**Experimental Stress Analysis**

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**Lecture no. # 04**

**Physical Principle of Strain Gauges, Photoelasticity and Moiré**

Let us continue our discussion on overview of experimental stress analysis, and what we have primarily focused the previous class was, for typical problems, for which you know the solution, we have looked at a kind of patterns you could good, you could get from some of the experimental techniques.

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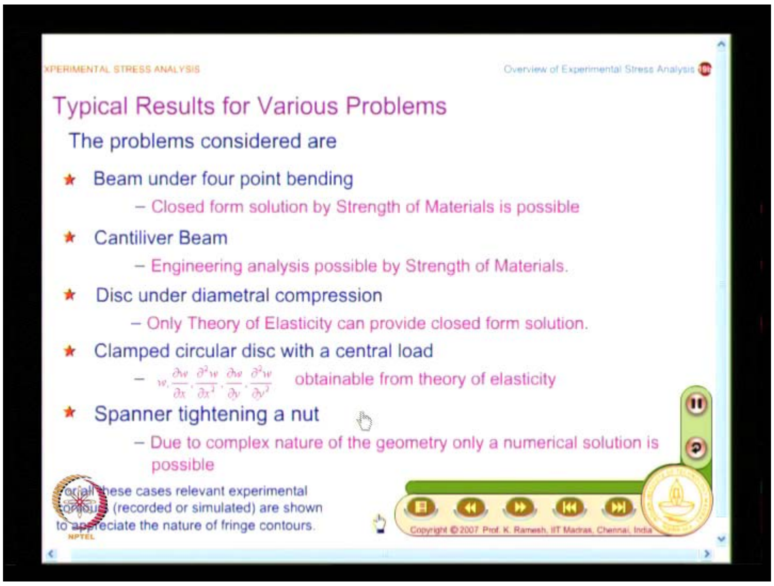


The problems considered were beam under four point bending, cantilever beam, disc under diametral compression, and also clamped circular disc with a central load. In all these cases, you have analytical solution possible for this stress field. So you have got a closed form expression for the stress field, you have got the strain field, and also the displacement field. And what we did was, we did a sample of experimental methods, some of them were directly from experimental result, some of them were simulated result to give a field of how the whole field information looks like. So, now your eyes get tuned to how to interpret whole field information to an extern possible. And finally, what we will do is we will go to the problem of spanner tightening a nut, and as I had told you earlier due to complex nature of the geometry, only a numerical solution is possible for this problem.

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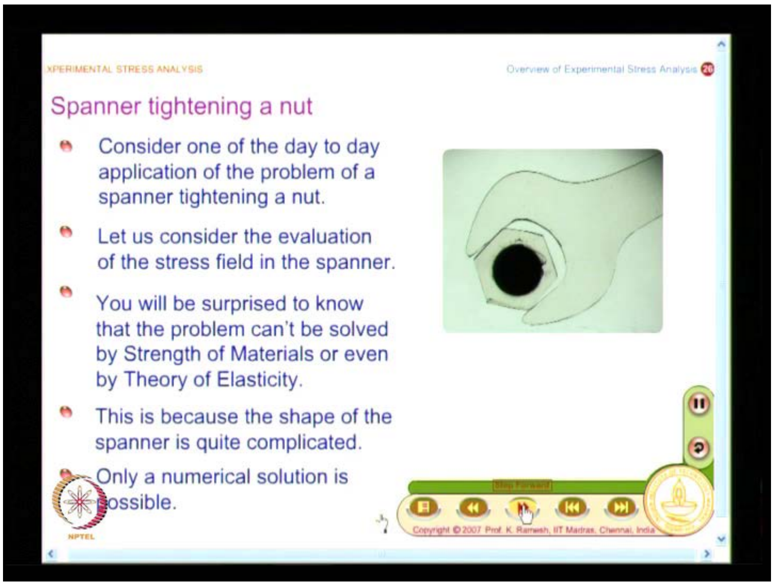


And that is what we are going to see and what I am going to look at is, we have already looked at, day to day application of the problem. And surprisingly you do not have solution from strength of materials or even by theory of elasticity. This is primarily because the shape of the spanner is complicated and you cannot define the outer boundary in a convenient fashion for you to do a theory of elasticity solution. And in this case, only a numerical solution is possible I do not have a close form expression, so I have to solve this problem numerically.

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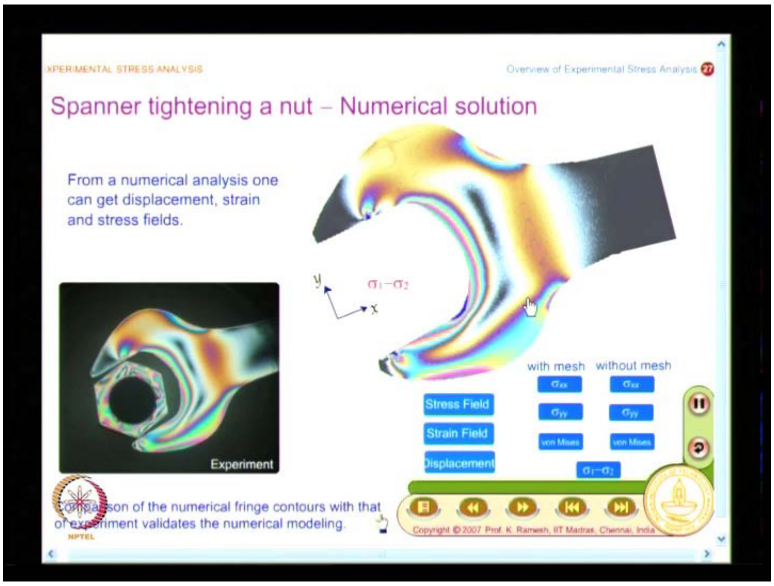


And let us see how the numerical solution is, you have very rich set of results that you get from a numerical solution. And in this case, the numerical method adopted is finite element method and what you have done is, you have mesh the spanner and what you find here is, this is the experimental fringe pattern and this is the simulated finite element result of sigma 1 minus sigma 2 contours. And here I want to point out a few things, when I do a numerical analysis I can get the stress field, I can get the strain field, I can also get the displacements, and if you go to commercial packages you would be able to plot specific contours.

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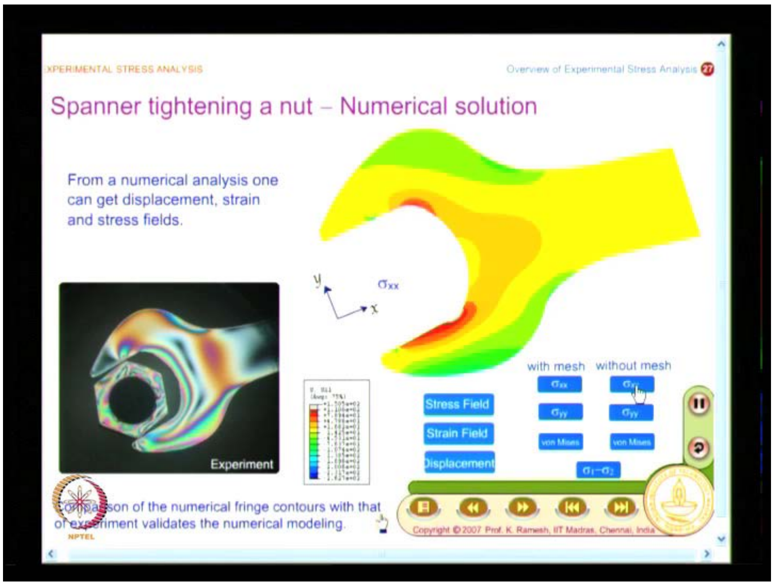

I have a sigma x contour and the software chooses its own colors, and then gives you an indication the red means maximum and shade of blue what you have here, it goes to less value of the stress information. You could see this without mesh; you could also see this with mesh.

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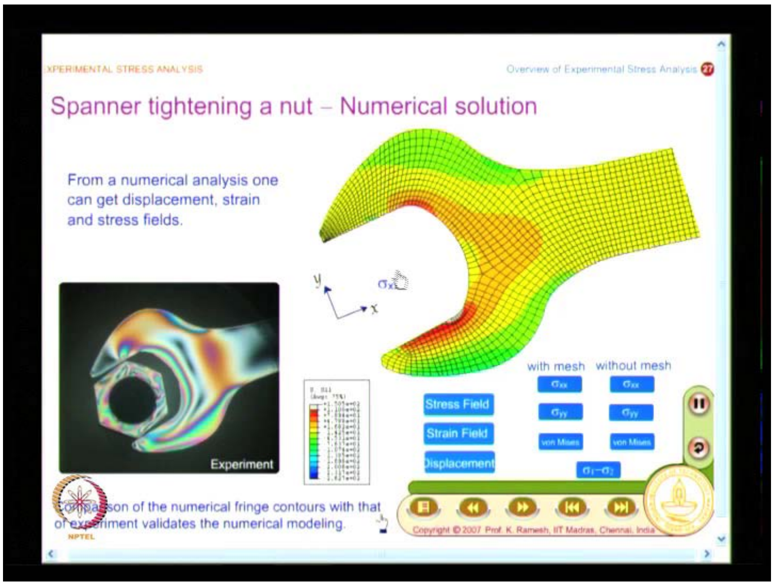


And for this you know you do not have to take the trouble of sketching it, because this is too complicated for you to sketch, the idea is to visualize what way you have the information available from a numerical solution. I have the mesh here and you have nicely done mesh these are all quadrilateral elements, and I have the sigma x x stress contour.

