Experimental Stress Analysis

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Lecture - 25

Coating Materials, Selection of Coating Thickness, Industrial Application of Photoelastic Coatings

Let us continue our discussion on reflection photoelasticity. I said this technique has been really used for solving several problems of practical interest. The methodology requires use of correction factors because I mention we make several approximations in the theoretical development and also in optical arrangement we comprise on pure normal incidence. 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 the versatility these are the 2 key factors and even now for some of the current problems people employ and go to photoelastic 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 require anything. When you are making your own design you need to verify whether whatever the kind of procedure that you have adopted has come and be useful for arriving at a right kind of design for a given problem.

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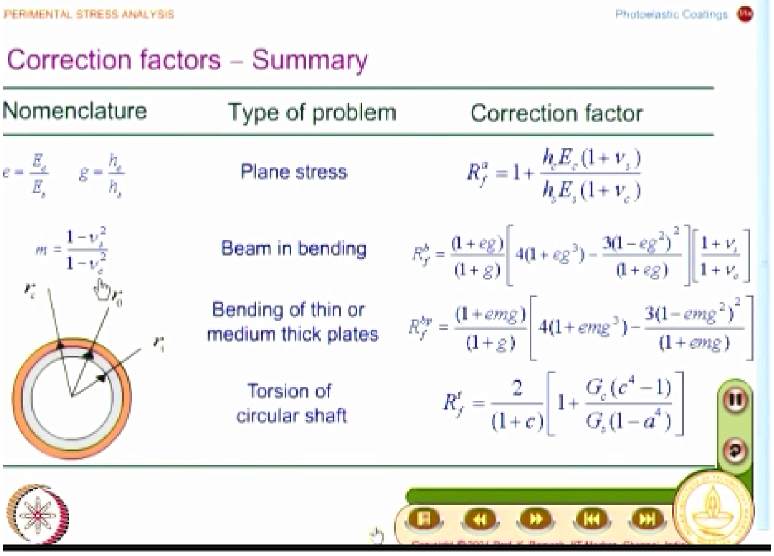

PERIMENTAL STRESS ANALYSIS

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	$R_f^t = \frac{2}{(1+c)}\left[1 + \frac{G_c(c^4-1)}{G_s(1-a^4)}\right]$

And we will look at what are the correction factors 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 Rfa where a denotes that you are looking at axial loading and this is labeled as Rfb b denotes bending.

And this is Rfbp to distinguish from bending of beams to bending of plates you have this as Bp and Rft is used for torsion. In all these expressions, you know in order to simplify your writing we have used e as ratio of Young's modules and g as ratio of thickness and m as 1-nu s square/1-nu c square.

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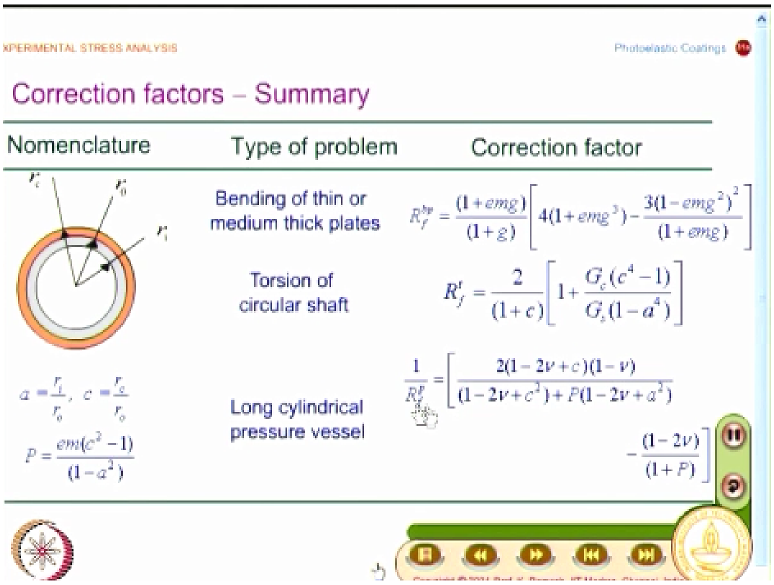

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$a = \frac{r_i}{r_o},\ c = \frac{r_c}{r_o}$ $P = \frac{em(c^2-1)}{(1-a^2)}$	Long cylindrical pressure vessel	$\frac{1}{R_f^p} = \left[\frac{2(1-2\nu+c)(1-\nu)}{(1-2\nu+c^2)+P(1-2\nu+a^2)} - \frac{(1-2\nu)}{(1+P)}\right]$

And I said that you also have the correction factor for pressure vessels because many engineering applications could be modeled as a pressure vessel and here it is written as 1/Rfb and you also have the definition of A and C and you also have a definition of what is the symbol p used in this expression. And you have to understand these correction factors are applicable in regions away from stress concentration.

When there is abrupt changes in the thickness then also this correction factors are not valid. The idea here is when you have a real problem on hand apply a coating of reasonable thickness so that you find out which are all the regions you have high stress gradient. Identify those regions then strip this thick coating 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 a way you circumvent when you have to analyze complex problems you have an engineering approach to utilizing the technique and 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 have heat exchanges where you have tubing and for these tubes people have analyzed and particularly nuclear industry you have to be very careful. So high pressure tubing the use of correction factors are very important. I also mentioned that you need to look at how to handle mismatch of Poisson's ratio that is what we will take it up now.

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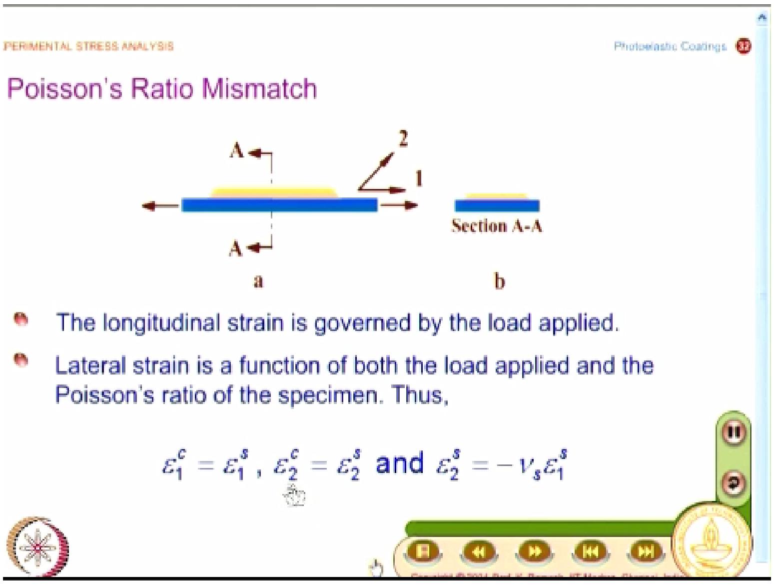

Poisson's Ratio Mismatch

- 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,

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

And let us understand the mismatch of Poisson 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 traverse to the specimen and I have a photoelastic 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 and 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 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 a uniaxial strain, then you have make special efforts to constrain to adjust 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 ratio of the specimen. So what I have here is epsilon 1c= epsilon 1s there is no problem.

