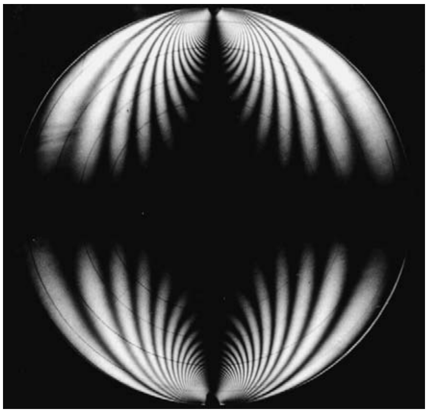
Optical Methods in Experimental Mechanics

Part 32: Photoelasticity IV—Observables and Interpretation

REVIEW AND PURPOSE

The previous article of this series developed the equation for the electric vector of light that passes through a dark-field linear polariscope that is used to examine the stress-induced birefringence at a single point in a slab of birefringent material. The light that exits the system is made to fall on a sensor that measures its intensity.

This article interprets the response of the sensor in terms of the stress parameters that cause the birefringence. A very simple experiment is described to illustrate how the light intensity is observed and used.



Photoelastic fringe pattern for disc in diametral compression obtained with a dark-field linear polariscope. Note that the isochromatic fringes showing stress magnitudes are partially masked by the dark cruciform isoclinic fringe that shows principal directions. Monochrome photo by Dr. Gary Cloud, ca. 1994.

Objectives of this article are to:
- *interpret the observable light from a linear dark-field polariscope that is used to measure stress parameters in a birefringent model,*
- *describe a simple experiment to illustrate point-by-point photoelasticity.*

PHOTOELASTICITY OBSERVABLES AND THEIR MEANINGS

Recall that Eq. 31.7 of the previous article expresses the electric vector of the light exiting the polariscope as amplitude times wave function. As was mentioned, only the amplitude is of interest in interferometry, whose purpose, after all, is to convert undetectable phase difference to measurable intensity difference. Extract from Eq. 31.7 the amplitude

$$E_s = A \sin\frac{\pi R}{\lambda} \sin 2\phi \qquad (32.1)$$

Sensors, whether they be our eyes, photocells, or detectors in a video camera, respond to intensity or irradiance; so, to be thorough, the square of the amplitude of the electric vector should be calculated. Bypass this step for awhile and simply ask the question, “For what conditions is the intensity zero?” The intensity will be zero when the amplitude is zero. Ignore the unhelpful case where the entering light amplitude A is zero, and two other independent conditions that result in zero amplitude present themselves. Both these cases yield valuable information about the stress field, so that they are studied separately.

The sensor responds to intensity, but we need look only at the amplitude for basic photoelasticity. Extract the amplitude from the photoelasticity equation and determine for what conditions the amplitude is zero.

Dependence on Stress Direction

No light falls on the sensor when,

$$\sin 2\phi = 0 \qquad (32.2)$$

meaning,

$$\phi = 0° \textit{ or } 90° \qquad (32.3)$$

Sensor output will be zero for two cases that are useful for determining stress parameters in the birefringent slab or photoelastic model.

The series, Optical Methods—Back to Basics, *is written by Professor Gary Cloud of Michigan State University in East Lansing, MI. The series 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 Proulx, journals@sem1.com.

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Recall from the sketch contained in the previous article the definition of ϕ as the angle between the polarizer axis and the first principal direction. Also recall that the polarizer and analyzer axes are mutually perpendicular. The conclusion is that the light is extinguished if the principal axes of birefringence, meaning the principal stress axes, are aligned with the axes of polarizer and analyzer. This result allows determination of principal stress directions.

In the first case, light is extinguished when the principal stress axes are aligned with the crossed axes of polarizer and analyzer. This result yields principal directions.

Dependence on Stress Magnitude

No light reaches the sensor when,

$$\sin\frac{\pi R}{\lambda} = 0 \tag{32.4}$$

meaning,

$$\frac{\pi R}{\lambda} = 0, \pi, 2\pi, \ldots \tag{32.5}$$

or,

$$R = 0, \lambda, 2\lambda, 3\lambda, \ldots \tag{32.6}$$

The conclusion is that the light is extinguished when the relative retardation, R, is a whole multiple of the wavelength used in the experiment. To get stress into the picture, collect from Part 30 of this series the relationship between relative retardation and principal stresses. (Author's note: Part 30, Eq. 30.6 is missing a "d." The correct form is shown below.)

In the second case, no light reaches the sensor when the relative retardation is an integer multiple of the wavelength. This result gives information about stress magnitude.

$$R = C_\sigma(\sigma_1 - \sigma_2)d \tag{30.6 corrected}$$

Substitute this result into Eq. 32.6 to obtain the conditions that the stress magnitudes must obey for extinction of light to occur.

$$\left(\sigma_1 - \sigma_2\right) = \frac{m\lambda}{C_\sigma d} \quad \text{where } m = 0, 1, 2, 3\ldots \tag{32.7}$$

To summarize in words, no light reaches the sensor if the difference between the principal stresses (twice the maximum shear stress) is an integer multiple of the wavelength divided by the product of the stress-optic coefficient and the thickness of the model. Clearly, this result can be used to obtain the principal stress difference if the sensor reads zero light, if m can be established, and if the stress-optic coefficient and model thickness are known. Determining exactly the value of m is not trivial, so more will be said of this problem presently.

