OPTICAL NON DESTRUCTIVE TESTING METHODS USING CONTINUOUS WAVE, PULSED OR DIODE TYPE LASERS

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Abstract: Optical Non-Destructive Evaluation (NDE) laser based methods include among others, Holographic Interferometry, its subsequent development into Electronic Speckle Pattern Interferometry (ESPI), and another speckle technique known as Shearography. These laser based methods are very attractive in that they provide full field view non-contacting means of determining material conditions, in engineering components, that may contribute or result in catastrophic failures. The major basic limitation of the above mentioned methods is experimental stability in that excessive motion or deformation of the object under test would cause wipe-out of information. This paper reviews the above three laser based optical NDE methods, namely holographic interferometry, electronic speckle pattern interferometry and shearography, used by the authors in the past, as tools able to measure deflections and their derivatives, as well as the detection and quantification of defects. Examples of Holographic Interferometry, ESPI and Shearography are included, together with recent results of the authors' research and development into the production of portable and relative inexpensive ESPI and Shearography equipment.

Keywords: Interferometry; laser; NDE; optical; speckle; shearography

1. Introduction

In general some of the technologies of non-destructive testing and evaluation have been available for some time, but industry has not recognized that they are not only applicable at the end of the production process, but that they are also applicable during the design and manufacture stages as well as during operation and only cease on retirement of the component. Development of non-destructive testing tools has been spectacular in recent years and particularly optical techniques where an important ingredient has been the practical application of lasers. As a result the inevitable resistance to the use of laser based techniques from defenders of long established methods appears to have reduced as a result of successful practical applications.

The use of polarized coherent light beams, typically found with various types of lasers, has resulted in the development of very attractive non-destructive evaluating techniques, seeking to detect flaws in critical parts of engineering components. The laser based methods are attractive because they are non invasive, non contacting, full view and often real time techniques of determining material conditions which might eventually lead to failure.

2. Optical NDE techniques

2.1 Holographic Interferometry

Holographic interferometry is a technique that makes use of the ability to record two slightly different scenes and display the small differences between them. The image of an object, captured on to emulsion type film, is made to interfere with the image of the object superimposed on it (real time), or with another image also stored on the same film, which was obtained by ever so slightly perturbing the object between the two recordings (double exposure). The interference created manifests itself as contour lines superimposed on the object's image and they are a measure of the amount of dimensional differences of the object at the two stress stages. Relatively speaking holographic interferometry is a recent non-destructive testing technique (Erf [1], Vest [2]), but is an extremely sensitive tool often revealing peculiarities in the object's inner structure such as de-bonds and de-laminations. Surface cracks and micro-cracks are also easily detected by this technique, which unfortunately did not find wide spread practical applications in the normal industrial environment because of its stringent stability requirements and therefore the best results have been obtained in the laboratories. This, in broad outline, is the background that the authors of this paper come from, with the main objective being to blend the experience gained in the laboratory on holographic flaw detection, together with recent technological advances in lasers, digital image acquisition, personal computers etc., in producing tools that can be used reliably in the workplace.

In a typical holographic interferometric set-up the two key components, as shown in the schematic arrangement (figure1), are the continuous wave laser and a very high resolution emulsion type film. In this basic set-up, widely accepted by investigators, the laser beam is divided into the object beam (illuminating the object) and the reference beam, by a beam splitter. Two kinds of holographic interferometry were executed in the laboratory, namely double exposure and real time and the results have been reported by Gryzagoridis [3,4,5]. These early practical applications in the laboratory

