

Detection of Sub-surface Defects in Multi-layered Polymer Composites by Speckle Pattern Interferometry

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Abstract — This Measurement Note introduces a new approach to the detection and characterisation of internal damage in polymer-based laminated composite structures. While it is well known that the initiation and propagation of internal defects hampers to a large extent the durability and reliability of composite laminates, the imaging of internal defects remains seldom used, mainly for cost and convenience reasons, as well as the non-complementarity of the methods (e.g. ultrasonics and X-ray). Electronic Speckle Pattern Interferometry (ESPI) presents a number of attractive features for being applied to this type of problem. The sensitivity and the possibility to scan over various sizes of imaging field, the absence of contact with the specimen, and the quasi simultaneous measurement in three directions, make it very adapted to the measurement of the displacements of a composite structure under complex applied loads. In this study, ESPI was applied to the characterisation of transverse micro-cracks in a $[0_2; 90_6]_s$ glass-epoxy laminate. It was shown that, provided certain precautions are taken for the measurement, ESPI is an efficient method for both qualitative and quantitative characterisation of the laminate. In particular, the axial displacement map, after being converted to axial strain, was successfully used to determine the axial Young's modulus of the transversely micro-cracked laminate, with a better accuracy than that provided by extensometers.

1. Introduction

The use of multi-material systems offers a number of key advantages over bulk materials, such as potential lightweight solutions, preserved design freedom and cost-effectiveness, this in combination with unique mechanical, electrical and optical functions [1, 2]. Such materials comprise multi-phase polymer composites, adhesive joints, encapsulant systems for micro-devices, micro-electromechanical systems (MEMS), and are of widespread use in the automotive and aerospace industry. However, the benefits of such increased material integration are often reduced by the lack of long-term stability of the system, specifically due to uncontrolled levels of internal stresses inherent to the multi-material assembly. Internal stresses, combined with harsh combination of environmental conditions and load cycles, often lead to premature failure of composite assemblies [3, 4, 5, 6, 7], as illustrated in Figure 1. For instance, in a laminate, internal stresses are responsible for the warpage observed at the macroscopic level [8], but also for microscopic failures at inter-laminar [9, 10] and intra-laminar levels [11, 12, 13].

Most of the above-mentioned applications will experience at least one of these types of damage during their service life. It is therefore crucial not only to be able to predict the occurrence of these defects, but also to detect and characterise them during their operating life. In composites, critical defects are most likely to appear below the surface, and a number of non-destructive techniques have been developed to characterise their dimensions, such as ultra-sonic detection, or X-ray based methods. However, the use of these methods have been limited to a large extent by their price and/or their sensitivity. As shown in Figure 1 a wide range of defects dimensions can be present in the same specimen, hence calling for multiple detection methods.

The aim of this note is to demonstrate that Electronic Speckle Pattern Interferometry (ESPI) offers a robust alternative to these methods for both the detection and characterisation of sub-surface defects in laminated structures, as it spans over a large range of dimensions. First, the measurement principle is described, and an overview of NPL's strain mapping installation is given. Second, the results of experimental characterisation of transversely micro-cracked laminates are presented, in two steps: firstly, qualitative assessment of the initiation of micro-cracking, and secondly quantitative evaluation of the loss of mechanical properties.

2. Background on ESPI Measurement Method

Electronic speckle pattern interferometry (ESPI) offers very precise measurement of the thermal expansion coefficient and elastic properties of composite specimens with relatively large dimensions and aspect

