Optical Methods in Experimental Mechanics

Part 42: Photoelasticity XIV—Reflection Photoelasticity

REVIEW AND PURPOSE

The article previous to this one described ways to construct a system of stress trajectories from an isoclinic pattern to complete the multi-part instruction manual for conducting an experiment with transmission photoelasticity.

Here, photoelasticity is extended so that stresses or strains over the surface of an actual prototype may be determined through the use of birefringent coatings. The basic devices, applications, theory, limitations, and advantages are discussed in enough detail so that a stress analyst can conduct a valid experiment.

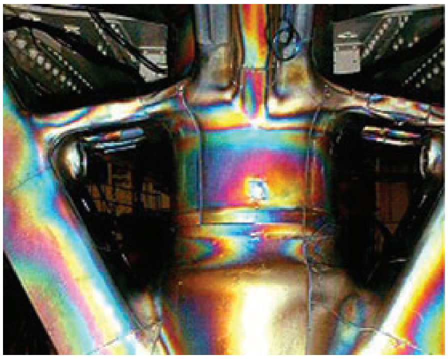
WHY CONSIDER REFLECTION PHOTOELASTICITY?

A characteristic of 2-dimensional transmission photoelasticity is that the analysis must usually be made with a model of the structure being studied, and, as we have learned, similarity rules are utilized to transfer the measured stresses to the prototype. This requirement might be seen as a disadvantage, particularly if the structure being analyzed has complex geometry or, as is true in many design optimization cases, only reasonable estimates of surface stresses or stress concentrations are needed. Some engineers and managers are not entirely comfortable with data taken from a model. In such cases, it is advantageous and cost-effective to analyze the structural component itself. Reflection photoelasticity is a technique that directly yields reasonably accurate strain measurement over the entire surface of the structure being studied.

Reflection photoelasticity is quite easy to implement, and it is an efficient way to obtain reasonably accurate whole-field readings of surface strains from a structure of any size or geometry. The range of applications is immense. The photograph appearing at the head of this article shows an example from an important application in the aircraft industry. Part 41 of this series showed a result from design optimization of a flat prototype part. Another example from a biomechanics study appeared as the lead photo in Part 30. With strobe lighting or cinematic photography, dynamic strain histories, as from an operating engine, can be obtained. The method has been widely accepted and used, or misused in some cases, in industry. The apparatus and materials have been readily available through vendors.

BASIC IDEA AND SETUP

The fundamental idea of the reflection photoelasticity method is that a birefringent material is bonded to the structure so that it undergoes the same strains as are imposed on the structure. Observation of the birefringence in the



White-light isochromatic fringe patterns from stress analysis of a complex aircraft landing gear using a photoelastic coating. Photo courtesy of Dr. Eddie O'Brien, Past President of SEM, Consultant—Aircraft Technical Solutions, Ltd.

This article describes how stresses or strains over the surface of an actual prototype are determined through the use of photoelastic coatings. Basic devices, applications, theory, limitations, and advantages are discussed.

Reflection photoelasticity:

- *provides strains or stresses on the surface of an actual structural component,*
- *does not require fabrication and testing of a model,*
- *can be used on parts of any size and those having complex geometries,*
- *can be used on a wide variety of materials and structures, including concrete, biological structures, machine parts, tires, and so on,*
- *can be used to measure dynamic or cyclic strains,*
- *is capable of useful accuracy but is often used in semi-quantitative analysis,*
- *is easy to use,*
- *is cost-effective,*
- *is widely accepted in industry.*

The series, Optical Methods - Back to Basics, *is written by University Distinguished Professor Gary Cloud of Michigan State University in East Lansing, Michigan. It began by introducing the nature and description of light and will evolve, with each issue, into topics ranging from diffraction through phase shifting interferometries. The intent is to keep the series educationally focused by coupling text with illustrative photos and diagrams that can be used by practitioners in the classroom, as well as in industry. Unless otherwise noted, the graphics in this series were created by the author.*

The series author, Professor Gary Cloud (SEM Fellow), is internationally known for his work in optical measurement methods and for his book, Optical Methods of Engineering Analysis.

