Experimental Stress Analysis

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Module No. # 04

Lecture No. # 28

Coating Materials, Selection of Coating Thickness, Industrial Application of Photo-elastic Coatings

Let us continue our discussion on reflection photo-elasticity. I said this technique has been really used for solving several problems of practical interest. The methodology requires use of correction factors, because I mentioned, we make several approximation in the theoretical development, and also in optical arrangement we compromise on pure normal incidents; a small angle of oblique comes into the picture and I also said that this is applicable for a variety of materials ranging from rubber to bone to composites to high strength alloys.

So, the range and versatility, these are the two key factors, and even now for some of the current problems, people employ and go to photo-elastic coating and find out how to get the pertinent information for design. And mind you, whoever does original design, they need all these experimental methods; if somebody copies the design, he does not requires anything; when you are making your own design, you need to verify, whether whatever the kind of procedures that you have adopted has come and useful for arriving at a right kind of design for a given problem.

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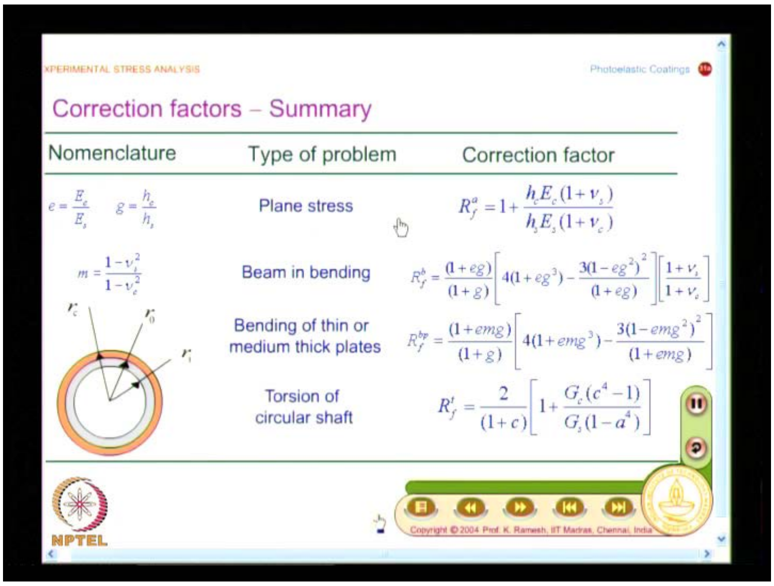

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings

Correction factors – Summary

Nomenclature	Type of problem	Correction factor
$e = \frac{E_c}{E_s}$ $g = \frac{h_c}{h_s}$	Plane stress	$R_f^a = 1 + \frac{h_c E_c (1+\nu_s)}{h_s E_s (1+\nu_c)}$
$m = \frac{1-\nu_s^2}{1-\nu_c^2}$	Beam in bending	$R_f^b = \frac{(1+eg)}{(1+g)}\left[4(1+eg^3) - \frac{3(1-eg^2)^2}{(1+eg)}\right]\left[\frac{1+\nu_s}{1+\nu_c}\right]$
	Bending of thin or medium thick plates	$R_f^{bp} = \frac{(1+emg)}{(1+g)}\left[4(1+emg^3) - \frac{3(1-emg^2)^2}{(1+emg)}\right]$
	Torsion of circular shaft	$R_f^t = \frac{2}{(1+c)}\left[1 + \frac{G_c(c^4-1)}{G_s(1-a^4)}\right]$

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We will look at, what are the correction factor we looked at and this is more of a summary depending on the type of problem, whether it is plane stress, beam in bending or bending of thin or medium thick plates and torsion of circular shaft. You have the correction factors available here and we have this as R f a, where a denotes that you are looking at axial loading and this is labeled as R f b; b denotes a bending and this is R f b p to distinguish from bending of beams; to bending of plates, you have this as b p, and R f t is used for torsion.

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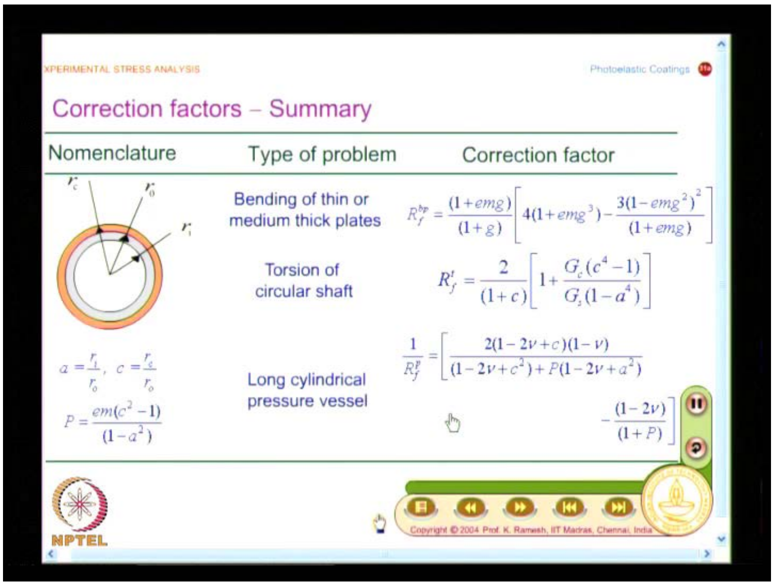

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings

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	Torsion of circular shaft	$R_f^t = \frac{2}{(1+c)}\left[1 + \frac{G_c(c^4-1)}{G_s(1-a^4)}\right]$
$a = \frac{r_i}{r_o}$, $c = \frac{r_c}{r_o}$ $P = \frac{em(c^2-1)}{(1-a^2)}$	Long cylindrical pressure vessel	$\frac{1}{R_f^p} = \left[\frac{2(1-2\nu+c)(1-\nu)}{(1-2\nu+c^2)+P(1-2\nu+a^2)} - \frac{(1-2\nu)}{(1+P)}\right]$

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In all this expression you know, in order to simplify, you are writing, we have used e as ratio of Young’s modulus and G as ratio of thickness and m as 1 minus nu s square divided by 1 minus nu c square. And I said that, you also have the correction for pressure vessels, because many engineering applications could be modeled as a pressure vessel. And here, it is written as 1 by R f p and you also have the definition of a, and c and also you have the definition of what is the symbol P used in this expression.

And you have to understand, these correction factors are applicable in region away from stress concentration; when there is abrupt changes in the thickness, then also these correction factors are not valid. The idea here is, when you have a real problem on hand, apply a coating of a reasonable thickness so that you find out, which are all the regions you have high stress gradients, identify those region, then strip this thick coatings, and then, put a thin coating.

So, you avoid the use of correction factors in stress concentration zones, because if coating is thin enough, then correction factor importance also diminished. So that is the way you circumvent. When you have to analyze complex problems, you have an engineering approach to utilize in the technique.

When you look at the correction factor for long cylinder pressure vessel, they are very important when you are looking at tubing, not for large pressure vessels. You know, you have a heat exchanger, where you have tubing and for these tubes, people have analyzed and particularly in nuclear industry, you have to be very careful. So, in high pressure tubing, the use of correction factors is very important.

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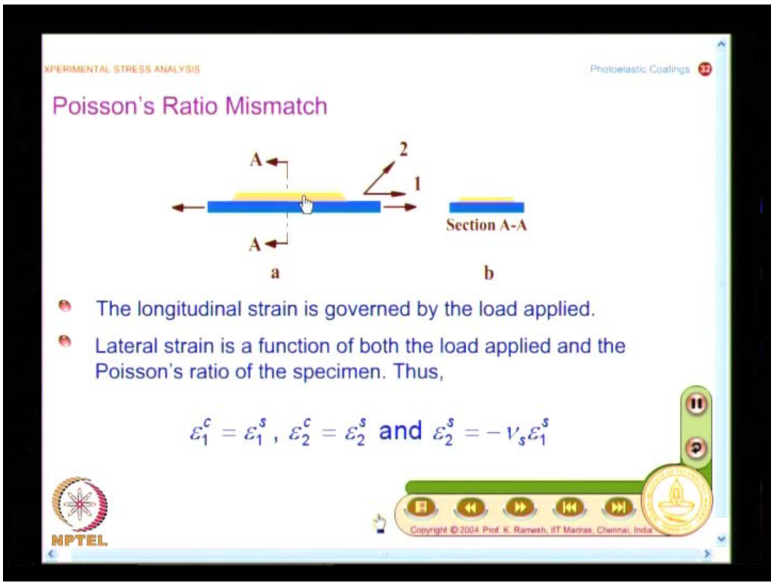

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 32

Poisson's Ratio Mismatch

- The longitudinal strain is governed by the load applied.
- Lateral strain is a function of both the load applied and the Poisson's ratio of the specimen. Thus,

$$\varepsilon_1^c = \varepsilon_1^s \text{ , } \varepsilon_2^c = \varepsilon_2^s \text{ and } \varepsilon_2^s = -\nu_s \varepsilon_1^s$$

I also mention that, you need to look at, how to handle mismatch of Poisson's ratio that is what will take it up now? And let us understand the mismatch of Poisson's ratio, how does this affect? So, what is shown here is, I have a simple specimen subjected to uniaxial tension, I take axis 1 along this specimen; I take axis 2 transverse to the specimen and I have a photo-elastic coating pasted on this and if you take a section here, I show the section will look something like this; it is deliberately shown that you have this coating interior; it is not extended to the full length to illustrate the point and what happens? When I apply a longitudinal load, the strain in the direction is completely governed by the load applied.

