Application of grating shearography and speckle shearography to mechanical analysis of composite material

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Abstract

The present work aims to compare two foremost shearography techniques for a quantitative experiment of composite material: digital phase-shifting speckle pattern and grating shearography. The chosen object was an open-hole tensile specimen fabricated by a non-crimped fabric. Both techniques of laser shearography measured surface strain and x-slope and revealed defects by catching the defect-induced deformation anomalies. In this comparative experiments, grating shearography had superiority in signal-to-noise ratio and spatial resolution to speckle shearography except the labour of the non-trivial specimen preparation. This comparative study will offer mechanical engineers a guideline for the reasonable selection of a technique of shearography for a particular test object.

Keywords: A. Fabrics/textiles; B. Anisotropy; C. Laminate mechanics; D. Non-destructive testing-optical full-field method; E. Manufacturing/Process-RTM

1. Introduction

In recent years, the quantitative strain analysis and the non-destructive evaluation (NDE) of materials and structures have benefited from the development of optical full-field methods (OFFMs). Speckle interferometry as a typical example uses a speckle pattern interfering with a reference coherent light or another speckle pattern. The principle for obtaining a fringe pattern is only the correlation between the speckle patterns before and after deformation. However, the interferometry using the diffused light is spatially subjected to speckle noise. Therefore, the image or the phase map degraded by the spatial noise requires a filtering or fitting inducing a degradation of its spatial resolution. Another representative displacement measurement technique is moiré interferometry, which is also based on two-beam interference. A grating is attached to the specimen surface and it deforms with the specimen surface. Due to the artificial grating, the wavefront is quasi-plane and the speckle noise is negligible. In other words, the image has a higher signal-to-noise ratio (SNR) than that of speckle interferometry. In return, the surface preparation is non-trivial and the grating dimension limits the measuring area.

Since digital image sensor has been introduced as a recording means, the digital image processed by a computer accelerated the progress of the automated fringe analysis. With the application of phase-shifting technique, the two classical interferometry became further automated and quantitative. For the sake of yielding strain, both techniques of interferometry need to differentiate a displacement field numerically. In fact, the calculation of a strain map from a measured displacement map is still a challenging part because the spatial noise often brings about serious problems in fringe analysis, in particular the spatial random noise of the speckle interferometry. On the other hand, shearography performs an optical differentiation to remove the procedure of the numerical differentiation. In this approach, the interference is created not between a reference and an object waves but between the waves coming from the two object points separated by image shearing. The shear distance being defined as the distance between the two sheared images is a useful parameter to control the performances of shearography such as SNR, sensitivity, spatial resolution and resolution. In addition, it is mostly insensitive to vibrations and accidental rigid-body motions. Because of these advantages, shearography technique has
been introduced into speckle interferometry. Strictly speaking, traditional shearography [1] using photographic emulsion as a recording medium have already existed prior to digital speckle shearography. Although the speckle shearography has the merits of the absence of specimen preparation and the direct strain measurement, the phase map degraded by the speckle noise still requires either a strong filtering or a fitting to isolate reasonable mechanical measurands. Similarly, grating shearography [2,3] is a next generation of moiré interferometry. The displacement derivative maps with an excellent SNR measured due to the grating and the technique of shearography are directly converted into in-plain strain and out-of-plane displacement derivative maps while grating shearography is possessed of the same shortcoming of non-trivial specimen preparation as moiré interferometry.

When an OFFM is selected, it is essential to have a sound knowledge of its capability and limitation. Therefore, this paper is dedicated to a side-by-side comparison between the two techniques of shearography in an open-hole tensile test of a heterogeneous material. And the capability and limitation of each technique will be assessed in the terms of its performances. A dividing line between speckle shearography and grating shearography in their actual application fields will be apparent.

