Non-Contact Thickness Measurements of Luminescent Photoelastic Coatings
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ABSTRACT

The University of Florida has developed a luminescent photoelastic coating that measures the corresponding strain field when applied to a structural component being subjected to external forces or loads. The coating is sprayed on the component, and then excited with proper illumination. In turn, the coating emits a higher wavelength luminescence that is captured in images taken by a digital camera. The optical strain response by the coating is intensity-based, and is related to the maximum in-plane shear strain. This technology will eventually be used to determine strain fields for complex three-dimensional members and to assist in calibrating computational methods that predict component failure. This research effort focused on the effect that the thickness of the coating has on the intensity of the luminescence, and hence the measured strain. Several different approaches were taken to discover the correlation between the thickness of the coating and its response. Some approaches yielded relevant data, whereas some did not. Ultimately, a thickness-dependence was discovered by both modifying the coating and the optical equipment.

INTRODUCTION

A photoelastic coating is a substance that can alter the polarization of light propagating through a substance as a function of the local stress/strain field, the thickness of the coating, and the optical properties of the coating (1). Photoelastic coatings can be used in many areas of study. In fact, they are extremely useful in stress analysis. Stress analysis is an important part of the prototyping process in a variety of areas: the automobile industry, the airline industry, and architecture. Stress analysis allows engineers to study the weaknesses in their designs in a laboratory setting, as opposed to ‘active’ testing—such as crash tests for car safety ratings. This promotes shorter testing time, cheaper testing methods, and less destruction to the sample itself.

The University of Florida has a developed a luminescent photoelastic coating (LPC) (2). This coating has two general components (Fig. 1)—a luminescent base coat and a photoelastic top coat—that are applied to the surface of test parts with conventional aerosol techniques (A). A luminescent photoelastic coating enables excitation of the coating with short-wavelength light (blue) and detection of the corresponding long-wavelength emission (red). Technical advantages gained by incorporating the luminescent dye in the LPC are:

1. separation of excitation and emission wavelengths; hence, the elimination of specular reflections via optical filtering,
2. diffuse emission fields on the surface of complex geometries, and
3. off-axis measurements on regions of ±45°.

These parts can then be tested and their corresponding strain fields, which vary with load, can be generated and analyzed.

In general, photoelastic coatings have several parameters that can influence the analysis of data: coating thickness, Poisson's ratio mismatch, temperature fields, and wave propagation and vibration (4) The focus of these experiments was the effect of coating thickness on the generated intensity data.

Luminescent dye and photoelastic material have particular emission spectra (Fig. 2a). In theory, if the emission of the luminescent photoelastic material is thickness-dependent, the fluorescence intensity may vary in different ways as a function of coating thickness at two different fluorescent wavelengths. It was the objective of this study to investigate if thickness information could be attained from the emission spectra in order to calibrate for thickness variations. A series of experiments was designed to test various specimens with different thicknesses at different wavelengths; the data was then compared to develop a thickness calibration.
THEORY

The general equations used to relate thickness and other parameters to the intensity generated by the photoelastic coating for a particular wavelength of excitation and analyzer angle are:
In a typical strain measurement experiment, a load (force) is applied to a specimen and a series of images is acquired at a sequence of analyzer angles. The resulting intensities are fitted to a sine function with which the effective magnitude and phase are computed. The in-plane shear strain and its direction are related to the measured intensity response as shown in Eqs. (1) and (2). The goal of these experiments was to find out how the coating thickness, \( h \), affects the emission intensity, \( I \), and therefore the strain field of the sample. Once the thickness effects were understood, the next step was to generate a thickness-correction technique to make the strain field representations more accurate.

\[
\frac{I}{I_{avg}} = 1 + \phi \sin(\Delta \phi) \sin(2\alpha - 2\theta)
\]  

\[
\Delta \phi = \frac{2\pi K h}{\lambda - \gamma}
\]

where:

- \( \lambda \) = wavelength
- \( \lambda' \) = \( \lambda_{ex} \lambda_{em}/(\lambda_{ex} + \lambda_{em}) \) (ex: excitation wavelength, em: emission wavelength)
- \( h \) = coating thickness (parameter being investigated)
- \( I \) = measured emission intensity
- \( K \) = photoelastic optical sensitivity (property of coating)
- \( \alpha \) = analyzer angle (setting on polarizer)
- \( \gamma \) = shear strain
- \( \Delta \phi \) = relative retardation
- \( \theta \) = in-plane principal direction
- \( \phi \) = polarization efficiency (property of coating)

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**APPROACH**

Several different approaches were taken to test for a thickness-correlation. The first test involved producing wedge specimens (Fig. 3) in which the photoelastic coating varies in thickness. The thickness across the specimen was measured using a dial gage (Fig. 4). The specimen (B) was excited with blue light and the emission was measured at a higher wavelength. It was hypothesized that the intensity would increase as the thickness of the coating increased due to the natural luminescence of the photoelastic coating.
Figure 3a. Three Wedge Specimens.

Figure 3b. LPC Wedge Specimen Illustration.

Figure 4. Thickness Measurement Setup. The dial gage was zeroed at the base of the wedge, and then thickness measurements were taken every 0.25 inches along the length of the wedge. From this data, a line was approximated to the wedge, and the slope of the wedge’s thickness was calculated. This was then used to relate the position of every pixel in this image, to the intensity at that point, and its corresponding thickness.
In the second approach, a step specimen (Fig. 5) was fabricated with a modified version of the LPC—an additional dye was added to the photoelastic overcoat (Fig. 2b) that emits at a higher wavelength \(_\lambda\approx 700\text{nm}\) than the luminescent undercoat \(_500\text{nm}<\lambda_{\text{LPC}}<650\text{nm}\). The fluorescence intensity of this dye is expected to be directly related to the photoelastic overcoat thickness. Since it emits at a much higher wavelength than the undercoat, it can be measured using band pass filters. Using different band pass filters (a 600nm filter and a 700nm filter \(c\)) the fluorescence intensity emission can be measured at both wavelengths prior to the load sequences. The resulting data would provide intensity values generated from the LPC undercoat—using the 600nm filter—and LPC overcoat (thickness dependent)—using the 700nm filter.

![Figure 5. LPC Step Specimen Illustration.](image)

**INSTRUMENTATION**

Using an optical technique for both approaches, different specimens were tested in order to determine a thickness-dependence relation for the LPC. For the first approach, a steel specimen was coated with LPC using a modified wedge technique. The specimen was excited with a lower wavelength luminescence (blue light emitting device—LED \(D\)); in turn the LPC emitted a higher wavelength luminescence that was captured by a digital camera. The actual test setup is illustrated in figure 6. The camera setup is illustrated in figure 7.
Figure 6a. Black Box Testing Setup. This setup is used when the three-point bender applies the load to the specimen. All of the testing is done within the black box, and all the data is transferred from the digital camera to the computer. Testing is done within a black box so that white light from the room does not also excite the LPC, which would alter the intensity data.

Figure 6b. Equipment Setup. The light that excites the coating is produced by an excitation source (blue LED’s) and then passed through an excitation filter before hitting the specimen. The light is then altered by the coating and reflected back through an emission filter before reaching a digital camera that takes a picture of the intensity field. These images are then sent to the PC for analysis.
Figure 7. Digital Camera Setup and Functions. blue LED--excites the specimen (SSP2) with blue light; digital camera: captures images and relays them to the computer; lens--filters for different wavelengths of light that are generated from the specimen. polarizer--polarizes the light that is reflected back from the specimen; quarter wave plate--controls the amplitude and angle of rotation of the emerging light vector. Neither the polarizer nor the quarter wave plate were used when testing for thickness.