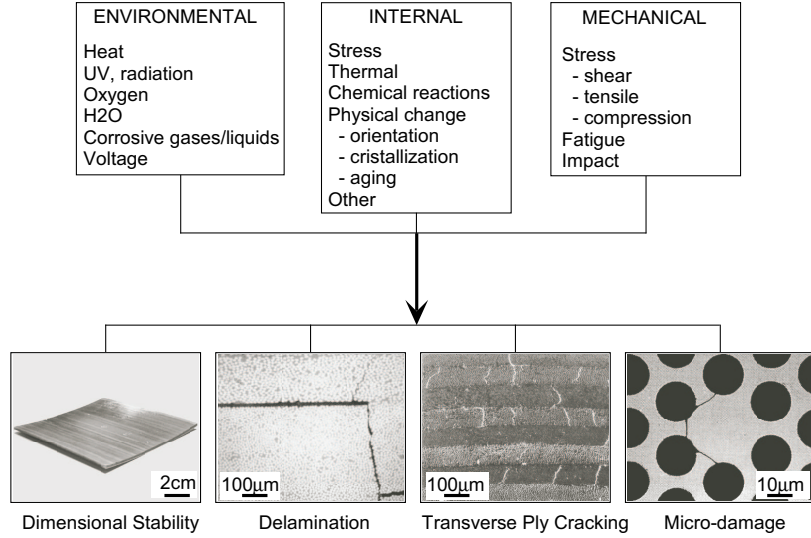


Fig. 1. Possible sources of degradation of composite systems and their commonly observed effects: warping (dimensional stability), inter-laminar failure (delamination, reproduced from Ref. [9]), intra-laminar failure (transverse cracking, reproduced from Ref. [14]), micro-damage (reproduced from Ref. [15])

ratios, such as plates or entire components, or locally within a larger specimen or part. It is a full field measurement method with which deformations under mechanical and thermal loads can be measured along three perpendicular axes without contact with the testpiece [16, 17, 18, 19, 20]. Sample preparation is easy and requires a minimum of handling [8].

The speckle effect is produced by the interference between the reflected rays when a non-specular, dispersing surface is illuminated with a laser beam [16]. The pattern is defined by the microscopically rough topography of the specimen surface. Any deformation of the surface results in a change of the speckle pattern. A correlation between the speckle patterns for an object in a reference state and in a deformed state gives information on the deformation of the object's surface. This is typically done by gray level difference of two digital video interferograms and some additional digital image analysis. For each interferogram, three or four images of the interference pattern are taken with a phase shift of the laser beam of 120° or 90° respectively, and they are combined to give a phase image, which holds information not only on the amount, but also on the direction of the deformation.

The ESPI installation used in this study (Ettemeyer AG, Germany) consists of an ESPI head, a hardware control and data acquisition system, and an image analysis facility. The software Istra[®] v.3.3 was used for the image processing. A compact unit, illustrated schematically in Figure 2, allows the quasi simultaneous measurement of in- and out-of-plane displacements. The in-plane displacements are given by the relative phase shift of two imaging beams. The out-of-plane displacements, i.e. parallel to the optical axis, are obtained from the amount of phase shift of an imaging beam with respect to a reference beam. One can thus measure the 3-D deformation of an object under a load.

This integrated ESPI head includes the laser source, mirrors, piezos, shutter, and video camera. The measurement sensitivity of the system, defined as the amount of relative displacement giving rise to an additional interference fringe, is

$$\text{out-of-plane: } s_z = \frac{\lambda}{2}; \quad \text{in-plane: } s_{x,y} = \frac{\lambda}{2 \sin \theta} \quad (1)$$

where λ is the wavelength of the laser and θ the angle between the imaging beams and the optical axis as shown in Figure 2. The speckle interferometer uses near infrared laser diodes ($\lambda = 0.780\mu\text{m}$), giving an out-of-plane measurement sensitivity of $0.390\mu\text{m/fringe}$. The distance between the front mirrors forming the imaging beam sources was 140mm and the distance to the object was varied following the values given in Table I. Table I presents a range of different configurations successfully used with NPL's set-up, and indicates the in-plane measuring sensitivity for both in-plane axes. Since information on the displacement gradient is carried by the entire phase image, and not just by the fringes, the effective in-plane sensitivity is about an order of magnitude better. The limiting factor of the sensitivity is the inherently high noise of the method resulting from the speckle pattern.