2. Speckle shearography versus grating shearography

2.1. Two shearography systems

The optical setups for speckle shearography and grating shearography are presented in Fig. 1, respectively. The italic descriptions in both figures mean the same elements are commonly used for both methods. In regards to the illumination systems for speckle shearography, a beam expander and a 50-mm Ø lens to regulate the expansion ratio of the beam illuminating an object are employed and the beam splitter and two mirrors are used to realize two slightly expanded beams, A and B. We chose 110-mW Diode-Pumped Solid-State laser with a wavelength of 532 nm on account of the high laser power requirement of speckle metrology. For grating shearography, the illumination system is composed of a spatial filter, a 150-mm Ø collimating lens and a mirror. Contrary to speckle shearography, a 10-mW HeNe laser with the wavelength of 632.8 nm was adopted. The high laser power requirement of speckle shearography is one of disadvantages, practically in realizing the illumination system in its optical setup. Both shearography systems have in common with a modified Michelson interferometer as a shearing and phase-shifting device. On the object surface, there is an important difference in specimen preparation because the mediums for a fringe pattern are different. First, speckle shearography is based on the speckle pattern that appears as a fluctuating intensity distribution. The sheared and speckled image presented in Fig. 2a is formed in the image plane, where the two waves separated by tilting the PZT-actuated mirror interfere each other. The primary interferogram \( I(i,j) \) on the CCD chip is phase-shifted by the piston movement of the PZT-actuated mirror and then one set \( \{ I_0, I_1, \ldots, I_n \} \) of the phase-shifted intensity maps is converted into the phase map \( \phi'_r \) for each loading step. We next determine the phase change map \( \Delta \phi_{r-d} \) between the reference \( r \) and deformed \( d \) states, which is a phase fringe pattern. Therefore, the surface kinematics is digitalized by the correlation between two-phase maps in the reference and deformed states. Second, as shown in Fig. 2b, grating shearography is based on the use of a diffraction grating fixed on the specimen. In the same way of speckle shearography, the shearing element separates slightly the beam diffracted from the grating. The interference between two diffracted beams directly gives rise to a fringe pattern, which can be converted into a phase fringe pattern by using the same temporal phase-shifting technique as speckle shearography. The phase change map is next obtained by the subtraction of the reference phase fringe pattern map from the deformed one. The surface kinematics is thus digitalized in the variation of the phase according to the deformation of the grating. In other words, the grating acts as the sensor for grating shearography.

The common algorithm for the phase determination is windowed discrete Fourier transform [4] and the software Frangyne developed from INM (French National Institute of Metrology) is used for both shearography systems to control PZT elements for driving the movable mirror and to process image data. The imaging systems have in common with a CCD camera with a standard lens system.

For speckle shearography the virtual images are directly observed by the camera whereas for grating shearography the real images focused by two lenses before and after the Michelson interferometer are observed on a rotating semi-transparent glass plate, which performs the optical filtering by averaging temporally speckle noise.

2.2. Limitation of speckle shearography compared with grating shearography

For grating shearography, the use of the grating provides quasi-plane wavefronts and no speckle noise while for speckle shearography the randomness of the speckle causes many noisy data points. According to Creath [5], other than points where the intensity saturates the element of image sensor, there are two main contributors to these noisy points, which can be presented as the fundamental limitations of speckle shearography compared with grating shearography.

(1) Low contrast (modulation) of the measured intensity at a given pixel as the phase is shifted.

When a speckle is sampled with an image sensor, the intensity of speckle will be averaged over its spatial resolution. Moreover the size of speckles over a measuring area is different and the intensity of the speckle will vary...
during the phase-shifting. Therefore, it is certainly impossible to perfectly resolve the analogue speckles under all situations. Alternatively, many researchers have approached this problem from the viewpoint of the statistical minimization of the loss of the contrast during the digitalisation of the analogue speckle pattern. It is obvious that such causes of low modulation is an inescapable expense of phase-shifting speckle shearography for the quantitative measurement. In the case of grating shearography, on the other side, the low frequency fringe pattern generated by two sheared quasi-plane wavefronts can be resolved as not being much dependent on the spatial resolution of the image sensor.

