Full-field optical techniques: applications to strain measurement and mechanical identification

Full-Field Optical Techniques: Applications to Strain Measurement and Mechanical Identification

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ABSTRACT

The paper aims at introducing basics on full-field optical methods applied to composites since those methods highly enhance the experimental characterisation of material and structure behaviour. Different classical methods are first introduced, focusing on their relative performances. The special interest of the grating shearography method is then emphasised. It is applied to a one-ply fabric coupon in uniaxial tensile loading. The comparison with strain gauges of different effective length shows the flexibility of the technique to perform adapted analysis. Since the method is capable to measure the surface slope and in-plane strain fields, it is shown that both those data are necessary to catch an in-depth understanding of the mechanical behaviour of the fabrics. Finally, the basic interest of these techniques coupled to numerical analysis is underlined. It is believed that such a coupling can lead to a complete renewal of the mechanical characterisation of materials and systems.

KEYWORDS: full-field optical techniques, fabrics, composites, identification, mechanics

1. INTRODUCTION

The literature on full-field methods is quite vast and a growing number of these techniques are now currently available on-the-shelf and used by many laboratories. These methods roughly comprise two broad categories: geometrical methods, such as grid method, moiré or digital image correlation methods, and interferometric methods, such as holography, moiré interferometry, ESPI or photoelasticity.

Full-field methods have been applied since a long time for studies of every types of materials and they proved to be particularly relevant to composite material analysis. Indeed, displacement and strain mapping are of great interest when dealing with heterogeneous and anisotropic materials.

The high flexibility of these methods and the advances in new optical component and information-technology equipment developments made them quite suited tools to investigate material and structure properties. The displacement or strain fields are unique features in order to characterise material heterogeneity. Moreover, these fields can lead to novel hybrid routes to identify materials and systems (Grédiac 1999, Vautrin 2000). Some of the major questions to answer now are how to quantify and control the performances of these methods and how to select the most relevant technique. These two questions are unsolved questions at the present time. Moreover, material scientists do not currently dominate basics in optics, data treatment, optimisation and numerical methods… to select a full-field method on well-founded bases. The selection process of a measurement method is usually a quite heavy task since the problem should be approached as a whole and therefore many quantities interfere.

The paper first introduces several full-field techniques and reports their principal performances. Then, it will focus on the grating shearography method and discuss in detail an application of the method to heterogeneous medium behaviour. The conclusion will emphasise the basic interest and power of full-field techniques to investigate and identify composite systems.

2. FRINGE PATTERN ANALYSIS

Except digital image correlation techniques, most optical techniques require to process fringe patterns. Full-field methods currently provide intensity patterns which encode the physical quantity, displacement or strain components for instance, the measurement of which is expected.
The intensity is usually assumed to vary as the cosine of a phase that is often directly related to the physical quantity of interest:

\[ I(\phi, k, \gamma) = I_0 \left[ 1 + \gamma \cos(\phi) \right] \]  
\[ (1) \]

where \( I_0 \) is the bias, \( \gamma \) the contrast and \( \phi(X,Y) \) the phase.

The intensity field \( I(\phi) = I(X,Y) = I(r) \) is recorded with a camera. The classical relation between the phase and the mechanical quantity writes:

\[ \phi(r) = \frac{2\pi}{k} \delta(r) \]  
\[ (2) \]

where \( k \) is a constant related to the encoding of the surface and \( \delta(r) \) the displacement at point \( r \) for instance.

At each pixel \( (X,Y) \) of the CCD detector, a sample \( I(X,Y) \) is acquired. The number of pixels sampling a period should be an integer denoted \( N \).


The local phase detection is now currently used since it permits to control the error on the calculated phase and can lead to fully automated procedures (Surrel 1999). However, several systematic errors may arise during the phase-stepping and phase-detection approach, the main ones being:

- periodic intensity signal not sinusoidal,
- phase-step miscalibration,
- bias time or spatial variation,
- mechanical vibrations.

Finally, the users have to select the right algorithm to reduce, or even cancel, the effects of the different causes of errors in phase analysis. The selection should be based on a careful analysis of the experimental set-up. Among the various algorithms which are available let us introduce a particularly efficient one (Surrel 1999). The following will focus on the computation of the phase \( \phi(X_i, Y_j) \) at a given pixel \((X_i, Y_j)\).