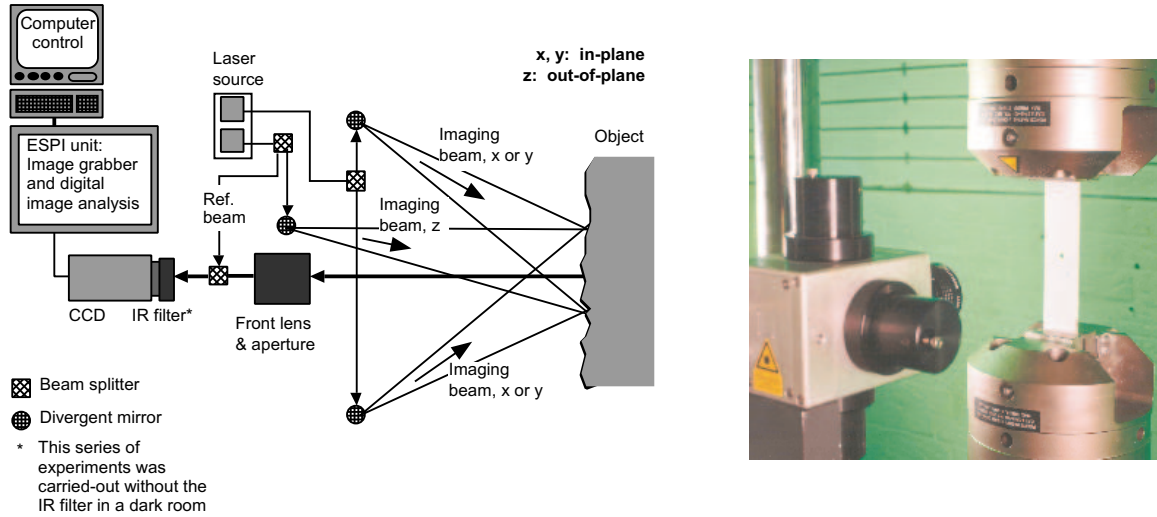


Fig. 2. Layout of the ESPI deformation measurement system

Table I. Optical configurations of the ESPI set-up

Lens	Distance to object (mm)	Imaging field (mm × mm)	Resulting calibration (mm/pixel × mm/pixel)	s_x, s_y μm/fringe
12mm F*8	392	122 × 91.7	0.163 × 0.158	2.22
16mm , 2* extender	352	37.4 × 28.4	$4.98 \cdot 10^{-2} \times 4.88 \cdot 10^{-2}$	2.00

Images were recorded with a 752×582 pixel built-in CCD camera operating at $25Hz$. A set of Pentax Cosmimar[®] macro lenses was used on the front end of the viewing system, giving an imaging field presented in Table I. The resulting calibration of the monitor screen in the x and y -directions, together with the lateral resolution achieved are also given in Table I. The time required for a measurement, determined by the frequency of the video camera and the speed of the shutters and phase shifting piezo devices, was approximately a third of a second for each axis.

Figure 3 illustrates the speckle pattern of an epoxy rod strained and measured in the x -direction, before and after the strain was applied to the sample. It also shows the image of displacements obtained through the difference of the two images of the deformed and undeformed state. A measure of displacements typically produces parallel fringes in an isotropic material without any defects from which quantitative values of displacements and deformations are obtained through the sensitivity by unwrapping the fringe pattern.

3. Experimental

3.1. Materials

Symmetric glass fibre-epoxy laminates were manufactured from prepreps (Ciba-Geigy Fibredux 913) and tested in uniaxial tension. This material was used for convenience purposes, as its thermo-mechanical properties have been extensively documented in previous studies at NPL [21]. The specimens dimensions were $250 \times 25 \times 2.19mm^3$, and the stacking sequence was $[0_2; 90_6]_s$. Composites plates were manufactured in an autoclave following the processing conditions prescribed by the manufacturer, which are 1 hour at $120^\circ C$ and 7 bar pressure (heat up rate of $3^\circ C/min$). The plates were then cooled down to the room temperature at a rate of ca. $2.5^\circ C/min$, and specimens were cut to the specified dimensions in accordance to ISO527-4, 1997, "Plastics - Determination of tensile properties - Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites". End-tabs of glass-fibre epoxy cut at $\pm 45^\circ$ were then bonded to the individual specimens using a Redux 312-5 film adhesive at $120^\circ C$ for 0.5 hour. The specimens were then stored in a dry environment until the test was carried out.