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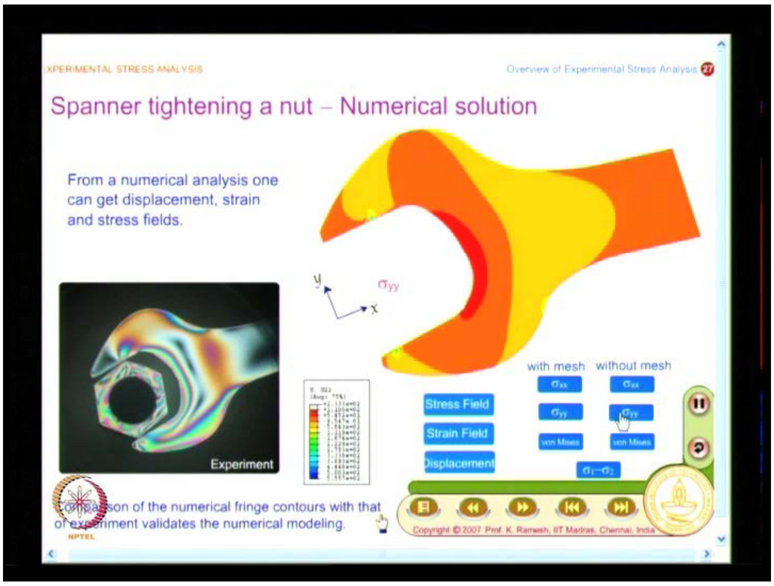


Similarly, I can also get the sigma y y stress contour and I can also get Von Misses stress contour.

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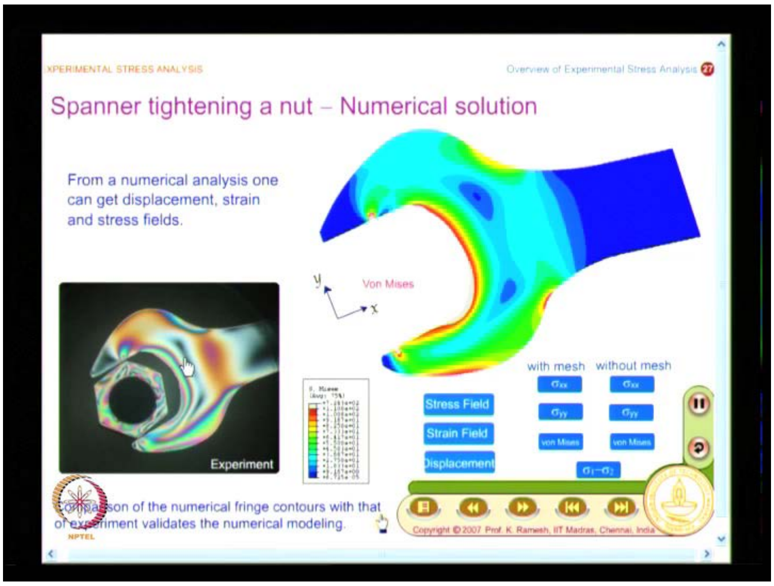


And if you look at Von Misses in certain aspects it captures certain geometry features of the photo elastic fringe, but the colors are totally different. Because the color is dictated by the standard finite element software package and what was done was we have developed in house software, what it will do is it will evaluate sigma 1 minus sigma 2. And also mimic the colors you get an experiment and this is plotted and an approach like this, helps you to quickly come to a understanding that you have very good comparison between what you observe in the experiment and what you observed in the numerical method.

And if you look at very closely I have these as a stress concentration region and what you have got and what you see in the screen you know my students have taken little time to apply the boundary condition appropriately, until the experimental fringe pattern matches closely with the numerically simulated results. So both the choice of elements, discretization and also the boundary conditions are improved until you get a close match between experiment and numerical solution.

So you have this, what is the difference here? Here when I have to find out I can get sigma x, but I can do this only by interpolation and based on final finite element formulation, I cannot go to the location of the coordinates plug plug simply x coma y and get this values directly. So that advantage you had in the case of analytical solution analytical solution the main advantage is if you have a possibility to solve it analytically there is nothing is equal to it, because the amount of computational effort required is very small. I simply plug in x y, I get the value which I want the moment I come to numerical techniques.

The greatest advantage is the shape of the geometry of the problem on hand does not post any restriction, but you have to do a lot of computational effort. But you get whole field information, so I can also get the strain field and till now you are not see a strain field as a plot. And this is with mesh and you can also see without mesh, this is epsilon x x similarly, I can get epsilon y y I can also get shear strain epsilon x y here. And I can also go and see the displacement field and this is what I get here I have the u displacement; I also have the v displacement.

So what I find here is when I have a numerical approach, I could get all the 15 quantities comfortably, but the very important aspect is I must match what I have in the experiment very closely by choosing the boundary conditions correctly. Once I have done this then I have solved the problem satisfactorily and a parametric analysis is very convenient, when I go for a numerical methodology. And what is seen here is here I have taken the effort of plotting fringe contours, what you get in an experimental techniques and that requires special software to be developed, it is not readily available in standard packages and we have this and this is best way to compare results of photo elasticity with the actual experimentation.

When you do a numerical analysis you can compare with photo elasticity comfortably and what I also want emphasis at this stage is you know though we have taken simple problems, we are gone and also studied in the process what are the approximations you do approximations you do in your analytical modeling. You know we have taken a beam under four point bending and it bends like this, and it is a three dimensional object it as a cross section. But what you have manage to do in strength of material is you just take it as a line that is all do the analysis and when I go to theory of elasticity, you do not consider that as a line, but you consider that as a two dimensional object. But in reality because you have fluxing, what you find here is you also have the poison ratio effect becomes very prominent. And what you find here is this is the compression side and this is the tension side. And this compression side bulges out because of poison ratio effect, this may be very difficult model from analytical point of view, but experiment looks at all this. So when I get the fringe pattern, the fringe pattern is deflective of all the three dimensional effect that happens in the model some you may have ignored it for the point of view was simplicity.

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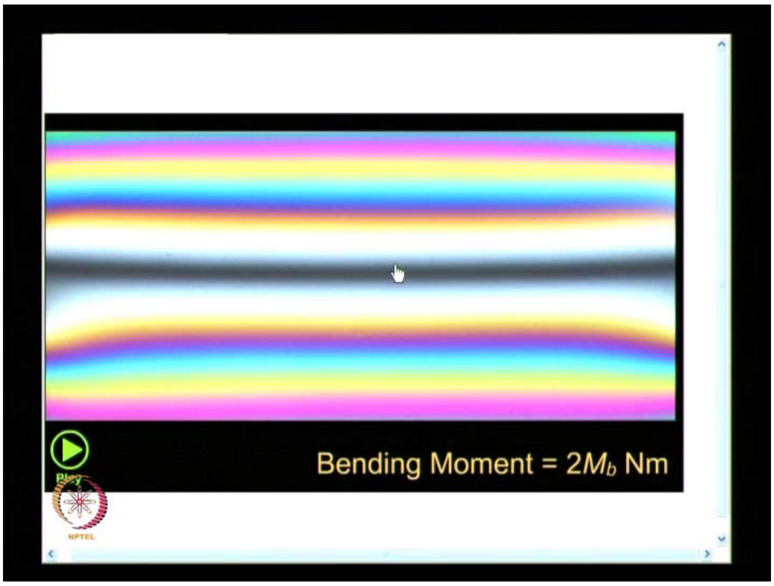


So that is why I said that experiment is giving you truth, and we also notice the fringe pattern observed in the beam. There was slight variation on the tension side and compression side if you look at it in a settle fraction, for a quick look it will appear as it is a symmetric, but for a very closer look it will have small deviation which could be neglected as a second order effects and carry on with it. So the point emphasis here is the moments you come to experiment do not discard the raw data.

Raw data is very very important. You may have an explanation to understand what the raw data means, if you do not have the explanation try to go and find out whether you have made any approximation, whether you can refine any of this, whether because in engineering what we do is we never want to solve a problem in three dimensional with all the complicities. I also mentioned earlier the success of engineering is approximation and if this possible I would like to work with a one dimensional solution, if one dimensional solution is not feasible I will go for a two dimensional solution. Only we have pushed to the wall that without three dimensional solutions, you will not get satisfactory result we go and attempt three dimensional solutions. The moment you go to analysis of plates and shells it is actually three dimensional problem, you bring in plates and shell theory approximation and try to live in two dimension, you do not want to go in three dimensions so that is the knowledge that will you have to get.

So what we have done is still now, we have done three lectures on overview of experimental analysis. In the first lecture we essentially looked at what is an analytical method, what is an numerical method and what is an experimental method. The second lecture the primary focus was, what is the information I get directly from an experimental technique. The idea is you may be a able to combine more than one experimental techniques and try to get of the 15 quantities some quantities of your interest, but what you get directly is from the physics of the problem physics of the experimental technique on which displaced. And in third lecture we try to look at what a whole field information is because you have to graduate from stress as a tensor at a point of interest, you have to go and find out how the stresses vary over the domain of the model that was the primary focus. And now what we will do is we will go and find out what is the physical principle each of the techniques is based on, now I am not going to get in to the details of how to perform an experiment or how to interrupt data.

