

Measurement of mechanical strain at interior locations

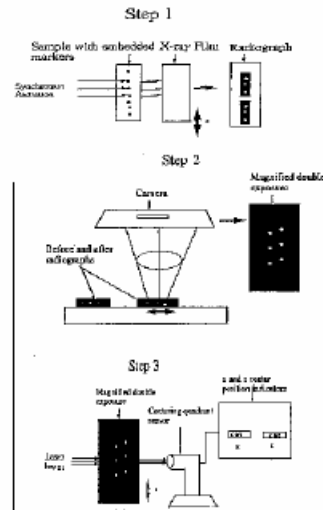
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Mechanical failure caused by overloading or by cyclic loading typically occurs at locations where deformation and mechanical strain are concentrated. Consequently, a great deal of effort has been invested in both calculating and measuring mechanical strain distributions for engineering structures and components. A wide variety of powerful techniques have been developed for measuring strain at free surfaces [1]. These methods range from real-time single point measurements using electrical resistance strain gauges to full field measurements using Moiré interferometry. None of these techniques can measure strain at non-surface locations in optically opaque materials. A technique for measuring the distribution of strain on a selected interior plane using synchrotron radiation is being developed using the facilities at CHESS and at NSLS.

The interior strain distributions are often different from the surface distribution especially when heterogeneous properties are present. In general the strain fields around inclusions are affected by the presence or absence of nearby inclusions. Surface and interior locations clearly have different nearest

neighbor geometries. Three specific interior strain distributions are of interest in this investigation: strain fields in adhesively bonded joints, strain fields between layers in laminated composites and strain fields around individual fibers in composites. The three problems generally involve relatively small structural features so maximum spatial resolution is desirable. The special properties of synchrotron radiation are critical to achieving high spatial resolution in the new method.

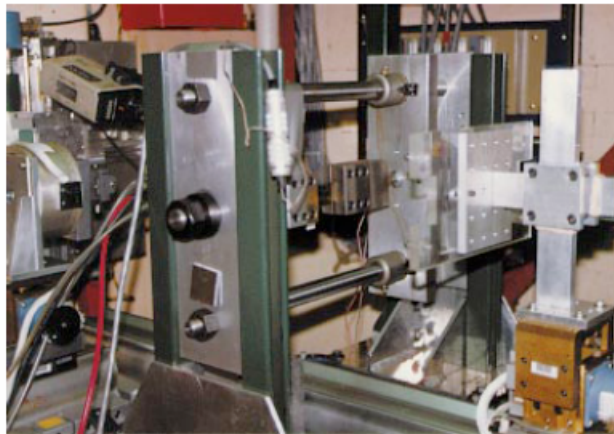
The goal of the method is to obtain high spatial resolution strain field measurements on a selected plane within a solid body. It is worth noting that strain information averaged through the thickness is not particularly valuable because spatial averaging in the through thickness direction would obscure the interesting and important regions of concentrated strain. The basic idea of the method is to implant x-ray opaque markers on a specific plane in a solid that is x-ray transparent and record radiographs of the precise location of the markers before and after mechanical loading. The two radiographs will then be carefully measured to quantify the deformation



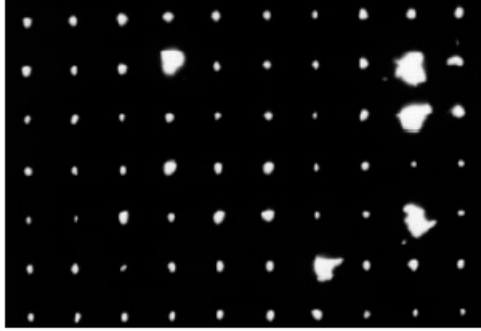
(Figure 1) Three step method developed to measure internal strain. 1. Use synchrotron radiation to photograph the markers before and after mechanical loading. 2. Enlarge the x-ray pictures to facilitate marker position measurement. 3. Use an electro-optical setup to measure the marker positions to a resolution better than 0.03 microns.

field. This process is carried out in three steps which are schematically illustrated in figure 1. The three steps are: 1) Use synchrotron radiation to photograph the markers before and after mechanical loading; 2) Enlarge the x-ray pictures to facilitate marker position measurement; and 3) Use an electro-optical setup to measure the marker positions to a resolution better than 0.03 microns, when referenced to the original photos. Strain can subsequently be calculated from the change in marker positions.

The exact experimental procedure used in the method is still being refined so that some of the specifics of the procedure have been and will be changed as improvements are made. Two general points should be kept in mind in understanding why certain techniques were chosen. First, higher spatial resolution requires placing markers closer and closer together. Unfortunately, the markers must be five diameters apart in



(Figure 2) Portable mechanical sample loading device installed in the C2 hutch at CHESS.