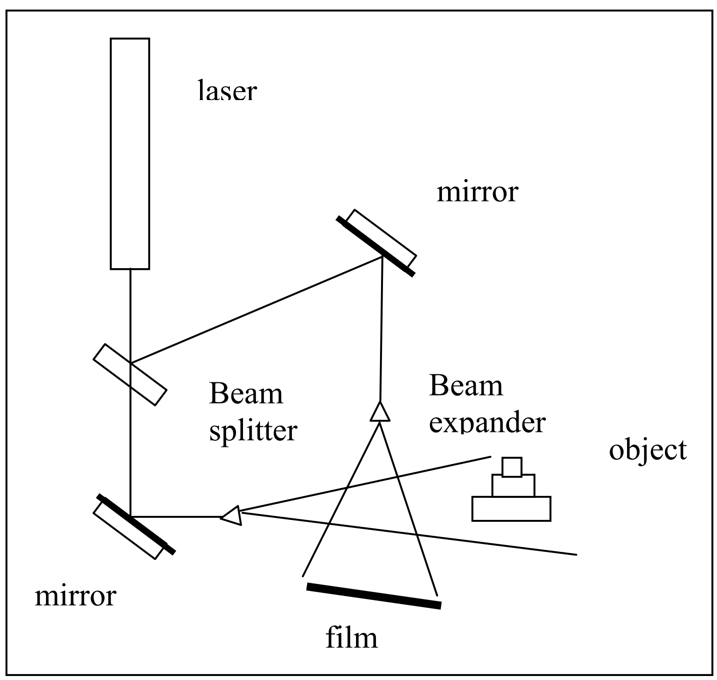

Fig. 1. Holographic set-up

were soon followed up with work in the industrial environment using a 1J pulsed ruby laser configured as a portable holographic system consisting of 5 modules, (figure 2). The ruby laser together with the necessary optics for the production of a double exposure hologram, were mounted on a hydraulically operated scissors trolley. The control/power supply, refrigeration unit, automatic film processor and the hologram viewing module completed the system. The system was tested in industrial environments, having traveled over long distances by road transport without requiring even minor adjustments, Gryzagoridis [6].

Fig. 2 The Pulse Ruby Holocamera

Technological advances in the digital image acquisition, lasers and personal computers fields enabled NDE researchers to opt for the image acquisition and video processing to generate speckle pattern correlation fringes, in relatively much more user friendly techniques then holographic interferometry.

2.2 Electronic Speckle Pattern interferometry (ESPI)

About 30 years ago the idea of using video systems was advanced by researchers such as Butters [7] and Macovski [8], as a natural extension of the traditional holographic interferometry methods, where the recording medium was Agfa, Kodak or Ilford holographic plates and film. The price that was paid at the time, for superior quality images, was relatively low sampling rate and long delays in the processing and analysis steps of the procedure. In video holography or electronic speckle pattern interferometry (ESPI), the system consists of the identical optical elements and layout configuration as the holographic interferometry with one single fundamental change. A CCD camera replaces the holographic film