And you know, I have always been saying, when you are dealing with strain, you should understand that is stress is uniaxial, but strain in general is biaxial or triaxial depending on the kind of specimen that you are looking at. If you want to have uniaxial strain, then you have to make special efforts to constraint the edges appropriately. Uniaxial stress is simple; uniaxial strain is not simple and what you should look at here is, I have applied a uniaxial loading, stress is uniaxial, but strain is biaxial.

So, the longitudinal strain is governed by the applied load, whereas the lateral strain is a function of both the load applied and the Poisson's ratio of the specimen. So, what I have here is epsilon 1 c equal to epsilon 1 s, there is no problem; and we have epsilon 2 c is also equal to epsilon 2 s, because we assume that the bonding of the coating is very carefully done so that whatever the strains developed in the specimen are faithfully transmitted to the coating; if the coating is very thin, then you do not have much of a problem and we are talking about a finite thickness coating.

So, I can think of a surface which is bonded to the specimen and a surface which is free; the top surface of the coating is free. So, if you look at what happens at the bonded surface, then epsilon 2 s is actually minus nu s times epsilon 1 s and this will be equal to the coating strain, no problem, but what happens on the top surface?

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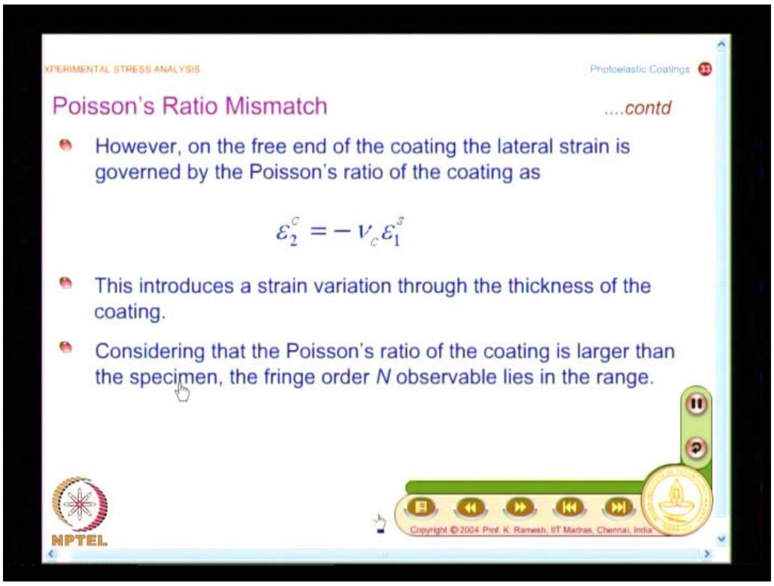

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 33

Poisson's Ratio Mismatch

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- However, on the free end of the coating the lateral strain is governed by the Poisson's ratio of the coating as

$$\varepsilon_2^c = -\nu_c \varepsilon_1^s$$

- This introduces a strain variation through the thickness of the coating.
- Considering that the Poisson's ratio of the coating is larger than the specimen, the fringe order *N* observable lies in the range.

On the top surface, the strain is related to nu c times epsilon 1 s, so this is the difference; see these are all second order effects. When you are developing a methodology, before we neglect certain aspects, we should also analyze and find out what is its influence. After your analysis, you find that influence is small enough, and then you can label it as second order effects, and then, carry on with your analysis. So, in order to appreciate what happens when there is a mismatch of Poisson's ratio, what we find is, there could be a strain variation through the thickness of the coating. Because you have a surface bonded to the specimen, where you will have only nu s, but when the surface is free on the other end of the thickness, it is governed by the Poisson's ratio of the coating.

See, we saw in the case of coating applied to bending problems or torsion problems, there was a strain variation in the coating was seen mainly because of the way the model or the prototype was loaded; you had a strain variation that is acceptable. But you can also have a small variation of strain through the thickness if there is a mismatch of Poisson’s ratio, this is one aspect of it; the other aspect is, when I have free edges, there also you have to bring in the Poisson’s ratio of the coating in your analysis.

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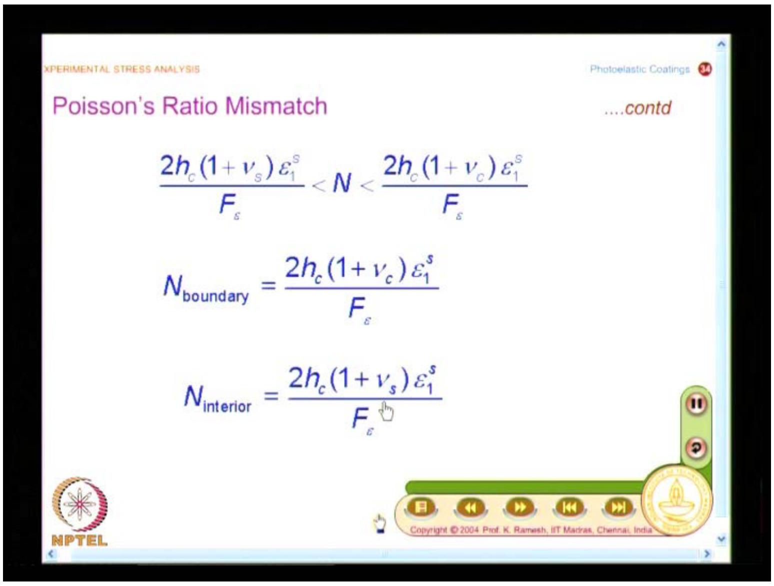

Poisson's Ratio Mismatch

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$$\frac{2h_c(1+\nu_s)\,\varepsilon_1^s}{F_\varepsilon} < N < \frac{2h_c(1+\nu_c)\,\varepsilon_1^s}{F_\varepsilon}$$

$$N_{\text{boundary}} = \frac{2h_c(1+\nu_c)\,\varepsilon_1^s}{F_\varepsilon}$$

$$N_{\text{interior}} = \frac{2h_c(1+\nu_s)\,\varepsilon_1^s}{F_\varepsilon}$$

And you know, people have done studies, and then, looked at what way one has to consider this, in which region Poisson’s ratio is important and for all this, we have also seen from the material property, the Poisson’s ratio of the photo-elastic material are in general larger than the specimen material. If you are looking at metallic specimens and what you have is, the fringe order n observable lies in the range. Straight forward application of your strain optic law, I do not know how many of you are able to see this, I will have epsilon 1 minus epsilon 2 as N F epsilon by 2 h c and this epsilon 1 minus epsilon 2 is written in this fraction here; because I know epsilon 1 s minus nu s epsilon 1 s, because epsilon 2 s is minus nu s epsilon 1 s. So, in one case, it may be controlled by the Poisson’s ratio of the specimen; in another case, it can be controlled by the Poisson’s ratio of the coating.

So, the N will have a range on the one end dictated by the Poisson’s ratio of the specimen; on the other hand, it is dictated by the Poisson’s ratio of the coating. So, you define what is a boundary fringe order. It is given as 2 h c into 1 plus nu c into epsilon 1 s divided by F epsilon and I can also write what is the interior fringe order. It is given as

2 h c into 1 plus nu s epsilon 1 s divided by F epsilon, this is the material strain fringe value.

