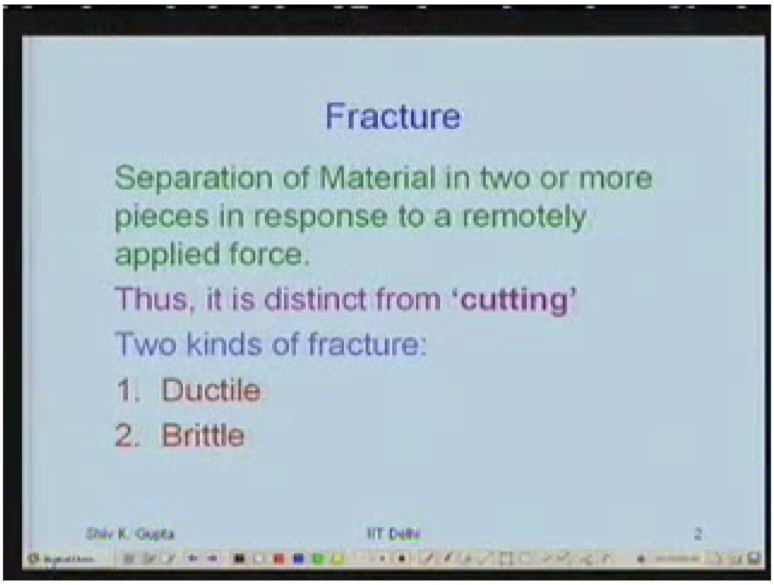

So I say separation of material in two or more pieces in response to the remotely applied force, this is very important the last part which I said the remotely applied force you can take a pair of scissors and cut the material I call it cutting you go to the lake machine you have seen this when you enter the workshop that you apply the tool and rotate the specimen you got chips it is separating in more many many pieces but I do not call it fracture I call that cutting because there the separation of material is taking place right at the place where I am applying the force so that is why I call it cutting.

The plane of application of the force is the plane of separation but in fracture the force is applied remotely elsewhere and that is why it is called a fracture. Seen that we did a tensile test the force is applied on the extreme ends to the collars you know, separation is taking place in the middle somewhere.

Similarly the glass slide when you test in bending you are holding two points and third point you are pulling but it fails anywhere not where you are applying the force. So that is the difference between cutting and fracture this fracture materials as you have already seen is of two kinds one I call a ductile fracture and other one I call a brittle fracture. The difference between the two is what we are going to look at to start with I say a material goes through a ductile fracture if it shows plastic deformation before separation like is in the case of aluminium or the steel specimen which are cylindrical in nature you deform them means you apply the force and they showed reduction in the diameter, they also showed the formation on neck and the permanent change in shape as a plastic deformation was seen and is fail.

When you join back the such broken pieces you cannot see the original shape of the material that is what is a ductile fracture to start with and brittle fracture when material fails within its elastic limit it does not (())(5:00) the yield point does not show the plastic deformation. In other words when the force is removed or it fractures all the elastic deformation is recovered because that is temporary. So when you join back some broken pieces or say fractured pieces you will get back the original shape and size, right.

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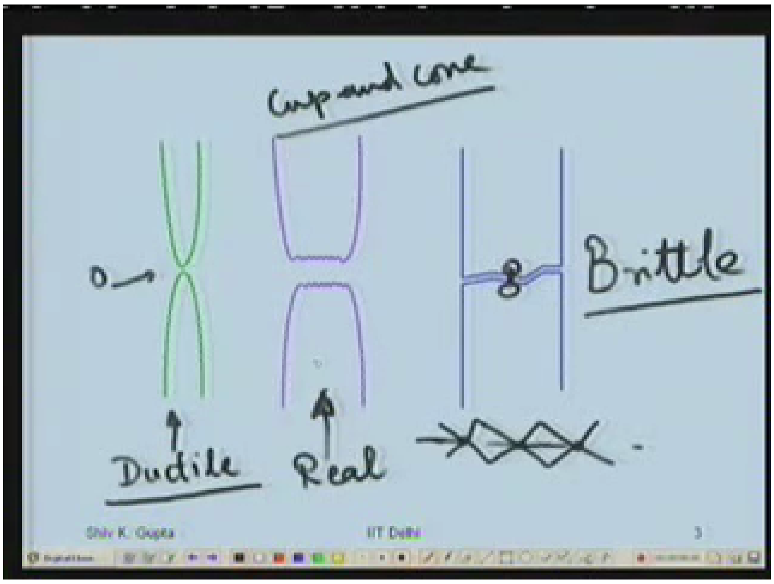

So that is what I show in the next slide the first one here is a truly ductile behaviour where material keeps on necking necking down to an area of cross section which becomes almost 0 and it cannot withstand any force therefore separation occurs that is a truly ductile behaviour but what you observed was not that what you observed in the lab is this is a real behaviour.

But here also the actual area of cross section contact is almost 0, you find these cavities formed and when you join these they let us say the cavities which is cavity which is of this side and when it is joined they hill from there this is not joining there, it is not making the complete material joining if you really look at let us say I show the one part and the second part the bottom is something like this.

In other words there is this plane where the actual contact is very small almost close to 0 is all the point contacts left and these cavities how do they form in the material is what we will see, is cavities formed in the material and thereby leaving almost 0 cross sectional area and the material separates that is a really ductile behaviour in what we find in most materials it is like this this is also called a cup and cone fracture.

While in the brittle behaviour the separation occurs as if something or some crack is propagating on the surface like this and when you join back it gives the original shape and size of the material there is actually a separation between the bonds let us make it exaggerated these items this the separation of the bonds between these items right here this bond is broken, right.

And here the area of contact becomes very small the bonds have to be separated with the applied force but here whatever force is applied separates the bond all over the region where this is separating that is the brittle behaviour within the elastic limit material is failing.

