Recent Developments in Shearography NDE of Composite Materials

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ABSTRACT

Shearography is a powerful tool for the nondestructive testing of composite structures both during manufacturing and in-service inspection. Shearography measures surface deformation derivative responses to changes due to applied stresses revealing both surface and subsurface/internal anomalies. For example, thermal stress may be used to detect and measure voids, disbonds, delamination's, damage porosity, cracks and embedded foreign material. Acoustic or ultrasonic signals may be used with Shearography to detect changes in material compliance, voids, delamination's and damage. This paper presents the background theory of Shearography NDT and applications in the characterization of composite materials.

Key Words: Shearography, composites, heat damage, material properties

Shearography Nondestructive Testing (NDT) is based on the phenomenon that when an object is subjected to a change in load, subsurface anomalies can produce slight local deformations on the surface. These out-of-plane deformations may be as small as several nanometres, but are easily imaged by a shearography camera.

Shearography NDT offers the QA or Nondestructive inspection community a convenient, noncontact optical inspection technique for composites in aerospace, automotive, launch, wind energy, marine, and , civil engineering applications both for new production and in-service inspections. A shearography NDT system consists of a laser light source, a shearing image interferometer, an image processing computer, display monitor and a means to provide a controlled and repeatable stress to the test object.

Shearography uses a common path, laser-based imaging interferometer to detect, measure and analyse surface and subsurface anomalies in structures by imaging sub microscopic changes to a test part surface when an appropriate stress is applied. Laser Shearography is non-contact (except for portable vacuum Shearography), non-contaminating and near real-time. And while laser light is a non-penetrating radiation, Shearography systems are capable of inspecting composite structures for both surface and subsurface defects such as impact damage, disbonds, delamination's, near surface porosity, wrinkled fibers, fiber bridging, foreign objects (FO), heat damage and cracks. Shearography nondestructive testing methods are mature and can be highly effective solutions for a wide range of composite NDT applications. Common successful applications include metal and composite honeycomb or foam cored panels with metal or composite face sheets, bonded elastomers or cork, solid composite laminates and fiber wound structures such as composite over-wrap pressure vessels (COPVs).

Figure 1 shows an example of shearography inspection of a honeycomb panel that includes the laser and optical elements for test part illumination and a shearography optical system consisting of a beam splitter with a 2 axis tilting mirror, a second mirror with a PZT Phase stepper and the CCD camera. The laser light is expanded through lenses to illuminate the test area on the panel. At two different locations on the surface of the panel, one location above bonded core and a second location above disbonded core, the applied load change will cause the phase of the reflected light to change differently. Light from point P1 in figure 1 is reflected from the panel surface where it is well bonded to the core. Light from point P2 is reflected from the surface above a skin-to-core disbond. If the stress is a slight temperature change or a partial vacuum, the panel face sheet above the disbond will deform out-of-plane shortening the point P2 distance to the shearography camera and phase shifting the light with respect to light from point P1.

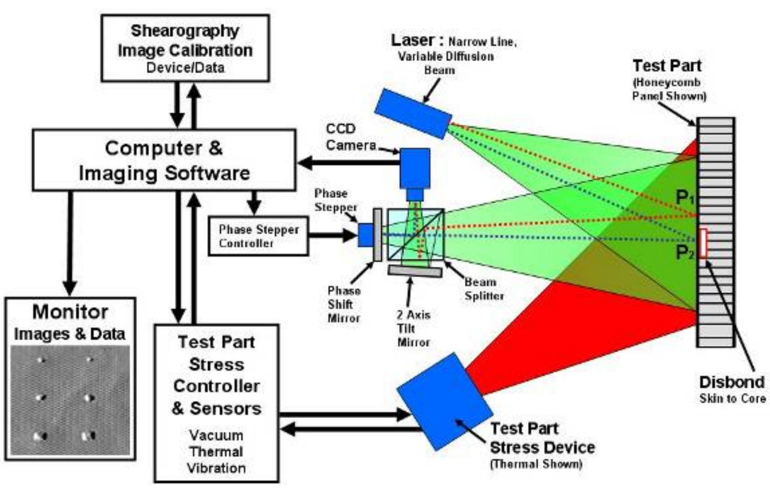


Figure 1 Schematic Diagram of a digital shearography camera and thermal stress system.

