DIGITAL SHEAROGRAPHY FOR NONDESTRUCTIVE EVALUATION AND APPLICATION IN AUTOMOTIVE AND AEROSPACE INDUSTRIES

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Abstract: Digital shearograohy has demonstrated great potential in revealing defects in objects especially in detecting delaminations in composite materials. It is gaining more and more acceptance by automotive and aerospace industries in the field of nondestructive testing (NDT) of composite materials. A key optical component used in shearography is a shearing device in which the shearing amount, shearing direction and under the most cases the phase shift technique are determined and introduced. The paper displays different shearing devices. A theoretical analysis and an experimental comparison between them are demonstrated. The new measuring system of digital shearography with a capability for simultaneous measurement both in x and y directions and new concept for shearing amount, i.e. the critical shearing amount at which the measuring setup has a maximal sensitivity, are developed and introduced. The measuring sensitivity, the manner of load and illumination are discussed in details. The recent developments of digital shearography for NDT and its potentials, limitations and application are demonstrated by examples of NDT for different materials.

Introduction and Background: The demanding requirements of product quality and reliability has led to the need for highly efficient NDT method that is real time, whole-field and non-contact-based. Optical method such as thermography, holography, Electronic Speckle Pattern Interferometry (ESPI) and shearography (as called Speckle Pattern Shearing Interferometry) etc. are emerging as strong candidate for new industrial NDT tools because of their virtues of being whole-field, non-contacting and non-contaminating. Of the optical techniques, shearography has already been proven to be a practical one and is gaining more and more acceptance by automotive and aerospace industries in the field of NDT of composite materials[1-6].

Sheargraphy is a laser based optical measuring and testing method that is similar to holographic interferometry and ESPI. Because of a utilization of a special shearing device, shearography, however, measures a gradient of displacement, not the displacement itself as holography or ESPI does. Stains are functions of displacement gradients; thus, shearography yields strain information directly. Because defects in objects usually induce strain concentration, it is easier to reveal defects with strain anomalies than with displacement anomalies. Moreover, a rigid-body motion does not produce strain; thus shearography is insensitive to such motion. This is a significant advantage of shearography, which indicates the usefulness of shearography in typical industry operation.

Although many advantages, a successful application of digital shearography for NDT in industries still depends on depth and type of defects, the type of materials, the shearing amount and direction, the manner of load and laser illumination, and so on. This paper will systemically analyze the effects of these parameters, in particular, their effects on the measuring sensitivity. The theory and methodology of recent developments of digital shearography for NDT are described. Its potentials, limitations and applications are demonstrated by examples of NDT for different materials

Measurement Principles of Digital Shearography: Digital shearography is a laser measuring technique based on digital data processing, phase-shifting techniques and interferometry. According to the common sense of interferometry, two beams with an identical wavelength are required for a purpose of interference. Usually, an identical wavelength for the two beams can be obtained from one laser by using a beam splitter, such as the object beam and the reference beam used in the setups of holography and electronic speckle pattern interferometry (ESPI)[7]. A distinguishing feature of shearography is the use of a self-reference interference system. Instead of using a reference beam, shearography utilizes a shearing device to bring the light waves from two points on the object surface into one point on the image plane, which results in an interference phenomenon, i.e. so-called speckle interferogram, without using an additional reference beam.

Fig. 1 shows a typical shearographic setup in which the modified Michelson interferometer is used as a shearing device. The modified Michelson interferometer brings the light waves from two points: P_1 and P_2, on the object surface into one point: P, on the image plane by tilting the mirror 1 a very small angle. The intensity of the interferogram is then registered by a CCD camera and saved in the computer through a frame grabber board. Assuming that the light waves reflected from the points P_1 and P_2 can be described by the exponential functions as following:

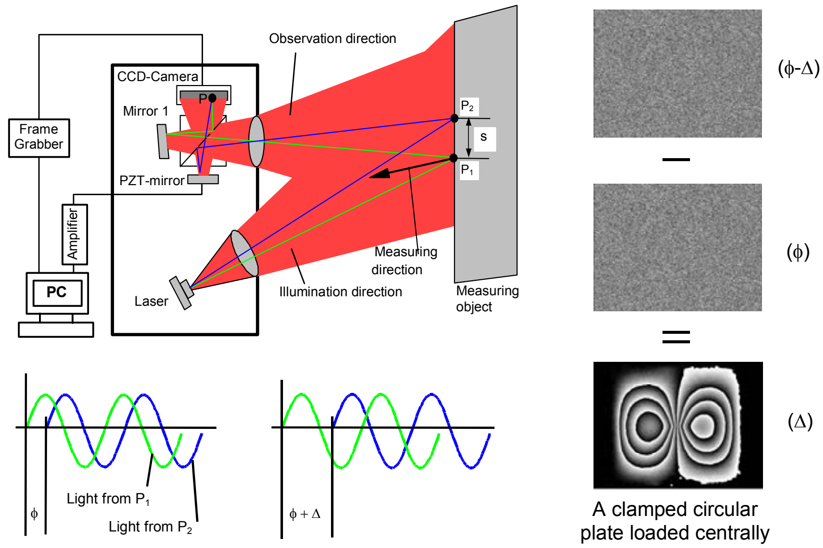

Fig. 1. Fundamental of digital shearography

$$U_1 = a_1 e^{i\theta_1} \quad \text{and} \quad U_2 = a_2 e^{i\theta_2} \tag{1}$$

where θ_1 and θ_2 represent the random phase angle of the light wave from points P_1 and P_2, respectively, and a_1 and a_2 are the light amplitudes. The total light field U_{tot} at the point P on the image plane is therefore

$$U_{tot} = U_1 + U_2 = a_1 e^{i\theta_1} + a_2 e^{i\theta_2} \tag{2}$$

What the CCD-camera can register is only the intensity, the intensity at the point P can be expressed by:

$$\begin{aligned} I = U_{tot} U_{tot}^* &= (a_1 e^{i\theta_1} + a_2 e^{i\theta_2})(a_1 e^{-i\theta_1} + a_2 e^{-i\theta_2}) \\ &= (a_1^2 + a_2^2) + a_1 a_2 [e^{i(\theta_1-\theta_2)} + e^{-i(\theta_1-\theta_2)}] \\ &= (a_1^2 + a_2^2) + 2 a_1 a_2 \cos(\theta_1 - \theta_2) \\ &= A + B\cos\phi \end{aligned} \tag{3}$$

where U_{tot}^* is conjugate-complex from U_{tot}, $\cos(\theta_1 - \theta_2) = [e^{i(\theta 1-\theta 2)} + e^{-i(\theta 1-\theta 2)}]/2$ (Euler equation), $A = a_1^2 + a_2^2$ and $B = 2a_1a_2$. $\phi = \theta_1 - \theta_2$ represents the phase difference between the light waves from the two points P_1 and P_2. After the object is loaded, the phase difference becomes ϕ' which is equal to $\phi' = \phi + \Delta$ (cf. Fig. 1). Δ is a relative phase change before and after loading between the light waves from points, which results from a relative deformation between the points P_1 and P_2 on the object surface due to the load.

Quantitative measurement of phase data can be obtained in digital shearograpy by using the phase-shifting technique[8-9]. The mirror driven by a piezo crystal device, as shown in Fig. 1, is just used for this purpose. Because the phase distribution ϕ and $\phi'(\phi' = \phi + \Delta)$ can be quantitatively measured, the relative phase change Δ, which is related to an relative deformation between the two points P_1 and P_2, can thus be easily determined by subtraction ϕ from ϕ'. An example of a clamped square plate loaded centrally is presented in the right side of Fig. 1.

If the angle between the illumination direction of the laser and the observation direction of the CCD-camera is equal to zero or close to zero, the relative phase change Δ is related to a relative deformation δw between the two points in the out-of-plane direction and is given by[10]:

$$\Delta = \frac{4\pi}{\lambda}\,\delta w \qquad (4)$$

where λ is the wavelength of laser used.

If the two points P_1 and P_2 are orientated in x direction (usually called a shearing in x-direction) and the distance δx (usually called the shearing amount) between them is very small, Eq. (4) can be rewritten by:

$$\Delta = \frac{4\pi\,\delta x}{\lambda}\,\frac{\delta w}{\delta x} \approx \frac{4\pi\,\delta x}{\lambda}\,\frac{\partial w}{\partial x} \qquad (5)$$

There is an analogous result for a shearing in y-direction with a amount of δy:

$$\Delta \text{ ¡Ö} \frac{4\pi\,\delta y}{\lambda}\,\frac{\partial w}{\partial y} \qquad (6)$$

Equation (5) and (6) show the fundamental of shearography. Because the distribution of the relative phase change Δ can be determined quantitatively and in whole field, the deformation derivatives can be measured directly without an additional numerical differentiate of deformation data. Consequently, shearography measure strain or strain concentration information directly. A rigid body movement produces a displacement, but no strain, thus shearography is insensitive to environmental disturbances and is suited well for industrial application. The increasingly easy availability of instruments such as laser, laser diodes and -of-course- computer, in conjunction with the development of new method for phase calculation, have greatly increased the range of problems for which digital shearography is one of the most viable means for nondestructive testing.

