

# Impact Damage Detection on Composites using Electronic Speckle Pattern Interferometry

D Findeis<sup>1</sup>, J. Gryzagoridis<sup>2</sup> and W. Bopape<sup>3</sup>

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*The paper presents the results from an attempt to detect damage resulting from impact loading events such as tool drop or bird collisions etc. on composite materials designed for structural applications in the aerospace industry. The investigation attempted to establish the possibility of detecting; beyond of what is obviously visible to the naked eye, the extent of damage inflicted on composite panels which were subjected to controlled impact. For the purpose, electronic speckle pattern interferometry was chosen as the non destructive evaluation technique to be employed in this study, because it is non-contacting, whole field, non limited to particular material types and provides fast and easy results in real-time. The specimens were subjected to low velocity impact energy levels by using an instrumented drop-weight impact tester. The results show that the probability of damage detection from impact is quite good even if the damage has been created at very low impact energy levels.*

**Additional Keywords:** ESPI, NDT, laser, optical speckle, impact

## Nomenclature

### Roman

- $f$  = final image after object stressing
- $i$  = initial image before object stressing
- $I$  = intensity of any point on the captured image
- $N$  = number of correlation fringes observed
- $r$  = resultant image
- $1$  = reference beam
- $2$  = object beam

### Greek

- $\alpha$  = angle between the line of observation (camera) and the normal to the surface
- $\beta$  = angle between the surface normal and the line of illumination
- $\delta$  = out-of-plane displacement measurement normal to the surface and along the line to the viewer
- $\theta$  = laser beam phase angle
- $\lambda$  = wavelength of the laser used
- $\Delta\phi$  = change in phase of the laser light

## 1. Introduction

Composite materials have found usage in many industrial applications and more recently are increasingly being used in aerospace panels and airframes. The use of composites in the aerospace industry is justified not so much by their absolute flexural strength but their specific strength (strength to density value) sometimes referred to as strength-to-weight ratio. However, the mechanical properties of composites may degrade severely due to defects and flaws arising from damage sustained for example through impact. This damage may not be visible to the naked eye and may result to the failure of a system, after a certain cycle or time of operation. It is known that impact causes the core or matrix in composites to crack in a characteristic way, known as star cracks, which are internal and difficult to detect when using traditional non destructive testing techniques. It stands to reason that impact damage, no matter how small, should be detected as soon as possible in order to monitor its growth during use of the component or structure. To this end it is desirable to employ a technique, either a theoretical numerical analysis model<sup>1</sup> or some form of non destructive testing technique such as for example thermography, shearography and electronic speckle pattern interferometry (ESPI), all known for their high sensitivity. In this case ESPI has been chosen as the NDT technique to be applied mainly because of its advantages over other techniques, in addition to the fact that the authors have had considerable experience in using this technique, having performed quite a few investigations in the past on engineering components of various materials including composites<sup>2</sup>. ESPI was first demonstrated by Butters and Leendertz<sup>3</sup> as a special version of holographic interferometry where the display of correlation fringes is directly upon a television or a personal computer monitor practically in real time. The correlation fringes are interpreted as a contour map of the surface displacement of an object when it is stressed and compared to a reference state. The stress on the object can be caused by minute mechanical, thermal, pressure or vacuum loading and the surface displacement can be measured either in the in-plane or out-of-plane direction depending on the choice of the sensitive arrangement or set-up of the optical components of the ESPI system. The out-of-plane displacement sensitive arrangement is the more versatile of the two as it makes better usage of the light emanating from the laser and has been preferred and employed by the authors either in their laboratory work or using their portable prototype<sup>4, 5, 6</sup>. Figure 1 shows a typical ESPI out-of-plane displacement measurement set-up where the object is illuminated by the "object beam" after it was expanded using a microscope objective lens. The object beam is the transmitted portion of the original laser beam that passes through the beam splitter. The reflected portion from the beam splitter, known as the "reference beam", is also expanded and introduced into the (closed couple device) CCD camera, normal to the reflected light from the object.

