# Out of plane deformation measurements of axially loaded composite materials using electronic speckle pattern interferometry

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## Abstract

The use of composite materials is fairly new and becoming increasingly pervasive. Composite materials are found in applications ranging from aircraft structures, automobile parts, to both heavy and light ballistic armor. The use of composite materials is recent, therefore existing theory and data on material performance is an opportunity area for development.

Strategies for theory improvement include development of computational methods to predict the energy required to create a fracture and the energy levels required to sustain a rate of crack propagation. It is necessary to generate data on these energy levels to test the validity of the computational predictions.

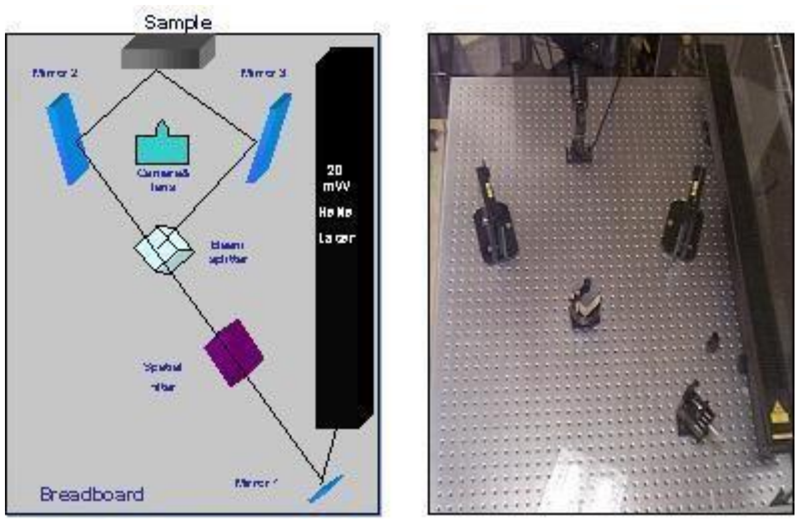
Previous methods to determine these energy levels were to measure the length of the crack over a given number of loading cycles. These techniques adequately address energy expended in the in-plane direction, but ignore energy expended in deforming the material in the out-of-plane direction. The focus of this study is to use Electronic Speckle Pattern Interferometry (ESPI) to measure the out-of-plane deformation of graphite/epoxy samples under quasi-static cyclical uni-axial loading.

## Introduction

Electronic Speckle Pattern Interferometry (ESPI) is a technique for measuring surface contours and deformation patterns to a high degree of precision and accuracy. ESPI employs a speckle pattern created by reflecting coherent light off a rough surface. The speckles are interference images created when the path lengths of converging rays reflected off the illuminated surface differ by half the wavelength of the coherent light source. Changes in path lengths of one half wavelength of the coherent light illuminating the surface will create a speckle.

Speckles are created in a pattern consistent with the surface being illuminated. When changes in the illuminated surface result in path length differences of half wavelength, a new family of speckles will be created. Hence, a surface with an irregular shape can be mapped to within one half a wavelength of the coherent light being used. A digital camera captures the speckle images. Computer techniques are used to extract a speckle pattern from the digital photographs of the material. These speckle patterns are then computer filtered to create high-resolution contour maps of the shape of the object. The difference in distance of successive contours, or contour interval, is a function of the geometry of the set-up. The optical set-up is depicted below in Fig. 1.

**Figure 1**: Diagram of laser optics (left) and photo (right) of actual Electronic Speckle Pattern Interferometry configuration at the Advanced Materials and Structures Laboratory at Rutgers University's Department of Mehcanical and Aerospace Engineering.




The laser speckle system passes the beam of a 28 mW, 633 nm laser through a 20 µm "pinhole" to create a laser speckle. The beam is then split and reflected off mirrors to converge on the sample. Splitting the beam creates a reference beam and a space directly in front of the sample where a camera can be placed to capture images of the speckle pattern.

## Method

The following method is used to measure out-of-plane deformation:

1. A sample of graphite/epoxy, configured according to the ASTM standards, is clamped into the jaws of an Instron materials testing system and placed under an axial load at a frequency of 3Hz.
2. Thirty photographs of the sample are recorded at a rate of 30 frames per second. This rate of image acquisition ensures that at least two complete loading cycles are recorded.

3. Two images, five to seven frames apart, are chosen to extract a fringe pattern. A program written in LabView© is used to extract a fringe pattern.4. The fringe pattern is then filtered and the contours are mapped with another LabView© program. 5. The magnitude of the deformation is determined by

   the contour interval. The contour interval is a function of the geometry of the set-up and is determined by eq. 1:

$$d = \frac{2\pi}{\lambda}\left[\cos\Theta_1 - \cos\Theta_2\right] \quad (1)$$

where: d = length of the contour interval, $\lambda$ = wavelength of the laser illuminating the sample, $\Theta_1$ and $\Theta_2$ = incidence angles of the two beams converging on the sample.