Interpretation of measuring results: In this section, an interpretation of shearographic measuring results will be described. Because it is well known how to interpret holographic/ESPI results, a comparison between holographic and shearographic measurement is presented. Figure 2 shows a difference between holographic and shearographic nondestructive testing. Assuming that a specimen has a delamination, a sufficient loading, e.g. by a thermal or a vacuum loading, will causes buckling on the sample surface. Coherent-optical methods are able to detect changes in the surface that are as small as micrometers. Holography detects a flaw by looking for displacement anomalies induced by the defect which look like a circular fringe patterns, whereas, shearography detects a flaw by looking for strain anomalies induced by the defect which look like a butterfly pattern in fringe pattern. Compared with holography which measures full-field displacement, shearography directly measures strain information and thus it is more direct and simple for detection of strain concentrations which are usually created at the positions of defects that decrease the strength of the structure.

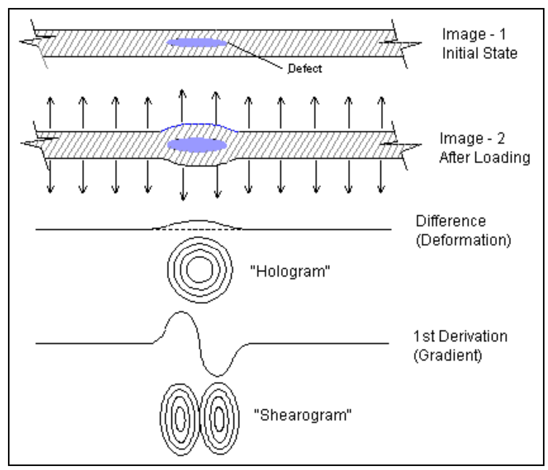

Fig. 2. Interpretation and comparison of measuring results between holography and shearography

To demonstrate the concept described above, a laminated plated with three debonds was inspected using a vacuum stressing. Fig. 3 left shows the holographic measuring results where some circular anomalous fringes appear at the positions of debonds, whereas Fig. 3 right shows the measuring result by using shearographic measurement where butterfly patterns appear at the positions of the debonds.

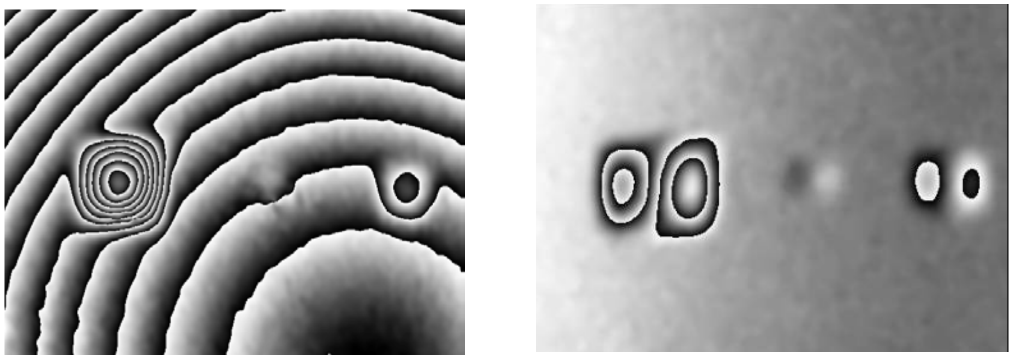

Fig. 3. left: Holographic NDT, in which circular anomalous fringe patterns appear at the debond positions, right: Shearographic NDT, in which butterfly patterns appear at the debond positions.

Instrumentation: In the aspect of hardware, digital shearography consists of three parts: a digital camera, a shearing unit and a laser device for illumination.