(2) Decorrelation of the speckle between the exposures before and after deformation

Speckle decorrelation is due to the collection of different scattering contributions between reference and deformed

Fig. 1. Optical setups: (a) speckle shearography and (b) grating shearography.
states. Both local object tilt ($\partial w/\partial x, \partial w/\partial y$) and in-plane object displacement $(u, v)$ result in a rotated and displaced collecting cone compared with the reference state, which gives rise to the decorrelation of the speckle. Other than the total decorrelation dependent on the speckle size, the increase of the decorrelation degrades rapidly the fringe visibility. Therefore, the application of speckle shearography is limited by a relatively small displacement and tilt of the object. On the other hand, a specimen grating for grating shearography is limited by its delamination from a host material in fracture mechanics application. According to Post et al. [6], the grating will delaminate along the crack border and span the gap, at least momentarily prior to complete separation of the specimen.

Table 1 shows the comparison in distinctive properties between speckle shearography and grating shearography except the effects of the shear distance and the numerical filtering. The characterization of two shearography techniques is continued through an open-hole tensile test for a stitched fabric laminate.

### 3. Comparative experiment between speckle shearography and grating shearography

The present work aims to compare two foremost shearography techniques for the experimental analysis of composite material. The specimen for the open-hole tensile test was made up from Non-Crimped New Concepts (NC2) developed by Hexcel Fabrics company. The NC2 is a kind of Multi-axial Multi-ply Fabrics, which consists of the ply construction and the binding system [7]. As shown in Fig. 3, the ply construction of this material is a biaxial double-ply reinforcement ($[0/90]_3s$), which were made of very homogeneous planes of Toray T700 12K carbon fibres having $E_f = 240$ GPa. The texturized polyester stitching yarn was used as the binding system. For a laminate, the stitched biaxial double-ply constructions are stacked like classical plies and then cured by Resin Transfer Moulding process. The used resin is RTM6 having $E_m = 2.89$ GPa. As presented in Fig. 2, the measuring surface of the same biaxial NC2 specimen is differently prepared with

![Diagram](image-url)
white-paint or a grating for two shearography experiments. It contains a central hole with a diameter of 4 mm and its stacking sequence is \([\{0/90\}_3]\), where the braces represents one ply construction. The thickness of the plate is 2 mm and the corresponding fibres ratio is 50%. Binding mass content is only 0.5% of the total mass of the plate. As confirmed in the enlarged photo of Fig. 2a with neither grating nor white painting, the stitching pattern is 5 mm \(\times\) 5 mm straight chain stitch and the crack-like intrinsic porous lines caused by stitching of dry preforms distribute regularly along the fibre direction. This stitching improves the mechanical properties in the through-thickness direction and the porous mediums caused by the stitching get better the through-thickness permeability in the manufacturing process such as RTM, whereas it can degrade the in-plane properties of the laminate because resin rich lines are formed within the gaps cleaved by the process piercing the fibrous plies.

The open-hole tensile test condition is presented in Fig. 2b. A displacement is imposed on the movable jaw and the load is controlled using a classical load cell. The measurements have been performed at 530 N. A uni-directional electrical strain gage with the spatial resolution of 2.5 \(\times\) 1.5 mm\(^2\) was located at the distance of 13.5 r from the vertical centreline of a hole for the far field strain, which was 183 \(\mu_\varepsilon\) in both experiments. For grating shearography, a grating is glued in the front surface of the specimen containing the drilled hole as shown in Fig. 2b. The horizontal line of the cross-type grating is carefully oriented parallel to the specimen and the loading axis. The chosen measuring area was 32.5 \(\times\) 26 mm\(^2\) for grating shearography. For speckle shearography, the same measuring area was covered with the white paint as presented in Fig. 2a. The paint was directly sprayed on the grating after the grating shearography experiment. The authors in many publications about specimen grating metrology have measured the deformation not on a host material but a grating, either intentional or not. In other words, they have neglected the reinforcing effect and the shear lag caused by the bond adhesive between the host material and the grating. According to the results of finite element analysis [8], in case of mechanical applications, the grating stiffness is negligible for large ranges of grating moduli while the shear lag effect is not always negligible. Therefore, the direct painting on the grating makes it possible to remain the same mechanical surface texture in both experiments regardless of the assumption of no shear lag. As regards the shear lag effect, the heterogeneity of measurand smoothes through the grating thickness \(t_s\), which means the inherent degradation of the spatial resolution of the order \(t_s\). For grating shearography, however, the inherent spatial resolution caused by the grating thickness can be neglected because the inherent spatial resolution induced by the shear distance is already dominant. Actually, the thickness of the boned grating was about 18 \(\mu_\text{m}\) while the shear distance for grating shearography is ten times as large as the grating thickness. However, if we introduce a high-magnification imaging system into this grating shearography or moiré interferometry for the applications requiring a spatial resolution of the level of the grating thickness, the shear lag effect will be an important cause degrading the spatial resolution.