Laser light from the entire illuminated area reflects from the surface of the test part and a portion enters the shearography camera aperture. Inside the shearography camera, the light passes through a beam splitter to create two identical images. The images are directed to two mirrors, then back into the beam splitter, to be recombined on a CCD detector. One image is tilted or sheared, with respect to the other image. The position of one image with respect to the other image can be off-set or sheared in any direction or amount. The position of one image with respect to the other image can be adjusted in any direction or amount. The amount and direction of this image shear is referred to as the Shear Vector and determines the sensitivity of the Shear Camera to surface and subsurface anomalies. The camera interferogram output is streamed to the computer where the images are processed in real time and displayed on a monitor.

Image calibration data combined with measured load change applied to the test part allows for repeatable inspection for anomalies, identification of structural elements or the measurement of physical properties of the test part.

The phase of light from each point on the part in one image is interfered with the phase of light from its paired point in the corresponding image. This pixel pairing is determined by the shear vector. The light intensity detected by each pixel in the CCD camera is determined by the complex summation of the light from these two points on the target. Figure 2 shows how the coherent, single frequency light from adjacent points on the part are combined in each pixel in the shearography camera. The random phase difference Φ results from the random surface roughness on a diffusely reflecting test part surface. Stressing the part causes a relative phase shift Δ between light from well bonded homogeneous material and light from the surface above defective or in-homogeneous material such as impact damage, voids, disbonds, sheared core, and variations in bond-line width. In two dimensions, this is expressed as the Δ(x, y). Structural features, such as skin thickness changes, core repairs and splice joints can also be detected and must not be confused with anomalies.

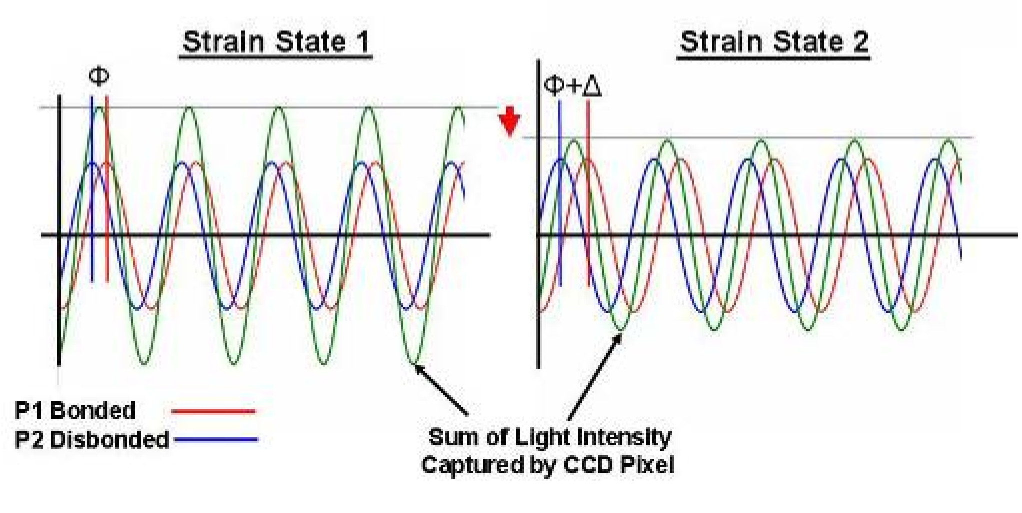


Figure 2 Change in signal intensity due to phase shift with a change in strain state.

The phase stepper in the optical system, applies a π/2 phase step at video frame rates (typically 30 frames/second) to one leg of the shearing interferometer to allow the calculation of the phase map and subsequent quantitative determination of the deformation derivatives between two strain states.