And we have epsilon 2 c is also= epsilon 2 s because we assume that the bonding of the coating is very carefully done so that whatever the strain 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-nu s times epsilon 1 s and this will be= to the coating strain no problem, but what happens on the top surface?

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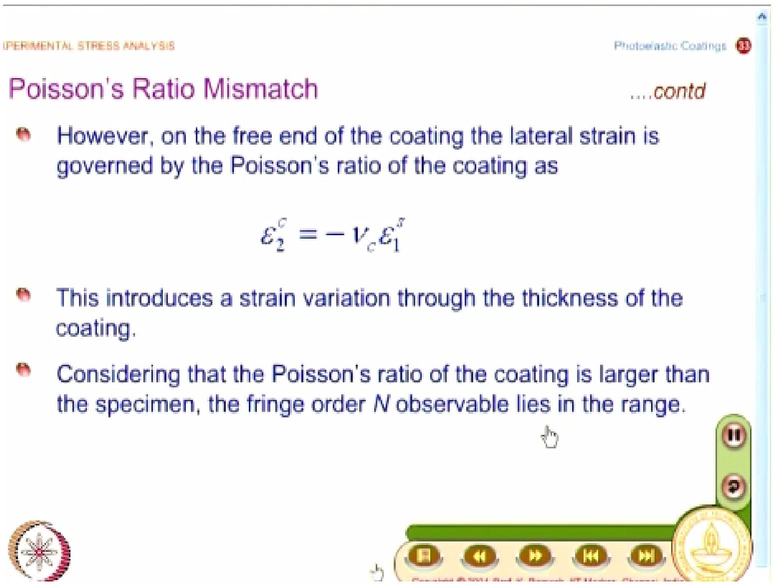

Poisson's Ratio Mismatch ....*contd*

- 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 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 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 ratio of the coating. See we saw in the case of coating applied to bending problems or torsion problems.

There was a variation in the coating the strain variation in the coating was seen mainly because of the way the model was loaded, 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 ratio this is one aspect of it. The other aspect is when I have free (()) (10:16).

There also you have to bring in the Poisson ratio of the coating in your analysis. And you know people have done studies and then looked at what way one has to consider this in which region Poisson ratio is important. And for all this we have also seen from the material property the Poisson ratio of the photoelastic 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 straightforward application of your strain optic law I do not know how many of you are able to see this.

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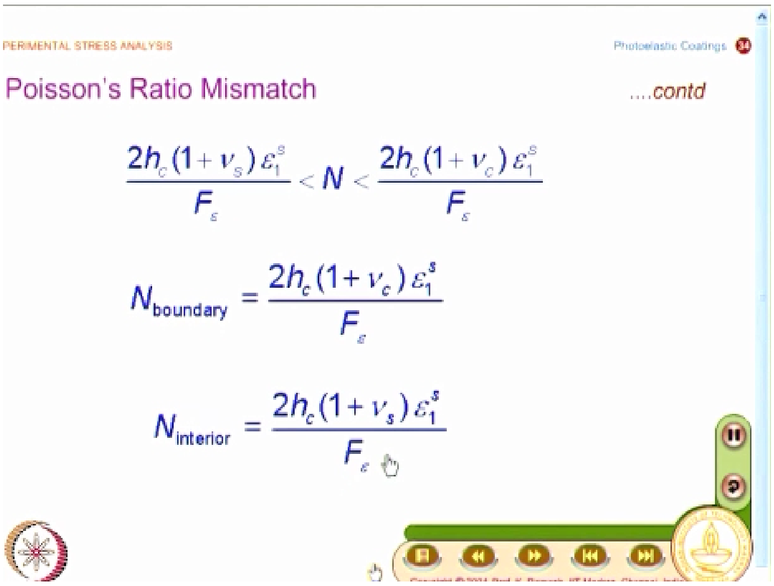

PERIMENTAL STRESS ANALYSIS

Photoelastic Coatings 34

Poisson's Ratio Mismatch

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

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

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

I will have epsilon 1-epsilon 2 s n f epsilon/2 hc and this epsilon 1-epsilon 2 is written in this fashion here because I know epsilon 1 s-nu s epsilon 1 s because epsilon 2 s is-nu s epsilon 1

s. So in one case it may be controlled by the Poisson ratio of the specimen. In another case it can be controlled by the Poisson ratio of the coating. So the n will have a range on the one end dictated by the Poisson ratio of the specimen.

On the other hand, it is dictated by the Poisson ratio of the coating. So you define what is the boundary fringe order it is given as 2 hc*1+nu c in the epsilon 1s/F epsilon and I can also write what is the interior fringe order it is given as 2 hc*1+nu s epsilon 1s/ F epsilon. This is the material strain fringe value. So what you need to recognize this. Poisson ratio mismatch can give problems.

Whether the problem is significant or not is what you will have look at and people have also done systematic experiments and then established how you can accommodate the Poisson ratio mismatch.

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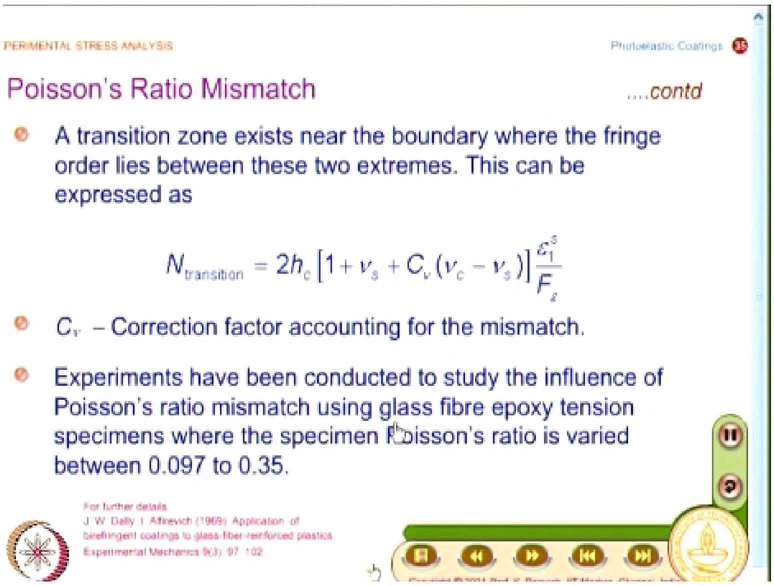

Poisson's Ratio Mismatch ....contd

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

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

- 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 order different at the boundary and the interior when you have a difference there has to be a transition zone. So people have identified the transition zone exists near the boundary where the fringe order lies between the 2 extremes which we saw earlier. And this can be expressed as n transition and that is given as 2 hc*1+nu s+ Cv where Cv is the correction factor accounting for the mismatch.

Cv*nu c-nu s the whole of which is multiplied by epsilon 1 s/F epsilon. And this is what I said that experiment 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 fibre by which I can change the Poisson ratio of the composite specimen comfortably.

And this is what was done. So the glass fibre epoxy tension specimen where the specimen Poisson ratio is varied between 0.097 to 0.35. When you use a composite by changing the volume fraction of the fibre it is possible to change the Poisson ratio.

