Experimental Stress Analysis
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Lecture – 07
Selection of an Experimental Technique

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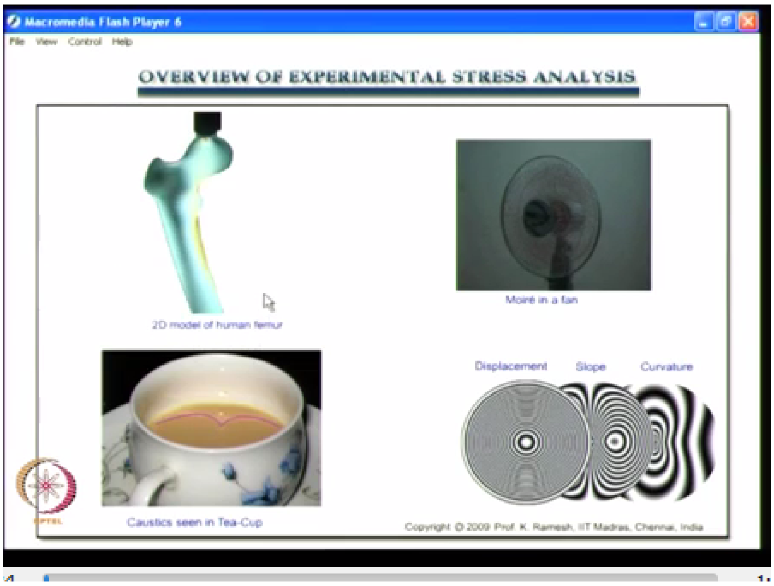

We come to the concluding part of our discussion on overview of experimental stress analysis and this slide was shown at the beginning of this chapter now you must be a lot more familiar on identifying various techniques that are depicted in this slide. Here, you see the use of photo elasticity for finding out the stress patterns.

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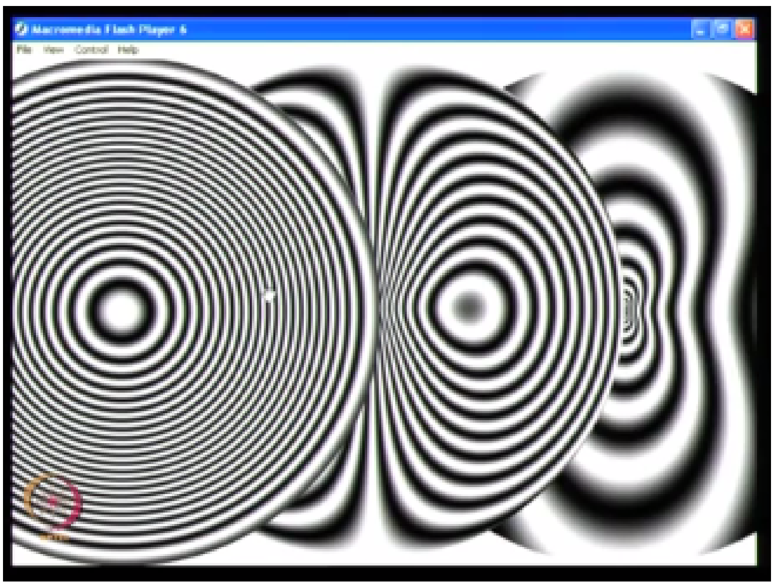

And here you find the use of techniques like Moire, holography or shearography to reveal various fringe patterns and you find here this as the out of plane displacements. Now, you know that this is the slope, this is the curvature information and each of this requires separate optical arrangements and you may be able to get this displacement by the technique of holography or speckle interferometry or shadow mining.

What you see is the simulated fringe patterns and when you really make an experiment, the fringe patterns will follow this closely but the quality of the fringes depend on what does a technique that is being used and the moment you come here, you see this as butterfly fringes and this you get from shearography, you can also get it from a variation of Moire and similarly you get this curvature fringes and curvature fringes what we saw?

We saw that you could get it from sharing interferometry or you could also get it from some variation of Moire technique. So, what you find here is now you have a familiarity how the whole field information looks like, so this knowledge will go a long way in appreciating when you do the experiments what you have the patterns and how you have to interpret them and so on and so forth.

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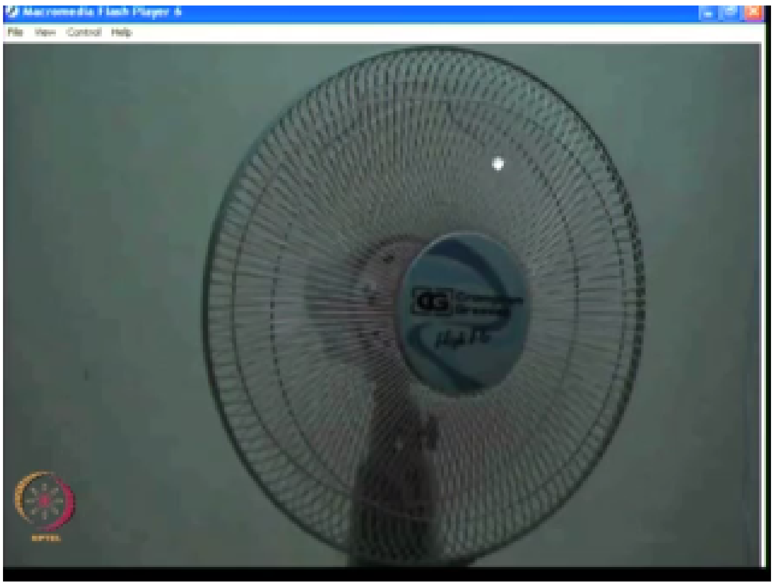

And these two corners slides bring out the physics, so each of the techniques there is a physics behind it and you have seen this is a method of caustics and this is what you have seen in the case of Moire and you have beautiful Moire patterns come and the term Moire has a origin from French, you have watered silk that was named as Moire and the same phenomena is when I seen in 2 gratings, it is also given the same name.

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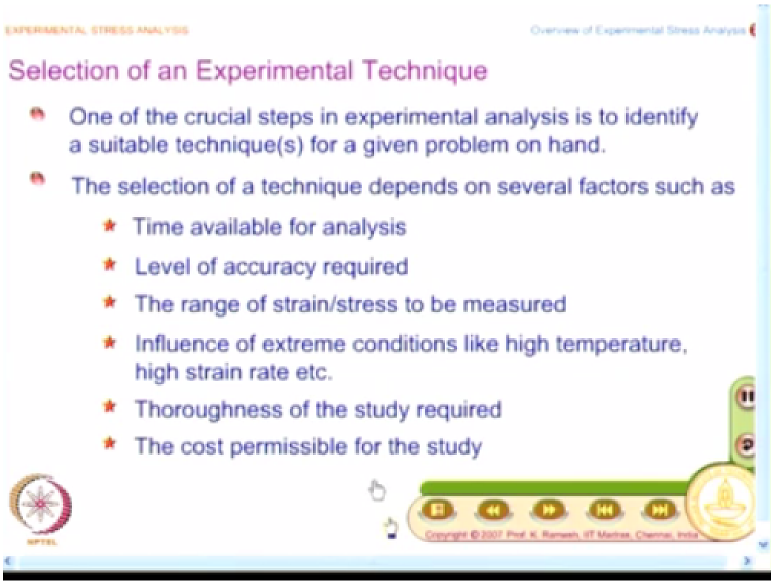

And we have been discussing on selection of an appropriate experimental technique and what we will do is we will go back and then review what we have seen till now. One of the crucial steps in experimental analysis is to identify a suitable technique for a given problem on hand and we have seen that it depends on several factors; time available for analysis, level of accuracy required, range of strain or stress to be measured, influence of extreme conditions like high temperature, high strain rate etc.

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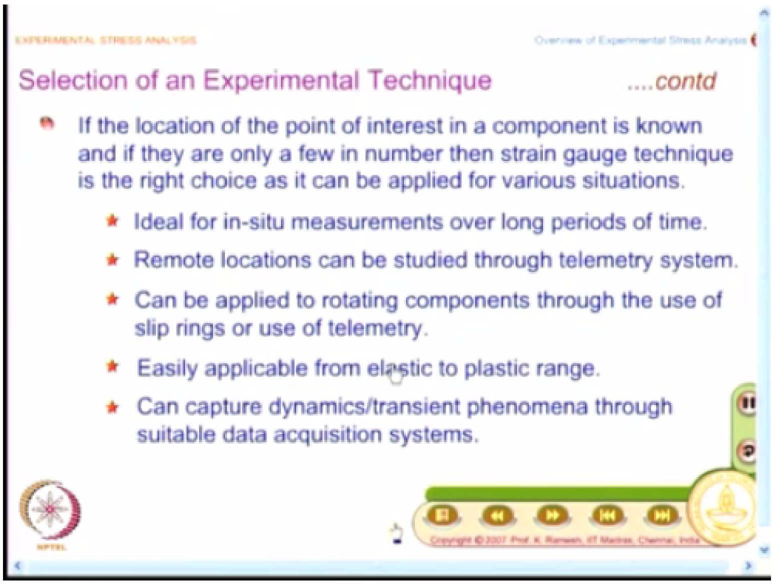

Then you also have to look at what is the thoroughness of the study required and finally the cost permissible for the study that is also equally important. Then what we looked at was; if the location of the point of interest in a component is known a priori and if only a few in number, then strain gauge technique is a right choice as it can be applied to various situations and one of the greatest advantage of strain gauge is ideal for in-situ measurements that is becoming necessary for monitoring structural health which is called structural health monitoring.