### Table 1

<table>
<thead>
<tr>
<th>Feature</th>
<th>Speckle shearography</th>
<th>Grating shearography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring area</td>
<td>Flexible: depending on the area of the illuminating beam</td>
<td>Small: depending on the grating size and the area of the illuminating beam</td>
</tr>
<tr>
<td>Power of laser</td>
<td>High power requirement due to the small opening aperture to generate the speckle pattern and the light diffusion on the object</td>
<td>Low power requirement due to the diffraction grating</td>
</tr>
<tr>
<td>Specimen surface</td>
<td>No preparation (white-color painting)</td>
<td>Non-trivial preparation (bonding of grating)</td>
</tr>
<tr>
<td>Wavefront</td>
<td>Random</td>
<td>Quasi-plane</td>
</tr>
<tr>
<td>Limitation of measurement</td>
<td>Decorrelation of speckles</td>
<td>Delamination of grating</td>
</tr>
<tr>
<td>Power of noise</td>
<td>High (speckle noise)</td>
<td>Low</td>
</tr>
<tr>
<td>Numerical filtering</td>
<td>Essential prerequisite in post-image processing</td>
<td>Optional procedure</td>
</tr>
</tbody>
</table>

![Fig. 3. Architecture of one ply construction of the biaxial double-ply fabrics (Hexcel Fabrics: BIAX 300).](image-url)
In the optical arrangements, the laser beam for speckle shearography with the wavelength of 532 nm illuminates the measuring area with the incidence angle of 46° while the laser beam for grating shearography with the wavelength of 632.8 nm illuminates it with the incidence angle of 49.41°, which is given by the grating equation. In the basic equation of shearography written below, the quantitative evaluation of the phase change \( \Delta \phi \) and the shear distance \( \Delta x \) are in need for extracting the displacement derivative because the wavelength of laser and the incidence angle are given values before an experiment.

\[
\Delta \phi = g \frac{\partial \mathbf{d}}{\partial x} \Delta x
\]  

where \( \mathbf{d} = [u \, v \, w] \) is the displacement vector at a point on the measuring area. The sensitivity vector, \( \mathbf{g} = \mathbf{k}_x - \mathbf{k}_i \) is a function of the incidence angle (\( \theta \)) and the wavelength of laser (\( \lambda \)), where \( i = -x \) or \( x \). The respective constant shear distances for speckle shearography and grating shearography are evaluated by phase-shifting grid method [9]. The strategy of the phase change measurement for two illumination vectors and one directional shear distance is schematised in Fig. 4. The flow chart has been filled with the image data obtained by both shearography techniques. The set of intensity fields between a reference and deformed states comprises 28 images for each method. In the end of the flow chart, we obtain two-phase change maps \( (\Delta \phi_{x,x} = \phi_{x,x}^d - \phi_{x,x}^r \text{ and } \Delta \phi_{-x,x}) \) for each method.