Using simple beam theory of the geometry that results from incident and reflected beams (a lesser elegant method than the classical approach) it can be shown that the out of plane dis-

<sup>1,2</sup> MSAIMechE

<sup>3</sup> Department of Mechanical Engineering  
University of Cape Town, Private Bag X3,  
Rondebosch, 7701, South Africa.  
E- mail: Dirk.Findeis@uct.ac.za

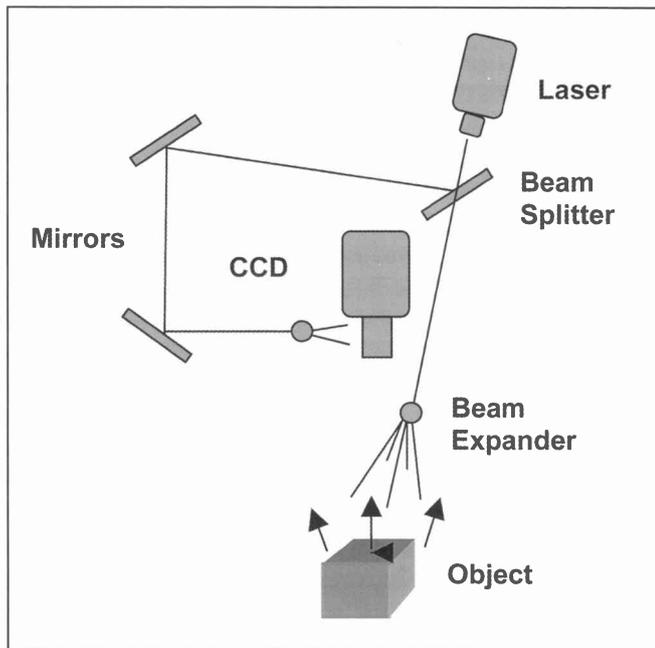


Figure 1: Schematic of out-of-plane displacement sensitive ESPI

placement of any point on the object can be calculated using the following equation

$$\delta = \frac{\lambda * N}{\cos \alpha + \cos \beta} \quad (1)$$

Provided we can minimize the two angles or make them approach zero, equation 1 reduces to

$$\delta = \frac{\lambda * N}{2} \quad (2)$$

Thus one obtains the level of the sensitivity of the measurement. In the case of a HeNe laser being employed as an illumination source the sensitivity of out-of-plane surface displacement measurement is of the order of 316 nanometers per fringe (approximately 1/300 of the width of human hair).

Same result regarding the out-of-plane displacement of a point on a surface of an object which has been subjected to minor stressing (thermal, mechanical, vacuum etc.) can be arrived at, by considering the light intensity an object reflects toward a camera.  $I_i$  of any point on the image that the camera captures is the sum of the amplitude of the two wave fronts (created by the reference and object beams  $I_1$  and  $I_2$  respectively) and the phase difference between them ( $\theta_1 - \theta_2$ ), formulated by the defining equation:

$$I_i = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\theta_1 - \theta_2) \quad (3)$$

When the object is stressed the surface deforms, the speckle pattern is altered and the intensity changes due to a change in  $\Delta\phi$  caused by the small speckle movement, hence

$$I_f = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\{(\theta_1 - \theta_2) + \Delta\phi\} \quad (4)$$

Fringes of correlation are produced when we subtract  $I_f$  from  $I_i$  with the resultant intensity given by

$$I_r = I_i - I_f = 4\sqrt{I_1 I_2} \sin\left[(\theta_1 - \theta_2) + \frac{1}{2}\Delta\phi\right] \sin\frac{1}{2}\Delta\phi \quad (5)$$

Maximum correlation is unity and it occurs when  $I_i$  is equal to  $I_f$  or that  $I_i$  equals zero, which is a certainty when  $\dots \sin \Delta\phi$  is zero; of course this implies that

$$\Delta\phi = 2N\pi \quad N = 0, 1, 2, 3, \dots \quad (6)$$

Under this condition black fringes are created (the images' intensity cancels out) as a result of the phase change resulting from a surface displacement given by

$$\Delta\phi = 4\pi\delta/\lambda \quad (7)$$

Combining equations 6 and 7 we obtain the same result as equation 2.

Similarly minimum correlation exists when  $\Delta\phi = (2N+1)\pi$ , in which case white fringes are produced (the two images intensity is not cancelled). If chosen to be utilized for measurement the white fringe next to a black fringe would represent a half fringe order with the same sensitivity as the black ones.

$$\delta = \frac{1}{2}\left(N + \frac{1}{2}\right)\lambda \quad (8)$$

In the manner described above the technique known as ESPI produces an image of the object under test having a pattern of alternating black and white fringes superimposed upon it. These fringes are a measure of the object's surface displacement in an in-plane or out-of-plane direction depending on the optical set-up.

