CHARACTERIZATION OF LOCAL STRAIN FIELDS IN CROSS-PLY COMPOSITES UNDER TRANSVERSE LOADING

BY

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THESIS

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**ABSTRACT**

Transverse matrix cracks often occur in fiber-reinforced cross-ply polymer matrix composites subjected to tensile loads. Experimental visualizations of strain fields are necessary to calibrate and validate computational models that predict strain development and transverse crack initiation. In this study, fluorescent digital image correlation (DIC) measurements are used to study the evolution of highly localized displacements and strains under transverse tension. Composite coupons and Aluminum 6061-T6 control samples, both with dimensions of 50 mm in length, 2 mm in width, and 1.25 mm in height, were prepared with one polished surface spincast with a solution of fluorescent nanoparticles to produce a DIC speckle pattern. Specimens were tested in a miniature load frame in an optical microscope. Using a long working distance objective lens and a monochrome camera with a 668.4 by 534.7 µm resolution, fluorescent images of the polished surface were captured periodically to track the developing strains in the specimen. Strains were successfully measured using DIC for composite specimens. Bands of strain were observed to form perpendicular to 0° plies and often traced along pockets of resin. Additionally, strain concentrations formed between tow borders and pockets of resin and were nearly twice the value of the average strain for the area of interest. These results were consistent qualitatively with a photoelastic study shown in literature.
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CHAPTER 1

INTRODUCTION

1.1 Motivation

Fiber-reinforced polymer matrix composites are valued for their high strength-to-density ratio and high stiffness-to-density ratio [1]. Composites are used in high-performance materials applications in many industries, including the aerospace, automotive, and marine industries [2–4]. One failure mechanism composites experience under tensile loading is transverse cracking. In particular, unidirectional composites and cross-ply composites experience transverse cracking, with cross-ply composites experiencing cracking on a characteristic length scale. The appearance of transverse cracks in a cross-ply composite leads to reduced stiffness, diminished elastic properties, potential for reduced strength and damage tolerance, and the cracks themselves can be difficult to detect [5]. A unidirectional specimen may separate in two through the development of a single crack.

Though transverse cracking has been extensively studied and modeled in literature [6–8], little research has been dedicated to understanding the development of strains that lead to transverse cracks throughout the specimen. Scalici et al. [9] examined the strain fields occurring in cantilevered E-glass/polyester composites subjected to bending loading. Tracy et al. [10] utilized microscale DIC to measure the local strain fields occurring in weakly-bonded SiC/SiC ceramic matrix composites under transverse tension; however, the fibers were used as a speckle pattern, providing a lower-resolution strain analysis only on the matrix. Canal et al. [11] performed a compression test on unidirectional E-glass/MTM-57 epoxy composites and used microscale DIC to analyze the strains occurring on the free edge during the test.
While many computational analyses and some experimental studies have been performed, there have been few experimental studies that examine the local strain fields that occur on the 90° plies of cross-ply composites as the composite is under transverse loading [8]. The nanoscale study of these strain fields could provide insight into why cracks occur in certain locations, what local strains the composite experiences before cracks develop, and moreover could aid in validating computational models.

1.2 Digital Image Correlation

Local strain fields can be visualized particularly well using DIC. DIC is an optical, non-contact, length-scale independent displacement and strain measurement technique [12]. To utilize this technique, a high contrast, non-repetitive, isotropic pattern must be applied to the surface of the specimen [13]. Once a suitable pattern has been created on the specimen surface, an initial image is taken of the sample before it has undergone deformation, like the image shown in Figure 1.1 a). The sample is then deformed and imaged periodically throughout the deformation process, resulting in a final image like the one shown in Figure 1.1 b). These images are then analyzed with a computer code or commercial program. The code or program examines an individual subset of pixels in the base image, shown highlighted in the white box in Figure 1.1 a). The program then tracks the subset of pixels to the following image and determines how much the pixels have moved with respect to the base image by minimizing a cross-correlation coefficient. With this, the full-field displacements are found. After the calculation of the displacements, the strains are typically calculated using a least squares fit [14]. In this study, DIC analysis was performed using Vic2D, a commercially available DIC software program.
Traditionally, if the specimen surface is not already suitably patterned, a custom pattern is created by application of paint or marker to the surface. Speckle patterns can be made small enough to provide microscale resolution [14]. To obtain nanoscale resolution, fluorescent silica nanoparticles are applied to the surface [16]. When excited with a light source such as a mercury lamp, these nanoparticles fluoresce to a size that is approximately four to five times their diameter. The nanoparticles adhere to the material surface via static electricity and do not affect the material properties in any way, as they are disperse and small compared to the sample size.

