Experimental Stress Analysis
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Lecture – 05
Fringe Patterns–Richness of Qualitative Information

We have been discussing about various experimental techniques, what is the physical principle behind the experimental technique. See, I have been saying if you have a problem on hand, you may not be able to solve all the quantities that you want by using one experimental technique. You may have to use multiple experimental techniques in a generic sense. I have shown that people have combined strain gauges and brittle coatings so that they could do and solve industrial problems very quickly.

We have also seen if I want to find out separation of stresses, interferometry technique and photoelasticity could be combined. On the other hand, people also thought of recording this information simultaneously, such equipments also have come. One is use and perform experiment separately, then process the information.

And once you decide that these are 2 information I want, people also devise new equipments wherein they could either simultaneously record or record one after another with the same optical arrangement with modification of what you want to insert.

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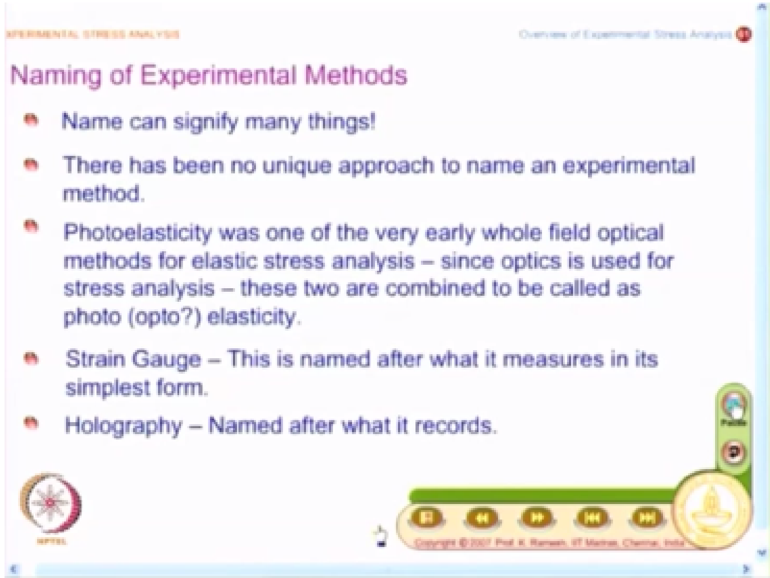

Such a development has also been seen in combining method of caustics and coherent gradient sensor. So, such information available the literature and now what we move on to do this is, let us have a very interesting discussion on naming of experimental method. You may wonder name can signify many things. You know if you look at the development of languages, if look at Sanskrit even for nouns they find out a root and then they explain because of such and such reason this is named like this.

It is a very well developed and it has a grammar which is scientifically proven and people find it easy for implementation in the computer. In fact, for natural language processing, Sanskrit grammar is so convenient you can translate from one Indian language to another language by intermediary Sanskrit and then go to it and if you look at because we are looking at naming of experimental technique, let us also look at what way names are given in Sanskrit.

I will give you one example. In Sanskrit, the shabda is very important and the phonetic condition of the word has some idea of what the word (()) (02:57) and if you want to talk about the tooth, the Sanskrit name for this is dantum and you will be surprised, if you do not have a tooth you cannot pronounce it. It is very interesting. You know why you say Sanskrit is so perfect, I am not getting into language division and things like that.

When there is a positive and scientific aspect attached to a particular language, as scientist we should recognize that merit and it so interesting. It is dantum you call it. I can call the tooth by several different names and the phonetic condition has a link to the meaning or what it (()) (03:38). So, if you are not having an understanding, then you can find out and think about it and go to the root and find out what the meaning is. So, it is not arbitrarily name. So, dantum you pronounce it, you need tooth for it and it is a tooth it indicates.

Now, let us look at have we named our experimental techniques scientifically, okay and if you look at one of the first technique was photoelasticity and there is a discussion. You know, there is no unique approach to name in experimental method and if you look at 1930s, one of the earliest optical methods that came into existence was photoelasticity. Why call it as photoelasticity, people have used optical methods to reveal the stresses.

So, they have combined optics and stresses and photography was also prevalent at that time when they were recording the information. So, they instead of combining optics and elasticity, they called it as photoelasticity, they called it as photo mechanics and even now there is a debate should we call as photo elasticity or photo mechanics or opto mechanics. There is a school of scientists who feel we have to go and rename all the techniques and because we are using optics why do not we call it as opto mechanics.

So, if you look at photoelasticity, you have just combined the sensor, optics is used as a sensor and you analyzed for elastic problem, so you call it as optoelasticity, photoelasticity, so that is how we have named it and when I come strain gauges what you do. This is what I cautioned because people named it as strain gauges, there is a danger that you get strain tensor. It is not so, it measures only a component of strain.

Because it basically measures strain, they call it as strain gauge and if we go to strain gauge literature you find special gird configurations where you find out the stresses. So, we call that as stress gauge, you have shear stress gauge, torque gauge, likewise you name it. So, strain gauge has got its name from this.