## 2. Experimental Procedure and Results

The main apparatus in this work consisted of a laboratory ESPI set-up used to perform non destructive testing on the composite specimens and a weight drop tester used to produce impact damage on the specimens. The specimens were manufactured from the wing of a UAV (unmanned aerospace vehicle) which was made available for the purpose by Denel Aerospace Systems. The specimens having an area of  $95 \times 105$  mm were 7 mm thick consisting of two fiberglass skins sandwiching a honeycomb. The specimens were impacted with a mass of 0.8 kg with an

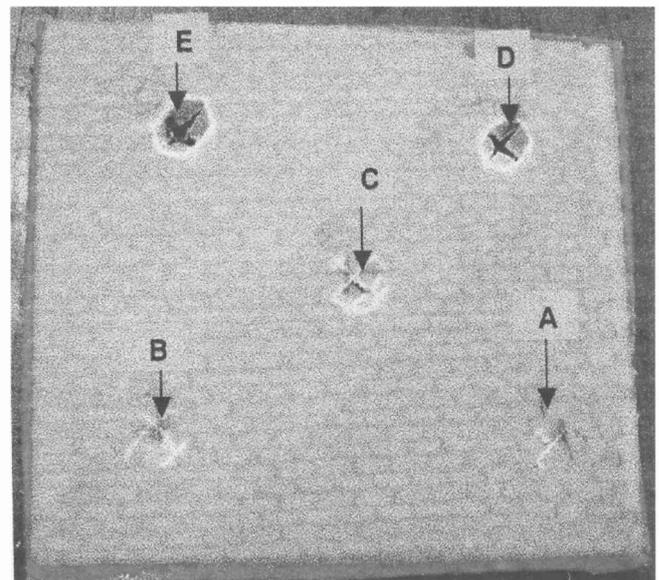


Figure 2: The test specimen subjected to various impacts energy levels

8 mm hemispherical impact tool attached to it that came into contact with the specimen's surface. The mass was dropped from heights in the range of 50 to 175 mm resulting in equivalent impact velocities of 0.3 to 1.4 m/s and associated energies of 0.39 to 1.18 J; after the initial impact the head was arrested to prevent secondary strikes. The specimens were subject to low velocity impact on one side (see figure 2) and inspected from the opposite surface; therefore the damage was regarded to be an internal flaw located at some distance below this surface.

This distance was defined, for our purpose, as the thickness of the specimen minus its deflection recorded during impact, an arbitrary parameter of course, however far more reliable than attempting to measure permanent deflection on the specimen's impacted surface. Table 1 below shows typical data obtained from the drop tester.

Max. Impact Energy (J)	Max. Impact Force (N) Impacted side	Max. Impact Force (N) Inspected side	Impact Velocity (m/s)	Maximum Deflection (mm)
(A) = 0.39	190.9	0	0.295	0.386
(B) = 0.58	207.4	0	10.36	3.739
(C) = 0.79	189.2	0	1.211	5.424
(D) = 0.94	197.5	0	1.368	6.646
(E) = 1.18	181.6	316.8	1.412	

Table 1: Drop test results for the composite sample

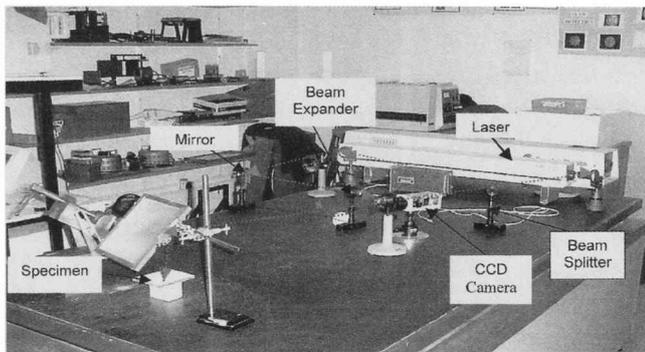


Figure 3: Out-of-Plane displacement sensitive ESPI laboratory set-up

The ESPI tests were performed using a laboratory set-up for out-of-plane displacement measurements (see figure 3) identical to the one represented as a schematic in figure 1. The object/