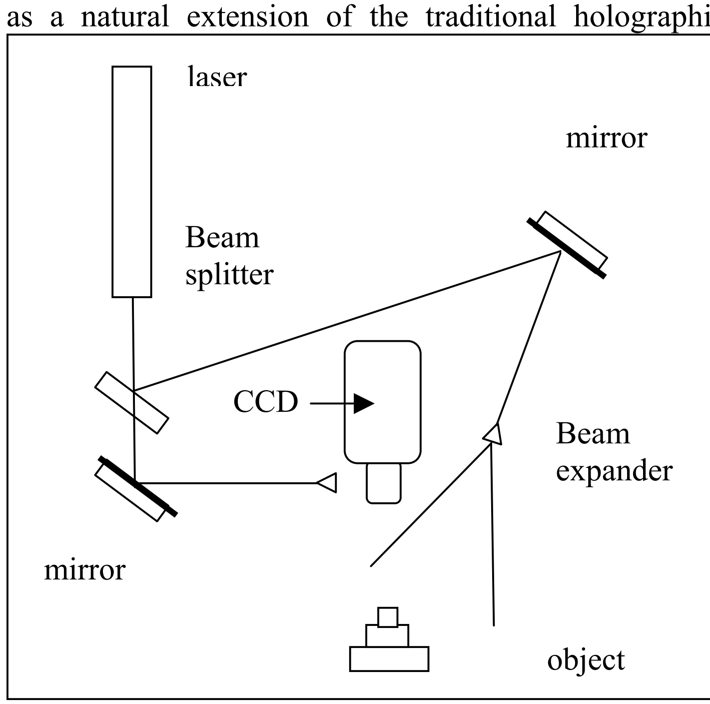

Fig. 2 ESPI set-up

or plate holder. (figure 3). The video signal is sent to the computer frame grabber where the complete image is stored in digital form. A simple adding or subtraction routine is performed with two stored images and the result is a final image with the characteristic fringe pattern indicating surface displacements. ESPI has a low resolving power because even the best CCD camera does not come even close to the resolving power of holographic film therefore the captured information is substantially reduced. On the other hand the high sampling rate and the ease of obtaining results by far outweigh the loss in image quality. However like holographic interferometry ESPI suffers from the same disadvantage of extreme stability requirements and the usage of continuous wave laser illumination restricts it to laboratory usage. In order for ESPI to become more widely applicable it must be able to work in real situations in the engineering environment under sometime hostile conditions. Using a pulsed laser reduces problems such as low power illumination and stability requirements and is the natural follow up from the pulsed holographic interferometry that was mentioned earlier above.

When using a pulsed laser such as a ruby, as a source of illumination in ESPI, the use of convex lenses and mirrors is not recommended because of the high energy that could result in air ionization. Spatial filtering of the reference beam is also not possible and therefore the reference beam is quite noisy. However the above are offset when one can operate in daylight or artificial light as opposed to near dark room conditions and at a much quicker sampling rate. Figure 4(a) is a schematic diagram of the pulsed ruby holocamera used by Gryzagoridis [6] in the holographic interferometric mode. Figure 4(b) is a schematic diagram illustrating how the holocamera was modified by the authors as an ESPI non-destructive testing tool. This testing facility proved very successful as demonstrated by taking it into industrial sites to perform non-destructive testing of individual components as reported by the authors in [9].

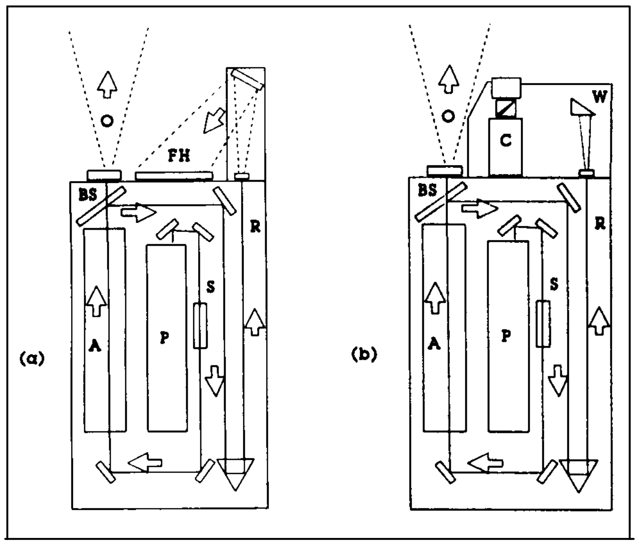

Fig. 4. (a) Holographic set-up: P- ruby pumping chamber; A- ruby amplifier chamber; BS – beam splitter, R- reference beam; FH – film/plate holder; O – object beam. (b) ESPI set-up: W – angle prism; C- CCD camera.

2.3 Shearography

Shearography is a novel non-destructive method used to inspect manufactured components for defects and flaws, because material discontinuities within objects, which alter the surface of an object, can be detected with this inspection method. Originally shearography was developed as a strain-measuring device but because it is tolerant to the hostile environment found in many industries, it is now being used routinely in the aerospace and rubber tire industry and is endorsed by the American Federal Aviation Administration [10]. One major difference between shearography and the previous two discussed optical techniques is that it allows full field measurement of the first **derivative** of the surface displacement field, by looking at discontinuity induced strain anomalies, and thus it provides more direct information about the defect. Another major difference is that there is no separate reference light beam created by splitting the light beam emanating from the laser, because the role of the reference beam is taken up by one of the mutually shifted object beams as a self-reference. Finally the requirement of vibration isolation is reduced considerably because only the displacement variation is measured in a pre-determined direction that is insensitive to rigid body motion.