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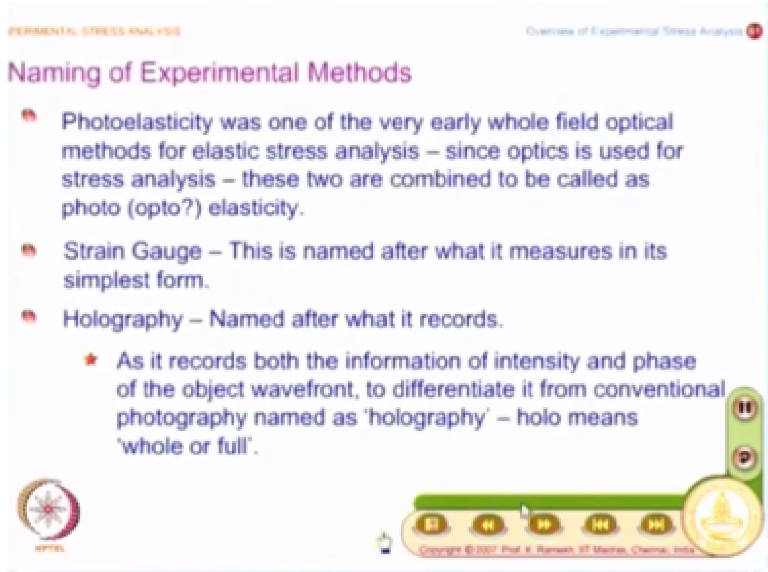

Then, you have holography. In holography, it is named after what it records and what we find here is I have mentioned that holography records both intensity and phase of the object wave front. Holo means hole or full, because I record both the information together following the example of photography, they call it as holography and we have also seen it is very fundamental contribution to the scientific community. So, whoever has developed the holography, he got the Nobel Prize for it. It is a very important development.

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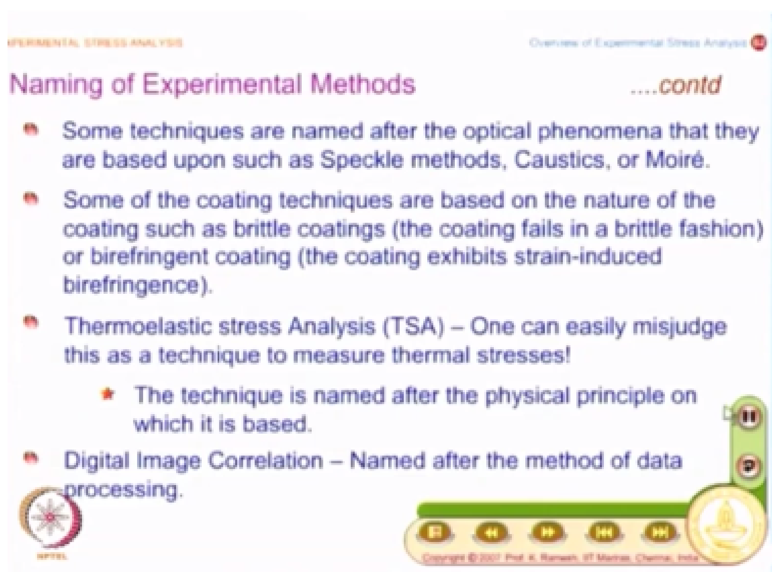

Then, what you have. Yu also have techniques where you use the physics. I said that in the method of caustics, you employ the principle of caustics in the formation of the shadow and you name it directly as method of caustics and whenever you a have 2 grid superimposed you get

Moire fringes and you call that as Moire.

Similarly, wherever you use speckles, speckles are formed on the diffusely reflecting surface, specularly reflecting surface, you qualify the surface and when you use those you call those methods are speckle methods and when we go to digital image correlation, it uses white light speckle but call it by a different approach. We have also seen coating techniques. What we have seen, we have seen brittle coatings and we have seen birefringence coating.

Why do we call it as brittle coating? I have a coat that is put on the model, it fails in a brittle fashion. In fact, when brittle coating was originally developed, they were all used for finding out plastic deformation and when you have a rolled steel, you have you have scale that are formed. So, they flake like a brittle coat, so they were able to identify zones of plastic deformation, that is how the whole technique developed. So, you name the technique based on how the coating behaves.

I set photoelastic coating. Other name for photoelastic coating is birefringence coating and I said in photoelasticity, the physics used is temporary or artificial birefringence and that is what is exhibited by this coating so you call it as photoelastic coating as well as birefringence coating. We also have another technique, thermoelastic stress analysis and I cautioned you again and again, do not misconstrue that this technique can measure stresses due to thermoelasticity. It is not so.

The physical principle used employs measurement of temperature which is very-very small and you call this as a thermoelastic stress analysis. So, it is based on the physical principle and I said I have one of the emerging techniques now is digital image correlation. It uses white light speckles; however, this is named after the method of data processing. I have digital images and then I look at undeformed and deformed configuration and then do a correlation. So, I call this as digital image correlation.

So, techniques are named differently. I do not have a unique approach and if somebody wants to develop a new technique, he coins what is more appropriate and what you see in coherent gradient sensor. Why technique is called coherent gradient sensor.

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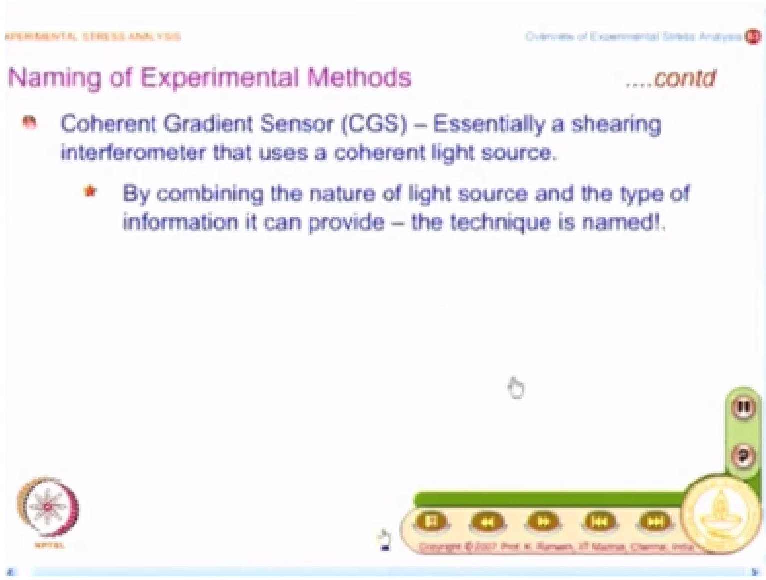