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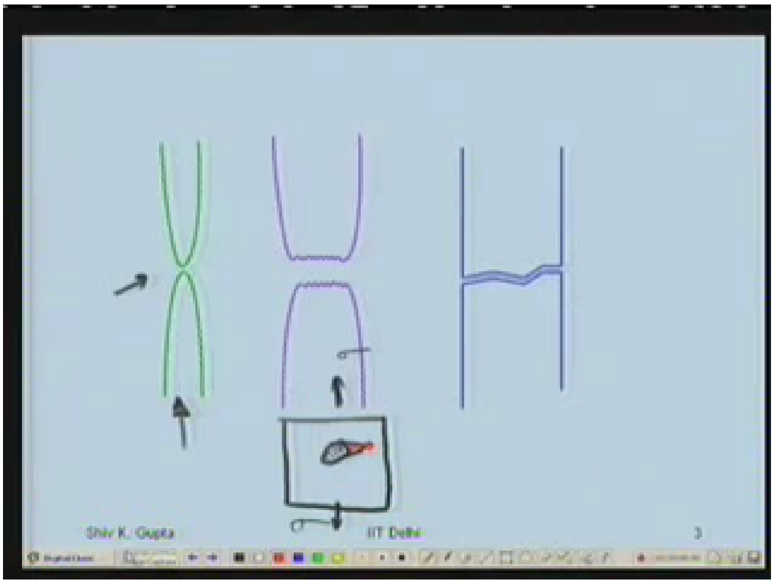

All right before we look at the brittle fracture one one more aspect I must tell you about this knowing that this is what we should expect in a truly in a ductile material you cannot add a material more ductile than copper probably try it on copper not a very expensive material either though it is not very cheap. Attempts are made and try to purify the copper as much as they could and was possible to get this kind of a behaviour as a impurities present for causing this, right this kind of a failure that can be seen not very difficult to understand that.

Let us say I have this matrix of copper in this matrix of copper let us say this is a slag inclusion which is a glassy matter particle, slags or silicates or oxides and is very hard as compared to copper. When I apply the force it is some kind of a particulate composites (()) (10:17) we talked about the composites earlier. So particles in a matrix of copper it is a hard and brittle particle.

That means yield strength of this material is here is higher than the yield strength of the neighbouring matrix. In other words when you reach the yield strength the stress you applied is enough, the matrix starts to deform plastically but this particle will not be able to deform plastically because it is still within its elastic limit the force or the stress which you have applied.

So that means the neighbouring region the material is flowing as a result there is a separation taking place at the interface, material here flows but this is not able to flow so therefore I form separation of the material and this is a kind of a cavity formed it is a kind of a void space form which is not interstitial void it is big void is because the material is flowing neighbourhood but this interface inside the interface this material is not flowing it is still elastically deforming and therefore this formation of void occurs that is what I mean when I say that voids are forming and the voids are growing, okay.

And then the applied stress becomes very high at such a corner like this that is what we shall see in a corner like this it becomes very high and the more and more plastic deformation goes on that place and this void space keeps on growing slowly. So that is why you get a real apparent area of cross section while it fails though actually it is going down to 0, right.

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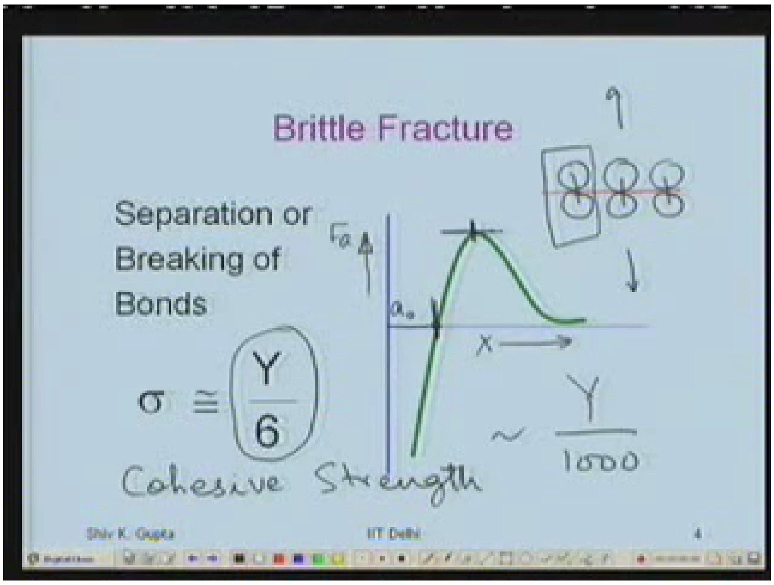

After having made that point we shall now first of all look at the brittle failure and then see when there is a ductility what more needs to be done. In brittle fracture as I already said let us say this is the plane of separation these are the items which are bounded above and below and when I apply the force in that direction I am pulling these bonds and separating these neighbours.

For this what I have done I have considered here only one set of pair of bonds or one bond formed between two atoms and this is the reciprocal or the reverse of the corner most curve and I apply this is the applied force in this direction and this is separation between atoms when 0 force is applied this is the bond length let us call it a 0, when I apply the tensile force this separates and once I reach this further separation is or further taking away of the atoms is very quick and rapid I do not have to apply more force in that, it is possible for us to work out that value of the force like we did exactly in the case of shear strength we can do that consider this to be a sinusoidal function and you will be able to work out this maximum value here of the order of Y by 6, where Y is the young's modulus.

So like we found out for the shear stress Mu by 6 it will work out to be Y by 6. That is the kind of stress I need to separate these two atoms, if I reach about 1/6th of the young's modulus or the elastic modulus I will be able to separate the bonds between atoms. But by that time no plastic deformation should have starting. If at stress less than plastic deformation would start, material will behave in a ductile fashion right this separation would not be able to take place immediately. So the stress required is Y by 6 of the order, right this is also called the cohesive strength of material but in reality materials are failing at the stress levels which are of the order of Y by 1000 (())(15:58) in mega pascals failure is taking place in mega pascals young's modulus is in giga pascals.

There is a difference and the order of magnitude difference is about 200 two orders of magnitude difference in these cohesive strength and the real value at which the materials do fail and this is because of the fact like in the case of plastic deformation we had the presence of dislocations the imperfections whereby the configurations the dislocation can move at a much lower stress and thereby ultimately give me a plastic deformation.

Similarly here there are stress raisers in the structure of the material and these stress raisers which are present in the material there is a concentration stress taking place at the stress raisers and thereby at the location of the stress concentration the bonds are able to break because the stress reaches there of the order of Y by 6 because of the stress concentration alright and once that happens that bond breaks when that bond breaks the next bond which is in the neighbourhood that fills the same stress that also breaks the failure occurs is a sudden failure which is called a catastrophic failure.

That is the yield strength is happens to be higher than the nominal stress you are applying not the consistent value of the stress concentration is there somewhere in the middle of the material but nominal stress which you applied is less than the yield strength you understand so plastic deformation does not occur.