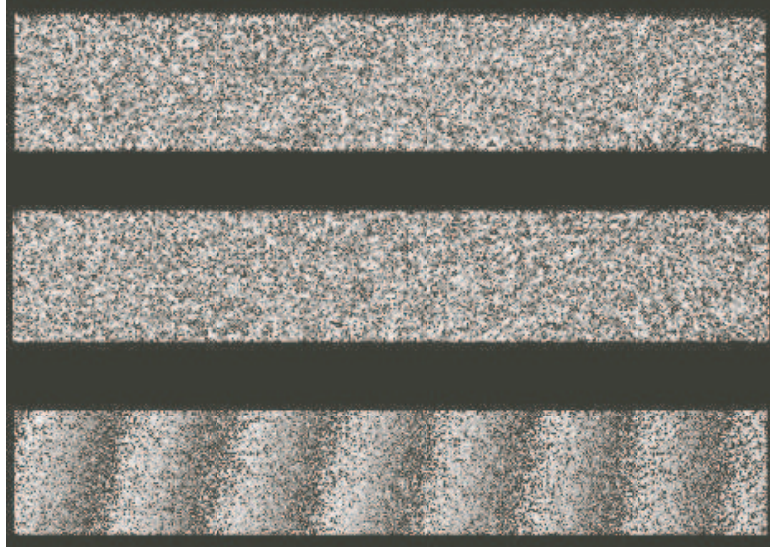


Fig. 3. Speckle pattern in the undeformed state (upper), under $4 \cdot 10^{-4}$ axial strain (middle), and the resulting typical fringe pattern, resulting from the subtraction of the two above images (lower). The sample was a 10mm large by 2mm thick model epoxy network parallelepiped. The fringes present an angle with the normal due to a small rotation of the sample in the grips

3.2. Loading Sequence & Analysis

Given the finite time required for each measurement, the mechanical tests were conducted under quasi-static conditions. The loading sequence processed from 0kN to 10kN by imposed steps of 150N at a loading rate of $\dot{\epsilon} \simeq 3 \cdot 10^{-3}$. The resulting time between two consecutive load-steps was approximately 5s , during which the measurement of the displacements in the three directions were triggered to start after the load had been reached for 1s , so as to reduce possible interference from the vibrations of the machine. Data reduction was carried-out according to the following procedures. In one case, a phase filter was applied to the raw results, followed by the unwrapping sequence. In the alternative case, the phase images were filtered with a routine that takes into account a 3×3 pixel area around the pixel of concern and preserves the phase information. Since the noise level - inherent to the method - was low, higher order filters were not needed. The median filter used and its characteristics are documented elsewhere [22]. The deformation fields can be evaluated from the filtered phase images along a line or over the entire area. A tilt correction can be performed during the evaluation of the phase images, in order to remove displacements due to rigid body translations, rotations (such as the one present on the interferogram in Figure 3), or constant strains. In these series of experiments, long specimens with tight dimensional tolerances were used; they were aligned with the loading axis, therefore tilt corrections were not necessary. Because the method gives a relative displacement field over a surface, average deformations were evaluated along equally spaced tracks forming a grid over the specimen area. The reported axial displacement values are the mean of four tracks, located at a distance from the edge of ca. 7 , 11 , 15 and 19mm . Using this approach, the perturbations associated with edge effects were minimised to a large extent.

This procedure provided the displacements over the specimen area and measurement tracks. The strains were obtained by performing a linear regression along each track, the obtained plots of displacement vs. position being quasi-linear. The slope of this Δy vs. y plot is the strain ϵ_y . The error $\Delta\epsilon_y$ was obtained from:

$$\Delta\epsilon_y = \frac{\left(\sum_{i=1}^N (\Delta y_i - \epsilon_y y_i - \epsilon_{y_0})^2\right)^{1/2}}{2N} \quad (2)$$

where ϵ_{y_0} is the ordinate at the origin of the linear regression, and N is the number of points along the track.

For the Young's modulus measurement, the window analysed covered $65 \times 20\text{mm}^2$, and the axial strain was also recorded using clip-gauge extensometers across the same area with a gauge length of

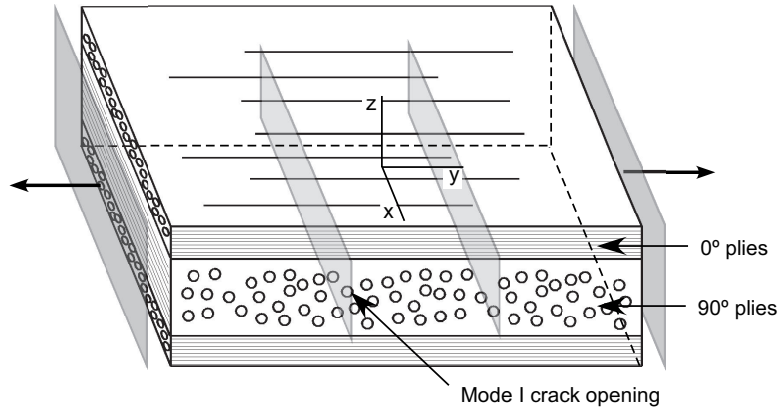


Fig. 4. Micro-cracked $[0_m; 90_n]_s$ laminate loaded in uniaxial tension

88mm.