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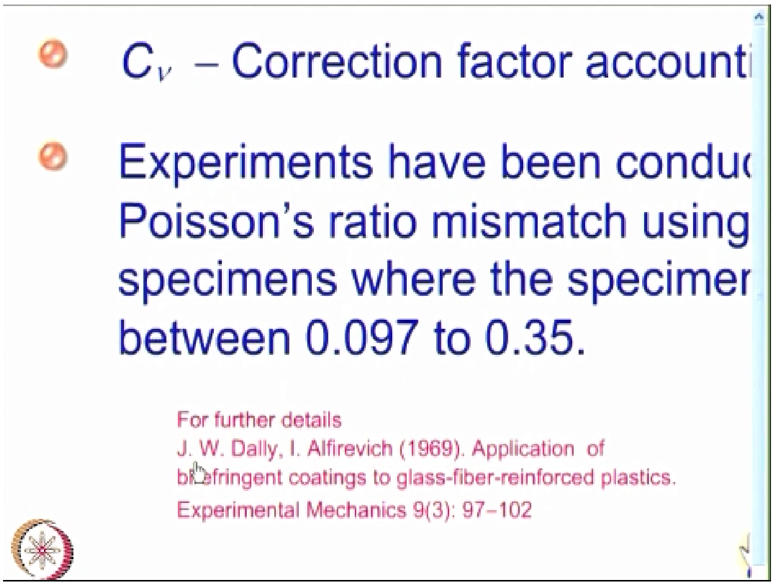

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- Experiments have been conduc Poisson's ratio mismatch using specimens where the specimer between 0.097 to 0.35.

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And further details you know you could get it from reference here. It is by Dally I Alfirevich. It was published in 1969 you have application of birefringent coating to glass fibre reinforce plastics. In fact, you have very nice pictures and they have also given thumb rules depending on the coating thickness what is the size of the transition zone and so on and so forth. And what is its implication when we want to do experiments.

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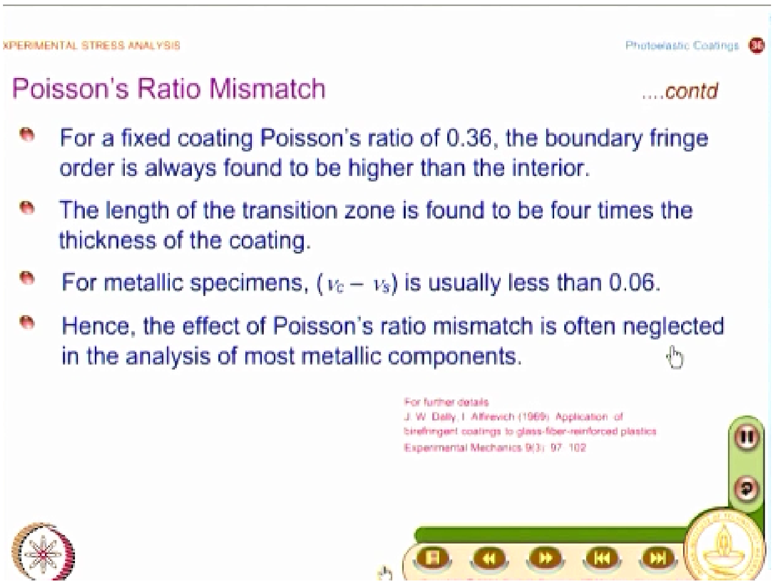

Poisson's Ratio Mismatch

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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
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And this is what you see here and what they have found is for a fixed coating Poisson 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 ratio mismatch and their length of the transition zone is found to be 4 times the thickness of the coating. So this is the contribution by the experiments conducted by Dally, I. Alfirevich.

They have also established the size of the transition zone. It is a function of the coating thickness. And what you actually have to look at is what is the change in the Poisson ratio You know metallic specimen the Poisson ratio is around 0.24 to 0.26 is what you have. So typically the Poisson ratio difference nu c-nu s is usually < 0.06. So the final conclusion is for most metallic components the effect of Poisson ratio mismatch is often neglected (()) (17:21) because before we establish that this is the second order effect.

We must do an analysis and then only say Poisson ratio mismatch can give you problems, but the level of influence is smaller so you can neglect it for metallic specimens when you do photoelastic coating technique analysis.

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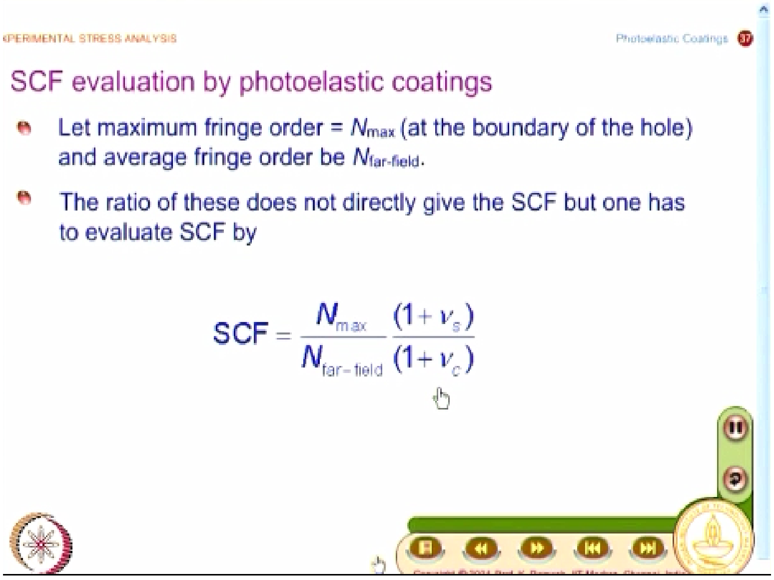

SCF evaluation by photoelastic coatings

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

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

However, when we go and do the SCF evaluation that is what I said when I want to find out the stress concentration factor. Photoelasticity is a very simple approach to find out stress concentration factor. And what we need in transmission photoelasticity 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 photoelastic coatings you have to have N max/ N far-field which is multiplied by 1+ nu s/1+nu c. So the Poisson ratio of the specimen as well as Poisson ratio of the coating influences your final result. So if you do not do this correction if you have a finite element analysis and you 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 plate with a small hole.

When you go to actual problems you have a finite plate with a finite sized holes. In general stress concentration factors are much higher than 3. And there is also a subtle difference in the case of theory of elasticity you would define stress concentration factor as maximum stress divided by far-field stress that will be 3 for an infinite plate with a small hole. For a finite plate it will be > 3.

But if you go and look at design coats they are defining stress concentration factor slightly differently. They would depend stress concentration factor as maximum stress/ ligament stress because that is what you can estimate for a finite body comfortably. And when the size of the holes keeps increasing the ligament stress also will keep increasing. So what you will essentially find is stress concentration factor will hover around 2.2, 2.3 and so on.

You should not wrongly conclude theory of elasticity gives me 3 whereas design gives me < 3 so I can always use 3 as the conservative value for my design then your design will fail because many people do not know this is a subtle difference. There is a definition shift between designers how they define stress concentration factor and how do you define stress concentration factor in analytical development you should know the difference.

