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

Module No. # 04
Lecture No. # 26
Introduction to Photo-elastic Coatings

See, we have looked at transmission photoelasticity elaborately, then we also had an idea of how photoelasticity can be applied for three-dimensional problems, then we moved on and looked at what way we can use digital image processing techniques to automate photo-elastic analysis.

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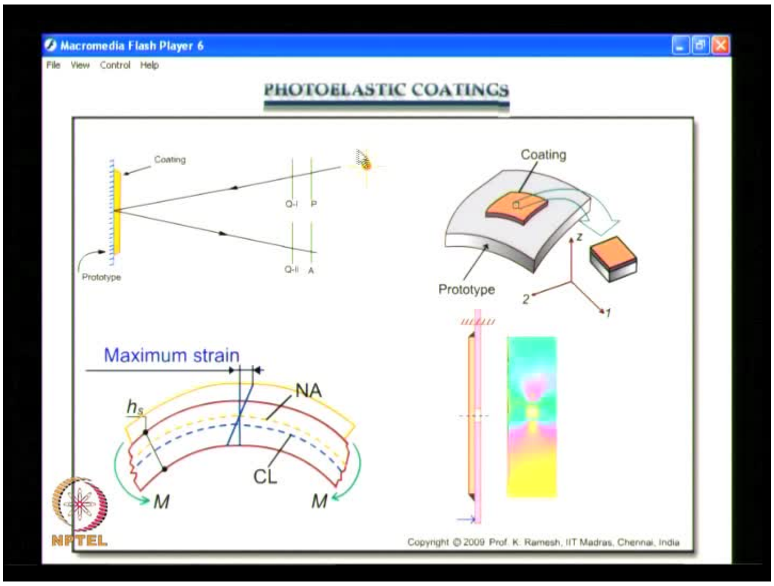

PHOTOELASTIC COATINGS

Now, we take up the industrial application of photo-elasticity, that has become a success with the advancement in photoelastic coatings, and what you have here is, I have the basic optical arrangement that is used and once you come to photo-elastic coatings, you know, you need to make idealizations on how do you translate the results seen on a coating to the specimen, and one of the important factors there is to consider what are known as correction factors, which will improve your prediction of the results.

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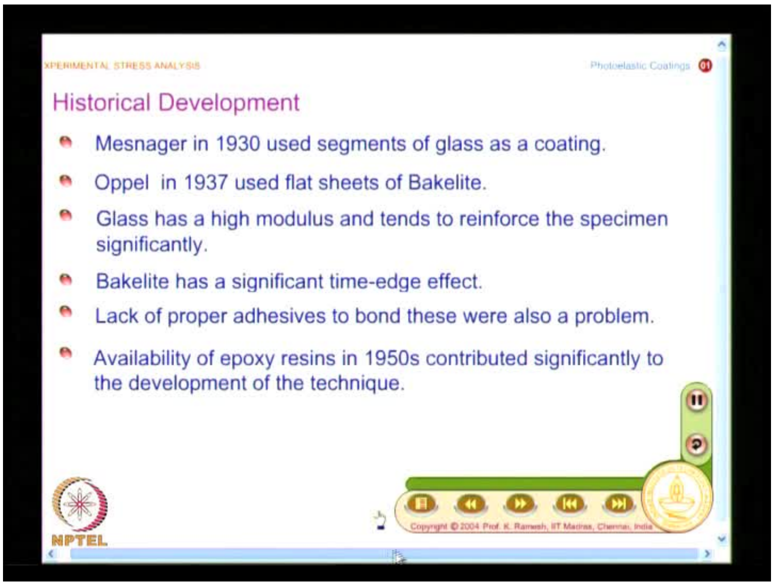

Historical Development

- Mesnager in 1930 used segments of glass as a coating.
- Oppel in 1937 used flat sheets of Bakelite.
- Glass has a high modulus and tends to reinforce the specimen significantly.
- Bakelite has a significant time-edge effect.
- Lack of proper adhesives to bond these were also a problem.
- Availability of epoxy resins in 1950s contributed significantly to the development of the technique.

And this shows the example of how the fringe patterns appear in photoelastic coating and this also shows on a specimen, I have a birefringent coating pasted on to it. And if you look at any of the techniques, we need to look at history behind it and what you have as historical development? We have Mesnager in 1930 used segments of glass as a coating. It is very surprising you know, we have looked in photoelastic materials, that glass is also a photoelastic material and it has a Poisson it has a Young’s modulus of 70 GPA equivalent to aluminum, whereas all other plastics, we had only 3 GPA; and because this has a very high value of Young’s modulus, one of the problems with glass was, it reinforce the specimen significant.

And after glass, what they tried? Oppel in 1937 used flat sheets of Bakelite. So, when we graduate from transmission photoelasticity to photoelastic coating, initially people concentrated only on flat surfaces; so, they initially used glass which was found to reinforce specimen significantly. The problem with Bakelite was, it has a significant time-edge effect.

And we have already seen in transmission photoelasticity, because of time-edge effect, you have spurious fringes that are formed. So, you do not want spurious fringes; so, Bakelite was also not a suitable material when you want to go in for photoelastic coatings.

And I said, any development in science on engineering was always tagged on to developments in material science. So, what you find was, availability of epoxy resins in 1950s contributed significantly to the development of the technique. So, it is the material research, which has helped in advancement of photoelastic coatings. This has multiple names, you can call it as photoelastic coating, you can call it as a birefringent coating based on what is the kind of material that we use and because you see the reflected light, this is also termed as reflection photoelasticity. And the other difficulty was lack of proper adhesives to born these coating were also a problem. So, the development of the technique fringes on development of proper adhesives and also development of epoxy resins.

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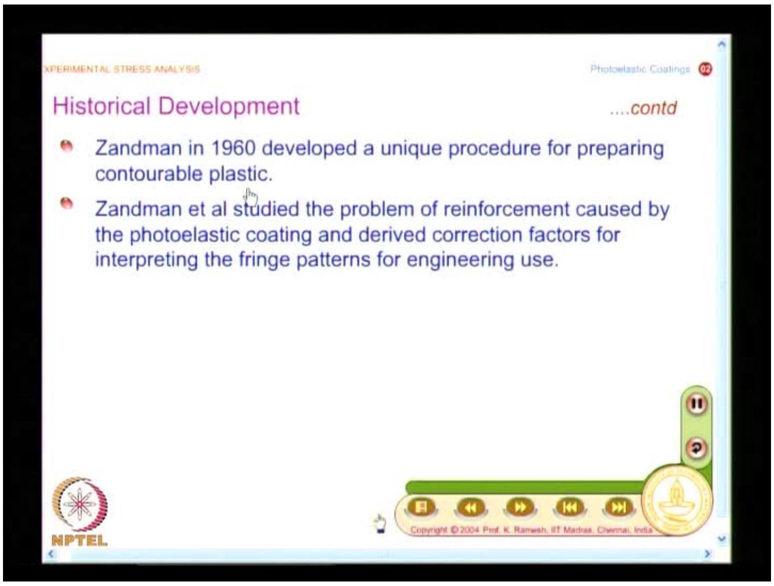

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 02

Historical Development ....*contd*

- Zandman in 1960 developed a unique procedure for preparing contourable plastic.
- Zandman et al studied the problem of reinforcement caused by the photoelastic coating and derived correction factors for interpreting the fringe patterns for engineering use.