4. Qualitative Detection of Micro-cracking

The laminate micro-cracking experiment generally involves a symmetric $[0_m; 90_n]_s$ laminate loaded in uniaxial tension. While the specimen is loaded, the 90° plies break repeatedly until all the fragments are shorter than a critical length, as illustrated in Figure 4. It is then impossible to reach the failure strength (or energy, depending on the interpretation) of the remaining fragments, as they are too short to transfer enough axial stress through the interface for another break to occur. Therefore, a saturation state is reached. The distribution of fragment lengths is analysed through stress transfer model(s), and a measure of interface performance can be derived. Very few models are capable of accurately accounting for the effect of interactions between cracks. Much discussion has been carried out during the past two decades on the nature of the result obtained and its interpretation. The micro-cracking process involves multiple damage modes, which renders the interpretation quite tedious, mainly due to the number of material constants to be obtained by independent measurements. In general, three micro-level damage modes are present in a micro-cracking test, thereby rendering the modelling an intricate task. Considerable success has been obtained by McCartney in modelling such effects [23, 24], the results of these studies are currently being incorporated in the module PREDICT of the UK Composite Toolkit, and are currently combined with powerful visualization tools in the present project, using CoDA.

The basic validation of most models hinges on the number of cracks present at a given stress. In order to count the cracks present at each load step, three experimental approaches have been followed. The simplest option is to perform a visual examination of the specimen while it is subjected to a quasi-static loading. One disadvantage of this method is that it requires the laminate to be transparent, which is not the case in most applications, for example with carbon fibre-based laminates, or to examine the edges of the specimen, where the stress state differs from the centre. With such composites, two alternatives are possible: sound detection, where a detector is placed at each end of the composite, so that the location of a new crack forming is determined; or X-ray scans. The first method is very effective but requires expert optimisation to maximise the low signal/noise ratio, while the second is generally limited by economic factors.

Several tests were carried-out using the ESPI system, with various load steps and imaging fields. It was found that the excess of surface displacement due to sub-surface cracking was close to the limit of detection in the y -direction (the loading direction) of our system when using a large imaging field. When a crack appears, some additional fringes are formed on the surface, but the additional displacement is very closely concentrated near the crack. With a large imaging field, the fringes tend to de-correlate, i.e. the pixel resolution is not sufficient to distinguish between two consecutive fringes. This phenomenon is illustrated in Figure 5.

At step 2 the specimen has been slightly loaded, and the fringes are not well-defined, this was mainly due to vibrations of the system, which tend to be more important for small loads. Effectively, fringes are much better defined at steps 20 and 30. At steps 40 and 43 some sub-surface transverse cracks can be seen, as indicated by the arrows on Figure 5. Notice that the interruption between consecutive fringes is a typical effect of de-correlation of the fringes. This is supported by the image taken at the

