Strength of Materials

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Lecture - 12
Photoelasticity

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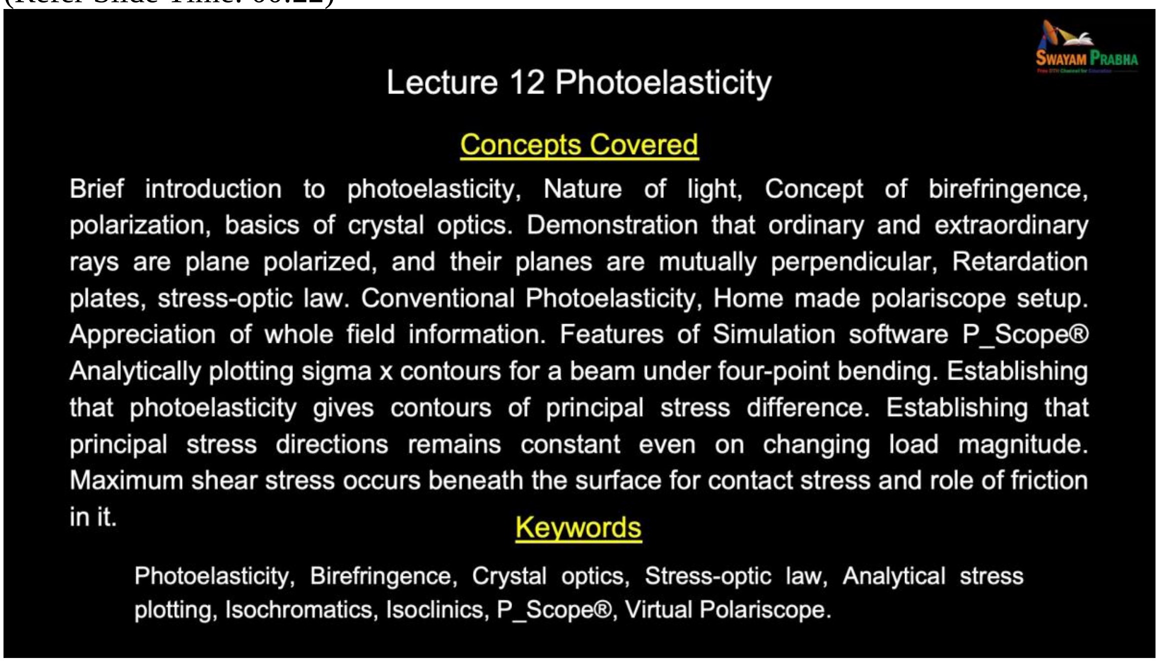

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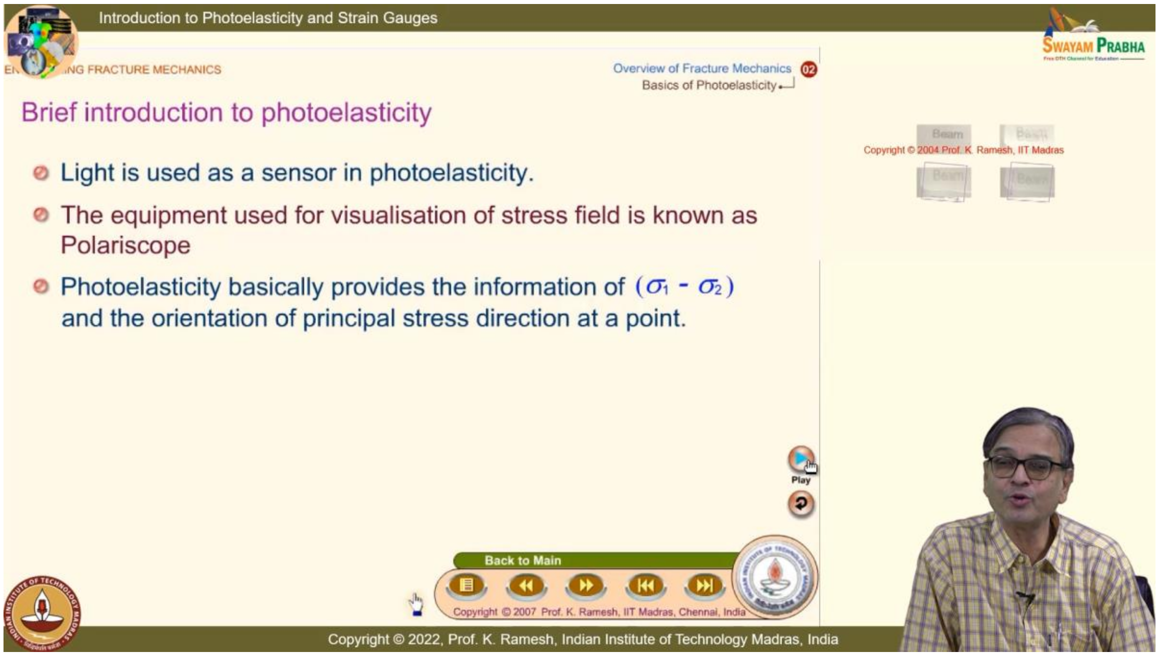

See, let us have a bird's eye view of principles behind the photoelastic technique. See, in your high school physics, you would have done about refractive indices and invariably you would have assumed that refractive index was like a number, like a scalar quantity. Am I right? It is no longer scalar quantity when you come to crystals. When you come to crystals, it changes from direction to direction and it behaves like a tensor of rank 2. And you know, with a long discussion we had on stress, we understood state of stress at the point is a tensor of rank 2. So, there is a happy everlasting marriage between refractive indices and stresses.

So, that has helped you to visualize the stresses, which otherwise you could not see, you could only see the deformation. That too I have cautioned you, if you see deformation with your naked eye, it is large deformation. For the purpose of illustration and to develop the theory, we exaggerate that deformation when you do sketches, but in real structures you do not want to see the deflection, ok. And what is the sensor? Light is used as a sensor in photoelasticity and the equipment that used for visualization is called a polariscope.

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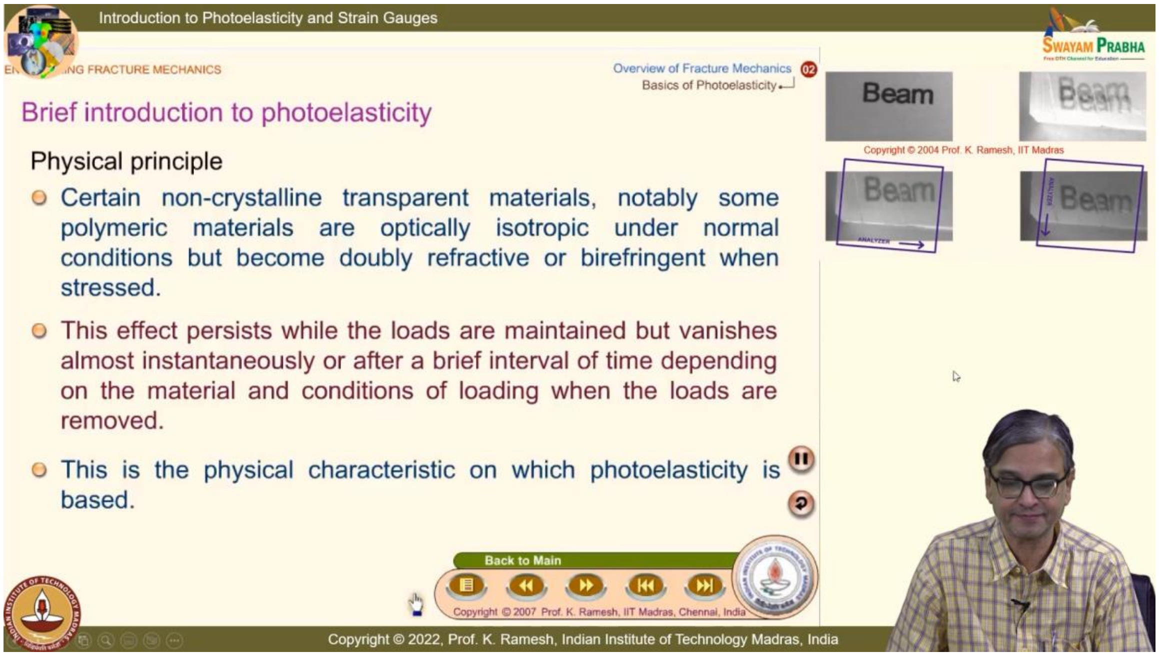

You call it as a polariscope mainly because you send a polarized beam of light. Why do you need a polarized beam of light? The answer is there, we use light as a sensor. And what you have is, it is very interesting, the central idea here is what is known as birefringence. Some of the polymeric substances, they become birefringent when loads are applied. When the loads are removed, they behave like a normal material, they behave like a normal material when the loads are removed.

So, it behaves like a crystal when the loads are applied. So, whatever you see as the variation can be related to stresses, that is the beauty behind it. So, if you say what is the physical principle, it is a birefringence. And you have an idea of what is birefringence shown here, bi means two. So, you see two refracted image of the letter beam when I put a crystal. We will also see that little while later, little more elaborately.

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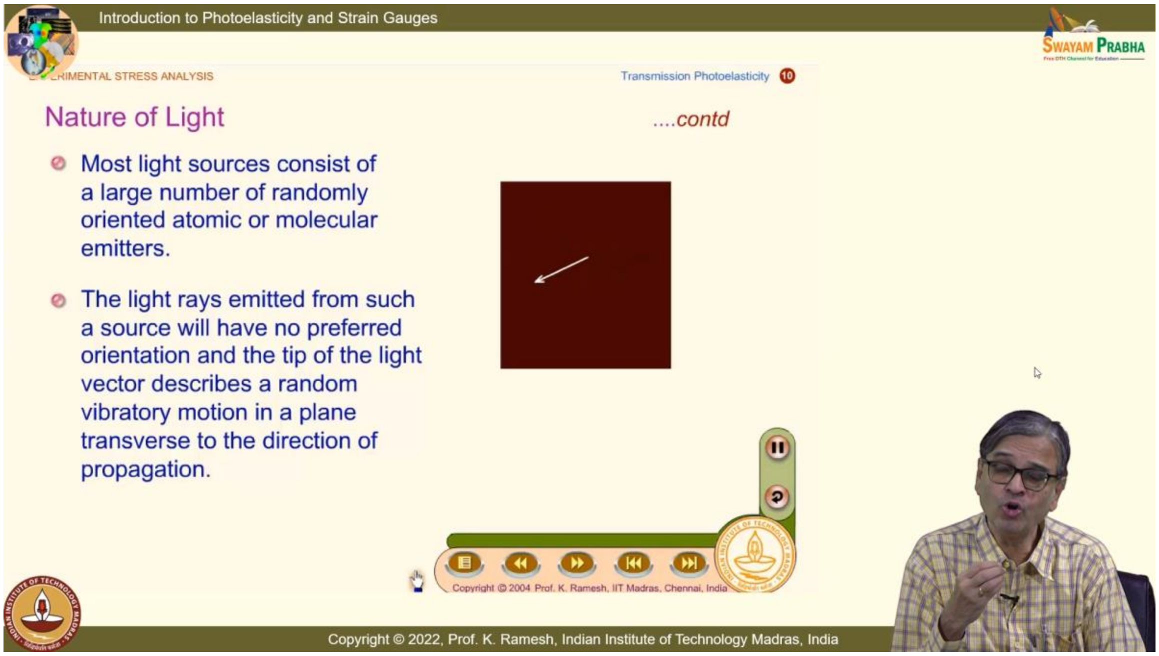

See, I said you have to send a polarized beam of light mainly because the natural light source is randomly vibrating like this. The direction is different, magnitude is also different. So, if I use that as a sensor, no way I can identify the modification introduced because of stresses to the light, fine. So, I need to have some discipline to the light and that discipline what I enforce, I call this as polarization. Even when you have any discussion point, some people have polarized views you see, is not it?

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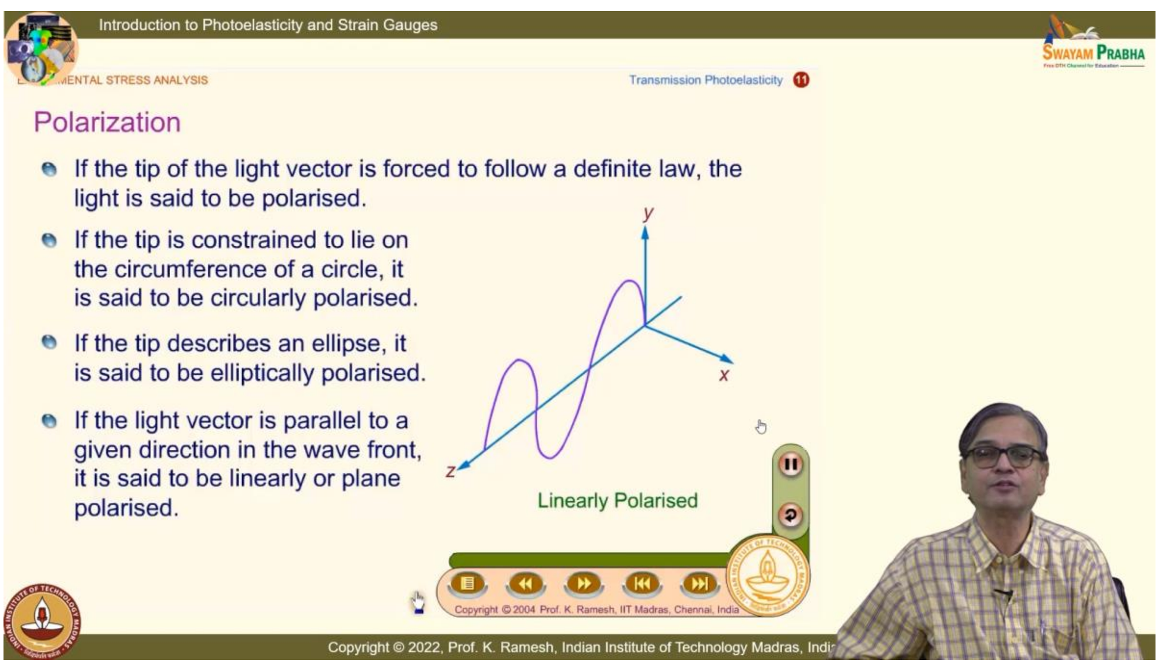

That is also used in common English. I have here it is used in a positive sense and you want to have polarization and this is used in even in signal processing, even your electrical signals are polarized for you to do it. And if you make the tip of the light vector is forced to follow a definite law, you call this is polarized. When it is circularly constrained, it is called circularly polarized. When the tip traces an ellipse, it is called elliptically polarized and when it lies in a plane, you call it as plane polarized. Essentially, you know what you have is the most general form of polarization is elliptical polarization. You can derive all the other polarization aspects from elliptical polarization.

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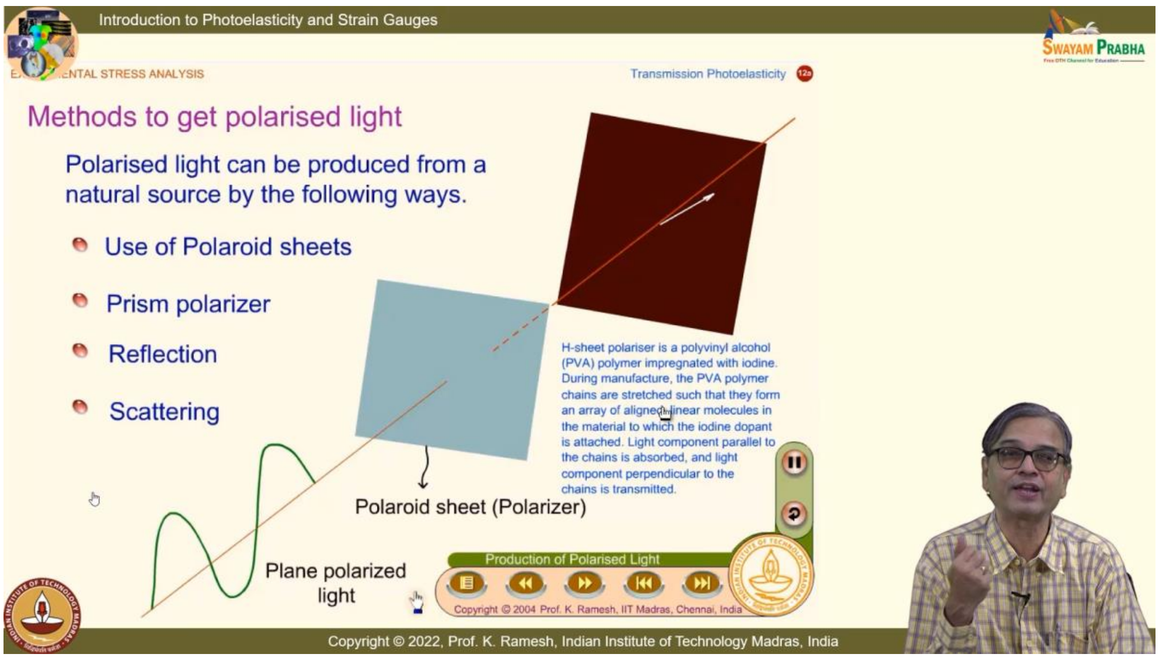

And how do you get polarized light? It can be by polarized sheets, that is what we will see. You can also have a prism polarizer, it can also be by reflection and scattering. And this beautifully illustrates when I have a random light like this, when I put a polarized sheet, I get only a polarized beam of light. And obviously, what do you anticipate? What will happen to the intensity of light? It will get decreased because some energy is lost because this polarizer sends only a particular component of light. Is the idea clear? And how do I investigate whether the light is polarized?

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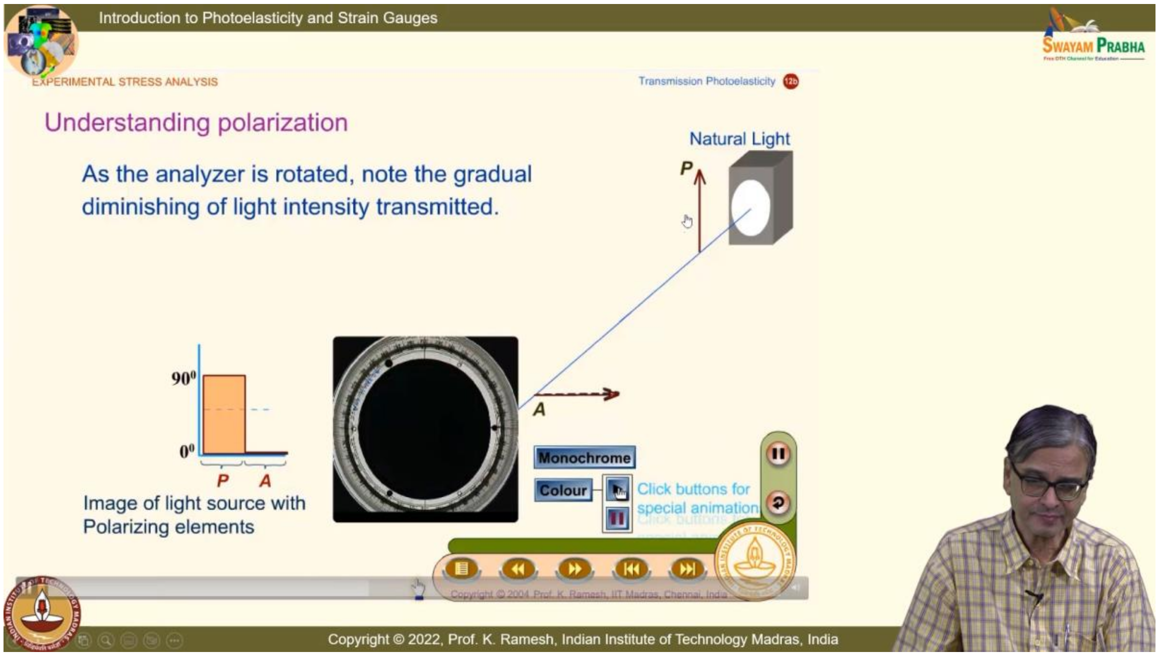

So, I should have two identical elements and put them crossed and gradually make them completely crossed, you find the intensity goes to zero. So, that indicates that what you have as shown is a polarized beam of light, which I have shown it for a white light now for a monochromatic light source.