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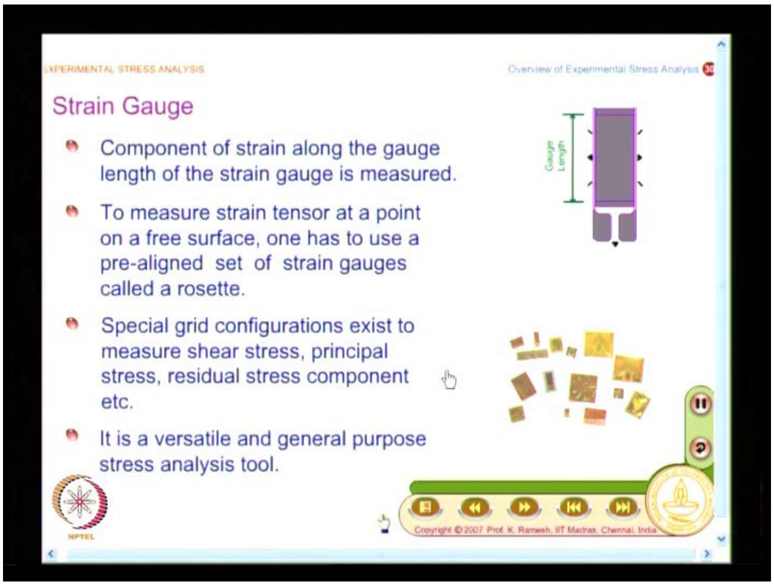


My focus is only to bring out what is the basic physical information each of the techniques is based upon and we will go from the technique like strain gauges to start with, because this is the most widely used technique. And as I mentioned earlier in this you get component of strain along the gauge length of the strain gauge is measured and here you have the typical enlarged view of the strain gauge and you call this as the gauge length.

So a strain gauge measures only component of strain, it is not measuring strain tensor. And what I have is to measure strain tensor I need to have three strain gauges, for you to do it on a free surface and they have to be pre aligned and you also have a name attached to it. If you have three strain gauges on a single based measure the strain tensor you call it as the rosette, you call that as a rosette. And what you have here is you also have special grid configuration you do not stop at only measurement of strain there may be require requirements where you may want to directly find out shear stress or you may want to find out principle stress or you may want to find out the residual stress component. So for all these cases you have special grid configured configuration exist.

And in this I am focusing may attention only on electrical resistance strain gauges and there are many other the measure methods to measure strain you have mechanical strain gauges, you have capacitance based strain gauges and we confine our attention to electrical resistance strain gauges.

And you have variety of them available and what you have to understand is it is a versatile technique and general purpose stress analysis tool. Because if you are working an adverse condition then also the methodology can be used, you can use strain gauges in you know below the sea surface where you have under water pipe line or whether you have offshore platforms you can do this, many techniques may not able to do it. On the other hand if you want to find out what happens on the top of the TV tower I can put a strain gauge and I have telemetry and then acquire data.

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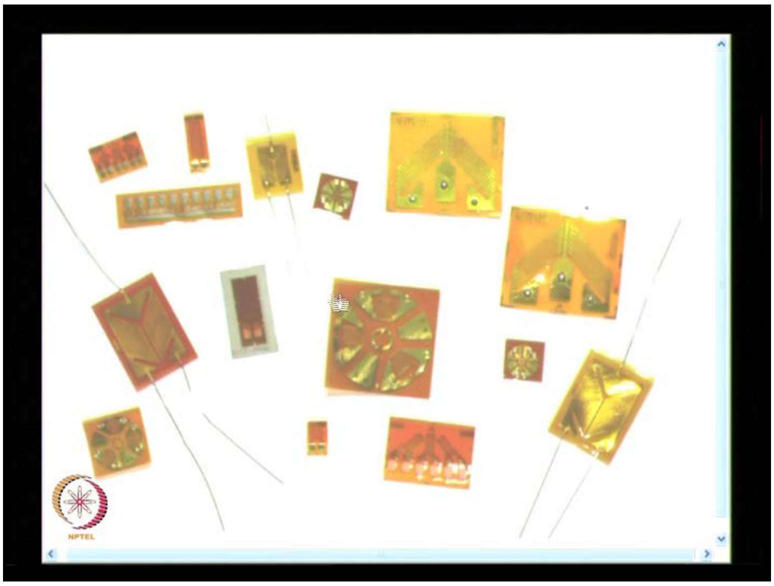

So it is a very versatile technique, it is very widely used and as I also caution earlier it has be used with care. And what you see here is you have a array of strain gauges for various applications and this you have a hole so this is meant for residual stress component. And I mention strip gauges this is what a strip gauges you have a series of strain gauges available in a strip and likewise you have varies grid configuration available.

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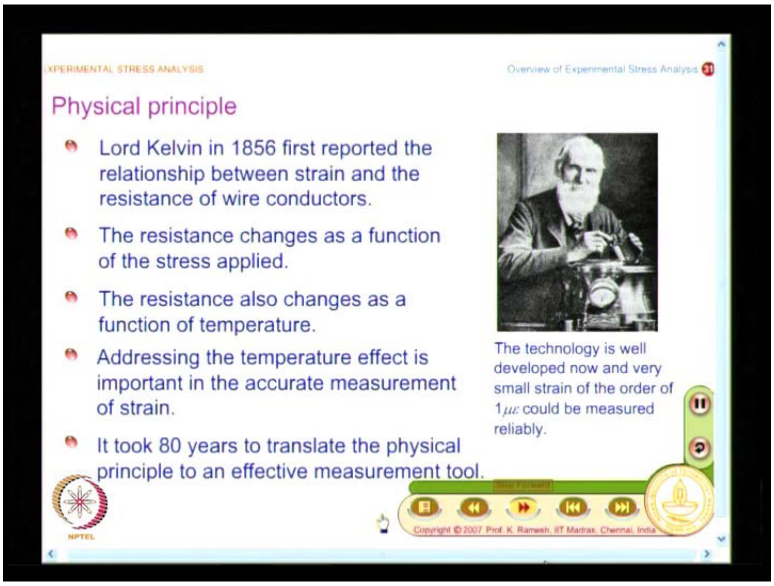


This is on various manufacturers you have given this and what is the physical principle this technique is based on. And it was reported way back in 1856, it was reported by Lord Kelvin and he found out a relationship between strain and the resistance of wire conductors.

So what he found was, when the resistance changes the resistance changes as a function of the stress applied. It was the very exotic information, so the resistance does not remain constant it is a function of stress. So it gives a scope, to meshes stress or strain from the strain gauge, if it is only that then the whole instrumentation would have been much much simpler, but what you find the resistance of a conductor also changes as a function of temperature. So you have a problem so you have a problem the resistance is a function of the stress applied is comfortable for strain analysis or stress analysis, but resistance is also a function of temperature gives you disturbance. And if you look at the technological development, you have to look at how this temperature effect is taken care of.

So what you find is addressing the temperature effect is important in the accurate measurement of strain. And if you look at from the physical principle as a technology it took almost 80 years to translate the physical principle to an effective measurement tool. Why this is so because you need to develop technologies where I delineate the effect of temperature and measure only the strain information. Whatever the resistance change is because of strain and it should be easily available for many people to use it and it took so much time and recently it also celebrated the 50th year of metal foil strain gauges. And what you have now is the technology is very well developed and you can measure 1 micro strain reliably known, very precise technique. And mind you 1 micro strain is 1 into 10 power minus 6 very small quantity, that that is another reason by the technology took so much time not only the temperature effect you are measuring very small quantity you should be sensitive to that, you are measuring 10 power minus 6. And you have to have certain level of confidence in the measurement, that is why the technology took a very long time to settle down and now we can measure 1 micro strain comfortable.

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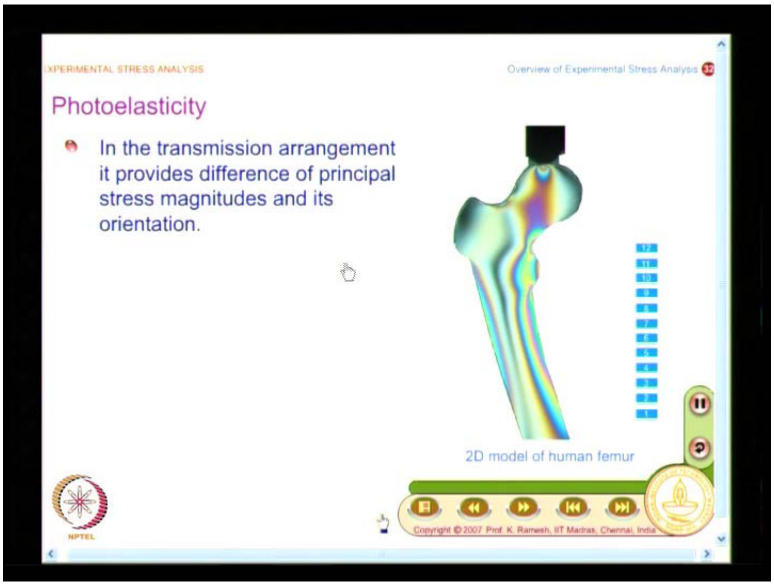


So what is the physical principle here resistance changes as the function of the stress apply. Then we move on to photo elasticity and though this course we will study in detail photo elasticity, right now we will confine our attention only to the physical principle and also bring out you have a transmission arrangement. And this you had seen in the beginning of the lecture also that you have a 2D model of a human femur which is analyze by transmission photo elasticity and you also have a reflection arrangement and the reflection arrangement is useful for prototype analysis.