And you need to do that for bridges, you need to do for dams and several structures are monitored over a period of time and this comes as ideal technique for that. You can also study for remote locations, you can also do it for rotating components and you can also work from elastic to plastic range and also dynamic or transient phenomenon. So, what we find here is; it is more of a general purpose technique and this is very advantageous when you go in for strain.

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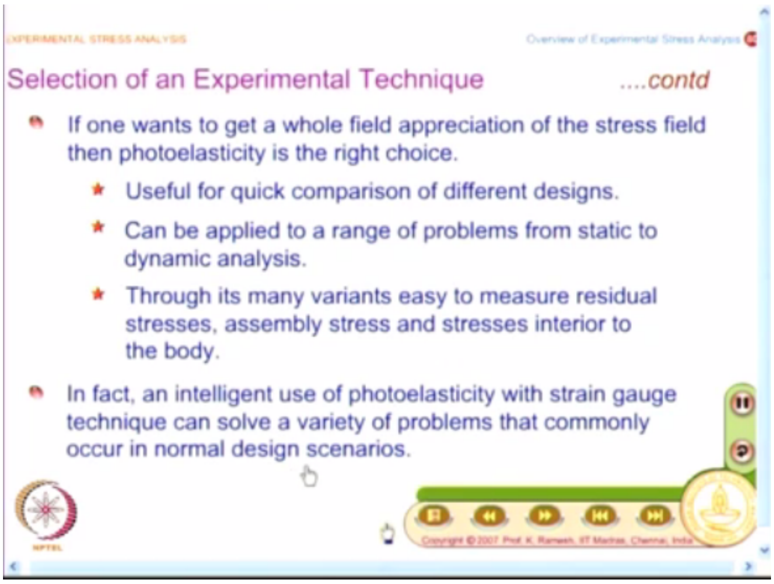

If you want to get some information, then you can always fall back on strain gauges in some way or the other, then what we have looked at first; we have also looked at in detail, certain issues about using photo elasticity. Suppose, I want whole field appreciation of the stress field, then photo elasticity is the right choice. We have seen for a stress concentration problem played with the hole, played with the elliptical hole.

And then you also saw a crack problem and you also saw the spanner different designs, so when I want to know what happens on the entire field photo elasticity, you would be able to do it quickly and as again, this also can be applied from static to dynamic analysis and you have many variants of photo elasticity, they can be selected for measuring residual stresses, they can also be used for assembly stresses and most importantly stresses interior to the body.

Anything interior whether you want to do it on human body; if you want to do a heart surgery it is much more complicated then what you can do on the surface. It is very expensive it is also delicate similarly, when I want to go and look at what is interior to the body, the problems are always complex and photo elasticity provides the revenue and you might have seen recently in the papers that Honda has asked certain components to be called back in the recent cars that they have fabricated, they have released to the market.

So, when you are really looking at the design, you have such flaws and people have to call back and then replace the component and in such applications, a detailed analysis involving both numerical and experimental analysis are must and if you go back in history, many engineering applications people have done detailed 3 dimensional analysis using photo elasticity. So, this is one of its strong points as far as photo elasticity is concerned.

And what you have is an intelligent use of photo elasticity with strain gauge can solve a variety of problems that commonly occur in normal design scenarios. Not only normal design scenarios, in also in special situation in fact you, have conquered aircraft though it is grounded now after the accident in France, this was one of the aircraft which had the least amount of failures in the field there were no accident, still it was grounded.

And it had a tail rudder, which was failing repeatedly, you know in those days about 70s, they are also done a finite element analysis to find out the cause for the rudder failure, from finite element point of view the rudder is found to be reasonably strong to withstand the service loads but nevertheless it was failing. Then, what they did? They took a strain gauge and put it on the rudder and made measurements.

When they compared their strain gauge values with design calculations, it also showed it is within the permissive limits. Then, what they did was; but the component was failing in the field, so you have to find out the cost, so something what they could not identify from numerical technique or a point by point experimental technique forced them to go for a whole field experimental measurement.

So, they applied a photo elastic coating, then they found the maximum stress point was slightly shifted and strain gauge was reading only 2/3 of its maximum value, so the moment they applied photo elastic coating identified the point of stress concentration, then they put strain gauges, then that design was perfected and the problem was solved. So, what you need to do is;

in many instances, in practical problems identifying what to do; which are the critical area itself, is a challenge.

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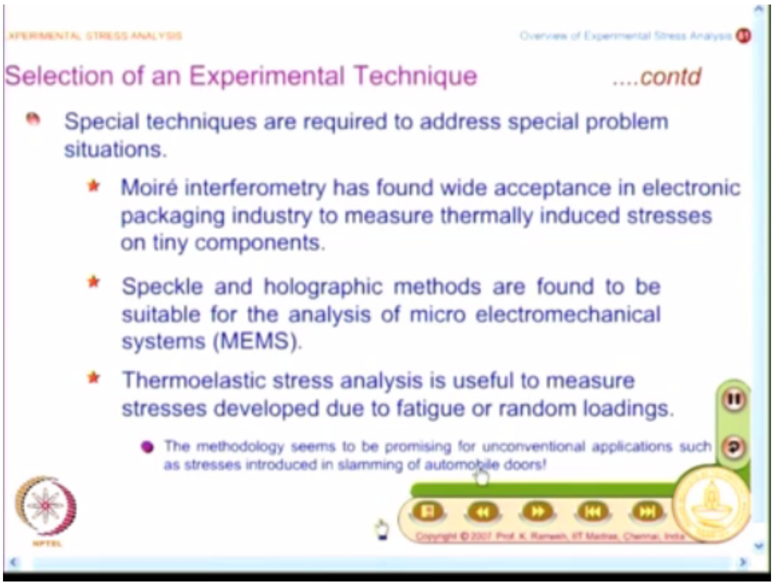

So, a combination of hole field and a point by point technique they go together and they help you to solve the problem, so day to day design problem you can handle and also in special situations. So, you can always fall back on either photo elasticity or strain gauges. For special situation what you have to do? You have to go in for special techniques, so you need special techniques to address special problem situations.

And the moment you think of Moire interferometry, you have to think of electronic packaging industry and you find it has found wide acceptance in electronic packaging industry to measure thermally induced stresses on tiny components. In this application, Moire is ideally suitable mainly because the components are very small, I cannot go and paste a strain gauge and Moire gives the whole field information.

And researchers have convincingly shown that Moire is applicable for these class of problems and we have seen for MEMS application, speckle and holographic methods are ideally found to be suitable. We have seen MEMS sensor how speckle method could be employed and we also saw in one of the references, they are used holographic method to study a micro gear rotating at 3, 60,000 rpm.

So, MEMS application if you have the need, then you think of either speckle or holographic methods. Then what you have? You have the method of thermo elastic stress analysis and this is useful to measure stresses developed due to fatigue or random loadings and there is a very special application people have applied using thermo elastic stress analysis. The methodology seems to be promising for unconventional applications such as stresses induced in slamming of automobile doors.

See, you may think it is; is it a problem worth analysis in fact, you know more and more competition on automobile industry, people are very particular about the shape, so they keep changing the shape of the automobile and they are all having streamlined contours, they also travel at very high speeds and there is also a pressure on them to bring out new variants and this is all sheet metal work and you need to find out for the given life, whether the doors will withstand.

So, slamming of the door is a random loading and people found because it is a 3 dimensional problem, it is not a 2 dimensional problem because you have a contoured shape and when you slam it and you need to make the measurement and people found that you can apply thermo elastic stress analysis. It is very interesting, so as technology advances you also get newer and newer problems in fact, if you compare the olden days, the cars did not have smooth contour.