Digital Camera is a tool to record intensity by means of gray level. Nowadays, different digital cameras are already available commercially. The main specification of a digital camera is its spatial resolution, i.e. the pixel number. A selection of the spatial resolution depends on specific applications and the available cost. A normal digital camera with a resolution around 700 pixels in horizontal and 600 pixels in vertical direction, e.g. Sony XC-ST70 or a Hitachi KP-M1 camera, can usually meet most applications. Besides the spatial resolution, the other important issue for selection of a digital camera is to see whether it is suitable for a commercial frame grabber. A commercial frame grabber usually delivers a corresponding library which is beneficial to a software development of digital shearography.

Shearing unit is a key component of shearography. Fundamentally, any device which is able to bring light scattered from two points on object surface through the lens of digital camera at one point of the image plane can be utilized as a shearing device. In the last decade years, different devices, such as an optical glass wedge[10], a bi-angle prism[11], a doubly-refractive prism[12], a modified Michelson Interferometer[3] and so on, have been utilized as shearing devices by different researchers. In digital shearography, the phase-shifting technique is applied. Therefore, one important issue to select a shearing device is whether a phase-shifting can easily be introduced in the shearing device. Among the shearing devices which have been used, the modified Michelson interferometer is the best method which can easily change the shearing amount and the direction by changing the tilting angle and direction from one of two mirrors and also can easily introduce a phase shift by moving the other mirror. Theoretically, the 90-, 180-, and 270-deg phase shifts can be obtained by moving the mirror through small displacements $\lambda/8$, $\lambda/4$, and $3\lambda/8$, respectively. However, a control for the accurate movements is difficult practically. Therefore, an automatic calibration method of phase shift by investigating recorded gray level has been developed.

To do the calibration using this technique, one has to let the voltage acting on the PZT mirror to work in the linear range of the relationship between voltage and displacement. As well known, such a relationship is usually nonlinear, as shown in Fig. 4. If this characteristic is known (usually, such characteristic is delivered by most of manufacturer of PZT), the linear range can be determined easily, such as from U_b to $U_b+\Delta U$. If such relationship is unknown, one should not use the ranges at the

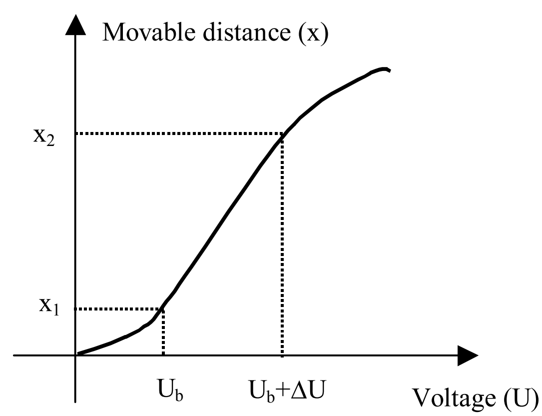

Fig. 4. Voltage-to-displacement relationship of a PZT mirror

beginning and at the end, for instance, a voltage range for an amplifier of the PZT is from 0 to 500 V, one should use only the range from 50 to 450 V. During the calibration, the intensity at voltage of U_b is recorded at first, whose expression is same as equation (3), then the voltage acting on the PZT mirror is changed, the mirror is moved and a phase shift δ is introduced. The intensity equation becomes:

$$I' = A + B\cos(\phi + \delta) \qquad (7)$$

By performing a real time subtraction of I (Eq.3) from I'(Eq. 7), the results of I_s can be observed in real time:

$$| Is | = |I' - I | = | B [\cos (\phi + \delta) - \cos \phi] | \qquad (8)$$

Because the intensity cannot be negative, the absolute value of the real time subtraction is presented on the monitor. While the voltage is increased continually with a small increment, e.g. 1 V, which results in a gradual change in phase shift δ, the gray level of $| I_s |$ is changed continually too. According the averaged values of the gray level of $|I_s|$ over a certain area (e.g. 9×9 pixels), one can find a voltage: $U_b+\Delta U$, at which the averaged value of $| I_s |$ is equal to zero. This means the phase shift δ in Eq. (8) is equal to 2π and the corresponding voltage change is ΔU, Because of the assumed linear relationship, a 90 deg phase shift corresponds to a voltage change ΔU/4. Starting at voltage U_b (the beginning voltage of the linear range), the voltages U_b, $U_b+\Delta U/4$, $U_b+\Delta U/2$, and $U_b+3\Delta U/4$, correspond to phase shift of 0, 90, 180 and 270 deg.