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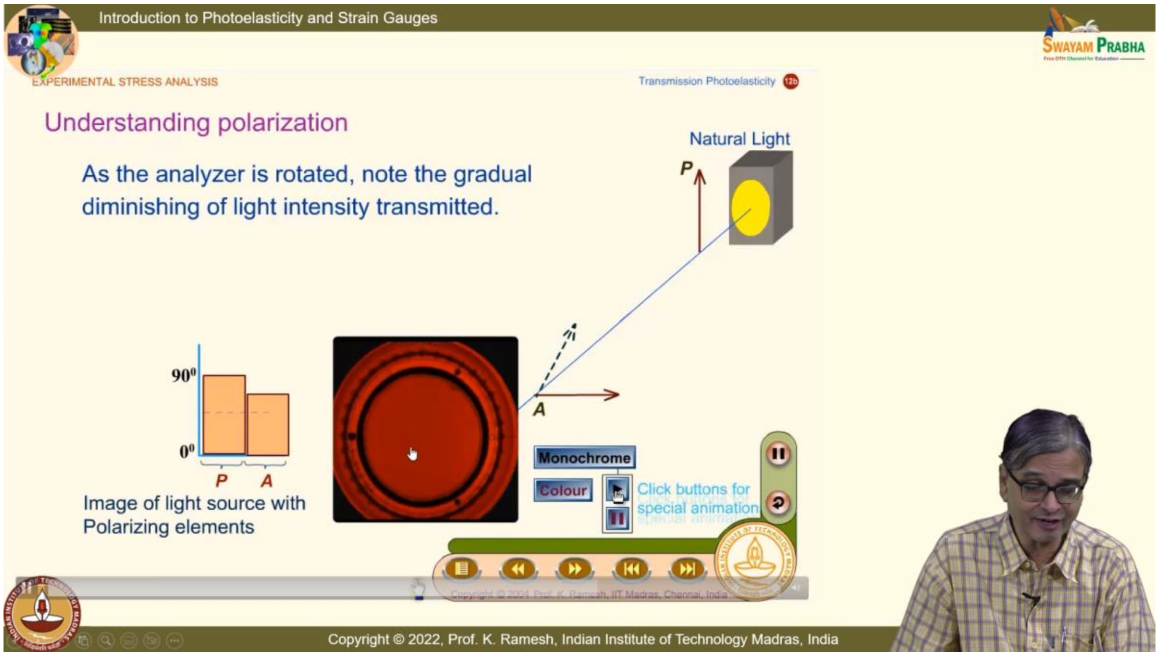

This light source is very strong and this is experimentally recorded. So, when it comes horizontal that is perpendicular to this, you call this as polarized, plane polarized and you see total extension of light.

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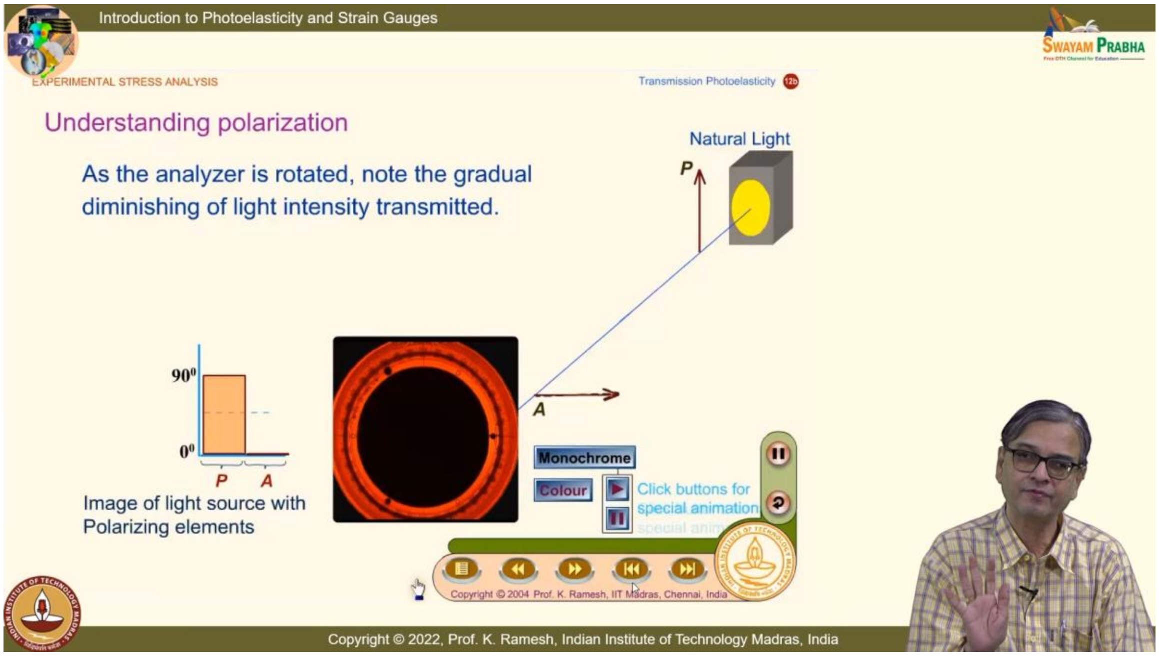

And this is a representation, you will have an optical element, but when you want to make a diagram, we simply put that as a line and we understand. So, you call this as a polarizer because I analyze, I call this as analyzer, materially both are identical, the axis are oriented differently, fine.

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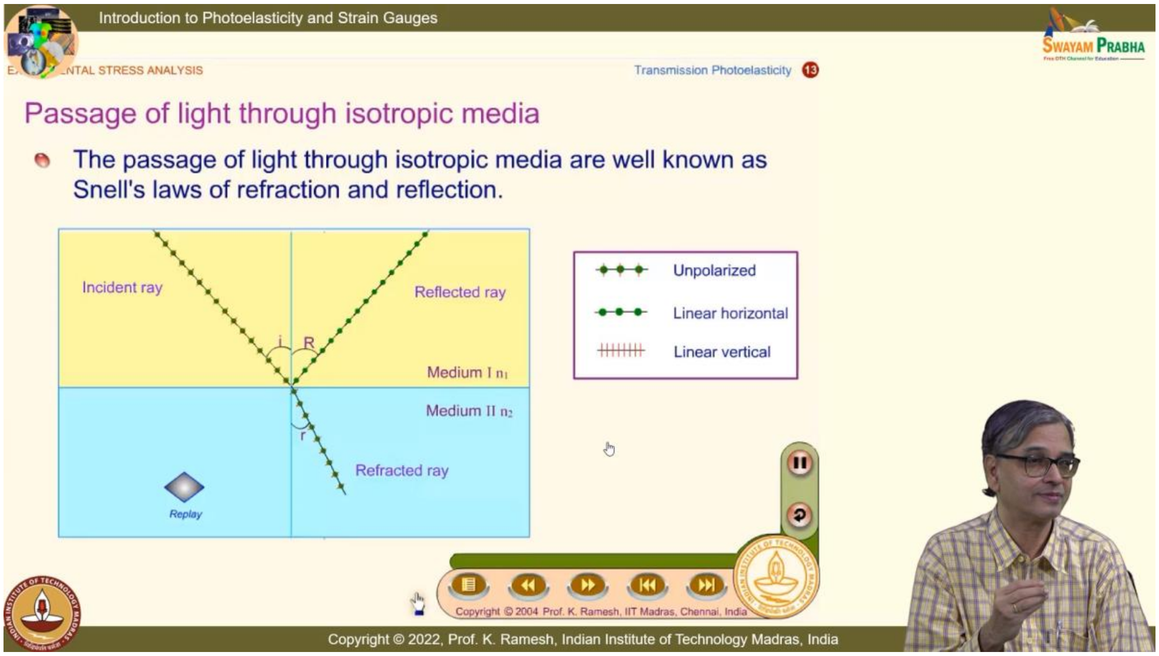

And in the case of an isotropic medium, when you say isotropic, it is optically isotropic. I can have elastically isotropic, optically anisotropic, all those combinations are possible. This you have studied in your high school physics, you might have also determined the refractive index of a glass prism and you would have put pins and then identified this.

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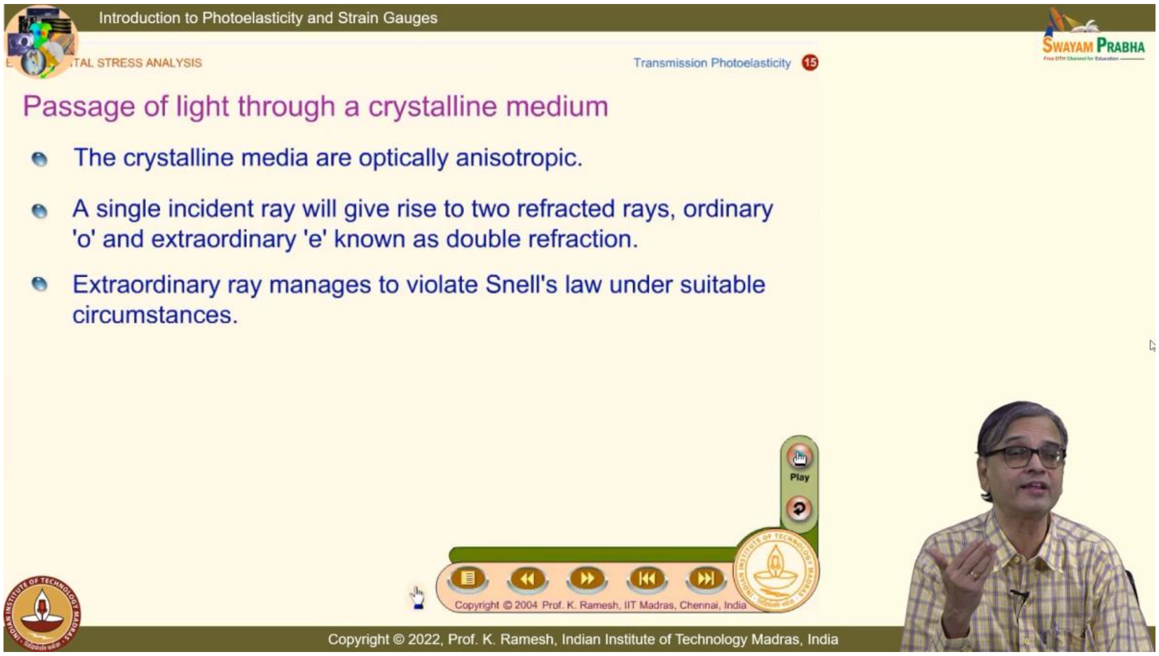

So, you have a famous Snell's law and how many of you remember, what way can you visualize the refractive index? Can you relate it to speed in some way, velocity? So, velocity you can, so that aspect we are going to use it in photoelasticity, fine. So, the fringe formation photoelasticity is by a phenomenon of temporary birefringence induced by loads. That is why we are able to relate the optical information to the stresses developed. So, when I send it through a crystalline medium, instead of one ray, I get two rays. One is an ordinary ray, another is an extraordinary ray.

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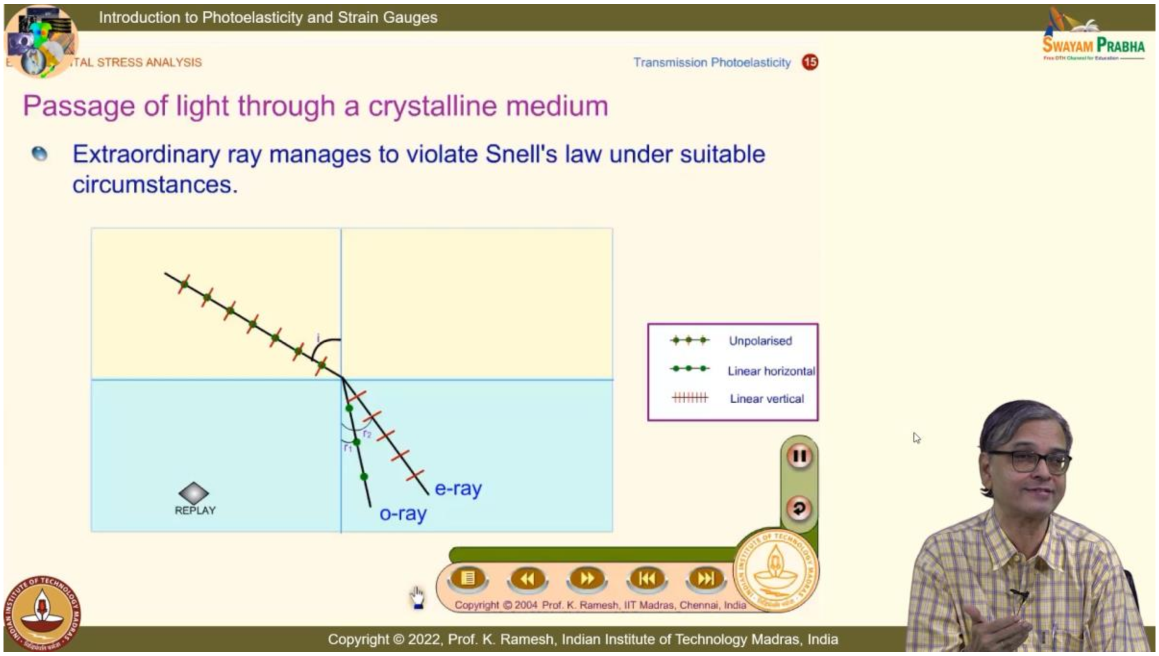

Indians understand what is extraordinary because we have a VIP culture, whoever violates the law, he is an extraordinary person. So, the extraordinary ray violates Snell's law, ok. So, for a single incident ray, surprisingly I have two refracted rays, one becomes two, fine. Not only that, and you also have how the light is indicated. I have a circle and a line, this is a representation in optics to show an unpolarized beam of light.

And when I have this ray inside the crystalline medium, one of the rays has only dots, another ray has only lines. So, they are mutually perpendicular, that is what is indicated. You know this is theory, we would also see by a simple experiment, indeed I get two rays, and they are plane polarized and mutually perpendicular, that happens inside the crystal. So, it is very interesting. So, this is the representation.

So, this is what you call thus as birefringence, it has two refractive indices. When you have associated this with velocity, what do you anticipate for the ordinary ray and extraordinary ray? They will travel with different velocities, that you can visualize, because you have Snell's law which relates the refractive index to the angle of incidence and angle of refraction, is that, is not it so? So, now you realize, because the angle of refraction is different for extraordinary ray, under certain conditions extraordinary ray can merge with ordinary ray, and it can have any ray of any angle of refraction, depending on the orientation with respect to the optic axis. So, that property is exploited in photoelasticity, only the ordinary ray faithfully follows the Snell's law.

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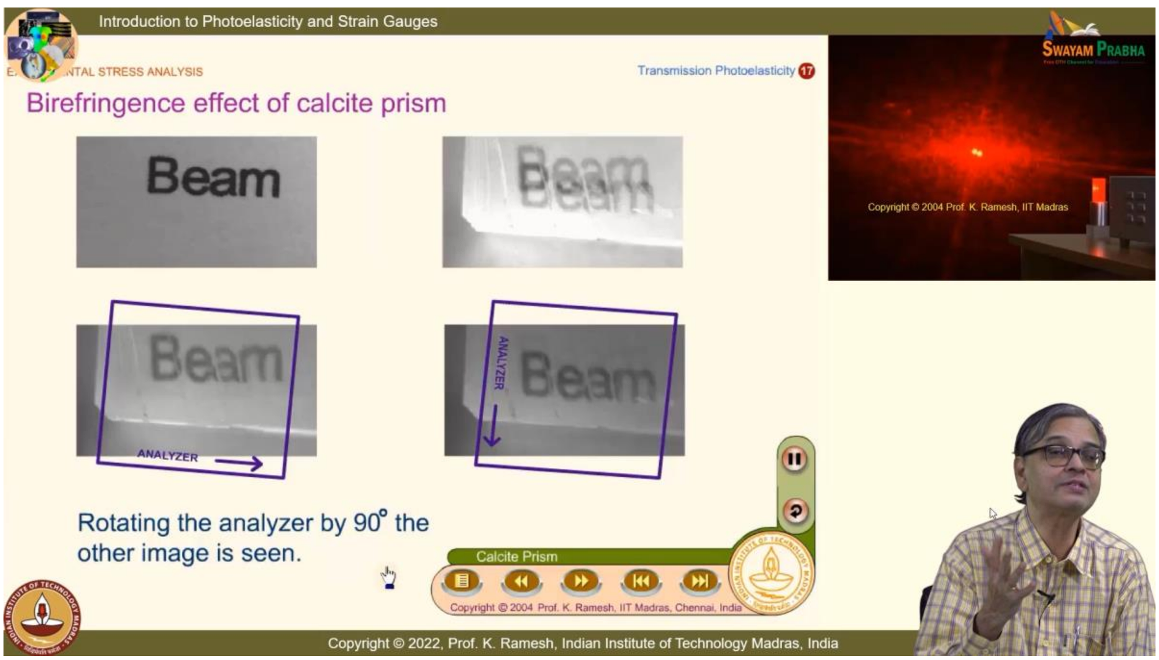

And this shows, I have rotated the crystal, I see two dots, that means I get two dots. So, I can have two dots seen, and when I put a calcite crystal, do I see two beams shear images, you are able to see very clearly.

And in this, I have successfully eliminated of the two images, one image, and you have already seen how to investigate a polarized beam of light, I put an analyzer, fine. And I have put an analyzer in this fashion, and you could very clearly see, I see only the top image. And I have put the analyzer perpendicular to this, you see only the bottom image. So, this clearly brings out what you have in a crystal or polarized, and they are also mutually perpendicular, fine. So, to illustrate this, you know we have put a calcite crystal, and looked at two images, and you are able to segregate these two. And this shows that when you rotate the crystal with respect to the incident light, you have this two beams are seen.