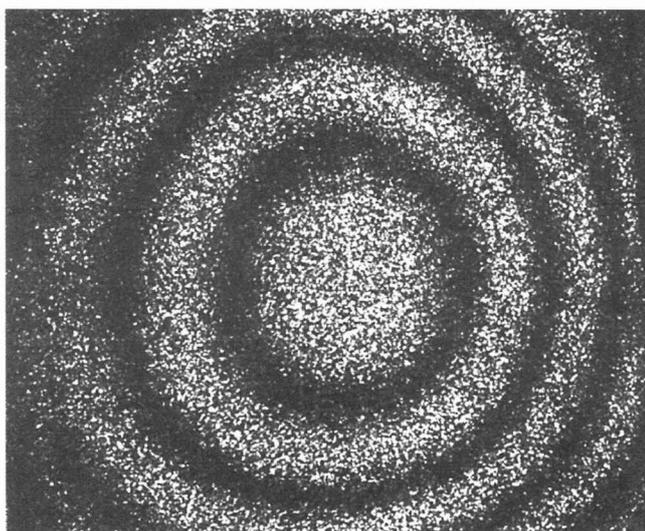


Figure 4: Undamaged specimen

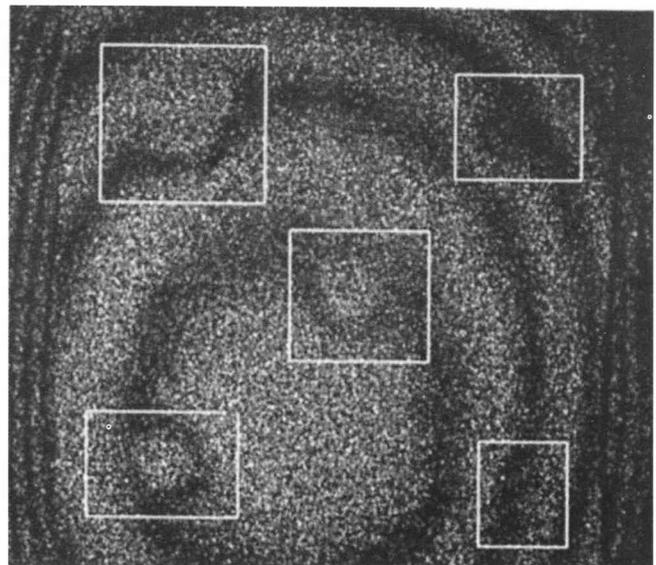


Figure 5: Specimen after impacts

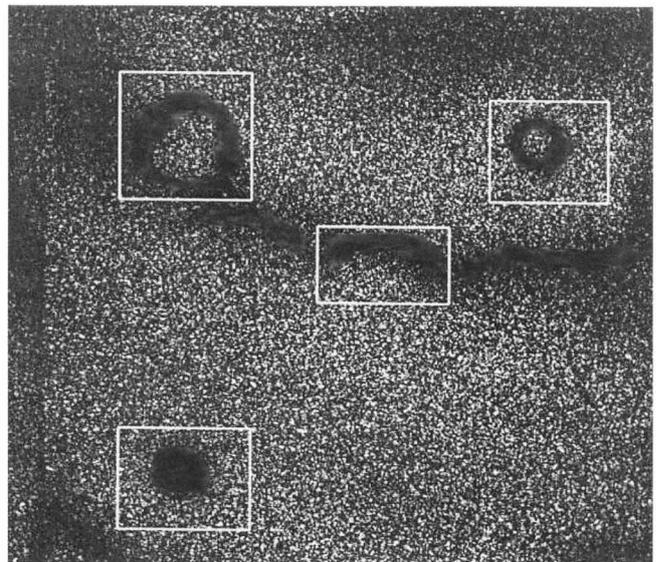


Figure 6: The 0.39 J impact unrevealed

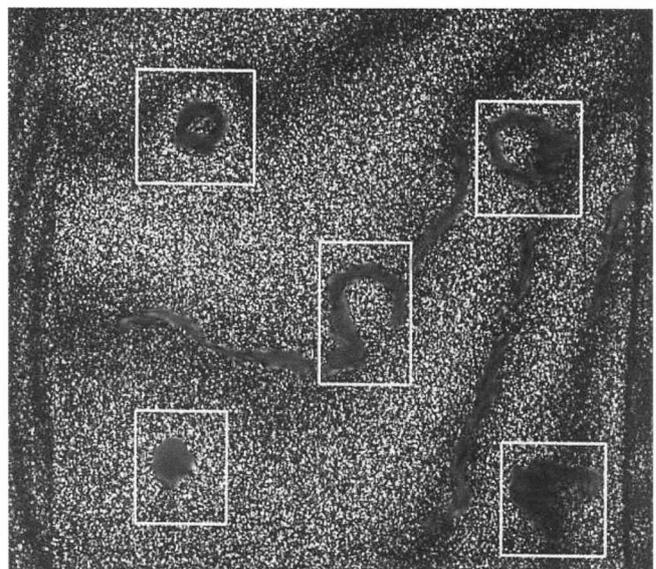


Figure 7: All defects revealed

specimen was positioned on the optical table, was illuminated by the laser and its image captured and stored by the CCD camera and the digitizer in the personal computer. A second image was obtained after the specimen was mildly heated for a few mo-

ments using a hair dryer. The two images were subtracted using the pc's software and the resulting image was displayed on the monitor depicting the characteristic ESPI fringe pattern.

Figure 4 is the ESPI image of the specimen prior to being subjected to the impact tests, and as expected the fringe pattern of an out-of-plane surface displacement after it was mildly warmed with the hot air from the hair dryer is symmetrical and void of any abrupt changes in their circular/elliptical form or local concentration of higher density fringes.

Figures 5, 6, and 7 are the results from the damaged specimen where the fringe pattern is clearly disturbed by the hidden impact damage.