The phase-stepping method requires the acquisition of \( M \) intensity samples \( I_k = I(\phi + k\delta) \) with \( k = 0 \) to \( M - 1 \), where \( \delta = 2\pi/N \) is the phase shift. Phase detection algorithms are most often written as:

\[ \phi(X_i, Y_j) = \arctan\left(\frac{\sum_{k=0}^{M-1} b_k I_k}{\sum_{k=0}^{M-1} a_k I_k}\right) \]  
\[ (3) \]

where \( \phi(X_i, Y_j) \) lies within the range \( [-\pi, \pi] \).

The use of the WDFT algorithm is recommended:

\[ \phi(X_i, Y_j) = \arctan\left(\frac{\sum_{k=0}^{N-1} k(I_{k-1} - I_{2N-2k}) \sin(2k\pi/N)}{N(I_{N-1} - I_{2N-2k}) \cos(2k\pi/N)}\right) \]  
\[ (4) \]

The main advantages of the WDFT algorithm are:

- its insensitivity to bias variation;
- its insensitivity to linear phase-step miscalibration.

Standard methods of phase stepping allow to evaluate the phase with a typical resolution of \( 2\pi/100 \).

Some of the main full-field methods will be now briefly introduced focusing on their characteristics. In this presentation, firstly are reported methods to measure displacements and secondly shearo graphical techniques leading to the displacement derivatives.

3. DISPLACEMENT MEASUREMENT

3.1. Grid method

In this \textit{geometrical technique}, a grid of pitch \( p \) (min: 0.1 mm typically) is deposited (bonded, engraved, painted) onto the material surface. This grid is simply a regular pattern of parallel straight lines. This grid acts as a \textit{spatial carrier}, the phase of which is modulated by the displacement field \( u(r) \) following:

\[ \phi(r) = 2\pi \frac{u_x(r)}{p} \]  
\[ (5) \]

\( u_x(r) \) being at point \( r \) the displacement component normal to the lines.

With a pitch of 0.5 mm and a phase resolution of \( 2\pi/100 \), a resolution of 5 micrometers is achieved.

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**Figure 1a. Initial state of the grid**
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3.2. Image correlation

The image correlation technique is also a geometrical technique. An image of the region of interest is taken in the unloaded and loaded states. The sample surface has to be marked, either by a light paint spray or by laser speckle. Although speckle is used, in this case it has nothing to do with speckle interferometry, since only the speckle intensity matters, not the speckle phase.

The initial image is divided into sub-images of typically 10 to 20 pixel size and a cross-correlation is performed between each sub-image and the final image. The location of the correlation signal indicates the translation of the area corresponding to the sub-image between the two states. The resolution on the displacement is claimed to be of a fraction of pixel (1/50 typical), but the spatial resolution is obviously equal to the size of the sub-image, that is, rather poor.

3.3. Interferometric moiré

In this technique (Post 2000), the wave optics phenomenon of diffraction is used. A grating (i.e. a pitch with micrometric pitch $p$; typically, $p = 1200$ lines/mm) is moulded onto the specimen. The grating (maximum size: 50 mm) is illuminated by two symmetric oblique collimated beams, and the light interferes on the screen where the image of the grating area is located (Figure 2).

The interferometric fringe phase variation due to loading is:

$$\phi(r) = \frac{4\pi}{p} u_x(r)$$

With a pitch of 1 $\mu$m and a phase resolution of $2\pi/100$, a resolution of 10 nanometers can be achieved. The spatial resolution is equal to few micrometers, i.e. the region of interest may be observed under a microscope.

3.4. Speckle (ESPI)

The speckle setup (Cloud 1998, Hack 2000) (Figure 3) is very similar to the moiré interferometric one, except that no grating is required here. Thus larger areas can be investigated with diverging beams. This makes this technique very handy and popular. The counterpart is that extensive spatial noise is present.
The spatial filtering which is necessary to remove part of this noise severely decreases the spatial resolution. The relationship between the fringe phase variation and the displacement is the same as above:

$$\phi(r) = \frac{4\pi}{\lambda} \sin \alpha \mu(r)$$  \hspace{1cm} (7)

Mind that the angle of incidence $\alpha$ varies across the field, due to the non-parallel illumination. The resolution on displacement is comparable to the one of gratting interferometry. The spatial resolution is at least the speckle size, which depends on the numerical aperture of the objective lens. When a CCD camera is the sensor, it is considered that the aperture should be chosen so that the speckle size is of the order of the pixel size. But remind that an extensive smoothing is required to remove speckle noise, so the spatial resolution may increase to 30 to 60 pixels. This crucial point is scarcely addressed by users or manufacturers.