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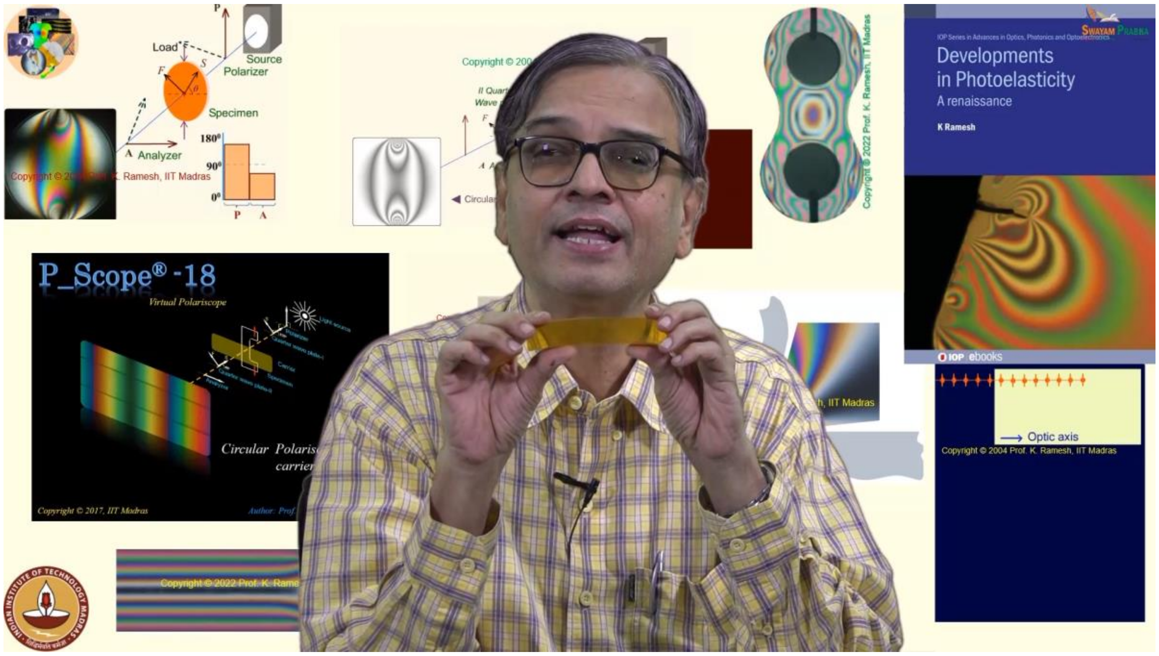

Now, we will see what is useful in photoelasticity. You all know when you take a crystal, it has an optic axis, see crystal is permanently birefringent, that is not useful for photoelasticity. Whereas, when I have a polymer like this polyurethane, it is easy for me, I do not have to be a superman to apply the load, I can easily bend it, fine. And you may think how do I extrapolate these results to metallic objects, fine. We will also see what is the comfort from elasticity.

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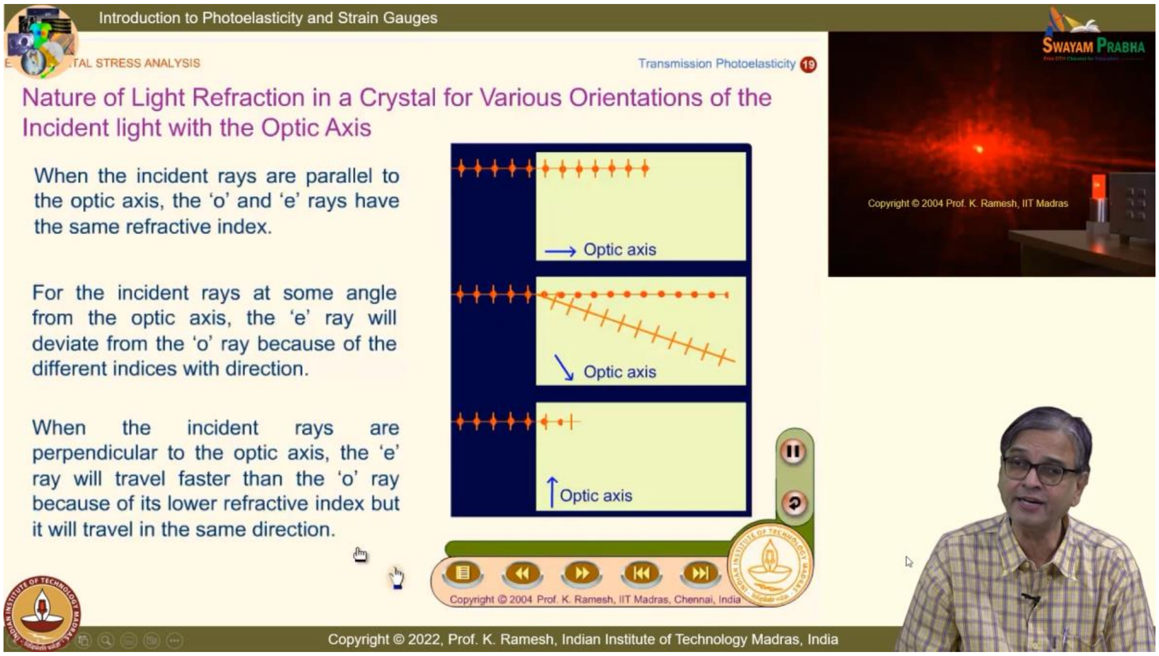

So, when I have the incident ray along the direction of the optic axis, there is no difference between a ordinary isotropic material and a crystalline material, both ordinary and the extraordinary ray travel along the same direction. But when I have this at an angle, ordinary ray will go in one way, extraordinary ray will go in another way, that is why I see two dots when I rotate the crystal. This is the reason why you saw two images of a beam, see now you all had a nice bath and come to the class and fresh, it is not that you are under the action of any intoxication, but you saw two images, is not it? Is not it? So, that is because of a physical phenomenon. And the third one is very interesting, what happens is when the incident ray is perpendicular to the optic axis, from the sketch you can see the straight lines have traversed this distance faster and the dots are trailing behind it.

Because we have already seen ordinary and extraordinary ray can have different refractive indices that is dependent on the direction of incidence and when it is perpendicular to the optic axis, they travel with different velocities, that is taken as an advantage. So, the net effect is when the light exits out, there would be a phase retardation between the ordinary and extraordinary ray, can you visualize that? And what you have is you have a simple harmonic motion, if I have two simple harmonic motions which are mutually perpendicular and if they have a phase retardation then net result is an ellipse. See, I have given a detailed lectures on experimental stress analysis, we normally take about 14 classes to establish the principle behind photoelasticity. We are only going to have a bird's eye view here, I am going to skip many of the proofs, whatever the statement I make every bit of statement can be mathematically proved, which is done in my experimental stress analysis course, it is also available in the YouTube, people who are interested you can always have a look at it.

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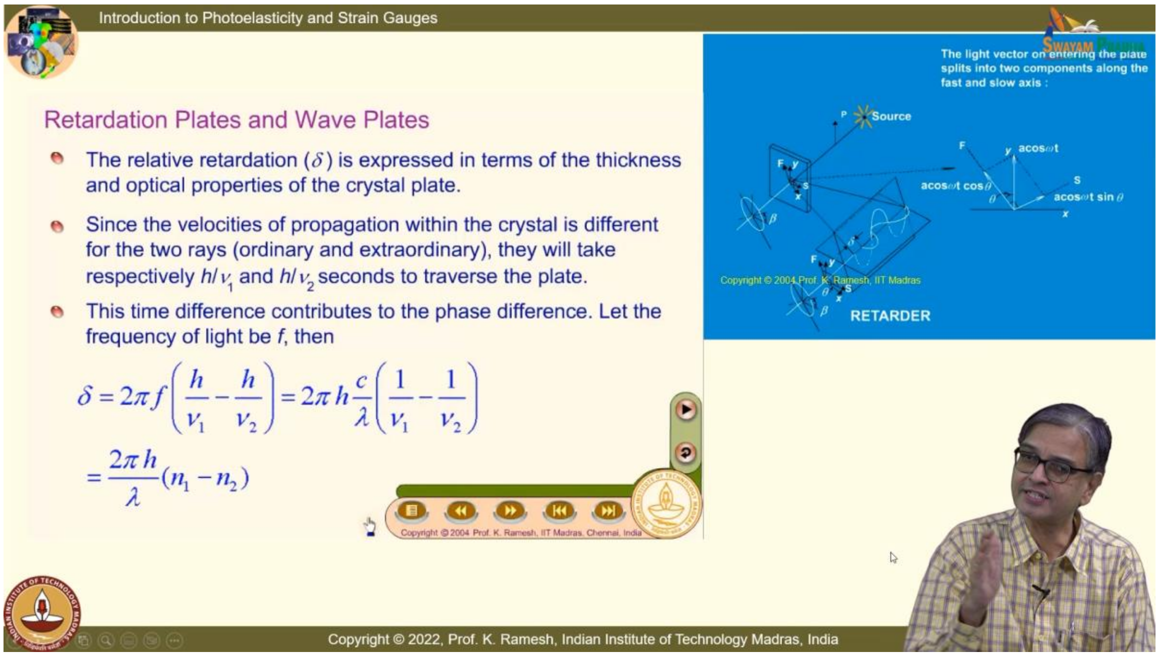

And you see here, I have a plane polarized light impinging on the model, it is a retarder and when it impinges on it, whatever the reference axis I have on the model acts like the optic axis. So, the component of light gets split into these two reference axis, one you call it as a slow axis, another you call it as a fast axis, because we have already seen within the crystal, whatever the ray that impinges on the crystal has a retardation acquired as it passes through it. So, what is attempted here is, I have a crystal plate, whatever this thickness is enlarged here to show as the light passes through the crystal, you have retardation acquired by it, ok. And let the relative retardation be expressed as δ and you can see here, you know it gets resolved and you can see two mutually perpendicular simple harmonic motion, you have a net retardation acquired when it exits out of the crystal, ok. And what you have here, I have the thickness is constant for both the ordinary and extraordinary rays, fine. The same distance each one of these rays travel with velocity v_1 and velocity v_2.

The distance is same, because their velocities are different, see this is God's gift to humanity and humans have determined this around 1816 or so, it took about 80 to 90 years for it to get developed, only in the early 20th century the method got stabilized, fine. And people have exploited this property and you are able to relate what you have as a retardation related to the refractive indices of the ordinary and extraordinary ray difference n_1 - n_2. Some of you can you recall when we discussed uniaxial stress, I showed the model and then I showed the stress tensor, I said photoelasticity gives me only one quantity and I said it plots $\sigma_1 - \sigma_2$. Now, you know the relationship from a crystal optics perspective, when the light goes into a crystal and comes out, it acquires a retardation depending on the properties of the crystal. If I use a different crystal, it may have n_1 and n_2 differently, fine.

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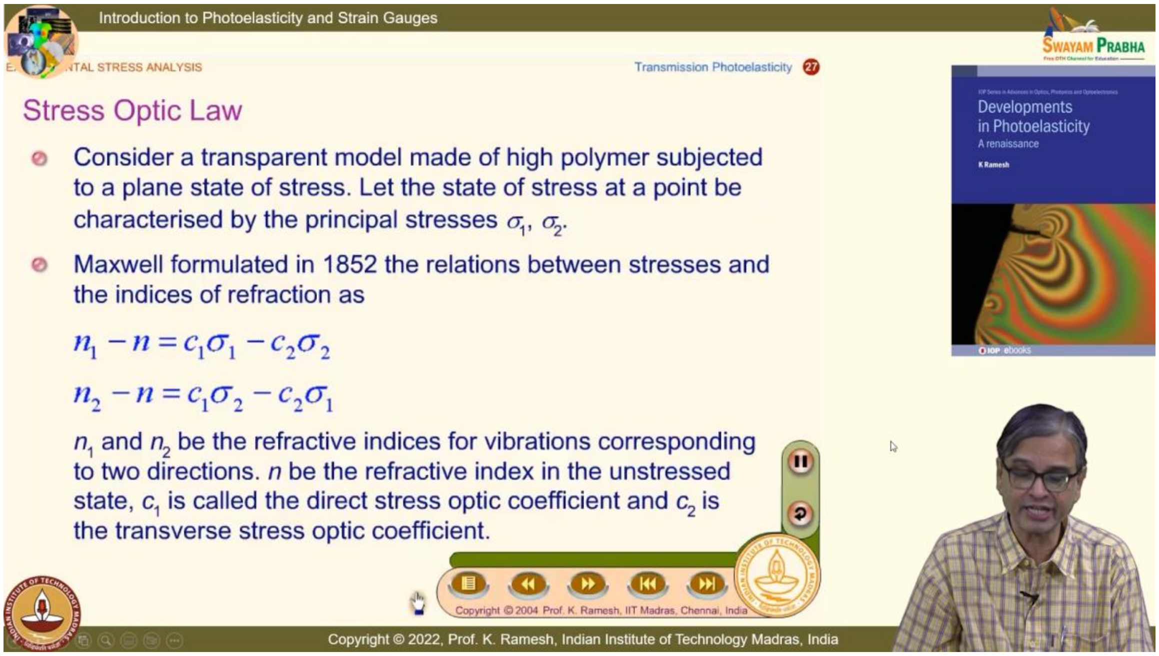

And here we will relate you to the stress, what you find is you know there is a relationship that is possible between stresses and the refractive indices. This was credited to Maxwell in 1852 formulated that. So, you have the refractive index which is independent of the order in extraordinary ray. So,

$$n_1 - n = c_1\sigma_1 - c_2\sigma_2$$
$$n_2 - n = c_1\sigma_2 - c_2\sigma_1$$

n_1 and n_2 be the refractive indices of vibration corresponding to two directions, n be the refractive index in the unstressed state, see this is an experimental observation. So, now by doing a mathematical manipulation, it is possible for you to relate the difference in refractive indices to difference in principal stresses.

See, I also have a book written which is published in 2021, which brings out basics of photoelasticity as well as current day applications. I showed that if you want to analyze a functionally graded material or a heterogeneous material like concrete or if you want to do locomotion studies of snakes or you want to find out stresses induced in the roots of a plant. So, ranging from mechanical engineering, aerospace, zoology and biology, photoelasticity spreads its wing to all these areas. So, you have all this very well documented in this recent book. Those of you interested can have a look at it, because it is very difficult to compress a vast subject in one hour class, fine.

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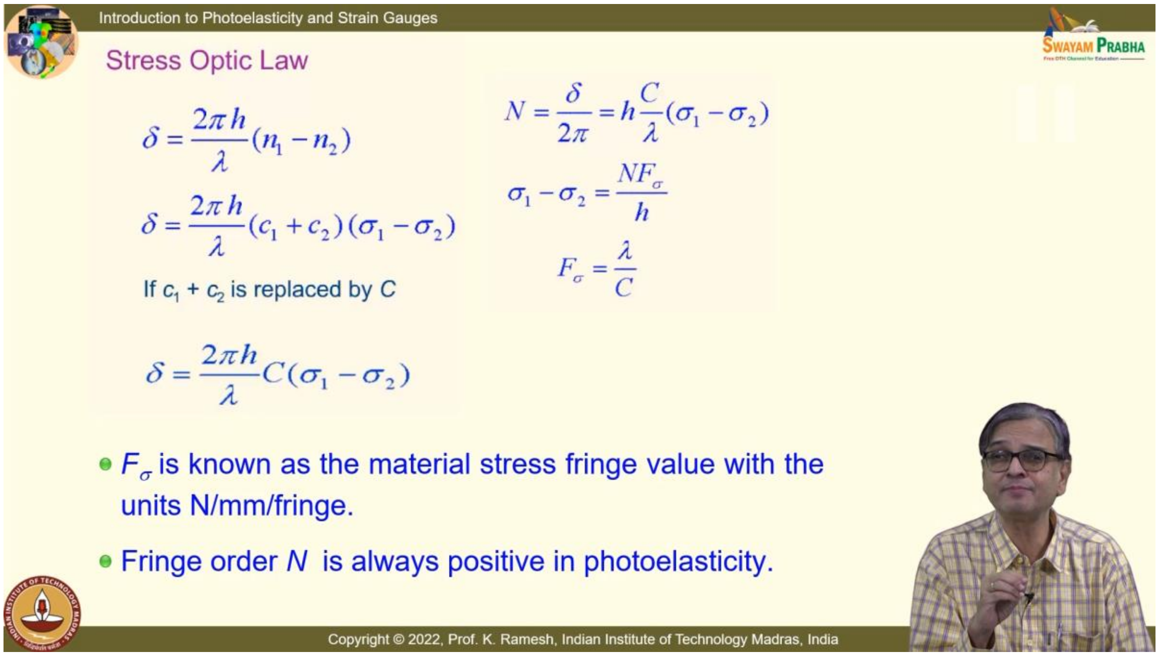

So, what I have here is, we know the retardation is related to n_1 - n_2. So, I also bring in a material property. See, I can have even plexiglass also a material. Glass is also a photoelastic material. In fact, in the early development of photoelasticity, only glass was used initially to find out the stresses, ok but glass is very inconvenient to handle, because it has a very poor photoelastic response.

You get very feeble fringes. So, what you have is, there is a constant which is related to the material and for demonstration purposes, you have polyurethane, which has a very small value of this material constant.

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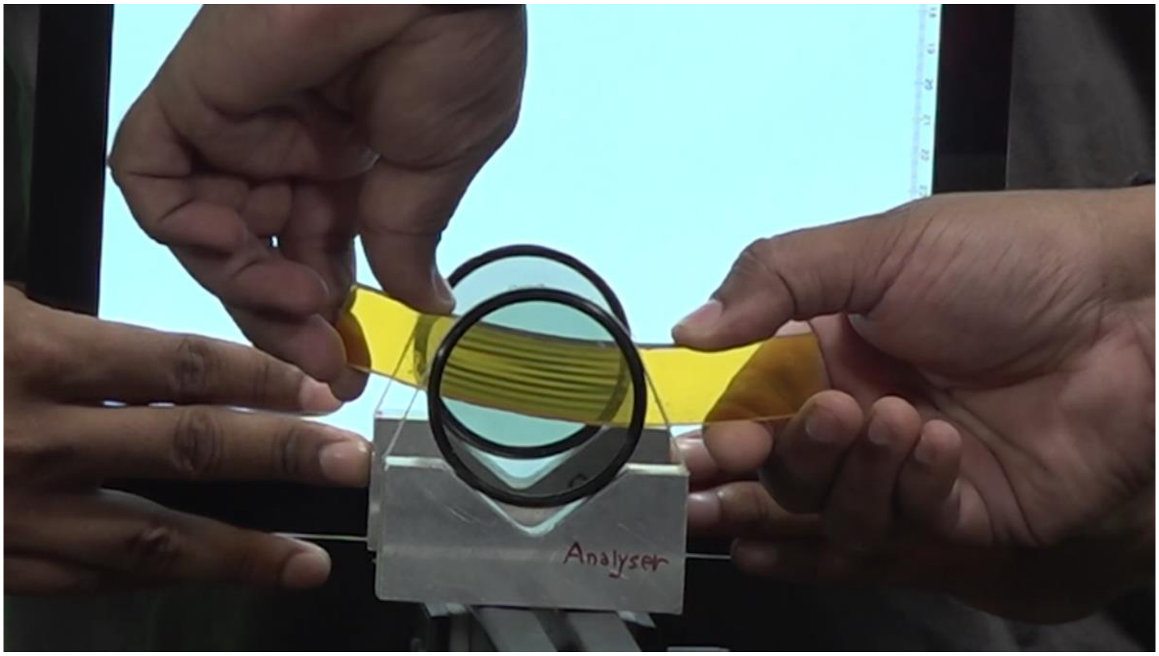

And when I relate whatever the retardation, what you see in the case of optics, when I have a retardation measured in terms of wavelengths, when you say retardation divided by 2 π, you call that as a fringe order. So, fringe order is given a symbol N and $N = \frac{\delta}{2\pi}$. So, when I do that, I get this as related to $\sigma_1 - \sigma_2$ and you bundle these as a material parameter, you call that as F_σ denotes it is a material stress fringe value. So, the idea is, if I know for a given material like polyurethane or a plexiglass or glass, then whatever the fringes you see can be interpreted to the magnitude of $\sigma_1 - \sigma_2$.