Initially, many of the applications were confined to flat surfaces. Later, it was shown by Sandman, who developed in 1960 a unique procedure for preparing contourable plastic. See, if you look at any of the industrial component, you have a very complicated surface and if I have to put a coating on top of it, I must be able to make the contour of the actual object. So, in a contourable plastic, technology is, you cast a sheet and when it is in a gel state, you take it out from the casting plane, and then, put it on the actual prototype, and then, allow it to take the shape of the actual object and in this process, no stresses are introduced. Because the plastic the whatever the polymer that we used is in a gel state, it easily forms the contour of the actual object; after it is cured about 24 hours, you get as a shell, and the shell is pasted on the actual object and do the experiment.

So, this was the very significant development, whatever Zandman as introduced and this is a very famous contourable plastic. And now, you have whatever the sheet in a gel state is put with the proper icing, and then, you have such gel sheets available; you directly by the sheet from them, take it to from the cold storage and contour it; you do not even have to caste it, and then, wait for whether it has reached a gel state or not, all that your steps are simplified, you have those sheets available, but it is expensive; in abroad, it is available; in India, it is still not come. So, if you want to take photoelasticity to solve industrial problems, photoelastic coating paved the way and particularly contourable plastic has made this technique very attractive.

And the moment you come to any of the coating techniques, you will also have to study a problem of reinforcement, whether it is significant or not, we will have to find it out, caused by the in this case photoelastic coating and Zandman provided correction factors for interpreting the fringe patterns for engineering use.

And this applies to all the coating techniques. Suppose even if you look at a strain gauge, it can reinforce when the specimen size is comparable to the size of the strain gauge. I said in the case of electro nic packaging, I cannot go and paste a strain gauge on the leg of those i c chips, because the sizes are comparable. On the other hand, an optical technique would definitely help in such situations and in the case of photoelastic coating, if I use glass, it has a very high Young's modulus and it is definitely going to reinforce. So, people dropped glass and now moved on to epoxy, nevertheless you know, when you are having a coating, if the coating is thin enough, then we do not have to worry about. In photoelastic coatings, coating thickness of 3 milli meters are not uncommon. So, you are really talking about sufficient thickness, so that you have to keep in mind.

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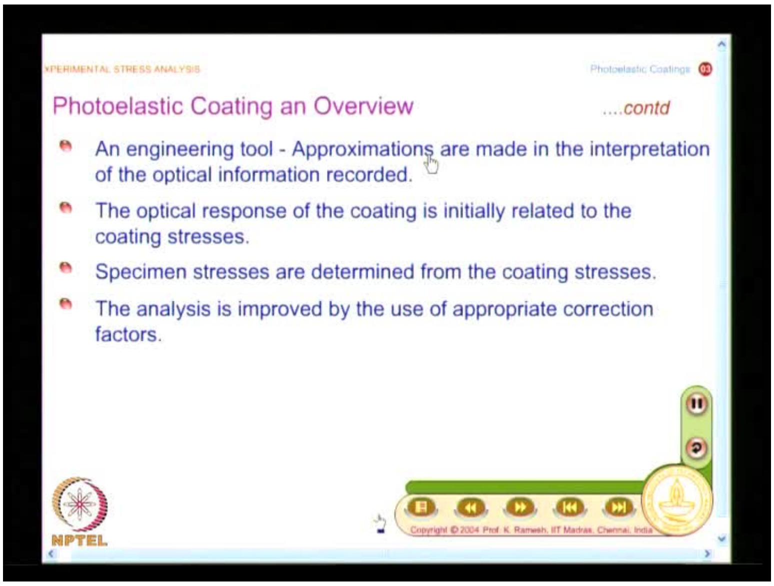

Photoelastic Coating an Overview ....contd

- An engineering tool - Approximations are made in the interpretation of the optical information recorded.
- The optical response of the coating is initially related to the coating stresses.
- Specimen stresses are determined from the coating stresses.
- The analysis is improved by the use of appropriate correction factors.

And you have to appreciate that, this is an engineering tool. And I have said engineering means approximations, and approximations are made in the interpretation of the optical information recorded. We say that, we want normal incidents in photoelasticity and you would find because of industrial application even that is compromised to some extent and what you do? First you get the optical information; the optical response of the coating is initially related to the coating stresses; so that is what we find out.

Because all the theory that we have developed in transmission photoelasticity are equally applicable in photoelastic coating with slight modification and those modification you can easily figure it out. So, the focus what we are going to do is, you will not spend much time on the optical aspect, we will spend much time on the mechanics aspect; we will initial look at how the optics information is translated, but we will essentially look at how do you find out the coating stresses; from coating stresses, how do you find out the specimen stresses, what kind of approximations are needed in this kind of analysis that is would be the focus.

And in engineering, when you are actually making certain approximations, you always bring in a correction factor. So, that is why it is the engineering tool, that is why we said Zandman contributed contourable plastic as well as a methodology to develop correction factors, which take into account the thickness of the coating and also it is possible reinforcement affect.

Then what you have? The specimen stresses are determined from the coating stresses and as I mentioned earlier, the analysis is improved by the use of appropriate correction factors. See, in transmission photoelasticity, we never even talked about correction factors; the marriage between physics and engineering so good in transmission photoelasticity, there is no need for correction factors; but in reflection photoelasticity even for calibration, you need to bring in the correction factor; if you do not bring in the correction factor, your evaluation of the calibration constant itself can be erroneous. So, right from the optical arrangement, even to calibration and even if you want to find out the stress concentration factor, you have to do it very carefully in reflection photoelasticity; in transmission photoelasticity, you just find out the maximum fringe order on the horizontal diameter and find out the average fringe order, you take the ratio, and your job is done.

And I have said, in all the coating techniques, Poisson’s ratio plays its spoilsport. So, you have to accommodate the role of mismatch of Poisson ratio in photoelastic coating systematically; so that you will see even in the evaluation of the stress concentration factor.

So, you will always have to look at, it is an engineering tool; you make approximations; because you make approximations, you improve your results by employing appropriate correction factors. This is engineering; you know, engineering always do like we that; we do not give up. See, if I am unable to solve the problem in all its totality, I do not give up; I at least bring in correction factors and make my result as acceptable as possible. Because in design, people want results with 50 percent accuracy that is good enough, because they always have factor of safety; they have such factors with accounts for deficiency in the analysis. Only when people develop some finite element code, they really talk of 0.1 percent accuracy, 0.01 percent accuracy; experimentalist do not operate that way; plus or minus 2 percent, most cases we will accept; 5 percent, 10 percent and even 50 percent are allowed; at least I am close the 50 percent to the result. Because the problems what you handle are very complex; even a very little information which is available with certain level of confidence can always go into a design calculations.