Berfield et al. [17] showed near linear correlation with microscale and nanoscale DIC measurements when utilizing fluorescent speckle patterns, as can be seen in Figure 1.2. These fluorescent speckle patterns resulted in displacement resolutions of approximately 17 nm over a 100 μm² field of view. In literature, Hamilton et al. [18] utilized fluorescent nanoscale DIC to examine local strains in composites, though under uniaxial tension rather than transverse tension. Berfield et al. [16] used fluorescent nanoparticles both on the surface and embedded in PDMS to examine the strain fields occurring while the specimen was in tension. A nanoscale DIC study has additionally been conducted to examine local strain fields on silica nanocomposites in uniaxial tension [19].
1.3 Thesis Overview

The research in this thesis utilizes nanoscale DIC to examine the local strain fields occurring on cross-ply composites due to transverse loading. Chapter 2 details the process of preparing specimens, as well as the methods with which the specimens were tested. Chapter 3 describes the results and corresponding discussion to the experiments described in the latter part of Chapter 2. Chapter 4 is a final summary of the work in this thesis as well as a description of potential future work that could improve this experiment.
CHAPTER 2

METHODS AND MATERIALS

2.1 Introduction

This chapter describes the methods employed to manufacture and test specimens, in addition to methods of data verification. Two types of specimens were created: carbon fiber composite samples, manufactured with a pre-preg machine; and Aluminum 6061-T6 control samples. After proper polishing procedures and cutting down to size, specimens were spincast with a solution of fluorescent nanoparticles to create a fluorescent DIC pattern. Both types of samples were then checked for correlation with translation and focusing tests, and lens distortion was corrected to produce accurate results. Finally, a procedure for the tensile testing of specimens while imaging for DIC is described.

2.2 Material Preparation

2.2.1 Composite Fabrication

Carbon fiber composites were fabricated by doctoral candidate Sang Yup Kim using an in-house pre-preg machine, a schematic of which is shown in Figure 2.1. The pre-preg machine take-up drum has a diameter of 0.78 m, its rotation speed can vary from 1-14 RPM, and the fiber translation speed can also vary from 6-84 mm/min.

Figure 2.1. In-house pre-preg machine schematic created by Sang Yup Kim.
The materials utilized were AS4-G-3k high-strength carbon fibers and Huntsman 8605 resin. Once the fibers were impregnated with the resin, they were distributed and laid out in sheets. These sheets were then arranged in a \([0/90_3/0/90_3/0/90_3/0]\) ply scheme, vacuum-bagged, and placed in an Autoclave (Baron BAC-36) at 50°C for 3 hours with a 2°C/min ramp rate, then cured in a convection oven for 12 hours at 80°C, then 2 hours at 120°C, and finally 3 hours at 150°C. This process produced composites with void fractions less than 5% verified by optical microscopy, as shown in Figure 2.2.

![Optical image of 90° ply of polished carbon fiber composite.](image)

**Figure 2.2.** Optical image of 90° ply of polished carbon fiber composite.

### 2.2.2 Nanoparticle Fabrication

Fluorescent nanoparticles were synthesized using the procedure described by Verhaegh et al. [20]. The nanoparticles were composed of a rhodamine isothiocyanate core approximately 150 nm in diameter and a protective silica shell that was 300 nm in diameter, shown in Figure 2.3. The nanoparticles were stored in a solution of ethanol in an environment with a temperature below freezing in order to prolong particle life. When being transported in areas with sunlight or UV rays, the nanoparticle storage containers were wrapped in Aluminum foil to prevent particle bleaching.
2.2.3 Specimen Preparation for DIC

Composite samples from fully-cured pre-preg panels were cut to a length of 50 mm and a height of 8 mm using a diamond-edge saw blade (Buehler Isomet 30HC.) The samples were then prepared for polishing by mounting them in a polishing fixture with one transverse edge parallel to the abrasive cloth.