Fig. 4. Strategy to obtain phase change maps in speckle shearography and grating shearography.
4. Results and discussions

4.1. Quantitative experimental strain analysis

To assess and compare quantitatively two techniques of shearography we considered four kinds of performance, which were SNR, spatial resolution, resolution and sensitivity. Fig. 5 presents SNRs of the measured phase change maps assessed by the definition described as 
\[10 \log_{10} \left( \frac{\text{signal variance}}{\text{noise variance}} \right) \] [10]. In the bar graphs about \(\phi_{x,x}\) and \(\phi_{x',x}\), the amount of spatial noise of each phase change map obtained by grating shearography is much lower than those by speckle shearography. It is due to the quasi-plane wavefront diffracted from the grating and the temporal filtering by using a semi-transparent rotating glass plate in the system of grating shearography. On the other hand, a large amount of spatial noise of speckle shearography is induced by the low modulation of the random speckle and the decorrelation of speckle between before and after deformation. To obtain a better SNR in a fixed external load the signal can be increased by augmenting the sensitivity to the phase change map because the spatial noise is almost independent of the increase of the sensitivity. The sensitivity can be accomplished by increasing the shear distance. However, it should be noted that the increase of the shear distance, i.e. the increase of the differentiation increment means the degradations of the inherent spatial resolution and the accuracy of the optical differentiation. When a geometrical discontinuity such as a hole, crack and notch exists in a specimen, particularly the preservation of a small shear distance is indispensable to approach as near as possible its boundary and to keep up with the high strain anomaly around it. Based on these considerations the shear distance for speckle shearography was chosen in 601 \(\mu \text{m}\). On the other hand, the shear distance for grating shearography was chosen in a smaller value of 200 \(\mu \text{m}\) due to the characteristic of its low spatial noise. In the third bar graph, the phase change maps obtained by grating shearography has a SNR of about 6.2 dB whereas the SNR of speckle shearography in using the shear distance of 601 \(\mu \text{m}\) is minus, which means the noise power is higher than the signal power. Therefore, the shear distance should be increased to improve SNR if this were an application that the spatial resolution was not important. In conclusion, compared with grating shearography, the controllable range of the shear distance to be applied in speckle shearography is severely restricted from a lower limit for sufficient SNR to an upper limit to preserve the spatial resolution and the accuracy of the differentiation.

As for the shear distance represented in the unit of pixel, digital shearography requires at least one-pixel shear distance. It is fundamentally difficult for speckle shearography to use such a small shear distance owing to the characteristic of a poor SNR caused from a low sensitivity. On the other hand, the shear distance of grating shearography can be turn down until one pixel even if it is dependent on the pixel size and its corresponding actual size on an object. In this case, the measurement has the smallest sensitivity and the best spatial resolution that the system is capable of providing. In an application requiring a spatial resolution beyond grating shearography, moiré interferometry can be alternatively adopted because the inherent
spatial resolution is dependent not on the shear distance but on the pixel size and the grating thickness. In addition to that, the capability to resolve the complex and minute fringes can be improved by using a high-magnification imaging system such as a microscope. Melin et al. and Han et al. [7,11] have introduced a novel system using such a principle, high-magnification moiré interferometry. The expenses of this OFFM are that the measurand is the displacement and susceptible to vibration and accidental rigid body motion. The measuring area is also highly reduced.

It is possible for grating shearography to isolate directly tensile strain and \( \Delta x \)-slope by using Eqs. (2) and (3) without filtering due to the small amount of spatial noise in the raw phase change maps.