(Figure 3) A 100X enlargement to a radiograph of 20 micron diameter by 25 micron thick gold markers made at the L_{α} absorption edge.

we will be able to see is of the order of a few microns. However, we are currently unable to micro-fabricate markers that are both a few microns

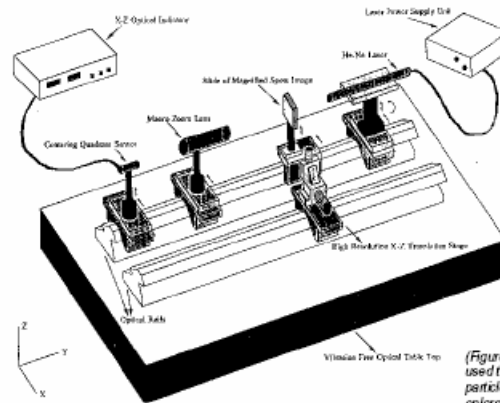
in diameter and 10 to 30 microns thick. By decreasing the marker size, the technique has the potential for about an order of magnitude improvement in spatial resolution. We are currently working on methods to approach that limit. The majority of the synchrotron work has been carried out at station C2 at CHESS using a portable mechanical loading device which is installed in the hutch (Fig. 2). Most imaging is done by tuning the monochromator to the absorption edge of the marker, which typically is the L_{α} edge of gold or the K edge of nickel. In some cases, very thick nickel markers have been imaged well above the absorption edge in order to penetrate ceramic loaded polymers that were hard to penetrate at lower energies. For highly absorbing samples, harmonic suppression is very important due to the tremendously greater penetration of the 3rd

order harmonics that may be present. We often use between 50% to 90% detuning to achieve harmonic suppression and to make the exposure times long enough to be easily hand-timed using hutch shutters. A typical radiograph is shown in Fig. 3 and consists of white dots on a dark background. Enlargements of the radiographs are made (33X) in a photo microscope, with care taken that corresponding markers in the before and after enlargement fall in the same part of the field of view of the microscope. This is necessary because the strains that are typically measured are on the order of 0.1% while the microscope magnification non-uniformity is typically 1%. A number of methods are possible for measuring the change in particle spacing to the desired accuracy of 1 part in 10,000. We developed the electro-optical set up shown in Fig. 4. Here, we project the image of the marker illuminated by a laser onto a lateral effect photodiode that detects the image centroid to about 0.25 microns. The markers are successively centered in front of the diode and their position read to 0.2 microns by an accurate servo stage with encoders. This process is now fully automated and computer controlled. The current gauge length of 100 microns and the stage resolution of 0.006 microns, referenced back to the original unenlarged image, yields a spacing resolution of roughly 75 ppm. The raw data consists of before and after coordinate sets. At present, simple averaging methods are used to smooth the

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(Figure 4) Apparatus used to measure interparticle spacing on enlarged radiographs.

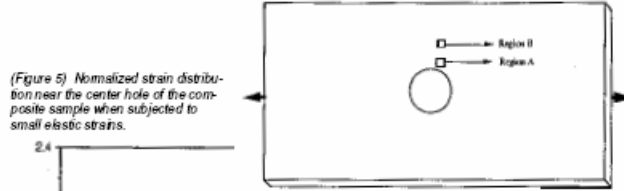
data as part of computing strain by differentiation. Regularization schemes are being considered for more optimal data processing.

To illustrate the type of results achieved, we show in figures 5 and 6 strains measured in a 4 layer graphite-epoxy composite. In figure 5, the strain around a circular hole at moderate load is shown compared to a calculated result. It is apparent that the agreement between theory and experiment is good. In figure 6, the strain distribution around the same hole is shown for a load that was large enough to cause local delamination. The strain distribution shows a large disturbance that could not have easily been predicted. Prediction of such a strain distribution would require detailed knowledge of the damage zone geometry which is not available. It is further worth noting that the damage was not visually apparent but was clearly seen in the strain data.

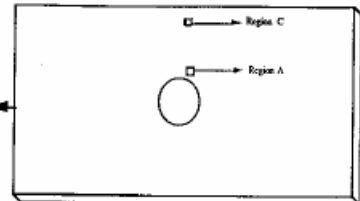
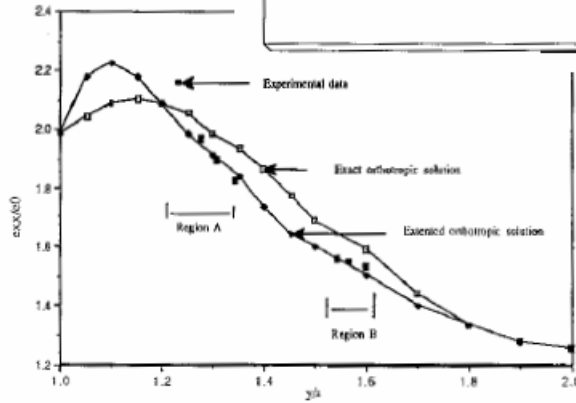
In summary, a new method for measuring strain distributions inside optically opaque objects has been developed, which relies on the unique properties of synchrotron radiation. The technique has matured to the point that successful experiments are more the rule than the exception. At present, the spatial resolution is 100 microns and the strain resolution is 100 ppm. Further improvement of spatial resolution of up to an order of magnitude may be possible before the diffraction limit is reached. Strain resolution improvement is also possible.

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2. Jordan, E. H., Ochi, S. C. U., Peas, D. M. and Budnik, J. I., "Microradiographic Strain Measurement Using Markers," Experimental Mechanics V. 34, No. 2, 1994, pp. 155-165.
3. Ochi, S. C. U., "Measurement of Internal Strains Using Synchrotron Radiation and Marker Particles," Ph. D. Thesis, Univ. Connecticut (May 1992).



(Figure 5) Normalized strain distribution near the center hole of the composite sample when subjected to small elastic strains.



(Figure 6) Normalized strain concentration near the hole (marked region A) of the composite sample when subjected to near delamination strain.