Is the idea clear? So, what you need to learn is, if you want to employ a photoelastic technique quantitatively, I need to know what is the material stress fringe value and what is the fringe order at the point of interest. Finding out the fringe order at the point of interest is easily said, but it is very difficult to do. That is where we are one of the leading labs in the world. We have developed many algorithms. Earlier, you know, if you look at these expressions, you have lambda coming into the picture.

Lambda means wavelength. Fine. I mean, when we investigated the polarization, I used two different wavelengths. One is a white light and another is a monochromatic source. So, early development of photoelasticity was centered around the monochromatic wavelength. And when you use a white light, you are all scientist now, fine.

You know what white light consists of. It has VIBGYOR. So, all the beautiful colors, that is why you see beautiful. See, God wants you to learn stress analysis colorfully, fine. So, when you use white light and we have made significant contribution on how to interpret the white light for evaluation of fringe order, subsequently how to get $\sigma_1 - \sigma_2$.

Fine. So, what you need is, you need to look at when I change the material, what happens. And when I know F_σ, I can get $\sigma_1 - \sigma_2$. There is also one more information I said, there is something like an optic axis. When you looked at that retardation, I showed a slow axis and fast axis. Can you relate it anything to what you have learned in stress analysis? When you say stress at a point, you are talking about principal stresses as well as the directions.

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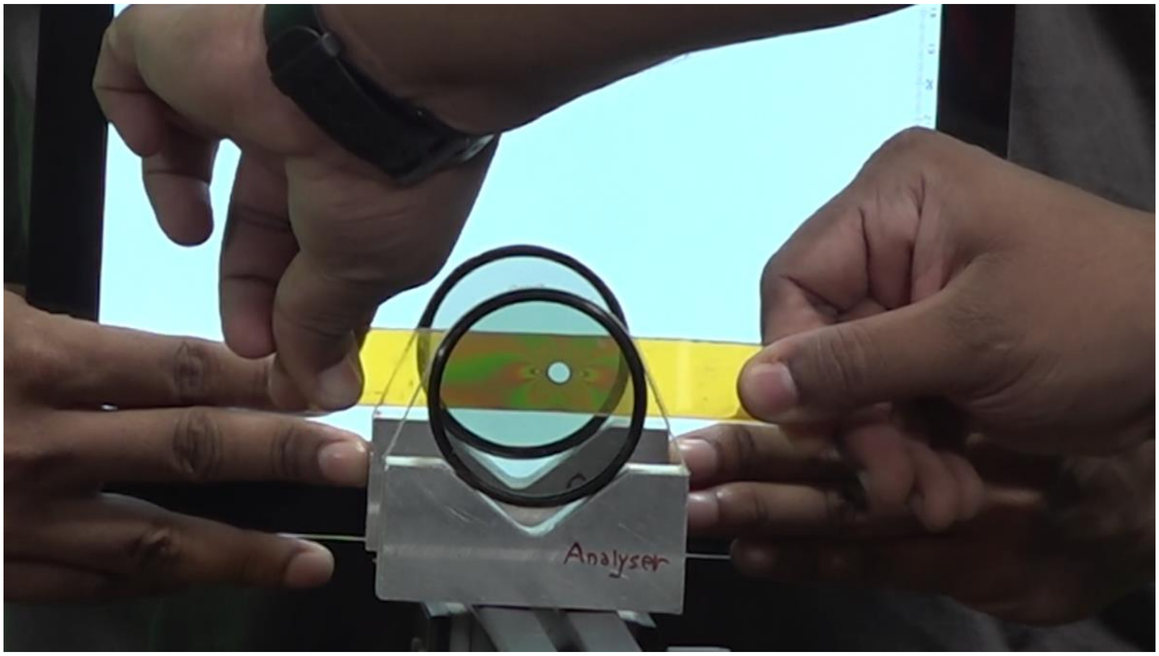

So, at a point of interest, the principal stress directions are behaving like the optic axis, what we have seen in a crystal. And this happens only when it is stressed. When it is not stressed, it will be like a normal material. When I put it, the light will be cut off if the analyzer is perpendicular to that. So, it is beautiful, it is nature's gift to humanity.

And F_σ has a very funny units that is Newton per millimeter per fringe, because you know the thickness of the material also matters in acquiring the retardation. And do you agree with this statement? Fringe order n is always positive in photoelasticity. Why is it so? Because we have adopted a convention how to label $\sigma_1 - \sigma_2$, no matter in which problem what I do. So, you cannot find out directly from one single measurement whether it is positive or negative, but scientists do not keep quiet. They have solved all these issues that is the details when you get into photoelasticity.

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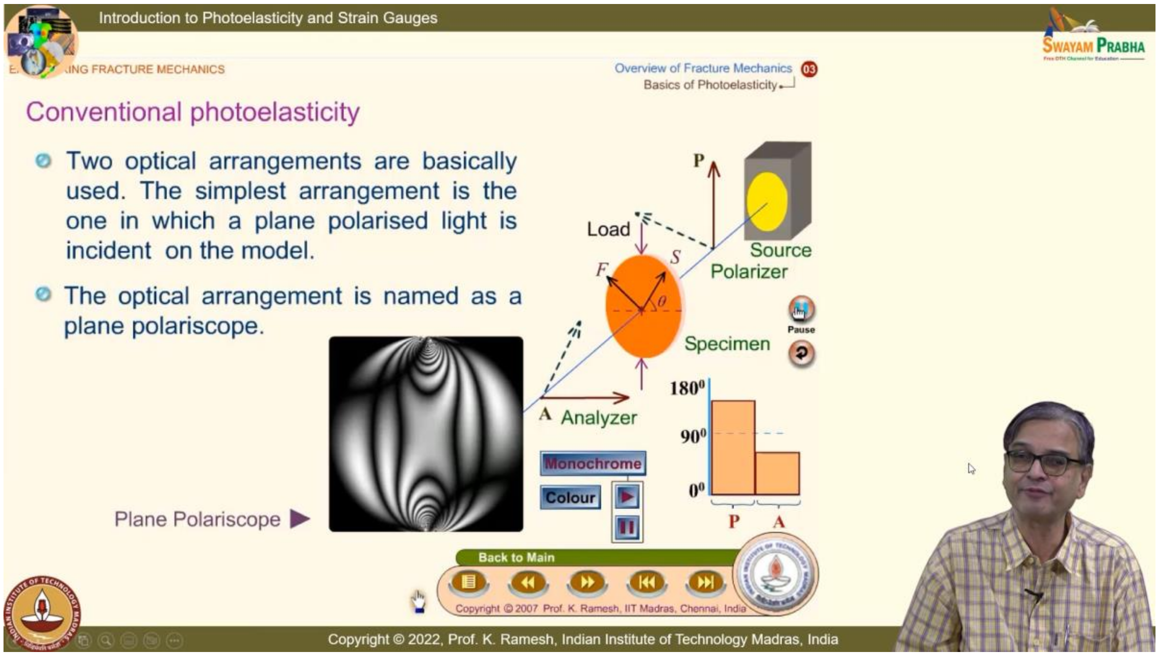

See, what I have is, you have a simplest optical arrangement where I send a polarized beam of light and the disk is loaded. And when these two elements are rotated in unison, you see one fringe pattern is moving over the other stationary one. I use a monochromatic source of light. When I change the source of light to white light, you will see one of the patterns become colorful, the other pattern remains black still, ok. So, I have this pattern is colorful and this pattern is black and this is related to the analyzer and polarizer and they are always kept crossed. So, you get an idea? So, whenever I have this black fringe, I can relate it to the polarizer and analyzer axis at that point in time that can be related to the principal stress direction, fine.

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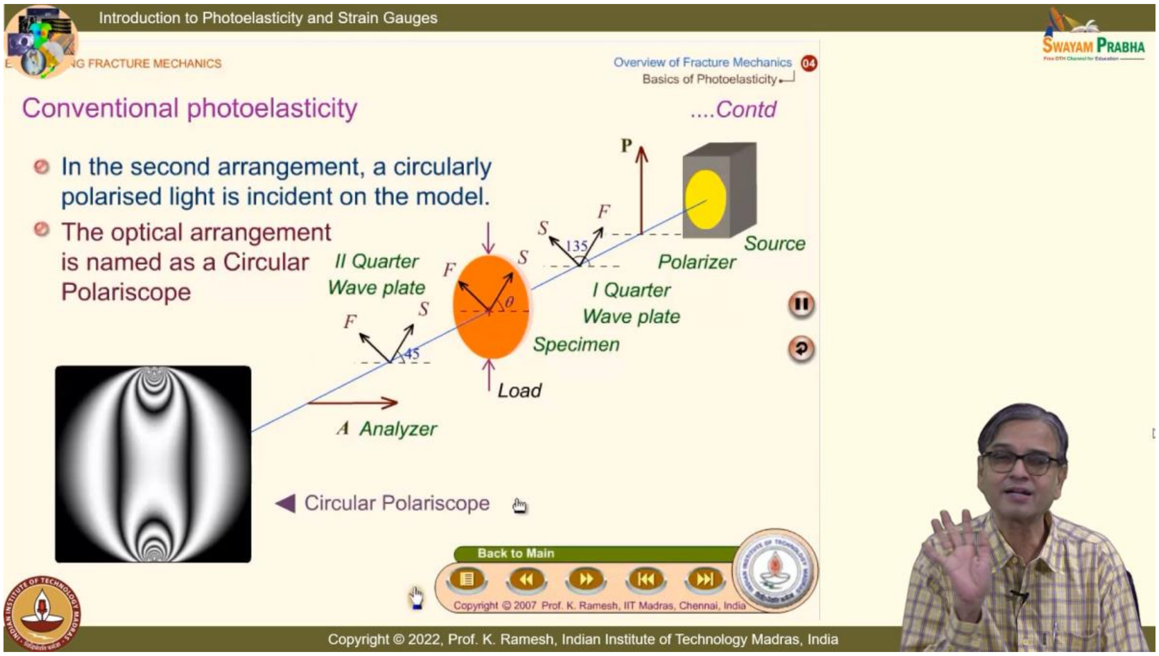

And now, I do not send a plane polarized light, but I put another optical element which will help me to make it circularly polarized. When I send a circularly polarized light, I have a convenient light. I see only one set of fringes.

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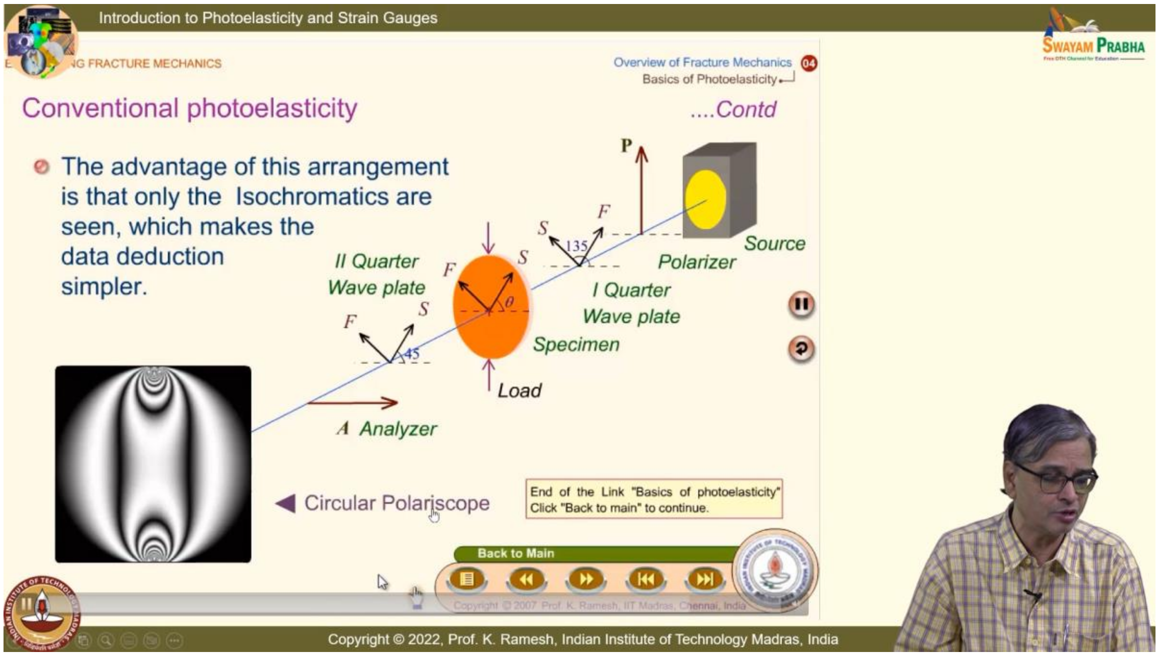

It makes my measurement very very comfortable and easy. In all my earlier slides, I have used only this arrangement to show you fringes. I have not used the monochromatic light source, but I have used the white light source. When I use a monochromatic light source, I will have only this as black and white. And you can also see one more thing. You know if you have this, I have the background as black and I rotate the analyzer, the background becomes white.

So, they are respectively called as a dark field and a bright field arrangement that you can do by manipulation of the optical elements. So, those are all the details with respect to photoelastic analysis. And I would only say that you should be trained in photoelasticity to identify the value of fringes, but if you have a color code by using the color code, you are in a position to see the color and then assign at least the integer fringe orders, ok.

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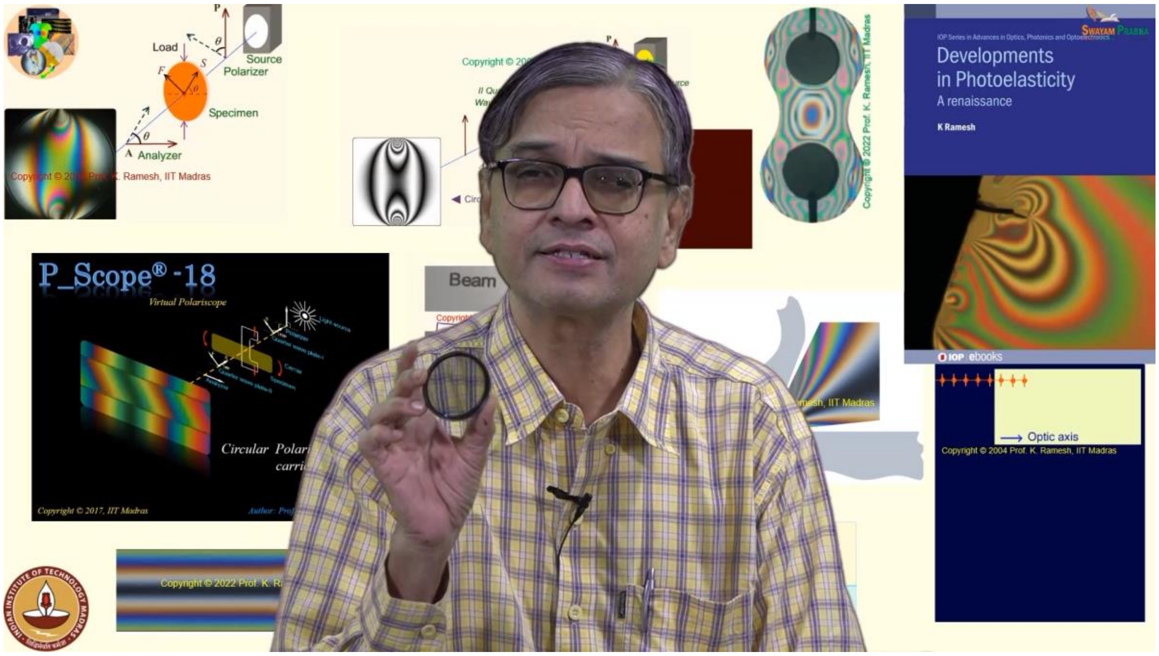

So, what you can actually do is, you can construct your own polariscope. You have these kind of elements readily available for DSLR cameras and using this, we will construct a polariscope and then view the fringes.

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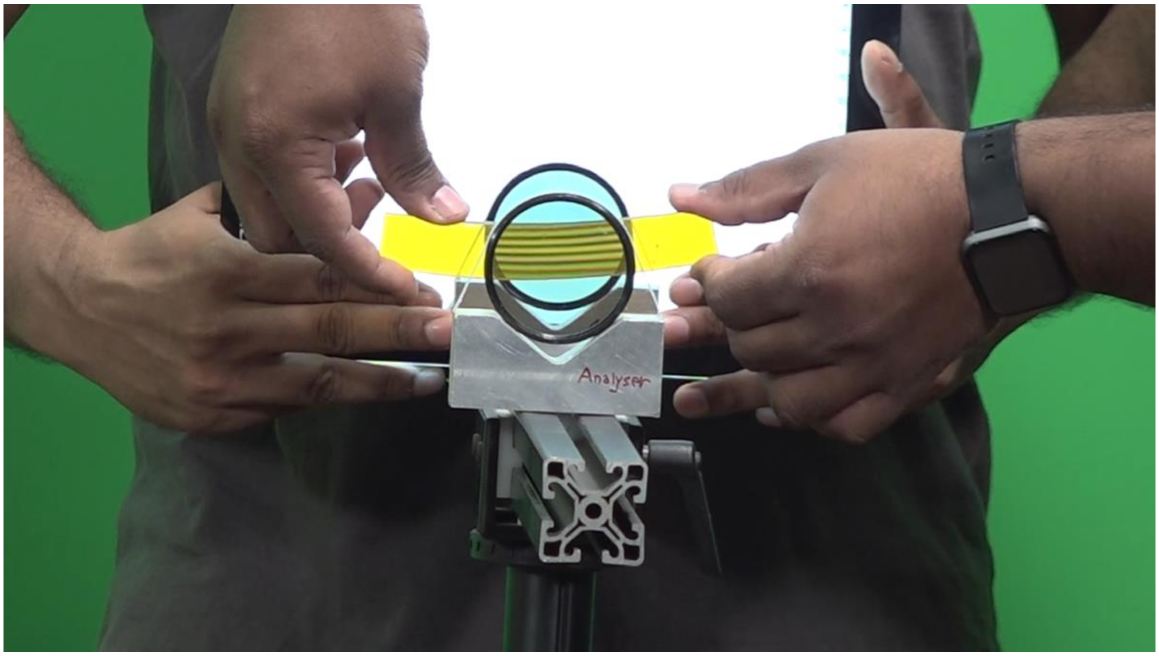

See, you can easily construct a polariscope by having the elements readily available in Amazon or any one of these online stores. So, you have these polarizing filters available for a DSLR camera. You can have two of them and you can even have a cell phone light, but because we are taking a video here, that light is not sufficient. So, we have a light source here. So, this acts like a light source. Now, you show the model which is under bending, you will see beautiful set of fringes, fine. What you need is, you need only a polyurethane and this just cost you 350 rupees each. So, within 1000 rupees, you can construct the polariscope, homemade polariscope, fine.