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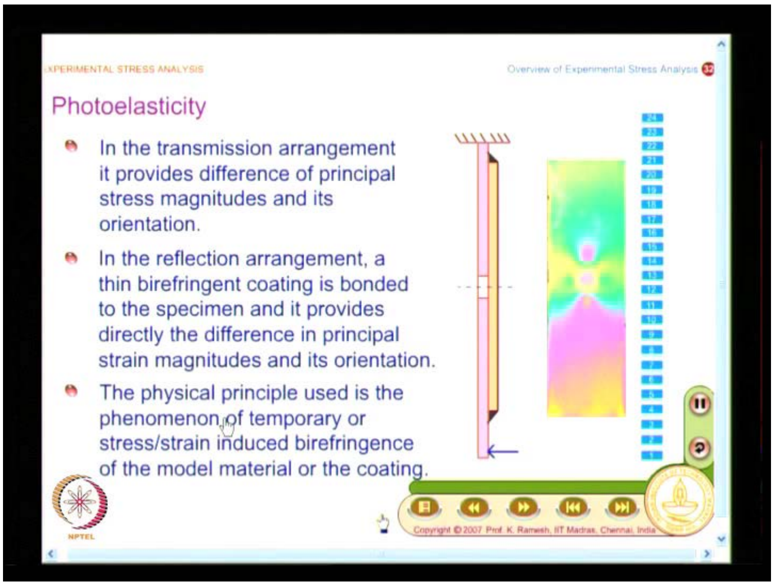


And what you have heard is, I have a cantilever beam and I have a hole and I put a coating, the coating has the property of stress strain induced birefringence. So I can get the fringe pattern like this, so the basic physics behind photo elasticity is temporary or stress or strain induced birefringence is the physical principle used is the phenomenon of temporary, because it does not stay once the stresses are removed this birefringence effect is also removed. So it see what you are having is you are understand birefringence all that will come when you understand crystal optics, and what we have seen in the last class was without getting into crystal optics, you have plotted for the problem of a beam under four point bending, how the contours are sigma 1 minus sigma 2 will look like, you saw the mesh horizontal lines and it matched with what you had seen in the experiment. So what you have here is the physical principle is stress or strain induced birefringence which is temporary.

The moment I removed the loads these effect vanish and you have many development that have taken place in photo elasticity. The photo elasticity is a very versatile technique like strain gauges and in fact in 1930s people when they were developing theory of elasticity many of those solution were actually verified by experiments using photo elasticity.

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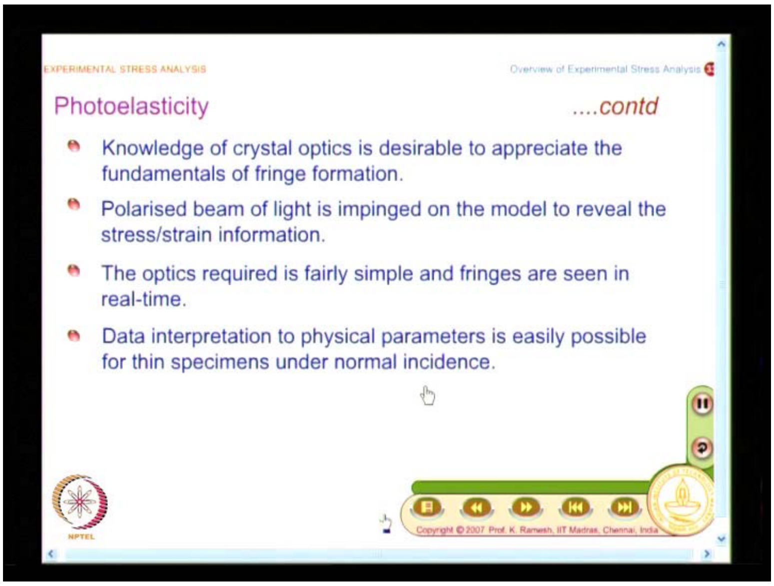


And that is what you are going to see and what you have here is, so you need crystal optics is desirable to appreciate, but we have already said that you can do it by this one. And what you do here is you use a polarized beam of light for reviewing the stress information, and the optics required is fairly simple and fringes are seen in real time this is very important, if you go to any one of the experimental technique for example, if you go to holography you will have a double exposure, only after processing you will know how the fringes are?

So you do not have any guidance on while applying the load whether the load does symmetry is maintain all that you will not be able to know, but with developments with computer based processing you could make even those techniques in real time. So when you look at any of the whole field optical techniques, one of the aspects you look forward is it providing fringe information in real time and photo elasticity does that. And data interpretation to physical parameters is easily possible for thin specimens. And the key point here is under normal incidence that will have to keep in mind if you are having a curved object then what you need to do is, you must immerse it in an liquid which has same refractive index as that and ensure that you have normal incidence.

See when you go to the final aspects of any of the techniques there will be restrictions. So it is a tool and how could you use the tool you get the information, so whatever the experimental technique you look at, you have to look at if it is positive aspects as well as it is limitation, within that constraint you should employee those experimental techniques. And I have mentioned the data interpretation is easy for thin specimen under normal incidence; you will appreciate only when you go to other techniques how difficult the data interpretation is?

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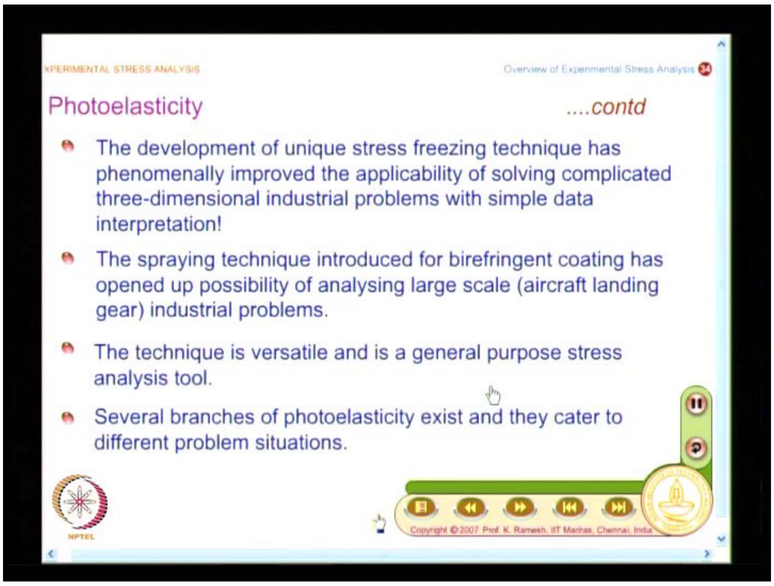


In this case is so simple that we will establish it based on crystal optics at a later point in the course. We have already seen from solid mechanics point of view that you get sigma 1 minus sigma 2 contours. And this technique has advanced mainly, because you have a unique technique called stress freezing, very interesting very interesting aspect. And that has made the application of this technique to three dimensional industrial problems, you know analyzing the problem as a hole is very difficult and what you do here is you take the advantage of analyzing the problem as the hole at the same time from analysis point of view you still ill live in two dimensions by slicing the model in to thin slices.

So what you have here is many industrial problems whatever the engines that you see across, whatever the nuclear reactors you come across the all gone through mandatory three dimensional photo elastic analysis. That is why the designs have become perfect, and designers particularly once the design has stabilized they would be very hesitant to change anything, because of any changes they would affected, there would be a history.

Once it is optimized and stabilized there no want to change it, and in those stages you need very good tools for you to give the pertinent information, if somebody copies your design does not different matter he does not require any test. One a person who develops the design from fundamentals he needs to go through experimental methods, he need to worry about analytical understanding, he needs to use numerical techniques appropriately and arrive at a final design. And if you look at in early stages three dimensional photo elasticity has placed very significant role and particularly because of a very interesting phenomena called stress freezing.

We will see that detail later, now you are being sensitize on what are the possibilities. So this is what in the case of transmission photo elasticity, on the reflection photo elasticity side people have also developed a spraying technique to put the birefringence coating on large industrial components. One of the components that people do is air craft landing gear which is very huge and they still do structural optimization based on photo elastic analysis. And this model will typically cover a two to three story building height, it is not a small model you are actually working on in a suppose they want to develop a 380, they would have only rig for the previous version a 320 or a 330 or a 370. And they would use that loading jack to make a three dimensional photo elastic model, put up a coating and do some structural optimization then finally, develop the landing gear and put it in loading rig and finally verify. So it is done for huge problems on one spectrum, on the other spectrum in dental mechanics if you find they put a flaws, they put a wire which goes round your tooth to hold it in place, those clamps are also analyzed by photo elasticity.

So it is a very small model, on the other hand you have a very huge aircraft landing gear. So the range is very vast and it depends on the user, how he uses the technique and like strain gauges its versatile general purpose stress analysis tool. And when you go to each of the technique what you find there are many many branches, this is only a first level course on experimental stress analysis, I would essentially focus on strain gauges and photo elasticity, because they are most versatile but we will have occasions to look at the physical principle begin other techniques.

Because each technique by itself is very vast, if we take photo elasticity, we are looked at only two variations one is transmission photo elasticity, another is reflection photo elasticity. If you go to photo elastic literature you have dynamic photo elasticity, you have photo plasticity, you have scatter like photo elasticity, you have integrated photo elasticity and there are many many branches. And now you have digital photo elasticity you have many branches to cover all are them in a single course is beyond in a human effort.