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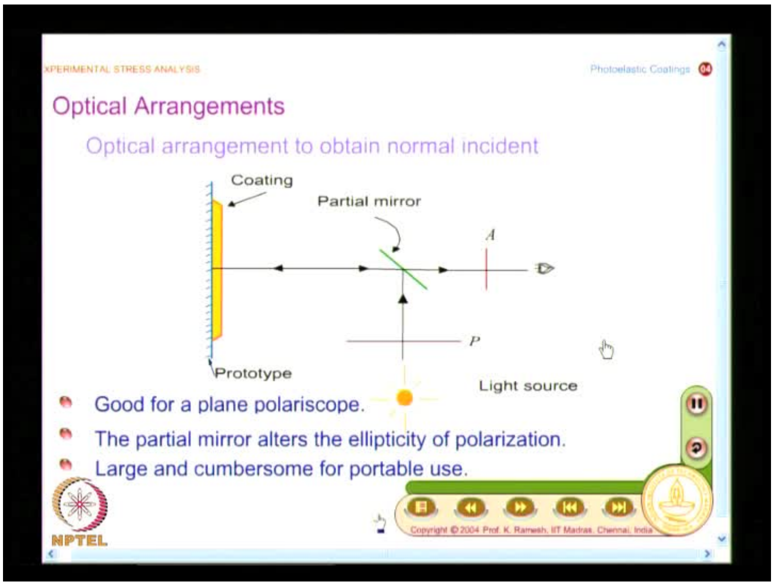
XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 04

Optical Arrangements

Optical arrangement to obtain normal incident

- Good for a plane polariscope.
- The partial mirror alters the ellipticity of polarization.
- Large and cumbersome for portable use.

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And we will see what kind of a approximations are made in a photoelastic coatings. We will also look at the basic optical arrangements and just observe the animations. So, what I have here is, I have the prototype here that is shown with the hashed line and I have the coating that is pasted on this; and in transmission photoelasticity, we always wanted a normal incidents. Suppose I want to have a normal incident, the possible optical arrangement could have a partial mirror here, so that the light passes through the polarizer, and then, part of it goes and hits on the model and whatever the light reflected that comes out and reaches your eye through the analyzer.

And what strikes you first? See, we will looked at in the case of transmission photoelasticity, thickness of the model is a key parameter, then we modified it; when we moved on to three-dimensional photoelasticity, we looked at as length of the light path, because depending on the size of the three-dimensional model and the angle of incidents, I may have different length; the length is the one which is going to determine the retardation seen in that light path.

So, if you look at, what can immediately guess when I have a reflection arrangement like this? Very simple, suppose I have thickness of the coating has h c, because light goes in and comes out, all those equations are equally valid, if I replace thickness by 2 h c, because the light actually travels twice the thickness of the coating. So, you get how transmission photoelasticity equations could be translated in to reflection photoelasticity.

Though this optical arrangement is a good enough for plane a polariscope, the use of a partial mirror affects the elipticity of polarization when I use it for a circular polariscope; and not only this, an arrangement of this nature is large and cumbersome for portable use; if you really want to have normal incidents in reflection arrangement, you cannot avoid a partial mirror, and partial mirror is good enough for a plane polarized light, but in a general elliptical polarization, it interferes to some extend on the state of polarization. This is one defect; the other defect is, in arrangement like this is bulky; is not efficient for you to carry around and set it up in an industrial environment.

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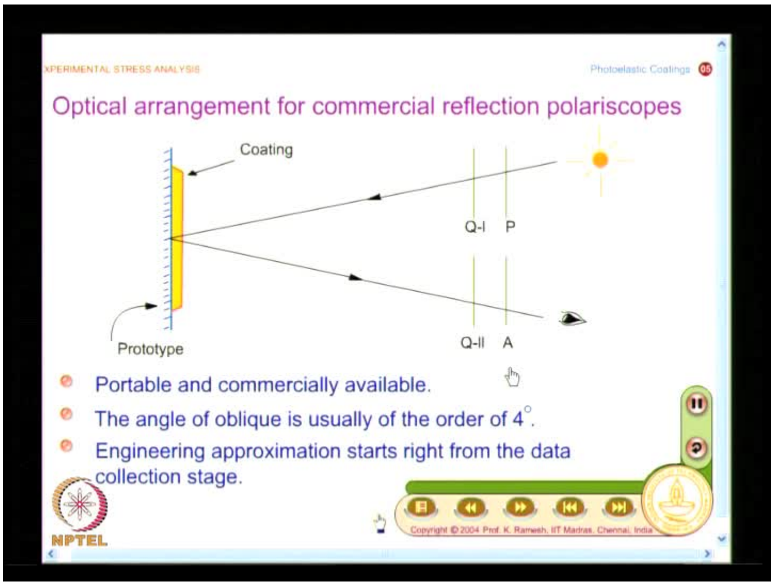

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 05

Optical arrangement for commercial reflection polariscopes

- Portable and commercially available.
- The angle of oblique is usually of the order of 4°.
- Engineering approximation starts right from the data collection stage.

So, what is the kind of arrangement that they have in a commercial reflection polariscope? Observe the animation again, so what I have here is, I have to send the ray of light to the model and I have to analyze only the reflected light. And what I can do this is, I have to do this at an angle, for me it is the reflected light; the way I can improve my technique is, keep this light source and your observation far away from the model, so it is about at least 2 meters is what is recommended; when you have that kind of distance, you know, this angle of oblique can be as small as possible; you do not want to have compromise fully on normal incidents; you do not want to impinge the light at 45 degrees, you do not want to do it that way; you want to have a shallow angle of oblique, and in order to achieve that, you view the model from a distance. So, in the case of reflection photoelasticity, now people replace human eye with the camera, so they use telephoto lens, which will focus objects at a distance very conveniently and by keeping the optical elements away from the model, you reduce the angle of oblique.

And this is of the order of about 4 degrees; the angle of oblique is usually of the order of 4 degrees and what you find here? Engineering approximations starts right from the data collections stage. And this set of optical elements can be put in a very convenient form and you can even hole it on the hand and you just need the light source and view the model, and you already know this P denotes polarizer; when it say Q 1, it denotes the quarter wave plate 1 and you have the quarter wave plate 2 and you have the analyzer. So, in order to maintain the angle of oblique as small as possible, you keep your optical elements at least about 2 meters from the specimen surface, because if I get it very close then the angle of oblique will increase. So, I would like to have it as small as possible and this is the optical arrangement of commercial diffraction polariscopes; many reflection polariscopes are available and their again you can employ digital photoelastic analysis.