So, what do you need to recognize is, Poisson’s ratio mismatch can give problems; whether the problem is significant or not is what you have to look at, and people have also done systematic experiments, and then, established how you can accommodate the Poisson’s ration mismatch.

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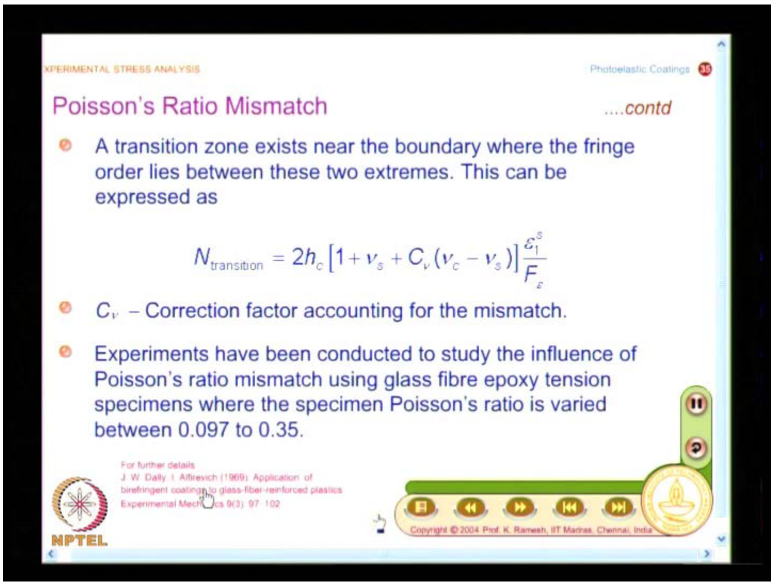

Poisson’s Ratio Mismatch ....contd

- A transition zone exists near the boundary where the fringe order lies between these two extremes. This can be expressed as

$$N_{\text{transition}} = 2h_c\left[1+\nu_s+C_\nu(\nu_c-\nu_s)\right]\frac{\varepsilon_1^s}{F_\varepsilon}$$

- C_ν – Correction factor accounting for the mismatch.
- Experiments have been conducted to study the influence of Poisson’s ratio mismatch using glass fibre epoxy tension specimens where the specimen Poisson’s ratio is varied between 0.097 to 0.35.

For further details
J. W. Dally, I. Alfirevich (1969). Application of birefringent coatings to glass-fiber-reinforced plastics, Experimental Mechanics 9(3): 97-102

So, what we have looked at earlier was, you had fringe orders different at the boundary and the interior; when you have a difference, there has to be a transition zone. So, people have identified a transition zone exists near the boundary, where the fringe order lies between the two extremes, which we saw earlier. And this can be expressed as N transition and that given as 2 h c into 1 plus nu s plus C v, where C v is the correction factor accounting for the mismatch; C v multiplied by nu c minus nu s the whole of it multiplied by epsilon 1 s divided by F epsilon.

And this is what I said, that experiments have been conducted by researchers and you know, if you want to study the influence of Poisson’s ratio, the best kind of specimen you can think of is composites. Because when I have a composite, I can change the volume fraction of the fiber by which I can change the Poisson’s ratio of the composite specimen comfortably and this is what was done. So, the glass fiber epoxy tension specimens, where the specimen Poisson’s ratio is varied between 0.097 to 0.35.

When you use a composite by changing the volume fraction of the fiber, it is possible to change the Poisson's ratio and further details you know, you could get it from reference here, it is by Dally and Alfirevich, it was published in 1969. You have application of birefringent coatings to glass fiber reinforced plastics in fact, you have very nice pictures and there also given thumb rules depending on the coating thickness what is the size of the transition zone and so on and so forth.

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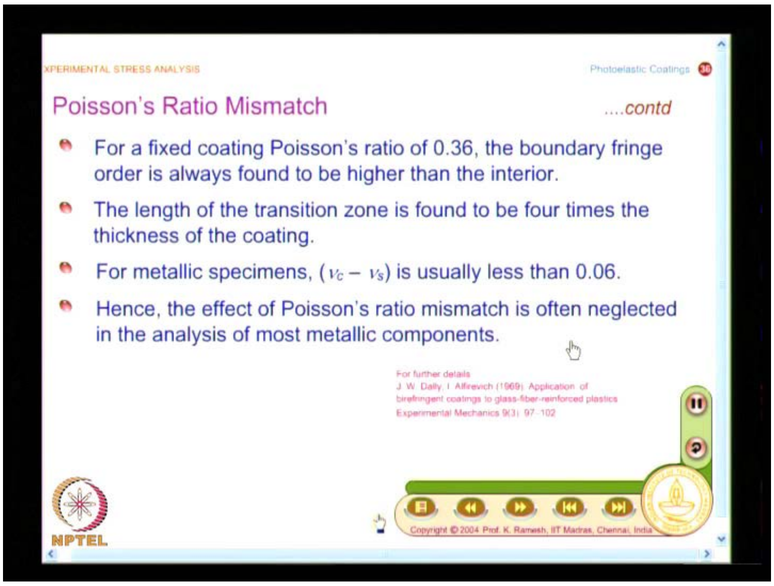

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 36

Poisson's Ratio Mismatch

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- For a fixed coating Poisson's ratio of 0.36, the boundary fringe order is always found to be higher than the interior.
- The length of the transition zone is found to be four times the thickness of the coating.
- For metallic specimens, ($\nu_c - \nu_s$) is usually less than 0.06.
- Hence, the effect of Poisson's ratio mismatch is often neglected in the analysis of most metallic components.

For further details
J. W. Dally, I. Alfirevich (1969) Application of birefringent coatings to glass-fiber-reinforced plastics
Experimental Mechanics 9(3): 97–102

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What is that implications when you want to do experiments? And this is what you see here and what they have found is, for a fixed coating Poisson's ratio of 0.36 which is reasonable to assume, the boundary fringe order is always found to be higher than the interior; it is mainly because of the Poisson's ratio mismatch and the length of the transition zone is found to be four times the thickness of the coating, So, this is the contribution by the experiments conducted by Dally and Alfirevich, they have also established the size of the transition zone; it is the function of the coating thickness and what you actually have to look at is, what is the change in the Poisson's ratio. You know, metallic specimens, the Poisson's ratio is around 0.26, 0.24 to 0.26 is what you have.

So, typically the Poisson's ratio difference nu c minus nu s is usually less than 0.06. So, the final conclusion is, for most metallic components the effect of Poisson's ratio mismatch is often neglected (( )). Because before we establish that this is the second order effect, we must do an analysis and then only say Poisson's ratio mismatch can give you problems, but the level of influence is smaller. So, you can neglect it for metallic specimens when you do for photo-elastic coating testing analysis.

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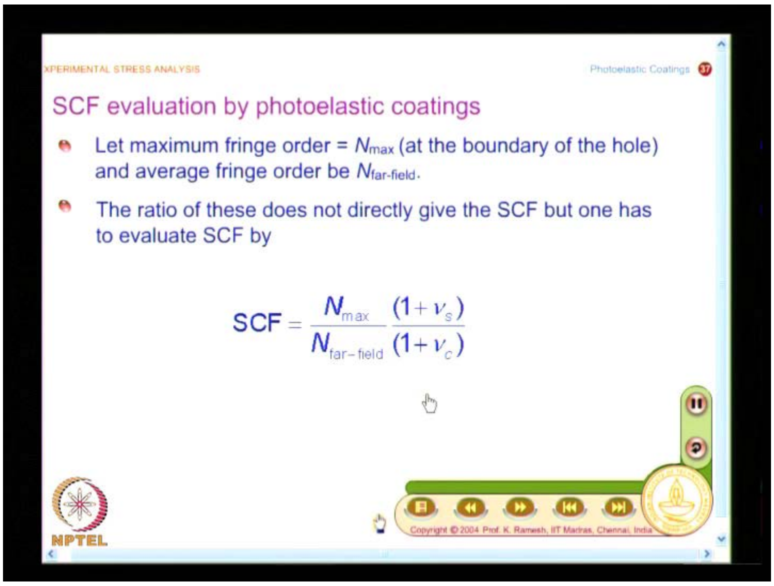

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 37

SCF evaluation by photoelastic coatings

- Let maximum fringe order = $N_{\max}$ (at the boundary of the hole) and average fringe order be $N_{\text{far-field}}$.
- The ratio of these does not directly give the SCF but one has to evaluate SCF by

$$\mathrm{SCF} = \frac{N_{\max}}{N_{\text{far-field}}}\frac{(1+\nu_s)}{(1+\nu_c)}$$

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However, when we go and do the SCF evaluation that is what I said, when you want to find out this stress concentration factor, photo-elasticity is a very simple approach to find out stress concentration factor and what we need in transmission photo-elasticity is, you need to find out N max and N far-field and the ratio directly gives you the stress concentration factor, but in view of the Poisson's ratio mismatch, you have to modify this expression slightly.

