

**Experimental Stress Analysis**  
**Prof. K. Ramesh**  
**Department of Applied Mechanics**  
**Indian Institute of Technology – Madras**

**Lecture - 18**  
**Fringe Thinning Methodologies**

In the last class, we had looked at how to find out material stress fringe value. First we saw the conventional method, then we moved on to develop a methodology, which utilizes the whole field information. After developing the methodology, I said, though you can also do by processing the photograph in the conventional way, collecting data manually, the method becomes advantageous when you go in for image processing approach and essentially aspects of digital photoelasticity.

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EXPERIMENTAL STRESS ANALYSIS

Digital Photoelasticity 01

### Introduction

- Human eye is replaced by a digital camera.
- In view of digital recording, data acquisition and processing could be easily done by digital computers.

MPTEL

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What we introduced was, in the case of digital photoelasticity, you replace the human eye by an electronic eye. You have a digital camera. These are essentially charge coupled devices. You call them as CCD camera and once you use a CCD camera, it is possible for you to get the image as an assembly of numbers.

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EXPERIMENTAL STRESS ANALYSIS

Digital Photoelasticity

### Uniform Sampling and Quantization

- Digitisation of the spatial co-ordinate  $(x,y)$  is called image sampling.
- Most common method is to use a regularly spaced square array of points.

Amplitude digitisation is called grey-level quantization.

– 8 bit grey level quantization is quite common which allows 256 grey level shades.

512x512 or 1024x1024 is quite common

Area of interest

Optical Image

Pixel

0 255

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And this is essentially called sampling and quantization. First you do a spatial discretization that you call that a sampling and you have an optical image and for illustration, a small zone is taken, which is looked at as assembly of very fine small elements known as pixel elements, and you call them as pixel, abbreviated as pixel. So you identify the image as an assembly of small picture elements and for each of this pixels, you assign a number between 0-255.

If you are processing a negative, it will give the light transmitted and if you are processing a positive, it will give the light reflected, so at the end what you get is, by using a digital camera, you are able to get intensity data at video rates. That is the advantage. So what you have here is finally, you get an image representation. This is essentially a matrix of integers and what will you have to keep in mind is what we call as a pixel is a very, very small area.

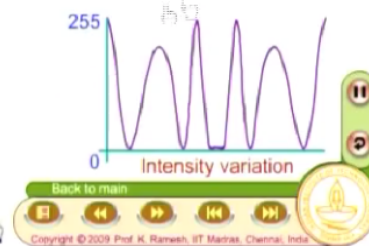
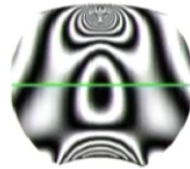
By appropriately using a lens, you would be in a position to even go to stress concentration zone and find out when you have very high fringe density, you have a decent resolution at the camera plane. So I can have optical magnification and then, enhance the features in stress concentration zone, that is how people solve when you have a very high fringe density, they optically magnify that zone, then take it up in your digital image and appropriately process it.

Now what we are going to look at is, we will essentially look at a very simple digital photoelastic technique, where we mimic what we have been doing it manually earlier. We will identify fringe skeleton. That is what we are going to look at and what you have here is.

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### DIP Methods for Fringe Thinning

- The intensity of pixels in the fringe band (dark/bright) varies.
- The variation is not resolvable to a fine degree by a human eye.
- The present day CCD cameras can easily recognise it and quantize it for further processing.



I have taken the problem of a ring under diametral compression. I had already mentioned the fringe features are very complex in the case of ring under diametral compression and if you know how to order the fringes, then you fairly understand how to go about a generic problem. So what I have here is, this is the load application point and what is shown here is, I have taken a line passing through these set of fringes and this portion is enlarged.

This is recorded in a digital camera and what you find is there is variation of intensity along this line, which human eye is not able to very clearly distinguish. On the other hand, when I go and look at the intensity values recorded, which I have to take care, you know, I may have to do time averaging and then you want to eliminate electrical noise, so you take several images in short time and take a time averaging.

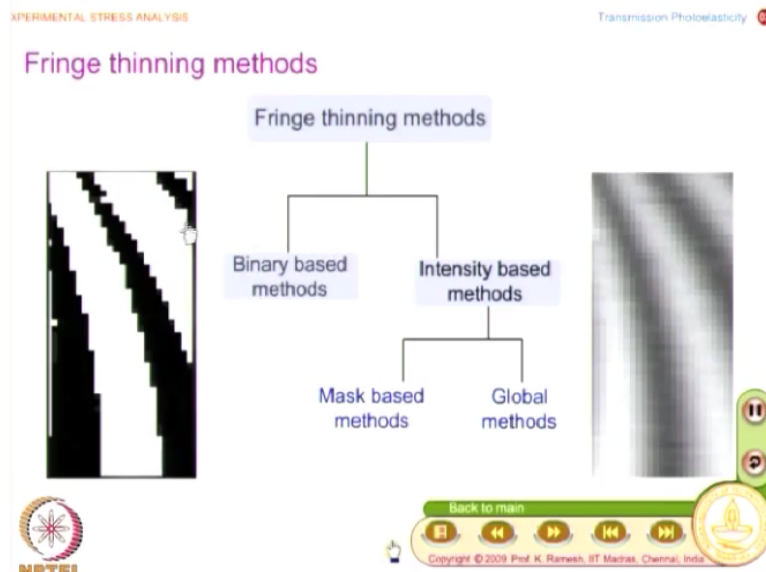
When you do that kind of image recording and when you look at the intensity variation, you get an intensity variation like this. So you find that intensity varies across the fringe thickness, what you see as a black fringe, it is not really black, you have a variation of intensity that is what you see here and this is decently captured by your digital camera. So the point here is the intensity of the pixels in the fringe band varies. The variation is not resolvable to a fine degree by a human eye.

The present day CCD cameras can easily recognize it and quantize it for further processing. So this is what is important, but even before we use intense information, people also have used only the binary information, identify the fringe area, and strip the outer pixels and get

the skeleton and if you look at the history of image processing, 1 of the earliest application of image processing was in optical character recognition.

So people wanted to recognize when people write a letter, each 1 may write it differently, so you should know how to identify whether this is letter A, B, or C. So they will try to get the skeleton from the hand written text and then identify from contiguity of the connectivity of the lines, identified as different letters. So people use that kind of an approach in photoelasticity as well.