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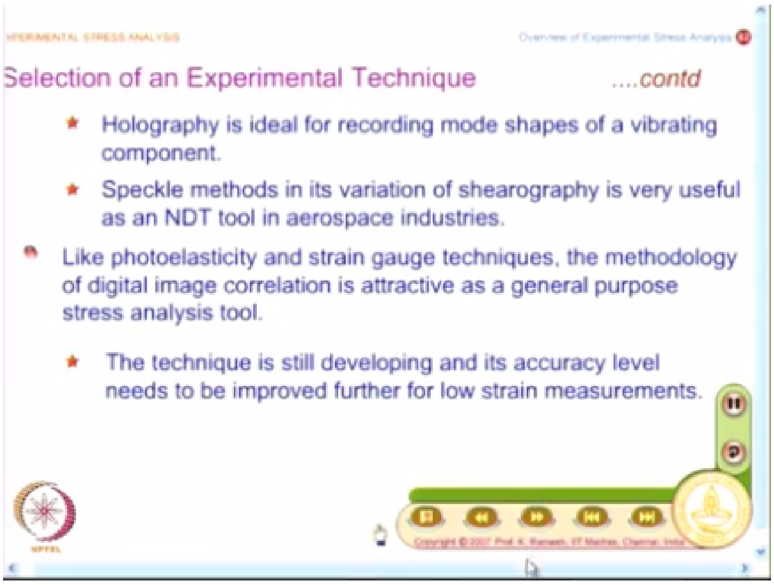

They were having box type and things; I am talking of 70 to 80 years back. Now, what you have? They all have streamlined contours, new manufacturing technologies and more and more increase in speed, so all that brings in new class of problems which also require newer techniques to solve. The moment you think of vibration; holography is an ideal choice. See I do not know whether you have done some experiment in your laboratory.

When you want to find out the mode shape, you would normally sprinkle sand or lycopodium powder on a flat object as long as I am working with a flat plate of different shapes, I can do the analysis with sand or lycopodium powder, find out the notes. Suppose, I want to do it for a turbine blade, which has the complex aerofoil shape and it is also twisted, so that is where holography came to the rescue.

Because it is essentially out of plane measurement technique, it found interesting application on finding out the mode shapes of a vibrating component and more and more the composites and honeycomb panels are used in space technology, so they all have the delamination problem and speckle methods in its variation as shearography is very useful as an NDT tool in aerospace industries.

And I have already caution that if you see butterfly fringes, you should not be happy you should be rather sad that you have so much of delaminations and you need to go and repair it, then inspect, then only send. So, you have to be very careful about that and what you need to look at is I have been saying photo elasticity and strain gauges are general purpose tools. On similar lines, methodology of digital image correlation is also attractive as a general purpose tool that technique is still developing.

And its accuracy level needs to be improved further for low strain measurements. Sometime back, the low strain was about 160 micro strain, now people say even you can go up to50 micro strain, so as the technology is improving, you are also improving the capability of the technique to measure smaller values of strain and this has a great potential. So, if time permits, we would also have some discussion on image correlation as we go by.

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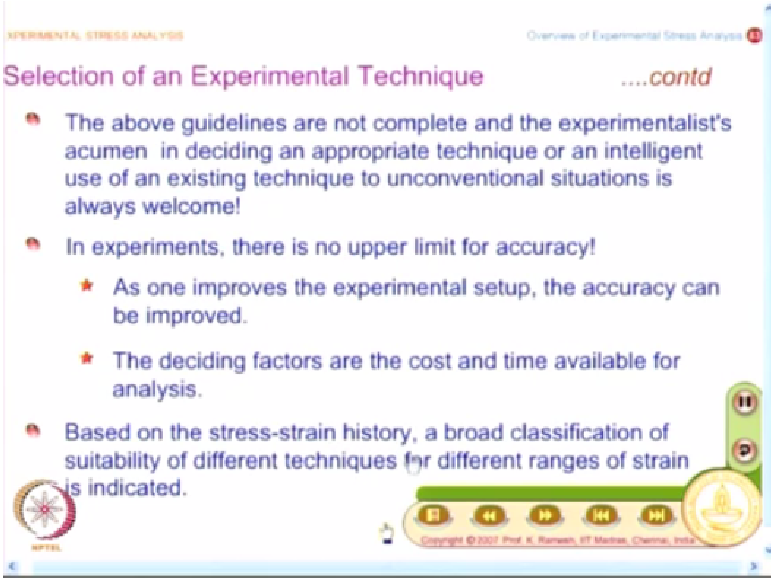

Then what you have? You have to keep in mind that whatever the guidelines that we have discussed so far they are not complete and the experimentalist acumen in deciding an appropriate technique is very much essential and you will also have to use a intelligent use of an existing technique to unconventional situations is always welcome, you should never forget that.

Because you know seemingly complex problems you could attack it intelligently with simpler combination of existing methods, so you are engineering acumen is required, like doctors have the acumen in detecting what is the disease, you people go to only to that doctor when he is able to identify the disease correctly and then solve your problem. So, similarly engineers also have to understand what is the requirement of the given design scenario, select an appropriate technique and solve the problem.

It is not that you know you; you are given a problem and you say that you will not be in a position to solve, designers want some answer which they can use, they can always use a factor of safety, if there is fuzziness in the answer but some answer is always required and another issue is what is the level of accuracy that you can expect in experiments and you have to understand, there is no upper limit for accuracy.

You can keep improving the accuracy in an experimental technique, you may start with a simpler rig and you make some measurements and once you understand this scenario you may want to improve it as much as possible, so as one improves the experimental setup, the accuracy can be improved. So, there is no upper limit for accuracy and you can keep improving the accuracy of an experimental technique.

And what decides? It is a cost and time, the deciding factors are the cost and time available for analysis. So, if somebody; designer wants a quick answer, you could give a number with certain level of accuracy and he can always use a factor of safety and carry on with the design and if you want the very precise analysis see normally, when people design if they want to make a helicopter to fly, they will make it fly first, optimization comes later.

So, only when they go what optimization, you need refined analysis and when you are talking about accuracy, I would also like to caution when you compare your experimental results with analytical solution. For example, if I want to find out the free end displacement of a cantilever, so you have PL cube/ 3EI and what you will do is; you will find out what is the displacement from your experiment and for the moment you consider that there is no shear deformation, the depth is very small.

But even then, when I make my analytical calculations I need to feed in the value of moment of inertia and moment of inertia is BD cube/ 12 and if you do not measure that depth of the beam correctly, then what will happen? You will make an error on analytical calculation of the displacement because I have BD cube/12, it will have a very high error and PL cube/ 3EI will not match with the experiment.

So, you should not always blame the experimental technique when analytical and experimental techniques do not match. In your analytical calculation, have you provided correct numbers for you to do the calculation? That is also very important, people ignore see if I give a 10 specimen to a student, he uses a scale and measure the thickness, you want to use a Vernier and then measure the thickness.

When thickness has to be measured, small distances have to be measured you should use the precision and this many people ignore, when they compare analytical method results to experiment even for analytical calculation, you need to feed in some measurement by making actual measurements on the component or the object. So, these measurements also to be precise and you should use principle of statistics, take few measurements take an average all that you should employ.

People never use statistics, they go and measure once and then say that this is the value, you will always have to have averaging procedure, so that is also equally important. So, when we say experiments there is no upper limit for accuracy you should also caution when you are doing analytical calculation, those calculations have to be accurate enough and what we will look at now is based on the stress strain history.

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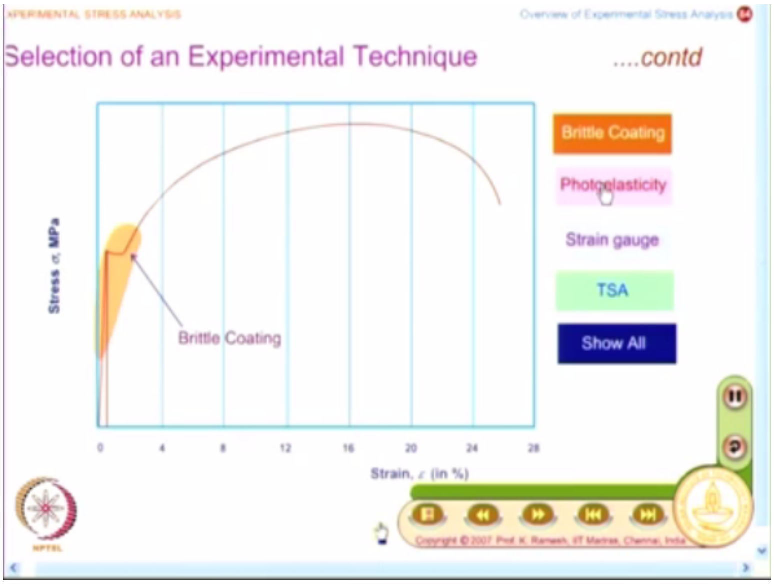

We will look at a broad classification of suitability of different techniques for different ranges of strain in the next slide, so this is what we are going to look at. So, you can broadly classify based on the stress strain range you want to find out and I have taken a typical stress strain graph, the idea is to show that I have a very small elastic region and a very large plastic region, the idea is to show that and what we will look at is; you make a sketch of this stress strain curve; a typical curve.

And we will go one after another brittle coating, photo elasticity, strain gauge, thermo elastic stress analysis, in which range can we use it? Because a visual representation always helps to quickly identify am i working on elastic or plastic region and what we are looked at in brittle coating. Brittle coating; we all said that the failure strain of the coating besides the lower limit and we saw that it is about 300 to 500 micro strain.