The difference between the principal stresses is an integer multiple m *of the wavelength divided by the product of the stress-optic coefficient and the thickness of the photoelastic model. Presupposed is that the correct integer multiple at which the light is extinguished can be correctly ascertained for the loaded specimen.*

POINT-BY-POINT PHOTOELASTICITY

The results obtained above may be used effectively for determination of stress parameters through point-by-point interrogation of a specimen in a simple linear polariscope. The approach works exceedingly well and provides very accurate results when properly used. In fact, it is employed often as adjunct to whole-field measurements when a precise result is to be obtained for a specific point, such as through use of so-called compensation techniques. It also has been implemented, for example, in photoelastic studies with infrared light, where a single small sensor was necessarily used and where a light modulator was required to facilitate tuned amplification and filtering of sensor signals having poor signal-to-noise ratio.

The simple dark-field linear polariscope can be used without any other apparatus for point-by-point determination of stress direction and magnitude in a photoelastic model. This approach:

- *yields excellent results if carefully implemented,*
- *is used as an adjunct to whole-field photoelasticity,*
- *might be the only option for studies at nonvisible wavelengths, such as in the infrared.*

A SIMPLE EXPERIMENT

Understanding of basic photoelasticity is enhanced by conducting or at least thinking about a simple experiment in which a linear polariscope is used to measure stress parameters. A linear dark-field polariscope is set up according to the plan shown in the previous article. Replace the general birefringent slab with a specimen in which the principal angles and the principal stresses vary from point to point, that is, a typical photoelastic model. The objective is to determine as much information as possible about the stress state at a chosen point in the model.

As an experiment, set up a linear polariscope with:

- *crossed polarizers,*
- *a photoelastic model,*
- *a narrow beam light source such as a laser or laser pointer,*
- *a photocell, or*
- *a white card or ground glass if observations of intensity are to be visual.*

The illumination source should be capable of projecting a narrow beam of light along the optical axis. A laser or a laser pointer is ideal. The sensor can be any small photocell or photodiode. If observations are to be made visually, then place a matte white card or a ground glass so as to receive the light passing through the system. Never place your eye in the path of a concentrated laser beam.

Now with a small load on the specimen, the polarizer and analyzer are rotated together, taking care that their axes are kept mutually perpendicular. Alternatively, the model can be rotated relative to the polarizers. Monitor the sensor output as the rotation takes place and stop when the sensor output is zero, meaning no light reaches the sensor. The principal stress axes at the chosen specimen point are now known to lie parallel to the axes of polarizer and analyzer and these principal angles are recorded.

To determine principal stress directions at the chosen point in the loaded model:

- *rotate polarizer and analyzer together, keeping them crossed,*
- *observe intensity at the sensor while rotating the polarizers,*
- *stop the rotation when the sensor output is minimum,*
- *at this point, the polarizers are aligned with the principal stresses,*
- *record the principal angle.*

The next step is to use the polariscope to measure the relative retardation at the chosen point when the model is loaded. The polarizer and analyzer are first rotated by roughly 45° from the positions established in the previous step, again keeping their axes orthogonal. Again, it might be easier to just rotate the model relative to the polarizers. The reason for this extra rotation is to keep the angle-dependent extinction from masking the retardation-dependent extinction. Start with zero load on the model, in which state the sensor output will be zero.

Increase the load slowly while observing the sensor output as it oscillates between zero and some maximum. Count the number of times the output passes through zero until the load reaches some chosen maximum level at which the sensor output is again zero. The number of times that the sensor output has passed through zero is the value m in Eq. 32.7. If the stress-optic coefficient, the wavelength, and the thickness of the model are known, then the difference between the principal stresses can be calculated.

To determine difference of principal stresses:

- *rotate polarizer and analyzer about 45° from the position established above,*
- *begin with zero load on the model,*
- *increase the load and monitor sensor output as it cycles between maximum and minimum,*
- *count the number of times the light intensity passes through zero until maximum load is reached,*
- *the number of cycles from black to black is the value* m *that appears in the equation for the principal stress difference.*

There are evident shortcomings in this experiment. A more dependable method to isolate retardation-dependent extinction from angle-dependent extinction would be useful. Recording of sensor output as a function of load would be better than counting the number of times sensor output passes through null. Trying to establish the exact point of zero intensity does not give the precision that more sophisticated intensity-level determinations are capable of. Finally, accommodation of noninteger (fractional) values of m would eliminate the need to stop the load at a precise integer value of m. These issues disappear with implementation of small but significant changes in the polariscope setup and experimental procedure. Still, the simple apparatus and steps outlined above are capable of providing excellent measurements.

The simple experiment described:

- *has various shortcomings,*
- *is easily enhanced to eliminate the problems,*
- *still, is capable of yielding excellent results.*

WHAT IS NEXT?

The next article in this series extends this analysis to the whole field so as to obtain fringe patterns that are easily observed and interpreted to simultaneously obtain the stress parameters over the entire extent of the model. ■

The next article extends photoelasticity to the whole field.