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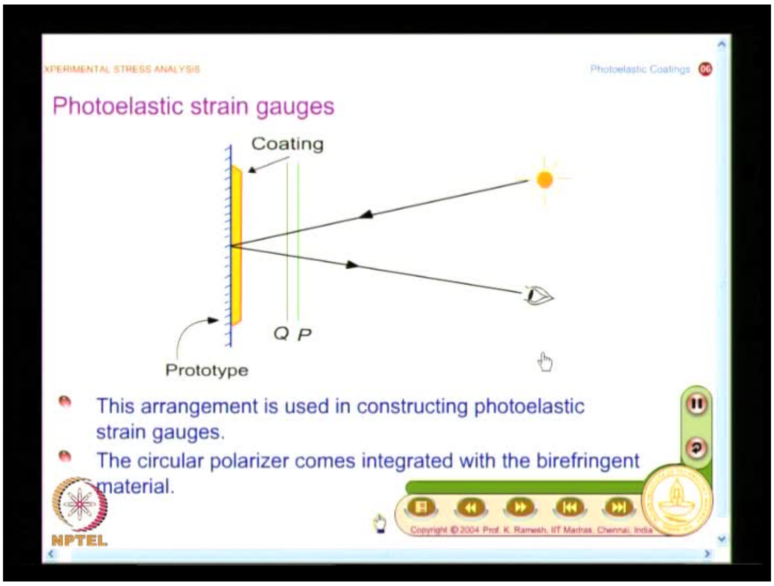
XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 06

Photoelastic strain gauges

- This arrangement is used in constructing photoelastic strain gauges.
- The circular polarizer comes integrated with the birefringent material.

NPTEL

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And one of the outcomes of this kind of approach is also what are known as photoelastic strain gauges; what I have done is, along with the coating, you will have the quarter wave plate and polarizer integrated with it. You know, these were developed in Germany, like you have electrical resistance strain gauge, you will have a small strip of plastic with it is own quarter wave plate and polarizer embedded and paste it on the model and view it in a normal white light, you will see fringes; when the model is loaded, you will see fringes on the optical, it is an optical strain gauge; it was popular for some time. So, the philosophy there is, they just put the quarter wave plate and polarizer integrated with the coating and you would see, you will see the isochromatics; you will not see isoclinics in this arrangement. You know, in those days, when you have a uniaxial stress or biaxial stress, even that knowledge was considered important. And people had strain gauges photoelastic strain gauges with the hole on it, and then, they will find out whether it is uniaxial state of stress, biaxial state of stress; it gives you quick information. Because in a strain gauge, you have to connect it to instrumentation and read the strain; here if there is load applied, you will see moment of fringes; it was very attractive. So, the circular polarizer comes integrated with the birefringent material.

So, what you look at now is, you have looked at, if I want normal incidents what is the kind of optical arrangement I should think of in referential photoelasticity. We saw that it requires the partial (( )); we said that it is bulky and also it interferes in elliptical elipticity of polarization; so it is not desirable to have that. So, we moved on to a commercial polariscope, where we allow certain angle of oblique, without which you cannot see the reflected light, so you have to live with that. and But what you have to look at is, what is the advantage of photoelastic coatings. The coating material is isotropic; the base material can be anything; it can be composite, it can be ceramic, it can be rubber, it can be bone, it can be aluminum, it can be steel, it can be concrete. So, what you find here is, all the so called engineering materials, you could have one technique which provides you the necessary information.

See, if you look at composites, they are anisotropic in nature and if you look at that material equation, they are very complex to handle. On the other hand, if you have to interpret only what happens on an isotropic coating, it makes your life simple on finding out atleast the surface trains on composites. And I said in any technique, material advancement has contributed to the development. So, people have developed coating from rubber to human bone, because the base material controls what should be the nature of the coating. Because you know, if you look at composites, they actually reinforce it with fibers. And one of the thumb rules says, if you look at the base material, the reinforcement material should have Young’s modulus 10 times that of the base material, this is the thumb rule only then, the fibers really reinforce the primary material. And here we have seen, when I use the glass, it is 70 GPA which is comparable to the metal, so it going to reinforce.

On the other hand, if I have a photoelastic coating which is the 3 milli meters, even though it is 3 milli meters, the Young's modulus uses only 3 GPA, whereas the metallic this one aluminum it is 70 GPA, and then, steel it is 200 GPA, hardly this coating will affect; even then, we have developed correction factors for other reasons. So, what we will have to look at is, the greatest advantage of a coating technique, you can apply to a variety of base materials provided you have appropriate coating properties.

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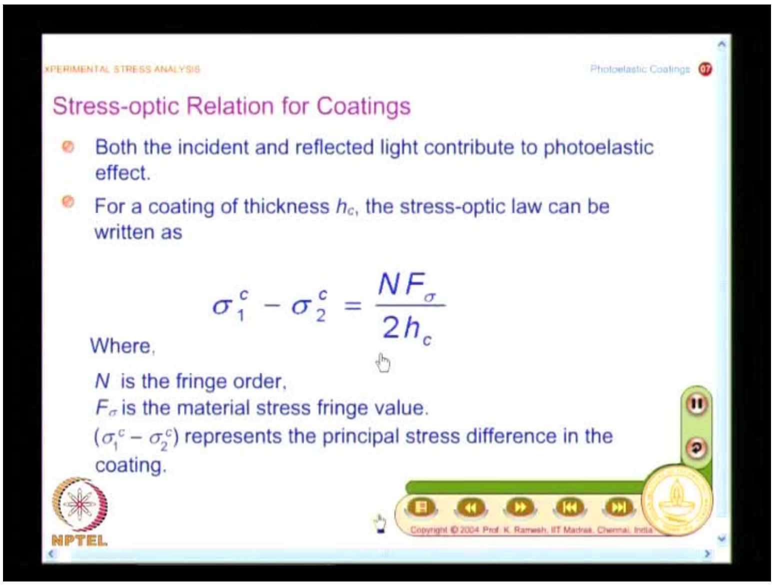

Stress-optic Relation for Coatings

- Both the incident and reflected light contribute to photoelastic effect.
- For a coating of thickness h_c, the stress-optic law can be written as

$$\sigma_1^c - \sigma_2^c = \frac{N F_\sigma}{2 h_c}$$

Where,

N is the fringe order,
F_σ is the material stress fringe value.
$(\sigma_1^c - \sigma_2^c)$ represents the principal stress difference in the coating.

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And now let us look at extrapolation whatever we have learned in a transmission photoelastic analysis, and we look at stress optics relation for coatings. And I have already drawn a pure attention at both the incident and reflected light contribute to photoelastic effect, because you are seen the light reflected. And I said for a coating of thickness h c, because the material what I use is birefringent, it behaves like a crystal when it is loaded; I can also write the stress optic law, where in I get the coating stresses since we are going to have specimen as well as coating, the symbolism used is a symbol c either at superscript or a subscript indicates that I am dealing with the coating and when I want to have sigma 1 c minus sigma 2 c, if I know the f sigma the material, then I can write this as N F sigma by 2 h c. You know, for developing this equation, we took about six to seven classes in transmission photoelasticity, because we need to know what is retardation, how it optics related, how the refractive index is looked at the ratios of velocities, how refractive index can be compare to stress sensor all that we developed. Now, we take that advantage, we take the advantage of that knowledge and we only look at, both incident and reflected light contribute to the fringe formation and what you have instead of h c, I had to put 2 h c.