If you have comments or questions about this series, please contact Jen Tingets, journals@sem1.com

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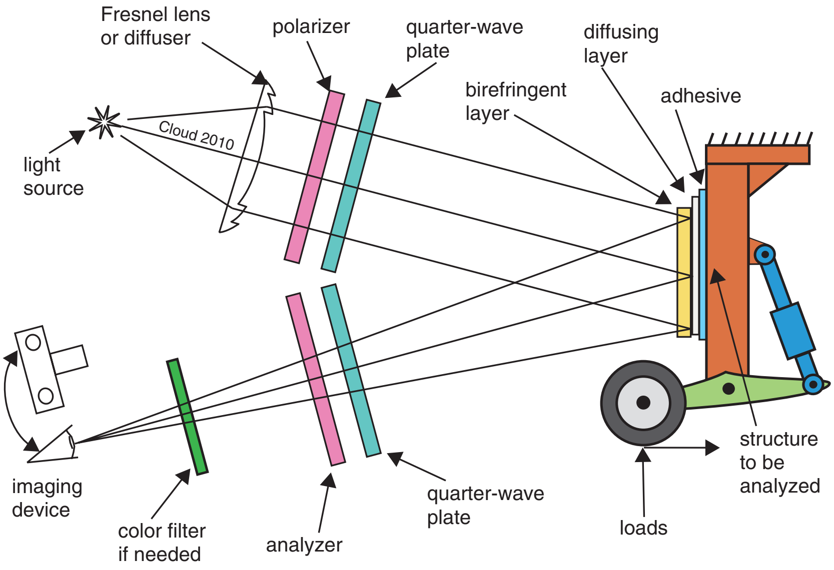
coating can then be directly related to the specimen surface strain. The basic apparatus is just a normal scattered-light polariscope as was described in Part 35 of this series, Figs. 2 and 3. For reflection work, the polariscope is "folded" in the middle. Alternative setups have been invented but will not be discussed here. The schematic below illustrates the basic setup.



The basic reflection polariscope is similar to a diffused-light transmission polariscope that is folded in the middle and includes in the optical path:

- *a light source that is usually a projection lamp,*
- *a crude collimator or diffuser,*
- *a polarizer,*
- *a quarter-wave plate,*
- *the birefringent coating attached to the specimen,*
- *a diffusing layer between the coating and the specimen*
- *a second quarter-wave plate,*
- *an analyzer that is the second polarizer,*
- *a color filter,*
- *a system to view or photograph the specimen coating.*

A device of this type is easy to fabricate, but commercially available systems are used most often. The light source is usually an ordinary projector lamp. In order to gain efficiency and reduce cost, most systems incorporate with the light source a crude Fresnel lens, which partially collimates the light, instead of a diffuser. The light source, collimator, polarizers, and quarter-wave plates are combined into a single unit, with the polarizers and quarter-wave plates mounted in calibrated rings so that they may be rotated (See Parts 35 and 39). The color filter may be clipped onto the unit as needed. Other attachments, including a device for performing stress separation via oblique incidence and another for precise fringe order determination, are part of the kit but are not discussed here.

COATING MATERIALS

Birefringent coatings having a wide span of properties are available or may be made from ordinary photoelastic materials. These range from low-modulus eurethane rubbers that are applied to specimens that might exhibit large strains to stiff resins that are used to investigate small strains in stiff structures. The materials are provided in flat sheets that may be wrapped around developable surfaces. Alternatively, coatings for convoluted shapes can be created via a "contour-sheet" technique whereby a partially polymerized resin sheet is molded to the specimen and then allowed to harden to form a shell. Objects can also be spray-coated with resin to create the birefringent coating.

Birefringent coatings:

- *are available in a wide range of stiffnesses and thicknesses,*
- *are chosen to fit the problem at hand,*
- *can be made using ordinary photoelastic plastics,*
- *are often purchased as flat flexible sheets that can be applied to flat or cylindrical surfaces,*
- *may be applied to complex surfaces using the "contour sheet" method,*
- *are usually attached to the specimen with cement containing aluminum powder, thereby creating the light-scattering layer between the specimen and the coating.*

The figure above suggests that there must be a separate light-scattering layer bonded between the plastic coating and the surface of the structure being investigated. The reason is that smooth shiny specimens create specular reflections that are difficult to manage because they create "hot spots" in the image. In practice, the birefringent layer is bonded to the specimen with a cement that carries fine metallic particles, thereby providing the dispersive layer. Sometimes a clear cement is used with coatings that have the scattering layer already bonded on one side. In other cases, the specimen itself is given a matte finish, so no additional dispersive medium is needed.

INTERPRETATION OF FRINGE PATTERNS

Keep in mind the very important fact that the STRAINS in the photoelastic coating ideally follow the STRAINS in the prototype, meaning that the photoelastic patterns do not directly indicate stresses in the prototype. Thus, the interpretations of the fringe patterns differ from those pertaining to transmission work.

