Applications of digital shearography for testing of composite structures

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Abstract

This paper reviews shearography and its applications for testing of composite structures. Shearography is a laser-based technique for full-field measurement of surface deformation. Unlike holography, it does not require special vibration isolation; hence it can be employed in field/factory environments. The technique has already received considerable industrial acceptance for nondestructive testing of composite structures. In this application shearography reveals defects in an object by looking for defect-induced deformation anomalies. Other applications include strain measurement, material characterization, residual stress evaluation, vibration studies and 3-D shape measurement.

Keywords: Shearography; D. Nondestructive testing; C. Residual/ internal stress

1. Introduction

Shearography is an interferometric technique developed to overcome several limitations of holography. Contrary to holography that measures surface displacements, shearography measures derivatives of surface displacements, thus eliminating the need to numerically differentiate displacement data to yield strains. More significantly, it eliminates the reference beam of holography, leading to the advantages of simplified optical setup, reduced coherence length requirement of laser, and not requiring special vibration isolation. These advantages have rendered shearography a practical measurement tool. Consequently, it has already received wide industrial acceptance for nondestructive testing [1]. Currently the rubber industry routinely uses shearography for evaluating tires and the aerospace industry has adopted it for nondestructive testing of aircraft structures, in particular, composite structures. Other applications of shearography include measurement of strains, material properties, residual stresses, 3D shapes, as well as vibration studies.

There are three versions of shearography employing different recording media: photographic emulsion [2], thermoplastic [3] and video [4]. Digital shearography employs a computerized process that is more user-friendly and cost-effective. It uses video sensors (such as CCD) as recording medium and digital processing technology to acquire image data and analyze the results thus eliminating the consumable materials used by the photographic and thermoplastic versions. This paper reviews digital shearography and its applications for testing of composites.

2. Digital shearography

2.1. Description of the technique

A typical set-up of digital shearography is illustrated in Fig. 1. The object to be studied is illuminated with a point source of laser light, and imaged by a video image-shearing camera consisting of a CCD camera and an imaging shearing device. The shearing device used is a birefringent crystal, which splits one object point into two in the image plane. Consequently, a pair of laterally-sheared image is received by the image sensor, and thus the technique is named as shearography. The key that allows video recording in shearography is the birefringent crystal serving as a shearing device. The shearing crystal brings two nonparallel beams scattered from two different points on the object surface to become nearly co-linear and interfere with each other. As the angle between the two interfering beams is almost zero, the spatial frequency of the interference fringe pattern is so low that it is resolvable by a low-resolution image sensor such as CCD. (Note that the spatial frequency of the interference pattern produced by the two beams is proportional to sine of the half-angle between the interference beams.) As the two sheared wavefronts transmitted by the two axes of the birefringent crystal are orthogonally polarized, a polarizer oriented at 45° to the crystal’s axes is needed to make the two wavefronts to interfere. Because the object surface is generally rough, the interference produces a random interference pattern known as a speckle pattern. The speckle pattern will be slightly altered when the object is deformed. In the measurement, two speckle patterns of the test object
(before and after deformation) are sequentially digitized into a micro-computer via a frame grabber. The difference of the two speckle patterns computed by the computer produces a fringe pattern depicting the displacement derivative with respect to the direction of shearing. A frame grabber with on-board processing capability allows the fringe pattern to be produced in real-time (i.e. video rate).

Fig. 2(a) shows a fringe pattern depicting the derivative of deflection with respect to \( x \)-direction of a rectangular and Fig. 2(b) shows the \( y \) derivative of the plate deflection. The plate is clamped along its boundaries and subjected to uniform pressure.

### 2.2. Principles of fringe formation

A shearographic image of an object may be mathematically represented as:

\[
I = I_o [1 + \gamma \cos \phi],
\]

where \( I \) is the intensity distribution, \( I_o \), the object image, \( \gamma \), the amplitude of modulation of the interference pattern, and \( \phi \), a random phase angle. Eq. (1) shows that the object image is modulated by a random interference pattern known as a speckle pattern.

After the object is deformed, this speckle pattern is slightly changed to \( I' \), represented as:

\[
I' = I_o [1 + \gamma \cos(\phi + \Delta)],
\]

where \( \Delta \) is a phase change due to surface deformation. Computing the difference of the two speckle patterns before and after deformation yields:

\[
I_d = 2I_o [\gamma \sin(\phi + \Delta/2) \sin(\Delta/2)],
\]

where \( I_d \), the intensity distribution of the difference, shows a fringe pattern. Dark fringe lines corresponds to \( \Delta = 2\pi n \); \( n \) is the fringe order. Traditional fringe analysis requires identification of fringe orders. The computerized shearography allows \( \Delta \), the phase change due to deformation, to be automatically determined using a phase determination technique.