If you look at that, I use a coherent source of light. It is essentially shearing interferometer. By combining the nature of light source and the type of information it can provide, the technique is name and you know researchers also want attention to their work, so one of the reasons why they coin a technique is to attract the attention of others to look at what this technique is all about. So, coherent gradient sensor is very famously known CGS which is essentially shearing interferometer.

Now, people called it as shearing interferometer because it has become a general purpose analysis tool. People do it for the thin wafers when you go for MEMS application, thin wafers are analysed for out-of-plane displacement, slope, curvature. So you have this. So, I combined the type of radiation that is used. I have a coherent source of light and I measure the gradient, so call it as a coherent gradient sensor.

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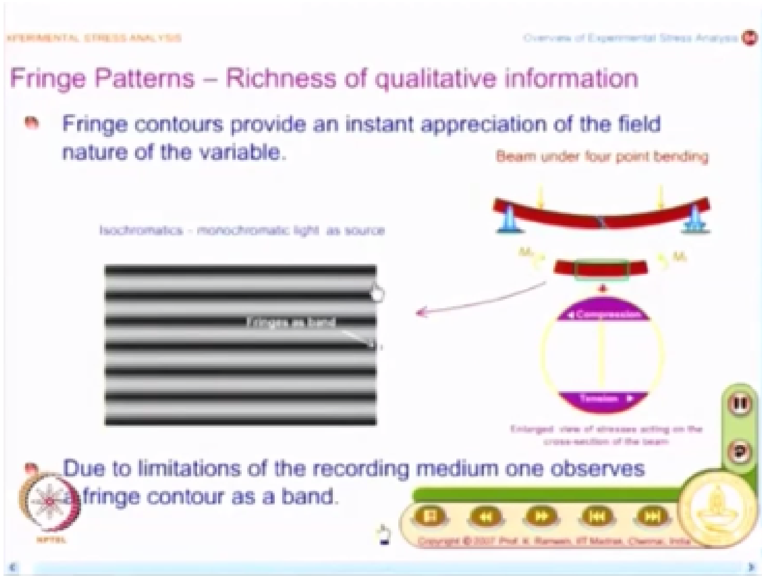

Next, we move onto to a very important aspect which we have also seen and discussed a little bit earlier. What we looked at was in most of the optical techniques, you get fringe patterns and we need to understand certain issues about how this fringe patterns solve. First what I need to do is I need to find out whether the interpretation what I do for the fringes is acceptable or not. A simple exercise is compared with an analytical solution.

If the comparison is correct, then you understand that this is what the technique gives. If the other approach looks at the physics of the problem, find out what all the physics can reveal then come and link that this is what the technique is capable of giving and what we find in the case of beam under bending. We have looked at the central portion and then we said we will plot contours of sigma 1-sigma 2, the analytical solution turned out to be horizontal lines.

When I look at the experiment what happens, I get this as horizontal lines but they are not in lines. I have a band, I have a band but nevertheless I got horizontal contours and we said why you see that as a band is because of the limitations of the recording medium one observes a fringe contour as a band. In all optical techniques, you will see only a band and one of the most challenging and difficult aspect for any experimental analysis is how to go and number these fringes.

Because I need to know the fringe order, then I need to use the appropriate equation and find out what is it that I will have to interpret on and what you find here instead of monochromatic light source.

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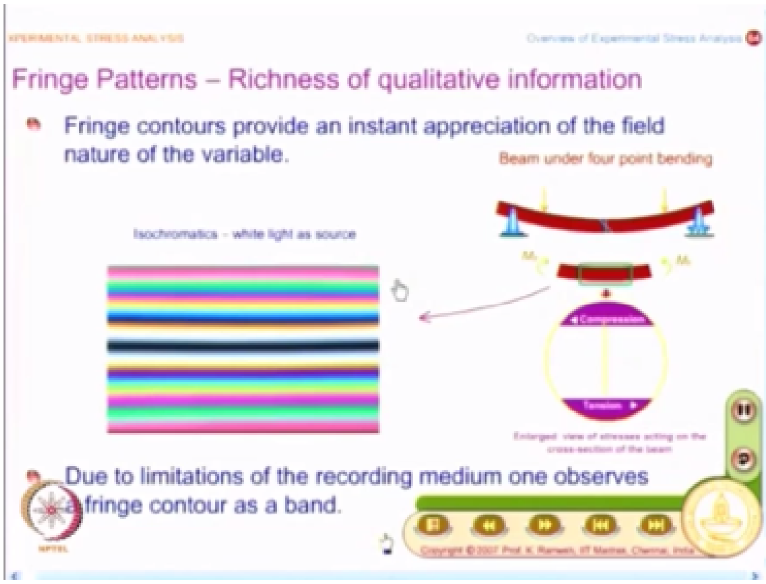

If I view these patterns in a white light source, I get not black-and-white contours but contours with colour, contours with distinctive colour and this is the specific advantage of photoelasticity. So, what I could do is by knowing the colour, it is possible for you to find out the fringe order.