The strains *in the photoelastic coating are assumed to be the same as the* strains *in the specimen surface, so the isochromatic fringe pattern does not yield directly the* stresses *in the specimen.*

Isoclinic fringes in reflection photoelasticity show principal strain directions. If the coating and the material are within the limits of elasticity or linear viscoelasticity, then the principal directions of stress and strain are the same. The utilization of isoclinic data, then, parallels that for transmission photoelasticity (See Parts 40 and 41), and nothing more needs to be said about isoclinics.

The interpretation of isoclinic data from photoelastic coatings is the same as that pertaining to transmission photoelasticity.

The interpretation of isochromatic data from the reflection method is another matter, and we must return to fundamentals. The first problem is to relate observed birefringence to strains in the specimen. Assume that strains in coating and specimen are the same and that the strains are uniform through the coating. Both these assumptions might be questionable in some cases; but, if they are true for the problem at hand, then the strain differences are equal.

$$(\varepsilon_1 - \varepsilon_2)_c = (\varepsilon_1 - \varepsilon_2)_s \tag{42.1}$$

In this article, the subscript "*s*" designates the specimen or structure, and subscript "*c*" applies to the birefringent coating.

Because the light passes twice through the birefringent coating, the previously derived relationships between stress and fringe order (See Part 32, equation 32.7) must be modified by putting in a factor of 2. Recall that m is the isochromatic fringe order, C_σ is the birefringent coating stress-optical coefficient (see Part 30), d is the coating thickness, and λ is the wavelength of the illumination used.

$$m = \left(\frac{2C_\sigma d}{\lambda}\right)(\sigma_1 - \sigma_2) \tag{42.2}$$

The stresses and strains in the coating must now be related to those in the specimen. If the coating is in the elastic or momentarily linearly elastic range (another assumption), then its constitutive equation in terms of the instantaneous Young's Modulus and Poisson Ratio is,

$$\varepsilon_1 = (\sigma_1 - \nu\sigma_2)/E \tag{42.3}$$

A similar expression obtains for the second principal strain. Use these relationships to evaluate the stress difference in terms of the strain difference for the coating,

$$(\sigma_1 - \sigma_2)_c = \left[\frac{E_c}{1+\nu_c}\right](\varepsilon_1 - \varepsilon_2)_c \tag{42.4}$$

Combine equations 42.2 and 42.4 to obtain the isochromatic order in terms of coating strain, and group the expressions for later convenience,

$$m = \left[\frac{2C_\sigma d}{\lambda}\right]\left[\frac{E_c}{1+\nu_c}\right](\varepsilon_1 - \varepsilon_2)_c \tag{42.5}$$

Put equation 42.1 into 42.5 and invert the result to get the *specimen strain* as an explicit function of the *coating* fringe order and *coating* material properties,

$$(\varepsilon_1 - \varepsilon_2)_s = m\left[\frac{\lambda}{2C_\sigma d}\right]\left[\frac{1+\nu_c}{E_c}\right] \tag{42.6}$$

Analysis shows that the difference between principal strain *difference at a point on the specimen surface is proportional to isochromatic fringe order in the coating and involves also:*

- *the wavelength of light,*
- *the stress-optical coefficient of the coating,*
- *the coating thickness,*
- *the Poisson ratio of the coating,*
- *the elastic modulus of the coating.*

This equation is often written in terms of a "K" factor that lumps the coating properties and that is offered by the manufacturer of the coating material,

$$(\varepsilon_1 - \varepsilon_2)_s = \frac{m\lambda}{2dK} \tag{42.7}$$

An alternate approach includes the $2d$ in the definition of K. Be certain that you understand the vendor's definition of the factor provided or, better, calibrate the coating material yourself using a specimen having a known strain field.

The coating material properties are often lumped into a "K" factor that is provided by the manufacturer.

This analysis may be carried further to find the stress difference in the specimen. Assuming that the specimen material is linearly elastic at the time, its constitutive relation is the same as that written in equation 42.4 for the coating but with material subscripts changed. If this stress-difference constitutive equation is combined with equation 42.6, the following result is obtained.

$$(\sigma_1 - \sigma_2)_s = m\left[\frac{\lambda}{2C_\sigma d}\right]\left[\frac{1+\nu_c}{E_c}\right]\left[\frac{E_s}{1+\nu_s}\right] \tag{42.8}$$

As is true of all photoelasticity, additional data and/or calculations are required to obtain the separate principal stresses or strains.

The analysis can be extended to obtain the principal stress difference in the specimen, in which case the specimen material properties must be considered.