Historically shearography had received limited acceptance on account of having to use photographic film as the event recording medium, but yet again with the advent of technology a new method was developed known as digital shearography. This new method utilizes the same technology as ESPI i.e. a CCD camera, a personal computer with an image digitizer etc. that allows non-destructive testing at video frame rates. A typical schematic arrangement of a shearography NDE testing tool is shown in figure 5. Because shearography is based on the correlation of the speckle produced by the illumination, that curious granular appearance of a surface, a light source of sufficient coherent length is needed, thus the use of a laser is indicated. Various techniques and arrangements of optics have been designed to split the image of the object into two images at the plane of the video camera, which views them as two images slightly offset to each other with a major portion overlapping. This is equivalent to bringing two separate points on the object to coincide in the camera's image plane and there allowing them to interfere with each other. More over the image shearing devices can be designed to produce sheared images in the vertical, horizontal or any other orientation. The speckle distribution is created by the laser reflection off the object's surface, and any deformation of the surface will cause the speckle pattern produced at the video camera's image plane to change. By recording an initial speckle pattern of the object, an initial reference strain level is produced. If the object is then stressed the speckle pattern is altered and comparison of these two speckle images yields areas of correlation that generate dark spots and areas of de-correlation which create bright spots. The result is an image consisting of the object in the background over-laid by alternating dark and bright zebra like bands, commonly referred to as fringes. Any discontinuities or abrupt changes in direction or fringe density are usually the manifestation of localized change in the displacement gradient as a result

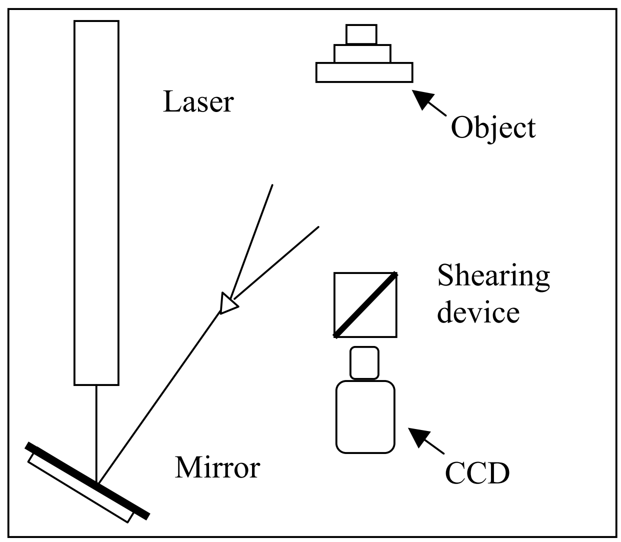

Fig. 5 Shearography set-up

of localized structural weakening which point to the presence of a flaw. Gryzagoridis at all [11] reported earlier work in Shearography and lately the authors have successfully developed a portable shearography system as part of a research programme with the South African Defence Force, Aircraft Division. Encouraged by the results obtained from the laboratory trials the authors proceeded to perform an on-site evaluation of the prototype at the local Air Force base in Cape Town. The system has performed very well in various field trials when required to inspect aircraft structures, helicopter blades etc. as reported by Findeis [12,13,14]. A brief description of the prototype is detailed below.

2.3.1 Portable Shearography Camera for NDT purposes.

The prototype or technology demonstrator depicted in figure 6 serves as an illustration of the Shearography NDE tool developed by the authors. The prototype comprises the Shearography Head mounted on a tripod, a personal computer, keyboard, SVGA monitor, diode laser, a CCD camera and power supplies. The Shearographic Head consists of a number of components and it is the system's input stage. A 50 mW infrared (810 nm) diode laser housed in this assembly also contains optics for collimating and enlarging the laser light beam. The light from this laser is not easily detected by the naked eye because it is mainly in the human invisible range. For best results the light can be seen against a white card in subdued normal light, very near its exit from the Head. The assembly housing the diode laser can be rotated in the horizontal plane for optimum illumination and video reception of the object under test. The image that is viewed by the CCD camera is created through a proprietary shearing device and a narrow band filter (810nm). The amount of shearing of the image (analogous to double vision), in any direction is controlled by flexible drive shafts through knobs. The camera is fixed to the base of the unit and is equipped with a zoom lens and customary controls. The overall dimensions of the Shearography Head are: Width: 300 mm- Length: 335 mm- Height: 100 mm- Mass: 6.5 kg. The tripod that has been provided is a robust GITZO standard photographic type equipped with various controls. The computer that is used in the system is a Pentium II /266 equipped with a Matrox Pulsar video digitizer. The operating system installed is Microsoft's Windows NT work- station. A proprietary shearography computer programme has been written which enables the processing of the images that have been stored in the computer, to produce the final shearographic image of the object undergoing a non-destructive test.