Half-baked knowledge can always give you problem. So you have to be very careful when you want to find out SCF in photoelastic coating. You should also put this correction factor. This comes from mismatch of Poisson's ratio.

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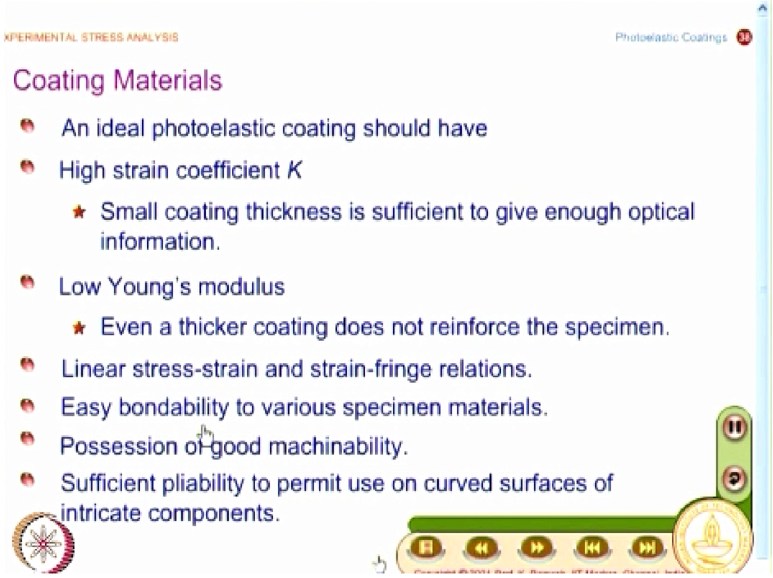

XPERIMENTAL STRESS ANALYSIS

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.

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 have to worry about the correction factor which is automatically taken care off 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 modules 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 interpretation becomes lot more simpler.

Easy bondability to various specimen materials because we have 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 component 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 that has 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 you a motivation that to learn this technique and also if opportunity exist for you to apply and obviously you will not have all these properties available in a single material. So you have to have a tradeoff and you have to do compromises. These are all the desirable requirements.

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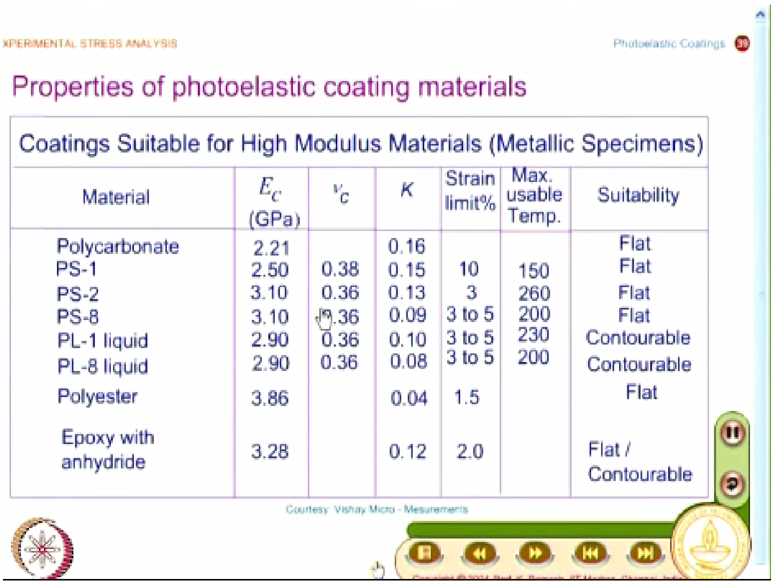

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings

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	0.36	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

And what you have is I said that the Young's modules is a very key factor because we do not want this to reinforce a specimen. So you have coatings available separately for high modules material and if you look at the Young modules it is around 3 GPa whereas all your material when you have metallic materials they have aluminum is 70 GPa and steel is 2 ton (()) (24:42) GPa. So if you have a coating which is just 3 GPa.

It will not reinforce that. So I can comfortably use photoelastic coating and from this table you write only 2 material. One is polycarbonate anther is PS-1 this is also commercially available from Vishay Micro Measurements and what you need to look at is K is around 0.16. 0.1 is what you see by and large for most of the materials and strain limit is it can go up to 10% of strain.

And because these are all plastic you cannot go beyond maximum of 260 degree centigrade and you also have whether they can be available in flat sheet or contourable form. When you have a contourable form you essentially have a liquid and you test it in your own laboratory or I also said with advancement in technology people also give you the sheets in gels 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 you need to look at here is for high modules materials the recommended coating has Young modules around 3 GPa and Poisson ratio is around 0.36 that is how all the materials that you have and most metallic materials it will hover between 0.24 to 0.26 or 0.28.

So this is how you have to look at the relevance of these numbers.

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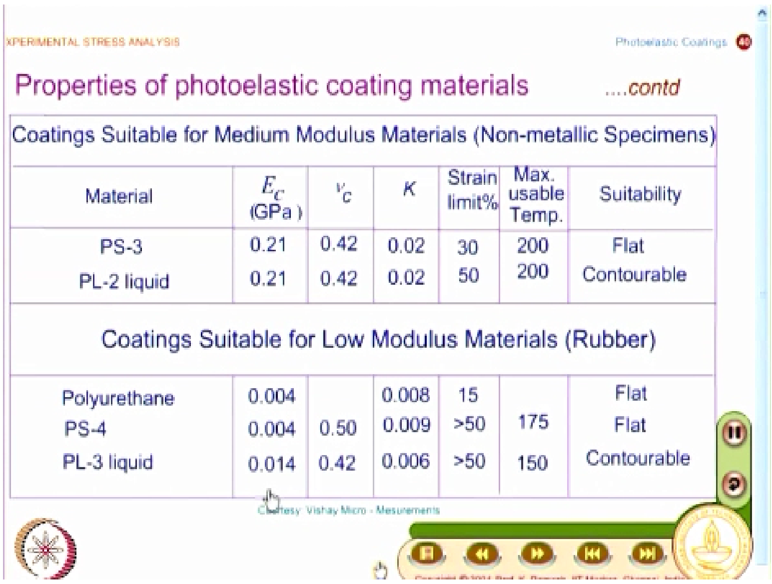

XPERIMENTAL STRESS ANALYSIS

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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)						
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

And when I go to Low modules materials and I have for Medium modules material separately and I have low modules material finally like rubber. So you have special materials available from Vishay Micro Measurements which is available at a Young’s modules of 0.21 GPa and you have strain limit of about 30%. And if you look at K for this it is considerably reduced 0.02.

Finally, when you come to rubber and here you have to be very careful. See you think rubber does it require any analysis in fact if you look at tyres which are used in aircraft very complex design. They are like layered composite you have reinforcements and during landing and takeoff tyres play a very important role and they have to withstand the entire weight and impact load and tyre design is very complex.

Do not think because you use your tyres in your cycles and then you also use in many of your common day-to-day applications. Many times familiarity brings as if you know everything about it. In fact, tyre design is very, 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 tyre applications you have to careful in selecting a suitable coating. So what do you have here is it is a low modules material and I choose a coating which has a very small Young’s modules it is 0.004 GPa polyurethane, PS4 and when you look at strain limits because rubber you know it can have a very large strain. So these are available > 50% applicable even for > 50%.