SENSITIVITY AND FRACTIONAL FRINGE MEASUREMENT

The sensitivity of photoelastic coatings is limited in that only 3 or so isochromatic orders are ordinarily observed on specimens that are made of metal and are in the elastic range. Usually, some method of interpolation and/or fractional fringe measurement must be implemented to obtain quantitative precision. Commercial apparatus has built into it a Coker-type birefringent compensator for establishing approximate fractional order and nearest whole orders. Goniometric compensation is used to determine accurately the fractional order. Facility for the Tardy method is built into commercial equipment. Phase shifting and/or RGB approaches have been used with considerable success in recent years. These techniques have not been discussed in this series of articles, but at least one of them must be learned if precision is sought when using photoelastic coatings.

Isochromatic orders from photoelastic coatings are usually low, so techniques for fractional fringe measurement must be implemented for precise studies.

LIMITATIONS AND ADVANTAGES

As mentioned above, the reflection method is successfully used on a broad variety of problems, including structures of all kinds, rubber tires, machinery, concrete, and biological material. Sometimes it is misused because the experimenter may not have an appreciation for the limitations of this powerful method. Brief summaries of the more important potential sources of error follow:

1. True normal incidence cannot be obtained with the common forms of the reflection polariscope, although a different arrangement that uses partial mirrors solves this problem. The light strikes the coating along an incline, and the observation direction is also inclined to the surface. To reduce errors, the distance from apparatus to specimen must be kept fairly large in order to minimize the angles of incidence and observation. In other words, minimize the included angle between the axes of illumination and observation. Given the resulting long observation distance, a telephoto lens is often needed. Even so, the photoelastic effect observed will be an averaged over some finite area of the specimen surface.

Potential sources of error in reflection photoelasticity include:

- *The light incidence angle and the angle of viewing are not normal to the coating in the usual setup, so the photoelastic effect is averaged over a finite area.*
- *The polarization of light is known to change when it is reflected or scattered.*
- *The stress-optic properties of the coating might not be accurately known.*
- *The specimen might be reinforced by the coating, thereby changing the strain field.*
- *If out-of-plane bending occurs, the coating does not accurately render the strain at the specimen surface.*

2. The polarization of light is known to change upon reflection or scattering. The change is dependent upon the nature of the specimen material, whether a metal or dielectric, and the reflecting surface. This potential source of error has been largely ignored so far.
3. Material problems are usually ignored, and manufacturer's K factors are used with possible accuracy loss. Material calibration is important in all types of photoelasticity.
4. Reinforcement of the specimen by the coating may be serious, especially when the coating is used on low-modulus structures such as plastic, wood, rubber, or biological tissue.
5. In cases where there is a strain gradient normal to the specimen surface, the coating indicates falsely the strain at the surface. Think of a thin plate in bending, a common application of photoelastic coatings. This error source is the "thickness effect," which is also important in strain gage work.
6. The correspondence of coating strain and specimen strain at an edge of the coating might be poor because the deforming traction is applied only at the bottom side of the coating. This deficiency would be especially serious at a stress concentration such as a hole edge.

- *The strain at the edge of a coating might not be the same as the specimen strain; this problem is especially serious at the edges of holes or similar stress risers.*

Items 1, 4, 5, and 6 in the list above suggest that thin coatings and/or low modulus materials should be used to minimize these errors. However, thick coatings of materials that are stiff and have high optical sensitivity yield higher fringe orders that are easiest to analyze. Coating thickness, strain-optical coefficient, and stiffness must be chosen with care to achieve a balance between sensitivity and acceptable error.

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The deficiencies noted should not suggest that reflection photoelasticity is a poor method. Rather, the conclusion should be that, with careful work, the method is capable in practical applications of 5–20% accuracy. For many design situations, such accuracy is more than acceptable; so, in these cases, reflection photoelasticity is a fine time-saving experimental tool. Incidentally, many designers do not require precise quantitative reflection data. They are interested only in locating and minimizing stress concentrations while improving strength-to-weight ratios. Semi-quantitative reflection observations using white light so as to obtain colored isochromatics are often sufficient for such work, and such results are easily and quickly obtained.

Reflection photoelasticity:
- *is capable of roughly 5 to 20% accuracy, depending on technique,*
- *is often used in a semi-quantitative mode using white light for design optimization.*

WHAT IS NEXT?

The next article in this series will provide an overview of techniques to extend photoelasticity so that it may be used to study stresses in three-dimensional objects. ■

The next article of this series will provide a broad outline of three-dimensional photoelasticity techniques.