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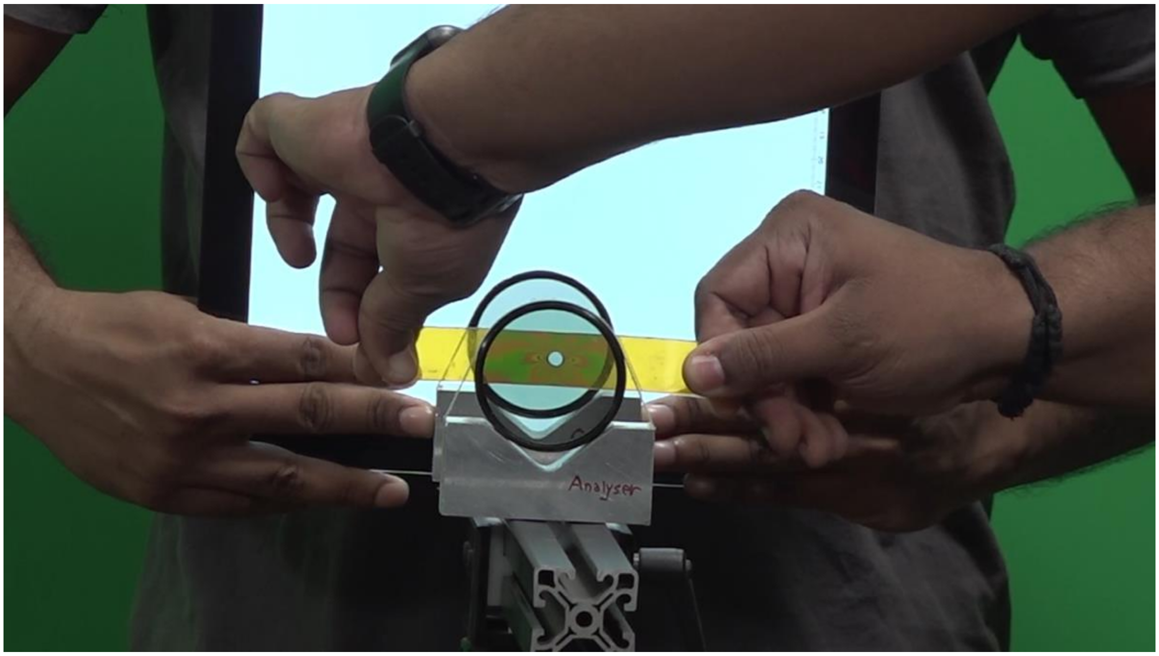

You can also show plate with a hole. So, what you need is, you need to just have a model and then apply the load. All the computations are done by the optics. You get beautiful set of fringe patterns.

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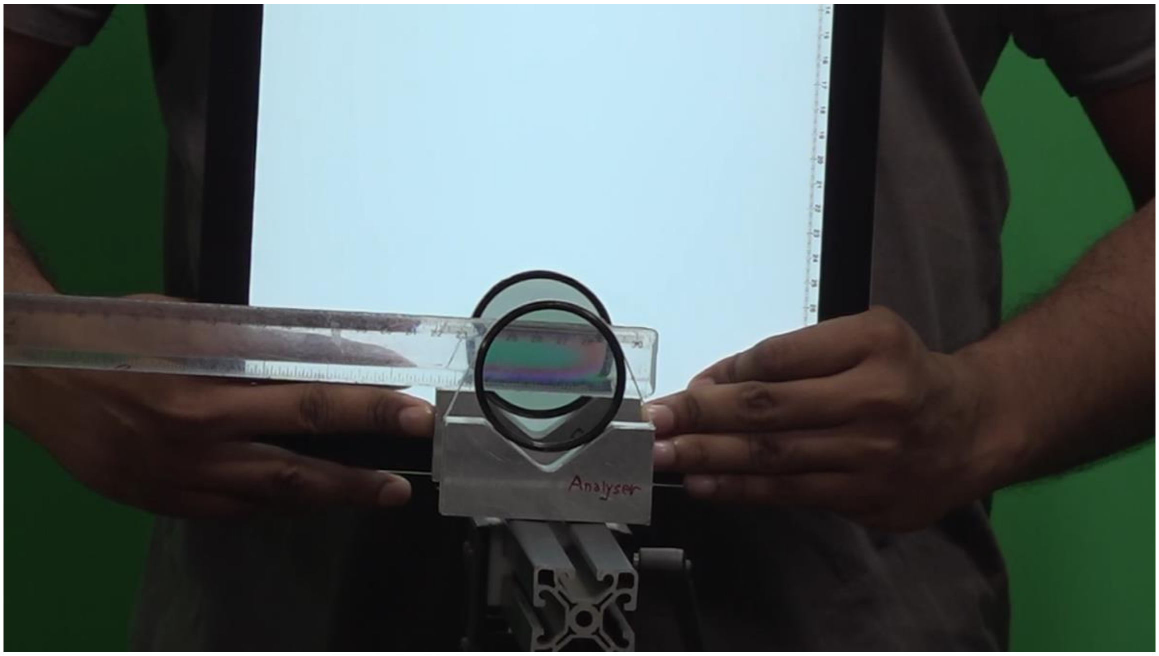

And you know, it is also very interesting to see what you have as a normal scale. It is not free from stresses. You see here, you have residual stresses.

You do not see it in normal light. This is a plastic, this is also photoelastically sensitive. So, you can really have fun in your home by constructing a polariscope yourself that cost you less than 1000 rupees. That is like having two pizzas.

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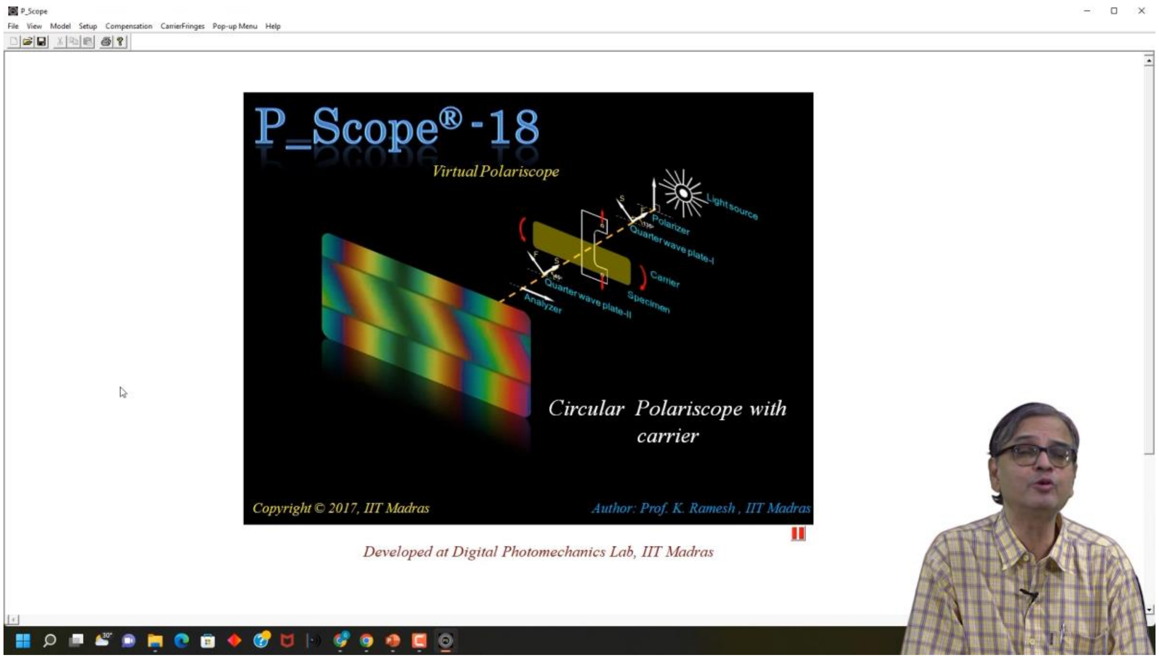

So, we have seen one form of fringes. So, we will have a look at, you know, we have also developed a simulation package to understand not only photoelasticity, but also constantly related to stress by a software called P_Scope.

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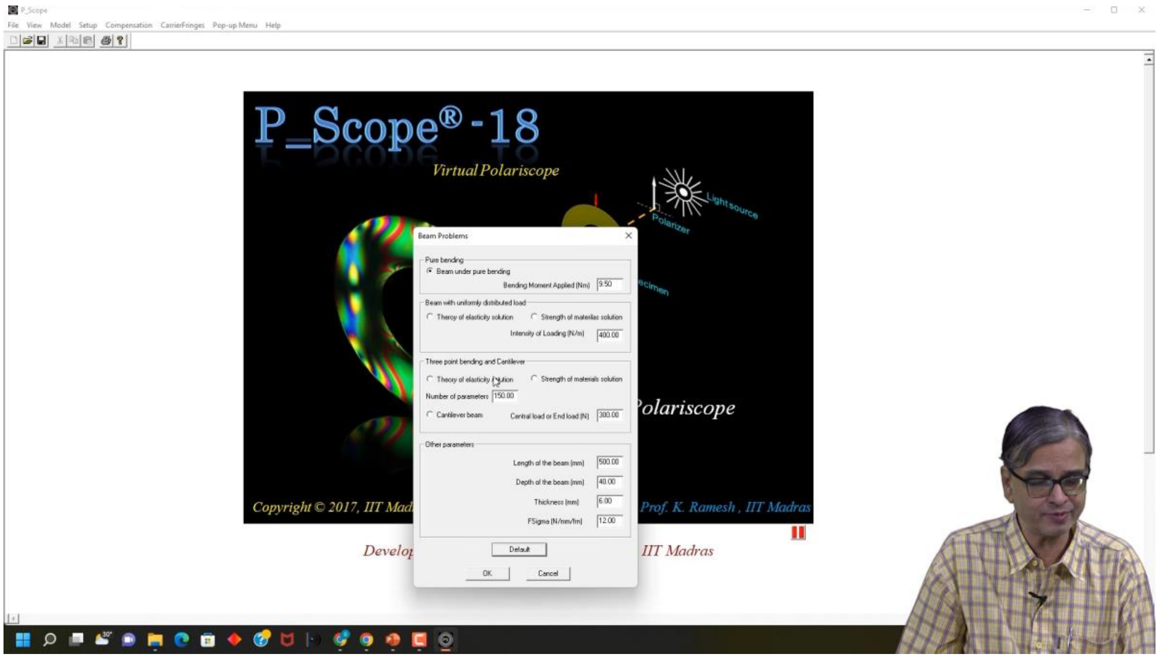

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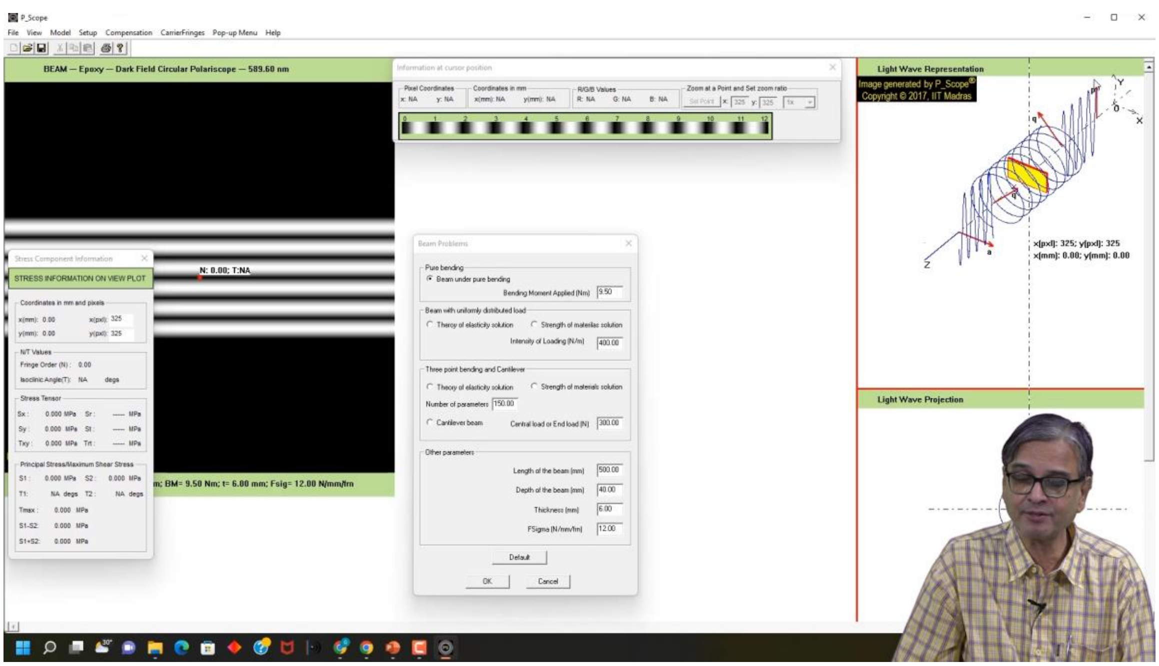

And you know, you have a set of models available. Since you are learning about beam, we will get into the beam first. And you can have various types of beams, which we will see later when we go to finding out the shear stresses in the case of a three-point bend specimen. Right now, we will confine our attention to beam under pure bending. And when you do this, you have a beautiful fringe pattern developed. And what you see here is, I have the optical arrangement where I have the polarizer shown here, then I have the quarter wave plate axis is shown here, then I have the beam, I have the second quarter wave plate, I have the analyzer.

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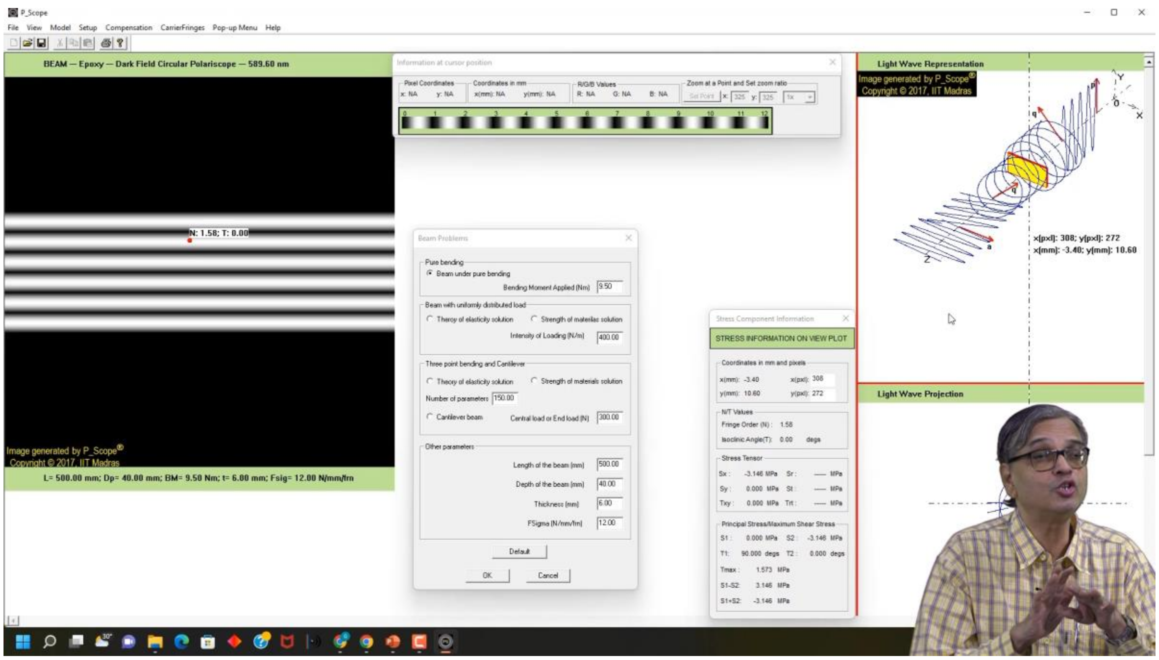

And what you have here is, when I click any point, I have light is fully transmitted. So, you have the changes to the light as it passes through the element is beautifully brought out in this. See, when you have a natural light to polarized light, that is diminishing in light intensity. But within the polariscope from the polarizer to analyzer, there is no loss of light intensity, there are no light absorbing component, fine.

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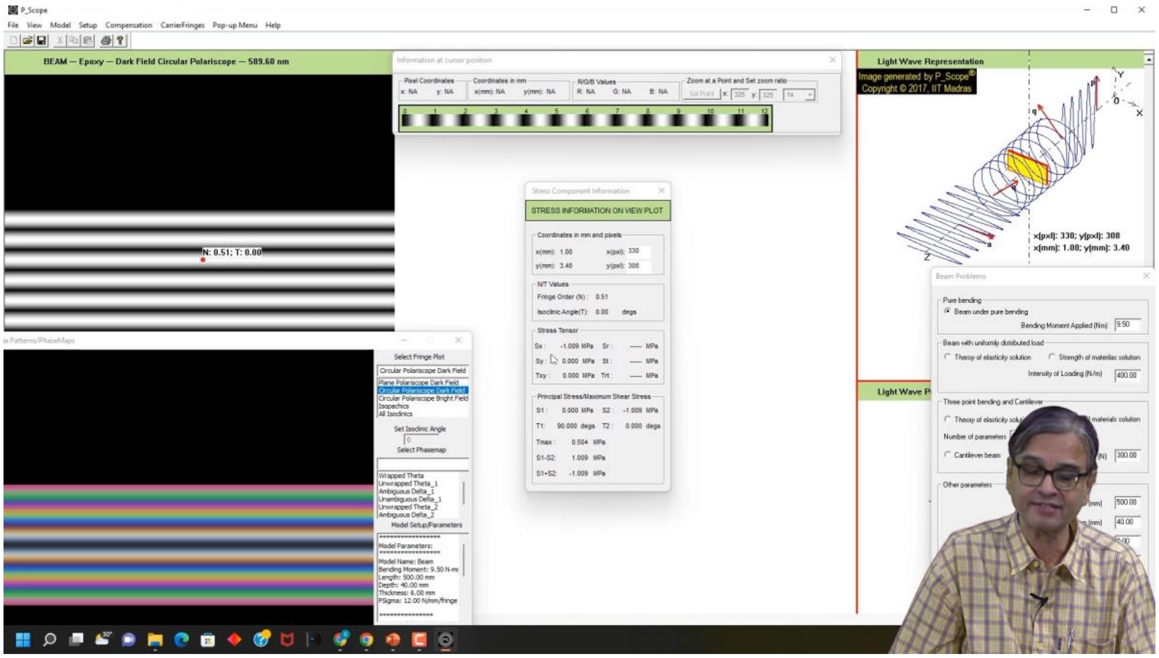

So, the intensity remains constant. And what you find here is, whenever I select a point here, when I get it very close to the actual fringe, you see the light is diminished. And you also see in this, what is the state of polarization as the light traverses the optical elements. So, you get a complete appreciation of what happens to the light at every stage. And you also have other facilities, because you have always seen fringes in color.