Fig. 3(a) and (b) shows 3D plots of the phase distribution in fringe patterns of Fig. 2(a) and (b), respectively, produced by the phase determination technique [5].

### 2.3. Fringe interpretation

The phase \( \Delta \) is induced by the relative optical path length change between the light scattered from two neighboring points, \( P(x, y, z) \) and \( P(x + \delta x, y, z) \) on the object surface. In this case the shearing direction is assumed parallel to

Fig. 1. Schematic diagram of digital shearography.

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Fig. 2. Fringe patterns depicting the deflection derivatives of a rectangular plate clamped along its boundaries and subjected to uniform pressure: (a) \( \partial w/\partial x \); (b) \( \partial w/\partial y \).

Fig. 3. Three-dimensional plot of the phase distribution determined by the phase shift technique, depicting (a) \( \partial w/\partial x \), (b) \( \partial w/\partial y \) of the plate deformation of Fig. 2.
the $x$-axis, and the amount of shearing is $\delta x$. It can be shown that $\Delta$ is related to the relative displacement $(\delta u, \delta v, \delta w)$ of two neighboring points separated by:

$$\Delta = \frac{2\pi}{\lambda} (A\delta u + B\delta v + C\delta w),$$  \hspace{0.5cm} (4)

where $(u, v, w)$ and $(u + \delta u, v + \delta v, w + \delta w)$ are the displacement vectors of $P(x, y, z)$ and $P(x + \delta x, y, z)$, respectively; $\lambda$ is the wavelength of light; $A$, $B$, and $C$ are sensitivity factors related to the position of the illumination point $S(x_s, y_s, z_s)$ and the camera position $O(x_0, y_0, z_0)$ by:

$$A = \left( \frac{x - x_0}{R_x} + \frac{z - z_0}{R_z} \right),$$

$$B = \left( \frac{y - y_0}{R_y} + \frac{z - z_0}{R_z} \right),$$

$$C = \left( \frac{z - z_0}{R_z} + \frac{z - z_0}{R_z} \right),$$

where $R^2 = x_0^2 + y_0^2 + z_0^2$ and $R_0^2 = x_0^2 + y_0^2 + z_0^2$. Note that $z(x, y)$ describes the object surface. Hence on the surface, $z$ is not an independent variable. Eq. (4) may be rewritten in the following form:

$$\Delta = \frac{2\pi}{\lambda} \left( \frac{\delta u}{\delta x} = B \frac{\delta v}{\delta x} + C \frac{\delta w}{\delta x} \right) \delta x.$$  \hspace{0.5cm} (6)

If the amount of shearing, $\delta x$, is small, the relative displacement can be approximated as the displacement derivatives respect to $x$. The direction of shearing determined the direction of the derivative, and it may be altered by rotating the shearing prism about the optical axis. Should the shearing direction be parallel to the $y$ direction, the derivatives in Eq. (6) becomes the displacement derivatives with respect to $y$. It is possible to employ a multiple image-shearing camera [6] to record the displacement derivatives with respect to both $x$ and $y$ simultaneously.

3. Applications

3.1. Measurement of out-of-plane displacement derivatives

Eq. (6) shows that the technique measures a combination of the derivatives of three displacement components. Therefore in general, three measurements with different sensitivity factors are required to allow the separation of the three displacement derivatives. If both the illumination and imaging directions are parallel to the $z$-axis, both $A$ and $B$ are approximately zero. In this case the technique measures only the derivatives of out-of-plane displacement component $w$. The measurement of plate deformation illustrated in Fig. 3 is a result of this optical arrangement.

3.2. Measurement of in-plane strains

Strains are functions of the derivatives of in-plane displacement components. For measurement of in-plane displacement derivatives, a dual-illumination scheme [7] shown in Fig. 4 is used. The object to be measured is alternately illuminated by two collimated laser beams inclined at equal angle $\theta$ to the $z$-axis. The orientation of the beams depends on the strain component to be measured. In Fig. 4, two beams illuminate the object symmetrically with respect to the $yz$-plane, and the strain component parallel to the $x$-direction. In this case, the phase changes due to object deformation for the right illumination beam and the left illumination are different because of the different illumination angles, and their difference eliminates the contribution of the $w$ displacement component. Therefore, the phase angle $\Delta$ of the fringe pattern depicts only the in-plane
displacement derivative \( \frac{\partial u}{\partial x} \) approximated by:

\[
\Delta = (4\pi \sin \theta / \lambda) \frac{\partial u}{\partial x}.
\]  

(7)

Should the illuminations be symmetrical to the \( yz \)-plane and the shearing direction be parallel to \( y \), \( \frac{\partial u}{\partial x} \) in Eq. (7) is replaced by \( \frac{\partial v}{\partial y} \). Indeed, the in-plane strain components parallel to any direction can be measured by adjusting the orientation of the illumination beams. With three different illumination orientations, the measurement system is equivalent to a full-field strain rosette.