And you also have flat and contourable type of classification. So what do 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 chose. See if I use the high modules material coating. The low modules material then I would be making a mistake because the coating will reinforce with specimen. So what you will have to be careful you need to choose the appropriate material.

So you have a catalogue available utilize the catalogue properly.

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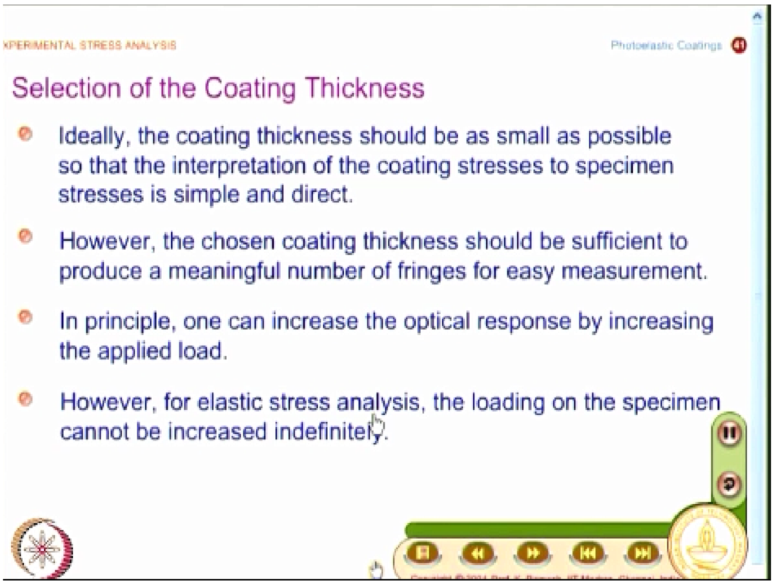

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Selection of the Coating Thickness

- 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.

And I also mentioned there is an issue of Selection of Coating Thickness. Ideally I want the coating thickness should be as small as possible. He 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 a meaningful number of fringes for easy measurements.

And we have seen in transmission photoelasticity 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 may start yielding. You do not want the specimen to yield in normal service condition. So that is an upper limit by which I can load it. So one of the issues talked about in photoelastic coating analysis is what are the maximum fringe order obtainable it is an issue.

That is why we 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 the elastic stress analysis.

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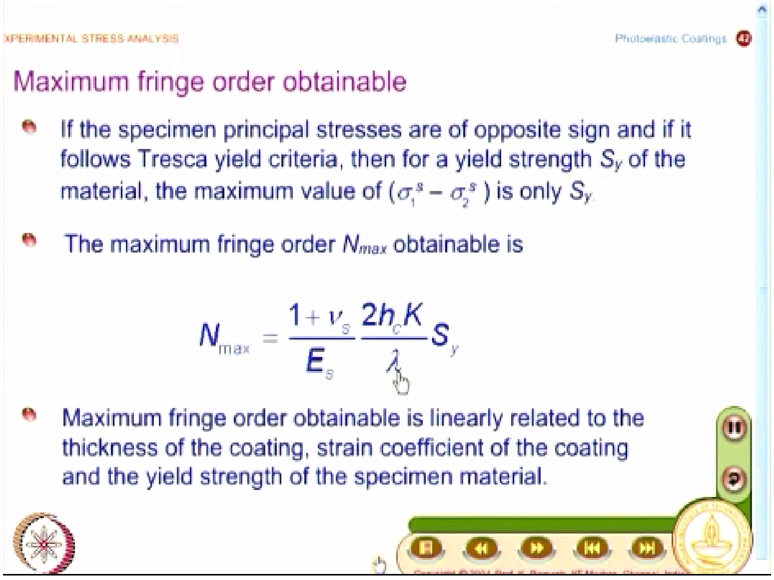

XPERIMENTAL STRESS ANALYSIS

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.

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 1s-sigma 2 s and suppose I consider that these principal stresses are opposite sign and suppose the material follow Tresca yield criteria then for yield strength Sy of the material, the maximum value of sigma 1 s-sigma 2 s is only Sy. So from this if I go back and find out what is the expression for principal stress difference recast that expression.

So you have maximum fringe order obtainable is a function of Poisson ratio of the material, Young's modules of the material and also the yield strength of the material. So what you find is if I am working on high strength alloys I can have very high fringe order, low strength alloys the maximum fringe order obtainable is smaller and most of you are aerospace and nuclear application you use high strength alloys.

So you will have reasonable fringe order seen in those structures. Suppose I want to apply it on mild steel that is also needs to be analyzed when you make a 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 the maximum fringe order obtainable.

So I have this expression N max=1+nu s/Es* 2 hc*K that is a strain coefficient of the coating material and you have the wavelength dependence and you have this as Sy as the yield strength of the specimen material.

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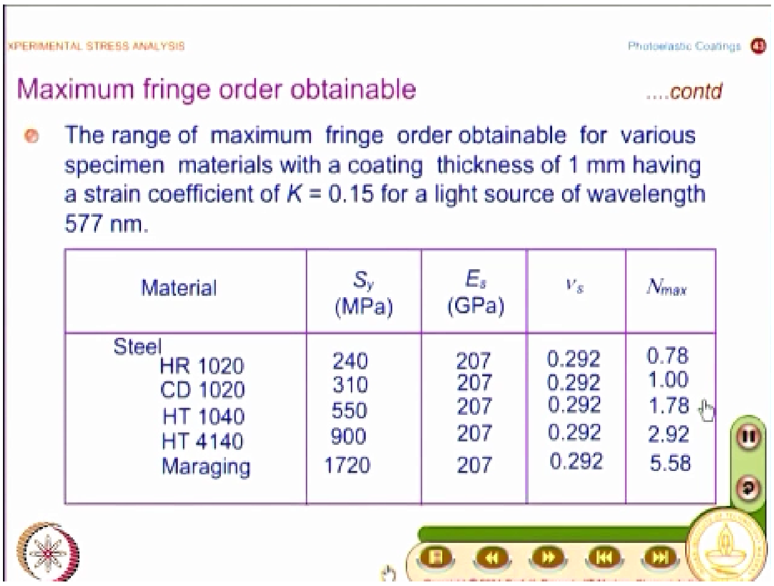

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings

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

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=0.15 and for a coating thickness of 1 millimeter and for a light source of wavelength 577 nanometer. Essentially the white light we had also looked at the color code where we saw repetition occurs at 577 nanometer you have a tint of passage and twice of this value you have another tint of passage.

And what you need to look at here is I have the yield stress tabulated here and yield stress 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. So if I am working on high strength alloys it will be very similar to what I see in the case of transmission photoelasticity I will see rich colors. By the 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 order obtainable are very small. And mind you this is when the specimen material yields and we will never load in actual service conditions to the extent of yielding. So we will operate much below this. So the message here is when you go for photoelastic 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 a knowledge that usually the fringe orders what you can perceive ARE smaller and that is the reason why you want to go for white light for illumination.