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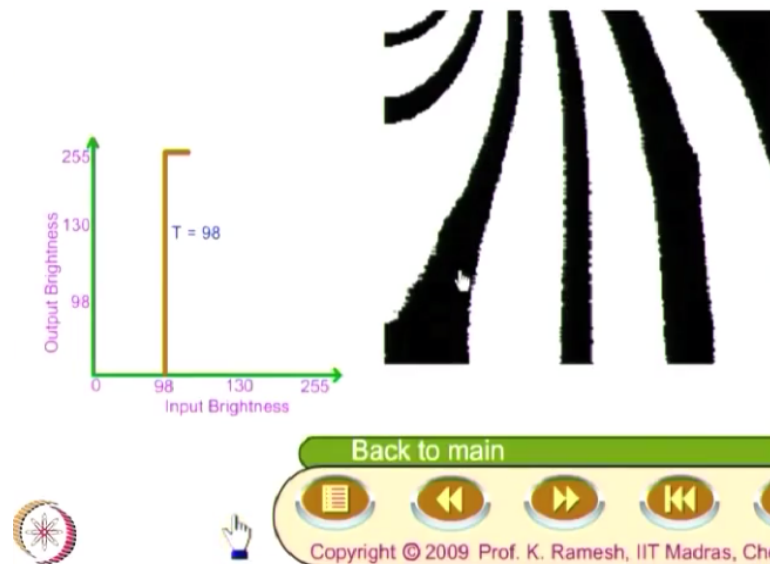
So I can classify fringe thinning methods broadly into 2 categories, 1 is a binary based approach, another is intensity based approach, and we have just now seen that what we see as a fringe has intensity variation over the band width of the fringe. One can view this as black and white picture, and that is what is done in binary based method. Essentially, whatever the developments that was in optical character recognition, we will directly apply it to fringes.

And 1 of the advantages in photoelasticity is the fringes are having very good contrast. We have also seen in the initial lectures, how do get fringe pattern from speckle interferometry. Speckle interferometry, I said it has inherent noise, unless you do filtering, I would not be able to extract data from this. On the other hand, when I go to photoelasticity, basic fringe pattern you obtain has very good contrast and that makes your processing of the image much simpler.

And if you look at either a binary based method or intensity based method, you need to first identify from an image, what is a fringe. Where the fringe is located. See this is where the human intelligence is very important. Suppose somebody gives you a picture, you would immediately say I have a thick fringe here, thin fringe here. I know this is the background. I know all these, the mind immediately tells you, even without your recognizing it.

The mind processes all the visual information and gives you a feeling that you are looking at a fringe pattern, which is very dense here, but the moment you go to computer processing, you need to develop methodologies to do this. How do we find out the fringe areas? How do you identify when a pattern is given? this is a fringe and this is a non-fringe area. Suppose I call fringe as black contours, I should identify the black contours and what we will see here.

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There is a very simple method what is known as an image processing literature is called thresholding and what I have here is I have deliberately had this image area as black and in thresholding what you do is, I look at the grey level values and I put a kind of a filter in this what I do is, I have discretized from 0-255 up to 255, you make everything as black at 255, you make it as white. That is why you see this as a black picture. Thus we have seen that images having 0 as pitch black and 255 as white.

Now if I make all the pixels black, I will not see the picture at all. Because photoelastic images have high contrast, you are in a position to apply a very simple image processing approach called thresholding to identify fringe areas and what we are going to look at is, I

would apply the thresholding. I will put a different threshold. I put the threshold now as 130, so what I have done is any grey level value before 130, I make it as black.

Any grey level value after 130, I make it as white. I start seeing black region and white region demarcated and black regions are nothing, but your fringe contour and if I change the threshold optimally, suppose I make it as 98, which is a very good threshold for this problem, I see so many fringe contours beautifully demarcated. This is 1 of the greatest advantage in photoelasticity, even a simple thresholding operation, you are in a position to identify fringe areas.

Because if I want to do on binary based processing or if I have to do intensity based processing, I must first do indentify the fringe areas and within the fringe areas, let me do some kind of processing and in a binary based algorithm, what we will try to do. We will try to strip these outer pixels until the skeleton is obtained. One of the very famous algorithm in this is by Chen and Taylor.

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**Chen and Taylor algorithm**

- The binary image obtained after thresholding is scanned left to right, right to left, top to bottom and bottom to top sequentially to eliminate border pixels forming the fringe band.
- During each such scan, for every pixel with a grey level value below the threshold (a point on a fringe), a 3×3 pixel mask is considered to eliminate the border pixel.

Legend:

- Non Fringe Pixels
- Fringe Pixels
- ▲ Fringe Pixels for Elimination

3x3 Pixel Mask:

$g(-1,-1)$	$g(0,-1)$	$g(1,-1)$
$g(-1,0)$	$g(0,0)$	$g(1,0)$
$g(-1,1)$	$g(0,1)$	$g(1,1)$

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I am going to give you only a gist of what this algorithm is and also some introduction to how people process images and essentially you will have a mask and this mask is identified as the centre pixel as  $G_{0,0}$  because its grey level values, it is labelled as  $G$  and then I have this as  $G_{1,0}$ .  $X$  is increasing this way and  $y$  is increasing downwards. So  $G_{-1,0}$ . So I have a 3x3 matrix where I want to take a decision on the centre pixels.

And what is also given pictorially is I want to identify with a triangle, this is the fringe pixel for elimination in this case and if I have white circle, it is a non-fringe pixel, then if I have dark circle, I consider them as fringe pixels. So what is done, is you identify a mask and you move the mask over the entire image and depending on the neighbourhood of the centre pixel, you write a condition and based on that condition, the pixel will be retained or eliminated.

These conditions have to be developed very systematically, to some extent your mathematical understanding will help. Beyond a point, many of the image processing algorithms, they develop filters, apply to the particular image for a class of images, you will identify a sequence of operations. You may a pre-processing methodology of a particular kind may work well for some class of images. Even a simple thresholding works in this case.

If simple thresholding does not work, people have to go for other methodologies to identify the fringe areas. Then, when they develop the filter, they will also have to find out whether this filter really works. It may work in most of the areas, some areas it will not work. So you have to have a conceptual development as well as implement it and see whether the methodology really works.