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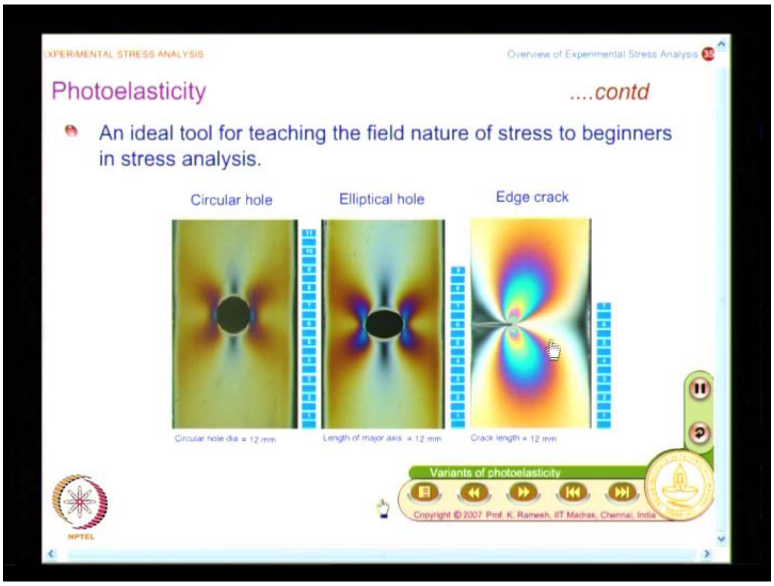


So need to do multiple courses and what you have here is photo elasticity is always an ideal tool for teaching the field nature of stresses to beginners. And here I must tell you you know stress concentration you all know right now, I have a plate with a circular hole, I have a plate with an elliptical hole and I have a plate with a crack. Now anybody in engineering will know what is stress concentration is, but if you look at the history people had mathematician and stress analysis had acrimonious debate, mathematician use to say a infinite plate with the small hole is equivalent to a plate without a hole and only with experimental judgment and other aspects they were able to convince whole lot of things happen the moment I introduces stress concentration.

So people understood there is something stress concentration which you cannot neglected and really when you look at what you find here is I have a uniform stress field if I do not have a hole. The moment I have a hole the stress field becomes biaxial, it is the stress field is also the stress magnetism is very high in this zone and also in this zone this is one thing the stress concentration means stress magnitude increase that is one thing, it just not that even the stress field essentially changes.

And it was English in 1913 who said that when we can analyze an elliptical hole he could do that by theory of elasticity. His result shown crack is not in a centre and crack is potentially dangerous at the that is the time the fracture mechanics does not develop and a new branch of a engineering fracture mechanics came into existence once people understood the cracks are more dangerous. And what you see here is you know I have a crack and crack where you have the least amount of material is removed.

And suppose I take the load as 6 in all the cases I have a plate with circular hole, I have a plate with elliptical hole, I have a crack and you do not need to explain you see you see very few fringes here, you see slightly more number of fringes here, and you see a I have not put that the 6, I put that the seven I this is when I put that the 6 you have a large number of fringes here. So if you have an appreciation of looking at fringe information the density indirectly indicates the stress level are high. So for a beginner you get the field nature, you understand what is stress concentration and you may wonder you know I have an elliptical plate, all these cases are finite geometry, I have a finite width and I have an circular hole.

Analytically what I could do is, I could do infinite plate with very small circular hole and here I will have polar coordinates to determine the boundary condition on the inner surface. And when I go to elliptical hole you have elliptic coordinates to specify the boundary condition on the inner surface, at infinity you could consider as a large ellipse, you could consider as a large circle that is a way you can approach a solution. So for infinite plate with small circular hole infinite plate with small elliptical hole, you have analytical solution possible and this goes by the person who as first solve the problem you have this as occurs this problem in theory of elasticity, this as English problem. And once you come here many have contributed (( )) solution is very prominent, William solution is very prominent. So in theory of elasticity when they analyze infinite geometry with any one of these defects or cutouts you have a name attached to those problem.

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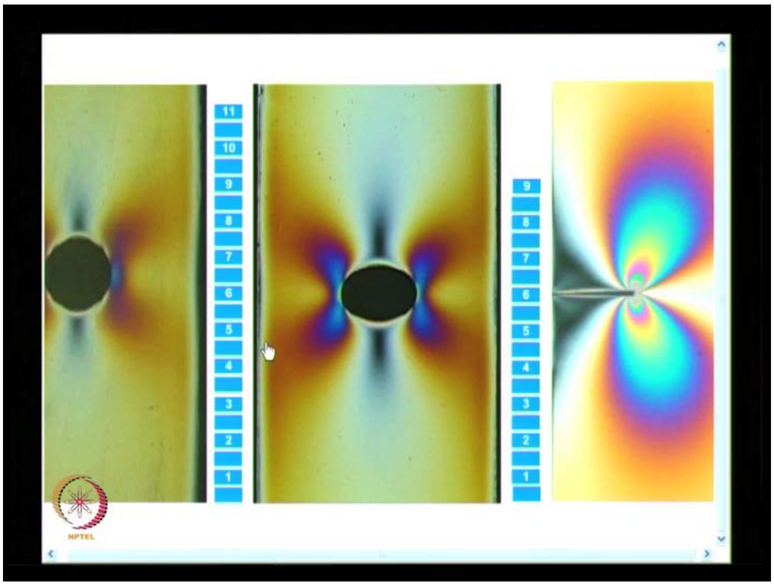


So photo elasticity is very good to understand stress concentration, to understand the field nature without much effort you are able to get it. And you get a closer picture when I have a look at it like this, make a some of you in this sketch and I would like to make a sketch of it. And the essential features you know you have this kind of fringe field and you have a fringe field like this, you have fringes forward tilted and so on and so forth.

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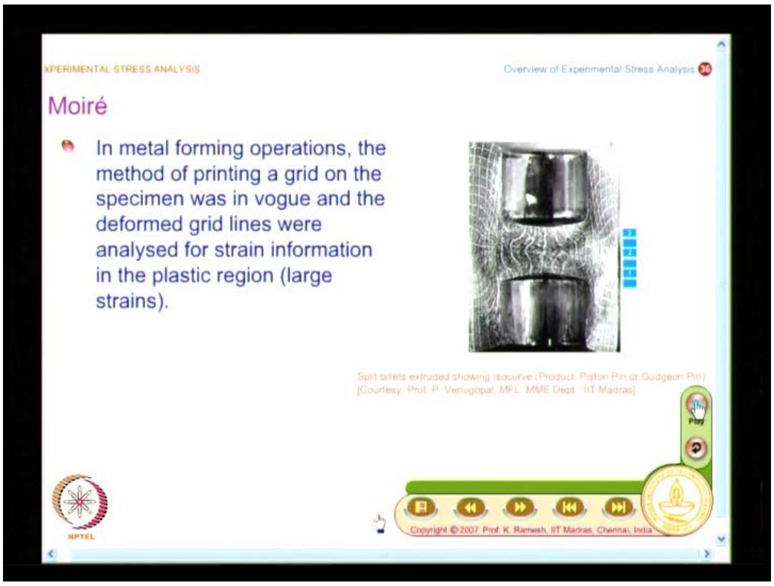


So now what we will do is, we will move on to the next experimental technique, we have already seen that moiré is what we have used for finding out the displacement information. And we will see what moiré is all about and what I am interested to show here is, moiré has an effect of magnifying the displacement that is a way I am going to look at it.

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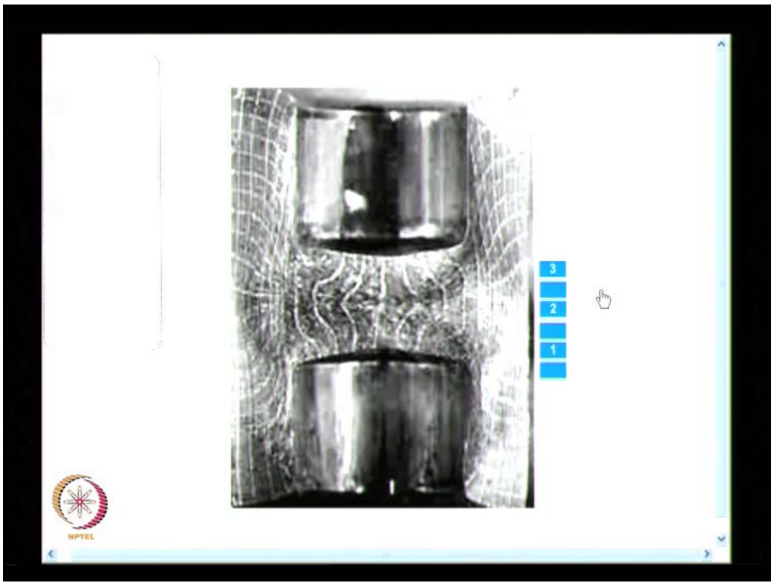

And what you have here is in the case of metal forming processes what they have is they have a billet and they will put a grid. You can see the grid here these are known as grid methods and what I have is when I do the metal forming operation I do a large plastic deformation.

So I am really taking of a very high value of strain and in this you do not require fine measurement even this grid deform like this. So you you get very valuable information on the nature of strain field from this. So, you have very large plastic deformation and for all this metal processing application people use the grid method, because that itself to sufficient to give you some information. And you could see here I have the grid initially and I have the final grid so much deformed.