It is also easy for you to identify how the gradient information changes, whether it is increasing in this direction or decreasing in this direction, you can find out whether the colour sequence is repeating in a particular fashion. Whether the colour sequence repeats in a particular fashion, then you can identify positive gradient and negative gradient, all that you can find. So, one of the most challenging aspect is quantitative extraction of data from all these experimental techniques.

But the focus of our attention now is to find out richness of qualitative information that you could get from fringe patterns, because this gives you a sense of comfort in looking at and interpreting the fringe patterns.

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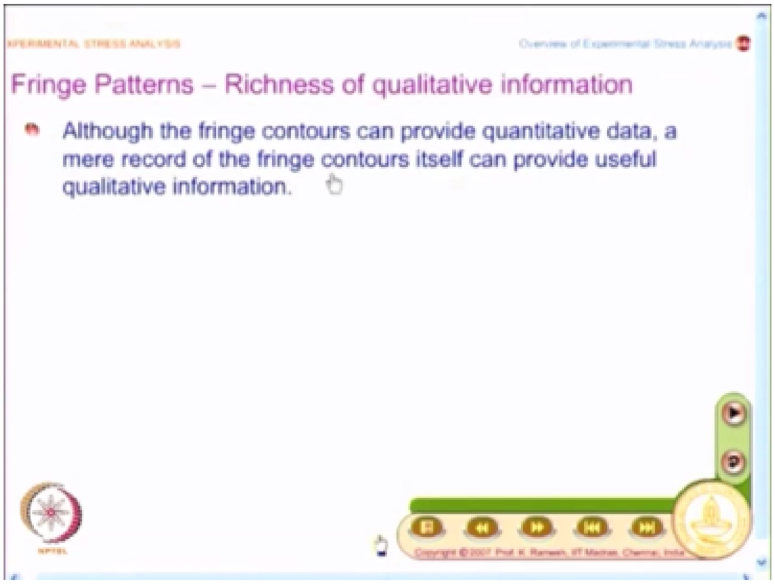

Let us look at what we have seen is fringe is a band, we have seen it and mere record of the fringe patterns itself can provide useful qualitative information. So, we have to look at what all the qualitative information that you could identify.

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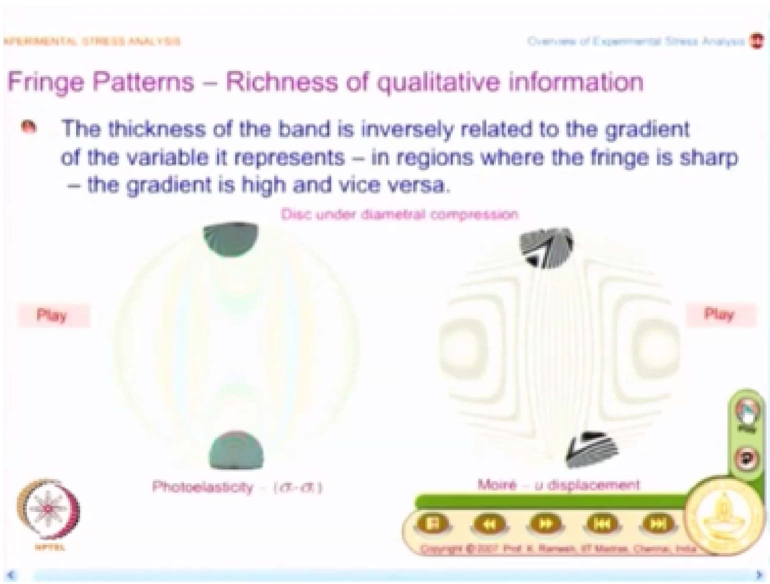

One another things what you could see is I get it as a band and if you look the fringe patterns closely are the bands of uniformed thickness. The thickness of the band is inversely related to the gradient of the variable it represents. So, that we will see, I have a fringe pattern from a photoelasticity because photoelasticity has formation in colour, a colour fringe pattern is taken and I also have a fringe pattern in Moire.

And what we will have is we will have a closer look at how the fringe thickness varies and this just shows that for you to draw your attention.

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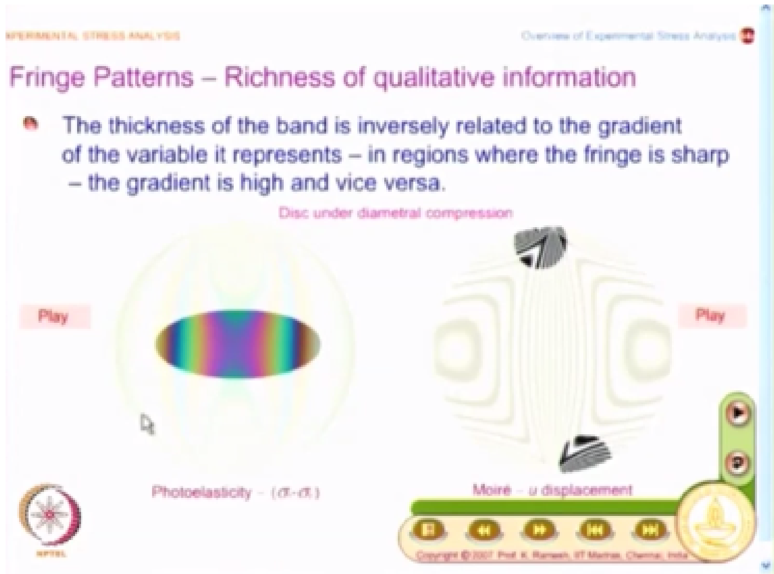

You have this fringe patterns drawn earlier, go back and then look at that fringe contour is not of same thickness, the thickness changes and that is what is tried to be shown in this slide. You have a very broad fringe here and let me repeat, I have very sharp fringes here and the same fringe becomes increasing in thickness. So, essentially what you find is that fringe band is not of constant thickness.