So what you have here is, the image has to be scanned left to right, right to left, top to bottom and bottom to top sequentially to eliminate border pixels forming the fringe pattern. So, now I have to develop a condition, how do I identify that this is a border pixel and how do I remove it. Visually it is very simple. If I give a photograph to you, and then if I ask you to mark the fringe skeleton, you will do it.

If your hand is not shaky, you will do a very good fringe, if you are an artist, you can really pick out that fringe contour very well, but once we go for image processing, irrespective of the user, we want the computer to give you the skeleton and mind you any of these processes blindly looks at the fringe area and keeps on stripping out the outer pixels and this you may have to do left to right, right to left, top to bottom and bottom to top.

You have to do all this and ensure that any curvature of the fringe portion is not left out. That is the reason why you do this kind of different processing and we will look at what is the kind of condition that you need for 1 such scanning direction.

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EXPERIMENTAL STRESS ANALYSIS Transmission Photoelasticity

### Chen and Taylor algorithm

....contd

- When the image is scanned from left to right, it is checked whether the point  $g(0, 0)$  is an edge point.
  - This is so when  $g(-1, 0)$  is not a fringe point and  $g(1, 0)$  is a fringe point.
- The process of erosion of fringe band has to be done systematically.

In this case the centre pixel can be eliminated.

$g(-1,-1)$	$g(0,-1)$	$g(1,-1)$
$g(-1,0)$	$g(0,0)$	$g(1,0)$
$g(-1,1)$	$g(0,1)$	$g(1,1)$

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And what I have is this is the pixel that is under consideration and we want to look at the images scanned from left to right and I want to find out whether the pixel  $G_{0,0}$  is a border pixel and do I have to retain or eliminate and I have shown a typical fringe, where it has different kind of thickness and what I have this as a blue pixel is it repeats the scanning process and I will redo the animation, then you can have a look at it.

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EXPERIMENTAL STRESS ANALYSIS Transmission Photoelasticity

### Chen and Taylor algorithm

....contd

- When the image is scanned from left to right, it is checked whether the point  $g(0, 0)$  is an edge point.
  - This is so when  $g(-1, 0)$  is not a fringe point and  $g(1, 0)$  is a fringe point.
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$g(-1,-1)$	$g(0,-1)$	$g(1,-1)$
$g(-1,0)$	$g(0,0)$	$g(1,0)$
$g(-1,1)$	$g(0,1)$	$g(1,1)$

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So we are scanning the image from left to right. We want to find out whether  $G_{0,0}$  is to be eliminated. What it does in the first, it has retained this pixel and now the blue pixel in this region. Now we will have to look at a 3x3 mask around it and investigate whether this pixel can be retained or eliminated. What we want to do is we want to look at  $G_{-1}$  is not a fringe point and  $G_{1,0}$  is a fringe point. That happens  $G_{-1,0}$ ,  $G_{0,0}$  and  $G_{1,0}$ .



So this is not a fringe point and this is a fringe point that is what is pictorially shown, if you look at this mask, you have this pictorially shown. This is not a fringe pixel and this is a fringe pixel, so I can eliminate this and when I eliminate this, I still retain a contiguity of the fringe. So you have a process of erosion initiated and likewise you write it for left to right, right to left, top to bottom and bottom to top.

So if you do the image scan in all these 4 direction, it would eliminate some pixels. It depends and we have already seen when you look at a fringe, the thickness of the fringe varies dictated by the gradient. In low stressed areas, fringes will be very broad. In high stress zones, fringes will be very sharp. So depending on the fringe width, the process will take time. I have shown this as a thick fringe here and this is thin for illustration.

Essentially this is a process of iteration. So when you are going for a binary based algorithm, it is essentially a process of iteration repeatedly it has to until fringe skeleton is identified and how does it identify this as a fringe skeleton. It merely finds out the middle point. It is not necessary when you have a very broad fringe. The centre coincides with points of minimum intensity. What you will have to really look at is points of minimum intensity.

Now what we will look at is we will find out how this intensity information could be effectively used and what are all the issues involved. Because when I have to go and do this, I have to develop an appropriate algorithm for me to do that. So we will take a very simple fringe. We will take a fringe, which is essentially vertical, then we will look at essentially horizontal, then find out what are the parameters that are important.

Then we take up a generic fringe and then find out what is required and when you look at the problem statement like this, you will find it becomes mathematically more and more complex, but fortunately me and my students have developed logical operators, which work fantastically for these class of images and that is what we are going to look at. So we have looked at a binary based algorithm, we had a sample that we will find out for 1 scanning direction, what is the criteria to eliminate the border pixel.

You must have fairly understood what is the physics behind it. We identified this as a border and then you are able to establish it and remove it depending on the condition. Now we will look at intensity based algorithm.

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The slide is titled "Fringe skeletonization" and is part of a presentation on "EXPERIMENTAL STRESS ANALYSIS" and "Transmission Photoelasticity". It contains a list of four steps:

- The edge image previously stored can be used to identify the fringe areas.
- Identify the skeleton point within the fringe area, based on the minimum intensity criteria.
- To identify the skeleton point, the pixels between the edges of the fringe need to be scanned appropriately.
- One of the simplest scanning schemes is row-wise scanning of the image.

The diagram on the right shows a "Fringe band" consisting of four vertical black bars. A red arrow labeled "Scan direction" points from left to right across the top of the bars. The text "...contd" is written above the bars. At the bottom of the slide, there is a navigation bar with a "Back to main" button, several navigation icons (home, back, forward, search, refresh), and a copyright notice: "Copyright © 2009 Prof. K. Ramesh, IIT Madras, Chennai, India".

And what we call this as fringe skeletonization. What is shown here is, we have already seen I can get a fringe areas identified by a simple process of thresholding and I have that as an edge image, which is previously stored. It can be used to identify the fringe areas. Now I have a very simple fringe band and I am sure that I have this as vertical, you can think of a beam under bending kept in a vertical direction and you can get fringes, which are horizontal.

Instead of horizontal, because I kept the beam vertical, I will have vertical fringes, and the fringe areas are easily identified and if you want to pick out the minimum intensity point, it is enough I scan it horizontally. Suppose I scan the image the horizontally and within the fringe band, if I identify the minimum intensity point and make that as a fringe area, fringe skeleton, then my job is done.