4. STRAIN MEASUREMENT

4.1. Introduction

Only few techniques allow direct strain measurement. Interferometric techniques can be used in a differential form, in their so-called shearographic version, where the interfering beams are those which are coming from neighbouring points on the object. The analog phase difference which is performed by the interference phenomenon allows to obtain an analog spatial differentiation, because information coming from adjacent points are subtracted. Practically, an element which separates the image of the region of interest into two laterally shifted images (“shearing element”) is introduced in the imaging part of the optical setup.

4.2. Grating shearography

We provide as an example some more details on the differential version of gratting interferometry, which can be called “grating shearography” (Bulhak 2000). The setup is displayed in Figure 4 below. A three-mirror device allows to illuminate the sample from four different directions from one single collimated beam.

Notice that contrarily to gratting interferometry where beams are simultaneously used in symmetric pairs, in gratting shearography the four illuminations are used independently, because the interference is created by the shear.

When light impinges on a vertical surface following the wave vector $k_1$ and is reflected, diffused or diffracted following the wave vector $k_0$, the optical phase variation due to a displacement of the surface following the vector $u$ is:

$$\phi = (k_1 - k_0) \cdot u = g \cdot u$$  \hspace{1cm} (8)

where $g = k_1 - k_0$ is the so-called sensitivity vector.

![Figure 4. Grating shearography set-up](image)

When a shearing element makes light coming from two points of the surface separated by $\delta r$ to interfere, the phase variation of the interference between an initial (unloaded) and a final (loaded) state is (equation 9):

$$\delta \phi = g \cdot (r + \delta r + u + \delta u) - g \cdot (r + u) - g \cdot (r + \delta r) + g \cdot r = g \cdot \delta u$$

The grating is illuminated successively by the four beams coming from right (R), left (L), up (U) and down (D) of wave vectors $k_R$, $k_L$, $k_U$, $k_D$ (Figure 5).

![Figure 5. Sensitivity vectors corresponding to the four possible illuminations](image)
obtain the following sensitivity vectors components in the \((x, y, z)\) frame of reference:

\[
\begin{align*}
\mathbf{g}_R &= \frac{2\pi}{\lambda} \begin{pmatrix}
\sin \theta & 0 \\
0 & 1 + \cos \theta \\
1 + \cos \theta & \sin \theta
\end{pmatrix} \\
\mathbf{g}_U &= \frac{2\pi}{\lambda} \begin{pmatrix}
\sin \theta & 0 \\
0 & 1 + \cos \theta \\
1 + \cos \theta & \sin \theta
\end{pmatrix} \\
\mathbf{g}_L &= \frac{2\pi}{\lambda} \begin{pmatrix}
\sin \theta & 0 \\
0 & 1 + \cos \theta \\
1 + \cos \theta & \sin \theta
\end{pmatrix} \\
\mathbf{g}_D &= \frac{2\pi}{\lambda} \begin{pmatrix}
\sin \theta & 0 \\
0 & 1 + \cos \theta \\
1 + \cos \theta & \sin \theta
\end{pmatrix}
\end{align*}
\]

and the differential displacement vectors components for the two shears H and V:

\[
\delta u_h = \frac{\partial u}{\partial x} \delta l = \begin{pmatrix} \delta u_x, x \\ \delta u_y, x \\ \delta u_z, x \end{pmatrix}, \quad \delta u_v = \frac{\partial u}{\partial y} \delta l = \begin{pmatrix} \delta u_x, y \\ \delta u_y, y \\ \delta u_z, y \end{pmatrix}
\]

where \(u_{ij} = \delta u_i / \delta x_j\). Denoting \(A = (2\pi/\lambda) \delta l \sin \theta\) and \(B = (2\pi/\lambda) \delta l (1 + \cos \theta)\), one finally gets from (2) the eight phase values:

\[
\begin{align*}
\phi_{HL} &= Au_{x,x} + Bu_{x,z} \\
\phi_{RH} &= -Au_{x,x} + Bu_{x,z} \\
\phi_{HU} &= Au_{y,x} + Bu_{y,z} \\
\phi_{DH} &= -Au_{y,x} + Bu_{y,z} \\
\phi_{LV} &= Au_{y,y} + Bu_{y,y} \\
\phi_{RV} &= -Au_{y,y} + Bu_{y,y} \\
\phi_{UV} &= Au_{z,y} + Bu_{z,y} \\
\phi_{DV} &= -Au_{z,y} + Bu_{z,y}
\end{align*}
\]

from which all partial derivatives can be obtained:

\[
\begin{align*}
\epsilon_{x,x} &= \frac{(\phi_{HL} - \phi_{RH})}{2A} \\
\epsilon_{y,y} &= \frac{(\phi_{UV} - \phi_{DV})}{2A} \\
\epsilon_{x,y} &= \frac{(\phi_{LV} - \phi_{RV})}{2A} \\
\epsilon_{x,z} &= \frac{(\phi_{HL} + \phi_{DH})}{2B} \\
\epsilon_{y,z} &= \frac{(\phi_{UV} + \phi_{DV})}{2B} \\
\omega_{x,y} &= \frac{(\phi_{LV} + \phi_{RV})}{2B}
\end{align*}
\]

where \(\epsilon_{ij}\) is the Cauchy strain tensor, \(u_{x,x}\) and \(u_{y,y}\) the two out-of-plane slopes.

Note that slopes can be independently obtained in two ways. From the preceding equations, one also gets the shear strain and the local in-plane rotation:

\[
\begin{align*}
\varepsilon_{xy} &= \frac{1}{2} (u_{x,y} + u_{y,x}) \\
\omega_{xy} &= \frac{1}{2} (u_{x,y} - u_{y,x})
\end{align*}
\]

Therefore, all the surface in-plane and out-of-plane strain and rotation fields can be obtained.

5. ONE-PLY FABRIC IN TENSION

Woven composites have gained considerable interest as construction and repair materials in transports and civil structures. The increasing use of woven composites in a large variety of structural applications still requires a more comprehensive knowledge of their mechanical behaviour.

Since the effect of the fabric cell cannot be predicted using Classical Laminate Plate Theory, the analysis of the stress distribution and deflection has been performed by using Finite-Element Methods (Whitcomb 1991, Chapman 1995, Naik 1996, Ito 1997, Nishiyabu 2000,) or various theoretical models (Ito 1997, Woo 1997). In recent references, a modified Electronic Speckle Pattern Interferometry method (Nishiyabu 2000) and Raman Spectroscopy (Lei 2000) have been utilised to study the strain heterogeneity due to crossing and undulating yarns.

In this study, we use the Grating Shearography method previously introduced. It has excellent performances in the aspects of resolution and spatial resolution (Bulhak 2000) and provides in-plane strains and out-of-plane displacement derivatives of a deformed object. Since this technique uses a small shear distance (0.113 mm in the present approach), the image doubling of the Image-Shearing Speckle Pattern Interferometry (Aebischer 1997) can be neglected.

5.1. Experimental conditions

Optical test-rig

The set-up used for this experiment is optimised to reduce signal upon noise ratio and to maximise spatial resolution (Figure 4). A 150-mm diameter collimated beam obtained from 10-mW He-Ne laser (\(\lambda=632.8\) nm) illuminates the surface of the specimen grating-1200 lines/mm and a classical three-mirrors arrangement (Post 2000). A screen that is located in front of the collimating lens L1 allows one part of the beam to pass. Therefore, the four necessary directions of illumination can be realised, with the same illumination angle of 49.41°.

The diffracted beam is focused by the lens L2, and then sheared by a Michelson interferometer. It has one special mirror, with a 3-PZT device PSH 1z NV from Piezosystem Jena, which can tilt or translate the mirror. Thus, a shear can be applied in x or y directions by tilting one mirror as well as the piston movement for the temporal phase stepping. Images are observed on a rotating semi-transparent glass plate to reduce speckle noises. Acquisition is performed by a Sony XC 75 camera equipped with a zoom lens and connected to a Matrox Pulsar frame grabber plugged in a PC.

The software Frangyne 2000-5, developed at INM (French National Institute of Metrology), is used to control the shear distances and to process image data. The software also executes the temporal phase stepping. The windowed discrete Fourier transform
algorithm (Surrel 1999) is used for digital phase determination.