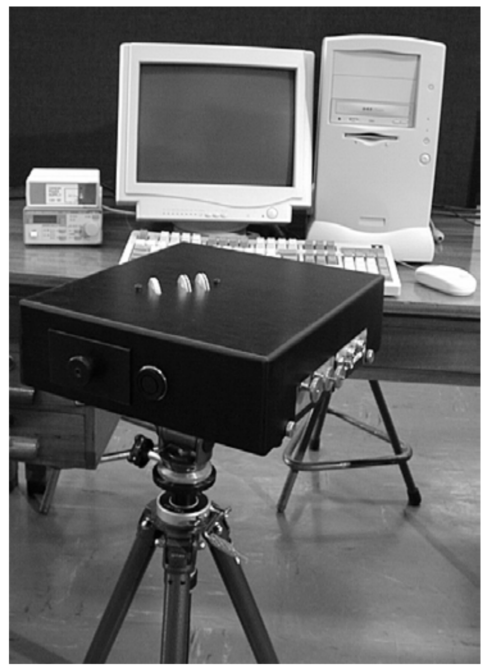

Fig. 6 Prototype of a Portable Shearography System developed by the authors.

2.3.2 Portable ESPI Camera for NDE purposes

Following the success of using a pulse ruby laser to produce the ESPI non-destructive tool, the authors have embarked on a project to develop a really relatively inexpensive portable ESPI Camera, along the lines of the Shearography one, that was introduced in the previous paragraph. It is felt that with the current advent of technology in the Diode laser field, where already one order of magnitude of greater laser power is available (500 mW), it is simply a matter of continuing our current research and development efforts to pulse the Diode laser and sinchronize the Closed Couple Device camera. We are hopeful that in the very near future we should be able to unveil a prototype.

3. Appendix

This appendix contains a sample of some of the work undertaken in the past using the three laser based non-destructive testing techniques detailed above. The purpose is to attempt to show the versatility of the techniques ranging from simple diagnostic or flaw identifying tools to their ability of determining the criticality of defects say on the basis of life extension of a component for example. It has been our experience that provided one selects the component stressing technique i.e. thermal, pressure or mechanical stressing that yields the most dramatic fringe pattern, one can proceed with performing stress and displacement analyses of the component to be tested, using information from codes, finite element analysis etc. In this manner the critical parameters once identified will form part of the decision making software controlling the testing routine. We therefore advocate links between ESPI, Shearography and rigorous analyses which for individual cases are likely to be more effective in the short term then others aimed at general form solution.

HOLOGRAPHIC INTERFEROMETRY (Industrial testing)

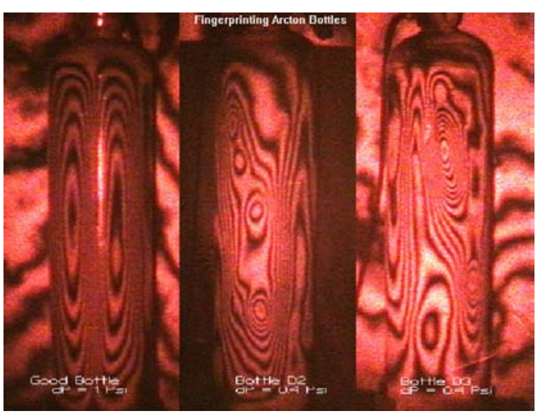

Fig. A-1. Testing of Arcton bottles using the Pulse Ruby Holocamera. The bottle to the left is a new one. The other two depict various flaws due to dents, internal pitting etc.