So I need to develop a scanning mechanism, which is appropriate to the image and within the fringe area, that is start of the fringe, end of the fringe within that pick out the minimum intensity. So here we are using the important heuristic information, at the fringe contour, intensity is 0. So you are really looking at the minimum density, so this is mathematically much more precise than a simple binary based algorithm.

Binary based algorithm is useful when somebody gives you a photograph and they want you to process it. It is not recorded with care to identify intensity variation. So you need both. In some cases, you need to use an existing photograph to extract information. In other cases, you record the photograph yourself, then I can go for intensity based processing. So this is what we are going to look at. We have to decide on the scanning direction.

So here we scan it row wise, that is what is illustrated here and when I do the scanning like this what I am going to do. Between the edges of the fringe, identify the skeleton point having minimum intensity. So that is determined and what I have here is, I have nicely determined the fringe skeleton and this was possible, this scanning was simple enough to do because the fringes are vertical, I could have a horizontal scan possible. Suppose I have fringes, which are horizontal.

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EXPERIMENTAL STRESS ANALYSIS

Transmission Photoelasticity

### Fringe skeleton extraction for arbitrarily shaped fringes

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- If the scanning is made column-wise, the algorithm can be applied to extract fringe skeletons which are primarily horizontal such as those occur in beams subjected to pure bending.
- To process the fringe pattern that is observed near a crack tip, one requires a more refined scanning method taking into account the curvature of the fringes.

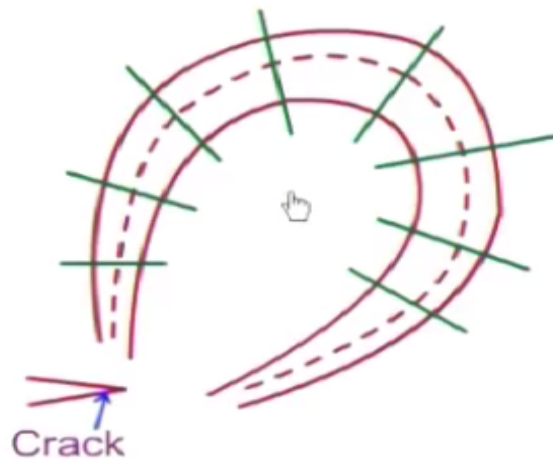
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What I can do. I can have a vertical scanning. I can repeat the same process. So when the fringes are horizontal or fringes are vertical, simple column wise scanning or row wise scanning can do the job of identifying the minimum intensity points. In 1 of the earlier classes, we have already seen in stress concentration, we have compared what is a fringe pattern in the case of a plate with a hole, plate with an elliptical hole, and plate with a crack.

If you look at the fringe pattern in the crack, it has the maximum fringe width, it has the minimum fringe width as well as maximum fringe width in 1 fringe order. A typical shape is like this. So what you have here is the typical shape in a crack is like this.

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What I have here. If I have to identify the minimum intensity point, I need to find out the edge normals, only then I can do that. So when I do that, my scanning has to be done appropriately for each of the segments. So a simple horizontal or vertical scanning will no longer be sufficient. The vertical or horizontal was sufficient because we had fringes essentially horizontal or vertical.

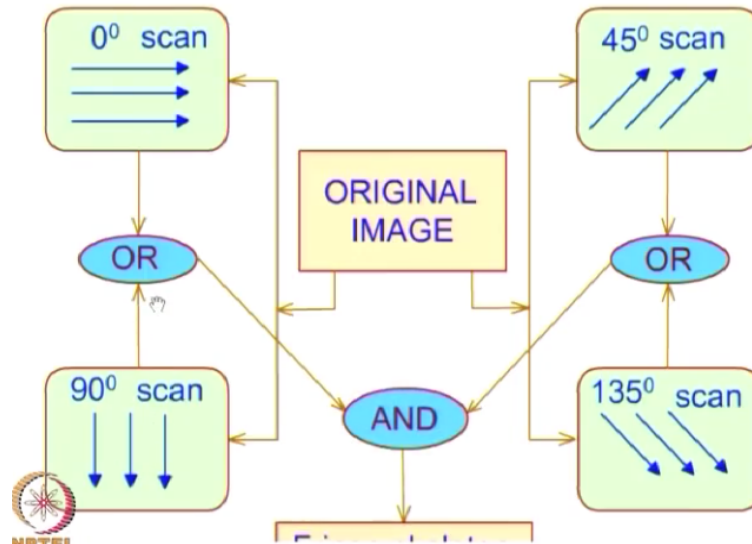
But in a generic problem, once we developed a methodology, I should be able to apply it to fraction mechanism problem. That is 1 of the very important practical requirement where external mechanics is needed and you have fringes of varying thickness only and you need to make a decent sketch of it. You need to have this and you need to find out, see because if I do a scanning like this, I will not be in a position to pick out the exact minimum intensity point.

So I must find out the edge normals and then do the scanning and this becomes mind boggling. How to implement this kind of a scheme digitally, even if you do not want to implement is digitally, the mathematics involved is high and it is mostly a repetitive type of processing and this is not advantageous from developing an algorithm. So you have only identified what is the difficulty in processing a generic fringe pattern.

And here only what we found was these logical operators has really helped. So the keep on here is 1 has to do enormous amount of computations, to extract the fringe skeletons. The reason is we have to find out the edge normal from geometric considerations of the fringe, which could be greatly simplified if you adopt a scheme, which employs logical operators,

which took sufficient time for us to develop and which is very fast and that is what we look at.

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I will take the original image. So when I say the original image, I will have the edges identified. Then I will scan it horizontally, get the skeleton image, scan it vertically, get the skeleton image, and process this by a or operator. Make a sketch of this. You need to have this algorithm. The algorithm is very simple and straight forward and I am doing a set of orthogonal scans, only to appreciate that this can help.

We have looked at fringes, which are vertical. This alone can provide the complete skeleton when the fringes are vertical. On the other hand, when I have fringes, which are horizontal 90-degree scan alone can provide you the fringe skeleton, but in a generic image, what we have found was I need to have a 0-degree scan. I need to have a 90-degree scan; I need to have a 45-degree scan as well as 135 degree scan.