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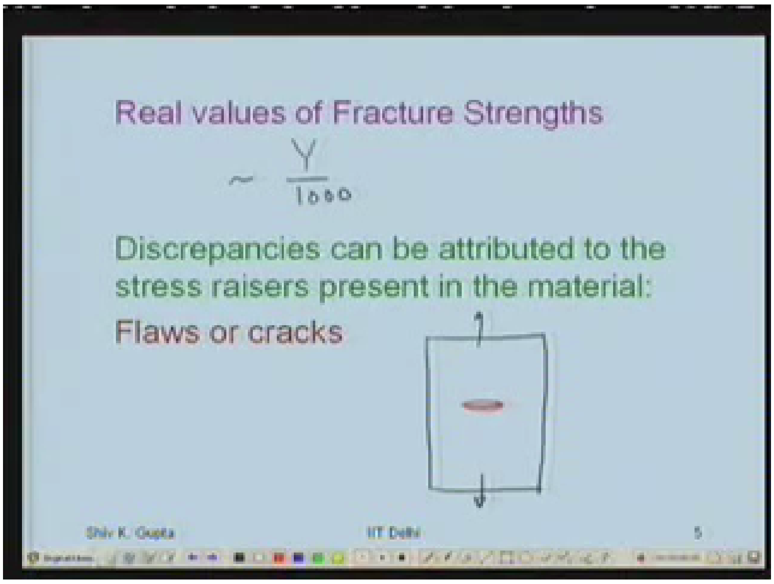

As I said the real values of the fracture strengths are in the range of Y by 1000 and we can attribute this discrepancies to the flaws or cracks in the material which are also called as stress raisers are just shown you want hard phase particle like that of a slag which is a silicate, glassy material very hard as compared to the matrix at the interface there can be a stress raiser, right.

So therefore there could be in concentration or stress taking place different places in the material. We shall take a specific kind of a shape and that is what I suggest is you can try this is not very difficult take a piece of paper and with a blade just make a straight cut here like this just make a straight cut like this and once you have made the straight cut apply the force in this direction gently do not be harsh with the paper.

So what you will see this flaw which is where actually you made a cut that means you have separated the bonds of the molecules as the atoms above and below in this region, what you would notice is this takes the shape of an ellipse. The separation occurs like this because once the force you have applied really speaking there is no force in this region because there can be no stress or no force perpendicular to free surface this is free it is not halt by anybody there is no bond is holding it, right.

So that is the kind of shape so we will considering the elliptical cracks or this flaws in the material elliptical in shape whereby there will be stress concentration at the tips of the flaw.

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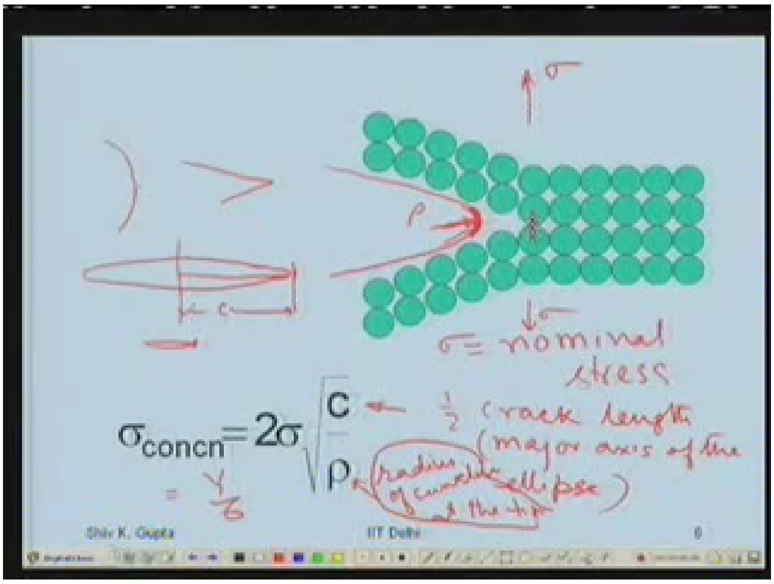

Alright this is what I am trying to show the end of the elliptical flaw this is the elliptical flaw in the material and there will be a stress concentration taking place at this point and that stress concentration that point is will not work it out but we shall just take this model 2 times sigma is the nominal stress sigma is the nominal stress which we have applied that is the stress applied in sigma like this.

But the stress at this point is this value where c is the half crack length or in other words half major axis of the ellipse and rho is the radius of curvature at the tip of the crack that is what I have shown here this is the radius on the tip of the crack, okay. So sharper this radius more will be the concentration that is if I have a radius like this or I have a radius like this this will give me more concentration, this will give me less concentration right that is the meaning of this physically.

And see of course if this is my ellipse, this is c whether it is this big, or it is this small see in this small stress concentration would not be so large one is the big one is stress concentration would be large here. So that is the stress concentration and this can become equal to Y by 6, once that happens this bond will break these two atoms will separate and then the c would have increased at the stress here would be even more that will separate automatically.

So one has to separate all others will follow suit that is why there is always a catastrophic failure whenever the flaw or a crack like this spreads then there is a catastrophic failure that is brittle failure typically a brittle failure is like that, yes please. No crack lengths are the range of micron and radius in the range of (())(24:22) atomic radius atomically sharp cracks usually we have.

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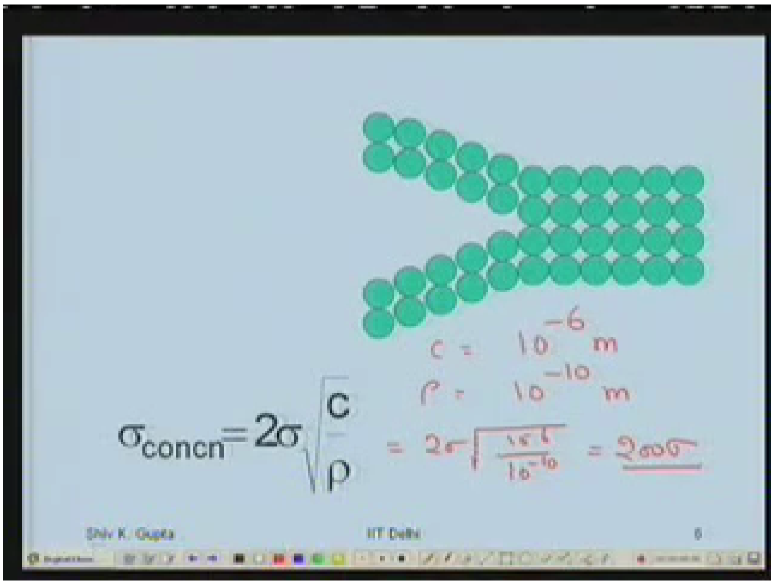