For the second approach, a steel plate was coated with the new LPC in a stepwise fashion. This sample was excited with varying light sources (1 LED, 2 LED’s, and 1 LED with polarizer). Then the data was recorded using four different filters (E) (600/10, 700 long pass, 700 narrow, and 600/40 (F)).

Figure 8. Processed Intensity Ratio Image. This is a sample processed image. The sample in the image is two bars placed on top of one another; the top bar is a wedge, and the bottom bar is a step sample. In this image, the intensity ratio (I700/I600) gradients are visualized by a color spectrum. The red corresponds to the highest emission intensity ratio, and the purple corresponds to the
The first approach yielded data that gave no conclusive indication of a thickness-dependence in the LPC. The data from this set of tests showed no thickness-dependence—a constant intensity value with respect to thickness (Figure 9).

The second set of tests gave promising results. Sets of images were taken for three different excitation scenarios: 1 LED, 2LEDs and 1 LED with a polarizer. For each excitation scenario, two filters were used to measure the emission: 600/10 nm and 700 nm. The intensity generated at 700 nm was then ratioed with the 600/10 nm intensities. These ratios showed a linear dependence with thickness (Figure 10). The maximum ratio was about 2.7; at the thickest point, the emission by the dye filtered at 700 nm is 2.7 times greater than the emission by the photoelastic coating filtered at 600/10 nm. Hence, the emission by the dye in the LPC can be separated from the intensity data and used to generate a thickness-dependence.
CONCLUSION

By adding another dye to the LPC, meaningful thickness results can be generated that do not interfere with the raw intensity readings produced by the LPC. There are some costs involved in adding this dye to the photoelastic coating. The thickness dye does minimally decrease the emission intensity of the luminescent undercoat compared to no additional dye due to the absorption of the undercoat emission by the thickness dye, but this can be compensated for by increasing the exposure time \(G\) of the sample. Increasing the exposure time means longer testing, but this is a small price to pay for meaningful thickness-dependence data.

Currently, other types of luminescent coatings—pressure sensitive paints and temperature sensitive paints—are in widespread use in a variety of industries. LPC is a strain sensitive paint and is a relatively new technology that is still in the research and development stage at the University of Florida. There are still other aspects of LPC that are not yet understood and need to be tested. The thickness-dependence problem is now on the right track to being understood. Once this effect is quantified, other areas—such as temperature dependence—can be focused on in order to perfect this form of photoelastic coating.

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NOTES

A. A single layer can also be formulated in which the luminescent dye is incorporated into the photoelastic coating (3).

B. The steel rectangular specimens used in both testing approaches have the following dimensions: 1/4" thick, 1.5" wide, by 18" long.

C. The nature of these filters is that they only allow a certain range of wavelengths to pass through them, therefore screening the light that the digital camera records. These filters typically have a range of 10nm, meaning that a 600nm filter would pass light with wavelengths ranging from 590nm to 610 nm. No other light would pass through the filter to the digital camera; the emission by the new dye at 700 nm would neither be
seen nor recorded by the digital camera. Therefore, the data collected when using a 600 nm filter accurately represents the LPC undercoat emission only; similarly, the 700 nm filter yields data from only the LPC overcoat’s emission.

D. The wavelength for blue light is centered at 485 nm.

E. A sample of what recorded data looks like is depicted in Figure 8. The camera takes actual pictures of the samples, but the data is hidden within the images themselves. Intensity and strain values can be extracted from that data.

F. For a 600/40 nm filter, the 40 refers to the bandwidth at half transmission.

G. The exposure time corresponds to the amount of time that the camera system is collecting data from the LPC. For example, if the exposure time for a particular experiment is two seconds, then the camera receives information for two full seconds for generating an image. In this time period, the camera is essentially continually receiving a certain range of wavelengths of light. The longer the sample is exposed, the more light the camera receives, and the more ‘intense’ the data readings. Hence, a sample that is exposed for five seconds will have a higher intensity reading than the same sample exposed for only one second. By increasing the exposure time of the sample, the same amount of intensity can still be generated as the original LPC.

REFERENCES