Laser device for illumination is one of the three most important parts of digital shearography in the aspect of hardware. Because of whole field measurements, the laser power used lies between several decades and a few hundreds of milliwatt, depending on the object size to be tested. The traditional laser sources for such applications, such as a He-Ne Laser, a Nd:YAG laser etc. is simply too big, expensive, fragile and a safety issue to the general public to use outside of laboratory and is, thus, impractical in real word applications. For industrial applications, an economical and light self-contained portable apparatus is desired.

As shown in Fig. 1, an interference phenomenon in shearography is formed by two light waves from two points P_1 and P_2, the optical path difference between them is obviously very small. Therefore, the requirement for a coherence length of the used laser is not great. Usually, a coherence length with several decades of millimeters or even a few millimeters is good enough for digital shearography. This characteristic of shearography makes a laser diode for illumination possible. Although a simple laser diode doesn't have a long coherent length, it is very small in size, and as such lend itself particularly well to being added into a portable shearographic sensor.

Laser diode light source

Fig. 5. A portable shearographic sensor using two 60 mw Hitachi laser diodes for illumination

In the shearographic applications the laser diode is allowed to expand as it naturally would, and produces an elliptical shape that is roughly 2.5:1 in ratio of height to width. In order to illuminate an entire area of object being analyzed, an illuminating method using multi-laser-diodes has been suggested [13] and is getting more and more acceptances for industrial applications [14, 15]. Fig. 5 shows a portable shearographic sensor using two 60 mw Hitachi laser diodes with a wavelength of 660 nm, which can be mounted on a tripod. It can illuminate an area of 405×325 mm^2 in a distance d = 1 meter.

Selection of a simple laser diode alone is not sufficient to ensure that the laser will work for a purpose of interferometry. This is largely because simply putting a power source in place to drive the laser diode allows for the emitted wavelength to vary over time due to the heat generated in the laser diode itself. As the laser diode internal temperature goes up and down, the wavelength changes slightly making shearogram increasingly difficult to achieve. In order to ensure that the laser diode light wavelength is a level that is able to produce a shearogram, it is necessary to regulate and be able to adjust the amount of power that drives the laser diode. Currently, three ways are available for achieving regulation of the laser diode wavelength: current stabilization, temperature stabilization, and the combination of both. The regulation for both current and temperature stabilization is required for a high-performance laser diode that is used for holographic/ESPI measurement and is required to be of relative long coherent length, e.g. longer than one meter. Because shearography doesn’t have high requirement in the coherent length, only the current stabilization or only the temperature stabilization is good enough. In the portable shearographic sensor shown in Fig. 5, a driver for the current stabilization manufactured by Thorlabs Ltd, is utilized. A detailed explanation of selection of the regulation method can be found in literature [15].

In the aspect of software, a user-guided software program with multi-functions will greatly benefit the digital shearographic NDT. A development of software program mainly includes generating a phase map of shearogram, smoothing the phase map, demodulating the phase map, and evaluating the measured results with multi-functions, such as differentiation and integration of measuring results, compensation of a tilting etc. A detailed description about the fundamental of the software development can be found from literatures [6,13]. Also the different software packages related to digital shearographic testing are currently commercially available, such as ISTRA-developed by Dantec-Ettemeyer GmbH, Germany, SHEARWIN-developed by University of Kassel, Germany, OMES-developed by Oakland University, Michigan, USA.

Applications: As a relatively new technique, digital Shearograohy has demonstrated great potential for NDT of materials, especially for NDT of composite materials and honeycomb structures. In this part, applications for NDT of different types of defects using different loading methods will be presented.

Fig. 6 shows nondestructive investigation of a glass-fiber reinforced plastic (GFRP) rotor vane by internal pressure (Δp≈0.01 Mpa). The internal pressure is an ideal loading method for NDT of tubes, pipes and any vessels that can be loaded by internal pressure. Fig. 7 shows a measuring result of a plastic PVC pipe with two flaws inside loaded by a 0.02 Mpa internal pressure change.

Fig. 8 to 11 demonstrate nondestructive investigation by digital shearography for a carbon fiber reinforced plastic (CFRP) specimen under tensile stressing, a GFRP plate under thermal stressing, a GFRP honeycomb panel under partial vacuum stressing and an aluminum alloy honeycomb panel under thermal stressing, respectively.