As the applied load on the test object is changed, two sets of phase stepped images are capture and the phase calculation is performed for each pixel over the image, using the following equation for the four phase step method:

$$\Delta(x, y) = \tan^{-1}[I_8(x,y) – I_6(x,y)/ I_5(x,y) – I_7(x,y)] - \tan^{-1}[I_4(x,y) – I_2(x,y)/ I_1(x,y) – I_3(x,y)]$$

Where I_1 through I_8 are eight sequentially phase stepped captured images, described by:

$$I1(x, y)= I'(x, y)+I''(x, y)\cos[\Phi(x, y)],$$

$$I2(x, y)= I'(x, y)+I''(x, y)\cos[\Phi(x, y)+\pi/2],$$

$$I3(x, y)= I'(x, y)+I''(x, y)\cos[\Phi(x, y)+\pi],$$

$$I4(x, y)= I'(x, y)+I''(x, y)\cos[\Phi(x, y)+3\pi/2],$$

$$I5(x, y)= I'(x, y)+I''(x, y)\cos[\Phi(x, y)+\Delta(x, y)],$$

$$I6(x, y)= I'(x, y)+I''(x, y)\cos[\Phi(x, y)+ \Delta(x, y) +\pi/2],$$

$$I7(x, y)= I'(x, y)+I''(x, y)\cos[\Phi(x, y)+\Delta(x, y) +\pi],$$

$$I8(x, y)= I'(x, y)+I''(x, y)\cos[\Phi(x, y)+\Delta(x, y) +3\pi/2],$$

and where,
I' = the bias intensity
I'' = the modulation intensity
Φ = the random phase variable due to reflection of the laser light from a test object
Δ = a quantity directly proportional to the differential displacement due to the test part deformation from the applied load change

The result of the phase calculation yields a wrapped phase map shown in Figure 3, Image 1 that shows the deformation derivative for a deformed flat metal plate with a changing point load at the center. The deformation is of an 8x8 inch metal plate with a 4 inch diameter reduced thickness in the center subjected to a changing load. Figure 3, Image 2 shows the unwrapped phase map. Image 3 shows the result of integrating the phase map and Image 4, shows a 3-D representation of the metal plate deformation. Shearography images, properly calibrated contain dimensional data as to the image scale on the test part surface in pixels/inch (mm) and the shear vector. This data combined with the phase information allows the numerical calculation of the actual deformation of the test part due to the applied load.

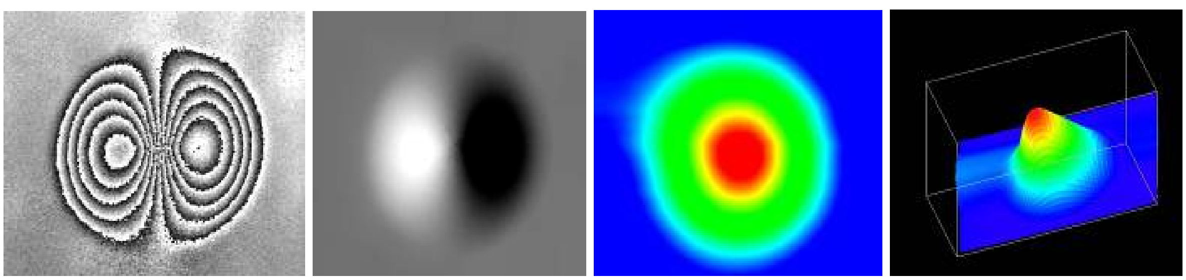


Image 1 **Image 2** **Image 3** **Image 4**

Figure 3 Shearography images 1) phase map of the deformation derivative 2) unwrapped phase map, 3) integrated unwrapped phase map and 4) 3D representation of the plate