And I mention in one of the classes, you have this fringe plotting by software when you have to go and mimic what is the way to get the fringe band. One of the information you use is variation as a variable. Even if you give a constant variation as a variable because the gradient changes, automatically the thickness of the fringes changes when the gradient is small, fringes very broad; when the gradient is very high, fringe is very sharp.

So, I can find out by looking at the fringe patterns whether the gradient of information is high or low, I can find out from thickness and this is not a property for photoelastic fringes, you see a similar one even in Moire. I go to Moire and then look at it.

You see this is very sharp, thickness increases thickness increases and that is how you find and the same fringe as thick and thin.

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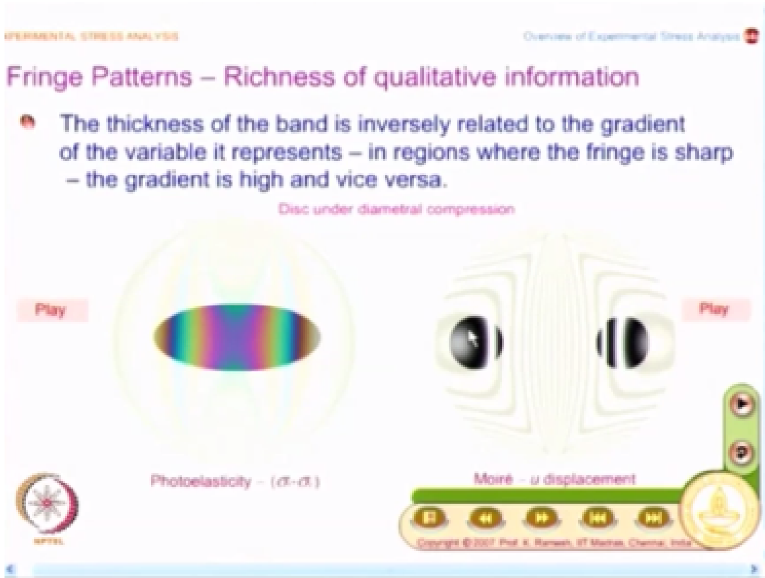

It is thinner here and thicker in the corner and this becomes much thicker. So, when you look at the fringe pattern, observe for all these indirect information. The fringe pattern speaks to you. This is how the distribution is. So, take note of it. Suppose, I have fringes closely packed, then I would say that this is the zone of high stress concentration.

Later on I can go and do a qualitative processing and try to get the actual data, that is a different issue, but the moment you look at a fringe pattern, you should react to it. You should know that this is stress concentration region and this is the region where I can scoop out material. I need to get that kind of information and you get that by looking at the thickness of the band as simple as that. So, this is one of the qualitative information you get. Then, what is the other information that you can think of.

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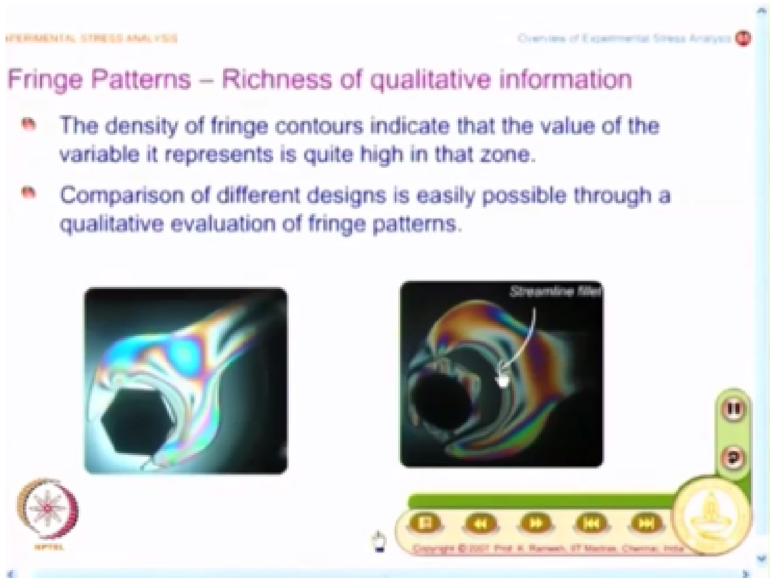

I have said that density of fringe contours indicates that the value of the variable it represent is quite high in that zone. Suppose, I want to compare 2 different designs and the ideal way is take the fringe pattern for both the cases and compare the fringe pattern and find out based on qualitative appreciation, how you can evaluate the different design. So, it is used as an optical comparative. One simple example is given and what you find here is I have an example of 2 different type of spanners and in one case I have given this as a streamline fillet.