The samples were polished using the polishing procedure described in Table 2.1. Each step was repeated as many times as necessary to eliminate scratches and additionally utilized a new piece of polishing paper each time. To create a low surface roughness, samples were then polished on two lapping cloths: first, on a silk cloth (Buehler Trident) with a suspension of 1 µm alumina particles in deionized water, and next, on separate silk cloth (Buehler Trident) with a suspension of 0.05 µm alumina particles in deionized water. Following the last step of the polishing procedure, samples had a surface roughness of approximately 50 nm. Polished specimens were then sectioned to a thickness of 1.25 mm using the diamond-edge saw blade.
A pre-polished aluminum 6061-T6 sheet was obtained from McMaster-Carr. Samples were cut using a waterjet cutter that did not abrade the polished surface, and were cut to the same dimensions as the composite specimens.

Polished samples were inserted in polydimethylsiloxane (PDMS) molds to prepare for spincoating. A dilute solution of fluorescent nanoparticles in ethanol was prepared and sonicated with a sonication horn for 20s in order to reduce particle agglomeration. Samples were then spincast with this solution. The recipe ramped for 10 seconds to achieve a speed of 1000 RPM, remained at this speed for 45 seconds, and finally ramped down to 0 RPM for 5 seconds. Both composite and control samples were spincast with a solution of fluorescent nanoparticles, producing the speckle patterns illustrated in Figure 2.4.
After the spincoating process, the samples were completely prepared for DIC, and end tabs were attached to promote load distribution onto the composite sample and to prevent specimen failure under the test grips. Aluminum end tabs were manufactured with a length of 14 mm and a tapered edge to promote evenly distributed loading to the composite specimens. The end tabs were sandblasted on their flat edge, cleaned, and then bonded to the composite samples using a thin, even layer of an epoxy adhesive (JB Weld.) While the adhesive cured, end tabs were clamped to samples using binder clips, providing enough force to ensure end tab contact with specimens without ejecting adhesive. The adhesive was allowed to cure for the manufacturer maximum recommended cure-time of 24 hours. This process resulted in composite specimens as illustrated in Figure 2.5. A reference schematic illustrating the region of interest, coordinate axes, and direction of loading is shown in Figure 2.6.
The area of interest was the central set of 90° plies and was imaged during all tests. The direction of tensile loading and x and y coordinates are included for reference.

2.3 Tests

A set of tests was performed to verify the validity of DIC data before testing composite specimens. All tests were performed while the load frame was mounted in a fluorescent optical microscope (Leica DMR) using a 20x magnification Leica long working distance objective lens (0.4 N.A. and 3.5 µm depth of focus.) Images were acquired using a monochrome CCD camera (QImaging Retiga) with a pixel density of 1.915 pixels/µm, producing a resolution of 668.4 by 534.7 µm, or 1280 by 1024 pixels. With this optical system, Hamilton [21] verified a displacement resolution of 20 nm for rigid body translations.

2.3.1 Validation and Control Tests

Before tensile testing, three tests were performed to check the correlation of the DIC speckle pattern and verify the correlation’s validity. Both composite and Aluminum specimens were tested in a rigid translation test and a focusing test to examine the correlation with Vic2D. Additionally, the moduli of Aluminum specimens were checked. Aluminum samples were tested
in tension, and the average strains were measured with Vic2D and compared with the applied stress to verify that the correct modulus was obtained.

2.3.1.1 Rigid Translation Test Procedure

In order to verify that the speckle patterns produced by spincoating would correlate and produce accurate results with Vic2D, a test was performed in which specimens were rigidly translated by a known distance. During the test, specimens were affixed to a dual-axis translation stage and imaged. The specimens were then translated by 10 μm in the horizontal direction and imaged, and next were translated in the vertical direction by 10 μm and were imaged again. These test images were then input to Vic2D, and the software was run to produce displacements and strains.

However, the contour plots for the $x$ and $y$ displacement showed barrel- and pincushion-shaped gradient patterns. These patterns are characteristic shapes that indicate the presence of lens distortion, according to Pan et al. and Yoneyama et al. [14], [22]. Vic2D’s distortion correction algorithm was utilized to correct the lens distortion and allow for accurate displacement and strain results. To correct the lens distortion, a rigid translation test was performed in both the $x$ and $y$ directions and the resulting images input to Vic2D. This test allowed for full 2D displacement lens distortion correction.