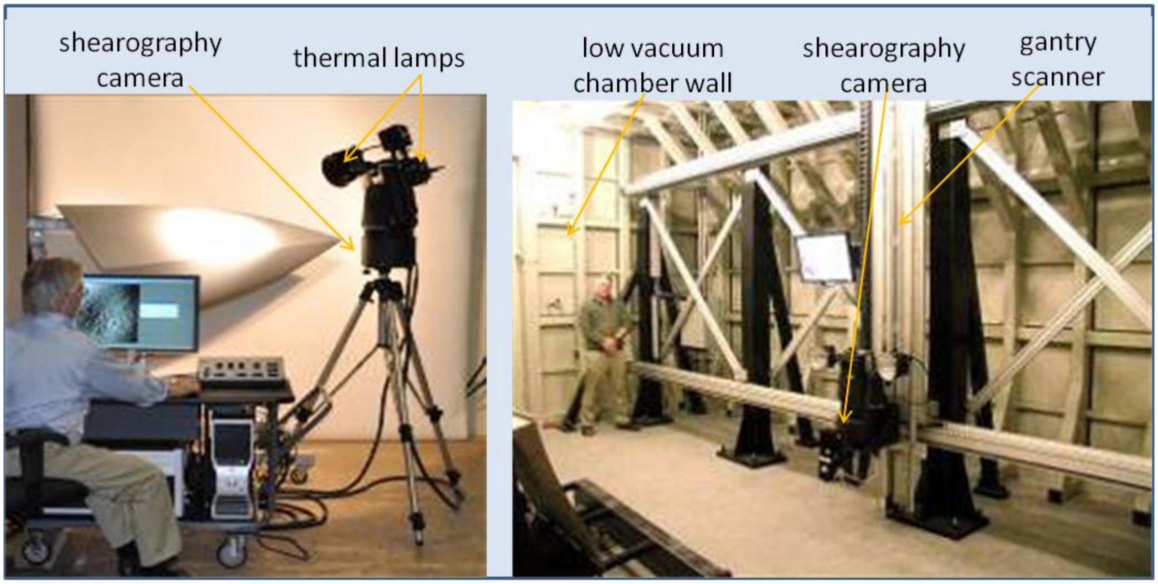
Shearography NDT requires a load change to be applied to the part to reveal defects. These changes are typically very low, compared to normal operating conditions of the test piece. **Table 1** lists the options of loading methods that are commonly applied including heat, vacuum, and pressure.

Table 1 Shearography NDT Stressing Methods for Composite Aerospace Structures

METHOD	UNITS	RANGE	APPLICATIONS
Thermal	Degrees Temperature Change	1 to 30°F	Laminate Panels Impact Damage, Delamination, Wrinkled Fibers, Porosity, Embedded Foreign Material, Repairs, Foreign Objects (FO) Sandwich Panel-Honeycomb, Foam Cores Impact Damage, Skin-to-Core Disbond, Damaged Core, Metal Core-Skin Disbonds, Repairs, Kissing Unbonds, Skin Delamination, Water Resin Transfer Molded Composites Resin Lean Areas, Porosity, Damage Engine Stators, Vanes, Composite Fan Blades, Erosion Strip Bond, voids, resin lean areas, Damage, FO Steel, Aluminum, Ceramics, Composites Surface breaking or near surface breaking Cracks COPV with metal liners Disbonds at the liner/composite bond, Fiber Bridging
Partial Vacuum	PSI, KG/CM² Pressure Reduction	-0.02 to -7.0 PSID.	Elastomers Coatings, Rubber and Plastic Voids, Disbonds, Tires, Solid Rocket Motor Liners, Rubber to Substrate Bond, Cork to Substrate Bond Sandwich Panels-Honeycomb, Foam Cores Impact Damage, Voids, Disbonds, Radomes, Aircraft Control Surfaces, Flaps, Air Brakes, Helicopter Blades, Turbine Engine Ducts, Laminated Wood Structures COPV (COPV Fiber Bridging, Liner Disbonds)
Pressure	PSI, KG/CM² Pressure Change	0.01 to 5,000+ PSID	COPV & Composite Rocket Motors Impact Damage, Composite Cracks, Broken Fibers, Fiber Bridging, Porosity

Figures 4 shows two examples of shearography stress mechanisms. Two 1 kW thermal lamps, shown in Figure 4a on the top of the shearography system tripod, apply IR energy onto a region of an aircraft radome. When the heat lamp is turned on, the surface temperature of the radome increases and the surface expands. Features or defects in or near the surface will cause a differential surface displacement that is detected by the shearography camera. Figure 4b shows a large vacuum chamber capable of handling large aerospace sandwich core panels and control surfaces. The shear camera is mounted on an X/Y scan gantry inside a shearography a vacuum test chamber capable of handling large aircraft sandwich core panels and control surfaces. The air pressure inside this chamber can be reduced from ambient to -5 psi in less than 15 seconds, although typical vacuum test pressures for aircraft sandwich panels is in the range of -0.1 to -1.5 psi.