But even this representation is not very convenient. See, in the case of photoelastic coating, one of the assumption I make is, I put a coating on the specimen; when I load the specimen, I want to persive the adhesive is so well bonded that whatever the strain developed on the base specimen is transmitted faithfully to the coating. So, of a instead of looking at stress optic law, I should essentially look at strain optic law; that is more appropriate. Because the way the model is loaded, the way the coating is loaded is different; so we will have to look at what is strain optic law.

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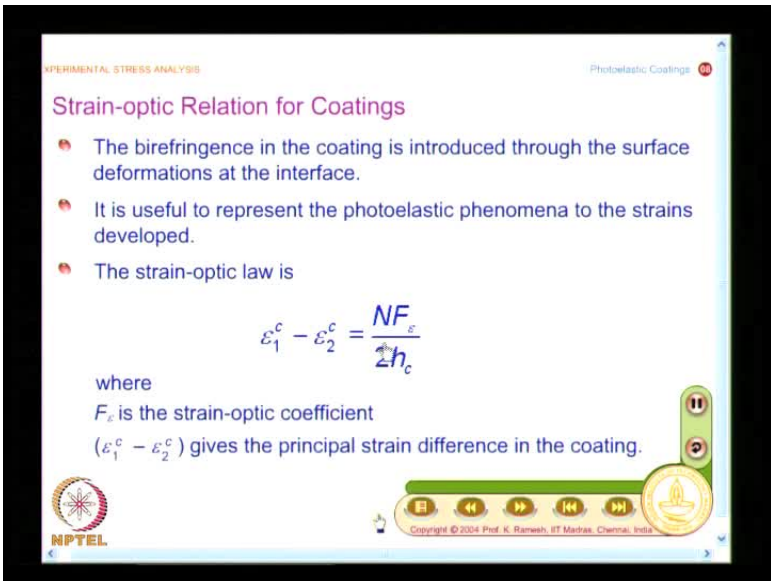

Strain-optic Relation for Coatings

- The birefringence in the coating is introduced through the surface deformations at the interface.
- It is useful to represent the photoelastic phenomena to the strains developed.
- The strain-optic law is

$$\varepsilon_1^c - \varepsilon_2^c = \frac{NF_\varepsilon}{2h_c}$$

where

F_ε is the strain-optic coefficient

$(\varepsilon_1^c - \varepsilon_2^c)$ gives the principal strain difference in the coating.

So, what I have here is, the birefringence in the coating is introduced through the surface deformations of the interface. Because we said that the coating becomes temporarily birefringent when loaded, how the loading comes? The loading comes; it is introduced through the surface deformation of the interface.

So, in view of this, it is useful to represent the photoelastic phenomena to the strains developed. And you know, strain is also a tensor of rank two, so instead of having sigma 1 c minus sigma 2 c, I could also think of writing it as epsilon 1 c minus epsilon 2 c. And

I will also bring in a material parameter; there we have said, you must be wondering why I was calling that as F sigma; at that time you would not have notice why a suffix sigma should be attached to F; I said it is a material stress fringe value. So, following the similar logic, we will have this equation with F epsilon; we will say a material strain fringe value, but we will have to find out what is say F epsilon that is the different story, but writing the equation is now much simpler. We follow a same logic and I write this epsilon 1 c minus epsilon 2 c as NF epsilon divided by 2h c; the factor 2 comes, because both the incident and reflected light contribute to photoelastic effect.

So, we call F epsilon is a strain optic coefficient, and epsilon 1 c minus epsilon 2 c gives the principle strain difference in the coating. See, the real utility of photoelastic coating, you will see only when this equation is recast comfortably, because ultimately what is that I want. My interest is not to worry about what are the coating stresses; my interest is to find out the stresses developed on the specimen; so that is where I have to bring in mechanics of solids. How do I find out the stresses on the specimen based on coating stresses? The coating is birefringent; that is why I call this as a birefringent coating; when the loads are applied, it acquires property of the crystal behaves like a crystal and you have the phenomenon of birefringents and fringes gets formed and their also many other shuttle issues.

See, if you look at transmission photoelasticity, we have never discuss how many fringes I will observe in an experiment; we have never even talked about it; depending on the load applied, you will get so many fringes; if the fringes are less in crystal load. Only when we discussed three dimensional photoelasticity, I said I have to calculate the load very carefully so that at stress freezing temperature, the model should be strong enough to withstand and also how many fringes you have to see on the slices and you have to do some calculation. As for as two dimensional photoelasticity is concerned, there was no discussion on how many fringes I will see; but the moment you have come to photoelastic coatings, we will also have to worry about how many fringes I would normally see in a photoelastic coating test; this becomes an issue. Because what do you want?

Many of your engineering components, you do not bond them to become plastic at service load conditions; you want them to remain only as elastic for various reasons. Because if there is a moving part involved, it has to remain elastic for it to do its function, and another important aspect what you have noticed here is, it is the strains that developed on the specimen get translated to the coating; so coating is not loaded directly. See, in the case of plastic, you know, if you directly load apply the load, you are really applying. Because of low Young's modulus, you will also have large strain developed and you will have many fringes seen, but here only the surface strain is transmitted, and surface strain in a service load condition you want to operate much will have to two thousand micro strain; even if you say it reaches two thousand micro strain, normally the number of fringes observed in a photoelastic coating test are minimal.

And we have also looked at in transmission photoelasticity, most of the time we worry about monochrome light source. And we have looked at the color white light only from the point of finding out the gradient direction and white light was used as an exception and transmission photoelasticity in conventional transmission photoelasticity, but with the digital photoelasticity, you have three fringe photoelasticity, where you use color for quantitative evaluation of data that is different. In reflection photoelasticity, because the fringes that you see normally are much less, you generally use white light; very occasionally you look at a monochrome light source; you look at white light only.

So, this is one difference, and we will also have a specific discussion what is the maximum fringe order you can see for a given coating and base material combination; it is dictated by the base material, because when it yields, what way it is going, the properties elastic properties will influence. So, the number fringes you see are very small. So, one of the caution, which I use to normally mention is, I have been saying, if I have good colors, it is very interesting and motivating for you to work; photoelasticity offers that benefit, but in the reflection photoelasticity if you see colors, it is the warning signal; the specimen is heavily loaded.