So if you are interested we can just put some numbers and see what happens c is sorry c is of the order of a micron let us say, rho is of the order of 1 angstrom could be 2 and some does not matter. Let us see what happens there if we do that 2 sigma under root 10 to the power minus 6 divided by 10 to the power minus 10 this becomes 100 and this becomes 200 sigma. So you applied Y by 1000 it becomes Y by 5 that is why the separation is taking place there understand that is the order of magnitude in materials which are very brittle materials like glass or porcelain or any ceramic material that is the kind of sharpness of the cracks we have.

And those of you might have looked out the crack length in the case of glass slide would have found the crack to be a micron or 0.8 micron or 0.9 micron that is the kind of thing you would have found out anyway, right.

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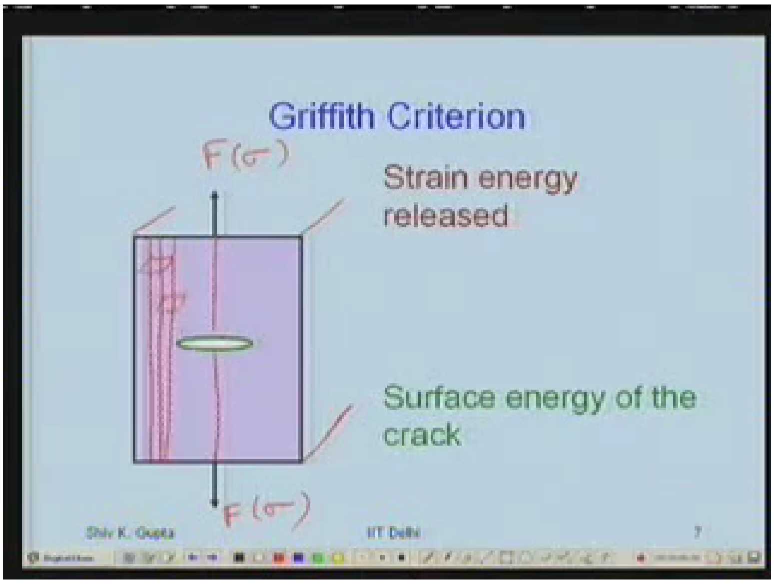

When I do not have a flaw in the material the flaw I have shown here and I apply a force like this or stress in other words let us say if I know the area of cross section I can convert into stress. The line of force why I talked about force lines of force like you have magnetic lines of force in a magnetic field this is a mechanical field after you apply the force and in the material lines of force should pass from top to the bottom uniformly like this.

In other words at any (())(27:10) small area of cross section you take because let us say this is the third dimension of the specimen perpendicular to the applied force the stress on that element or the same element you take elsewhere would be exactly the same when there is no flaw in the material that is what should happen in other words these number of lines of force passing through an unit area is the same.

However when there is a flaw present like this, okay in the material these lines of force cannot go across the flaw why it cannot go across like this why it cannot go across this material is like a free surface here nobody is holding it can there be force?

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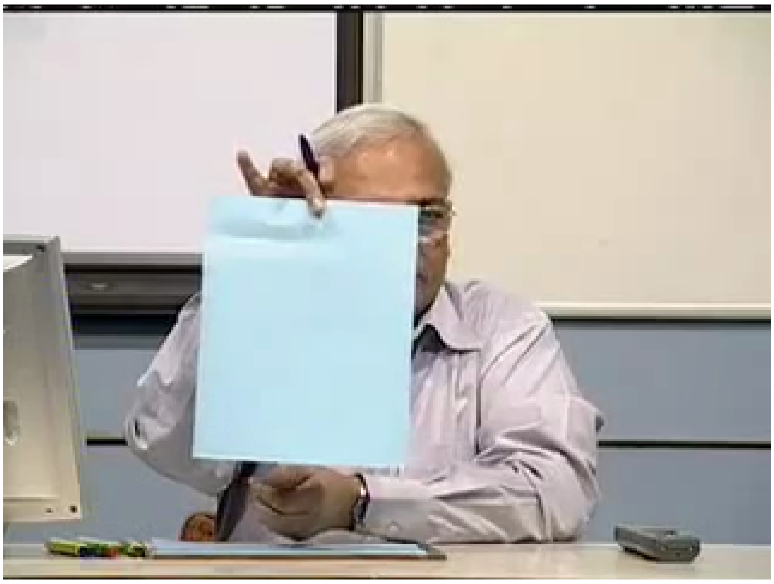

This is the piece of paper I have I am not holding it here is there a force? Force is here when I do this, when I do not do this there is no force here, line of force cannot pass across, right. So I cannot have a force or stress perpendicular to the surface which is free. Therefore this line of force cannot go across.

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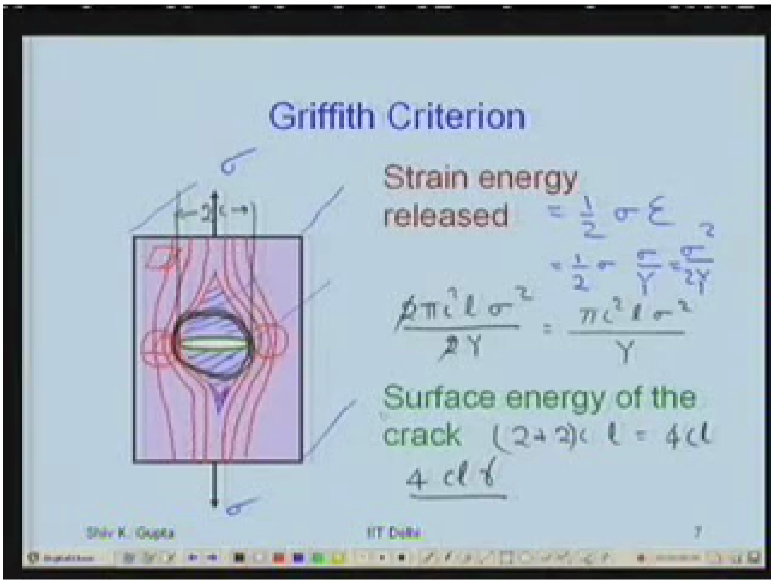

So when I apply the force what happens this is line of force bends across and passes close to the tip what happens is so like this the lines of force concentrate in this region that means what I try to say earlier if I take that incremental area whatever I had taken here let us say same area if I take now here there more line of force passing through that, stress is concentrated in these places while there is a region in the material where there is no lines of force passing through and there is no stress there in that region.