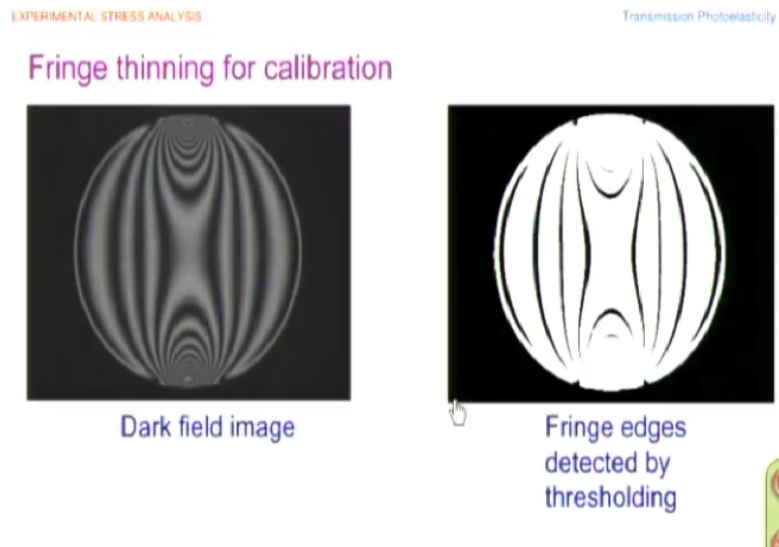
So in essence, once I have original image, I will globally search the image only 4 times, 1 in 0 degree, 90 degrees, 45 degrees and 135 degrees. Because I do it only 4 times, no iteration involved. The number of operations are fixed and what is the advantage of this approach is by the use of appropriate logical operators, you are able to successfully remove the noise that is generated in each of the scan, each scan will give you skeleton, as well as some noise.

What we do is by doing the logical operators, retain the fringe skeleton and remove the noise and what are all logical operators. I have a 0 degree and 90 degree scan and I do a or

operation between the 2 and I have a 45 degree scan and 135 degree scan. I do a or operation between the 2. Now I do the logical and of these 2 results. So 2 or operations and one and operation provides you fringe skeleton free of noise. This is only a statement.

This statement has to be verified from actual processing of the fringes. That we will see.

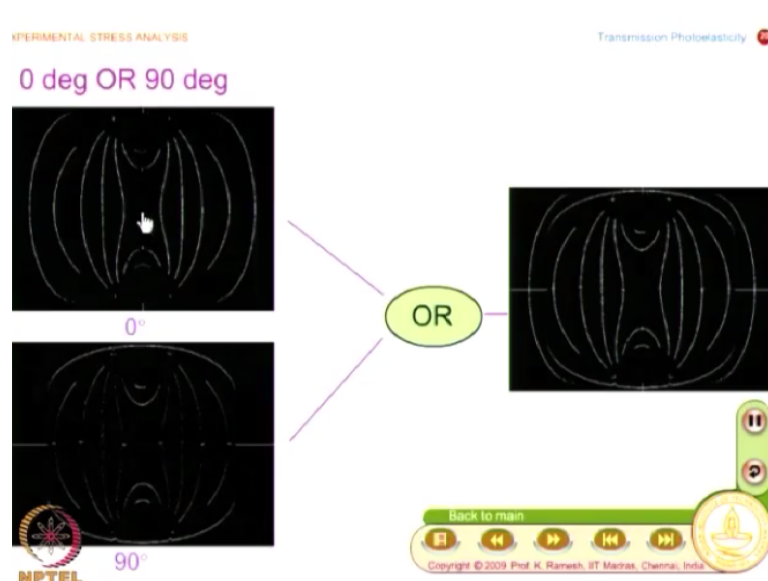
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And what I have here is I have the disc under diametral compression fringe pattern and this is the edge identified image and I have this edges are identified and what I have to do is, I have to go and find out the fringe skeleton. And here what you find is the fringes are not only either horizontal or vertical it has an arbitrary shape primarily vertical. So what you will find is in 1 of the scans it will pick out.

Horizontal scan will pick out more points, vertical scan will pick out only some points. That is the kind of information that you will have and we will see that.

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So I have these 2 scans are done, 0 degree scan and 90 degree done, and I will enlarge this picture. So what you will find here is horizontal scan because the fringes are primarily vertical, it has picked out quite a number of points but whenever the fringe becomes tangential, the scanning direction becomes tangential, you lose some data, you lose some data here. And we will also see the other scan.

I mentioned that this gives you only small information and it has identified in the zone where the 0 degree scan has not returned you the value. That is the advantage, so this is complimentary, but it introduces noise. It introduces noise in some other direction. So now what I do is I do a logical or operation, I take a logical or operation of these 2. I get a fringe skeleton, which is reasonably complete but it still has noise.

You have unwanted information like this. So what you find is scan the image horizontally and vertically each scan provides you some fringe points and some noise and a logical operator helps you to connect all the fringe points, all the fringe points are now collected. But you also have noise and what you find is you go to another set of orthogonal scans you are able to get all the fringe points but noise in a different direction.

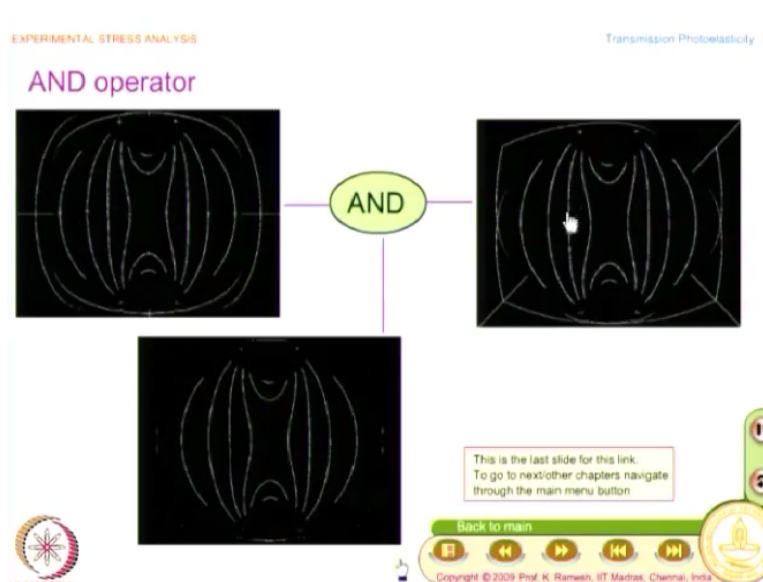
So when I do the logical and the noise is eliminated, that is the principle behind it. So we will go and see this is the or operation, 0 degree scan and 90 degree scan I have or operation I have this fringe pattern. Now I go and see the other orthogonal scans. I look at the 45 degree scan and 135 degree scan and here again I will enlarge the picture. And what you find is, it is able to identify the skeleton in these portions.