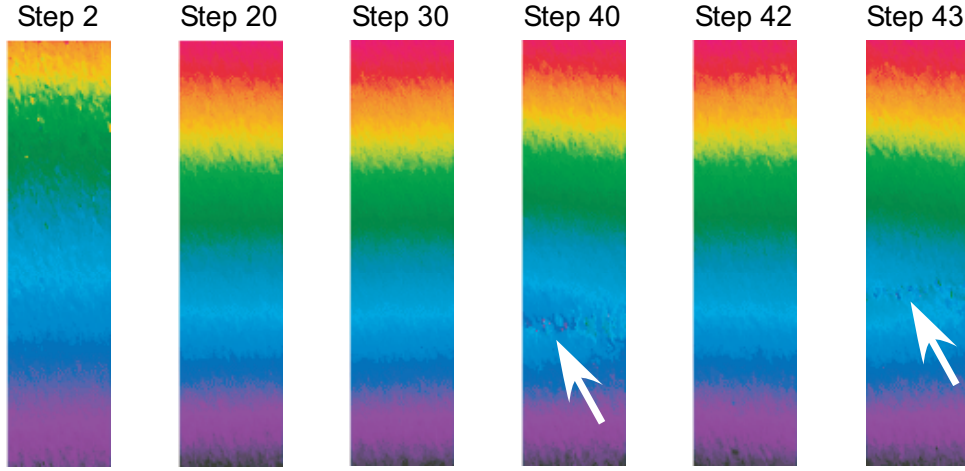


Fig. 5. axial displacement map of a $[0_2; 90_6]_s$ laminate loaded in uniaxial tension. Steps numbers defined in section 3.2 are indicated; the scales of colormaps from edge to edge are respectively 11.9, 108, 225, 322, 460, 475 and $486\mu m$

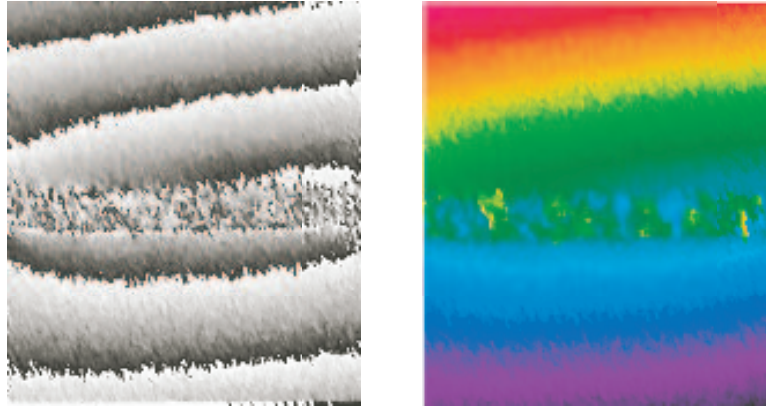


Fig. 6. Micro-cracked $[0_m; 90_n]_s$ laminate loaded in uniaxial tension, reduced imaging field

next step, which does not present such a discontinuity: the de-correlation has been attenuated by the phase-map summation process. Two solutions are envisaged to overcome this problem. First, the spatial resolution of the camera could be enhanced (current CCD cameras with a 1024×1024 pixels resolution are available). One other option is to reduce the size of the imaging field and enable the ESPI head to travel at each load step so that it covers the area of interest. In the present work, it was chosen to test the feasibility of the latter. A $2 \times 2mm^2$ imaging field was used, the ESPI head was kept in a fixed position at the center of the specimen, and a sub-surface crack was clearly observed when it appeared in the middle of the observation window, as shown in Figure 6. The image of surface displacements in the axial direction presents a local maximum where the crack has appeared, it can be used directly to validate stress-transfer models. This method, however, is limited by the small area observed, and would require a travelling ESPI head to be developed together with the software analysis.

When a larger imaging field is used, it has already been mentioned that the system in its current configuration is not sufficient to ensure that all sub-surface cracks are captured. However, the observation of out-of-plane displacements gives a different picture. While the axial displacements lead to de-correlation of fringes where the increase in displacement is too large, the out-of-plane displacements remain small, even when a sub-surface crack appears. Hence, it was found that z -displacements accounted for the presence of sub-surface damages, as shown in Figure 7. This image of z -displacements was obtained for a laminate that had been loaded up to 8kN prior to the experiment, i.e. which was already transversely micro-cracked. The presence of micro-cracks is confirmed by negative out-of-plane displacements, which are presented in green and dark green color on this plot. A higher magnification shows that the line are well-defined, although this type of plot will need some additional filtering of the data. This method