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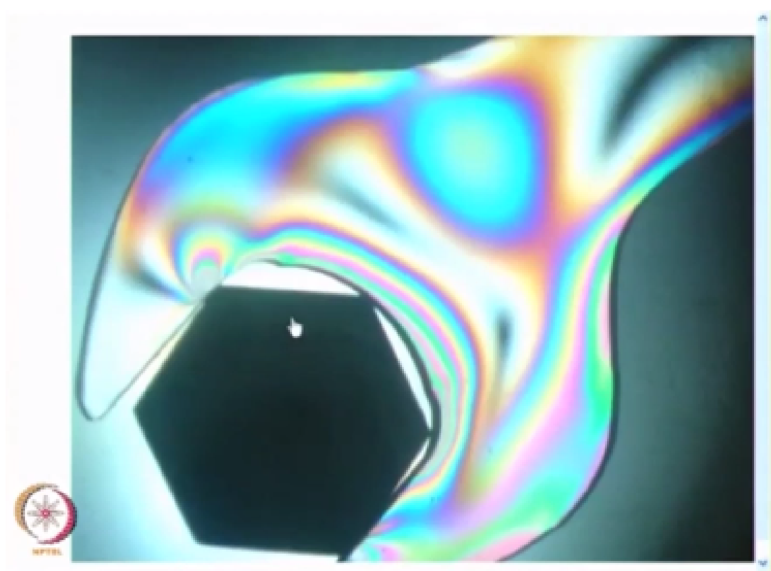

Let us understand what is the idea here and you are all mechanical engineers so you know how a fillet is made. Suppose I coat any machining process, it is easier to make a subclass fillet, because the machining operation is simple, I can go and make a circular fillet and why do I make a fillet.

I would like to minimize the sharp geometry changes and then I would like to have a smooth variation and this smooth new variation you could do by a fillet. So, you essentially reduce the stress concentration. If you look at forging operations or casting operating, when you look at forging or casting, I do not have the restriction of having only a circular fillet. I am doing a machining. In a machining operation circular fillet simplifies you are fabrication of the component.

When I go for casting and forging, I have the luxury of choosing any type of fillet I want. Noncircular fillets more common in those applications and how do they arrive at such odd shaped fillets; and you have an example here and what you find here, I have this contour like this and I can also enlarge it further and what you find here the fringes are many in this zone. They are not tangential to the boundary. I would like you to make a sketch of it.

This is a example problem that is shown, I have one circular fillet here and I have another circular fillet here, I have another circular fillet here. They are not joined, so you do not have a smooth transition here and when I make a spanner out of it, I find is this zone, the fringes are not tangential to the boundary and you focus only on this region. You do not have to focus on the other regions, make a neat sketch, bring out that the fringes are not tangential.

So, when you have a fringe pattern you have to look at very closely and try to extract as much information as possible and obviously I have a load application point, I have fringes originate here. So, it also indicates stress concentration zone and what I find here is as such when you see only one design, you will only see oh these colours are good, the fringes are good, that is the way you will interpret. Only when you see a counterexample, you will find that the knowledge is different.

Now, what I will do is I will go and show the other one, then come back to this, okay, so that you will know what is the difference.

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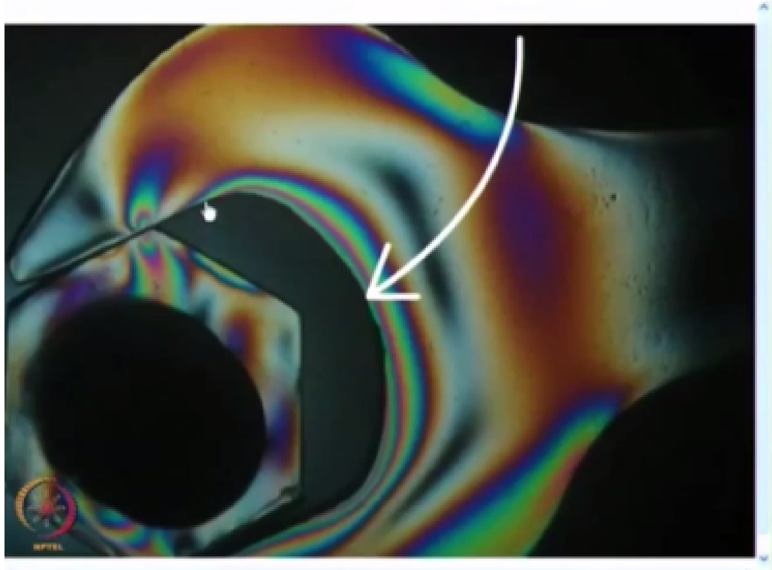

Now, I take this example and what I find here the fillet is smooth, it is noncircular here and you find more or less these fringes are tangential to the boundary. It merges with the boundary of this and these are called streamline fillets. So, only when you see the difference you will know what is the advantage and they are very strong. You do not worry about the nut, you concentrate only on this region that I am showing the arrow, you need to worry about the fringes.

You find the fringes are parallel to the boundary. By and large there are some small aberration is there here but compared to the earlier one, here the fringes are lot more smoother and parallel to boundary and in fact when people design some of those castings and forgings, they take a photoelastic model which is slightly large in shape and then keep on shaving the material until for the given loading, you get the fringe tangential to the boundary.

In fact, there is a famous book by Heywood designing by photoelasticity where he talks about how to get a streamline fillet. When you get the streamline fillet, the component will have very high strength, nothing happens to the component and I can afford to have a streamline fillet which is not always circular in a forging and casting there is no problem and you know these spanners are done by forging. So, I can afford to have a noncircular fillet and take advantage of our understanding of stress distribution.

So, let us see these fringe pattern one after another. I see this as tangential to the boundary and I go back and then show the other one, you will find that this is different and this is a fictitious example. You know you do not have a spanner like this. This is done to illustrate. I have a combination of circular fillets here, so when I do is I have a lot of deviation from this and this is not strong. You can have failure initiated in this and in service it can fail.