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So I can really make some kind of quantitative information from this and in fact the credit for this goes to professor P.Venugopal, of the manufacturing where the material and metallurgical department IIT madras. And what you have seen is the get gin pin that is what this information shows and so people have always look at they put a grid, they always wanted how to go and find out very small deformation, this is for large deformation is.

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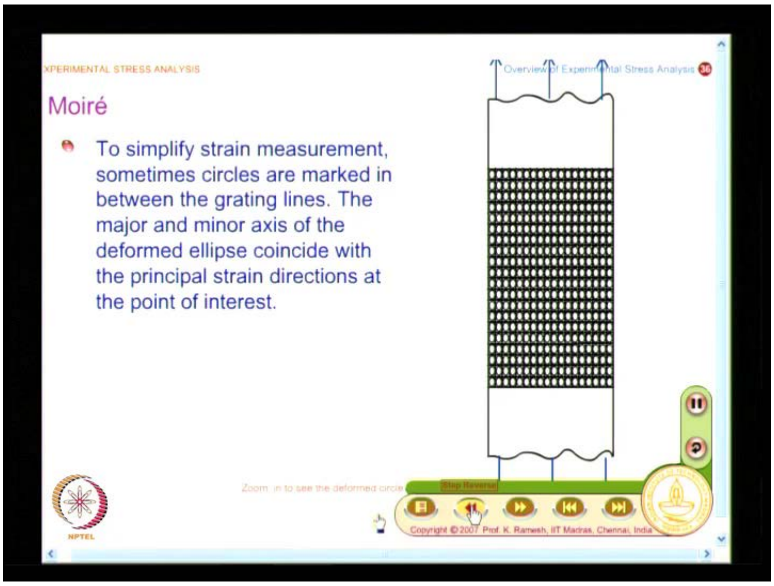

Now what people did is people know also to simplify strain measurement, what you can do is you can have a not only the grid, in the grid you also put a circle.

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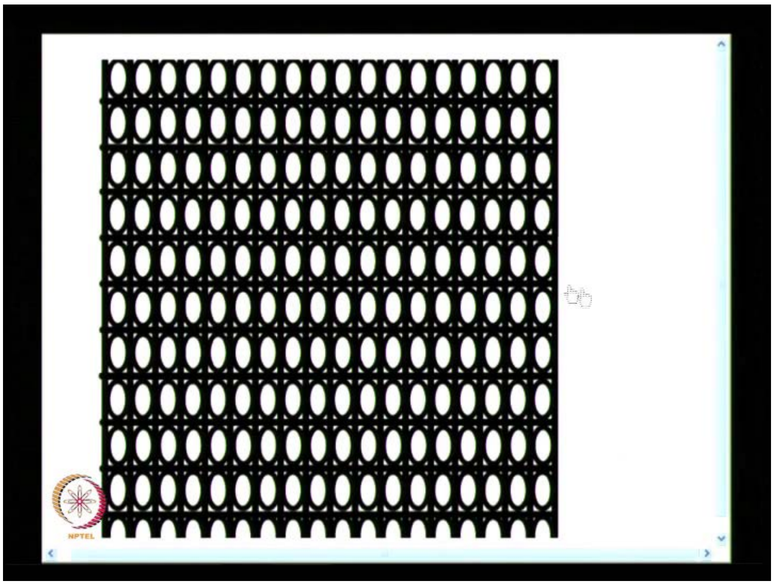

I will show a magnified view and then you see the animation for two three times, you will have an appreciation I have a circle I have circles mark and they become ellipses, circle mark become ellipses. Can you see that so what you find is you also find the stretch direction you also find the stretch direction and by looking at the change in the geometry of the circle, you will also be able to find out some information about the major strain axis, minor strain axis and so on and so forth. So you are able to from the grid if you also put a circle it is advantageous, so I have a circle that gets deform to an ellipse.

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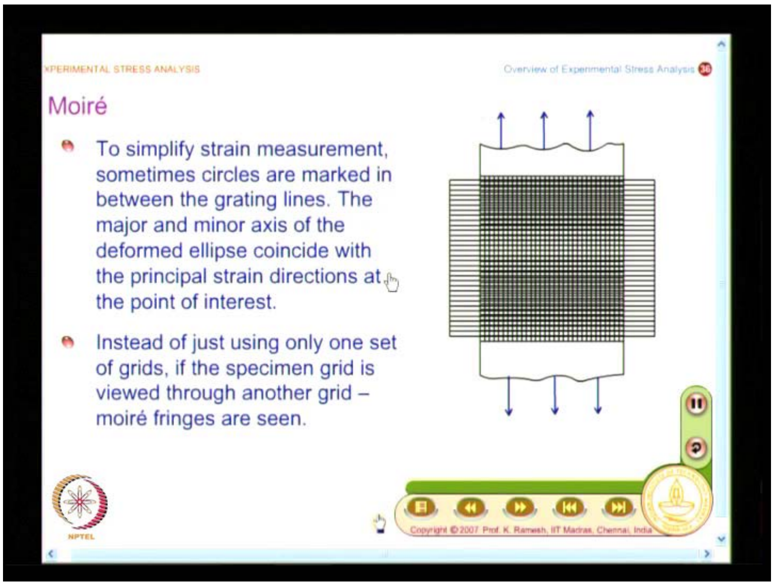


And now what I am want to do is people fell that, of just using a one grid, if I have more than one grid it makes it little more comfortable that is how moiré started developing. And what you find here is I have a specimen, on the specimen I have a grid and I view it through another grid like this. And what you find here is I have stretched it slightly, but I see a play of fringes on the specimen I am able to see the fringes they are horizontal fringes.

So what we have found is people have used initially grids then they improvised it and put within the grid a circle you get little more information from the deformed picture of the grid. Then they realize that if I put not one grid, but I put one grid on the specimen and view it by another grid I get little more information and somebody ask me what is the grating in one of the classes where we said what moiré gives you directly. And what you have here is, this is the grating this is the grating here and this is nothing but horizontal bars here and when I put another grating which is very similar, you see beautiful fringes where I rotate them relatively. So what you have here is it is by mechanical interference you see these fringes. Moiré is not a optical inter parametric techniques it is the mechanical interference of the grid that what you get it so I get this when I rotate it relative to the other I also get it when I translate it with respect to.

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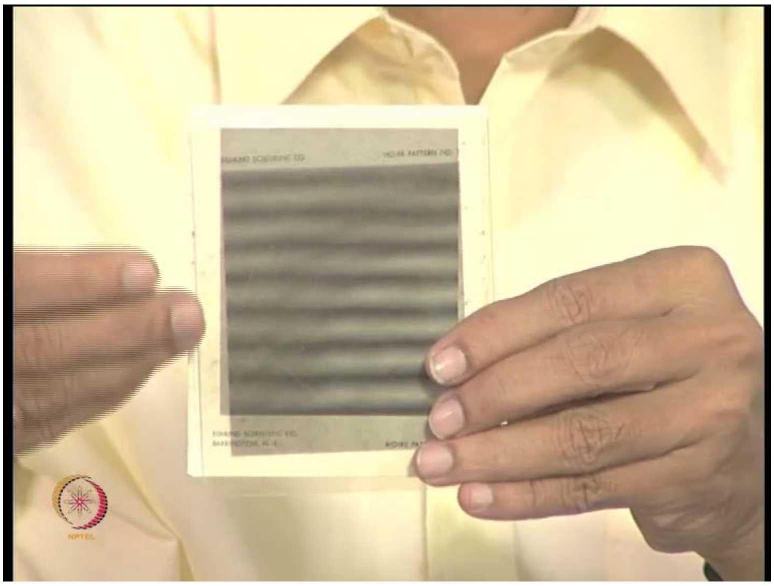

So the idea here is, I get this nice patterns and I can interpreted appropriately if I conduct the experiment very carefully. Here I have shown very course grid, suppose I have fine grids suppose I have fine grids I have you are you are not able to see the grid lines at all and the fringes are lot more smoother the fringes are lot more smoother if I have these the grids finer and finer. And here I am not making any stress analysis, I am only showing you mechanical interference of true grid patterns and the grid pattern can be anything and I have this and I have I have radial lines.

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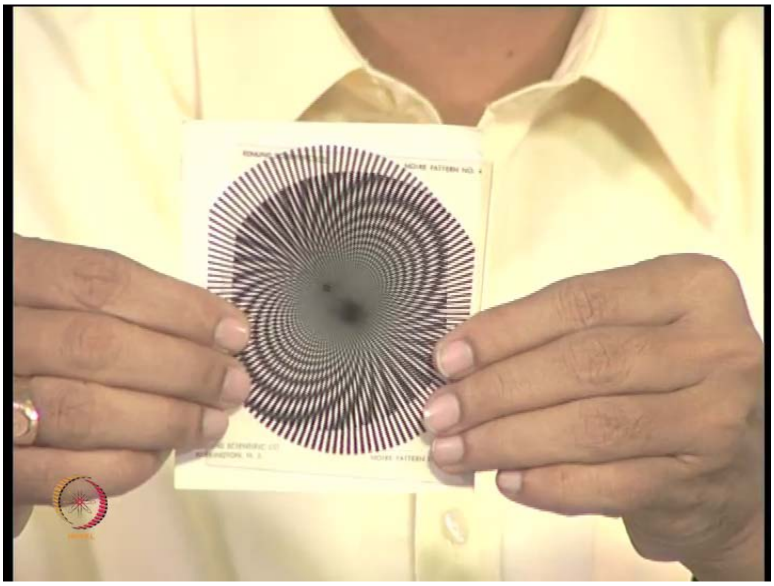

And when I put the radial lines so beautiful may be in Tata salt I thing they have this as the pattern for on that cover. So in you know if you do fairy design or anything, if you want have interesting pattern, you could get from some of this information and do it. I am just translating and rotating the grids with respect to each other, I get nice play of patterns. And what you have to look at is you have to develop these experimental techniques for you to extract information, and like friction moiré is nuisance. Friction is a nuisance of our application, friction is needed in breaking unit friction without friction you cannot have breaks.