After the program completed its initial displacement and strain analysis that were affected by lens distortion, the average displacement predicted by Vic2D was recorded for each image in both the $x$ and $y$ directions. The two largest predicted displacements in the $x$ and $y$ directions were then entered into Vic2D’s correction algorithm. Appropriate spline coefficients were selected for each test, and the distortion map was applied to the test file and saved. Running the analysis again produced the corrected displacements and strains.
2.3.1.2 Focusing Test Procedure

During tensile testing, out-of-plane movements and Poisson effects caused the sample to fall out of focus [23]. Refocusing the camera before taking each image results in reliable image correlation in Vic2D. However, refocusing produces noise in the data; thus, a test was devised to determine the level of noise induced by refocusing.

As in the translation test, specimens were affixed to a dual-axis translation stage and imaged while undergoing no deformation or displacement. The camera was then completely unfocused, then refocused again, and a second image was taken. This process was repeated several times, producing 5-7 total refocused images. The test images were then input to Vic2D, and the software was run to produce displacements and strains for each image. The absence of real deformation or displacement indicates the reported displacements and strains are measurements of refocusing noise.

2.3.2 Tensile Test Procedure

Samples were loaded in tension in a miniature load frame (Ernest F. Fullam, Inc.,) illustrated in Figure 2.7. The samples were securely clamped in flat-faced stainless steel grips with emery cloth adhesively attached to the gripping side in order to prevent slipping at high loads. Displacement data was measured during the tests using a linear displacement sensor (Vishay Micromeasurements,) and the applied load data was measured using a 100 pound capacity load cell (Entran,) Tests were operated by a LabVIEW (National Instruments) program, and were conducted at an average displacement rate of 4 µm/s.
Figure 2.7. A sample is shown held in the load frame grips. On the right, the load cell collects data in situ during the test, and the displacement transducer provides feedback to the motor to maintain a consistent speed. A 20x objective was used to image specimens.

Before each test, specimens were gripped tightly in grips with emery cloth glued to the gripping surface, and a 542-nm mercury lamp was activated to take fluorescent images. One image was always captured before any deformation to act as a reference image. The light source was then covered by a shutter. Fluorescence was only reactivated when images were acquired in order to prevent photobleaching of the fluorescent nanoparticles. One translation test in the $x$ and $y$ directions was performed before each tensile test in order to provide unique images to correct lens distortion in the images.

Once the specimens were gripped, the load was zeroed, and the LabVIEW program initialized to begin collecting load and displacement data and automatically operate the load frame in tension. Load frame displacement was paused periodically to allow for imaging purposes. Before each image, the camera was refocused on the area of interest on the specimen.
Following tensile testing, the fluorescent images were input to Vic2D, and the software was correlated with the specimen’s unique translation test to correct for lens distortion. Once an appropriate lens distortion map was applied to the images, the program was then run again to produce displacements and strains.
CHAPTER 3

RESULTS AND DISCUSSION

3.1 Introduction

This chapter first examines the results of the rigid translation tests and focusing tests and also details the correction of lens distortion. Next, the stress-strain plot and modulus results of the Aluminum control tensile tests are discussed. Finally, the local strains of composites under transverse tensile loading are studied and discussed.

3.2 Validation and Control Tests

3.2.1 Translation Test Results

For a test displacement of 10 µm, Vic2D consistently reported a calculated displacement of 10 ± 0.1 µm, illustrated in vector form in Figure 3.1. However, evidence of lens distortion appeared in the displacement contour plots, illustrated in Figure 3.2. Figure 3.2 represents the 3D contour plots obtained from the displacement fields, with the $x$ and $y$ axes corresponding to the $x$ and $y$ directions on Figure 2.6, and the $z$ axis corresponding to the change in displacement.

![Figure 3.1. Vic2D reported displacements of 10 ± 0.1 µm for a rigid translation test of 10 µm in the $x$-direction.](image)
Figure 3.2. Displacement contour plots for $x$ and $y$ displacement illustrate barrel and pincushion distortion, respectively.

In this example, the $x$ direction displacements show barrel-type distortion, and the $y$ direction displacements show pincushion-type distortion. A rectilinear shape would signify that the displacement data is correct; thus, since the displacement contours had curvature, lens distortion created false displacements in both the $x$ and $y$ directions that were incorrect. Standard deviations for the false displacements were calculated for each image and were within the range of 0.05-0.4 µm, producing false strains between -0.1% and 0.1%. The correction process resulted
in displacements with standard deviations in the range of 0.001-0.003 μm, and false strains on the order of $1 \times 10^{-04}\%$. The corrected displacement maps for a sample translation test in the $x$ and $y$ directions are shown in Figure 3.3. The contour plots now have a rectilinear shape and are no longer barrel- or pincushion-shaped, indicating that the distortions have been corrected.