So, what you do is, I do not do a qualitative analysis. Even a simple qualitative exercise can help you to improve your design. So, this is another aspect of richness of qualitative information, okay.

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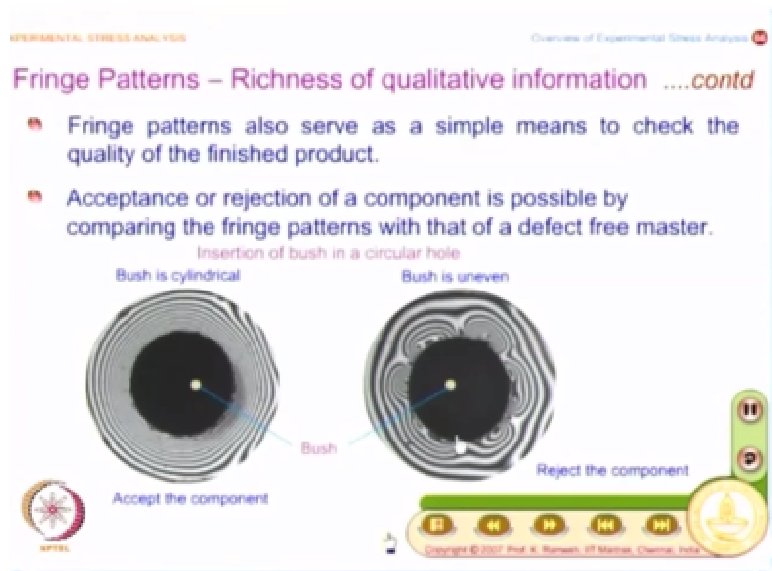

In a production line, I would like to inspect whether my component and is being manufactured correctly or not. I can have an optical comparative and what we are going to look at is insertion of a bush in a circular hole. This is what we are going to look at as an example. So, what we are going to look at is how fringe patterns helps you to check the quality of the finished product. What I am going to do in quality checking mode, I will accept or reject based on some evaluation of fringe patterns.

I have example here. I have one example where I have a perfectly circular bush inserted in annular plate and you all know line is problem, you need to get concentric fringes. I do get concentric fringes. This is not what happens in an actual production line. In actual production line, if you do not maintain the cylindricity of the bush, you can have surprises like this and what

I see here, I see extra flowery pattern.

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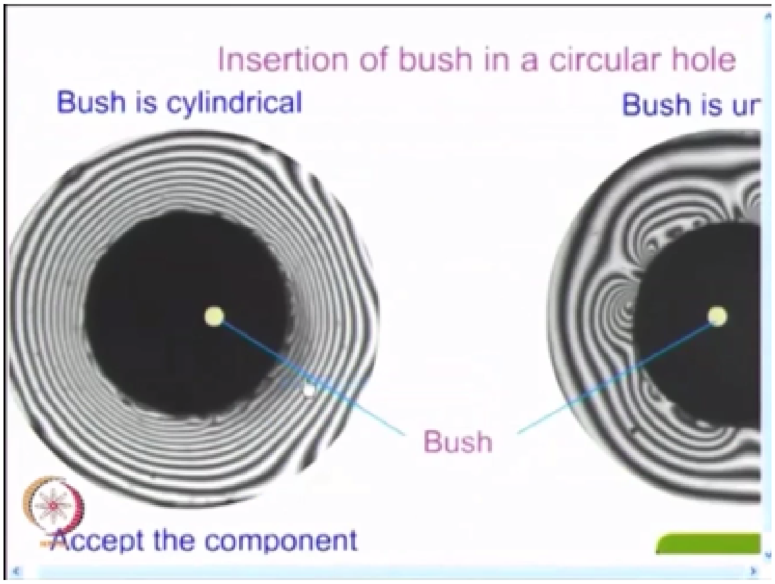

Let us look at little more closely here. So, what I have here is, I have bush as cylindrical, you can go and accept the component and while you sketch it what you do is you do not have to draw all these fringes, you say essentially they are concentrated. When I have a noncircular bush which has undulations, which are not visible to the naked eye but when I insert I get this flowery patterns on the inner boundary. I have inserted a bush in a circular hole.

It should behave like (()) (28:35) problem, concentric circles I should get but instead what I get is I get fringe pattern like this and in this case the deviation is quite obvious. It is very striking. The fringe pattern what I find very striking, I can quickly say something has gone wrong. If the variations are very subtle, then I cannot make a judgement. In fact, one of the most difficult thing is if you have a member and stretch it.

Invariably, if the member is not stretched correctly, you will always have some amount of bending and if you take a specimen which can respond optically, any small misalignment will show up in the optical fringe pattern. So, simple experiments are really very difficult to conduct. Even a simple tension, so one of the ideas what they suggest is if you have a situation where you need to verify the alignment, go for optical techniques and improve your alignment based that.

So, optical elements are very good. They are very sensitive to anyone of this loading peculiarities and what we see here you have concentric fringes and you have the fringes which are coming as a flower and that is what you have. I want you make reasonable sketch to bring out this difference, that is the idea. You have a flowery pattern and you have concentric circular and that gives you an idea that something has gone wrong and you can take corrective action.

You can go and modify your production line, inspect how the product is made, go and improve the process parameters. So, you can take some kind of corrective action. So, now you realise that by looking at mere fringe patterns we have extracted quite a bit of data. We can find out stress concentration zone, we can compare different designs, we can also accept or reject a component based on some of this information.