Mechanical conditions
The aim of this experiment is to analyse heterogeneous strain fields in fabrics under uniaxial tension. Therefore a one-ply lamina with a large unit cell is used. The coupon is a T700S/M10 12K plain-weave carbon fabric (48192, Hexcel Corporation). The fibre and resin tensile moduli are 230 GPa and 3.2 GPa respectively.

Figure 6 presents the tensile test machine and the coupon. The structure of the fabric is clearly visible. A unit cell consists of two half warp yarns crossing over and under two half fill yarns. Since one ply only is involved, a resin rich region caused by loose weavings is clearly identified in the middle of each unit cell.

The sample is equipped with aluminium end tabs and a displacement is imposed on the movable jaw. The load is assessed using a classical load cell. The specimen has been loaded in 4 steps, respectively 243N, 450N, 693N and 860N. The load is applied in the warp direction.

Last, a grating is bonded in the middle of the specimen. In this experiment, Grating Shearography provides a measuring area of 16×22.5 mm² which corresponds to a 164×251 pixel² image. Therefore, considering that the size of each unit cell is 8×8 mm², the effective area comprises about 6 unit cells and 6 pure resin regions in the covered field.

![Figure 6. Mechanical set-up.](image)

5.2. Experimental procedure

During the tensile test, deformations of the surface specimen induced by external loads are digitised in the form of phase maps that corresponds to the changes on the grating. At each load step, eight phase difference maps for the combination between 4 directional illuminations and 2 applying shear directions are determined. Six intensity maps obtained by phase stepping technique are used to calculate one phase map for each of the eight combinations. Frangyne calculates the phase change maps for each combination between two different load steps. In this calculation, no fitting nor filtering methods are used, thus the spatial resolution remains maximum at about 0.114 mm.

Three different electrical strain gauges (ESG) are located beside the grating. The effective length of the first one is 10 mm (ESG1). It is close to the size of the unit cell, therefore the related strain value should characterise the homogeneous behaviour of the fabric. ESG2 and ESG3 are smaller (1 mm) and they have been located in the middle of a warp and a fill yarn respectively. All the strain gauges measured $\varepsilon_{xx}$.

In-plane strains and out-of-plane displacement derivatives are analysed at each measuring step using Frangyne. Considering the optical conditions, the phase variation of $2\pi$ corresponds to 3691.44 $\mu$ε for normal and lateral strain measurements and respectively 1845.72 $\mu$ε or 1696.38 $\mu$rad for shear strain or slope measurements. Finally, Gaussian average filtering is applied to in-strain maps and out-of-plane displacement derivative maps to increase highly the signal-to-noise ratio. In the end, all filtered images with physical information have the spatial resolution of about 1 mm. However, the original image before filtering keeps the spatial resolution at about 0.114 mm.

The tensile strain, the lateral strain, the shear strain, and the two out-of-plane rotations are depicted in Figure 7a, b, c, d, e. All the recorded information is shown except the in-plane rotation: this parameter is very poor in such an experiment. To calculate the shear strain maps and the out-of-plane displacement derivative maps, we used the method of spatial phase unwrapping. The strange horizontal lines were induced by some faulty noise pixel during phase unwrapping.

![Figure 7. Strain, shear and slope maps which result from Grating Shearography.](image)
5.3. Discussion

Comparison with strain gauge measurement
The area corresponding to ESG1 on the grating is shown in Figure 8. As the cross section shows, the tensile strain field varies about 50% of the mean value within the ESG area. With this refined observation, it is clear that this gauge will underestimate the maximum strain.

![Image of ESG1 and Grating Shearography](image)

Figure 8. Comparison between ESG1 and Grating Shearography ($\varepsilon_{xx}$).

Strain gauges average the strain over the sensor surface, therefore, it is necessary to average over the same effective surface the strains derived from a full-field method to be able to compare the two sets of data in a quantitative way.

Figure 9 compares the values respectively measured by the electronic strain gauge and derived from the strain field which results from grating shearography over the same area. The result underlines the great interest of the full-field measurement method compared to a classical discrete approach. It reveals that the data treatment from the strain maps can be useful to adjust the spatial resolution in order to obtain suitable averaged values, in agreement with study objective of the. Strain gauges obviously cannot adjust their effective length.

Shear strain heterogeneity
Shear strain maps have been depicted in Figure 7.c. It is shown that shear strains may reach high magnitudes in the vicinity of the six resin rich regions.