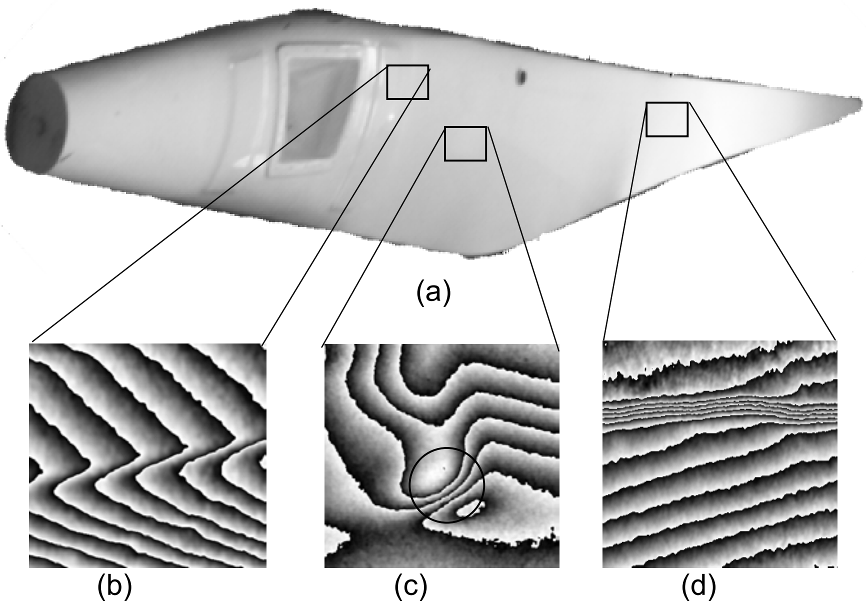

Fig. 6. NDT of a GFRP rotor vane about 5 meters in length by internal pressure (about Δp = 0.01 MPa); (a) view of the rotor vane, (b) showing the passage of lamination, (c) showing a delamination, and (d) displaying a micro crack.

Fig. 7. NDT of a plastic PVC pipe with two flaws inside loaded by an internal pressure change of 0.02 Mpa; (a) live image, (b) measuring result

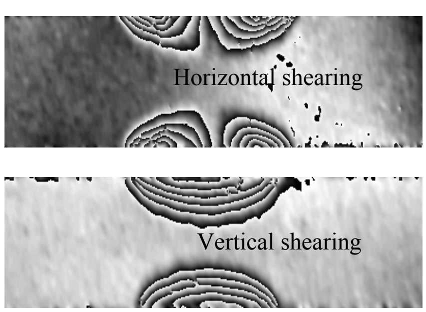

Fig. 8. Delaminations in a CFRP specimen under tensile loading

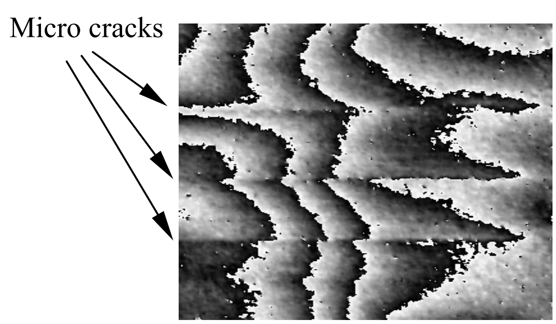

Fig. 9. Micro-cracks in a GFRP plate under thermal stressing

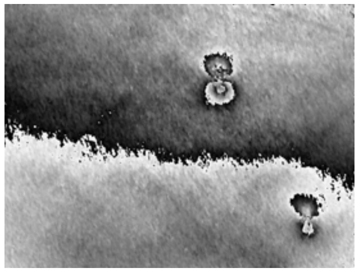

Fig. 17. Disbonds in a GFRP honeycomb panel under partial vacuum stressing

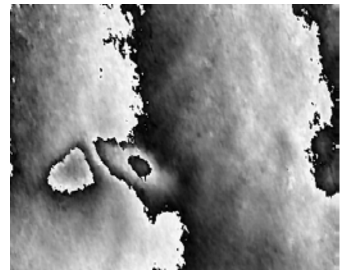

Fig. 18. A disbond in an aluminum alloy honeycomb panel under thermal stressing

Conclusions: The recent developments of digital shearography for NDT and its applications have been presented. A systematical analysis from optics, instrumentation, hardared and software development has been described in details. The new development of digital shearography offers new possibilities for NDT of smaller and deeper defects in different materials, specially, for NDT of small delaminations, disbands and microcracks in composite materials, honeycomb structures and thin plates, It is expected that a wide range of applications of the technique will be seen in the near future.

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