**System emplacement**

Installation and operation of the laser system required significant reorganization of the laboratory workspace. Once this task was completed, all power requirements of the system were met with existing house electrical supply.  The system will ideally measure samples of varying length along the entire length of the sample. To accommodate samples of varied length a support system was designed and constructed that allows the entire optics board, to which all laser and optics components are fastened, vertical travel over the full range of sample length and position.  The clamping jaws of the Instron materials testing system are contained in an upper and a lower head. The upper head is free to rotate about the vertical axis and the lower head is fixed. Pumping hydraulic fluid into an actuator through hoses causes vertical movement of the upper head. The positioning of the hoses and their attachment to the upper head causes a small, repeating rotation of the upper head during each cycle. This rotation imparts a twist to the sample during the loading cycle.

The ESPI system would read the twist as an out of plane deformation. When the sample twists in the direction of the camera, an exaggerated out of plane deformation will be measured. When the sample twists away from the camera, no deformation, or a diminished deformation will be recorded. This twist then will introduce massive errors in our results given the scale of deformation to be measured.

To eliminate the twist it was necessary to restrain the upper head from rotation about the vertical axis without impairing its vertical translation. The restraint also had to be lightweight so as not to add a degree of inertia that would adversely affect the load cell reading. To accomplish this an anti-rotation device was designed and constructed of 6061 aluminum. This bar clamps to the central shaft connecting the upper head to the actuator. Roller assemblies constructed of hardened steel are attached to the ends of the bar with low friction bearings. These roller assemblies ride on the columns that support the upper head and actuator, thereby preventing rotation.

It was desired that the laser and optics components be protected from falling objects, dust, dirt, and other foreign matter that may damage the optics surfaces or impair image acquisition. To afford this protection a cast acrylic housing that encloses the optics board while providing complete access to all sides of the board was designed and constructed. With the completion of this enclosure, all physical requirements of the system were met.

## Results

**Figure 2**: Fringe pattern subtracted from an overly reflected graphite/epoxy sample.

Successful focus and aiming of the laser creates a speckle pattern on the sample that has a "grainy" appearance to the naked eye. Initially our goal was to create a family of fringe patterns on a graphite/epoxy sample. A previously delaminated sample was placed into the Instron and a cyclical load was applied. Attempts to map contour patterns on this sample were unsuccessful due to the highly reflective surface of the sample. We have found that the shiny surface of the graphite/epoxy sample reflects the laser light in an interference pattern, visible to the eye, which the fringe subtraction software misreads as a speckle fringe. An example of this is presented in Fig. 2.

Strategies considered to overcome this, centered around techniques to alter the surface of the composite sample without affecting its mechanical properties. These strategies include lightly abrading the surface of the material with a very fine grade of sandpaper, sand or glass bead blasting the surface, and painting the surface. For cost and expediency considerations, the sample was painted with an ultra-flat black paint. The ESPI system measures changes in the position of the sample so painting it should introduce no measurement error providing no paint flakes off the sample during the loading cycle.

Attempts to map the surface of the sample after painting it were met with poor results. Specifically no usable fringe patterns were obtained. It became clear at this point that the ESPI system was not a "turn-key" tool and significant calibration would be required.