As newer and newer materials are developed, you may be able to bring it down but the threshold limit is about 300 to 500, so you will have brittle coating in this zone, so you are operating in this zone. So, you have to start from this portion to this portion, this shape of the shadow is just for convenience, shape of the colour is just for convenience, so it is about 300 micro strain will be like this.

Because we always know that when it has this elastic point, it is about 2000 micro strain, so we talked much below that and we cannot go to lower strain levels in brittle coating and this has been used to identify plastic deformation, so this is the typical range where brittle coating can be employed. What you need to worry about this is the end point and the start point roughly; roughly this range and when I say photo elasticity, what does it indicate?

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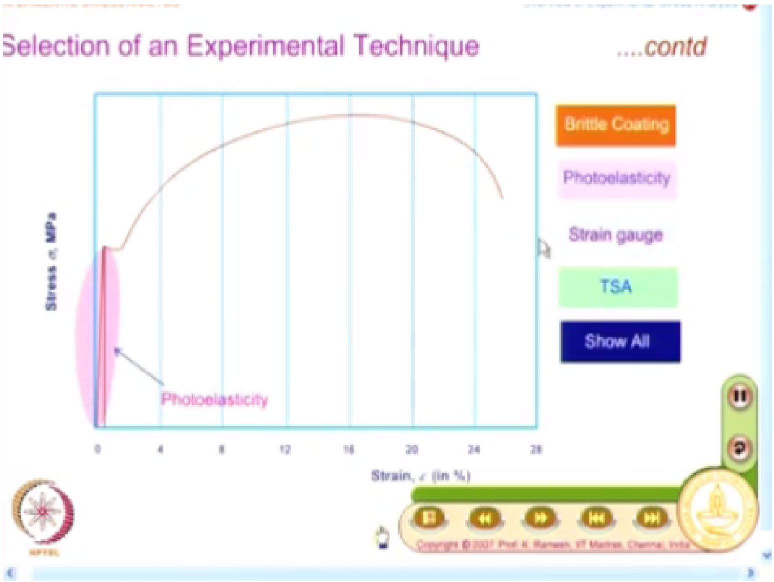

I am essentially living in the elastic region, so a photo elastic analysis will confine only in the elastic region, it will give you information, if I have to go for plastic region, I have to go for photo plasticity. Currently, we are only looking at photo elasticity, so you will get this information for the elastic region and the moment you come to strain gauge, we have seen currently you have techniques which can measure even 0.5 micro strains.

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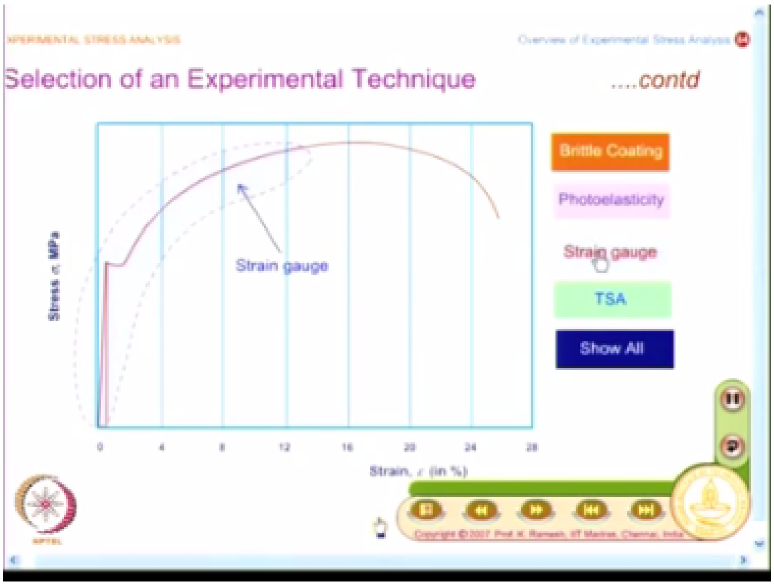

So, that means almost close to 0 and you can also go to the plastic region about 10, 12% of strain, you can easily measure with strain gauges. So, you can also understand why we say strain gauge is a versatile technique, so it has a longer range I can go from elastic to plastic comfortably.

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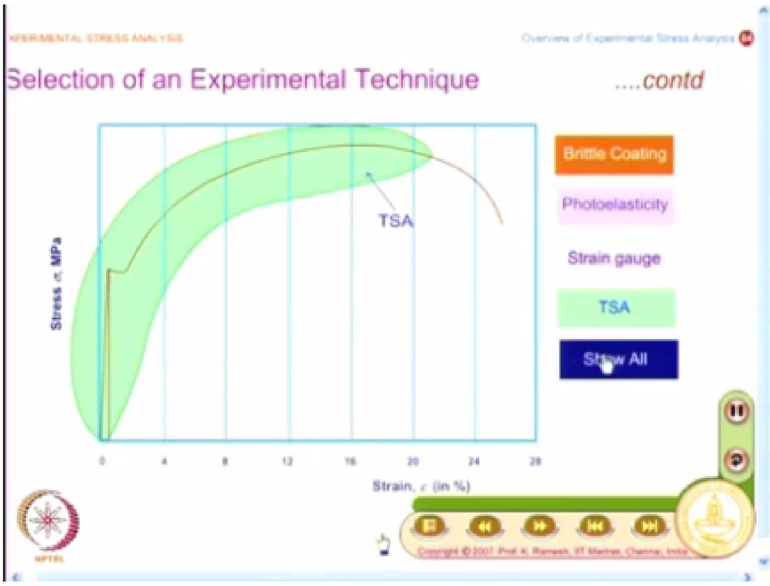

And thermo elastic stress analysis is proposed as a whole field strain gauge technique, that is how they are propagating the technique now and you can go from elastic to plastic region and this is more of a whole field representation but the instrumentation is very expensive, understand that. Strain gauge instrumentation is lot more simpler when you compare it to TSA but even that instrumentation is costly, it is not cheap and now you have a relative zones for different techniques shown.

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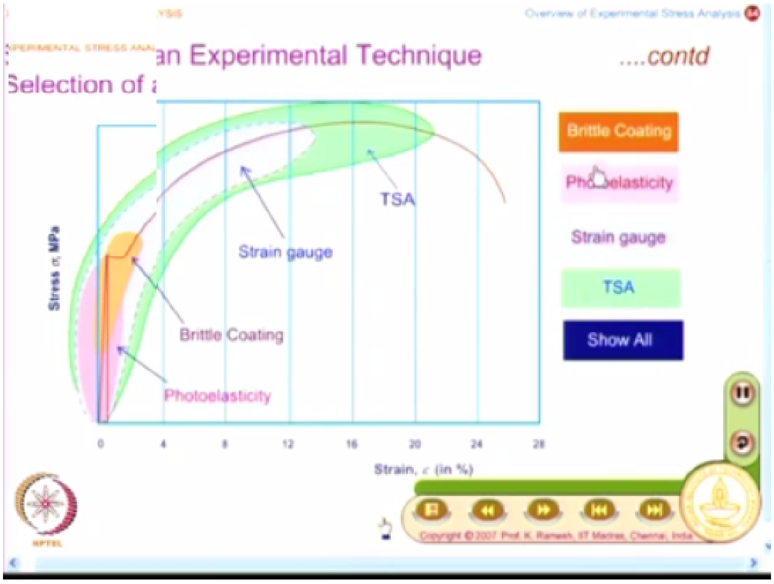

So, this is TSA, this is a strain gauge, this is brittle coating and this is photo elasticity. So, when you are confronted with a problem where you need to find out strain in a particular region, this graph you will be able to find out which way you will select the existing technique okay. I have shown only 4 techniques here, we will have a similar graph for other 4 techniques.

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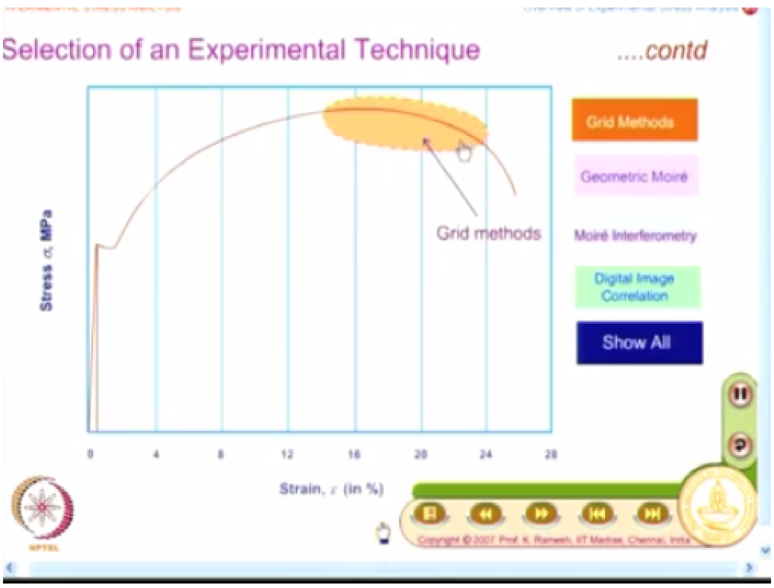

They are grid methods, geometric Moire, Moire interferometry, digital image correlation and you know grid methods were the one, which is used for very high plastic region, then you have geometric moiré and Moire interferometry is refinement of geometric Moire and digital image correlation. It has a large range but it does not have accuracy at lower strain levels. So, when you look at grid methods, the range is somewhere here.