Focusing now on the lower fill yarn, it is clear that the two diagonally opposite corners, which correspond to resin rich regions, undergo positive shear strains although the two other corners sustain negative shear strain values.

![Image of Shear deformation of the wrap and fill yarns](image)

Figure 9. Strain comparison after the adjustment of the virtual effective length

It is easy to get a qualitative outline of the global shear behaviour of the yarns when the fabric is loaded in tension along the orthotropic axes. Figure 10 displays some basic results. The local areas with no shear are naturally located on the symmetry axes and are symbolised as squares with zeros. The shear strain effects on a warp yarn are also displayed. Zero shear locations are the same, Zero positions are the same, however non-zero values in the corner are the opposite of the previous one.

![Image of Tension/bending coupling effect](image)

Figure 10. Shear deformation of the wrap and fill yarns.

Tension/bending coupling effect
Figure 7a presents the map of $\varepsilon_{xx}$. Tensile strain of the fill yarn in the matrix dominant direction is higher than the value of the warp in the fibre dominant direction.
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Those two tensile strain concentration crescent shaped regions appeared between the vertical centre line of the fill yarn and the vertical border lines of its.

Looking at a cross section of the tensile strain surface along the horizontal lines (Figure 11 and 12), those tensile strain concentration regions give rise to two peaks. However, the tensile strain decreased significantly from the beginning of the warp yarn. This line is the beginning of the fibre dominant region.

![Figure 11](image1.png)

**Figure 11.** Tensile strain profile along x1 line parallel to the loading direction (fill region).

![Figure 12](image2.png)

**Figure 12.** Tensile strain profile along x1 line parallel to the loading direction (warp region).

The lowest tensile strain values occur in the resin rich regions but it does not in the middle of the warp yarn. Such a result on the warp yarn gives rise to two valleys in the 1D profile graphs (Figure 12).

![Figure 13](image3.png)

**Figure 13.** Local bending effect due to the stretching of the warp yarns.

This unexpected phenomenon is induced by the local tension/bending coupling effect due to the tensile loading of the warp yarn. In fact, this particular effect is quite significant when dealing with a one-ply plain-weave composite since, in that case, there is no adjacent ply which can constrain the flexural deformation of the ply.

Figure 13 is providing a rough schematic view of the local bending effect due to the stretching. The strain induced by local flexural deformation is a compressive one in the D-E zone but a tensile one in the E-F zone. As regards the local bending effect, both the C-D and F-G regions remain unchanged before and after deformation. The effect is more pronounced since the area where the bending effect occurred is a resin rich region. Therefore, two strain valleys appear in the warp yarn region and two peaks in the fill yarn one as already shown on Figures 11 and 12.

Actually, as presented in the out-of-plane displacement derivative maps [Figure 7d (x-slope), Figure 7e (y-slope)], warp yarns go down and fill yarns go up by reason of stretching the specimen. To characterise the local slope behaviours within the cell fabric, the averaged values (global slope) are subtracted from the original maps.

The two local slope maps (Figure 14.) which are finally obtained are in agreement with the previous analysis Sharp changes of x- and y-slopes occur at the crossing of the warp and fill yarns. The fundamental interest of the slope mapping is clearly enlightened by this analysis.
Figure 14. Local slopes maps

So, there should be considerable lateral tensile strain within the ascended fill yarn. As shown in Figure 7b, the fill yarns are in tension and there are two valleys within the warp yarn. The flexural deformation induced by the local bending effect can also explain the heterogeneity of the lateral strain even if the main point is the compressive strain due to the Poisson’s effect.

6. CONCLUSION

Full-field methods are quite relevant tools to analyse the behaviour of materials and systems. However the efficiency that can be achieved is highly depending on their integration in the complete characterisation or identification approach. In particular, one should carefully select the resolution and spatial resolution of theirs in agreement with the final objectives.

The utilisation of the Grating Shearography method has led to a well-founded knowledge of the mechanical behaviour of the fabric reinforcement. In particular, it has been possible to characterise the tension/bending coupling effects in the warp and fill yarns and the shear strain concentration in the resin rich region. Moreover, the strain values have been measured with a high resolution in the rage 53 με to 3.25 με and a good spatial resolution, from 0.114 to 1 mm, depending on the kernel size of Gaussian filter. More efficient hybrid numerical and experimental approaches based on this method should be set up in the near future.

7. REFERENCES


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