So there is a volume in the material around the flaw where there is no stress therefore there is no strain and therefore no strain energy stored in the material and there is a region near the tip where there is a concentration of the stress, right. So this is what is happening in the material when I have introduced the flaw which is in the form of an elliptical you can say a crack or a flaw in the material this provide me two free surfaces which are the surfaces of the ellipse elliptical surface rather and if you take the third dimension you can put the third dimension there. This will go along the pole lengths the whole geometry will be the same around the pole lengths or whole depth of the specimen because from the front surface to back surface the whole thing will be spreading in the same manner, okay.

So there is a volume in which there is no strain energy stored so strain energy is released that is one thing what is happening when a material has a flaw and I apply a stress and I am still in the last signature of the material. What is the strain energy stored in a material when you apply a stress and there is a strain sigma I mean epsilon strain is there, what is the strain energy stored per unit volume of the material? Sigma epsilon, right it is half of sigma epsilon because there is a straight end relationship between stress and strain hooks lies away and the area of the triangle is this, area under the curve.

This can be replaced epsilon can be replaced by sigma as sigma divided by Young's modulus which you can write as sigma squared divided by 2Y this is per unit volume of the material and that energy in this volume is not stored, question is I must estimate this volume while people have made their effort for us let us not worry about it, what they did was they estimated this as a cylindrical region and then take the rest of it which is on the other side also equal to the cylindrical region.

So double the volume of the cylinder and this we have said already size of the flaw from here to there I said half-length is c so it is 2c, right. So this radius or the c therefore the cylinder area is Pi c square and double of that is 2Pi c square and if you take the volume, the lengths so it becomes 2Pi c square into l is the volume in which the strain energy not stored and the strain energy per unit volume is sigma square upon 2Y. So this is the strain energy released from the material but release matlab energy is decreased so it becomes minus negative.

So the second term which we have introduced is a surface free surface elliptical surface of this crack that means it is a surface energy like the external surface and that surface energy I must know the area then multiply the specific surface energy which energy per unit area of the material, right. In this case considering this the minor axis to be very small as compared to the major axis because what I said was you make a fine cut and apply the force so it will take this shape.

So that is going to be minor axis is going to be very very small so I can take the top surface to be 2c, bottom to be 2c and of course the length is l, okay so it becomes 2c plus 2c into l that is 4cl and 4cl into gamma, right so that is the thing which is going to happen in a material when I introduce a flaw or when I did not have a flaw, I did not have a flaw I had applied stress sigma I had some strain energy stored in the material that is it.

But once I introduced a flaw or remove that volume from which the strain energy stored and this strain energy is released from the material but I introduce a flaw therefore I introduce a surfaces external surfaces and therefore I introduce this much surface energy.

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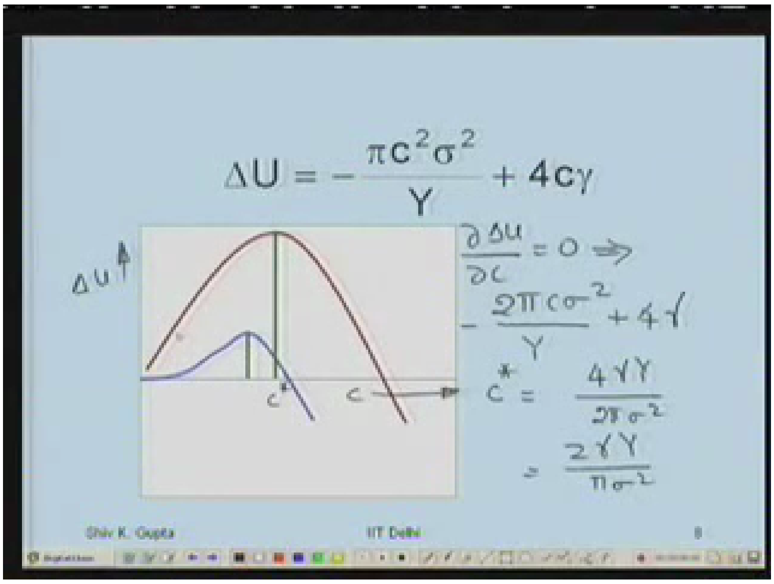

So if I make the balance of these two energies which I can write should delta U if I am writing it is taking per unit length of the crack, okay the length l has been made 1 so it becomes this these are the two terms which I had talked about Pi c square sigma square l by Y and 4cl into gamma l has been taken unity so it is per unit length it becomes this energy. First term is negative, second term is positive it goes a square of c this goes as linearly with c.

So what is happening here is if I show on this axis delta U and c on the x axis well this is the term which is negative and goes at square of c and this is positive term and goes at c initially for small values of c which of these two terms will be more? Second term will be more for large values of c it is this term which will be more. Therefore it is like like in the case of nucleation kinetics the two terms one was q and other was square same way it is one way square, another is linear so it passes through a maximum at some value of c let us call it c star.

And it can be worked out this maximum can be worked out by differentiating this and putting the derivative to 0, I do that differentiate this it becomes and if it is 0 the first term should be equal to second term and I can get from there the c what you are calling c star but you notice that it depends upon the nominal stress you have applied sigma, smaller the value of sigma you applied more will be c star that is the situation like this, higher the value of sigma you apply smaller will be c star is that the way what I am trying to look at in the material?