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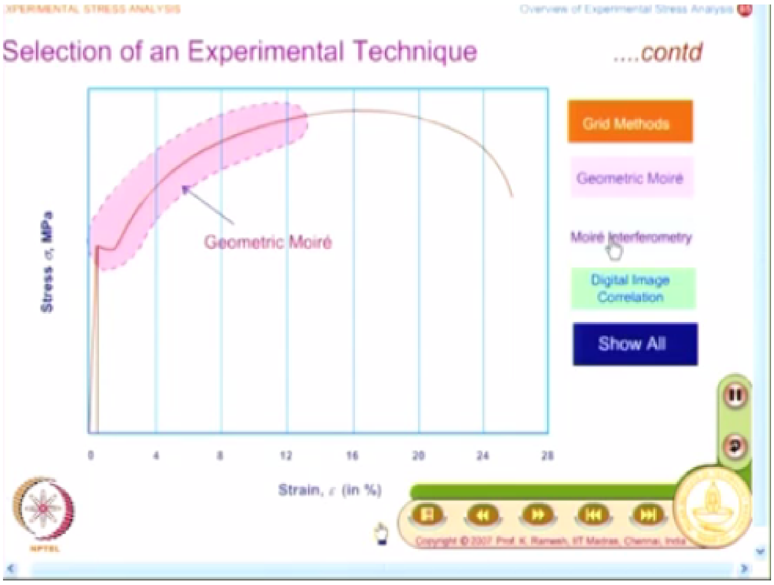

It is only in the highly plastic region, you have the grid methods are applicable and when you come to geometric Moire, I would have it somewhere here, this is how I will be able to do this and if I want to lower this, then I can go for Moire interferometry and what you need to worry about is this end point and start point. This shape is for convenience, for aesthetic beauty some shape is drawn.

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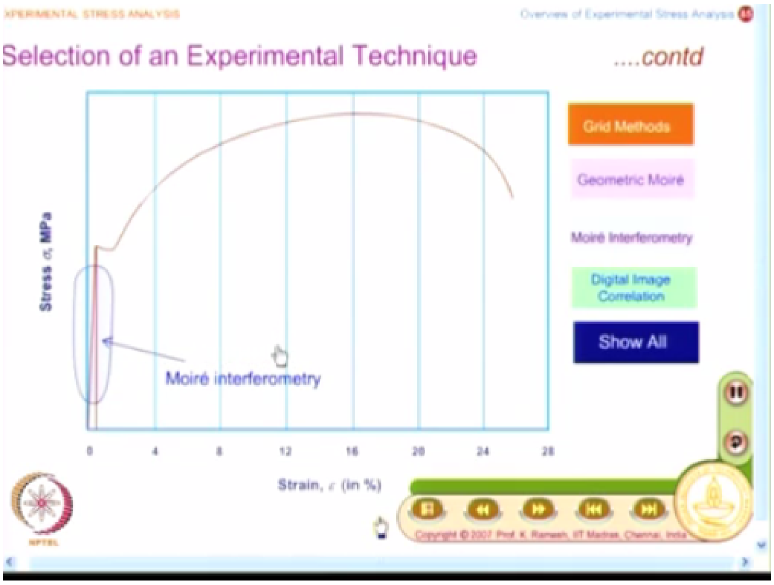

The issue here is what is the range of strain that you are really looking at and Moire interferometry cannot measure very small strains, it can go down but it cannot go close to 0 and these are you know pictorial representation; numbers are not given, so you find that this is the range that you are really working with Moire interferometry.

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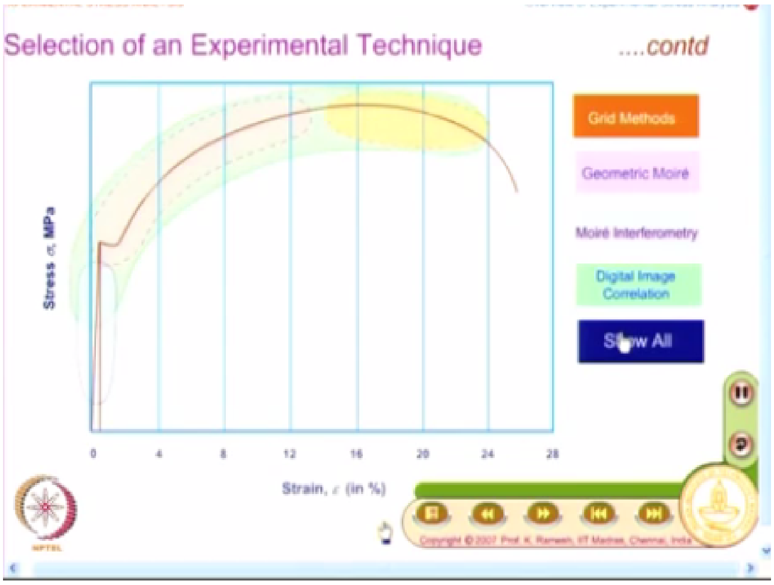

And when I come to digital image correlation, I can go from this to this and I have already said that this can be brought down by improvement in technology, researches are working across the world and they bring down this to as close to 0 as possible. They are now come to the claim is now about 50 micro strain and it is only a question of time that they improve the technique further and now you have relative appreciation of various techniques.

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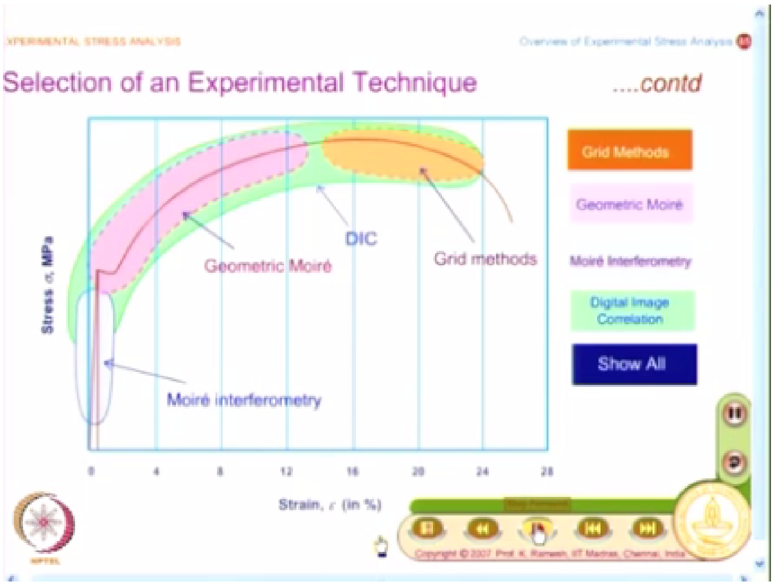

I have grid methods, I have digital image correlation, I have geometric Moire and I have more interferometry, so this gives you a reasonable appreciation on how to decide the techniques based on the strain range.

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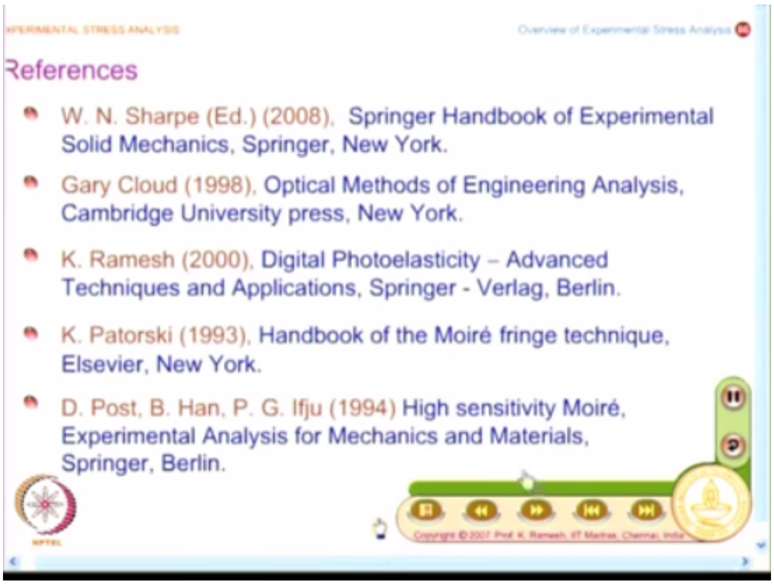

And now we come to the important step of looking at what are all the references that you need to have a look at and you have a recently published Springer handbook of experimental solid mechanics. This has a large number of techniques compiled in one volume and this is the third edition of such handbooks from Society for experimental mechanics and this is edited by W. N. Sharpe.