When subject to an external lower pressure of less than a psi, the air in the sealed core will put internal pressure on the skins. Features or defects in the skin will cause a differential surface displacement than neighboring area which is detected by the shearography camera.



a. Thermal Shearography b. Vacuum Shearography

Figures 5 Stress loading examples a) Shearography camera with two 1kW thermal lamps testing an aircraft radome b) large low vacuum test chamber for aerospace parts.

Composite helicopter blades for example are easily tested in production with either thermal or vacuum shearography methods. Figure 5 shows a production shearography system with dual shearography cameras and gantries in a 32 ft. test chamber. The pressure reduction during inspection cycles between ambient and about 1 psi below ambient. Helicopter blades can be scanned in less than 15 minutes.

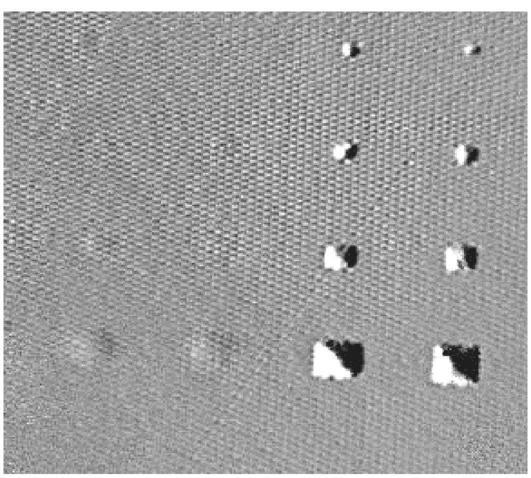


Figure 6 Spacecraft reflector NDT STD tested with thermal shearography showing disbonds.

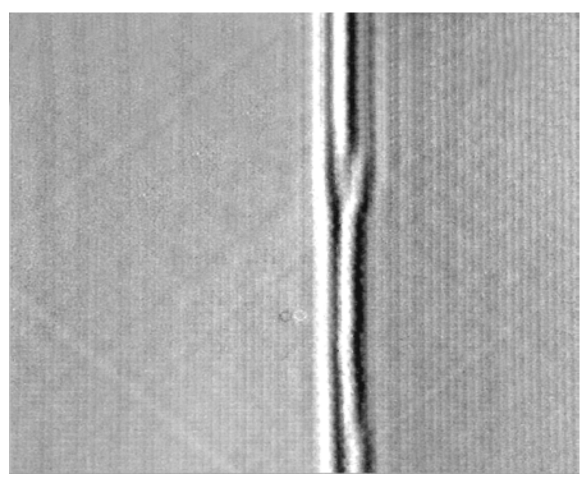


Figure 7 Wrinkled fiber in carbon fiber laminate imaged with thermal shearography.

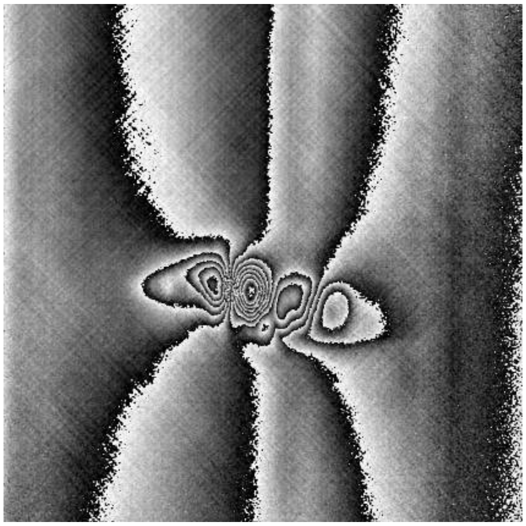


Figure 8 Thermal Wrapped Shearography image of non-visible impact to a solid laminate wing panel