Note that the damage that resulted from the lower impact energies and therefore the damage furthest away from the inspected surface is sometimes not clearly visible, or not at all as is the case for the damage attributed to the lowest (0.39 J) impact energy and absent in figure 6 (bottom right in the pictures).

The results of attempting to establish the probability of detecting a flaw are shown in figure 8.

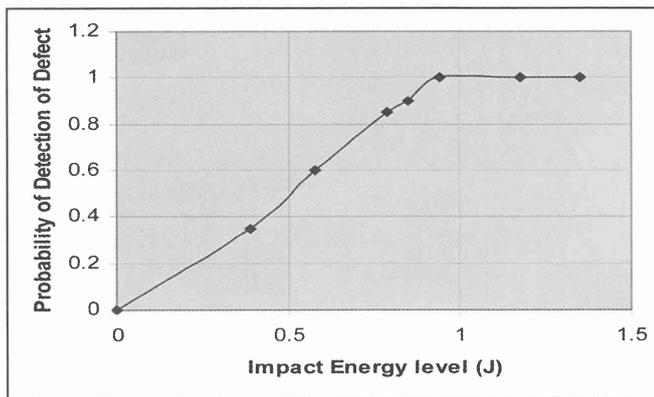


Figure 8: Probability of detecting damage vs. impact damage levels

Since there obviously is a relationship between damage extent and impact energy level, seven specimens were prepared and inspected twice ten times each. The results reveal that the probability of detecting a flaw that was created due to impact energy greater than 0.94 J is 100 % since out of 10 tests the flaw was detected each time.

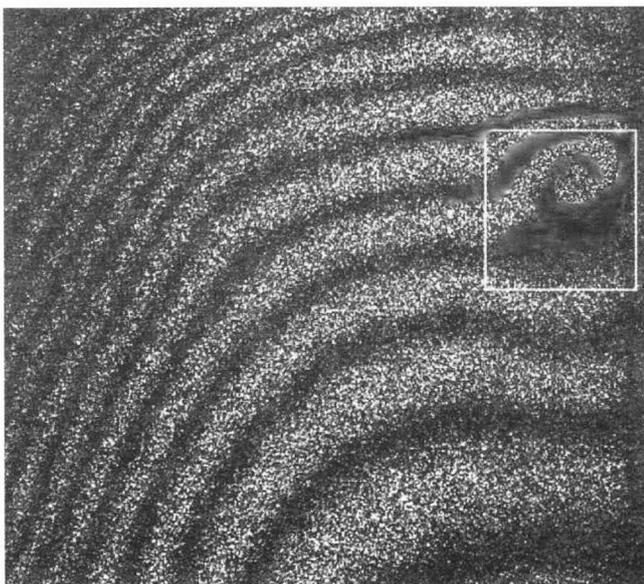


Figure 9: Damage due to 0.58 J

Similarly for the specimen created with an impact energy level of 0.395 J only 3 to 4 times was the flaw indicated by the ESPI tests. Figures 9 and 10 are typical interferograms obtained.