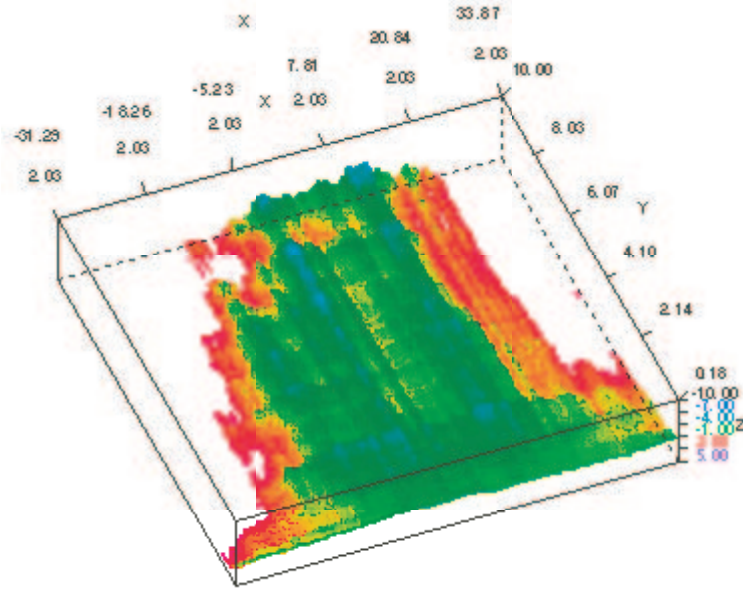


Fig. 7. Out-of-plane displacements of a micro-cracked $[0_2; 90_6]_s$ laminate loaded in uniaxial tension. The x axis corresponds to the y direction in mm , the y axis is the load in kN , and the z axis is the z -displacement in micrometers

provides a very efficient way to assess the occurrence of micro-cracking in an area larger than the previous one, of $65 \times 20 mm^2$. On a quantitative point of view, out-of-plane surface displacements need to be correlated to appropriate models in order to provide useful information. However, on a qualitative point of view, the results shown in Figure 7 demonstrate that it is possible to detect the initiation of sub-surface defects in laminates. The next section shows how these results can be applied to a fundamental quantitative analysis, that of the Young's modulus.

5. Young's Modulus Loss During Micro-cracking

The previous section detailed the use of ESPI for the analysis of local phenomena. However, ESPI can be used with larger imaging fields for a global analysis of the surface displacements. The purpose of the present section is to demonstrate its use in such a configuration, to measure the global axial strain of a symmetric $[0_2; 90_6]_s$ laminate in uniaxial tension, and the associated axial Young's modulus. The measurement of Young's modulus, for both isotropic or anisotropic bodies, essentially hinges on the accurate determination of the applied force and the resulting displacement. Converting these values to stress and strain, one then applies Hooke's law ($\sigma = E\epsilon$, where σ is the stress, E is the Young's modulus and ϵ is the strain) to calculate the modulus. Thus, in theory, only two easy measurements and the most basic equation of materials science are needed. The reality is other, as the stress versus strain curve is not, in most cases, linear at the origin. While most force sensors are linear over a large range of loads, this is not true with most displacement sensors. Extensometers and strain gauges, although widely used, suffer from severe limitations. First of all, strain gauges measure only a small area of the specimen, and they need to be glued to the specimen, which is likely to involve artifacts due to stress transfer between the specimen's surface, the gauge and the glue. Furthermore, when they measure strains in two directions, one should keep in mind that they are calibrated for isotropic materials, and not directly applicable to anisotropic materials. And finally, in the case of the laminates considered in this work, the initiation of a defect in a region near the gauge would bias the measurement, as suggested by the results of the previous section. An extensive comparison of results obtained through the use of strain gauges and ESPI will be carried-out in a later stage of the present project.

With the laminates used and considering the micro-cracking phenomenon, extensometers would seem a more reliable solution: they allow a large gauge length to be measured, and therefore permit to average the effect of micro-cracks across a long distance. However, they suffer from two limitations: i- edge effects will be taken into account, because the extensometer is positioned on the edges of the specimen, and ii- extensometers have a finite compliance, in general non-linear with the applied strain. As a result, when