It is not able to identify in some zones, you are actually doing the scan like this 45 degree like this and it is identifying some noise here. And if I look at the other scan 135 degrees it complements, where I got information in 45 degree scan I do not get information in 135 degree scan. But I get what is the information missing in the other scan you are able to get it here.

So I do orthogonal scans I am able to get the data complimentary from each of this and do a logical or operation. So when I do a logical or operation I get this, and what you find here the fringe skeleton is reasonably comprehensive and it has branches of noise. And in the zone you do not see much noise in some other applications you will also see noise even in this depending on the fringe orientation, the fringe orientation is a key point.

So in a very generic problem a 0 degree, 90 degree, 45 degree and 135 degree scans really help. Now what I do is I do the and operation of these 2 or results and that is what I am going to see here.

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So I have this 0 degree, 90 degree scan image, 45 degree, 135 degree scan image and I get finally the skeleton as good as this. You see only the fringe in the area where you have seen the fringes, and of course the information at stress concentration zone is lost and which was not that even in your edge detected image. Even when you had the edge detected image, you did not have the fringes in the stress concentration zone and how to surcommand this.



You take a photograph with a higher optical magnification in that zone and repeat the same process you will be able to extract the information. Why that is not attempted here because my focus is to find out  $F$  sigma, and  $F$  sigma we have already seen, we will collect data in an annular region near the centre  $0.35r$  to  $0.5r$ . So I am not interested in the data near the load application point.

So for our application this is good enough, and this is what we have here, I have the data to be collected only in this zone and this is an annular zone I wanted and I can also zoom it further. So what I see here is I have the black fringe in which I see the white line as fringe skeleton and in this zone I can definitely find out 40 data points, because our requirement is only 40 data points.

So for the problem on hand I do not have to go and worry about information extraction in stress concentration zone, I have the necessary data. So once I have this 40 data points what is that I can do, I can go to my Gauss elimination procedure and find out the  $F$  sigma value by simply processing that matrix what you have got. And you can also make it insensitive to the data points, which is not done in the present application.

You know I want to show you what is the difference the choice of data points also matters. And what is shown here is I have the fringes reconstructed, because we know the stress field in a circular disc, using the theoretical information, it is possible for me to reconstruct. And this is to illustrate if you do only 1 least square analysis, your choice of data point matters. You know I have this choice of data points and these choices of data points do not lie precisely on the fringe skeleton.

In some points it has matched some points it was not matched. But nevertheless you are able to see the collection of data points lying on the fringe contour. The accuracy can be improved slightly better. So for this it is better that you go for a sampled least square analysis. So you are able to make the process of identifying  $F$  sigma independent of the data points collected. But this illustrates what is a basic procedure.

Now my interest is to tell you how do I do a theoretical plotting of fringes and why this is needed. See in a case of  $F$  sigma, I am essentially solving a linear problem, in a linear problem reconstruction of fringes is not that critical you will definitely have the fringes akin

to what is seen in experiment. The same method of processing data in a least square sense is also extended to finding out stress intensity factor in factor mechanics problems.

In those problems it is essential that you reconstruct the fringe pattern to ensure that your iteration has given you the correct minimum value. We saw a linear least square methodology for  $F$  sigma calculation, the least square methodology becomes non linear when I go for factor mechanics problem. In non linear problems I have dual iteration. Iteration you will not know whether it is a local minima or a global minima.

The essence is you have to identify the global minima not the local minima, and people have reported in some of the cases you get the parameters converged but it gives the fringe pattern different from what is the actual experimental fringe pattern. So it is a must that you always reconstruct fringe pattern and you need to know how to reconstruct fringe pattern. And the reconstructed fringe pattern how does that look like.

I have a beautiful thickness variation. This is not experimentally recorded. But it is very close to what is experimentally recorded I see thin regions the same fringe becomes very broad here, how is this achieved. In fact, I raised this question when I talked about fringe bands, I said how to do it I will reserve it for 1 of the later classes and I tell how do I mimic the thickness variation also.

And even the thickness variation you can do it by a very simple mathematical step, you do not have to worry depending on the fringe gradient, I should go and tell the program that make the thickness as so much, nothing of that sort is required. And how do I do the theoretical reconstruction, this is what we will see.

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## Theoretical Reconstruction of Fringe Patterns

The isochromatic patterns correspond to the loci of maximum shear stress, expressed in terms of the cartesian stress components as

$$(2\tau_m)^2 = (\sigma_x - \sigma_y)^2 + (2\tau_{xy})^2$$

Using the stress-optic law

$$\left(\frac{NF_\sigma}{h}\right)^2 = (\sigma_x - \sigma_y)^2 + (2\tau_{xy})^2$$

And we know what do these isochromatic patterns correspond to, they correspond to loci of maximum shear stress expressed in term of the Cartesian stress components as  $2\tau_m$  whole square =  $\sigma_x - \sigma_y$  whole square +  $2\tau_{xy}$  whole square. Note the difference this is in-plane shear this is maximum shear stress. And in any problem where you have an analytical solution, it is possible for you to find out the right hand side.

I know  $\sigma_x$ ,  $\sigma_y$  and  $\tau_{xy}$ . Even if you do not have an analytical solution, suppose I solve the problem numerically, then also I have the right hand side. So I can get it by numerical or analytical solution, only the plotting basic is similar the implementation will be slightly different. And what do we get from stress optic law, you get  $NF\sigma/h$ , so this is related to this.

Now what you see as fringe pattern you see as fringe pattern only the fringe contour  $N$ . Suppose somebody gives you a problem and asks you to plot a contour what is the normal way which you will do. A contour is 1 where the value remains constant, so you will go and find out the  $xy$  coordinates of that. That is how anyone will try to do, suppose I look at this expression I have  $NF\sigma/h$  whole square =  $\sigma_x - \sigma_y$  whole square +  $2\tau_{xy}$  whole square.