Figure 9 Thermal Shearography image of an eight inch diameter composite repair on and aircraft vertical stabilizer

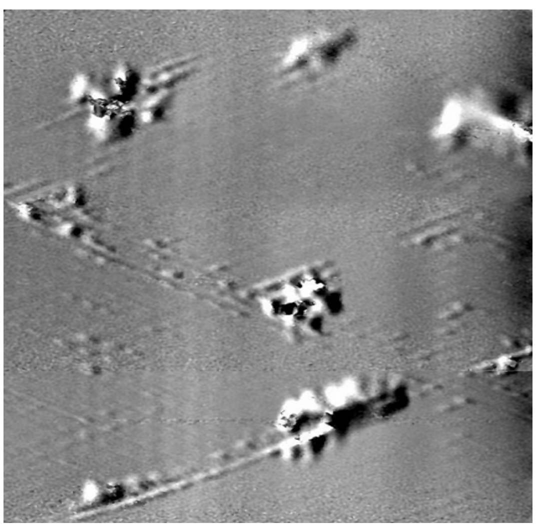


Figure 10 Pressure Shearography image of a composite tube showing porosity, voids, and poor consolidation

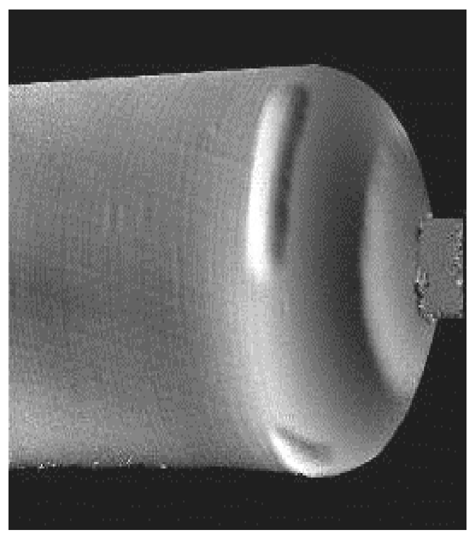


Figure 11 Shearography image of the end of a 6.3 inch diameter COPV showing fiber bridging on the barrel transition area.

Laser Shearography is a robust Nondestructive Testing process that can be used as a primary inspection method or to confirm findings by other NDT methods where company procedures have called out inspection processes also in use. Laser Shearography can be used for whole body part inspection such as control surface structures and multi-contour solid laminate or composite skin to core configurations where conventional Ultrasonic TTU systems require complex contour following software for testing. The Laser Shearography process for large structures can also be used as a quick find process for location of indications in order to mark and identify for further indication analysis and repair. With the advent of composite manufacturing in more and more market segments this NDT process is easily applicable as a primary or secondary test method.

References

D. Gabor, "Microscopy by Reconstructed Wavefronts," Proceedings *of the Royal Society*, Vol; A197 Nature Vol 161 London, United Kingdom: Royal Society, London (1949), p 454.

E. N. Leith and J. Upatnieks, "Wavefront Reconstruction with Diffused Inllumination and Trhee Dimensional Objects, "Jurnal of the Otical Society of America, Vol 54, No. 11, New York NY, Optical Society of America, Nov 1964 pp 1295- 1301.

[3] S. Johnston, "Holographic Visions", Oxfiord University Press, 2006 p. 194

[4] "Laser Based Nondestructive Testing Methods," Nondestructive Testing Handbook, Second Edition, Vol 9, Special Nondestructive Testing Methods, The American Society for Nondestructive Testing, 2003.

[5] S. Nakadata, Phase Detection of Equidistant Fringes for Highly Sensitive Optical Sensing, *J. Opt. Soc. of Am.*, A, 5, 8(1988) pp. 1265-1269

[6] "Laser Based Nondestructive Testing Methods," Nondestructive Testing Handbook, Second Edition, Vol 9, Special Nondestructive Testing Methods, The American Society for Nondestructive Testing, 2003.

[7] Hung, Y.Y., "Shearography: A New Optical Method for Strain Measurement and Nondestructive Testing", *Optical Engineering*, 21, 391-5

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