Figure 3.3. Corrected displacements in the $x$ and $y$ directions, respectively. The flattened shape indicates that the distortion has been removed and that the displacements are now accurate.
3.2.2 Focusing Test Results

Resulting \( \varepsilon_{xx} \) strain contour plots from an example focusing test are illustrated in Figure 3.4. Image 1 is the reference image and displays zero strain, as expected. The images following Image 1 have each been refocused separately.

The strain contours remain close to zero strain in all plots. Resin-rich areas show no noticeable pattern or preference to high or low strain. No consistent strain patterning was detected in focusing tests. The mean strain for each contour plot was averaged across all data points on the image. All image mean strains were averaged to obtain the noise level of 0.0016% with a standard
deviation of 0.015%. The strains measured in the tensile test are on the order of tenths of percent strain; thus, the focusing noise does not significantly affect tensile test results.

3.3 Tensile Tests

3.3.1 Aluminum Control Tensile Tests

Before composite samples were tested, Aluminum coupons were tested in tension to confirm the validity of the DIC strain data. The average strain over the entire area of interest, $\bar{\varepsilon}_{xx}$, was calculated with Vic2D. The average applied stress was obtained by first calculating the applied stress for fifty data points that were collected at the same time the strain image was captured; these stresses were then averaged to create the average applied stress, $\bar{\sigma}$.

The average strain and average applied stress were then plotted against each other and used to obtain the value of the modulus. The expected modulus for the Aluminum alloy is 68.9 GPa [24]. A plot for an Aluminum sample is illustrated in Figure 3.5. The modulus is obtained by linear regression and is calculated to be 69.02 GPa with an $R^2$ value of 0.9911. However, the alignment of the specimen in the grips can affect the modulus, and consequently affects the strain as well. In this case, the sample was aligned well, and the $x$-direction displacement contour plot appears as expected: vertical lines that increase in value in the $x$-direction, illustrated in Figure 3.6. The $x$-direction displacement contour plots of improperly aligned specimens appear not as straight, vertical lines, but as oblique angles, as shown in Figure 3.7. The resulting stress-strain plot, shown in Figure 3.8, due to the added effect of bending, has a higher slope of 77.65 GPa with an $R^2$ value of 0.9989.
Figure 3.5. Average applied stress, $\bar{\sigma}$, vs. DIC-computed strains, $\bar{\varepsilon}_{xx}$ for a properly aligned specimen.

Figure 3.6. X-direction displacement contour plot showing proper alignment.

Figure 3.7. X-direction displacement contour plot showing improper alignment.
Figure 3.8. Average applied stress, $\bar{\sigma}$, vs. DIC-computed strains, $\bar{\varepsilon}_{xx}$ for an improperly aligned specimen.

3.3.2 Cross-ply Composite Tensile Tests

The 90° plies of cross-ply composites were imaged during tensile testing. Composite specimens tested in tension displayed characteristic bands of strain that extend along the $y$ direction, perpendicular to the 0° plies. The strain bands can connect with each other at oblique angles and can form strain concentrations. Strain bands can be seen developing in a composite pictured in Figure 3.9, along with the respective average load and average strain at the moment the image was taken. In Figure 3.9, strains develop in a composite specimen as the displacement is increased.

In Figure 3.10, an overlay of the final strain contour plot at $\bar{\varepsilon}_{xx} = 0.31\%$ with an optical image of the composite shows where the strain bands are forming with respect to the fibers and the matrix. In this specimen, strain bands sometimes form over pockets of resin. However, strain bands do not form over all pockets of resin, as can be seen in the green region in the center of Figure 3.10. This may be due to the misalignment of fibers; pockets of resin on the surface could become densely-packed sets of fibers less than a millimeter into the thickness of the composite.
Figure 3.9. Developing DIC strains of a composite specimen in transverse tension. Scale bar is 100 µm.
Composite specimens also develop high strain concentrations that can visually overtake strain bands in contour plots, an example of which is shown in Figure 3.11. In this case, the strain concentration branches between the border of a tow (highlighted with a dotted line) and a pocket of resin with few fibers. The highest value of strain in the concentration is 0.825%, almost two times greater than the average applied strain in the area of interest. Additional strain bands are visible in the image and can be seen more clearly when the scale is reduced as shown in Figure 3.12. In Figure 3.12, strain bands can be seen growing perpendicular to the 0° plies, starting at the border of the tow. The strain bands more consistently trace in the y direction through areas with higher resin content and less densely-packed fibers.
Figure 3.11. Strain contour plot at $\varepsilon_{xx} = 0.43\%$, $\bar{\sigma} = 138$ MPa overlaid on optical image. Dotted line indicates border of tow.