\[
\varepsilon_{xx} = \frac{\partial u}{\partial x} = (\Delta \phi_{\Delta x} - \Delta \phi_{-\Delta x})/2C_1
\]

\[
\frac{\partial w}{\partial x} = (\Delta \phi_{\Delta x} + \Delta \phi_{-\Delta x})/2C_2
\]

where \( C_1 = (2\pi/\lambda)\Delta x \sin \theta \) and \( C_2 = (2\pi/\lambda)\Delta x (1 + \cos \theta) \). The isolated raw tensile strain (\( \varepsilon_{xx} \)) and \( \Delta x \)-slope (\( \partial w/\partial x \)) maps have resolutions of 18.13 \( \mu \)E and 11.79 \( \mu \)rad, respectively, and both maps conserve an inherent spatial resolution of 120 \( \mu \)m. In the same way, each map of speckle shearography has an inherent spatial resolution of 249 \( \mu \)m but it is practically difficult for speckle shearography to extract reasonable quantitative information without filtering owing to its poor SNR. The smaller shear distance in grating shearography resulted in smaller sensitivities of 0.17288/\( \mu \)E for tensile strain and 0.37568/\( \mu \)rad for \( \Delta x \)-slope while the larger shear distance in speckle shearography gave rise to larger sensitivities of 0.61758/\( \mu \)E for tensile strain and 1.37818/\( \mu \)rad for \( \Delta x \)-slope. We made the sensitivities of speckle shearography increase in despite of the loss of the spatial resolution, however, the SNRs of speckle shearography in Fig. 5 were much smaller than those of grating shearography. The change of the performances with respect to the amount of the shear distance was summarized in Fig. 6a.

In practice, the poor SNR of speckle shearography makes it difficult to isolate directly the mechanical measurands and thus a low-pass filtering can be used to increase the SNR numerically. Simultaneously the low-pass filtering affects both the spatial resolution and the resolution as presented in Fig. 6b. Gaussian and sine/cosine separable median filtering module is employed for the low-pass filtering because a Gaussian kernel is more effective than a box kernel with a same spatial resolution in the aspects of the suppression of noisy pixels and the rejection of high frequency components. Moreover, in place of the use of a larger Gaussian kernel the introduction of a separable median filter is more efficient to remove the salt-and-pepper, if it still remains in the image filtered by the precedent Gaussian kernel. The separable median filter helps the phase change map to preserve the details because it picks out automatically the salt-and-pepper noise. This filtering module is applied to the phase change maps and then the mechanical measurands of Eqs. (2) and (3) are isolated by using the filtered phase change maps, i.e. \( \Delta \hat{\phi}_{\Delta x}, \Delta \hat{\phi}_{-\Delta x} \) (Post Process I), where the width at half height of the used Gaussian kernel (\( 2\sqrt{2 \ln 2 \sigma} \sigma \) is the standard deviation of the Gaussian kernel) was 725 \( \mu \)m. Post Process I was also applied for grating shearography. It should be noted that the filtering for
Grating shearography has been used not for the isolation of mechanical measurands but for the use of the same post processing procedure.

The tensile strain and x-slope maps of both methods obtained by Post Process I were presented in Fig. 7 and the performances of both techniques before and after post-image processing were compared in Table 2. The generally known strain distribution of the open-hole tensile specimen is shown on the tensile strain maps in the left column of Fig. 7. High values of strain were concentrated above and below the hole while the zones in the left and right of the hole were relieved from stress. The x-slope maps in the right column of Fig. 7 present local slope anomalies of the measuring surface induced by the stitching yarn, the undulation between the stitching patterns and the crack-like resin rich lines in the reinforcement placed in the $90^\circ$-direction just under $0^\circ$-ply. Further analysis about the x-slope maps will be continued in Section 4.2.

As schematised in Fig. 6b, the low-pass filtering for the improvement in SNR and resolution degrades the spatial resolution. Consequently, the spatial resolution of both strain and x-slope maps of speckle shearography in the first row of Fig. 8 deteriorated from 249 to 800 $\mu$m while the resolutions improved into 0.84 $\mu$m for the tensile strain map and 0.51 $\mu$rad for the x-slope map. Similarly, the spatial resolution of the strain and x-slope maps of grating shearography in the second row of Fig. 8 is degraded from 120 to 748 $\mu$m and the respective resolutions improved into 0.91 $\mu$m for the tensile strain map and 0.59 $\mu$rad for the x-slope map. In despite of lower sensitivities, grating shearography provided similar resolutions due to better SNRs in comparison to speckle shearography.