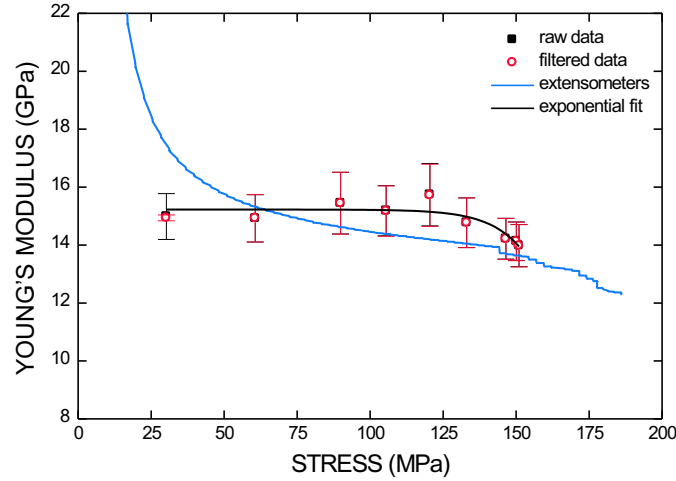


Fig. 8. Axial Young's modulus of a $[0_2; 90_6]_s$ laminate loaded in uniaxial tension vs. the applied stress: comparison of raw data, filtered data, and extensometer-based values, the black line (exponential decay fit) is a guide for the eye

the basic Young's modulus (chord) method is used, one obtains an axial Young's modulus such as that plotted in Figure 8. As it can be seen from the plot, it is remarkably difficult to define a single value from this curve, which deviates to a large extent from the ideal straight horizontal line that should be observed until the onset of micro-cracking. The above-mentioned effects, together with slight slippage of the extensometer on the specimen, are enough to generate a large uncertainty on the value of the axial Young's modulus. When the ESPI values are used instead, the data benefits from a full field and contact-free measurement, and a quasi-constant value is obtained until micro-cracking starts (Figure 8).

In the present experiments, the laminate was not taken to its ultimate failure, so that additional tests can be performed on the same specimen. When micro-cracking starts, above 125MPa, the Young's modulus is decreased by approximately 1MPa. The extensometer values are in a similar range, provided the onset of microcracking can be determined accurately, which requires another mean of detection. One of the main weaknesses of the ESPI analysis is the time required for a proper analysis, which explains the limited number of points on the graph of Figure 8. Current developments of ISTRA[®] and NPL's automated analysis protocol will however soon allow to overcome these difficulties. Finally, the filtered values match closely the raw data, which indicates that this filter, at the present 3×3 level, can be used without decreasing the sensitivity of the technique. It was found, however, that there was only a small improvement of the error associated with each measurement, which is certainly due to the track measurement protocol. The filtered images provide a better resolution of the fringes, and the error associated with a measurement over the whole area would certainly decrease more importantly.

Finally, one should notice that the Young's modulus values determined constitute an upper bound to their real value. The reason is the de-correlation of fringes that can occur when a transverse crack initiates. De-correlation corresponds to the disappearing of one fringe, and introduces an error on the axial strain measured of s_y . This error might be compensated by the least squares calculation of ϵ_y . One possible solution to account for de-correlation is to compare the results of y and z displacements at each step and determine if a fringe has disappeared in the load step. This type of procedure can be fully automated in the future.

6. Conclusions & Recommendations

ESPI is an effective strain measurement method, provided certain experimental precautions are taken. Given the high sensitivity of the ESPI measurements, the principal concerns for standard tensile tests are the stiffness and stability of the experimental set-up, the proper dimensioning of the samples, and an appropriate loading programme. The positionning of the ESPI unit, the sample, and the loading system

must be rigid and free of vibrations. The specimen size and the viewing field must be adapted to the expected deformations. The measurement procedure requires quasi-static conditions, and the size of the load steps must be adjusted to provide an optimal number of interference fringes in order to increase the signal-to-noise ratio and to avoid de-correlation of the speckle patterns.

In the present work, the ESPI strain mapping technique was successfully applied to the detection of sub-surface micro-cracks in $[0_m; 90_n]_s$ laminates. While the in-plane measurement was quite tedious and required a number of adjustments and further developments, the out-of-plane measurement permitted to assess the presence of sub-surface micro-damage straightforwardly. The in-plane axial strain ESPI measurement was further used to determine the stress behaviour of the axial Young's modulus of the laminate. It was proven that ESPI offers a reliable alternative to strain gauges and extensometer measurement of the displacement, as the Young's modulus values were undoubtedly more reliable than those obtained using conventional methods. It was further possible to assess the loss of Young's modulus due to transverse micro-cracking.

7. Acknowledgements

The research reported in this document was carried out by NPL, as part of the "Measurements for Materials Systems" programme funded by the Engineering Industries Directorate of the UK Department of Trade and Industry. The authors also wish to thank N. Paine (Pentax UK ltd.), and T. Walz (Ettemeyer AG) for valuable advice and help with setting-up the ESPI head.

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