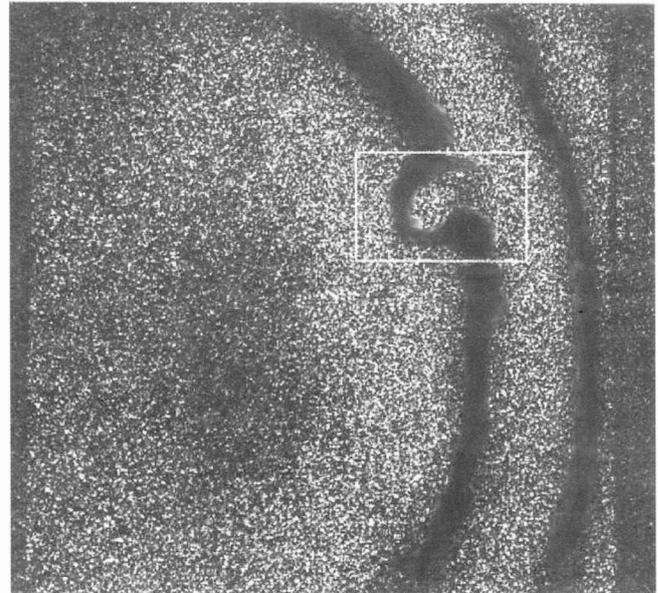


Figure 10: Damage due to 0.79 J

In order to establish with certainty if a defect could be detected through the surface skin and the entire thickness of the core, a de-bond or de-lamination was produced by separating the honeycomb from the skin. Since the specimen was 7 mm in thickness and the surface skins were 1.0 mm each, the ESPI managed to pick up the de-lamination 6 mm away or deep from the surface that was being inspected. The result is shown in figure 11 below, where the fringe concentrations in the bottom left of the image reveal the location of the delamination.

As emphasized, these results are specific to the component tested.

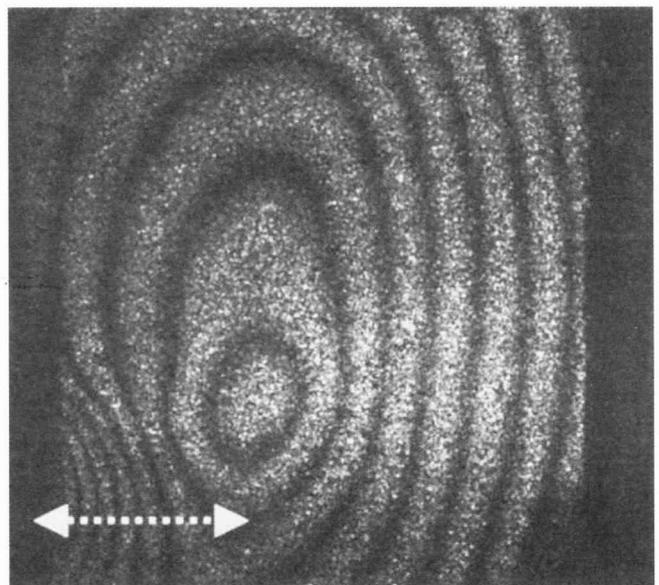


Figure 11: De-lamination revealed

### 3. Conclusions

The results from this work are clear evidence that ESPI is a powerful non-contacting, full field, high sensitivity, NDT technique

which yields rapid and reliable qualitative information regarding sub surface defects such as damage from low velocity impacts and core-skin de-laminations in composites. On the basis of fringe pattern analysis and the evidence presented by the tests, it is reasonable to conclude that defects will distort a fringe pattern and generate localized higher spatial density fringes in regions where strain concentrations are present in a structure. Furthermore with the proper approach the fringe patterns are quantifiable. The results also show that the probability of damage detection from impact is quite good even if the damage has been created at very low impact energy levels. In figure 8 we see that for the particular composite tested, even at the very low impact energy of 0.4 J a defect created by an eight mm semispherical surface 6.6 mm from the surface had a probability of 35 % of being identified with the ESPI technique. Defects resulting from manufacturing inconsistencies or during service cyclic loading such as de-bonds and de-laminations were easily detected, with this particular composite, even at the furthest depth position i.e. the second core-skin interface.

The above quantification relies on the human to interpret the results obtained. Work is in progress to attempt automating this process via a computer based fringe interrogation approach.

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