<table>
<thead>
<tr>
<th>Measurand system</th>
<th>Tensile strain map</th>
<th>Local x-slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speckle shearography + Post Process I + $(\Delta x=601\mu m)$</td>
<td><img src="image1" alt="Tensile strain map" /></td>
<td><img src="image2" alt="Local x-slope" /></td>
</tr>
<tr>
<td>Grating shearography + Post Process I + $(\Delta x=200\mu m)$</td>
<td><img src="image3" alt="Tensile strain map" /></td>
<td><img src="image4" alt="Local x-slope" /></td>
</tr>
</tbody>
</table>

**Fig. 7.** Post-image processed tensile strain and x-slope maps of speckle shearography and grating shearography at 530 N.
Let us observe tensile strain concentration on the net section along the centreline of hole perpendicular to the loading axis for more detailed analysis. Fig. 8 compares the strain concentration distribution measured by grating shearography before and after Post Process I. The used filtering suppressed the fluctuating spatial noise while it also smeared out the maximum value near the hole. The comparison among grating shearography, speckle shearography and an analytic solution are presented in Fig. 9. The analytic solution of the orthotropic open-hole tensile plate was obtained by using Lekhnitskii’s model [12] under the plain stress condition. The mechanical properties used for the model were $E_{xx} = 59.85$, $E_{yy} = 55.82$, $G_{xy} = 4.26$ GPa and $\nu_{xy} = 0.048$, which were obtained by the classical method using electrical strain gages. Considering the results of both methods obtained by the same Post Process I in Fig. 9, first, speckle shearography underestimated the high gradient caused by the strain concentration compared with grating shearography. It is thought that this phenomenon was due to the difference in shearography approximation induced by the different shear distance as follows.

$$\frac{\partial u}{\partial x} = \frac{u(x) - u(x - \Delta x)}{\Delta x} \quad (4)$$

As shown in Eq. (4), the increase of the shear distance as the optical differentiation increment brings about the decline in accuracy because the shearography uses the average slope between two points separated by a shear distance instead of the differential coefficient at one point. Therefore, the smaller shear distance in grating shearography that could be used due to the feature of its excellent SNR improves the accuracy of the optical differentiation. Second, the local fluctuation is observed in the speckle shearography obtained by Post Process I. This can be caused from the local heterogeneity in the specimen and/or the spatial noise but the speckle shearography has a much higher-scale local fluctuation than that of grating shearography. Since the same specimen has been used and there is no correlation between the distributions obtained by the two methods, the factor of the local heterogeneity can be isolated.

<table>
<thead>
<tr>
<th>System</th>
<th>Speckle shearography ($\Delta \xi = 601 , \mu$m, $\theta = 46^\circ$)</th>
<th>Grating shearography ($\Delta \xi = 200 , \mu$m, $\theta = 49.41^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution of tensile strain and x-slope maps ((\mu)m)</td>
<td>249</td>
<td>800</td>
</tr>
<tr>
<td>Resolution of tensile strain map ((\mu)x)</td>
<td>12.68</td>
<td>0.84</td>
</tr>
<tr>
<td>Resolution of x-slope map</td>
<td>8.27 (\mu)rad</td>
<td>0.51 (\mu)rad</td>
</tr>
<tr>
<td>Sensitivity to tensile strain ((\mu)x($/(\mu)x))</td>
<td>0.6175</td>
<td></td>
</tr>
<tr>
<td>Sensitivity of x-slope ((\mu)rad($/(\mu)x))</td>
<td>1.3781</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Comparison in performances between speckle shearography and grating shearography

Fig. 8. Tensile strain concentration on the net section along y0-axis: grating shearography before and after post-image processing.

Fig. 9. Tensile strain concentration on the net section along y0-axis: grating shearography vs. speckle shearography vs. Lekhniskii’s model.
Therefore, the higher local fluctuation in speckle shearography appears to be still the effect of the spatial noise with a higher power than the signal. On the other hand, the local fluctuation is not observed in the vicinity of the hole on which the power of signal is relatively concentrated because the used filter has effectively rejected the relatively small noise in that part.