So, that is what you see here. So, stress concentration factor if I use photo-elastic coatings, you have to have N max divided by N far-field which is multiplied by 1 plus nu s dived by 1 plus nu c. So, the Poisson's ratio of this specimen as well as Poisson's ratio of the coating influences your final result. So, if you do not do this correction, if you have a finite element analysis and evaluate the stress concentration factor, it will not match. Because essentially you are going to find out SCF for finite body problems, for all finite body problems either you have to depend on a numerical approach or an experimental approach. Analytical approach you will have stress concentration factor only for an infinite geometry; do not think for all holes, stress concentration factor is 3, that was developed in theory of elasticity for an infinite plates with the small holes. When you go to actual problem, you have a finite plate with finite sized holes in general stress concentration factors are much higher than 3 and there is also a suttle difference. In the case of theory of elasticity, you define stress concentration factor as maximum stress divided by far field stress that will be 3 for an infinite plate with small hole; for a finite plate, it will be greater than 3. But if you go and look at design codes, they are defining stress concentration factor slightly differently; they would define stress concentration factor as maximum stress divided by the ligament stress, because that is what you can estimate for a finite body comfortably and when the size of the hole keeps increasing, the ligament stress also will keep increasing.

So, what you will essentially find is, stress concentration factor will hover around 2, 2.2, 2.3 and so on. You should not wrongly conclude area of elasticity gives me 3, whereas design book gives me less than 3, so, I can always use 3 as the conservative value for my design, and then your design will fail. Because many people do not know, this is a certain difference, there is a definition shift between designers how they define stress concentration factor and how do define stress concentration factor in analytical development; you should know the difference; half break knowledge can always give you problem.

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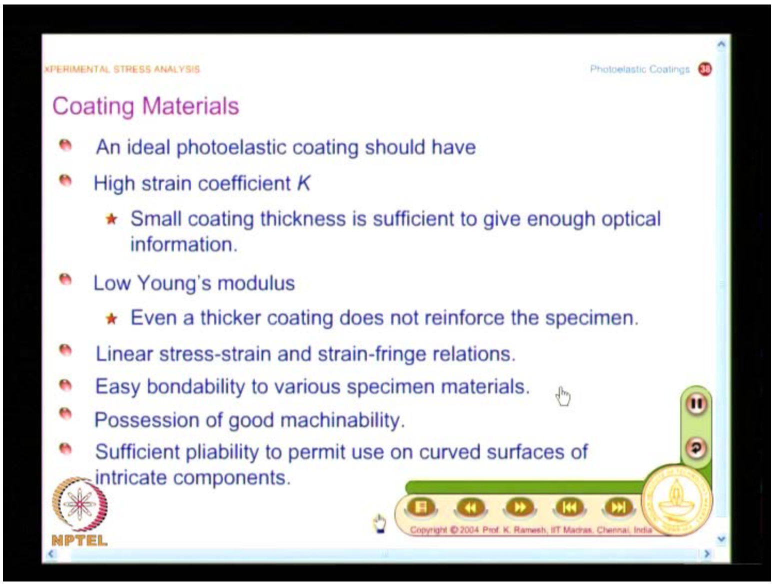

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 38

Coating Materials

- An ideal photoelastic coating should have
- High strain coefficient *K*
    - ★ Small coating thickness is sufficient to give enough optical information.
- Low Young's modulus
    - ★ Even a thicker coating does not reinforce the specimen.
- Linear stress-strain and strain-fringe relations.
- Easy bondability to various specimen materials.
- Possession of good machinability.
- Sufficient pliability to permit use on curved surfaces of intricate components.

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So, you have to very careful when you want to find out SCF in photoelastic coatings this also put this correction factor; this comes from mismatch of Poisson's ratio and what should be the property of ideal photoelastic coating should have? Obviously, we want to have high strain coefficient K; the reason is I need to get enough optical response and we have also seen, if the coating is thin enough, I do not that worry about the correction factor, which is automatically taken care of; only when the coating thickness is considerable, then correction factors are very important. So, from that point of view, you want to have high strain coefficient K and the reason is small coating thickness is sufficient to give enough optical information.

And you want to have low Young’s modulus, because you do not want this to reinforce the specimen, and you want to have a linear stress strain and strain fringe relations so that interpretations becomes lot more simpler; easy bond ability to various specimen materials, because we had seen earlier, people used glass, it was difficult to bond and it should also have capacity for good machinability and particularly when I want to go for complex industrial components, the coating material should have pliability for me to form the shell of the actual object. In fact I would try to show you some practical examples let us been reported in the literature to give you a flavor how this methodology is relevant even today for solving complex problems that will also give a motivation that to learn this techniques and also if opportunities exist for you to apply.

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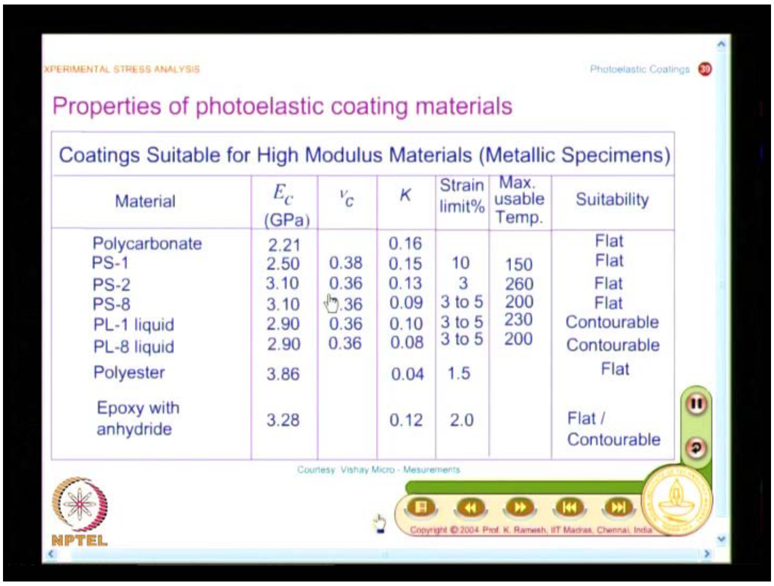

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 39

Properties of photoelastic coating materials

Coatings Suitable for High Modulus Materials (Metallic Specimens)

Material	E_c (GPa)	ν_c	K	Strain limit%	Max. usable Temp.	Suitability
Polycarbonate	2.21		0.16			Flat
PS-1	2.50	0.38	0.15	10	150	Flat
PS-2	3.10	0.36	0.13	3	260	Flat
PS-8	3.10	.36	0.09	3 to 5	200	Flat
PL-1 liquid	2.90	0.36	0.10	3 to 5	230	Contourable
PL-8 liquid	2.90	0.36	0.08	3 to 5	200	Contourable
Polyester	3.86		0.04	1.5		Flat
Epoxy with anhydride	3.28		0.12	2.0		Flat / Contourable

Courtesy Vishay Micro - Mesurements

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Obviously, you will not have all these properties available in a single material. So, you have to have a trade of and you have to do compromise, these are all the desirable requirements. And what you have is, I said that the Young’s modulus is very key factor, because we do not want this to reinforce specimen. So, you have coatings available separately for high modulus materials and if you look at the Young’s modulus, it is around 3 GPa, whereas all your materials when you have metallic materials, they have aluminum is 70 GPa and steel is 2 10 GPa. So, if you have a coating which is 3 GPa, it will not reinforce that, so I can comfortably use photo-elastic coating. And from this table, you will write only two materials: one is polycarbonate, another is PS-1, and this is also commercially available Vishay Micro-Measurements.

And what do you need look at is, K is around 0.16; 0.1 is what you see by enlarge most of the materials and strain limit is, it can go up to 10 percent of strain and because these are all plastics, you cannot go beyond maximum of 260 degree centigrade and you also have whether they can be available in flat sheets or contourable form; when you have a contourable form, you essentially have a liquid, you casted in your own laboratory or I also said that, with advancement technology, people also give you the sheets in gel state properly preserved with dry ice and it is available for a high price.