Fig. 5(a) shows a fringe pattern reconstructed from the phase difference of two illumination beams depicting \( \frac{\partial u}{\partial x} \), the horizontal strain component, of a cantilever beam fixed on the left and subjected to a point load at the free end (right). Fig. 5(b) is the predicted theoretical fringe pattern. The comparison shows a good agreement.

4. Residual stress measurement

The method of hole-drilling stress release together with strain gage is commonly employed to determine residual stresses in materials. In the process, the strain released by drilling a hole is measured with a special strain gage rosette. Shearography may be used to replace the special strain gage rosette, and the residual stresses are accordingly determined. This eliminates the need to mount the special strain gage rosette and the critical alignment requirement of the drilled hole with respect to the positions of each gage in the rosette. This method has been applied to measurement of residual stresses in plastics and composites [8]. Fig. 6 shows three fringe patterns revealing the three different degrees of residual stresses using the shearography and hole-drilling technique.

A rapid detection of residual stresses is suggested [9]. Instead of drilling a hole, a micro-indentation is produced on the object surface to relieve residual stresses, and shearography is used to measure the deformation produced by the indentation. The deformation of the indentation for the material having residual stresses will be considerably different from that without residual stresses. For this application, a shearographic scheme with relatively large shearing is employed. With is optical arrangement, the technique basically compares the deformation of two different regions on the object surface. In essence, one region acts as a reference for the other. As the deformation due to stress relief by a micro-indentation is very localized, the other region is hardly affected and thus it serves as a reference beam. Thus the technique measures the absolute displacements around the neighborhood of the indentation. With both
illumination and imaging direction parallel to the z-axis, only the out-of-plane displacement is measured.

Like hole-drilling, the indentation also releases residual stresses. Fig. 7(a) shows a fringe pattern due to indentation without residual stresses whereas Fig. 7(b) shows a fringe pattern due to indentation plus relief of residual stresses. Note that without residual stresses, the fringe pattern is approximately axially symmetrical. The presence of residual stresses will cause the fringe pattern to be deviated from the axial-symmetry. The directions of principal stresses are indicated by the two axes of symmetry, and the residual stress magnitude is related to the degree of deviation from axial symmetry. As the mechanics of stress relief is very difficult, research is currently being conducted to determine the residual stresses. At present, the measurement with this method is only semi-quantitative. The technique, however, provides a fast means of detecting residual stresses. It can be used in a field/production environment. Besides, the micro-indentation can be so small that the technique may be considered as nondestructive.

5. Measurement of vibration and time-dependent deformation

The time-integrated recording technique [10] can be used for the study of steady-state vibration. In the measurement, the CCD sensor in the camera integrates the intensity of the vibrating object with an integration time greater than several vibrational periods. The integrated speckle images can be processed to yield a time-averaged fringe pattern depicting the derivative of vibrational amplitude. The time-averaged fringe pattern is described by a Zeroth Order Bessel function of first kind. Fig. 8 shows a time-integrated fringe pattern depicting the derivative of the amplitude of a plate with respect to the horizontal direction. During time-integrated recording, the plate was vibrating steadily at 300 Hz.

High-speed shearography [11] has recently been developed to allow time-dependent deformation in an object to be studied. This is achieved by continuously digitizing the speckle images of a deforming object using a high-speed digital image acquisition system. The image acquisition system used in the experiment is a Kodak EktaPro Model 4540 High Speed Motion Analyzer, which has a maximum frame rate of 40 500 frames/s. After recording, the images are downloaded to a video tape and can be played back at the normal video rate of 30 frames per second. A fringe pattern can be produced by computing the difference of any two speckle images. These images are then digitized by a microcomputer through a frame grabber. The displacement versus time for any point of interest can be extracted by plotting the phase change of the speckle pattern at the point versus time from the computer memory. The total phase change can be obtained by integrating the phase curve. Fig. 9 shows the phase variation versus time of a point on an object vibrating at 600 Hz acquired at a speed of 4500 frames/s. In essence, the technique is equivalent to many massless and noncontact deformation sensors for measuring dynamic deformation. For example, an image digitization of $256 \times 256$ is equivalent to 65 536 sensors.
Fig. 9. Displacement versus time at a point of a plate vibrating at 600 Hz, acquired with the high-speed shearography.