So you should not get (( )) by the colors, you should really take corrective measures, and then, improve your design. These are like thumb rule type of thing, depends on various factors, but you will have to keep in mind, if you do not see colors be happy about it; if you see colors, you have to worry about it. But if you do not see colors, the problem may be the coating, may have got peeled off; if you do not if you do not bond it in all the coating techniques, you have to follow the suppliers recommendation whoever is supplying with the adhesive, he will give the recommendation what is the surface preparation, what is the curing cycle, what is the kind of pressure applied all that you should follow faithfully; if you do not follow that faithfully, the strains of the specimen would not be transmitted to the coating; so, this is one issue. Even if the strain is transmitted faithfully, the number of fringes normally observed in a photoelastic coating test are generally smaller.

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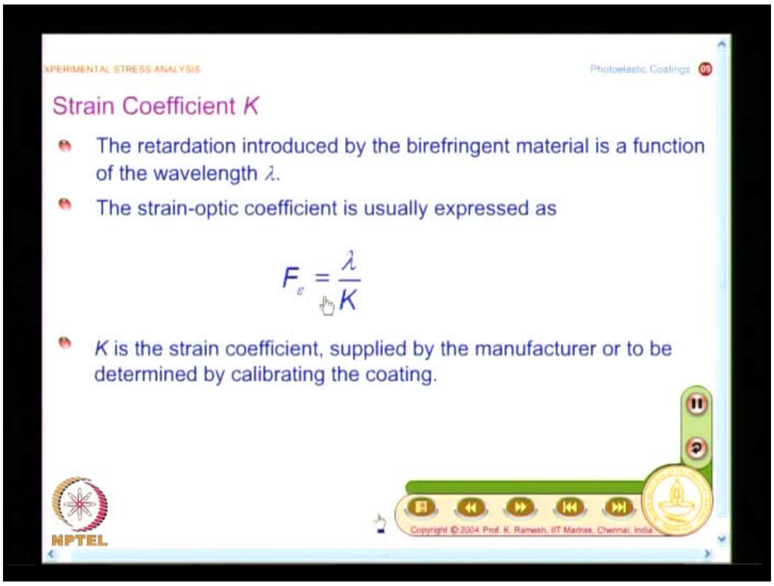

Strain Coefficient *K*

- The retardation introduced by the birefringent material is a function of the wavelength λ.
- The strain-optic coefficient is usually expressed as

$$F_\varepsilon = \frac{\lambda}{K}$$

- *K* is the strain coefficient, supplied by the manufacturer or to be determined by calibrating the coating.

And we also define a factor called strain coefficient K, this is very similar to what you have seen in a transmission photoelasticity. In transmission photoelasticity, you have defined F sigma as lambda by capital c, here it is defined as, F epsilon is defined as lambda by K, and you have to recognize the retardation introduced is the function of wavelength lambda. Now, you have the definition of F epsilon; F epsilon is related to lambda by K; K is the strain coefficient, it is supplied by the manufacturer or to be determined by calibrating the coating, is also a shuttle difference. In normal transmission photoelastic analysis, you do not handle capital C; you only evaluate F sigma and many of your calculations you do with F sigma. And I have already said that, arithmetic in transmission photoelasticity is very simple; only the conceptual understanding is little involved; the same applies to refraction photoelasticity also, arithmetic is very simple.

Instead of finding out F sigma or F epsilon, we would find out what is K. By calibrating the coating material, you essentially find out K. And I also said, photoelastic coating can be applied from a range of material from rubber to high strength steel; rubber has a very low Young’s modulus and if I have a coating material, that should have much lower

Young’s modulus so that it does not reinforce the surface of the rubber. So, in those applications it may be proved on to directly take a tension specimen and pull it which is made of the coating material and find out F sigma, from there you find out K; ultimately you want to have K. Finally, you are going to develop an expression involving sigma 1 s minus sigma 2 s as the function of the fringe order observed and also the thickness of the coating and elastic properties of the base material will come, that will be the final expression; and what you need to see here is, K is much more fundamental in the case of photoelastic coating.

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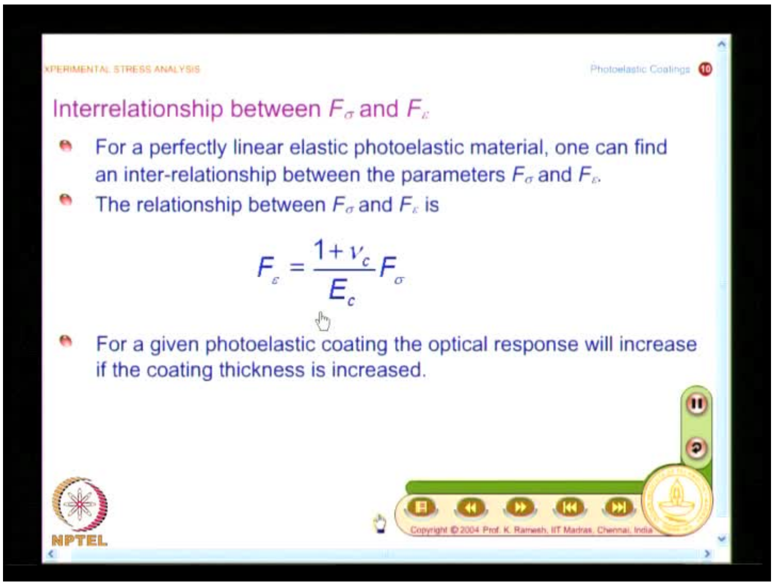

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 10

Interrelationship between F_σ and F_ε

- For a perfectly linear elastic photoelastic material, one can find an inter-relationship between the parameters F_σ and F_ε.
- The relationship between F_σ and F_ε is

$$F_\varepsilon = \frac{1+\nu_c}{E_c} F_\sigma$$

- For a given photoelastic coating the optical response will increase if the coating thickness is increased.

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And what is the inter relationship, because we all deal with isotropic material. For a perfectly linear elastic photoelastic material, one can find an inter relationship between the parameters F sigma and F epsilon, which is straight forward; it does not require any great mathematical skills. I can find out F epsilon as 1 plus nu c divided by E c into F sigma. So, what it shows is, if I find out F sigma, I can find out F epsilon; if I find out F epsilon, I can find out F sigma from this inter relationship; and that is what I said, when I have to go and find out the calibration constant for the coating that is to be applied on rubber, finding out F epsilon may not be practical; find out F sigma is more practical; you take the coating material, make a tension specimen and pull it, find out F sigma; find out what is the F epsilon from this inter relationship.

Once I know F epsilon, I can also report it what is the value of K, because I know F epsilon equal to lambda by K. And another basic observation is, why you want to have a thick photoelastic coating. See, I said number of fringes you generally see in a photoelastic coating test is small and if you want to apply any coating, it should be as thin as possible is desirable from analysis point of view. But from practical consideration point of view, I must see some fringes; if I do not see some fringes, how do I make measurement and there are also developments. See, the digital imaging hardware has also influenced photoelastic coating test; what I could not persive with human eye, I could do a very refine analysis with a digital photoelastic technique. So that also says I can go for a thinner coating; if I go for thinner coating, it is always advantageous by mathematics it becomes very simple; if I go for a thicker coating, I do not give up, but I bring in correction factor that is how engineers operate.