In fact, I have a chapter on photo elasticity in this handbook that covers the modern development of photo elasticity and also gives in a nutshell variants of photo elasticity and this is a very useful reference, then you have a very famous book optical method of engineering analysis by Gary cloud published in 1998. So, in all these, you need the author, you need the year and the publisher, it is a University Press, you will be able to access it.

And what you also have to look at is Gary cloud has given a series of articles in experimental techniques, he is writing articles on various optical methods for displacement, stress and strain measurement. Those articles are very very interesting, you can have a look at it, it is experimental techniques. Then you have a book on digital photo elasticity written by me and this completely covers the development of photo elasticity from conventional techniques to digital photo elasticity.

And exhaustively gives you various methodologies including phase shifting techniques and Fourier transform techniques, colour image processing methods and also application to fracture mechanics and stress separation etc. Then you have handbook of Moire fringe technique, so what I want to focus in this set of references is you know for each of the technique, you have so many books.

And imagine if there could be a handbook specifically written for Moire technique, imagine how many different types of optical arrangement they would have discussed and in a small one semester course like this, we would not be able to do justice on all this at least, you should have these references and then have a look at it at your leisure time or if you want to have additional information, you can always look at it.

So, I have a handbook on Moire published in 1993 and in 1994, high sensitivity Moire and here the focus is more on applying this Moire technique for thermal stress gradient problems, you have this electronic packaging, what they have applied, some of these also come in this handbook but there is also a separate chapter that was written in the book on experimental analysis for mechanics and materials.

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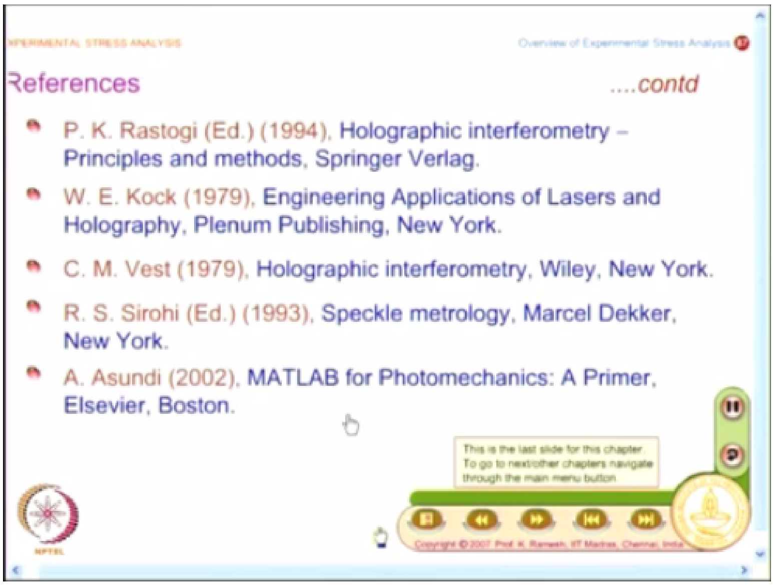

Nevertheless, in this course we have had a look at basic physics and that is the best that you could do in a course like this and next you have 2 references on holography. I have a book on holographic interferometry by Rastogi, this is edited book; published in 1994. Then, you have engineer applications of lasers and holography by Kock published in 1979 and for each of the techniques; sub techniques also you have separate books available.

And you have another book on holographic interferometry; C. M. Vest and finally you have a book on speckle metrology, a group of interferometric techniques, you have holography followed by speckle and you have a book by R. S. Sirohi. He had a very good lab at IIT Madras and several of his students have made significant contributions in the area of speckle metrology and we need to be proud of and finally you have a book by Asundi.

You know more and more computer processing is done and he had come out with how MATLAB can be used for photo mechanics. We have already seen when we looked at trends in experimental mechanics that the current trend is on finding out phase shifting techniques. They are used in several interferometric methods and all these interferometric methods use CCD camera as electronic eye and image processing is done.

And for many of these image processing application, MATLAB could be advantageously used, that is why Asundi has come up with a book on MATLAB for photo mechanics and this is also an interesting book and apart from this, you know I have been saying that you have for this course, you know you can follow the book of mine and that is what we had seen earlier, that is what I am going to use for this course.

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And the CD looks like this, you have an ISBN number here and even this conveys a message, the message what you have here is you have conventional techniques like brittle coating and this is your Moire for finding what in plane displacement, then you have strain gauges, photo elasticity, so all the conventional methods which are time tested come in this category and in this you find; you have use of Moire interferometry for finding out crack tip stress field equations.

And I have been saying that you have to use phase shifting methods and this is the spanner where you find these are not fringe pattern, these are face maps, that is a subtle difference between fringe pattern and the face map and this indicates the advancement of phase shifting techniques in the field and here you have this laser speckle and these are the white light speckle and this is where image correlation is being used.

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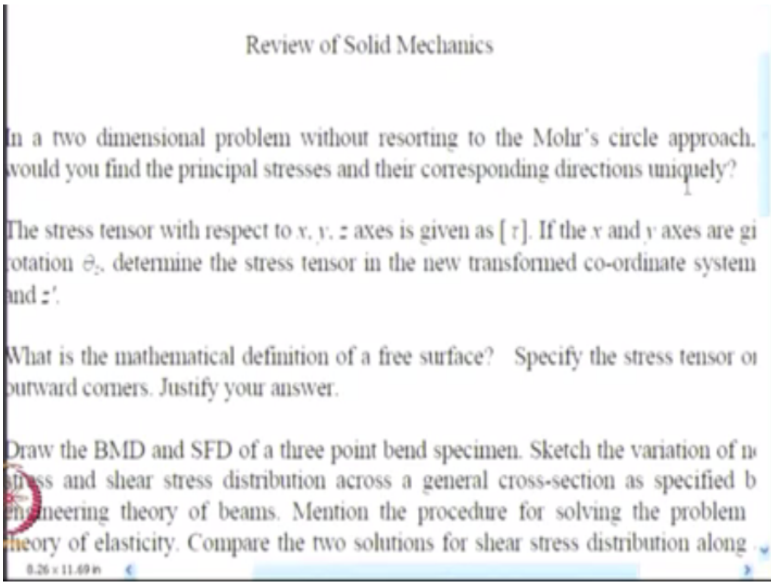

And this is becoming a more of a general purpose technique and this is the book, which I will use and in fact, the book has more animations than what I show in this course. Then, what we will look at is you know, I have an interest to look at your review of solid mechanics. This was given as your first assignment and my interest is to bring out 1 or 2 important aspects from this assignment.

And the first question is like this; in a 2 dimensional problem without resorting to the more circle approach, how would you find the principal stress and their corresponding directions uniquely? See what you need to understand is; you have done a course in strength of materials where you find out principal stress direction, where you also find the principal stress magnitude and if you look at in your learning, your focus was mainly on failure analysis.

You are finding out tresca yield criteria or von mises yield criteria, wherein you need only magnitudes of principal stresses, you never bothered about the direction theta and because you do not bother about direction theta, you also do not look at what are the nuances in finding out the direction. In fact, if somebody says you have an expression for theta, whether it represents maximum principle stress direction or minimum principle stress direction, you cannot half and say with your simple calculation of the trigonometric equation.

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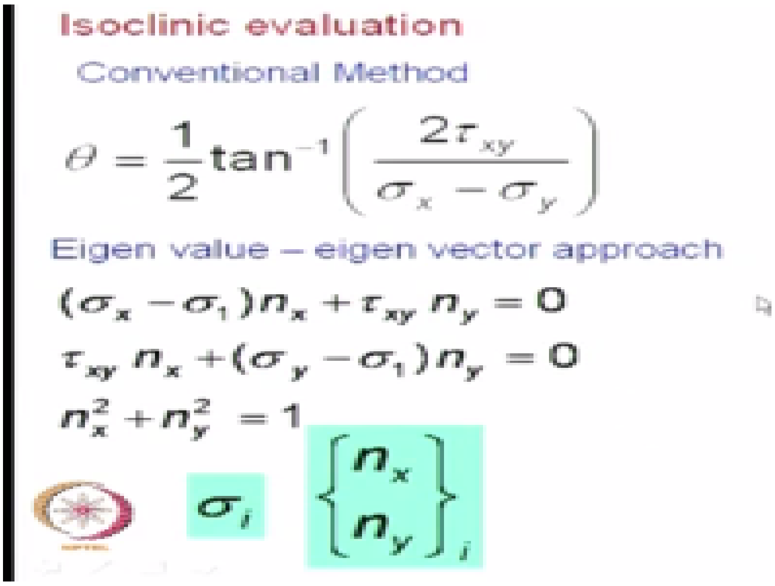

Let us look at that equation, you will not be able to say that from that equation and this is what the equation you have all learnt; theta = tan inverse 2tau xy divided by Sigma x - Sigma y multiplied by 1/1/2, this expression being a trigonometric expression, it is multi value. So, it will give you multiple values of theta and how will you associated? You will be able to associated, if I go to more circle, if you know how more circle is drawn and how to interpret it.