Figure 3.12. Reduced-scale strain contour plot at $\varepsilon_{xx} = 0.43\%$, $\bar{\sigma} = 138$ MPa overlaid on optical image of composite specimen.

The appearance of high strain bands branching between $0^\circ$ plies is consistent with a photoelastic study conducted by Puck et al. [25]. In this case, a transverse section of a macromodel composite material, shown in Figure 3.13, was loaded in the horizontal direction and imaged photoelastically under cross-polarized light. The higher-order fringes, located to the left and right
of the fibers, represent regions “in which the matrix is highly distorted” [1]. Though this test was performed on a much smaller scale, the results suggest that if fibers are perfectly aligned through the thickness of the composite, higher strains may preferentially follow pockets of resin.

![Figure 3.13. Isochromatic fringes for a macromodel composite loaded in transverse tension show larger strains to the left and right of the fibers [25].](image)

### 3.4 Summary

Lens distortion in the system was corrected using Vic2D and allowed for accurate displacement and strain measurements. Another test revealed a low amount of noise incurred from refocusing. Testing Aluminum control samples in tension provided results that verified the accuracy of the displacement and strain measurements and also reinforced the necessity of carefully aligning tensile specimens in the grips to obtain accurate DIC data. Composite specimens tested in tension displayed strain concentrations and strain bands that often traced along resin pockets between the 0° plies.
CHAPTER 4

CONCLUSIONS AND FUTURE WORK

Transverse matrix cracks often occur in fiber-reinforced cross-ply polymer matrix composites subjected to tensile loads. The research in this thesis is a step forward in using DIC to examine the strain fields which may enable prediction of the structural response of composite materials under transverse loading.

Composite and Aluminum control samples were manufactured and prepared for DIC. A set of validation experiments was performed on both types of specimens to ensure the collected data was accurate: rigid translation tests and focusing tests were performed on both types of specimens, and control tension tests were performed on Aluminum samples. Rigid translation tests revealed the presence of lens distortion, which was corrected in Vic2D to provide for displacements accurate to within 0.005 µm. Focusing tests showed that refocusing incurred false strains on the order of 0.015%. Aluminum control samples were loaded in transverse tension, and DIC was utilized to calculate the average strain to compare against the average applied stress. These tests measured the correct modulus of the material and demonstrated the strain data to be accurate, provided that specimens were aligned properly in the grips.

Following the validation and control experiments, composite laminates were loaded in transverse tension, and DIC was utilized to analyze the strain fields occurring on the surface. Strain bands were shown to have formed between and perpendicular to the 0° plies; these bands often followed small pockets of resin and additionally were seen originating at the border of a tow. Strain concentrations were also seen to form, and were nearly twice the value of the average strain in the area of interest. The strain fields seemed to be in agreement with a photoelastic study conducted by Puck et al. [25].

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Future experiments carried out using this system would benefit from a stronger gripping system with an additional structure to aid with aligning specimens in the grips. Additionally, a higher-capacity load cell would be required in order to be able to induce more transverse cracks.

A potential strategy to image a transverse crack could be to “pre-notch” the specimen with a diamond blade saw or razor blade, then image the composite on the area that is the known transverse crack characteristic length scale away from the notch. This could present a more natural transverse crack than simply imaging in the pre-notched area.

An additional area for improvement in this test is leveling the surface of the composite specimen. Specimens with a beveled surface required more time spent focusing while trying to relocate the exact area of interest, and thus more time is spent bleaching the fluorescent nanoparticles. If entirely flat specimens were manufactured, the time spent refocusing would be reduced, and the particle bleaching would be abated as well.
REFERENCES