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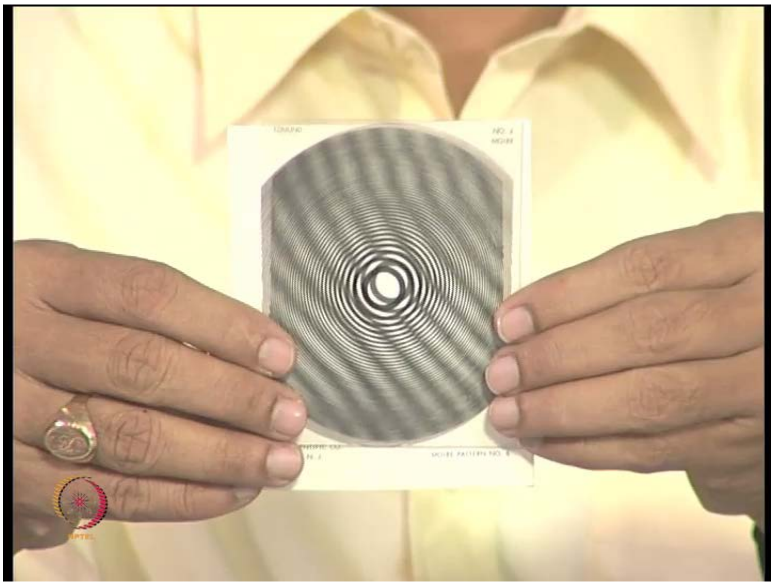

So you do not want friction in certain application where the IC engine you have this piston ding moves you want this way as smooth as possible. And now you have another set of get pattern where I have concentric circle and I and when I move the both the grids I get different set of patterns.

So what you have here is this is called a grating and one is pasted on to this specimen and view it with the another one. So I have a master grating and specimen grating, so what we come here is if you at this diagram very carefully compare to that this is the simulation where I have some control on what way I move the specimen grating. And here the specimen grating is the checked pattern, I have reason for it because I also mention in some application I get only one information and some application I will do one experiment I will try to get two information we will see that. And what you find here is this most slightly, but I see a number of fringes, so indirectly you can understand that its some short of a magnification effect that moiré helps you to measure.

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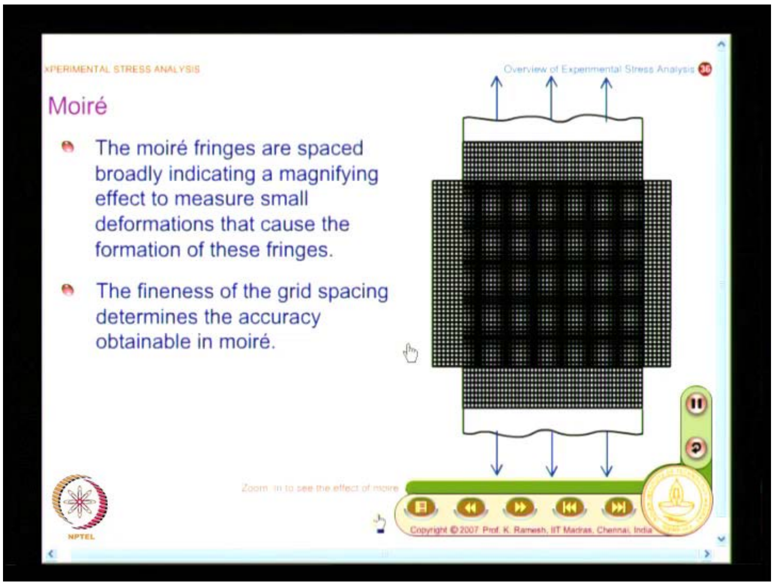


So I want to measure very small deformation and moiré helps better than the grid, and if I want to go for finer and finer information I need to have finer and finer grids. So moiré fringe spacing's, are fringes are spaced broadly indicating a magnifying effect to measures small deformations that cause the formation of these fringes. And if I want improve the accuracy I need to have finer and finer gratings that is what I want to do.

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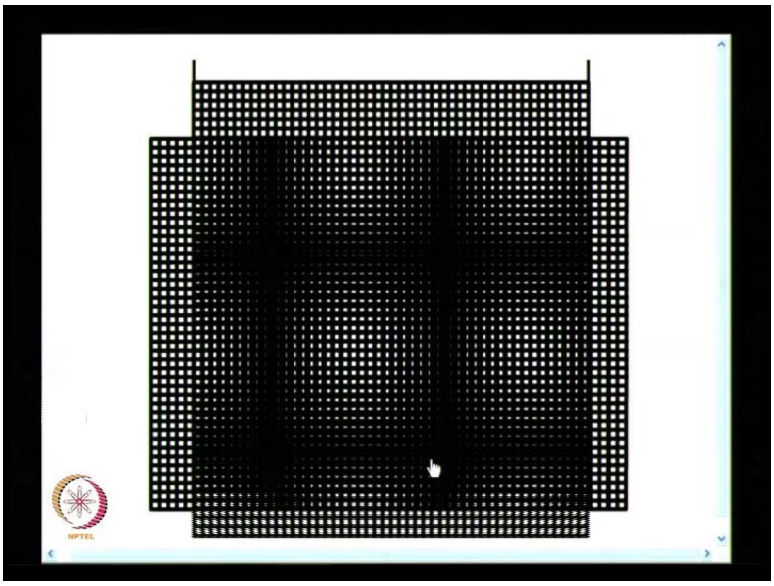

So if I have a finer grating, I have a better chance of measuring small deformation. And what you have here is I have two grids, I have this I called as master grating. This attached to the specimen which is pulled, because of poison ratio effect the thickness comes down, and you see horizontal you see horizontal fringes as well as vertical fringes.

So that means what you have to interpret horizontal fringes separately, because you always seen I have a grating. Whatever the fringes perpendicular to the grating direction you will find out whether the grating is aligned in x direction and you get the v displacement, if the grating is align in the y direction you get the u displacement. Here I have the cross grating so I get simultaneously u and v displacement.

And you know strain is a tensor once I get displacement information I can also find out the slope that is nothing but the strain. And if I want to strain tensor I need three information, people also have develop a grid at 45 degrees super impose over that. And I also caution you know the experimental is develop the technique they develop it and see what maximum information get out of it. But from a user point of view and data interpretation point of view it always better that you have one information at a time. Because you get much better information when you want to do that, so the finest of the grid spacing determines the accuracy obtainable in moiré and that what we shown in here and let us look at some numbers.

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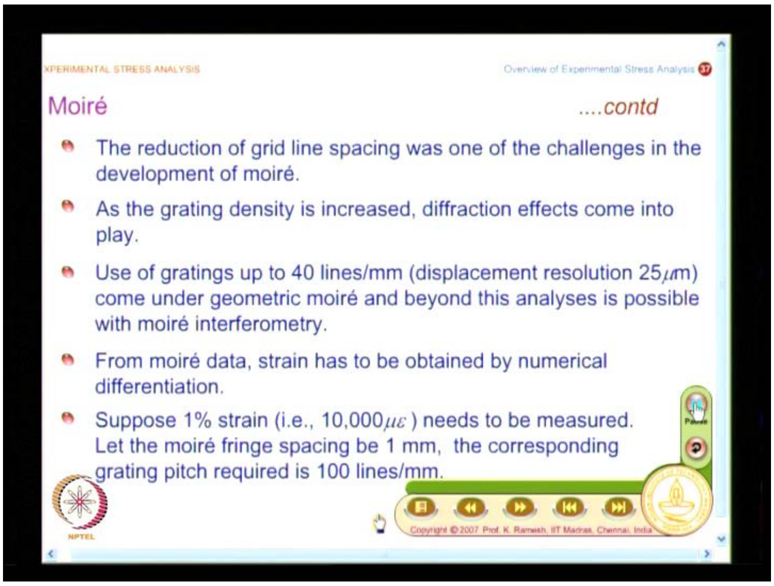

So what you find is if you look at the moiré literature, the grid line spacing how fine it is was the very big challenge for scientist to develop and when you think off moiré you cannot forget the contribution by Daniel Post and its co workers they are developed the technique very well. And as a grating density is increased I will also have do bring in diffraction effect for interpretation, what we find is grid you can easily analyze and I can have some grating, I can use just the geometric information and then interpret the fringes that is what you call the geometric moiré. Suppose geometric moiré we will find the limitation for meet to make finer measuremen,t I need to go finite number of lines then you find from optics point of view diffraction effect have to be brought in an do for interpretation.

So the interpretation becomes little involved, as you go by fortunately whatever the equation that you develop in geometric moiré also equally applicable for moiré interferometry. And what will do is, we decide this based on the line per millimeter if you have 40 lines per millimeter up to that, you can interpreted is based on geometric moiré principle and displacement resolution is of the order of 25 micrometer. And 40 line per millimeter is very fine that result is very very fine that is not a you you imagine you have millimeter is so small and within that you have a 40 lines black and white lines. So it is not something very high, some you it is very fine and you have not worry about that and what you can do is from moiré data strain has to be obtain by numerical differentiation.