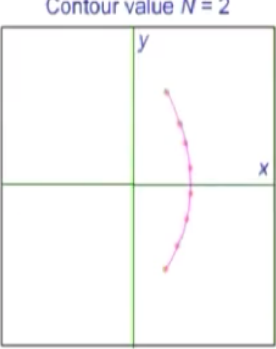
I have  $\sigma_x$  is a function of  $x$ ,  $y$   $\sigma_y$  is a function of  $x$ ,  $y$  and if you really plug in those values, invariably this will be a non linear equation. And if you have a non linear equation when I want to do the estimation of  $x$ ,  $y$  for a given value of fringe order  $N$ , it becomes iterate and let us look at what is a difficulty there.

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EXPERIMENTAL STRESS ANALYSIS Transmission Photoelasticity

### Theoretical Reconstruction Of Fringe Patterns ...contd

- One approach to plot fringe skeletons is to find the co-ordinates of fringe points in the entire field corresponding to a particular fringe order and join them appropriately.
- In most problems, the governing equation of the co-ordinates will be non-linear.
- Iterative evaluation of co-ordinates is not only time consuming but could also be erroneous.



And I would get for a fringe order 2 some points like this in my domain and I essentially join them by a line. So when I do like this, then I will have to worry how do I bring in fringe thickness variation, how do I do the calculation all that you have to think of it, and in fact nowadays fringe plotting is so simple people has developed and established programs also published and it is not a big deal.

In earlier days, there are several research papers are written how to plot fringe skeletons it is not so simple. So the important aspect is in most problems the governing equation of the coordinates will be non linear, iterative evaluation of coordinates is not only time consuming but could also be erroneous. So an approach like plotting a fringe contour like talking a fringe order  $N = 2$  collecting all the data points and connecting them as a contour is not the solution.

This is not the way that we have to approach the problem of fringe contour. We will have to go by a different approach that approach also should ensure even mimicking the fringe thickness. So what we will do is see computers are very faithful servants. If you ask them to do repeated calculation it will do without a murmur, that is a greatest advantage. So what we will do is we will use the computer that way.

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## Theoretical Reconstruction Of Fringe Patterns

- A scanning approach will be quite effective. In this, the fringe order at every point forming the grid is to be evaluated.
- This evaluation is straight forward and does not require solving any non linear equation.
- Fringe thickness variation could be easily mimicked by plotting these points, which lie in the range  $N \pm e$  where  $e$  is usually of the order of 0.1 – 0.2.

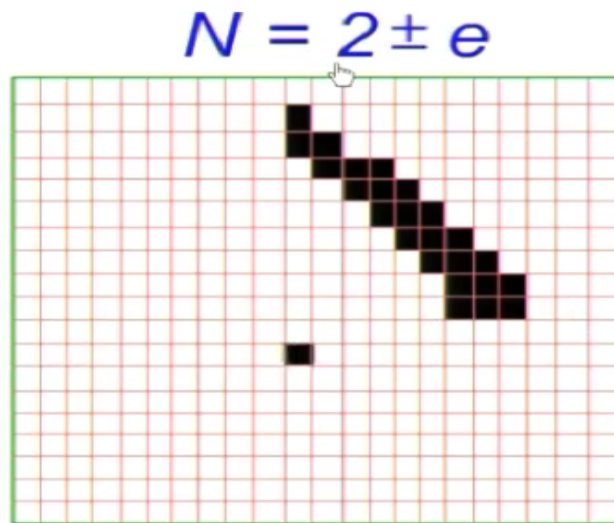
So we will do a scanning approach, this will be very effective fringe order at every point forming the grid needs to be evaluated, because you and I have to do the calculations. Scanning approach is not the right way to do. Scanning approach would be boring and time consuming after 2 - 3 calculation you will say forget about it. A computer will not do that and it will faithfully follow what you say.

So we have already seen that an image can be identified as assembly of pixels, so if you bring in that pixel level of scanning and plot it you will get fringe contours which are continuous. And what you need to check here the first advantage is the evaluation is not iterative, this is evaluation is straight forward and does not require solving any non linear equation. What you essentially do here is you find out the fringe order at every point forming the grid and I said the grid could be at the pixel level.

And I also said I must be in a position to mimic the fringe thickness. And fringe thickness variation could be easily mimicked by plotting these points which lay in the range  $N \pm E$ . And  $E$  could be of the order of 0.1 to 0.2, it automatically picks out fringe width. When fringe gradient is very high fringes will be very narrow and fringe variant is very small fringes will be broad and this is automatically taken care of by your mathematical strength.

So you do not plot a fringe of fringe order  $N$ , but you plot a fringe order of  $N \pm E$ , a small value. If I take a very large value of  $E$ , you know I can adjust it is equivalent to like high contrast processing or low contrast processing of your images. That kind of an effect it will show and that is what is shown here as an animation.

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I have essentially fringe, identified this as assembly of pixels and this is what you would see here, and essentially I want to plot a fringe of  $N +$  or  $N = 2 \pm e$ . So I keep on doing this calculation repeated so whenever I find this satisfies this automatically the fringe thickness is also identified. And in this plot I have shown only for 1 fringe order and in fact you can develop the logical condition in a manner in 1 shot it plots all the fringe patterns.

So that is the greatest advantage. Some of you are good at computers please go and develop the fringe contour for at least circular disc under diametral compression, you can take it as a home exercise and try to do it. And that will give you a feeling, once you do for 1 problem you will feel like doing it for several problems and you will get a visual appreciation of how the fringe contours look like.

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### Comments on Fringe Ordering

- Methods to ordering fringes could be formulated on the basis of properties of isochromatic fringe field, isoclinic fringe field and also certain principles from Mechanics of Solids.
- A ring under diametral compression represents various important aspects of a general fringe field such as source, sink, saddle point, singular point and isotropic point.
- Source, sink, and saddle points correspond to isochromatic fringe field and singular and isotropic points correspond to isoclinic fringe field.
- It is to be noted that there is no standard procedure to order fringes.



So what we have seen is we have also looked at the  $F$  sigma calculation and now we have to go to the very important topic and which I said I will reserve it separately is how to identify fringe orders. Because I need to get fringe order  $N$  and  $F$  sigma for me to get stress values in anyone of the actual problem. I need to get  $F$  sigma,  $F$  sigma calculation we have just now seen and we have to get the fringe order  $N$ .