## Calibration

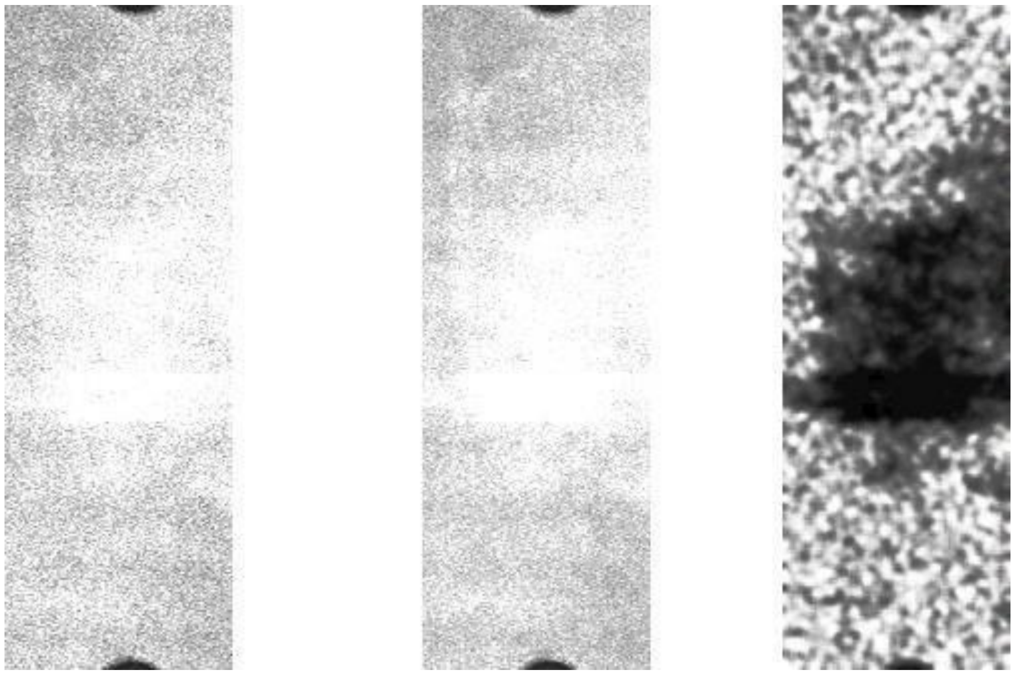
Calibration can be approached with two different methods. Inspection of eq. 1 shows that the contour interval depends on, and is very sensitive to, the difference between the two angles of incidence. One method would be to adjust mirrors 2 and 3 on the optics board to yield the angles of incidence necessary to map out of plane deformations of the desired scale, see Fig.1. This method would be problematic given the great measurement sensitivity to these angles, and the difficulty in measuring them to the necessary accuracy.

Another method would be to measure a sample of known deformation and vary the positions of mirrors two and three on the optics board until contours were successfully mapped. This trial and error method, while not as elegant as that method described above, has overwhelming advantages in simplicity and ease of execution.

To pursue the second method a calibration sample was constructed to similar dimensions as the actual ASTM sample. The calibration sample was made of two aluminum plates, one much thinner that the other, fastened together. A hole was drilled and tapped through thicker plate. By placing the calibration sample in the Instron with the thinner plate facing the camera and turning a screw through the back of the thicker plate the thinner plate can be made to deform toward the camera a known distance. A 10-32 screw was used which produces 2.19 μm of out of plane deformation per degree that the screw is turned.

The calibration procedure followed was to begin with the smallest angle of incidence that the optics board geometry would permit and attempt to map deformation of the calibration sample over a range of deformations. First, an image of the speckle is acquired when the sample has no deformation. Following this, images are acquired with 197, 394, 591, 788, & 984 m of deformation. Each increment corresponds to a $90^{o}$ turn of the screw. Fringe patterns are subtracted from each image of the deformed sample and the initial undeformed image. Examples of these speckle images and the subtracted fringe pattern appear below in Fig. 3.

**Figure 3**: (a) Speckle pattern of the calibration sample with no deformation. (b) Speckle pattern of the calibration sample deformed at 197 μm. (c) Subtracted fringe pattern.



(a) (b) (c)

When the subtracted fringe pattern presented in Fig. 3(c) is mapped no contour intervals are found. This fringe pattern is representative of all fringe patterns obtained with this mirror configuration The geometrical set-up of mirrors 2 and 3 are not appropriate in order to measure deformations on the 0-984 μm scale, see Fig. 1.

## Conclusions and future Work

The first stage of this project, i.e., set up of the ESPI facility, initial calibration of the method, data acquisition and validation of the operational software, has been completed successfully. During the second stage of the project, i.e., analysis of the acquired images, we opted for the input and help of the system's vendor. After some modifications to the position and focus of the spatial filter recommended by the vendor usable speckle images are being obtained. The vendor has provided us with good fringe patterns taken from an aluminum plate. Successful filtering and mapping of these fringe patterns verifies that those programs are operational. No usable fringe patterns have been obtained yet, and so no deformations have been mapped. In order to do so the mirror configuration on the optics board must be adjusted to measure the desired level of deformation. Efforts to do so are ongoing.

## List of abbreviations

ESPI: Electronic Speckle Pattern Interferometry
ASTM: American Society of Testing Materials  m:
□micro meters

nm: nano meters
mW: milli Watts

## References

**Aebischer, H. & Waldner, S., (1999)** A Simple and Effective Method for Filtering Speckle-Interferometric Phase Fringe Patterns. Optics Communications Preprint, Vol. 162, pp. 205-210.

**Cloud, G., (1995)** Optical Methods of Engineering Analysis, Cambridge University Press, 1st Edition.

**Kujanwinsica, M. & Salbut, L., (1993)** Material Studies of Composites by Automatic Grating Interferometry. Interferometry VI - Applications, Proceedings of the International Society for Optical Engineering, Vol. 2004, pp. 282-288.