You will be able to fix the theta what I have calculated corresponds to sigma 1 direction, the theta what I have calculated +90 degrees will give me sigma 2 direction and normal calculation you do not require at all, so you do not worry about it and when I use this standard analytical expression, this expression cannot give it. So, you need to do something extra, so when I do an experimental technique, you should also anticipate that if I have to find out the sigma 1 direction and sigma 2 directions.

I need to find out use auxiliary methods to convincingly find to whether it is direction for sigma 1 or sigma 2 and this was the problem in digital photo elasticity. So, the question is how will you find out mathematically? So, you have to pose the problem differently, so what you need to do is; you need to pose the problem differently, you can do it as a Eigen value, Eigen vector approach, go to the fundamental definition of principal stresses.

So, I get principal stresses are Eigen values and the direction cause any nx and ny as the corresponding direction, so I have the Eigen value and Eigen vector. So, when I repose the problem as Eigen value and Eigen vector, it is possible for me to find out the value of sigma 1 and corresponding theta, which you are not associated, you will know sigma 1, sigma 2, many people also do not know how we label sigma 1 and sigma 2.

They are algebraically numbered; the greatest one is sigma 1, the smallest one is sigma 2 and sigma 3 that is how it is arranged. Any number you get is not sigma 1; you do not arbitrarily name it there is a convention behind it. Now, the question is; I get 2 values of theta from this, suppose I take the 2 least values; the first 2 values, how will they associate theta to sigma 1 direction and theta to sigma 2 direction?

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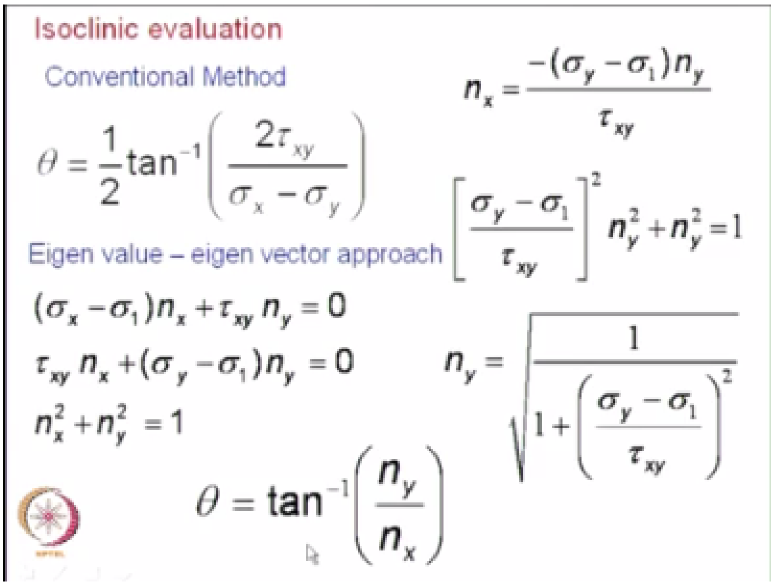

That, I can do if I reformulate the problem as an Eigen value and Eigen vector approach, so when I do that, it is possible for me to find out nx and ny from simple arithmetic and you need to know that this has to be post as Eigen value, Eigen vector approach, that is good enough for you to go into the details of it. So, analytically also we need to do special efforts to find out this, so when I do by experiment particularly by photo elasticity, you will see that I have to use some kind of a calibration for me to associate the direction obtained to sigma 1 or sigma 2.

And the emphasis here is more on, you know finding out the principal stress direction here and what we will now look at is the other question; you have the next question is stress tensor; find out the stress tensor in a transformed coordinate system? In fact, the whole of strain gauge analysis, if we know the tensor transformation law, you can comfortably understand. Stress is a tensor of rank 2; strain is also a tensor of rank 2.

So, the second question essentially asks you to recapitulate your expressions understanding on transformation loss. So, once you know the transformation law, hole of strain gauges, you can handle and the third question is very interesting; what is the mathematical definition of a free surface? Specify the stress tensor on free outward coordinates justify your answer. See all this you have studied in solid mechanics but you are not studied it with this viewpoint in mind okay.

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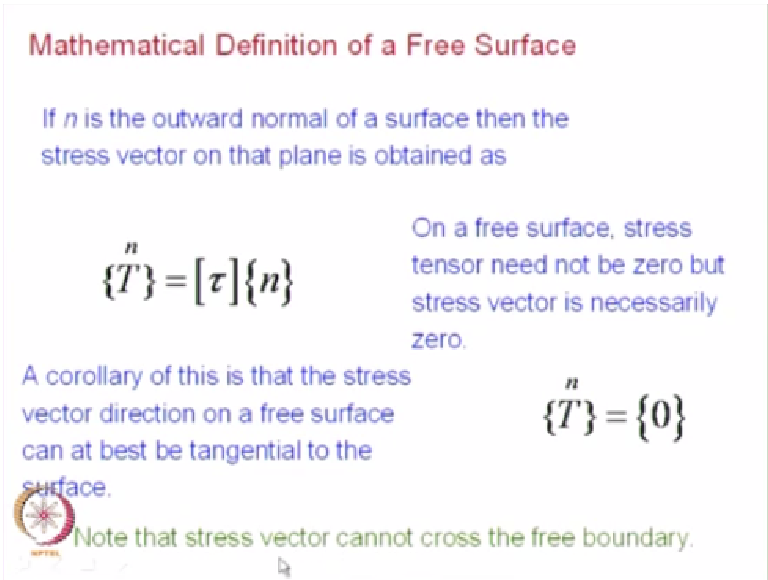

Now, let us get into the details of this now. So, what I have here is; I have a mathematical definition of a free surface and we have to go back and find out how do you get the stress vector and what we have learned in solid mechanics? We have learned state of stress at a point; state of stress at a point gives you totality of all the stress vectors on all the possible infinite planes passing through the point of interest.

So, you have in; if I take the point of interest, I have infinite planes passing to the point of interest and how do you define a surface? A surface is defined by an outward normal, so if n is the outward normal of a surface, then the stress vector on that plane is obtained as; you all studied it; **"Professor – student conversation starts"** Can I have an answer from the class? Stress vector can be obtained by multiplying stress tensor with the direction cosines. **"Professor – student conversation ends".**

What you have here is; I have Tn = tau * n, where this is the direction cosine vector and this is the stress tensor at the point of interest and this is the stress vector acting on plane n. Plane is defined by outward normal and you have this as Tn and what is the definition before we prove it on a free surface, stress sensor need not be 0 but stress factor is necessarily 0, so the mathematical definition of a free surface is Tn = 0.

We will see this by an example, so what we see here is; if I have to find out on any specified plane, the stress vector I can go to Cauchy's formula. Then I make a statement on a free surface, stress vector is necessarily 0, so it is defined like this and what is the corollary of this? The corollary is that the stress vector direction on a free surface can at best be tangential to the surface.

In fact, we have used some of these properties earlier in your course but you are not looked at from this perspective and this knowledge will go a long way in writing boundary conditions not only in experimental stress analysis, but also when you apply numerical techniques and this concept is not emphasized in your solid mechanics course usually. When experimental is teach it, they may show that this is useful in experiment so this has to be emphasized.

So, that concept is develop, so what we have now saying is a corollary of this is that the stress vector direction on a free surface can at best be tangential surface in other words, stress vector cannot cross the free boundary. So, that is what I get from looking at Cauchy's formula and this mathematical expression and finally I come to the axiom that stress vector cannot cross the free boundary.

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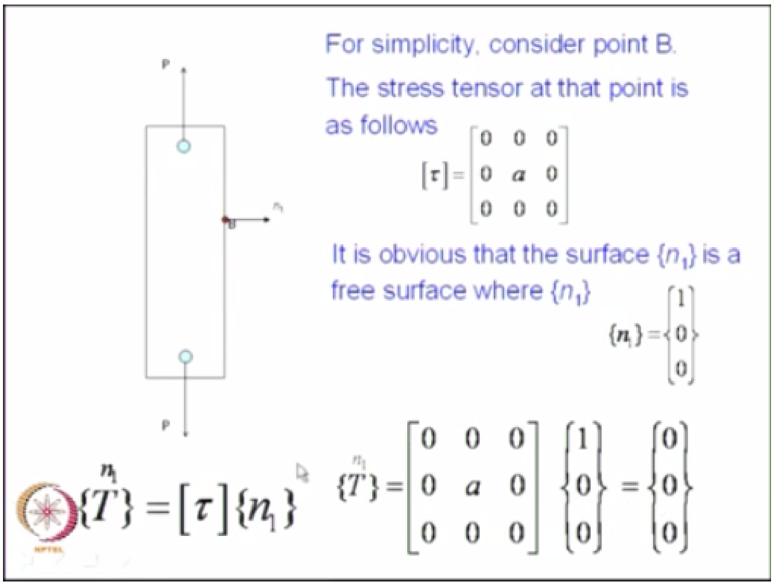

You must have heard shear cannot cross the free boundary when you are done bending, the same thing is put in different words it is more of a generic statement now. Let us take a simple example problem, I have a simple tension specimen and let us consider a point B, where is a point B? I have a point B located somewhere here on this and I want you to tell now how will you classify this surface; the line which I am showing here, how do you classify this surface?