So, we will see the fringes in color, ok. And I will also put it, you have several windows like this, you can have this in any way. Now, I have this put here. And you also have all the details of any particular point. If I take any particular point, it will tell you what is the stress acting there, this is σ_x: - 1.009 MPa, it will give you what is theta 1 and what is theta 2, it will give you σ_1 and σ_2 and associated direction.

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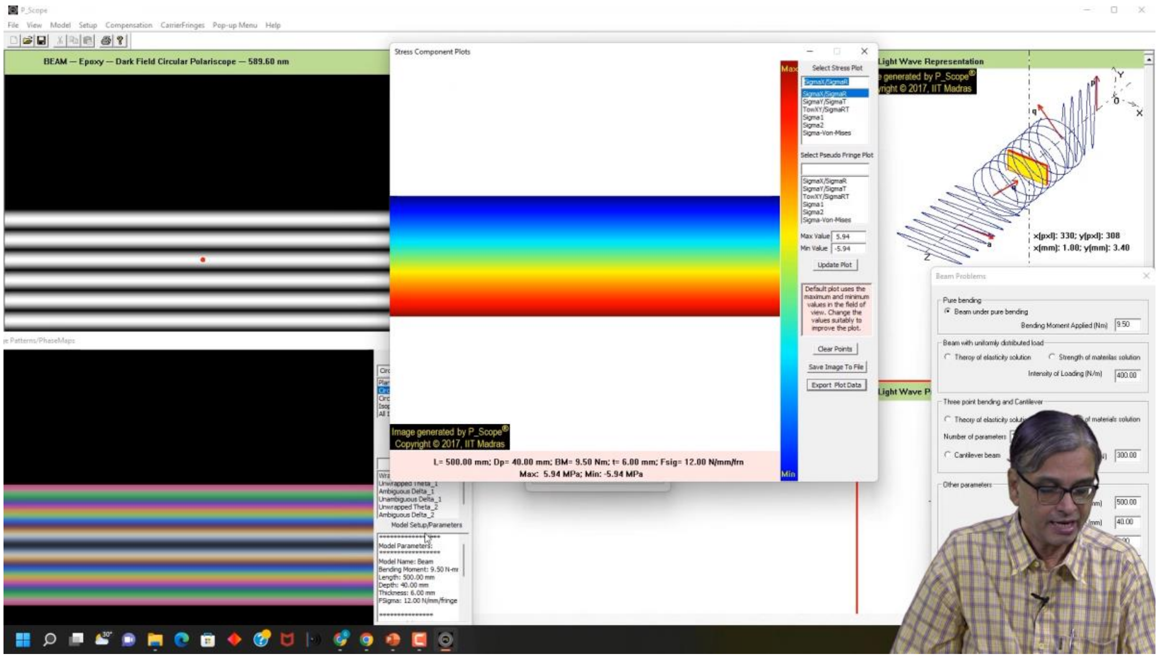

You know, when you do photoelastic experiment, you will not get all of this. Since it is a simulation package, it also helps you to appreciate concepts related to stress analysis. So, now what I will also do is, I will look at the stress component plot, and I know that we are getting only σ_x. So, I will plot σ_x here, ok.

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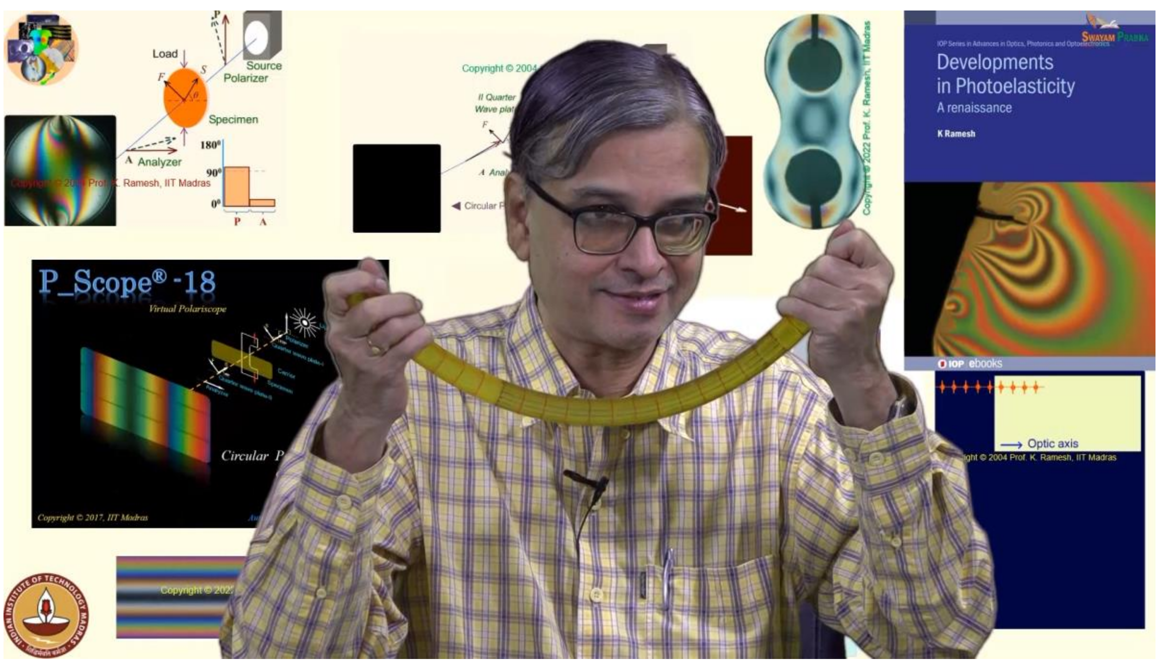

And you know, what we have done is, we have taken a beam, where when I have the bending moment is positive, it is bent like this, bending moment is positive. No, bending moment is positive means, it is bent like this, this anticlockwise positive.

Because in the class, I have always shown is bent like this, when it is bent like this, the top surface is under tension and bottom surface is under compression. When I have positive bending moment, that is what you see here, it is put as 9.5 Nm, it is bent like this. And what I have here is, the stresses are marked from blue to red, and blue is the minimum value.

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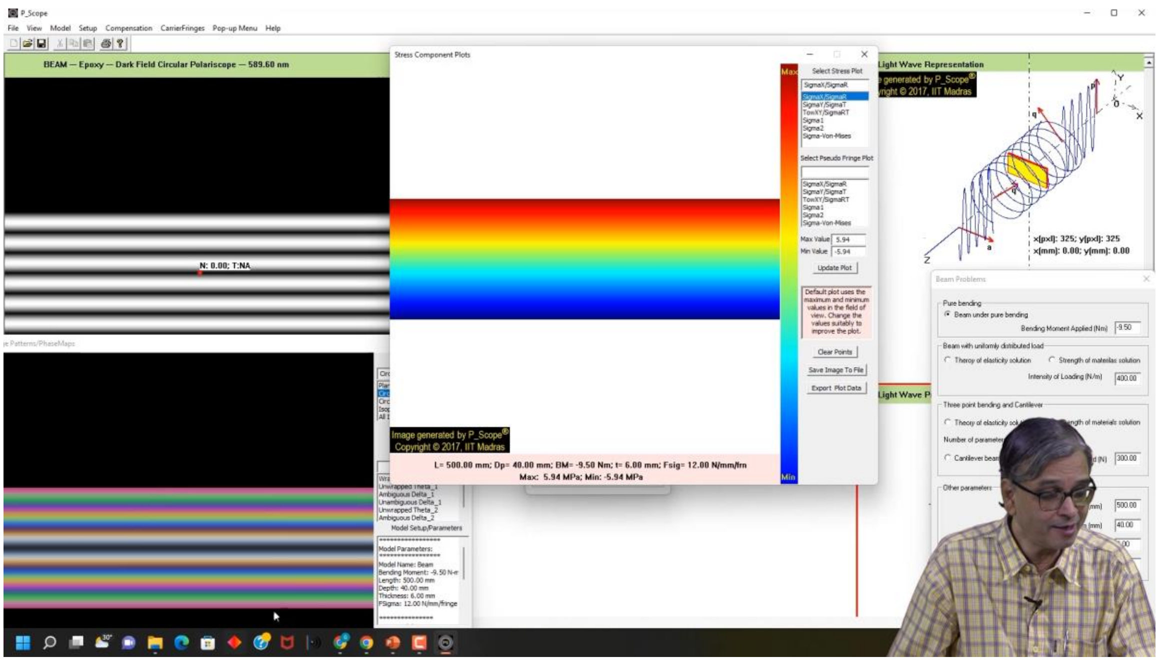

So, the top fiber is compressed, so it is blue, and it varies from - 5.94 to + 5.94. Now, what I do is, I go and change this to, and look at the fringe pattern, we will have to look at the fringe pattern, all these are recomputed when I change the load. I will put that as a clockwise, that means I am bending it like this. Let us see what happens to our plots, it has to do the computation and do the plotting, and what you find is, fringe pattern remains same, but the stress pattern changes, it ought to be, because photoelastic fringes, they do not sense the sign difference, $\sigma_1 - \sigma_2$ is always positive, but stresses have to be different.

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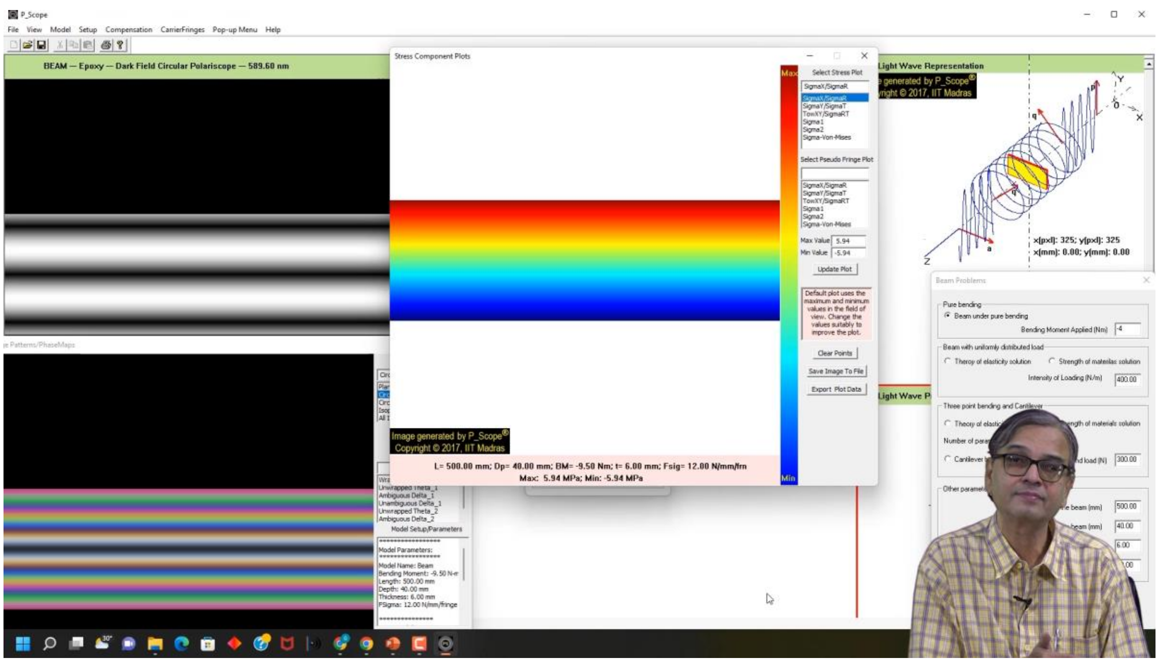

Let me ask another question, suppose I reduce the load by half on the model, see we are living in linear wall, linear elasticity, fine. Why we want to live in the linear elasticity, when I want to do multiple loads, I can superimpose, I can add them together, fine. What I want you to think is, when I half the load, what do you expect the stress pattern to be, and what do you anticipate about the principal stress directions, think about it. Now, what I will show is, I will take one more example to show the principal stress direction, but here what I am going to do is, I am going to make the load as minus 4, something close to half, and I would see less number of fringes, ok and I also see less number of fringes in this, and also you know I have this plot going from - 5.94 to + 5.94 is the, I mean the value I have to see, I have this as 2.5, the plot is for a longer distance, but the maximum stress is also reduced by half, closer to half.

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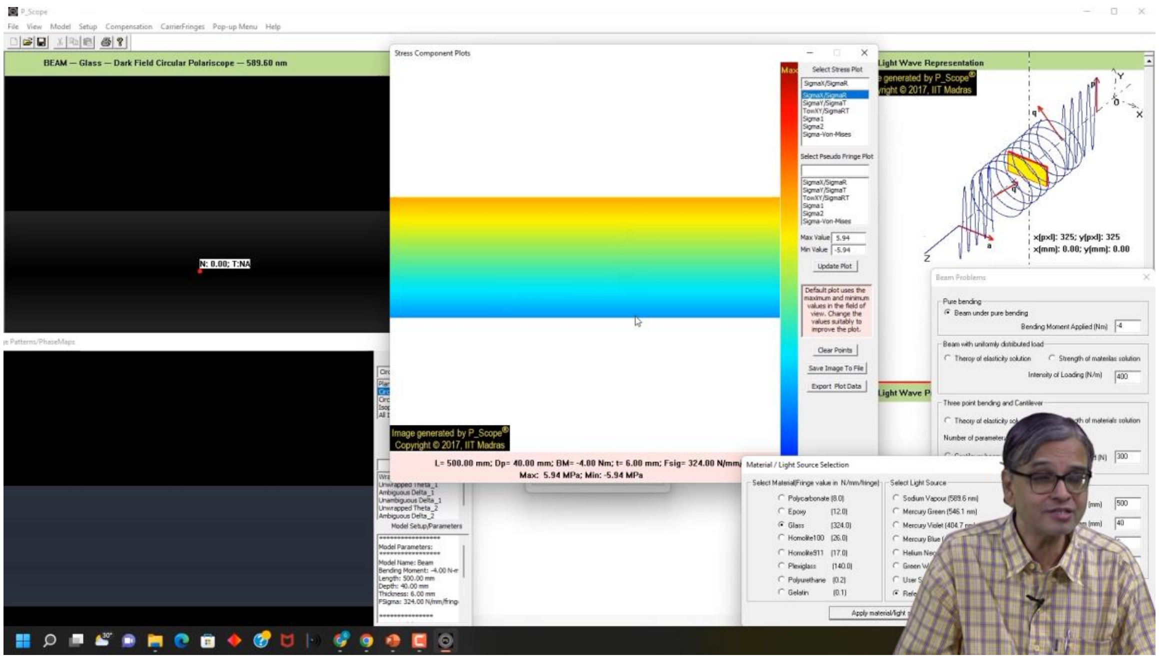

Now, I said people have used initially glass, fine. Let us change the material to glass, you know glass has a very high value of this photoelastic that F_σ value, when it is very high means, its response is very small. So, I am going to get something very close to zero here, ok. So, I have glass, and then I put the material, and then I see the fringes what happens to this, I have this is very close to zero, has anything changed to the stresses? It is very interesting, see I told you we start with material which I can easily flex, it is polyurethane.

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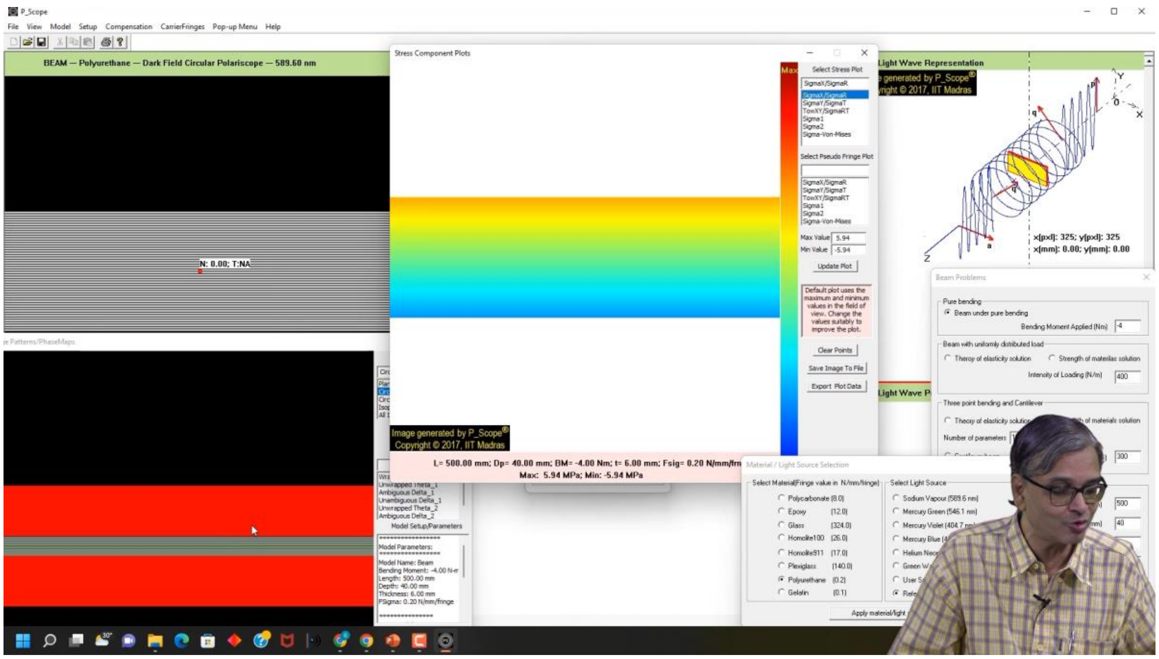

Suppose, I go to polyurethane, polyurethane is very, very small, see the epoxy initially the default one was 12 Newton per millimeter per fringe, if I go to polyurethane it is only 0.2. So, I am going to have hundreds of fringes, and if I go to glass it is 324, I get almost zero fringes, let me go to polyurethane. And I have such high density of fringes, and the color code beyond goes beyond this, so you have a plot of red beyond the narrow region where it can do, there is absolutely no change in polyurethane, the stress values. The stress values remain same for epoxy, the default material, it remains same for glass, it remains same for polyurethane, but optical response is different, ok, so that is the comfort.