Correction factors are part and parcel of reflection photoelasticity; even for simple calculations, you have to bring in correction factors, but it is an engineering tool and has been solved for a variety of problems. Assembly stresses, see, you must have seen in several towns, they now put this central lighting, you have a huge pole that is put and you have a lamp on top of it and if you go and look at, how this lamp post is clamped to the ground, you have thick bowls and that had assembly stresses problem and this was sorted out by performing a photoelastic coating test. Now, it is well proven design, but when the initial design was developed by tighting those bowls, you had developed assembly stresses and eventually the failure of that pole was because of stresses introduced during assembly. See, assembly stresses how do you model analytically? You cannot model it easily; it is so difficult and photoelastic coating came to the rescue.

And another instance, where photoelastic came to the rescue was in the analysis of redder of a concede aircraft. The redder was failing repeatedly and what they found was, they had done a finite element analysis; they had also done a strain gauge analysis. The design was based on strain gauge analysis, but still the redder kept failing and strain gauge is a point by point technique; then people decided at why not apply a photoelastic coating on the redder, when they took the measurement, they found the location of the strain gauge was slightly away from the maximum stresses zone; so it was only reporting 75 percent of the stresses. So, you had an error in strain gauge value, because it is shifted away from the main point of interest; with photoelastic coating being a whole field technique, they could use that information and redesign the redder, and then it had fairly a good life.

So, if you look at photoelastic coating, it is a very industry friendly technique, like I said, it is only a tool; you should know how to employ the tool correctly. So, for those assemble stress problem, what you have as light poles, photoelastic coating helped and in many engineering applications you find.

So, you want to have sufficient optical response in a photoelastic coating test, if the coating thickness is increased, you get sufficient optical response, but when the coating thickness increases, interpretation becomes difficult. So, you have to have a tradeoff; you have to have a compromise; so that that is part and parcel of engineering. And you will see in correction factors what we will find out is, they will say that you put a coating of reasonable thickness over the over the specimen, find out packets of stress concentration, then peel of this coating and put a thinnest coating possible, because in a stress concentration, I already have sufficient stresses to develop sufficient number of fringes. So, this is how they handle the problem from engineering sense. Coating thickness is a nuisance, but without coating technique, I cannot see the fringes; so identify packets of high stress concentration, then redo the analysis with the thinner coating.

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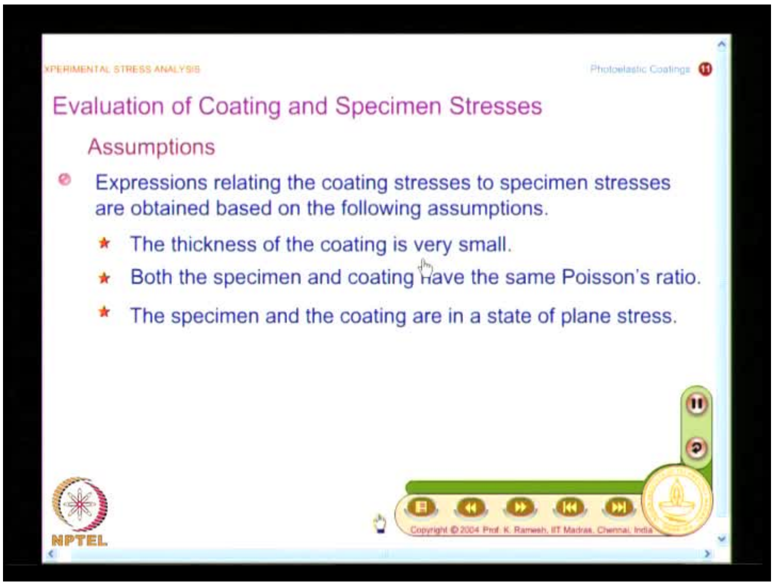
XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 11

Evaluation of Coating and Specimen Stresses

Assumptions

- Expressions relating the coating stresses to specimen stresses are obtained based on the following assumptions.
  - The thickness of the coating is very small.
  - Both the specimen and coating have the same Poisson's ratio.
  - The specimen and the coating are in a state of plane stress.

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Now, we look at what is the mathematics behind it, because the focus is evaluation of coating and specimen stresses and we have to make an assumption; without assumption, we cannot proceed; are we satisfying all the assumptions in the coating testing is what we have to examine. And just now I said, the thickness should be sufficient for me to see fringes, but when I do the analysis, I want to claim the thickness of the coating is very small; so this is the assumption that I make.

And I said, do not think when I make assumption, we are making a crime; is not so. I pointed out that, when the Young's modulus of coating material is much smaller than the base material, even though the thickness appears considerable, it really it does not reinforce. In certain class of problem, it affects; in certain class of problem, it is not a very serious mistake. So, the thickness of the coating is very small and I said in all the experimental methods, Poisson ratio will be a nuisance, and here, you assume both the specimen and coating have the same Poisson's ratio.

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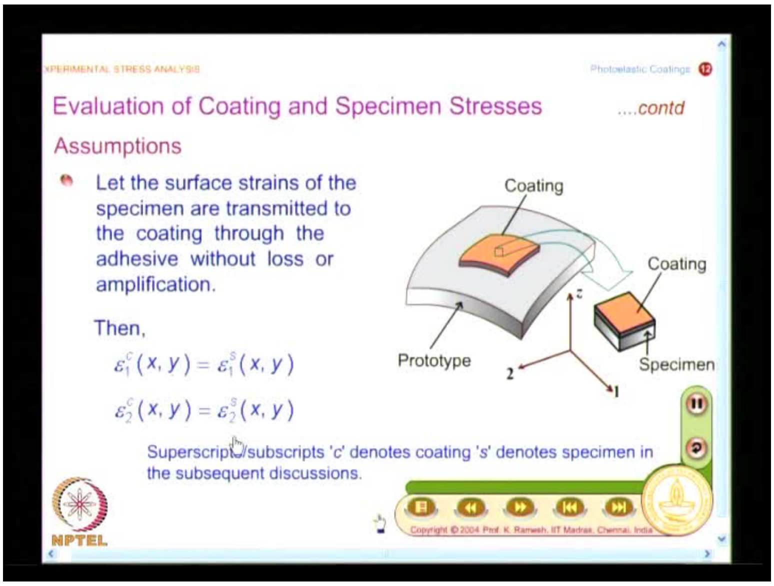

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 12

Evaluation of Coating and Specimen Stresses ....*contd*

Assumptions

- Let the surface strains of the specimen are transmitted to the coating through the adhesive without loss or amplification.

Then,

$$\varepsilon_1^c(x,y) = \varepsilon_1^s(x,y)$$

$$\varepsilon_2^c(x,y) = \varepsilon_2^s(x,y)$$

Superscripts/subscripts 'c' denotes coating 's' denotes specimen in the subsequent discussions.