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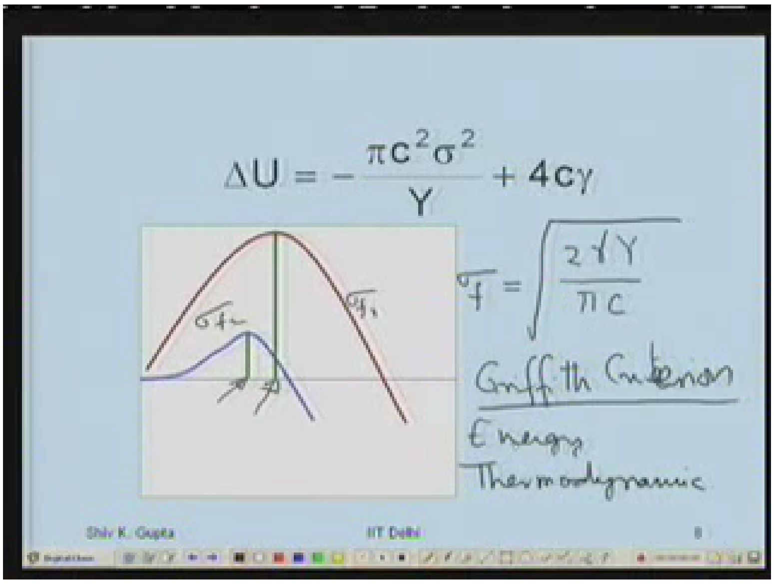

What is happening is I am testing it from a testing material I start applying the stress from the 0 level go on increasing go on increasing the stress material fails. So I should find out what is the stress at which the material fails rather than c star so I rewrite this expression and on rewriting I can write this as sigma and call it sigma fracture is equal to 2 gamma Y by Pi c times under root I will just take the sigma on to the left side and taken the under root or the rest of the term and c on to the right side this is what is called the Griffith criterion, this is also called the energy criterion, also called the thermodynamic criterion.

So this writing this tells me if this failing at a force like sigma f let us say 1 and I can find out what is the crack size that has propagated. If it has failed at sigma f 2 I can find out what is the crack size that is propagated. In other words the materials are going to have cracks usually they come up during the manufacture, during handling, during processing of the material this scratches and cracks can come about and I may have no control over this.

So there would be ranging from a small size to a big size of course the size cannot exceed the size of the specimen it is very important it cannot exceed the size of specimen or the material but there could be varying sizes at the same time their orientations could be varying, what I have seen is you have the flaw and the stress is applied at normal to the surface of the flaw, right. If the force is applied at an angle to the surface of the flaw only the component which is normal to it will be able to give me this result, right.

Therefore the crack may not be very rightly oriented sometimes, but cracks are there, scratches are there, flaws are there in the material and these flaws or scratches or cracks which are there out of these the one which is most rightly oriented and biggest in size is the one which is likely to fail at the lowest value of stress because see the denominator so maximum size and rightly oriented normal to the applied stress the one which has the biggest size normal to the applied stress is the one which will propagate the first for the smallest value of sigma.

Gamma is the material property constant, Y young's modulus is material property not going to change with the structure or presence of the flaw these properties are not going to change, Pi is a constant is the c only. So therefore the materials could fail if I take a specimen one specimen, second specimen, third specimen, fourth specimen they may all fail at different values of sigma, sigma fracture may not be same in all specimens that is the meaning of it for the same material because their scratches are randomly oriented in one it may be exactly normal to the applied stress, other one it may be at 80 degrees the biggest one, 90 degrees, other one it may be at 60 degrees. So the one at 60 degrees will fail at a higher stress, one at 90 degrees will fail at the lowest stress, right.

So all those we are testing the glass slide you will not find the same result, they will all have different results, different specimens you are testing, okay. And this Griffith criterion or the energy criterion, thermodynamic criterion is also a necessary criterion for cracks or the flaws to propagate in a material. However, it is also sufficient in case of certain materials like glasses, ceramics, porcelain which have brittle materials known brittle materials or silicates and oxides is applicable and workable it is sufficient. But it is not sufficient in other ductile materials it is necessary but not sufficient, why is it not sufficient we shall see, right.

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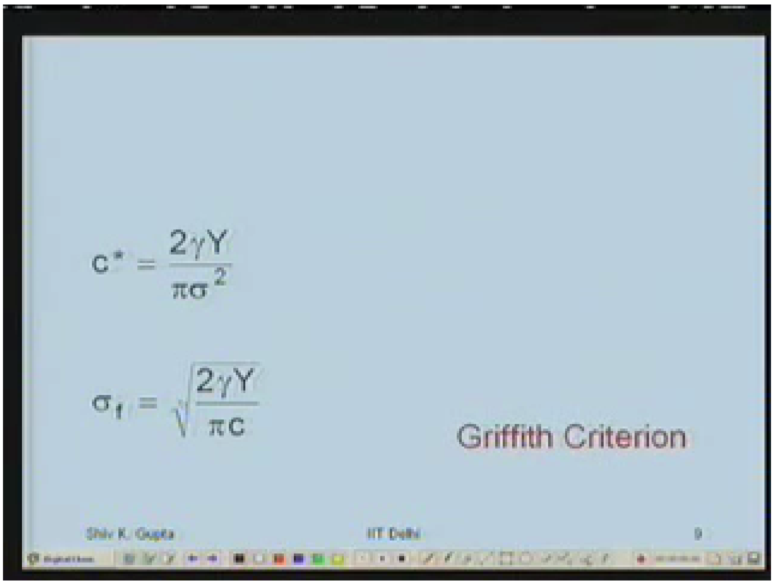

That is only thing I have rewritten the same thing here which I wrote there it is no different, we try to we do our best but while handling, while using suppose a scratch comes about ya scratch can come about if you talk about a size which is of 1 micrometre 1000 of millimetre, right we are talking about that it is not easy for you to see in glass slide that this is scratch is there but it is there on the surface, you feel it absolutely smooth, no problem, you will not even see this come on this surface here there may could be much deeper scratches then the 1 micrometre could be much bigger in size, right.

So that is during handling it happens when I am using this I rub it like this I might cause the scratch, right so that is during handling, during usage these things can come upon, right.