So, even you have a plane stress or plane strain problem, you can mathematically show if the body force remains constant or zero, the stress is independent of elastic constant, it is a very powerful result that you get from theory of elasticity, that is why people do experiment on plastics, and you can directly correlate to your structures made of aluminum or steel.

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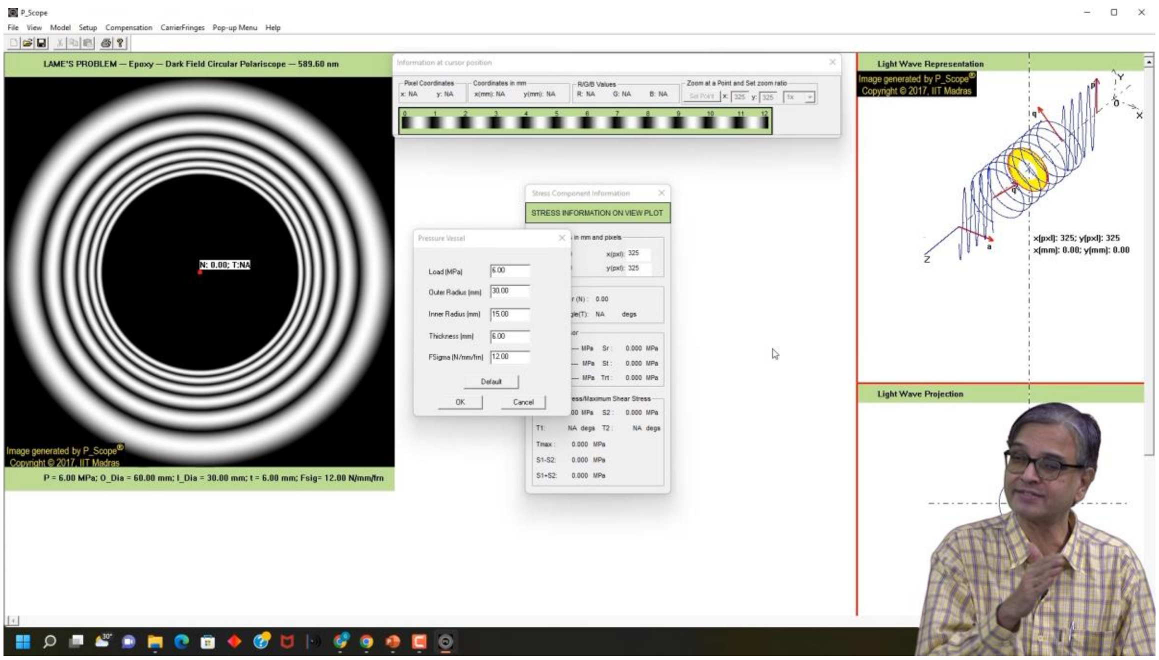

We have also been looking at problem related to pressure vessel, so I will take a problem related to pressure vessel, and you have the parameters for the problem, so you can select this. And what you see here, in black and white you can see very clearly here I have this concentric circles, in the case of beam these fringes were equidistant, and I said these are not equidistant which was not that directly clear when you had color, but when you have black and white you are able to see, so this distance is changing as a function of distance, and this is a thick cylinder. So, thick cylinder is the first problem you solve in the next higher level course, we have seen thin cylinder you have determined hoop stress, and you have also determined if it is closed a longitudinal stress, and we saw that as a biaxial state of stress, and also caution that when you want to find out the shear stress, whether it is a local maximum or global maximum you have to investigate. A planar problem becomes three-dimensional, you cannot always live in a planar situation, so that is the caution that we have looked at.

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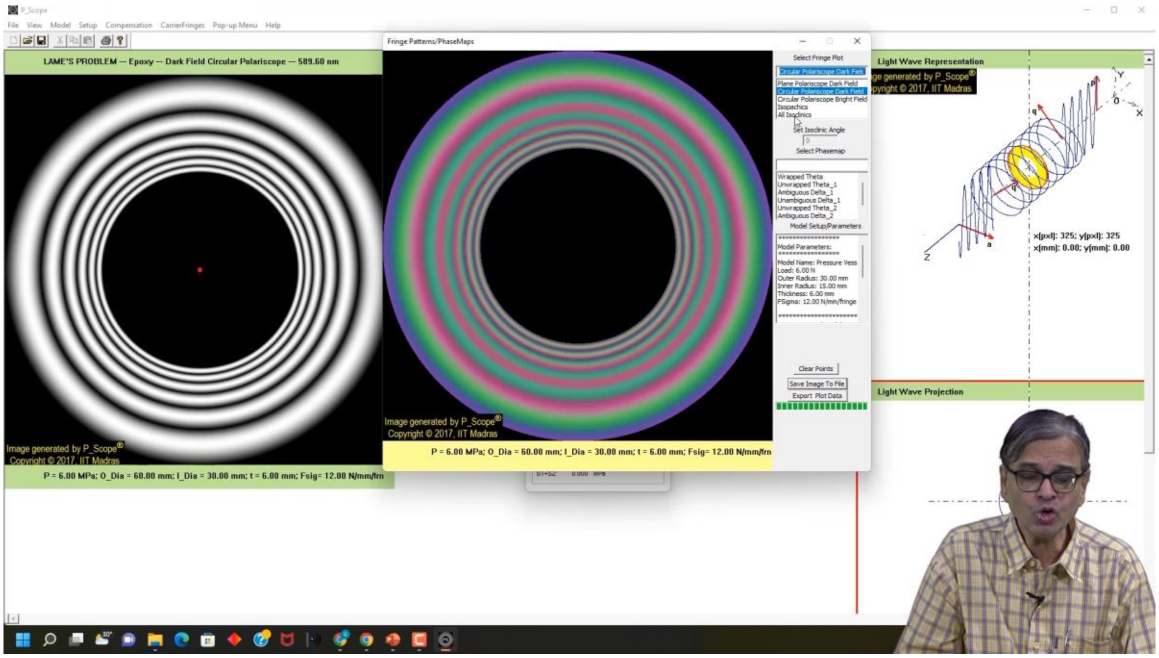

Now, what I will do is, I will also show you the fringe patterns in color, which you have already seen it in the class, and I also have another pattern which you have already seen it in the class that is what we have seen.

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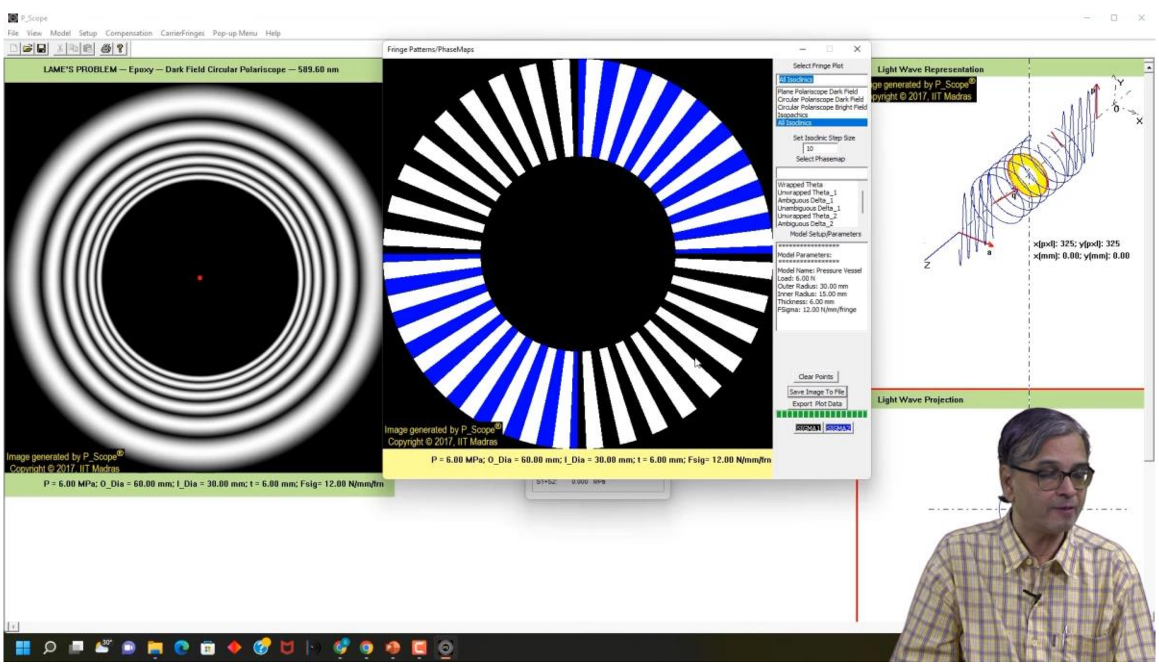

I can also look at all the isoclinics present in the problem, see when I use a polariscope I will see only one set of isoclinic at a time, which can I can also show you.

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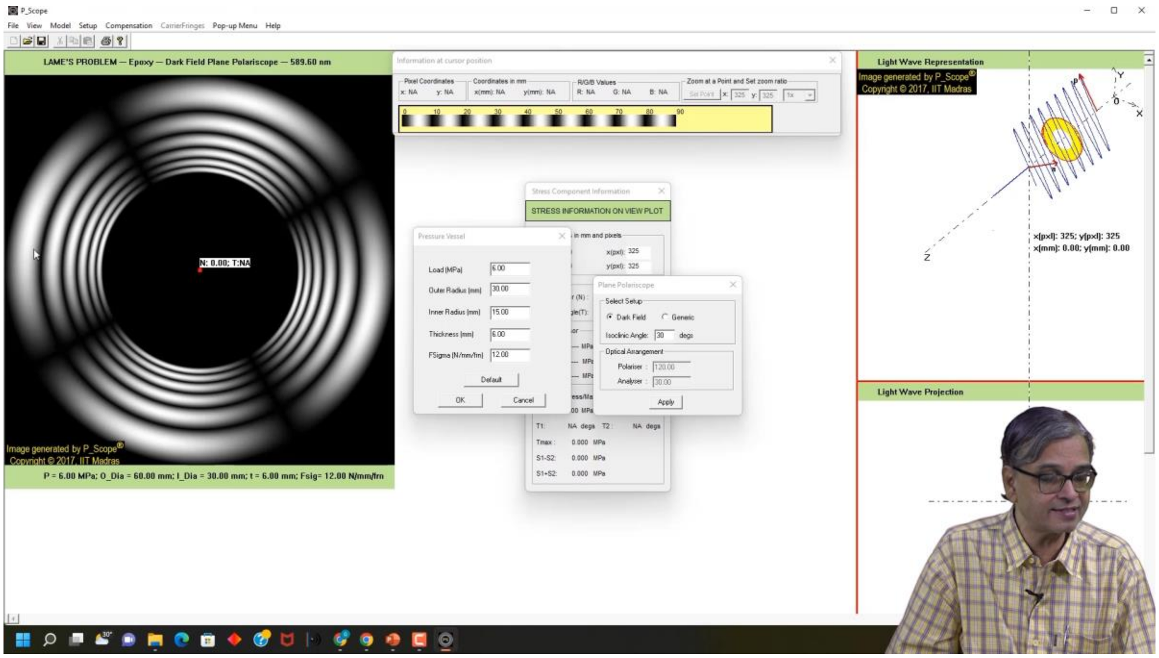

So, I have this as model, I put this as a plane polariscope, and then I have the dark field, I have the isoclinic angle if I put it as 30°, apply I can simulate that. So, what I will do see is I will see this as a plane polariscope, when I see a plane polariscope I will have two fringes superimposed, for a given plane polariscope I can see only one set of fringes like this.

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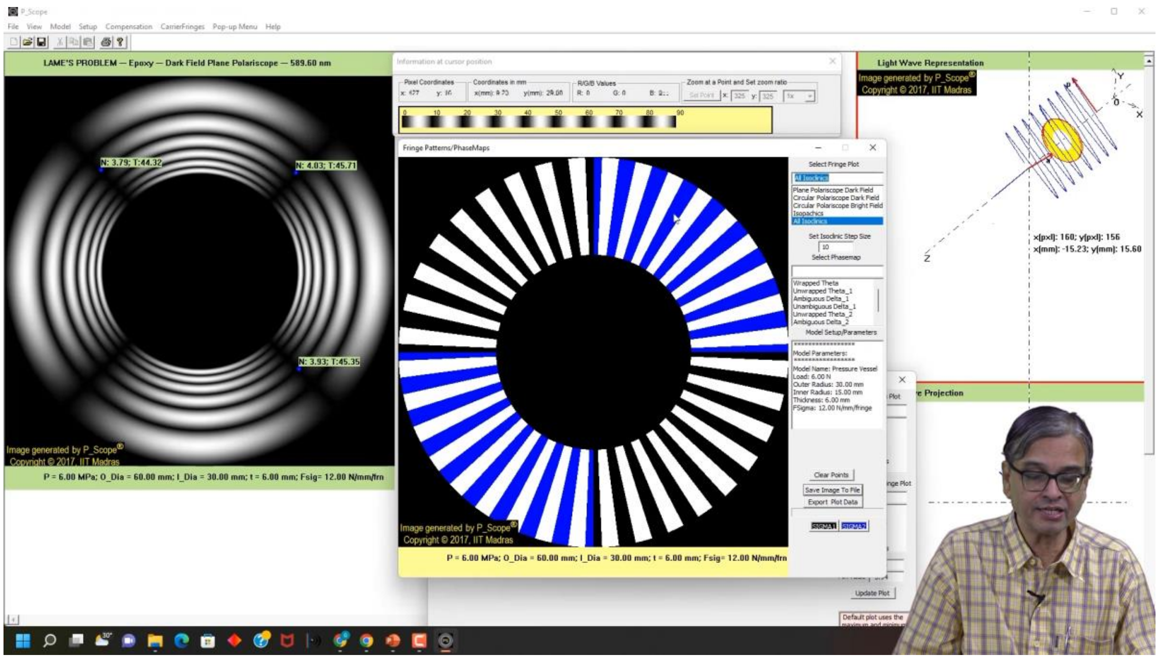

Suppose, I change this to 45°, and then I apply, I get this as a 45° isoclinic all the branches.So, if I go and click it, I will know what is the angle there, this is the fringe order is 3.93 and this is about 45.35, depends on because the fringe is very wide enough, it is difficult for me to click the exact position, ok. And you have this as label like this, so you have the comfort when you want to learn photoelasticity how to label the fringe order, for known problems you try to experiment with the simulation package. So, you gain some understanding and extrapolate it for a practical problem. Now, what you have is I have collated all this, because it is theoretically done, you have all the isoclinics put, we have seen that as radial lines in this problem, and I have blue line which is showing the σ_2 direction and black lines are σ_1 direction, ok.

So, now the question is let us also look at, I will just have half of it, I will just have half of it, and then I will show the, what is the stress magnitude that we have determined?

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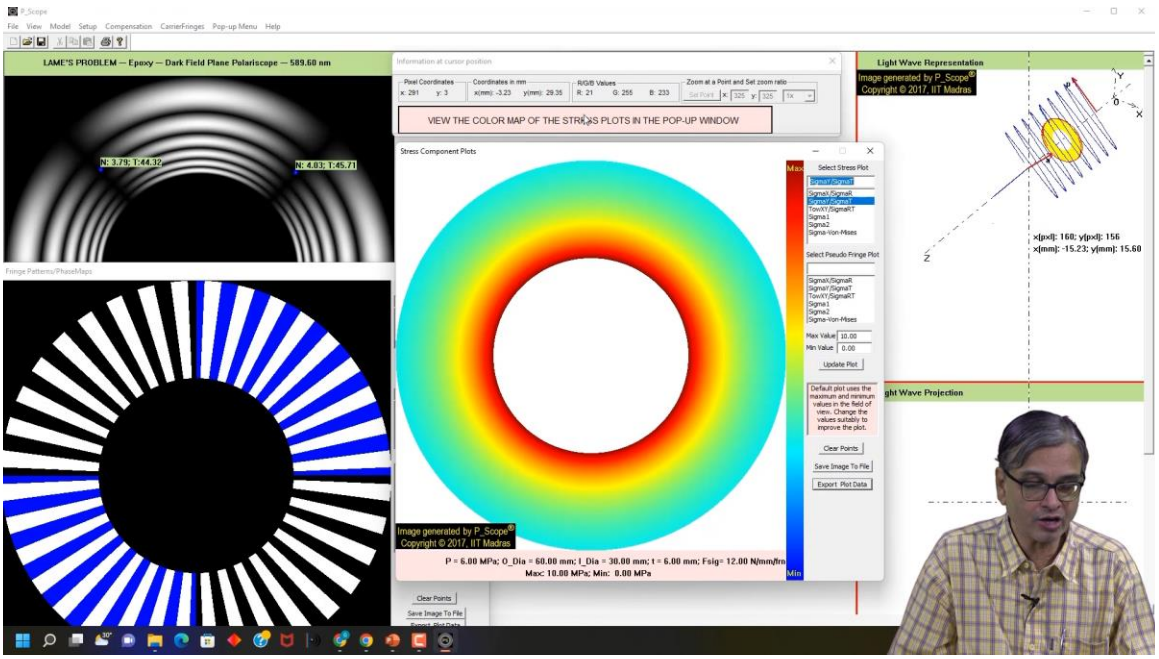

We have determined in your thin cylinder only hoop stress, but here you will have hoop stress as well as radial stress is possible, but we will have this as σ_θ, σ_θ is plotted like this. Now, the question is you know we have done it for a load of 6 MPa pressure, so what I will do is I will reduce this by 3 MPa that means, I am reducing the load.

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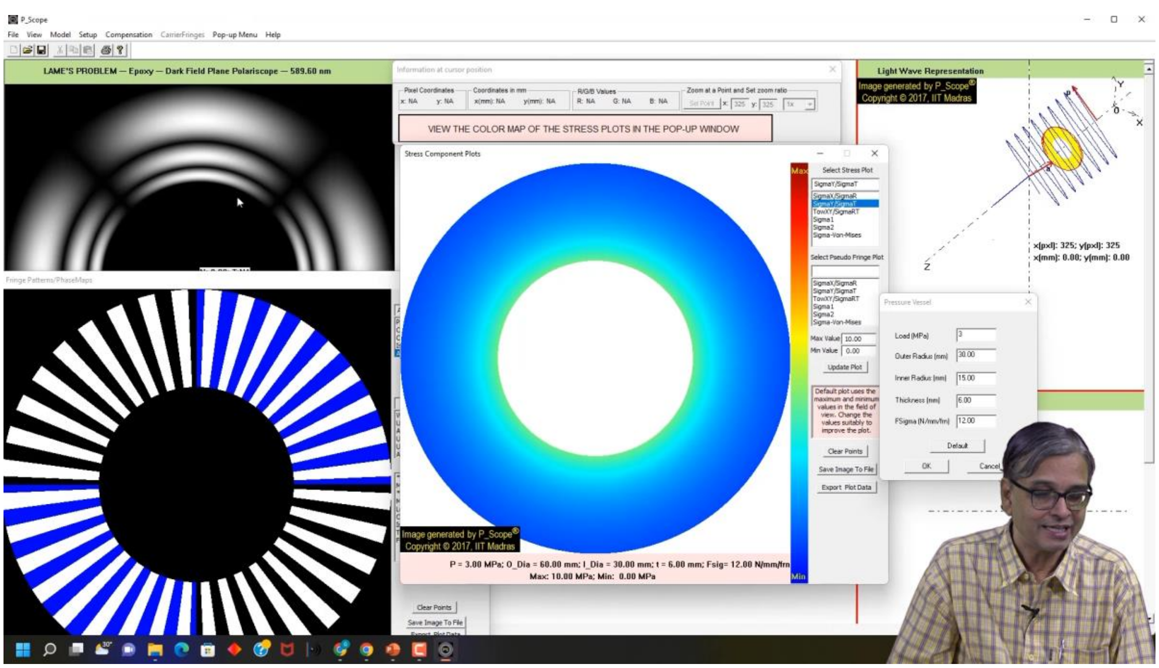

The question is in the case of a beam, we have looked at the optical response has changed, you know I also wanted to tell you what happens to the principal stress direction, what is the expression for principal stress direction can you recall? Write down, write down, because I am going to ask the following question, I want an answer.