If an additional Gaussian filter with a width of 1099 μm is applied to the tensile strain map processed by Post Process I (Post Process II), the remaining spatial noise is considerably suppressed but an additional smearing occurs near the hole as shown in Fig. 9. Here it is worthwhile noting that the kernel size of filter can easily control the spatial resolution and resolution. In this approach, grating shearography provides a wider range for these interdependent performances due to the small spatial noise, which can be suitably adjusted according to the degree of heterogeneity of the object to be tested.

4.2. Qualitative surface deformation anomaly analysis

The x-slope maps of Fig. 10 obtained by both techniques reveal the surface deformation anomalies of the biaxial NC2 plate stressed by 530-N tensile load. The x-slope map of speckle shearography also smoothed by Post Process I to extract surface kinematics concealed by the speckle noise. On the other hand, the x-slope map of grating shearography was not filtered. Therefore, the respective spatial resolutions of the phase change maps in Fig. 10b and c are 800 μm for speckle shearography and 120 μm for grating shearography. For the purpose of a better comparison with the real photo of the measuring area, the x-slope maps are represented into 14 gray levels.

Considering the architecture of the specimen fabricated using the biaxial double-ply NC2 of Fig. 3, we can predict some structural defects. The first one is the crack-like resin rich lines created by the piercing process using a needle. Their distribution in the first ply of the 0°-direction can be confirmed in Fig. 10a. As drawn in Fig. 10d, similarly, the resin rich line in the 90°-ply right under the first ply distribute regularly in the 90°-direction at each width of the reinforcement yarn separated by the stitching. As presented in Fig. 10c, these defects are clearly revealed by grating shearography, particularly this phenomenon is more serious in two local lines near the middle of the measuring area. Fig. 10b obtained by speckle shearography also reveals such defects in the two local lines while it fails to evaluate distinctly the other resin rich lines. It should be noted here that a y-directional shear distance must be applied for the investigation of the 0°-directional resin rich lines of the uppermost ply. Although both methods evaluate the surface kinematics, the internal defects could be also detected because they were near enough from the surface. However, the other subsurface defects can influence the surface deformation, provided they are serious. It is thought that these disturbances can be evaluated with subsurface NDE systems using ultrasonic, acoustic, microwave sensors and so on.

Second, the chain-stitching loop makes a certain undulation of the uniform fibrous preform between the stitching patterns. In addition, the stitching yarn pressed with the resin during the cure causes a local disturbance along the stitching yarn. However, the surface of the cured plate is a level plane because of a curing mould. The small-scale undulations on the reinforcement yarns are revealed by both methods, but on the other hand the local disturbances around the stitching yarns of which width is maximum 500 μm can be detected by only grating shearography.
In this comparison, the surface deformation anomalies detectable in grating shearography could not be revealed in speckle shearography. This is because each method is not capable of resolving the field smaller than its spatial resolution. Therefore, grating shearography is an OFFM capable of a broader range of spatial resolution and hence it is more appropriate for such applications as this microstructural composite.

5. Conclusion

Two major shearography techniques were compared for an open-hole tensile specimen made of microstructural NC2: speckle shearography and grating shearography. Both methods measured the surface strains and the x-slopes and revealed the defects by catching the defect-induced deformation anomalies. In this comparative experiments, grating shearography had superiority to speckle shearography except the labour of the non-trivial specimen preparation. In particular, it was proven that grating shearography is an OFFM capable of a broader range of spatial resolution due to more excellent SNR than speckle shearography. Moreover, grating shearography was more accurate than speckle shearography because a smaller shear distance could be applied. This comparative study will offer a guideline for the reasonable selection of shearography for the objects to be tested. Practically, grating shearography proven as a more appropriate method for the present object will be adopted as the experimental method for the characterization of mechanical properties of NC2 laminate.

References