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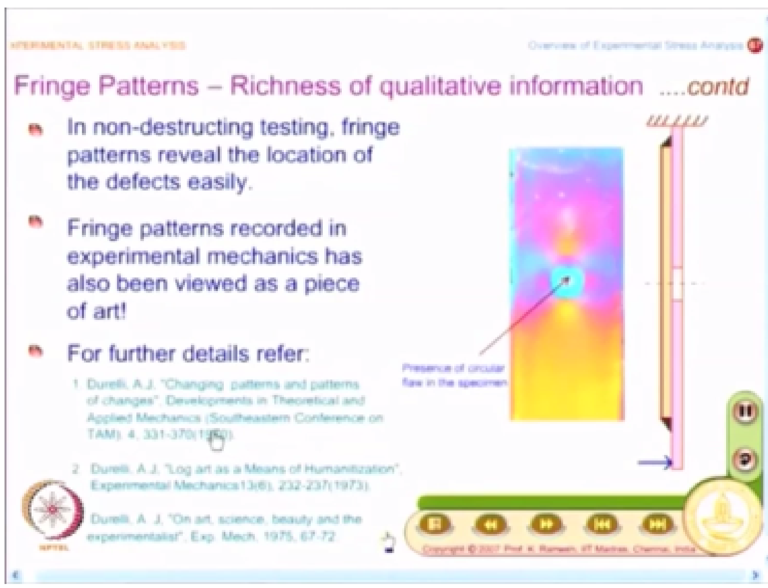

So, that is quite useful, I mean we have been able to take note of this and another advantage what you have is I have a defect here, what I have is I have a plate with a hole and I have a coating put on this and you know here I have taken example, so I know that there is a hole present and now I am interpreting that you have a hole that is seen in the fringe pattern. In fact, to find out internal flaws, people have attempted putting a photoelastic coating and when the model is loaded, the fringe signature can identify presence of flaws in the member.

So, this is another approach, people have used it and identifying a flaw in a structure is a very challenging aspect and what is the difference between an ultrasonic technique. In an ultrasonic technique, even benign flaws will be detected because it only looks at material separation. On the other hand, if I have a technique where the model is loaded those flaws which are sensitive which can pose problem to you, only those will be revealed.

See, collecting lot of information is not necessary. You need pertinent information for a given problem. So, this is one of the reasons they site. If I use acoustic emission technique, you are searching a needle in a haystack because you get so much information, identifying your pertinent information is extremely difficult. So, on the other hand if I have a technique which can reveal those flaws which are going to give you problem alone will be detected is well and good.

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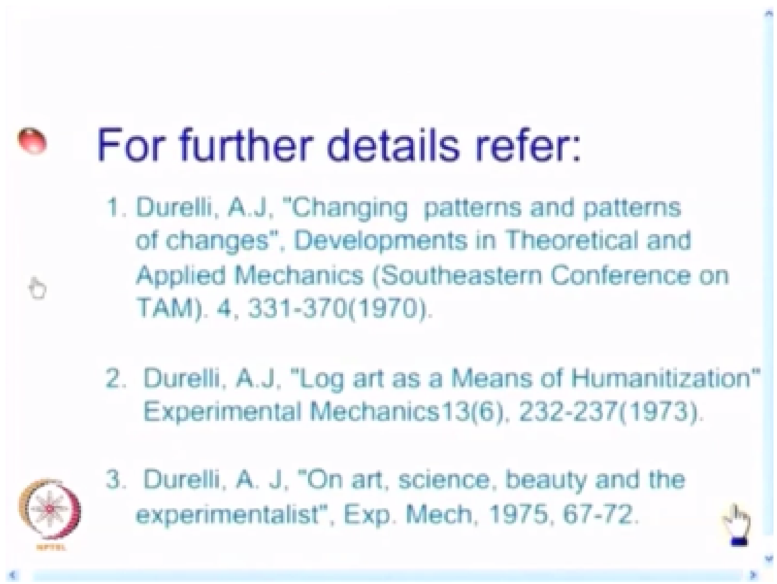

I also emphasised in one of the classes that people also have looked at all these fringe patterns as piece of art. In fact, Prof. Durelli has made significant contributions in looking at fringe patterns like this. So, my interest is all of you please just note down some of this reference details. You do not have to write the full reference. You know, he has a paper in developments in theoretical applied mechanics in 1970. This maybe we not be in a position to get it but at least the experimental mechanics will be able to get it.

So, you write down this experimental mechanics and write the page numbers and the year. You do not have to write the title of the article. You can easily search it based on the reference. There is another paper in experimental mechanics on art, science, beauty and the experimentalist. So, people have written not one paper, 3 papers he has written and variety of fringe patterns he has shown and it is very interesting because you know when you are looking at optical techniques, you should also look at the other side of it.

There is beauty attached to it, lot of qualitative information that you can get out of it. So, what you need is you need to have some of these references. You should not just focus only on your stress analysis, you should also know related information that makes your learning lot more enjoyable and purposeful, and we will see in the next class how material research. See, if you look at any scientific advancement, it is the invention of new materials that contribute to it and what we would look at is in which way experimental mechanics has gained because of material research.

Every advancement of science, you know if you look at (()) (34:50) it has a route from your space technology. They had titanium based allies which are also found to be biocompatible, that is how percolates. When you do high-tech research, it percolates down to human suffering alleviation. So, we will see material research development, how it has helped experimental mechanics in the next class.