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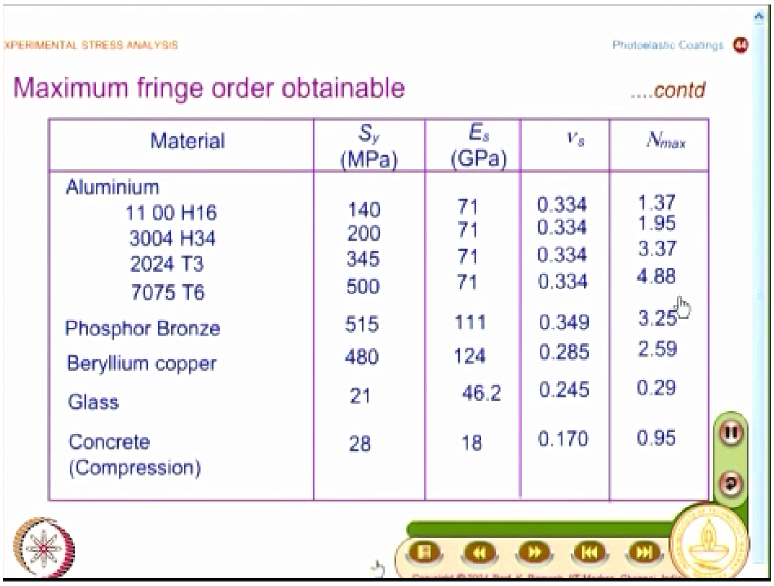

Maximum fringe order obtainable ....*contd*

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

And I also have this table for some more material. The idea is to have a picture the same thing happens in the case of aluminum also. So aluminum it ranges from 1.37 to 4.88 people also use photoelastic coating in concrete. And concrete the maximum fringe order is only 0.95. So this gives you an indication that photoelastic coating the fringes observable are very less. So it is better you go for white light illumination.

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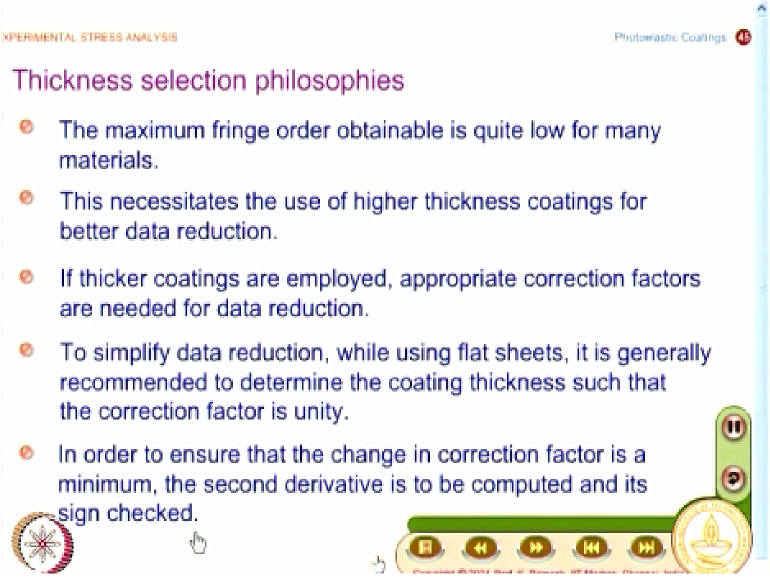

Thickness selection philosophies

- 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.

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 date reduction. And what happens if thicker coatings are employed appropriate correct 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 you a 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. The other aspect is in order to ensure that the change in correction factor is minimum. The second derivative is to be computed and it 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 that you would like to have a correction factor not to change drastically because of small variation in thicknesses

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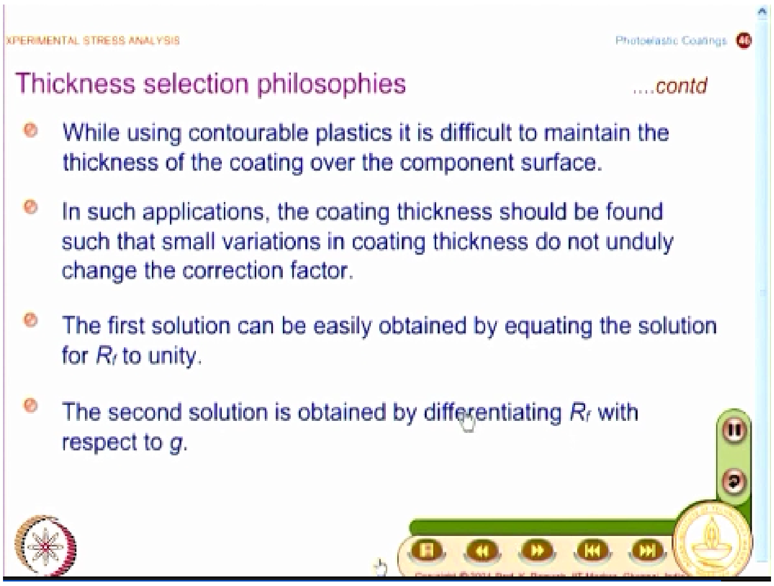

XPERIMENTAL STRESS ANALYSIS

Photoelastic Coatings

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*.

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 a variety of practical situations.

So in such cases the coating thickness should be found such that small variations in 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=1. In some application you may find the thickness, but thickness may not be suitable that decision also you have to take.

So thickness selection does not end here. It only gives you a possible selection of thickness. What happens when Rf= 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 thickness.

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 where engineering acumen and filter out whether you will employ these kind of approaches. Finally, you always have what is the available thickness readily from manufacturers is also dictates the final selection. So this is one of the consideration based on analysis whether I want to correction factor Rf=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 (()) (42:19) and others it was a monograph published by society of experimental mechanics that was only book available earlier on photoelastic coatings that had nice pictures on some of the components that they had analyzed at that point in time.

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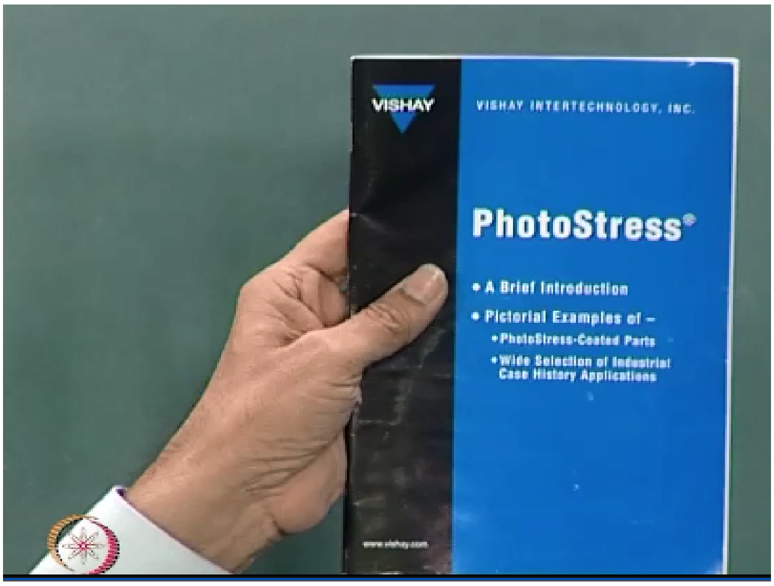