So, you could also get them, but that is contourable and this is needed for complex industrial components and what do you need to look at here is, for high modulus materials, the recommended coating have Young’s modulus around 3 GPa and Poisson’s ratio is around 0.36, that is how all the materials you have and mostly metallic materials, it will hover between 0.24 to 0.26 or 0.28.

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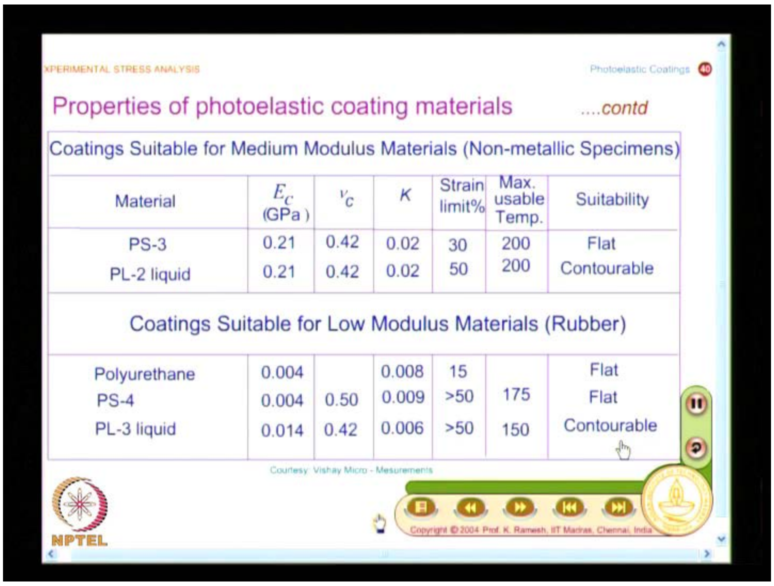

Properties of photoelastic coating materials ....contd

Coatings Suitable for Medium Modulus Materials (Non-metallic Specimens)

Material	E_C (GPa)	ν_C	K	Strain limit%	Max. usable Temp.	Suitability
PS-3	0.21	0.42	0.02	30	200	Flat
PL-2 liquid	0.21	0.42	0.02	50	200	Contourable

Coatings Suitable for Low Modulus Materials (Rubber)

Material	E_C (GPa)	ν_C	K	Strain limit%	Max. usable Temp.	Suitability
Polyurethane	0.004		0.008	15		Flat
PS-4	0.004	0.50	0.009	>50	175	Flat
PL-3 liquid	0.014	0.42	0.006	>50	150	Contourable

Courtesy: Vishay Micro - Mesurements

So, this is how you have to look at the relevance of these numbers. And when I go to low modulus materials and I have medium modulus materials separately and I have low modulus materials finally like rubber. So, you have special material available from Vishay Micro-Measurements, which is available at a Young’s modulus of 0.21 GPa and you have strain limit of about 30 percent and if you look at K for this, it is considerably reduced to 0.02.

Finally, when you come to rubber and here, we have to be very careful. See, you think rubber does is it requires any analysis. In fact, if you look at tires which are used in aircraft, very complex design, they are like layer composite, you have reinforcements and during landing and takeoff, tires play a very important role and they have to withstand the entire weight and impacts load and tire design is very complex. Do not think because you use tires in your cycles, and then, you also use many of your common day to day applications, many times familiarity brings as if you know everything about it. In fact, tire design is very complex from material modeling point of view, from fabrication point of view and also from analysis point of view. So, you need to analyze rubber also. So, in tire applications you have to be careful in selecting a suitable coating.

So, what you have here is, it is a low modulus materials and I choose a coatings which has a very small Young’s modulus; it is 0.004 GPa, polyurethane, PS-4. And when you look at strain limits, because rubber it can have a very large strain, so these are available greater than 50 percent, applicable even for greater than 50 percent and also you have flat and contourable type of classification. So, what you need to keep in mind is, for different type of specimen materials, you have variety of coatings available and you have to pick and choose. See, if I use high modulus material coating to a low modulus material, then I would be making a mistake, because the coating will reinforce this specimen. So, what will you have to be carefully is, you need to choose the appropriate material. So, you have a catalogue available, utilize the catalogue properly.

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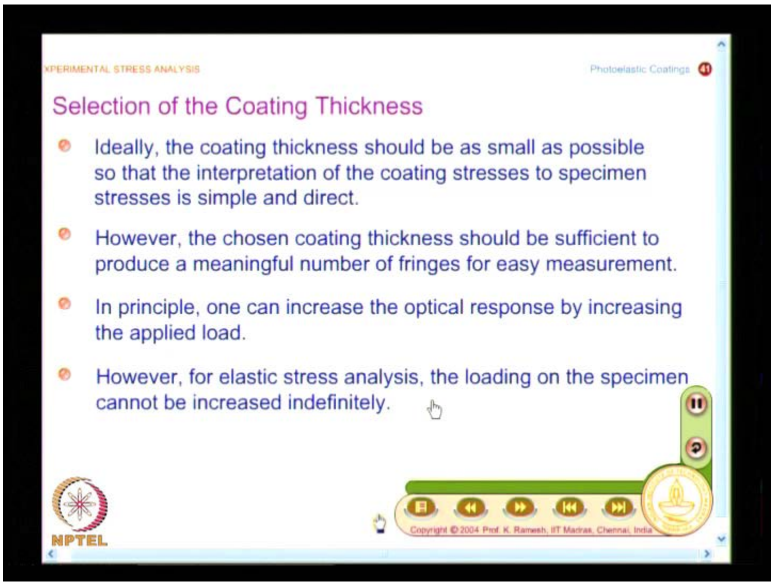

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 41

Selection of the Coating Thickness

- Ideally, the coating thickness should be as small as possible so that the interpretation of the coating stresses to specimen stresses is simple and direct.
- However, the chosen coating thickness should be sufficient to produce a meaningful number of fringes for easy measurement.
- In principle, one can increase the optical response by increasing the applied load.
- However, for elastic stress analysis, the loading on the specimen cannot be increased indefinitely.

I also mentioned, there is an issue of selection of coating thickness. Ideally, I want the coating thickness should be as small as possible. We said, we want to have a very high value of K, then I can have coating thickness as small as possible and we also want to have the chosen coating thickness should be sufficient to produce the meaningful number of fringes for easy measurement.

We have seen in transmission photo-elasticity, by increasing the model thickness, I can increase the number of fringes. The same philosophy also applies here; if I do not have sufficient optical response, I cannot make measurement. So, in order to make measurement, I can increase the thickness of the coating that is one method; the other point of approach is by increasing the applied load. Increasing the applied load, I cannot do it comfortably beyond a limit. In the case of metallic components, when I do an elastic stress analysis, because if I increase the load, the specimen starts yielding; you do not want the specimen to yield in normal service condition, so there is an upper limit by which I can load it.

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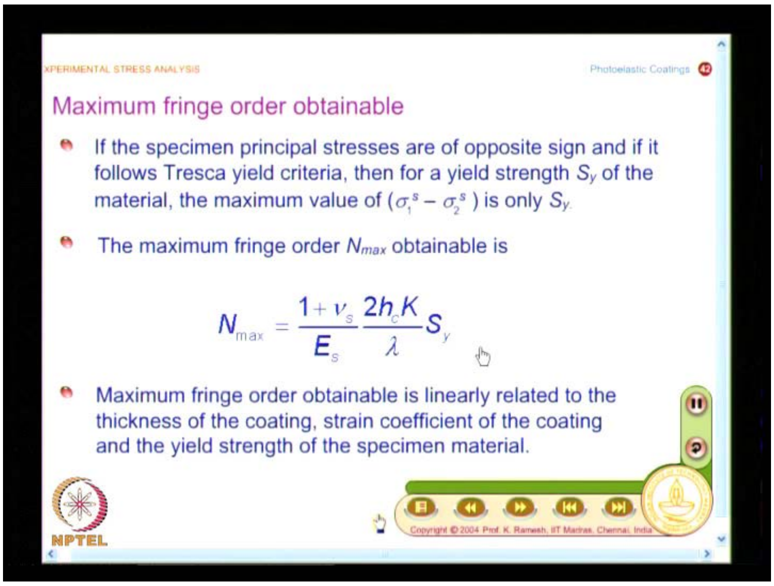

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 42

Maximum fringe order obtainable

- If the specimen principal stresses are of opposite sign and if it follows Tresca yield criteria, then for a yield strength S_y of the material, the maximum value of $(\sigma_1^s - \sigma_2^s)$ is only S_y.
- The maximum fringe order N_{max} obtainable is

$$N_{\max} = \frac{1+\nu_s}{E_s}\frac{2h_c K}{\lambda}S_y$$

- Maximum fringe order obtainable is linearly related to the thickness of the coating, strain coefficient of the coating and the yield strength of the specimen material.