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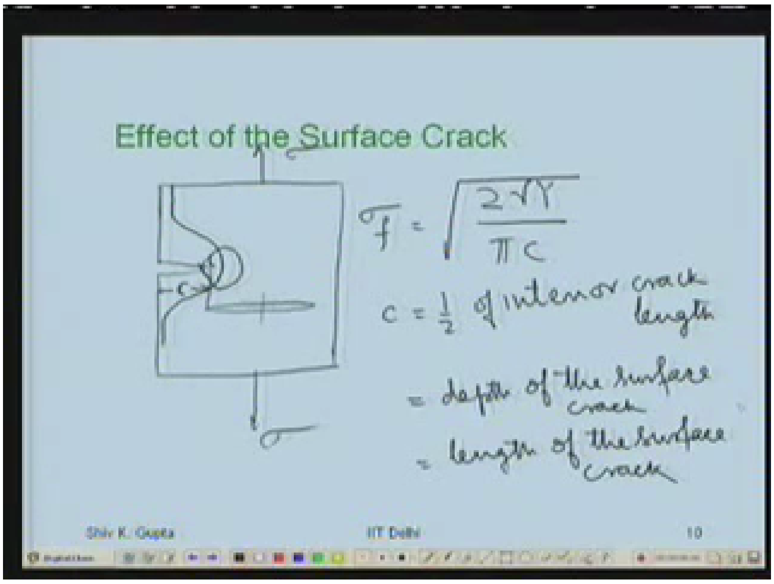

Now let us before proceeding further I have a material which I showed you the crack in the inside now let us say I have a similar crack elliptical crack on the surface and I apply the force like this, right and let us say from the surface its depth is c should try to look at the stress concentration the tip of the crack, okay this stress concentration which is taking place here will be similar to what has happened in a 2c crack which was inside, geometrically you can see that this flow of lines will be similar when this is 2c inside, here it is only c get the same concentration.

So when I say the Griffith criterion sigma f is equal to under root 2 gamma Y by Pi c c is half of the interior crack length and it is equal to the depth of the surface crack or is equal to surface length of the surface crack this goes to say that surface crack is more deleterious than the interior crack in the material and during handling you cause the scratches only on the surface, right.

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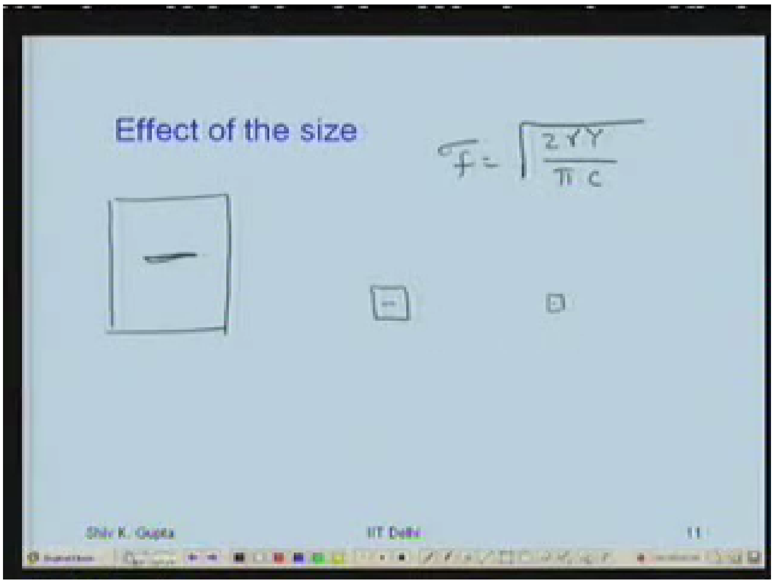

Now let us talk about the effect of the size of specimen, there are three specimen sizes which one shall fail at the applied stress, which is the least first one yes because the sigma is dictated by this size of the crack, gamma and Y the material property, Pi is a constant is dictated by c, chance is the c is that big here but c cannot be that big it is more than the dimension specimen, c can be probably this big whereas c can be only this much.

So crack size is in the biggest specimen can be big the biggest specimens have smaller strength, smaller the volume of the material higher the strength you could have that is too for brittle materials, smaller the volume of the material higher the strengths fracture strength, okay.

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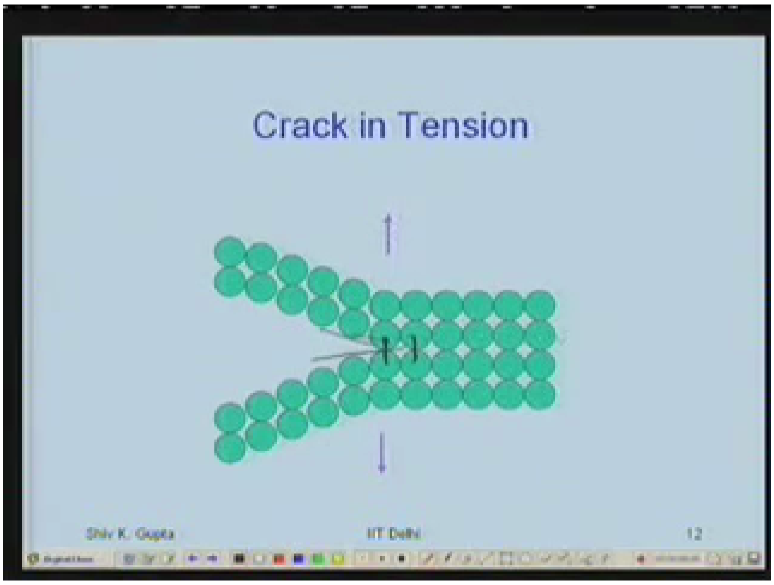

Now let us see the situation when a crack is in tension and (())(51:31) when the crack is in compression, when the crack is in tension there is a stress concentration here as I said and this will be pulled apart because in tension pulled apart means these atoms will be separated and once these atoms is separated to this becomes crack extends and there why causing this concentration here and that goes on and fails but is the same thing is in compression.

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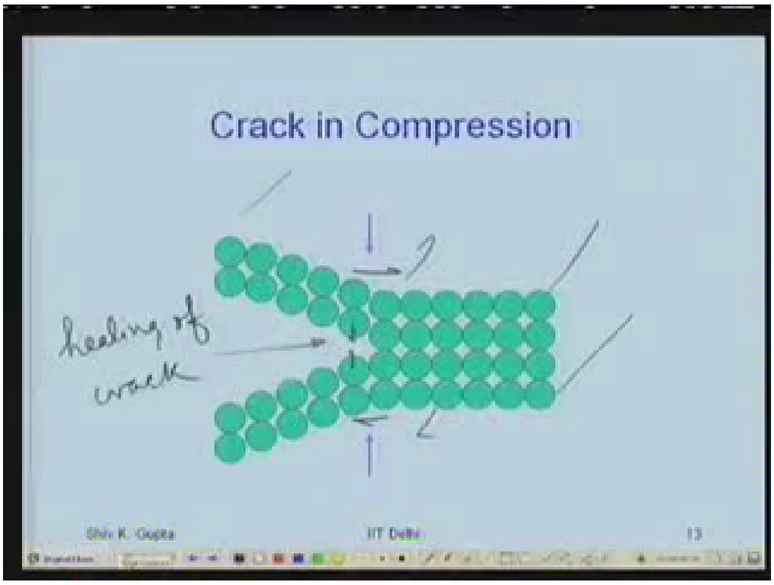

There is a stress concentration but it is trying to pull them push them together when that happens these will also be pushed together and they are brought together they can form the bond, they come close enough they can form the bond provided no small atoms have entered this free surface, where do the small atoms enter flaws like this on a free surface where do they do so small atoms like nitrogen, oxygen, nascent oxygen, nascent nitrogen, or hydrogen if they do not enter there why do they enter normally like this at the surface.