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- A Brief Introduction
- Pictorial Examples of –
  - PhotoStress-Coated Parts
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And recently Vishay Micro Measurements has brought out nice book on PhotoStress and which says pictorial examples of photo stress coated parts. And it also gives wide selection of industrial case history applications. My interest is to enthuse you to take up photoelastic coatings for your solving industrial problems and if you look at the kind of 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 PhotoStress has been applied. And this has very interesting set of pictures if you have an opportunity please get all 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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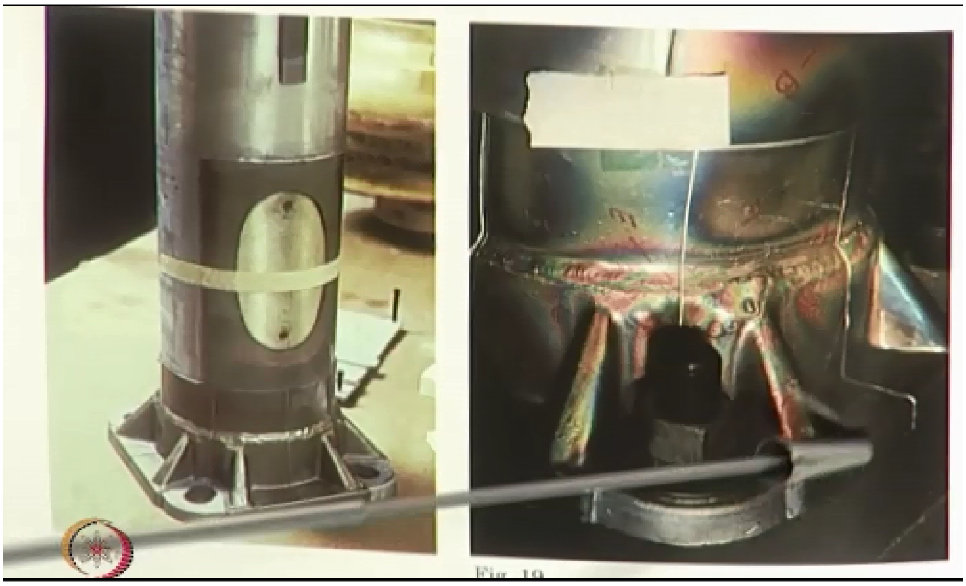

This is an example which shows how photoelastic coatings is useful for studying assembly stresses and this is the mass that is used for street lighting. And you have here it is tightened after tightening with the bolt it has developed rich colors indicating a very high value of stressors because of assembly.

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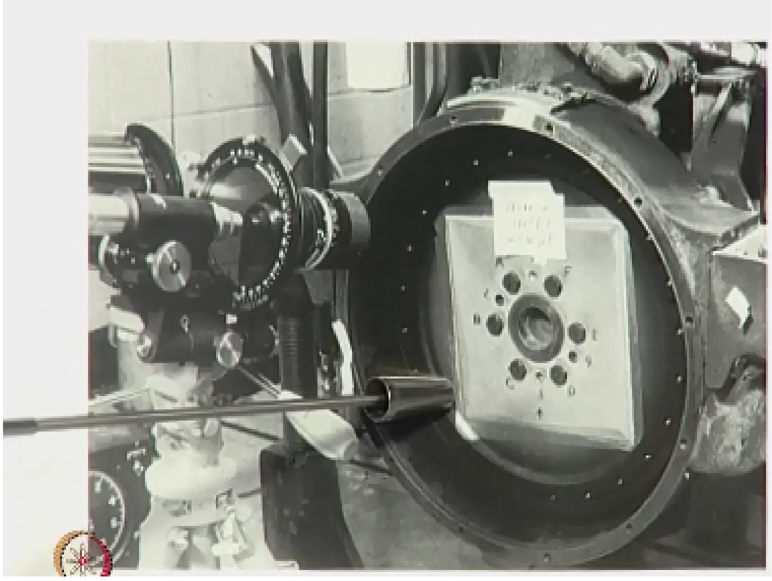

This shows another example of application of photoelastic coatings. Here you have a flywheel that is being analyzed.

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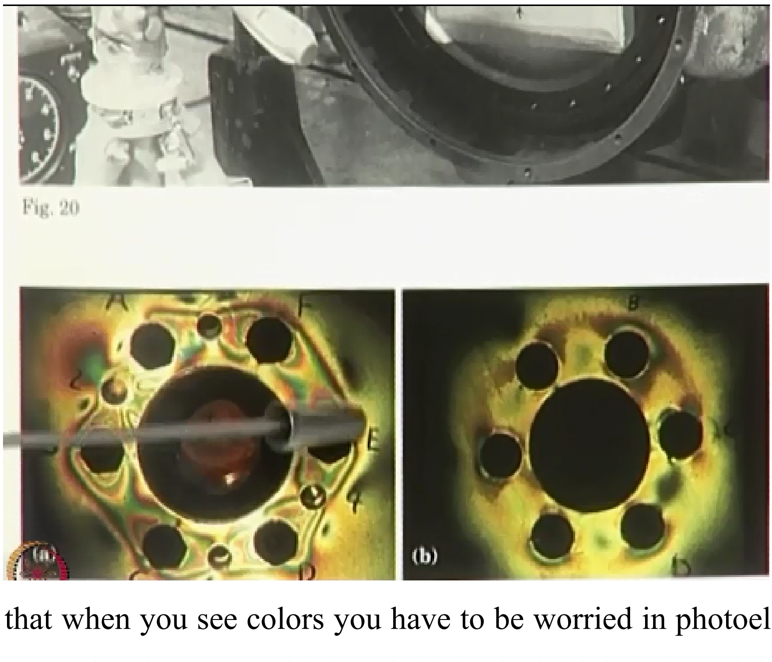

I had mentioned that when you see colors you have to be worried in photoelastic coating test that indicates the stress levels are very high and this is the initial design of flywheel and these are the stressors due to assembly. Based on this input when the design is modified you have the final set of 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 coatings can be affectively utilized for studying the assembly stressors and also take corrective measures for improved design.

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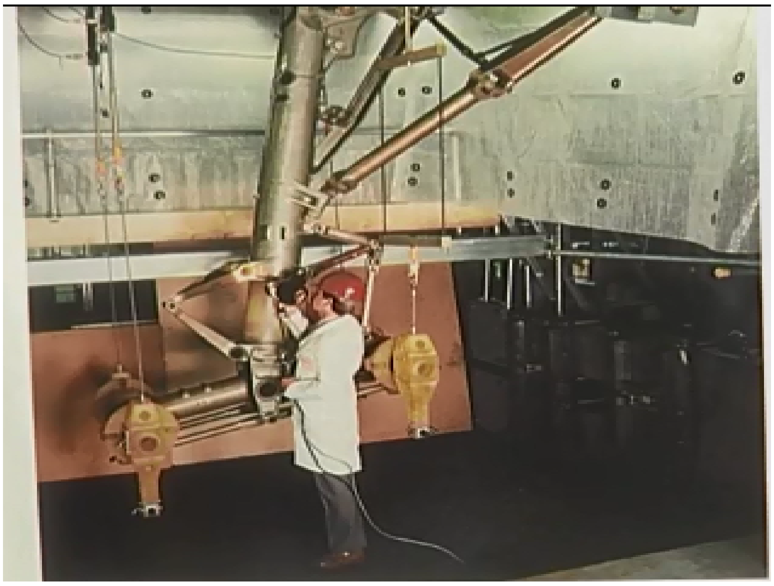

This shows another example of what is the use of photoelastic coating in solving industrial problems. This is the model of A330, A340 Landing Gear and what you have here is you can see the size of the model compared to the human being standing. And what is interesting is you have this as a epoxy model 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 or employ to tame the epoxy material so that they get the model free of (()) (46:13) stressors when such a huge model is being cast. So what do you have here is the figure clearly shows that this model is made of epoxy. You can distinguish it from its color. So the entire model is made of epoxy that is coated with photoelastic coating and you can see the individual person watching for stress concentration using a reflection polariscope held in his hand.