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So, one of the issue talked about in photo-elastic coating analysis is, what are the maximum fringe orders obtainable, it is an issue. That is why we will look at what is the selection of coating thickness, we want to have a tradeoff between optical response and use of correction factors or reinforcement effect and also look at what way the analysis influences it. I am essentially looking at an elastic stress analysis and from the equations we can go back and find out, what is the maximum fringe order obtainable and that is what is given here. So, what you have here is, essentially we are going to get sigma 1 s minus sigma 2 s. And suppose I consider that, these principle stresses are of opposite sign and suppose the material follows tresca yield criteria, then for a yield strength S y of the material, the maximum value of sigma 1 s minus sigma 2 s is only S y.

So, from this, if I go back and find out what is the expression for principles stress difference, recast that expression. So, you have maximum fringe order obtainable is a function of Poisson ratio of the material, Young’s modulus of the material and also the yield strength of the material. So, what I find here is, if I am working on high strength alloys, I can have very high fringe orders; low strength alloys, the maximum fringe order obtainable is small and most of your aerospace and nuclear application you use high strength alloys. So, you will have reasonable fringe orders seen in those structures.

Suppose I want to apply it on mild steel, that is also need to be analyzed when you make the component out of mild steel, that also needs to be analyzed; you will not have very high fringe orders. So, that we can actually calculate for a given coating material, for different specimen material what is an maximum fringe order obtained.

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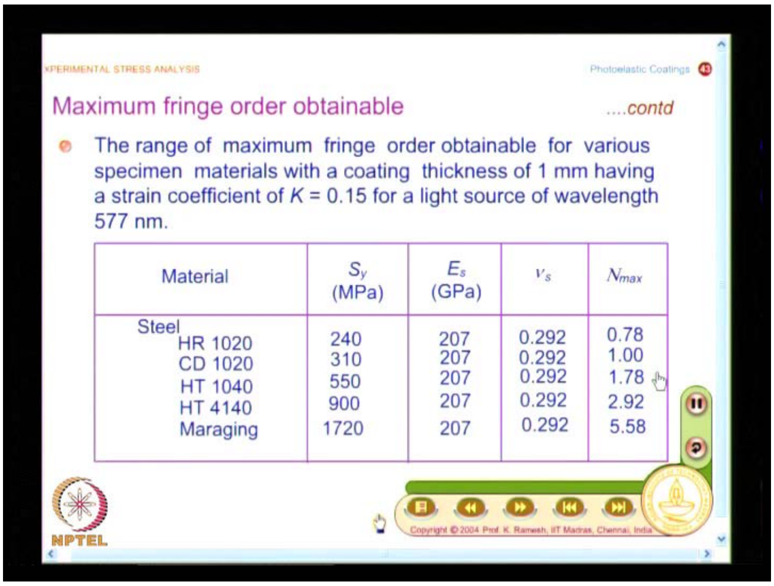

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 43

Maximum fringe order obtainable ....*contd*

- The range of maximum fringe order obtainable for various specimen materials with a coating thickness of 1 mm having a strain coefficient of $K = 0.15$ for a light source of wavelength 577 nm.

Material	S_y (MPa)	E_s (GPa)	ν_s	N_{max}
Steel				
HR 1020	240	207	0.292	0.78
CD 1020	310	207	0.292	1.00
HT 1040	550	207	0.292	1.78
HT 4140	900	207	0.292	2.92
Maraging	1720	207	0.292	5.58

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So, I have this expression N max equal to 1 plus nu s divided by E s into 2 h c in to K that is the strain coefficient of the coating material and you have the wavelength dependence and you have this as S y as the yield strength of the specimen material. And I also have a table which gives you for a variety of materials what is the fringe order obtainable and what you have is, we have taken a coating material of K equal to 0.15 and for a coating thickness of 1 millimeter and for a light source of wave length 577 nanometers, essentially the white light you had also looked at the color code, where we saw repetition occurs at 577 nanometers; you have a tined of passage and twice of this value you have another tined of passage and what you need to look at here is, I have the yield stress tabulated here and yield strength is increasing and for a HR 1020 steel, the maximum fringe order obtainable is only 0.78, whereas on a maraging steel, it is about 5.58.

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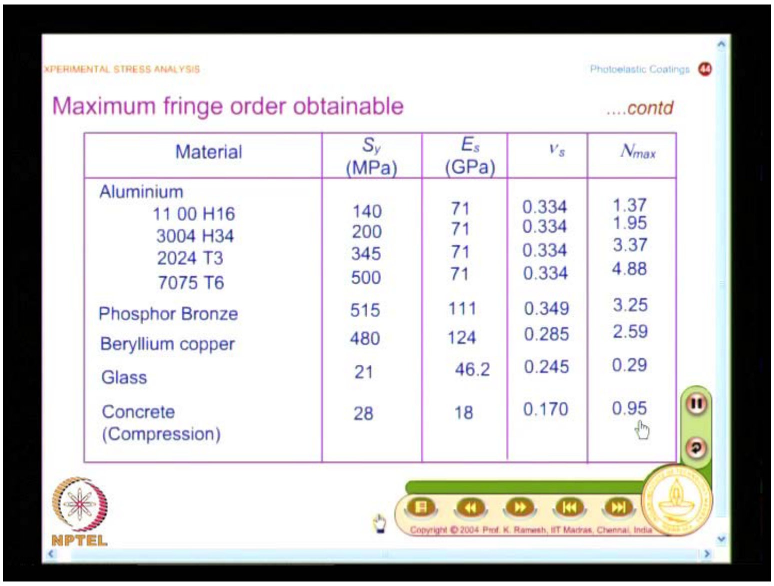

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 44

Maximum fringe order obtainable ....contd

Material	S_y (MPa)	E_s (GPa)	ν_s	N_{max}
Aluminium				
11 00 H16	140	71	0.334	1.37
3004 H34	200	71	0.334	1.95
2024 T3	345	71	0.334	3.37
7075 T6	500	71	0.334	4.88
Phosphor Bronze	515	111	0.349	3.25
Beryllium copper	480	124	0.285	2.59
Glass	21	46.2	0.245	0.29
Concrete (Compression)	28	18	0.170	0.95

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So, if I am working on high strength alloys, it will be very similar to what I see in the case of transmission photo-elasticity; I will see rich colors. But a thumb rule is, if you see rich colors, you have very high values of stress, you should never forget that. And in the case of common materials, the fringe orders obtainable are very small and mind you, this is when specimen material yields and we will never load in actual service condition to the extent of yielding; so we will operate much below this. So, the message here is when you go for photo-elastic coating analysis, the specimen material indirectly influences what is the maximum fringe order that I can anticipate to observe in a test. And this also gives knowledge, that usually fringe orders what you can perceive are smaller and that is the reason why you want to go for white light for elimination. And I also have this table for some more materials; the idea is to have a picture, the same thing happens in the case of aluminium also. So, aluminium it ranges from 1.37 to 4.88, people also have used photo-elastic coating in concrete and concrete the maximum fringe order is only 0.95.