Yes because when they go there they form the bond and thereby use the free energy on the surface these atoms they are on the surface to lower the free energy by that see and therefore the small atoms if they have entered you are maintained nicely, neatly this is for possible for them to (())(53:29) and therefore crack will start healing do not tell me that I cannot fail a material and compression put a break here keep on loading weight on to this to crush it is possible to crush it.

It is not crushing because by coming together they are forming the bond because the applied stress is going to give me the shear somewhere in some plane, some crack will shear cracks can also I have shown you the crack propagating in tension, cracks can also propagate in shear, right. Let us say for example the shear stress applied is of this nature it is time to push these atoms on top to the right and these ones to the left (())(54:32) it can break the bond between these two. So under shear also it can happen but then you need much higher stress then the tensile stress.

Similarly the applied stress could also be if this is the third dimension of the solid could also be a shear stress like this what I call it tearing node you are try to tear part, right that is also shear and crack can propagate like that also, right tearing is easy for me to show on a piece of paper, tearing is the shear the second one which I showed is not easy but the third one is easy to show.

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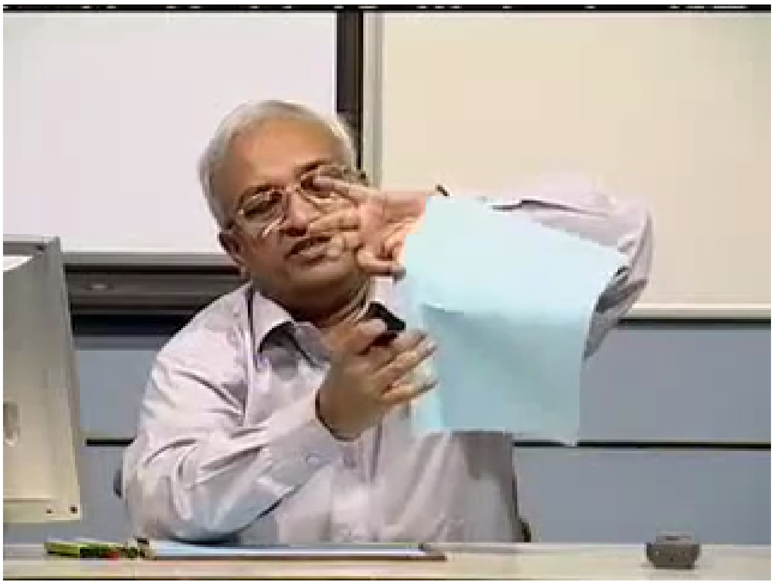

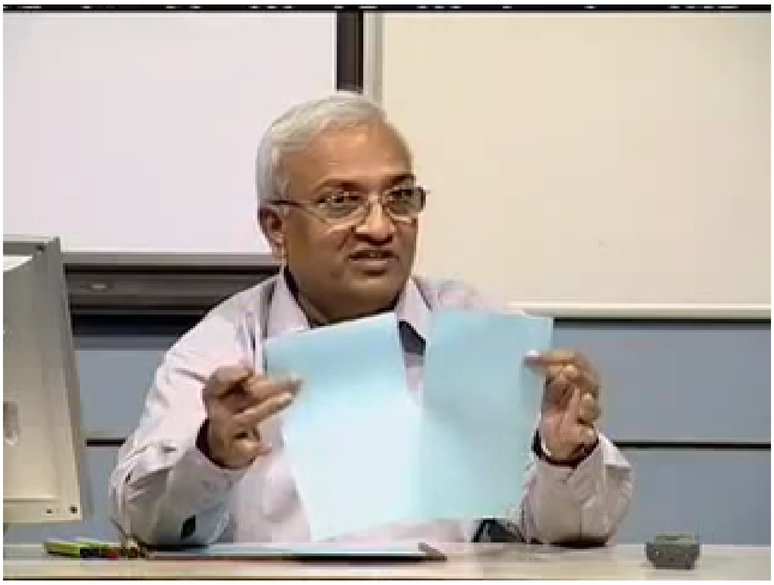

Suppose this is the flaw like this you apply the shear stress like this and tension I said was this this is much easier this is little more difficult it can still be done that is tear and this is opening, this is tension is called the crack opening mode that is more deleterious that happens in the least applied stress, shear occurs at a higher applied stress, alright can have the shear components applied compression can happen.

But by enlarge materials behave stronger in compression, the brittle materials because of this reason that is possible for them to heal if there is a crack all cracks let us say are normal to the applied stress then they will start healing but shear can but shear require a higher stress applied nominal stress will be higher. So therefore these brittle materials we tend to use them in compression rather than in tension we do not and let us say porcelain or China or anything.

Say for example you are using the separators where the cables long distance cables are taken on the poles you put porcelain for draping round the cables the porcelain and pulling so the crack porcelain part is in compression all the time support they are providing to the cable and there are two cables which is supporting both are carrying the current you do not want them to shot at the same time so you use porcelain which is an insulator but you maintain them in compression better take the draping it around, alright.

So on compression the porcelain or China or brittle materials would be definitely better (()) (57:29) is a brittle material we try to make lake bed which takes a whole load of the machine and the job which you are doing all the vibrations it bears a much better way, I cannot make the structure component of a or I cannot make a bridge from the (())(57:51) because there will be tensile loads also coming not only compressive load tensile loads will also be coming and once there is a tensile load material is going to behave in a much worst (posi) condition if it is a brittle material catastrophic failures can take place. So the brittle materials are avoided in tension, in compression we make use of them, right we shall stop here.