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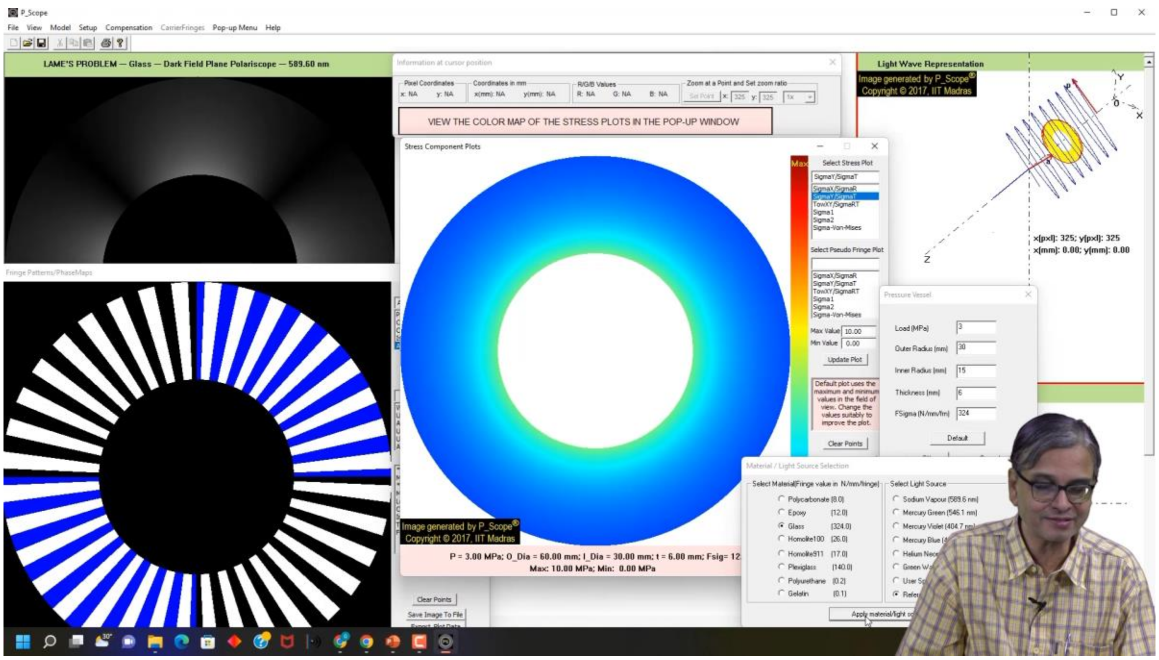

See, I am living in linear elasticity and I am reducing the load by half, what do you anticipate to the principal stress direction? Stress magnitudes are changing, stress magnitudes are one half of it, you look at the expression, there is advantage why we want to live in the linear region, you should also taste that advantage. What do you anticipate to the principal stress directions? What will happen to the principal stress direction? Let me simplify the question, will they vary or will they remain same? There are only two possibilities, which one would you choose? What happens investigate, what happens to the numerator, what happens to the denominator, everything goes in the same proportion.

So, what will happen, what is what is your take? It remains same, let us see that. Now, I have reduced the load by half, let us repeat the whole thing, I have the fringes reduced and then I have the stresses reduced, the isoclinic remains same, the all isoclinic also remains same. See, do not tell me that you are showing me a simulation, I do not know whether you calculated it or not, take it from me that it is calculating it afresh for any one of the loads. So, you also understand a very subtle point, the greatest advantage of living in linear domain that when I double the load or half the load or change the load in a linear proportion, in the same proportion stress magnitude change, principal stress direction cannot change, because I have the ratio remain same that you can get a grasp of it. And we have also been seeing glass, ok, so we will also change this to glass and then see. So, if I go to glass what happens to this? I hardly see any fringes, but the stress magnitude do they change, they do not change.

So, in linear elasticity when the body force is constant or zero for both plane stress and plane strain, photo elasticity gives the stress magnitudes which can be correlated to your metallic prototypes. And in fact, if you are designing a new aircraft and then want to design a landing gear, they use photo elasticity to optimize the landing gear, because it is a dead weight. Every kilogram you save, you save enormous amount of fuel. And even today chemical engineers go and spray this photo elastic coating and then make measurements and reduce the weight. Every ounce of material that you save, it is enormous amount of fuel saved.

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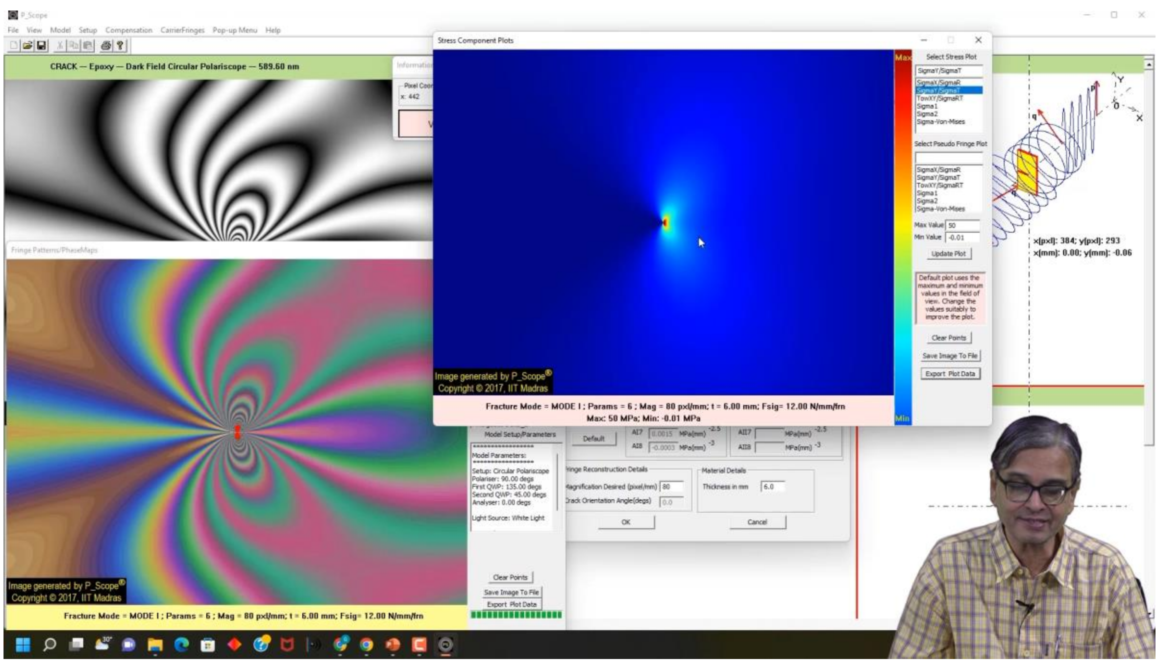

And you know you also have other interesting models, we have also seen crack and then we will have a beautiful crack fringe pattern here. And you have the fringe pattern seen like this, they can also be seen in color, you have beautiful colors. And even in this when you want to understand fracture mechanics, if I want to know the stress components, see the advantage of a simulation is you can understand concepts of solid mechanics with the assistance of photo elasticity. See when the photo elasticity was developing, people were working only on glass. And you know it is only in 1822 to 1882 or something like that, those was the period where the concepts got developed.

At that time they did not have an advantage of looking at it from a photo elasticity and then learn the concepts better. So, your batch is very lucky. Now you have both the advantage of photo elasticity to show you the fringe patterns in color. And you can also understand concepts related to stress analysis very easily, ok. So here you know we also have stress magnitudes, fine, it is infinity, so I have to put this because I told you at a crack tip it becomes singular.

So, I have to put a value for me to do that, so I will put this as 50, I will update the plot, I have the fringe pattern like this. Because when you doing a simulation, simulation will go only mathematically.

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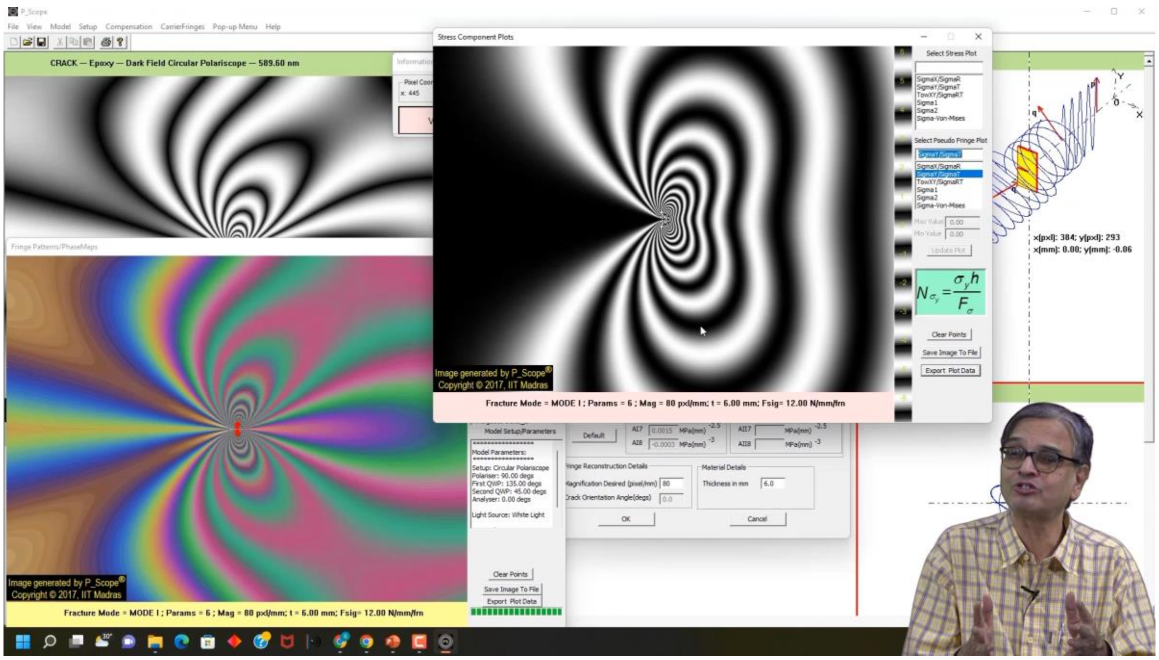

A physical material it will not go beyond yield and you have the σ_y stress component is like this. And you also have simulated fringe contours, you have the σ_x how the σ_x contour changes, it is all very complicated. You have very high level of stress, the idea is we have looked at what happens to a free outward corner, what happens to a re-entrant corner, re-entrant corner I said it is infinity, singular, that is what you have got.

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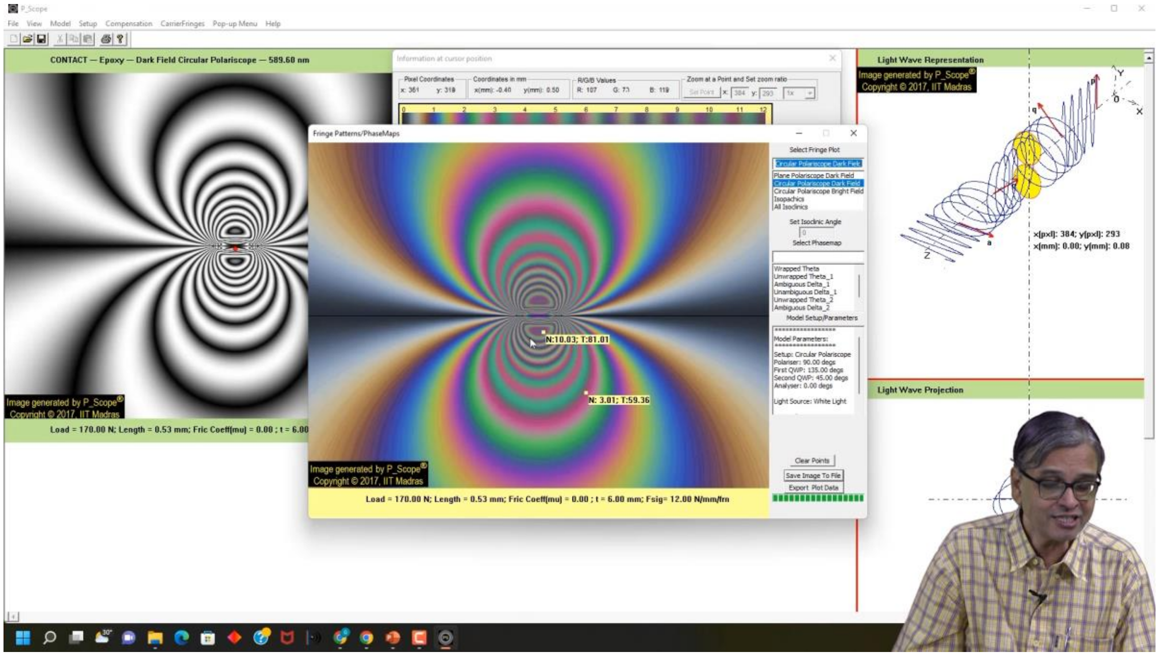

And then I can re-plot, so you can learn all of this. Then another interesting problem that is not normally taken up even in your second course, but is very important which happens even in the case of a simple railways is this. You have what is known as a contact stress, you know whenever you have a concentrated load, the concentrated load is actually happening over a small area. I also showed an ellipsoidal distribution that is known as a Hertzian contact. Where do you go for all that when you do mastication, you have this contact analysis necessary for your tooth well being. When you have implants, if the contact stresses are very high, you are going to have problem with the tooth implant also.

One of my student has done a beautiful work on dental analysis and if the stress levels are high, you have what is known as bone resorption and the implant comes out, bone gets weakened and all that. So, you need to look at how to handle this situation. And what is interesting in this is, the maximum stress occurs beneath the surface that is what is important in contact stress analysis. See if you look at you know when I increase the fringe order, if I go to this fringe order, it shows this as fringe order 10 that is the highest fringe order and this is about fringe order 3. So, the highest fringe order, this is the top surface, it does not occur on the surface, it occurs beneath the surface.

So that is the reason you know you find that people put the roads and then you have pits formed. See in India what happens is if the road is rated for a particular carriage weight, you know the lorry fellow will load twice that value that axial load is very high. So, you are applying excessive contact load on the road and failure happens beneath the surface and you have pits formed. That is why that is the reason for all your potholes. First is poor quality construction, second one is abuse of this when something is rated for some load, you should respect that. See Indians are very good at chalta hai attitude, we have to come out of this chalta hai attitude and respect convention rules and follow rules.

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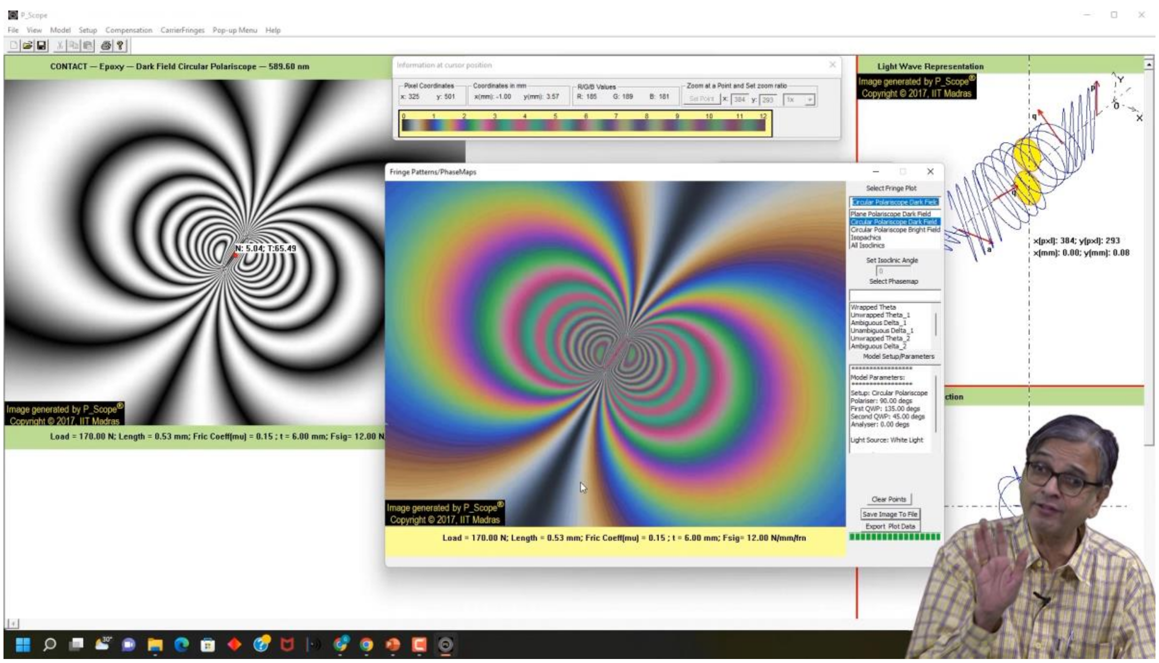

Then what happens is when I introduce friction, these are all very interesting from a practical point of view because you know you are learning the course in 2022, you cannot say that I will know only slender member and close my eyes for everything else, it is not possible to do. So, when I have this, the friction pulls its eye and it is coming making it closer to the edge. Is the idea clear? This is one of the problems in railways and I have one PhD student who is looking at some of these aspects. So, they are all very important for your day to day living.

Tomorrow when you get into the train, you want to go safe to your destination. So, with this we have a bird's eye view of what is photoelasticity and I have tried to give you the essence of it without any proof. We have also looked at how you can construct your own home made polariscope at a very nominal cost and you can also have a thorough learning when you have a simulation package like this. This is also very cost effective because when you go for modern day polariscopes which all have digital image, data acquisition, data analysis, it costs anywhere between minimum of 10 lakhs to 40 lakhs. These days and also with your dollar appreciating every other day when compared to the rupee.

So, these are all becoming out of reach. So, in that context your home made polariscope you can construct within 1000 rupees and if you have a simulation package like this, you can understand both photoelasticity as well as solid mechanics much better. Thank you.