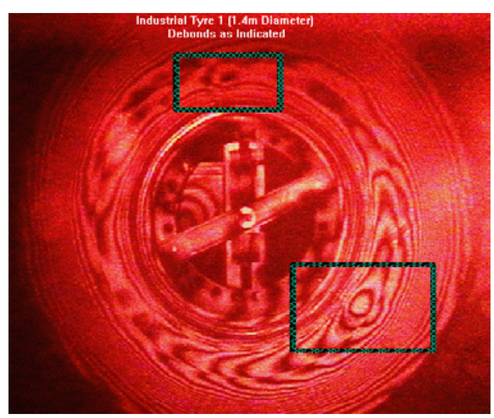

Fig. A-2. Testing of industrial tires using the Pulse Ruby Holocamera. The tire 1.8 m in dia. used for under-ground mining equipment depicts two areas of fibre de-lamination.

CRACKS IN A PRESSURE VESSEL (An ESPI study)

A small aluminium cylinder, resembling a pressure vessel was employed. The cylinder had an axial and a circumferential thumbnail crack manufactured at 180 degrees apart, in an axi-symmetric manner. The cylinder was subjected to internal pressure and using the ESPI set-up, out of plane surface displacement measurements near the cracks were obtained. Examples of the ESPI fringe patterns obtained around the axial cracks across half of the cylinder and their finite element analysis counterparts are shown in Figure A-3. Comparisons were made around the crack size with typical results presented in figure A-4 which displays good agreement between the experimentally determined displacements in the vicinity of the crack with those predicted by the finite element analysis.

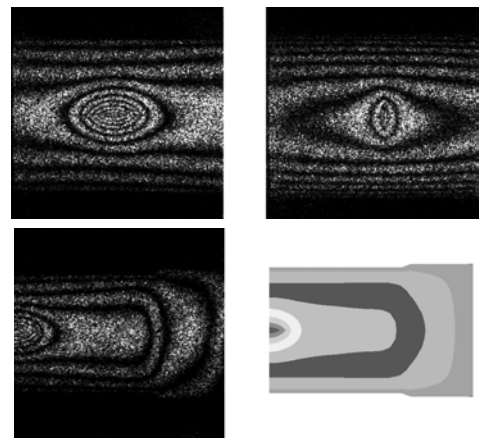

Fig. A-3 ESPI vs. FEA results

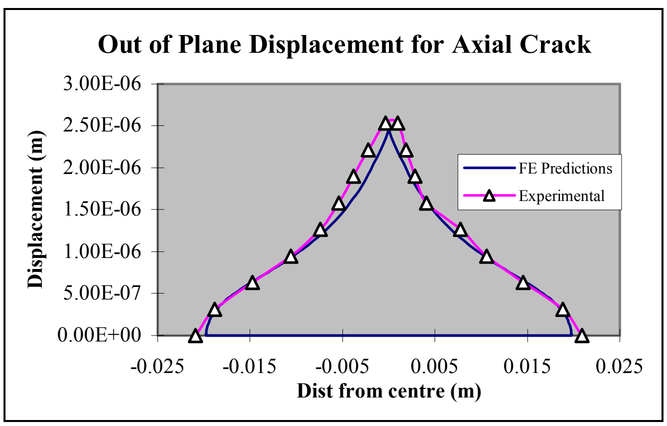

Fig. A-4 Typical ESPI and FEA results from an axial thumbnail crack.

FLAWS IN A HELICOPTER ROTOR BLADE (Shearography study)

A sample originating from Ysterplaat Air Force Base was a section of an helicopter rotor blade constructed as a composite with an aluminium honeycomb core covered with aluminium sheeting. The small de-lamination at the edge of the blade was observed by simply warming up the surface of the blade for a short few moments with a flood lamp.

The two adjacent images depict the same small de-lamination except that the one on the right exhibits more fringes as a result of longer exposure to the heating with the flood lamp. Shearing was in the vertical direction.