And you know, polycarbonate we have seen, polycarbonate material property we saw, it has the Poisson ratio of 0. 28; many materials have 0.25, 0. 68 all this metallic materials and this is much closer. And poly carbonate is a very popular coating material in photoelastic coating also; second assumption also can be reasonably satisfied. The third assumption and the specimen and the coating are in a state of claim stress; that also can be easily satisfied is not a difficulty and what do we see? And we also have a very nice way of looking at it, I have this as the prototype that is given in a gray shade; on the prototype, I put a coating at a place of interest, which is large enough and I take a small element, which is shown here and I have a full freedom to select my access at the point of interest.

So, to minimize our mathematics, I take an access along the principle stress direction 1 and 2, and they also in isotropic material coincides with principle strain directions, and I take the thickness as, this as direction Z. And imagine, this coating is very large enough, this is not because it is a small place, it is represented; the representation is I have a prototype of some thickness on which a coating is put; I am looking at a small elemental area, where I have a coating as well as the specimen and what is the important assumption that I make. Which I have already mentioned it, I have an adhesive which is good enough such that the surface strains of the specimen or transmitted to the coating through the adhesive without loss or amplification.

And what I have? On the coating I will have a strain epsilon 1 c, which the function of (x, y); I will also have the strain epsilon 2 c, because I have taken my access of reference along the principle strain directions and if I have to say the surface trains are faithfully transmitted, what do I mean physically? I physically anticipate the strains in the coating and the strains in the specimen are identical. For a moment we close our eyes on mismatch of poisson ratio, but we have started the assumption, both have the same Poisson ratio, so that does not whatever happens to the specimen, happens to the coating also; if there is mismatch in Poisson ratio, I have to bring in a correction factor. This is what I said, while developing the basic equations, we make certain assumptions; but when we actually put the methodology in practice, I violate some of these assumptions because of exigency in the experiments, but I improve upon my results by bringing in correction factor.

So, what I am going to have is, I assume epsilon 1 c equal to epsilon 1 s, and epsilon 2 c equal to epsilon 2 s, this is what I am going to have. And what I have here? I have already mentioned, when I have a superscript or subscript with c denotes coating and s denotes specimen in all our subsequent discussions; we will have that symbolism followed.

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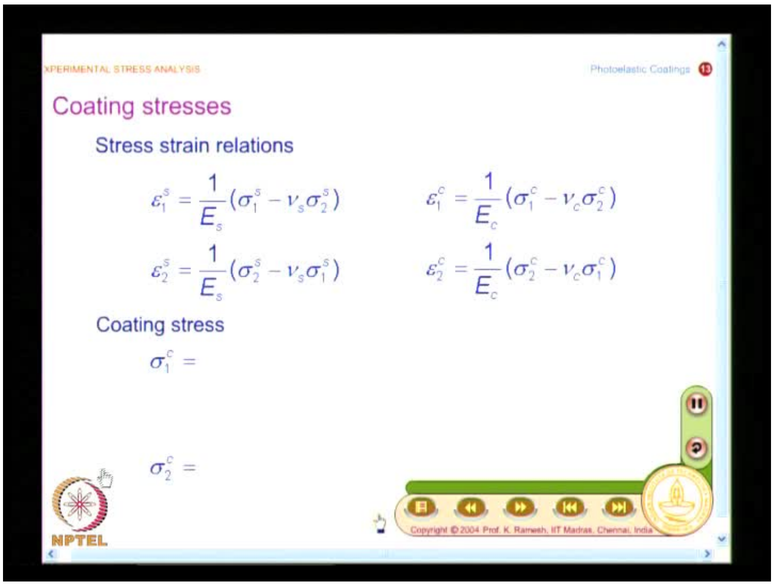

Coating stresses

Stress strain relations

$$\varepsilon_1^s = \frac{1}{E_s}(\sigma_1^s - \nu_s\sigma_2^s) \qquad \varepsilon_1^c = \frac{1}{E_c}(\sigma_1^c - \nu_c\sigma_2^c)$$

$$\varepsilon_2^s = \frac{1}{E_s}(\sigma_2^s - \nu_s\sigma_1^s) \qquad \varepsilon_2^c = \frac{1}{E_c}(\sigma_2^c - \nu_c\sigma_1^c)$$

Coating stress

$$\sigma_1^c =$$

$$\sigma_2^c =$$

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And what is my ultimate goal? My ultimate goal is, I have to find out the coating stresses and specimen stresses, how do I go about? I am just going to make a beginning of it and the later, you do the development at home and come back for the next class.

So, I can look at the stress strain relations and which you know very well. When I am also looking at a plane stress situation, I can write epsilon 1 as simply as 1 by E s sigma 1 s minus mu s sigma 2 s, these are all very well-known equations; epsilon 2 s as 1 by E s into sigma 2 s minus mu s sigma 1 s. On similar lines, I can also write epsilon 1 c, epsilon 2 c in terms of coating stresses and now, we have the basic assumption epsilon 1 c equal to epsilon 1 s; epsilon 2 c equal 2 s. Now, you have strain stress relations, what is the next step? You can find out the coating stresses as well as specimen stresses from all these quantities.

I have this epsilon 1 c like this and what I want you to go to the room, and then, work on what is the expression for sigma 1 c and sigma 2 c; it is fairly simple and straight forward, take it as a home exercise. When you for the next class, give me the expression for sigma 1 c and sigma 2 c in terms of the Poisson ratio of the coating specimen and also the specimen stresses and this expressions will be same when I go and see brittle coatings. In brittle coating, we will handle them individually; in photoelasticity what we get? We always get only principle stress difference or principle strain difference that is where the whole thing changes.

So, in this class what we have looked at is, I said photoelastic coating has made application of photoelasticity to industrial problems very attractive and I said it is a very nice engineering tool and approximation start write from data recording. Because in transmission photoelasticity, we wanted normal incidents; we maintained that even in three dimensional photo elasticity; even if I analyze a three dimensional model, though I have not mentioned it explicitly, I may immerse it in a liquid, which has a same refractive index, and then, when I put the ray of light, it will still write in a normal incidents. Though the model is complicated shade, the moment I come to reflection photoelasticity, because I have to look at the reflected light, I compromise on normal incidents and in order to simplify that or minimize whatever the error introduced, one of the requirement is I keep the polariscope for away from the model so that I reduce the angle of oblique.

Then we looked at what is a strain optic relation and I said, what is the interrelationship between F sigma and F epsilon, and then, we moved on to look at, how to find out this specimen stresses. And specimen stresses, you have to find out first from coating stresses, determine the coating stresses, from coating stresses go on to specimen stresses and what is the basic assumption? The strains are faithfully transmitted and you will have to go and get me the expression for sigma 1 c and sigma 2 c is very simple arithmetic; if you do it at your rooms, your preparations for examinations becomes very simple and this is fundamental for any of the coating techniques. Thank you.