That is a free surface because it is an unloaded boundary you can easily call it as a free surface now, what we are going to look at is; we will go and find out; what is the stress vector on this surface, if it turns out to be 0, then what we have said? A mathematical definition of free surface is the stress vector on that surface is 0; we will indirectly prove that and what we will do? We will take the stress tensor at the point and that is given as like this.

Because I have; what I have is; I have the y direction; I have the y direction on this, so I have some value if I know what is the cross section; I can find out the stresses and it turns out to be some magnitude a, so stress tensor for this problem is given in this fashion. So, I know the stress tensor and I have said that this is the free surface and a surface is represented by its outward normal, so let me find out the outward normal.

I have n1 and how do you define the outward normal? You can easily write, it is nothing but 100 and you have a Cauchy's formula now, I have a stress tensor which is not 0, it has an element but when I have this tau * n, what do I get? When I want to find out tau * n, I get this a null vector, so you can go back and verify for several problems what you are studied in your strength of materials, whichever problem you have looked at you will invariably find that Tn = 0 is completely satisfied on the free surface okay.

I also said there is a corollary, what is the corollary here? Now, I have the surface suppose, I take a plane which is perpendicular to this and what is the direction of stress on that, that is tangential okay, so that is what it says. On a free surface, stress vector can only be tangential, the same thing suppose, I take a beam, this is free surface; this is free surface, so on the free surface what I have?

I can go back and calculate what is Tn and Tn will be 0, suppose I cut it perpendicular, I will have stresses perpendicular to that, so it will be tangential to the boundary and the other one suppose, I have this as a cantilever beam and apply end load, I apply; I consider this as fixed end and I apply a end load like, this it behaves like a cantilever, then I will also have shear and in shear what you have? You have this as parabolic variation.

When you have parabolic variation, you have top fibre is 0 and bottom fibre is 0, why do you say the top and bottom fibre is 0? Because this is a free surface shear cannot cross a free boundary because shear exists in pairs, you have one shear you have another shear here because this is 0, this also has to be 0, a generalization of that is Tn = 0, okay and this is a very, very useful concept.

The moment I know that shear cannot cross a free boundary, I know how the distribution of shear stress I can picture it, it has to be 0 on the top fibre, it has to be 0 on the bottom fibre because they are unloaded boundary okay. Now, what I have here? I have seen for this problem on a free surface stress vector is 0, we have seen. Suppose I take another problem, where I have a projection.

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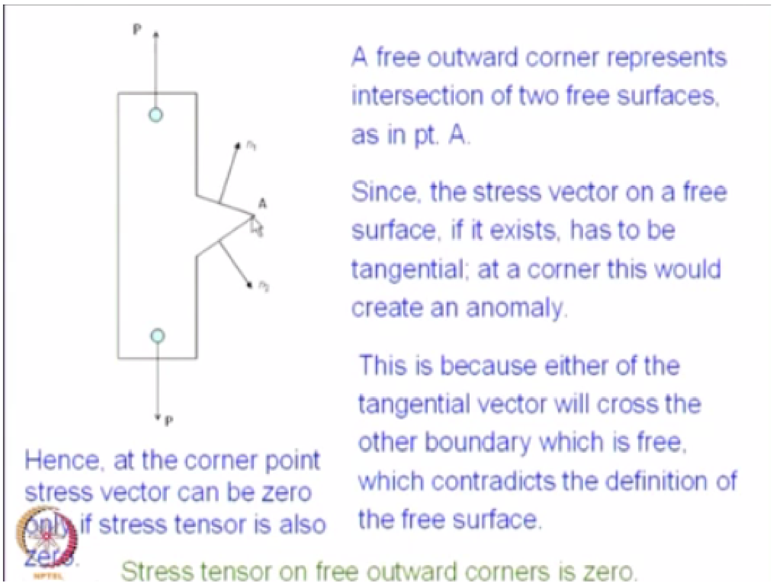

I have a projection like this and I am not interested in finding out stresses at all these points, I would like to know what is the stress magnitudes at the sharp corner, a. Can anybody say? When I have a sharp corner like this, suppose instead of this corner I have a corner which is like this, I have a cut out here then it lacks like a v-notch and you have singularity at the crack tip at the angle and so on, you call that as re-entrant corner.

Suppose, I have an outward corner, I can go from my knowledge of stress vectors and then show that this tip stress tensor has to be 0, a very useful information and what I have here is a free outward corner represents intersection of 2 free surfaces as in point, a. I have; this is a free surface given by outward normal n1 and this is a free surface given by outward normal n2 and what I have; the stress vector can only be tangential.

So, if I take this point, it can be only tangential like this or if I take this surface, it can be tangentially like this, so I cannot have a contradiction. For the contradiction to satisfy, it would create an anomaly, so I have to have stress tensor to be 0, so its contradicts the definition of free surface and finally what you have is stress vector can be 0 only if stress tensor is also 0, it is a very useful information.

In fact, when you go to photo elasticity, when you want to find out the fringe orders, this will be used as one of the methodologies to find out the 0th fringe order and you can also verify when you have a finite element solution and plotted. If you have stresses on free outward corners, then you can go and tell the analyst, you have done something drastically wrong on the boundary conditions.

So, it is both useful for fringe ordering in photo elasticity also for verifying your finite element solution and this is a very useful result, so what I have here is; I have a sharp corner and this is the outward corner, I have seen this outward corner. What happens to this outward corner? The same logical holds good and particularly in this case, there is also another subtle point I am applying a load with a pin, I am applying load only here.

So, on the entire surface what happens? In this particular loading arrangement, the entire surface also has 0 stress okay but in general, any free outward corner like this; any free outward corner like this, you will have stress magnitude, stress tensor is also 0, not only the stress vector, stress tensor is also 0 and that is a very useful concept that you can take advantage of. So, what I have here is; I have set of only 5 simple problems.

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And then the next problem is you know; essentially you have to find out the shear distribution on a 3-point bend specimen, suppose I have this as the beam and I have supported like this and I put a sharp load like this now, what I need to do is from your strength of materials, if I want to find out the shear distribution over the depth, what is the variation? It is a parabola okay but what will be the variation when I come closer to the loading point.

It is no longer a parabola in fact, if we go and look at the way you learnt shear force and bending on diagram you started with concentrated loads, you found what the bending moment diagram, shear force diagram but if you go and look at theory of elasticity, you would have started with distributed loading because a distributed loading I can specify the boundary condition easily.

I will find it extremely difficult to specify the boundary condition when I have a concentrated load. I have to use Fourier harmonics and then take several harmonics and then only find out what is the load acting on the member. In principle, I can solve shear distribution by theory of elasticity for this problem also but that would be very complicated and you will find it is no longer parabolic; the shear is still 0 at the top fibre.

Because we have seen shear cannot cross a boundary; free boundary and you will have a maximum value near the surface and reduces to 0. So, if you do not put reinforcement, your design will fail, so that is the pulse of the third question and this is interrelated to the earlier question and you will go and find out in photo elasticity, shear variation can be easily identified without much effort by a simple photo elastic analysis, so that is part of your lab exercise.

So, this brings to the conclusion of overview of experimental stress analysis in fact, I have followed a different approach wherein we had looked at what is the advantage of an analytical, numerical and experimental method, what are the differences, what are the specific features of each of this, then we moved on to what an experimental technique give directly, so that gives you an information that is linked to the physics of the experiment on which it is based.

Then, we looked at what these experiments; how the physics is employed, what is the physics behind each of this experimental technique in some detail. In the process, I have also said which class of problems this could be applied later on, we also saw how to name an experimental technique, what are the trends in experimental mechanics, then we also had a reasonable discussion on selection of an appropriate experimental technique.

In fact, that is very, very crucial if you have that mind set when we discuss some of the techniques in detail later, you will always look for while understanding the development of the technique which class of problems this could be applied that thinking process also will get initiated and that you see in a very unique way in the presentation, which we had seen. We had also looked at as a function of range of strain, how these techniques could be selected.

And I am sure at this stage you are quite clear that each of the experimental technique exploits a particular physics and if you understand the physics, then you can do interpretation and we have also seen the literature on this is voluminous in fact, doing justice to all the experimental techniques in a one semester course is extremely difficult, so we would focus our attention on photo elasticity, will essentially see transmission photo elasticity, reflection photo elasticity and also some ideas about 3 dimensional photo elasticity.

Then, we will spend time on strain gauges and also a little bit about brittle coatings. If time permits, we will also spend a few lectures on digital image correlation because it is an emerging technique and with whatever we have discussed, if you are interested you can always go to any one of the references and read; do self-reading and try to find out how those techniques could be employed, readymade equipment available and so on and so forth. Thank you.