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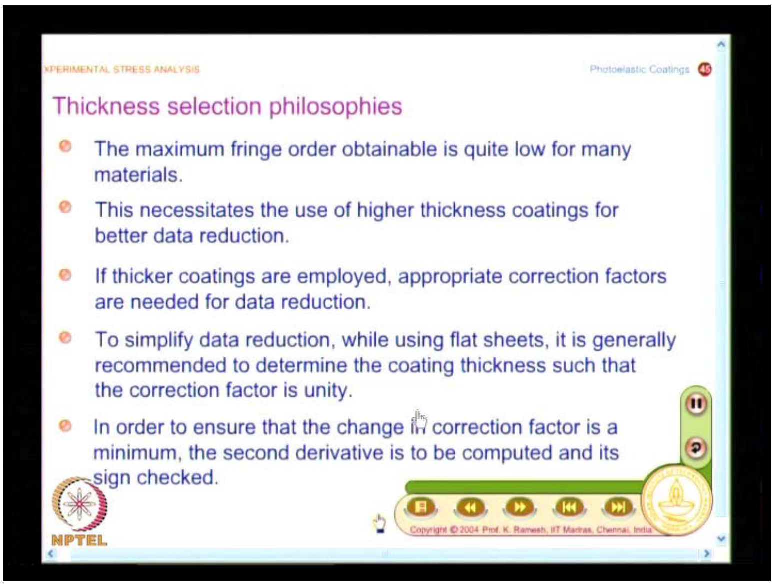

Thickness selection philosophies

- The maximum fringe order obtainable is quite low for many materials.
- This necessitates the use of higher thickness coatings for better data reduction.
- If thicker coatings are employed, appropriate correction factors are needed for data reduction.
- To simplify data reduction, while using flat sheets, it is generally recommended to determine the coating thickness such that the correction factor is unity.
- In order to ensure that the change in correction factor is a minimum, the second derivative is to be computed and its sign checked.

So, this gives you an indication that photo-elastic coating, the fringes observable is very less; so it is better you go for white light elimination. We have seen that the maximum fringe order obtainable is quite low for many materials; this necessitates the use of higher thickness coatings for better data reduction and what happens? If thicker coatings are employed, appropriate correction factors are needed for data reduction.

So, you need thickness selection philosophies for you to address these issues and what I have here? To simplify data reduction, I have also mentioned it earlier, while using flat sheets, it is generally recommended to determine the coating thickness such that the correction factor is unity, whether keeping it unity helps your particular application or not, that needs to be verified; but this is one of the philosophies that one can think of, because the focus is to simplify data reduction.

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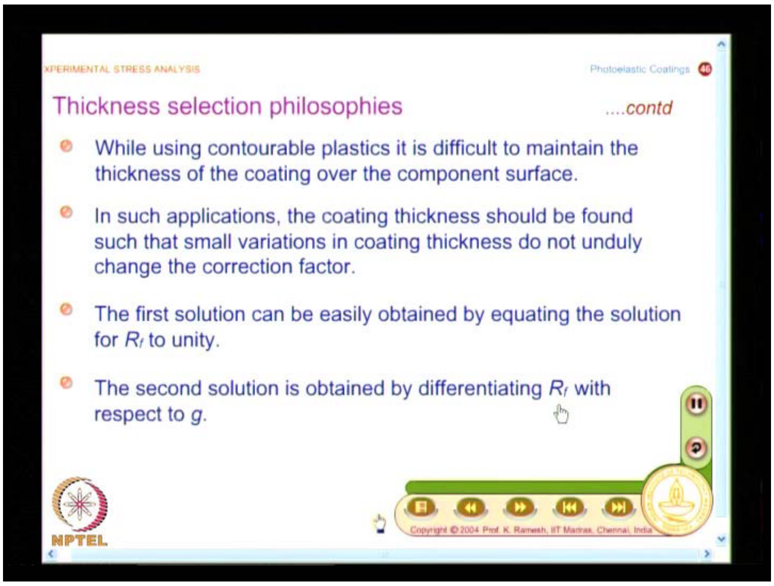

Thickness selection philosophies ....*contd*

- While using contourable plastics it is difficult to maintain the thickness of the coating over the component surface.
- In such applications, the coating thickness should be found such that small variations in coating thickness do not unduly change the correction factor.
- The first solution can be easily obtained by equating the solution for R_f to unity.
- The second solution is obtained by differentiating R_f with respect to *g*.

The other aspect is, in order to ensure that the change in correction factor is a minimum, the second derivative is to be computed and its sign checked. Because what you want is, when there is a thickness change, this becomes important when you go for contourable plastic; you will not be in a position to maintain the thickness uniformly. So, there you would like to have a correction factor not to change drastically because of small variation in thicknesses and that is what is summarized here. While using contourable plastics, it is difficult to maintain the thickness of the coating over the component surface.

So in such applications, the coating thickness should be found such that small variations in coating thickness do not unduly change the correction factor. In fact, we are going to see a variety of problems which are very complex in shape, where contourable plastics have been employed to analyze variety of practical situations. So, in such cases, the coating thickness should be found such that small variations and coating thickness do not unduly change the correction factor and how do we do it?

The first solution can be easily obtained by equating the solution that is the correction factor to unity, because the focus was to find out the thickness such that correction factor is equal to 1. In some applications, you may find the thickness, but thickness may not be suitable; that decision also you have to take. So, the thickness selection does not end here; it only gives you a possible selection of thickness what happens when R f is equal to unity.

The second solution is obtained, that is, the thickness should not change the correction factor should not change for small variations in coating thickness is obtained by differentiating the correction factor expression with respect to g, and you have already seen g as ratio of thicknesses. So, whatever the expression you have for correction factor, that needs to be differentiated with respect to g and ensure that whatever the correction factor you get is not changing drastically for small changes in the thickness. Because it is very difficult to maintain thickness for large structures, there could be small variations and these are only philosophies you know, it is not the end result. As an engineer, you should apply your engineering equipment and filter out whether you will employ this kind of approaches. Finally, you always have what is the available thickness readily from manufacturers also dictates the final selection. So, this is one of the considerations based on analysis, whether I want to have correction factor R f equal to 1 or change of correction factor should be minimum for changes in thicknesses.

Now, you know, if you look at the literature, there was a book by Zendman and others, because the monograph published by society of experimental mechanics that was the only book available earlier on photo-elastic coatings, that had nice pictures on some of the components that they had analyzed at that point in time. And recently, the Vishay Micro-Measurements has brought out nice book on photo stress and which says a pictorial examples of photo stress coated parts and it is also gives wide selection of industrial case history applications. My interest is to enthuse you to take up photo-elastic coating for your solving industrial problems and if you look at the kind of the problems that have been analyzed, that will give you an idea how to go about it

The idea of showing this book is that, it has a rich collection of examples, where photo stress has been applied and this has very interesting set of pictures. If you have an opportunity, please get hold of this book and read through it. My interest is to give you an appreciation that, what variety and range the problems can be tackled using photoelastic coatings.

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Fig. 19

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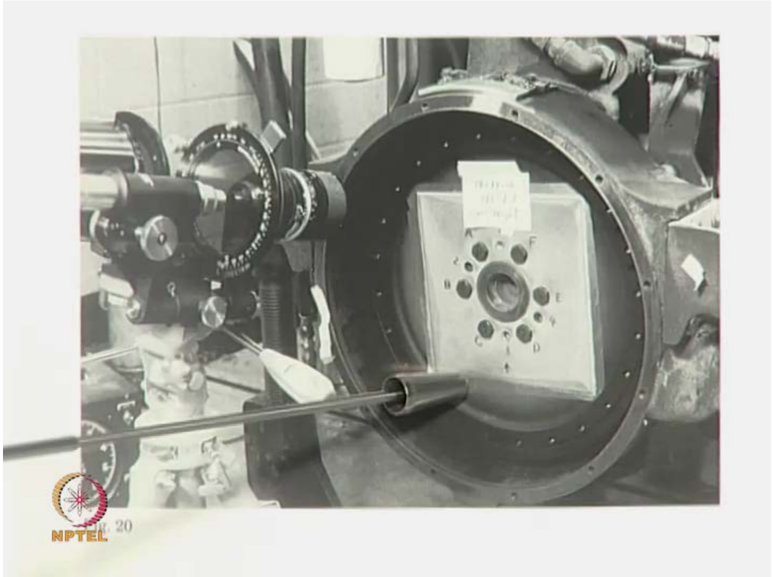

ig. 20

This is an example, which shows how photo-elastic coating is useful for studying assembly stresses and this is the mass that is used for street lighting and you have here, it is tightened, after tightening with the bold, it has developed rich colors indicating a very high value of stresses because of assembly. This shows another example of application of photoelastic coatings; here you have a fly wheel that is being analyzed.