So it is better that you go for moiré interferometry where you have final displacement measurement. On let me ask suppose I want to measure 1 percent of strain, thus 1 percent look small or big you go to a bank and ask for a loan, if he says 1 percent you will definitely go and take the loan, because you find 1 percent is small. But it all the some of the smart mans what they do is they 1 percent it, but 1 percent per month that means 12 percent per year. On the other hand if somebody gives you 1 percent as your interest for your investment, you will never put the money. 1 percent in strain analysis is small or big, some says small, if not so it is a very huge value and what I want to caution here is I said that long time back I said the example of somebody going to a doctor.

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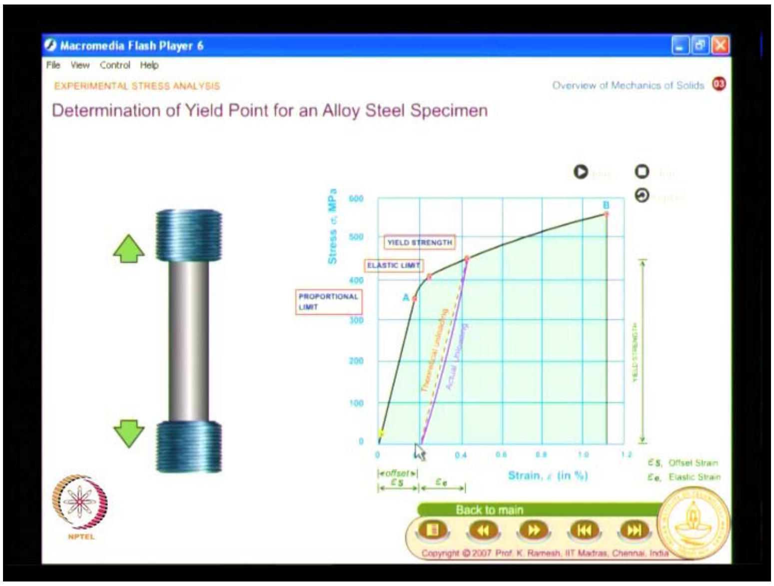


And then finding out whether 1.105 degree temperature is small or big he should not refer encyclopedia and when you have difficulties in finding out the yield point which is not mark sharply, then what you do is you have the offset method and then you locate the yield point on the curve stress strain curve. I have an alloy steel which is pulled here and I have the stress strain data and this is what I have I do not see very clearly the demarcation of the going from elastic to plastic, it is very smooth.

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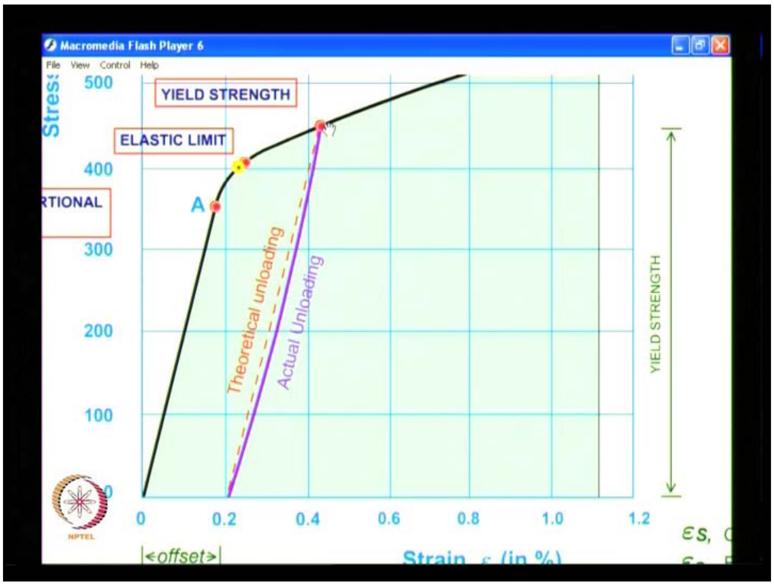

What is usually done is you draw a offset at 0.2 percent and 0.2 percent corresponds to 2000 micro strain. And what you have here is I have this as the proportional limit and this as the elastic limit and you have the yield strength. So what you find is at 2000 micro strain the material has yielded, but you permit that for you to find out what is the yield strength of the material, when you are not able to accurately locate it in your stress strain curve. And many actual components they work under theyyou know I have the component interacting with one another and I have cant launch strain, I have to live much below 2000 micro strain.

So, typically you will live within thousand micro strain also you will not cross that strain in many of your mechanical and aerospace components where you have matting members and you cannot have large deformation there. So 1 percent of strain look small, but it is not small in strain analysis point of view, because at 0.2 percent of strain the material has yielded. So many of this techniques you know, you work only regions beyond yield, so I have to come and measure lower strain then I have to improve my experimental refinement, data accusation and how do I do the experiment so on and so forth. And that is what is done that is what is done in the case of moiré.

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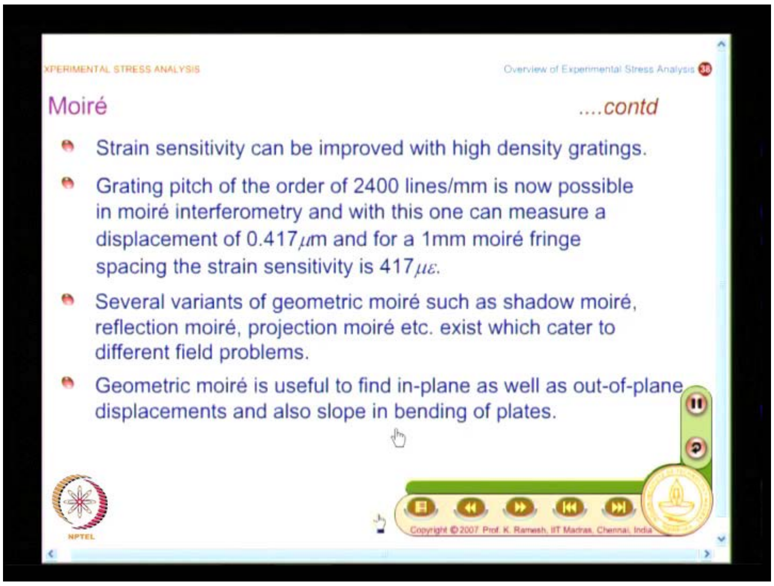


So what you find here is, strain sensitivity can be improved with high density gratings, and what you find is 2400 lines per millimeter is now possible. It is the theoretical limit; people have achieved the theoretical limit by real hard work. And with such high density grating, I can measure 0.417 micrometer, but look at other thing. if I have 1 fringe is 1 millimeter, moiré fringe spacing is 1 millimeter, the strain accuracy is only 417 micro strain. And I said we want to work much below 1000 micro strain. So moiré interferometry has a limitation, it cannot go below a certain level. So it is good for large deformation problem, it may not be good for small strain measurement, but certain specific applications the method of moiré is very, very good. So that is where you know domain of application you have to find out.

So what you find here is the grating pitch of this high order has been used, and like I said you have various photo elastic methods, I have geometric moiré that is what you had seen in some of those simple examples. Then you have several variations, you have shadow moiré, you have a reflection moiré, you have projection moiré, which cater to different field problems. And if you recall, we had seen a reflection moiré has been used for finding out the curvature in the last class. And geometry moiré is useful to find in-plane as well as out-of-plane displacement and also slope in bending of plates.

So, you have to use particular kind of moiré for a particular application, like you use reflection photo elasticity for prototype analysis, you will also use if I want to find out, out-of-plane displacement, I will go for a geometric moiré, I will go for shadow moiré, and then if I want to find out curvature or slope, I will have to use appropriate moiré method. And if I want to have finer and finer measurement, I will go for moiré interferometry, I can go for very small measurement of strain. And do you have any questions at this stage.

(( ))

Yeah

yes

We will see that later, may you know if you look at IC chips a lot of thermal stresses are developed, if you go and look at any one this electronic packaging people are now develops semiconductor technology would to the extend you can pack as many transistors in a very, very small place. But one of the challenging problem there is the heat generation, how would the heat generation is dissipated. And people have done very experimental approach using method of moiré to find out the stresses on the IC chips the legs and all those electronic packaging components. If you want to look at that moiré is only technique which can reveal that, so you have to select the technique for a given application. Now you have distil mage correlation you have grid method these are all for large deformation problem, but for small deformation you have to use if you are able to use a strain gauge well and good I go up to 1 micro strain. But I cannot put a strain gauge on electronic packaging, because that is comparable in size. So you will not do that and if I want still finer measurement I will go for holography and find out very small displacement, for nano mechanics people use holography very well. So there is nothing like one technique has to be patronized, other technique has to be dropped.

For the problem on hand, which techniques is ideal that is one issue; another issue is, whether you have the facilities to do that, you may have a technique available in the literature, but you should also have the facilities, because experimental facilities are expensive. And you may want to design answer yesterday, that is how industries come, they want result yesterday; when they come today, they want result yesterday. So, you have to solve the problem in a very shortest possible time. So we will also discuss towards the end of overview of experimental analysis, a detailed discussion on, how do you go about selecting different techniques? Very general guidelines; you may not have there is nothing like one to one matching for you to find out, the technique for a particular problem, you can have multiple techniques, so it depends on varies factors. Thank you.