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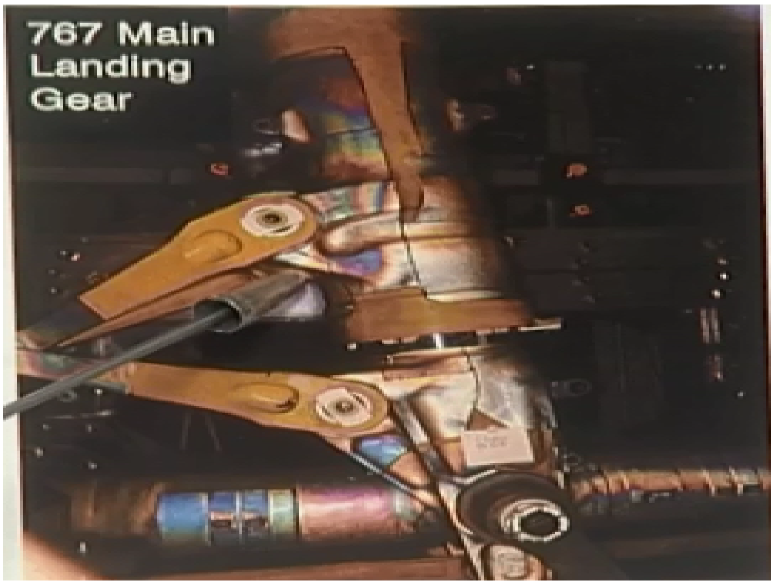

This shows another example of component of Landing Gear. This is a 767 Main Landing Gear how photoelastic coating reveals stress patterns for a problem of practical interest.

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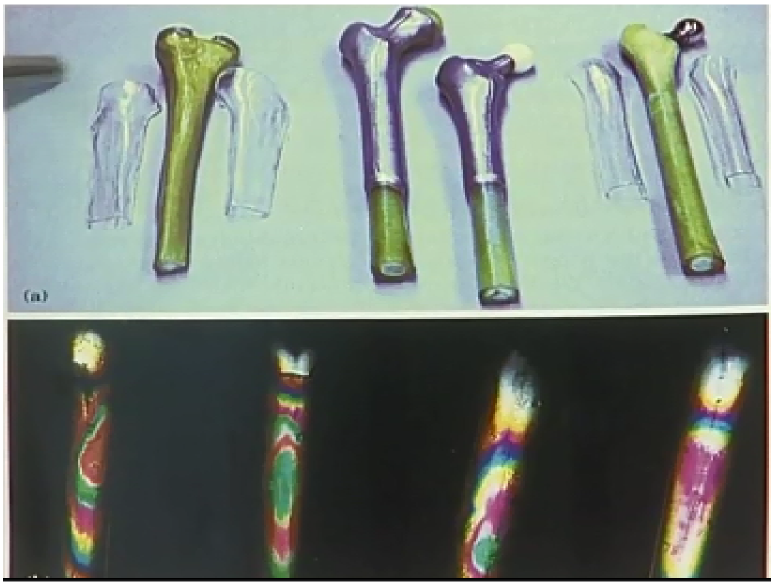

This shows another example of application of photoelastic coating and here it is for prosthesis example where you have hip replacement and you would not analyze what is the influence of this implants. You have a shell which is made by contourable plastic which is bonded on to the bone and these are all the respective fringe patterns obtain for various configuration. So you have a range you have seen for metals. Now you see for applications of photoelastic coating to bone.

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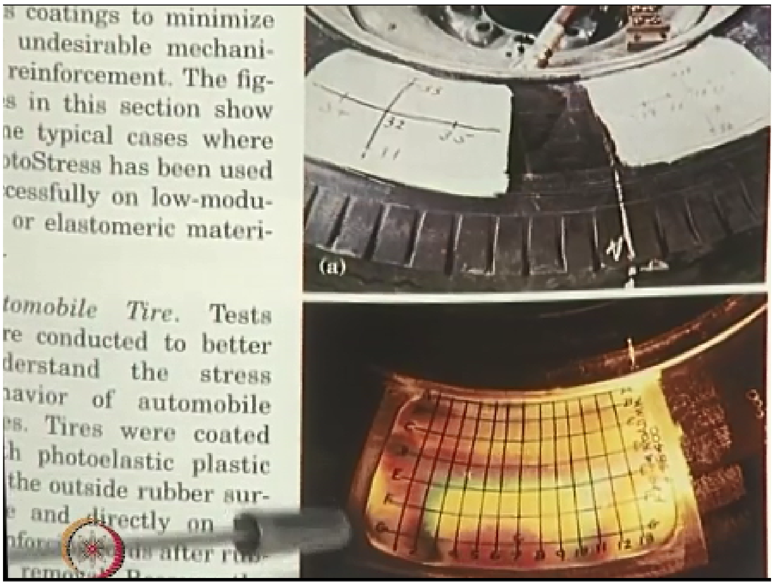

s coatings to minimize
undesirable mechani-
reinforcement. The fig-
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ne typical cases where
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Finally, you see application of photoelastic coatings to the tyre of aircraft application and you see the tyre bonded with photoelastic coatings and these are all the fringe pattern observed and mind you here you have to use the appropriate coating material to reveal the stress patterns. See what we have discussed in today class was we looked at that photoelastic coatings is industry friendly technique.

And correction factors are part and parcel of it because we make approximation in the optical arrangement as well as when you are having a coatings 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 transition zone.

And we also concluded that as long as I work on metallic specimen we can ignore the influence of Poisson ratio mismatch. However, for finding our stress concentration factor it is desirable that you bring in a small correction which is given 1+nu s/ 1+nu c. Then we moved on and looked at what are the different kinds of photoelastic coating materials and I said you have coating materials specifically available for high modules specimen materials.

Medium modules specimen material and low modules 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 which concentrate on design and development like an aircraft industry and also other key industries where they generate original design.

We have seen a variety of problems where phtotoelastic coatings has been applied even for some of the very recent aircraft like Boeing 777 or 767 and also Airbus A380. People have used photoelastic coatings to verify the design of Landing Gear so that should enthuse you to understand what is the (()) (50:32) of photoelsatic coating and also employ it when you have an opportunity to do any of those design developments. Thank you.