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Fig. 20

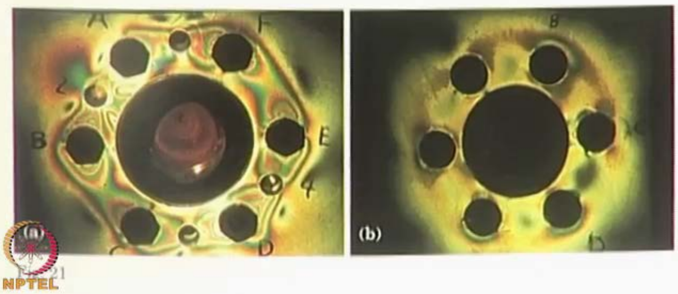

Fig. 21

I had mentioned that, when you see colors, you have to be worried in photo-elastic coating test that indicates the stress levels are very high and this is the initial design of the fly wheel and these are the stresses due to assembly. Based on this input when the design is modified, you have the final set of assembly fringe patterns which are very good from design point of view; from photograph point of view, you do not see colors; from photogenic point of view, this figure is very good; but from design point of view, this is what we want and this shows how photoelastic coating can be effectively utilized for studying the assembly stresses and also take corrective measures for improved design.

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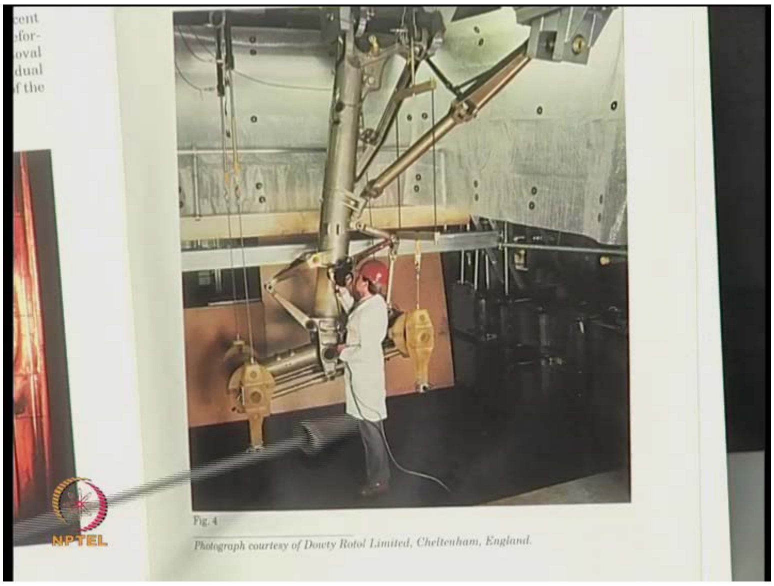

Fig. 4

Photograph courtesy of Dowty Rotol Limited, Cheltenham, England.

This shows another example of what is the use of photo-elastic coating in solving industrial problems. This is the model of a A 330, A 340 landing gear and what you have here is, you can see the size of the model compared to the human being standing and what is interesting is, you have this as an epoxy model that is very clearly seen from the color; you can see from the color, that this is the model made of epoxy. In fact, chemical engineers are employed to tame the epoxy material so that they get the model free of residual stresses when such a huge model is being cast.

So, what you have here is, the figure clearly shows that, this model is made of epoxy; you can distinguish form its color. So, the entire model is made of epoxy, that is, coated with photoelastic coating and you can see the individual, the person watching for stress concentration using a reflection polariscope held in this hand.

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This shows another example of a component of a landing gear, this is, a 767 main landing gear, how photoelastic coating reveals stress patterns for a problem of practical interest.

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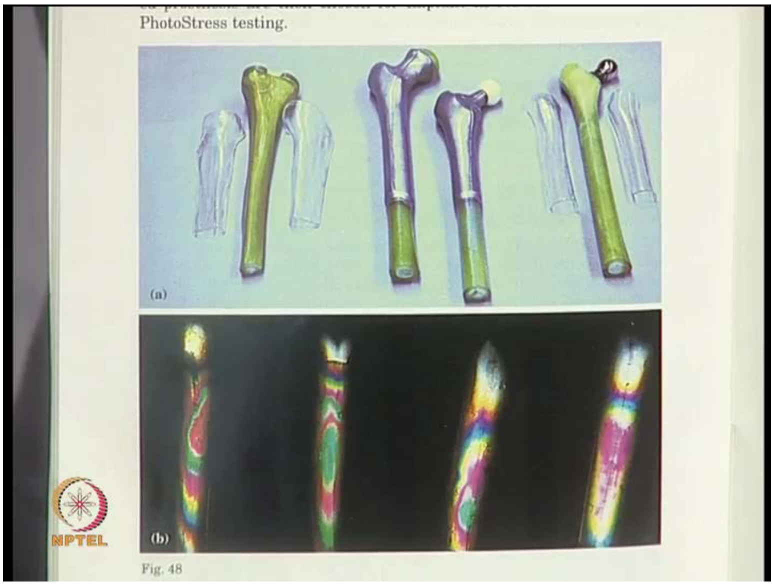

This shows another example of application of photoelastic coating and here, it is for (( )) example, where you have (( )) replacement and you want to analyze what is the influence of this implants; you have a shell which is made by a contourable plastic which is bonded on to the bone and these are all the respective fringe patterns obtained for various configuration.

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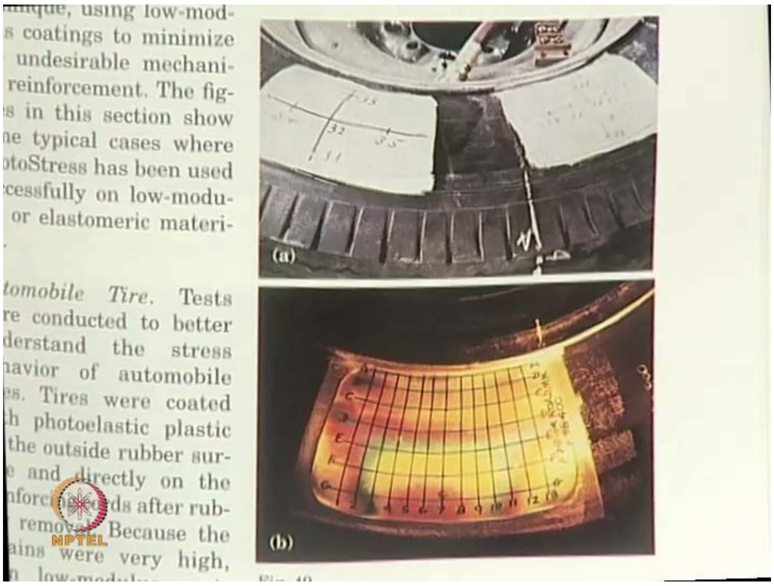

ique, using low-mod-
s coatings to minimize
undesirable mechani-
reinforcement. The fig-
s in this section show
ne typical cases where
otoStress has been used
cessfully on low-modu-
or elastomeric materi-

tomobile Tire. Tests
re conducted to better
derstand the stress
havior of automobile
es. Tires were coated
h photoelastic plastic
the outside rubber sur-
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ains were very high,

So, you have a range; you have seen for metals, now you see for application of photoelastic coating to bone. Finally, you see application of photoelastic coating to the tire of an aircraft application and you see the tire bonded with photoelastic coating and these are all the fringe patterns observed and mind you, here you have to use the appropriate coating material to reveal the stress pattern.

See, what we have discussed in today’s class was, we looked at that, photoelastic coatings is industry friendly technique and correction factors are part and parcel of it. Because we make approximations in the optical arrangement as well as when you are having a coating of reasonable thickness you need to account for it and in order to correct those kind of errors, you always bring in a correction factors, then we also looked at what is the influence of mismatch of Poisson’s ratio; we found out thumb rules what is the size of the transmission zone and we also concluded that, as long as I work on metallic specimens, we can ignore the influence of Poisson’s ratio mismatch; however for finding out stress concentration factor, it is desirable that you bring in a small correction which is given as 1 plus nu s divided by 1 plus nu c.

Then we moved on and look at, what are the different kind of photoelastic coating material and I said, you have coating materials specifically available for high modulus specimen materials, medium modulus specimen materials and low modulus specimen materials. Finally, we also looked at what is the maximum fringe order obtainable in a photoelastic coating test and in order to give an enthusiasm that this technique is very widely used in industries with concentrate on design and development like an aircraft industry and also other key industries, where they generate original designs, we have seen a variety of problems, where photoelastic coating has been applied even for some of the very recent aircrafts like Boing 777 or 767 and also Airbus A380. People have use photoelastic coating to verify the design of landing gears, so that should enthusiast to understand what is the method of photoelastic coating and also employ it when you have an opportunity to do any of those design developments. Thank you.