If somebody gives the fringe order  $N$  is very simple but you have to identify for complex problem, how to label the fringes. And you know certain aspects could be understood if you look at properties of isochromatic fringe field and also properties of isoclinic fringe field and you can get some kind of a help from principles of mechanics of solids. So what I need to do is I have to go and see what are all the properties of isochromatics.

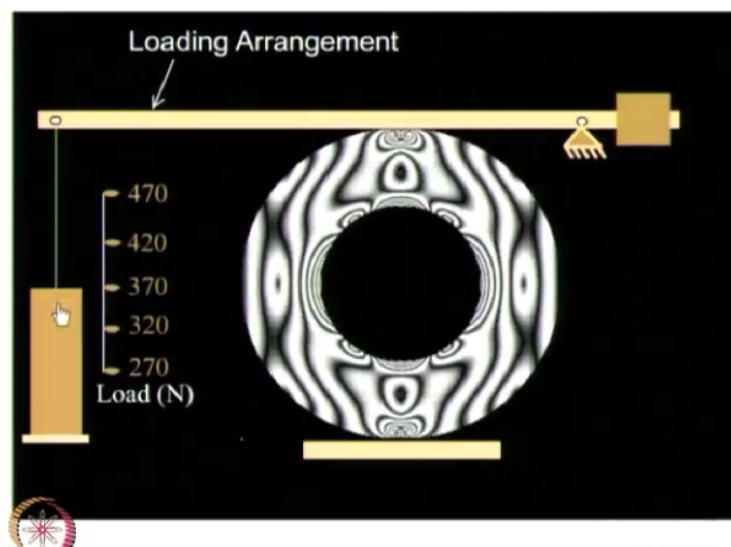
What are all the properties of isoclinic and I am going to take problem of ring under diametral compression to illustrate the properties of isochromatic fringe field as well as isoclinic fringe field. And even before we look at those properties let me list only the names, I am not going to explain them I want you to look at the fringe pattern and try to figure out yourself.

And if you look at the problem of ring under diametral compression represents various important aspects of a general fringe field such as source, sink, saddle point, singular point and isotropic point. That is why we want to go for ring under diametral compression, so when I understand all these features that serve as guide points for me to order the fringes. That is what is very important.

These points could be classified certain belonging to isochromatics and certain group belonging to isoclinic. If you look at source, sink and saddle points corresponds to isochromatic fringe field, singular and isotropic points correspond to isoclinic fringe field. And now I go and look at the last aspect, it is to be noted that there is no standard procedure to order fringes, you must keep that in mind.

These are all guidelines, the guidelines you have to use it intelligently, guidelines are different from standard fixed step for identifying this. Guidelines will help you how to thread the path.

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And I am having a very nice illustration of fringe field in ring under diametral compression, this I will magnify it and what you need to look at is I have this load being varied, this is a level arm loading frame. And as the load is varied you have fringes are developing and moving and the idea is to just look at the fringe field. See for few minutes, you need to see what all special features you look at.

Very interesting things are happening, I want to take out this portion and then see what is that you observe, what is that you observe in this zone what is happening, as the load is increased a very interesting feature happens. You see this, even if I take you to the laboratory to make you look at this feature, you would not be able to observe. Because of the animation what I have I am able to repeatedly show this and you can see what is happening.



What is happening at this point, the fringes go and vanish here, fringes go and vanish here, are you able to see. The fringe go and vanishes, so what is it called in fluid mechanics. Suppose the fluid flow, it is a sink. So you have a sink, you have a sink in the case of isochromatic fringe field, you see this beautifully and let me show you 1 more feature. Let me focus on this part of it, what is happening here.

I have something special happening in this zone and I have something special happening here. As the load is increased in one case fringe go and vanish, in another case only the density increases, only the density increases. Fringe does not vanish, you should, after me telling you this, you observe it, so in this zone what is happening is fringes come out of it and then they become denser and denser and this remains as such.

And we have seen we had enough clue earlier, we had set what is the 0th fringe order, I said 0th fringe order does not move even when the load is changed, is not it, because 1 of the thing, 1 of the aspects what I discussed was in a plain polaroscope, suppose you are given only 1 monochromatic light source and you had to identified the difference between the isoclinic and the isochromatic fringe field.

I said if you have polariser analyser crossed, if I rotate them isoclinics will move. On the other hand, if I change the load isochromatics will move exception is 0th fringe order. And that you see here, what I said you see here that when the load is increased 0th fringe order remains as such. And you also see an interesting aspect, this is a high stress concentration zone and in this case the fringes emerge out as the load is increased.

And so that is what we have seen and keep looking at this fringe pattern for 1 more minute, and there is also another interesting feature which I would take it up in the next class. So you understand now the fringe contours in the case of a ring is much more complex we have reserved the discussion towards the later part of the course, so that if you learn how to order fringes here you can order fringes in any problem that you come across with reasonable confidence.

Because fringe ordering is a tricky issue. Even for experts if there is a very complex problem the phenomena is not understood you may make a error in judgement. And that is why you need to know this feature, so if you know these features you know there will be an indirect

check. I can approach the fringe ordering from approach and label the fringes, I can verify by the other approach if the ordering is correct by both the approaches you should get 1 unique value.

So that is how you decide on the fringe ordering accuracy. If you have the luxury of colour code, then nothing = it. But some cases you know you are doing a dynamic test and even recording fringe pattern at high speed itself is so complex. Even if you get a monochromatic photograph, you are very happy. So there are occasions where you need to live with monochromatic light source and you need to interpret the fringes.

And fringe ordering is the most complex aspect and that is what we have looked at in today's class. We have made a beginning in that direction. We have looked at how to find out the data points that is required for  $F$  sigma calculation. We have looked at fringe thinning methodologies and in the actual data collection, I have not shown how you go and collect, 1 simple way is to just click the cursor and pick out data, that is how you do it conventionally.

With modern techniques in digital photoelasticity, because I get fringe order at every point the domain within the annular region of  $0.3$  to  $0.5r$ , you can even automatically collect the data by writing a code. So with use of image processing techniques the analysis could be made much more refined where you use principles of statistical methods in processing experimental data. Thank you.