Fig. 10. Comparison of shearography with C-scan ultrasound. An edge pullout and a delamination in a graphite composite panel are revealed by both techniques. Time required: 1 s for shearography and 10 min for ultrasound. Moreover, fluid coupling is needed in the ultrasonic testing.
Moreover, the technique does not influence the real behavior of the structure under study.

6. Nondestructive evaluation

6.1. Flaw detection

Shearography permits full-field observation of surface deformation in a test object. As a flaw in an object usually induces strain anomalies, shearography reveals flaws by identifying the flaw-induced strain anomalies that are translated into anomalies in the fringe pattern. Although shearography measures surface strains, both surface and internal flaws can be detected. This is because the internal flaws unless very remote from the surface also affect the surface deformation.

Shearography has already received industrial acceptance for nondestructive inspection. An earlier report of the NDT applications can be founded in Ref. [1]. Shearography is particularly effective in revealing delaminations in composite structures, including tires. It is also suitable for inspecting pressure vessels. Recently a new application for rapid evaluation of hermetic seal of microelectronic packages [12] is developed which employs high-speed shearography.

6.2. Shearography versus ultrasonic

Fig. 10 is a comparison of the result of digital shearography and that obtained by a C-scan ultrasonic technique on a composite sample. The edge pullout and a delamination are detected by both techniques. However, digital shearography revealed the flaws in a fraction of a second, whereas the ultrasonic technique required point-by-point scanning of the part and it also needed the fluid coupling of the transducer to the object surface. One limitation of shearography is the need to impose stresses (or additional stresses) on test object.

6.3. Method of testing

Flaw revelation by shearography is based on the comparison of two states of deformation in the test object. Development of nondestructive testing procedures employing shearography essentially becomes the development of a practical means of stressing which can reveal flaws. Ideally, it is desirable to impose stresses similar to the stress-state found in service. If components under testing are loaded in a stress mode similar to the actual one experienced in service, shearography can be used to reveal critical flaws only (i.e. flaws that create strain concentrations and thus reduce the strength of the component). Cosmetic flaws can be ignored and false rejects can be avoided. Examples of cosmetic flaws include those located in low stress regions which will not jeopardize the strength of the structures. In this regard shearography has an advantage over ultrasonic techniques. Ultrasonic techniques detect flaws by identifying inhomogeneities in the materials and provide no direct information about the criticality of the flaws. However, exact duplication and application of actual loading may be difficult or impractical in the testing. Therefore, for each nondestructive inspection application, development of a practical means of stress is required. One precaution in stressing the test object is the prevention of rigid body motion. Excess rigid body motion would cause de-correlation of the speckles in the two images (deformed and undeformed) resulting in degradation of fringe quality. Excessive rigid body translation, however, can be negated by the technique report in Ref. [13].

Several methods of stressing which normally do not produce intolerable rigid body motion are: pressure stressing, vacuum stressing, thermal stressing, acoustical stressing and vibrational excitation. Microwave, which excite water molecules is ideal as a stressing means for detecting moisture in plastics and nonmetal composites. Other stressing techniques reported in Ref. [14] for holographic nondestructive testing are generally applicable to shearography.
Several examples of the nondestructive testing application are illustrated below:

Fig. 11 shows several delaminations in a honeycomb panel. The skin of the panel is graphite epoxy. The means of stressing is partial vacuum.

Fig. 12 shows a delamination in a filament-wound composite pressure vessel. The means of stressing is internal pressurization.

Fig. 13 shows several separations in a large cord-reinforced rubber panel. The means of stressing is partial vacuum.

Fig. 14 shows a crack in a composite turbine blade. Thermal stressing by means of radiating the object surface with heating is used.

Fig. 15 illustrates the application of shearography for evaluating bonded composite structures [15]. The means of stressing is vibrational excitation. The weakness along three adhesive-bond lines of a composite assembly is revealed by shearography. Interpretation of the image data is as follows: a perfectly bonded area should appear as dark, and any deviation from “perfect darkness” is indicative of weak bond; a bright region in the image indicates an unbonded area.

7. Conclusion

A review of shearography is given and its application for testing composite structures has been presented. Shearography is a practical technique, and therefore, it is rapidly gaining acceptance by industry for nondestructive testing, particularly of composites structures. However, the technique is still relatively young and its full capability awaits further exploration.
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References


Fig. 14. A crack in a composite turbine blade. Thermal stressing by means of radiating the object surface with heat is used.

Fig. 15. Weakness in three adhesive-bond lines of a composite assemblies. Vibrational excitation is used to stress the object.