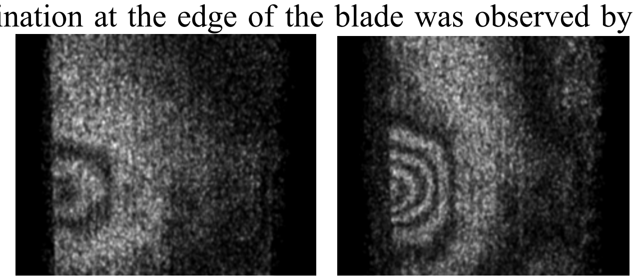

Fig. A-5 De-lamination on a helicopter rotor blade revealed using Shearography

Heating the surface of the skin of the helicopter rotor blade with the flood light, produced the characteristic fringe pattern of the derivative of the surface displacement. Attention is drawn on the fringe appearing approximately in the centre of figure A-6 exhibiting a double lobe, where a pinhole is located. Shearing was in the horizontal direction.

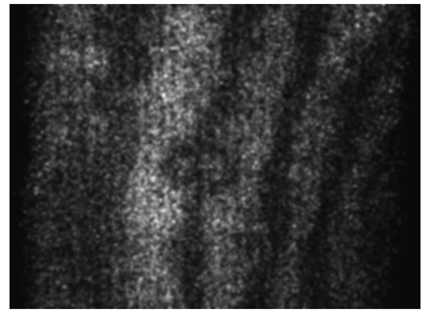

Fig. A-6 A small pinhole revealed at the surface of the rotor blade skin

COMPARISON OF ESPI AND SHEAROGRAPHY IMAGES

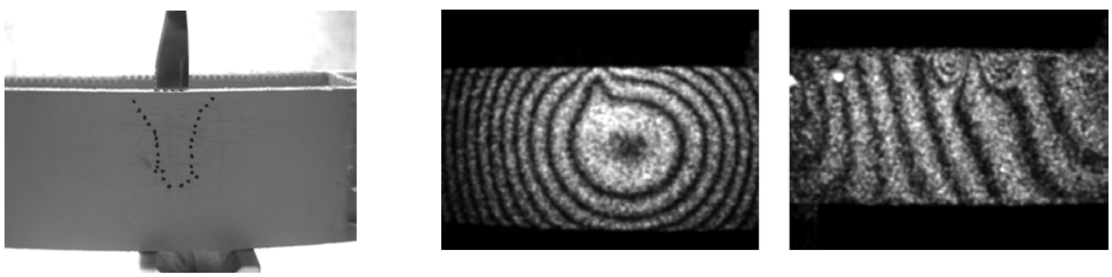

Fig. A-7 Honeycomb wing section with a de-lamination on the most inner skin. The middle image was obtained using ESPI. The far right by Shearography.

COMPARISON OF ESPI AND SHEAROGRAPHY IMAGES

Findeis [15]

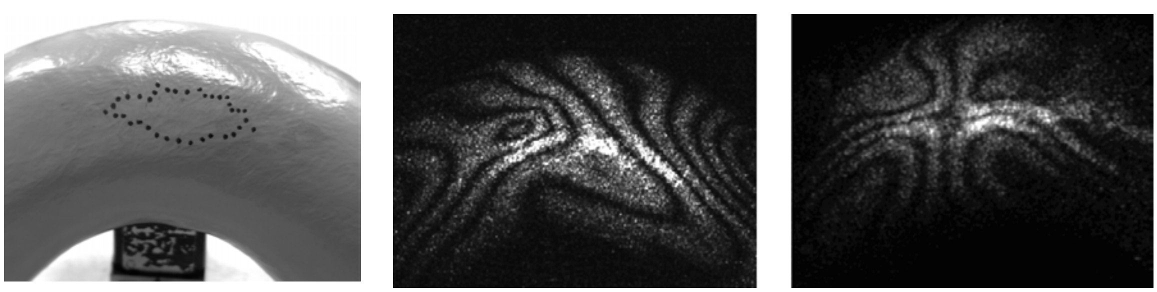

Fig. A-8 The glass fibre reinforced elbow contains a star crack in the inner surface. The middle image was obtained using ESPI. The far right by Shearography

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