Benchmarking Shearographic NDT for Composites

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Abstract

This paper reviews Digital Shearography in its current state of development. The technique was originally proposed as a strain measurement method but has more recently found an equally important role in the field of non destructive testing. Digital Shearography, as is currently practiced in research laboratories and in industry, reveals defects beneath the surface of an object by identifying anomalies in the field of surface displacement gradients. Shearography as a non destructive testing tool has found innumerable applications involving a wide range of materials and in particular has had notable success in identifying debonds and delaminations in composite material structures. In the face of distinct advantages over other NDT methods, such as full field view, non-contacting and real time evaluation, and proven in a vast number of applications in the laboratory/field/factory environment, surprisingly it does not yet have a standard, like for example an ISO International Standard. The objective of this paper is a call for the standardization of Digital Shearography based on the involvement of interested parties calling for the start of the process, perhaps as is suggested here, by the technical committee TC 135 of the ISO.

1.0 Introduction

It is a well established fact that in industries relating to aerospace, automotive, boating, sports, weapons technology etc. the usage of composite materials is ever increasing and will continue to do so in an exponential manner. Modern composite materials that are being researched and produced aim at satisfying engineers who are continuously searching for materials that exhibit high strength, low density, are stiff or flexible, are relatively free from corrosion effects, abrasion and even impact. Besides the fact that composites do posses the properties mentioned, the distinguishing characteristic of these materials is that in a given structure the synthesis of all the various material components takes place almost simultaneously providing just about near finished shape.

Irrespective of what material is used, not only during the manufacture of components and structures but subsequently during in-service use, they will acquire and accumulate defects that eventually will shorten their life. The end of a component’s life is of course inevitable, such is the manner of things, however what is desirable is to monitor defects and replace the component before the occurrence of catastrophic costly events.
To determine the serviceability of composite structures or components, non-destructive methods of testing are required during manufacture and obviously during service and operation. Engineering NDE professionals will agree that no single technique provides the total solution and that it is best that a combination of techniques be employed for increased reliability, knowing very well that each technique will come with strengths and deficiencies. This approach although highly desirable, unfortunately in many cases, will be problematic because of economic constraints.

Equipment of all types, of non-destructive testing capability, is available and has been used in monitoring components and structures of composite material nature. What is becoming slowly apparent though is that among the large number of NDT techniques employed to monitor the health of composite structures, very few seem to show sufficient or notable breadth of applications. The available NDT equipment invariably will fall under one of the three categories ranked as a) Mature and proven technologies, b) Young technologies with limited but slowly increasing in volume and breadth their track record of successful applications and c) Innovative or newly emerging techniques that are still in the state of further research and development.

This paper focuses in particular on one of the two non-destructive testing techniques that are emerging as favorites in the quest of successfully and reliably detecting defects and flaws in composite components or structures. The techniques of Digital Shearography and Thermography, as it is evidenced in the literature, have been continuously providing examples of success in detecting defects among the wide range of types of flaws/defects in composites. Just to mention a few of these defects; delaminations, cracks, inclusions, voids, impact damage, broken filaments/mats etc. Both the above mentioned techniques fall under category b as described earlier, with Digital Shearography being the junior of the two, perhaps due to the fact that it is the most recent addition in NDT equipment capable of reliably testing composite materials.

2.0 Background on Digital Shearography

Shearography has its origin as a strain measurement technique (1974) and later as a non-destructive testing tool (1982) reported by Hung. Technological advances in lasers, digital cameras, frame grabbers etc. enabled researchers to refine the technique and in some instances produce portable equipment. Examples are Digital Shearographic portable equipment developed at the Non Destructive Testing Laboratory of the University of Cape Town (UCT), or at the Applied Research Laboratory of the Pennsylvania State University, as well in industry, Dantec-Ettemeyer.

Digital Shearographic non-destructive testing reveals the presence of flaws or defects as a localized disturbance in the fringe pattern depicting the gradient of surface displacements on the test piece. The fringe pattern is generated in response to any stress being applied on the object such as mechanical, thermal, pressure or vacuum, and emerges superimposed on the object’s image, after the subtraction of two images of the object’s surface, one before and the other after the stress was imposed. The anomalies in the fringe pattern basically display the position and approximate size of the defect, however not its depth relative to the surface. Typical laboratory Shearographic
NDT systems, similar to the one depicted in fig. 1, include personal computers housing software to process the images of the object under test. The images are obtained via a digital camera viewing the object through some shearing optics and are stored in the image digitizer. A single wavelength light source (a laser) is used to illuminate the object and produce the required speckled image, Gryzogoridis at all 7.

![Laser](image1)

**Figure 1. Typical laboratory Shearographic system**

![Image Shearing device based on the Michelson interferometer](image2)

**Figure 2. Image Shearing device based on the Michelson interferometer**
The technique of digital shearography requires the use of an image shearing device which is placed in front of the camera. Two laterally displaced images are focused by the camera to the convenience of the operator in a horizontal, vertical or in any other plane by simply rotating the shearing device in front of the camera lens. A modified Michelson interferometer, as the one shown in figure 2, or a glass wedge or a birefringent prism are commonly utilized to shear the image. The Michelson interferometer type is preferred by the authors in that it allows the flexibility to vary the magnitude of the shear by manipulating one of the mirrors accordingly. This is an important feature in digital shearography because the magnitude of the shear is largely responsible for the sensitivity of the system.

The shearing device splits the incoming reflected beam, from the laser illuminated surface of the object, into two beams that are orthogonally polarized forming two overlapping images of the surface of the object under test. The intensity of the light wavefront emanating from a point in the overlapped region of the sheared images can be imagined as the superposition of the light wavefronts emanating from two adjacent points on the surface of the object under test. The intensity distribution of the “first” image is given by

\[ I_1 = 2A^2 \left[ 1 + \cos \alpha \right] \] (1)

where \( A \) is the real amplitude of the light wavefront, assumed constant along the surface, \( \alpha \) may be regarded as the phase difference between the two neighboring points on the surface. This image is stored as the reference image for the technique. At this stage by stressing the object its surface will deform and the two adjacent points will change positions and hence their optical path lengths will change. Thus the intensity distribution of the “second” image is similarly given by

\[ I_2 = 2A^2 \left[ 1 + \cos(\alpha + \delta) \right] \] (2)

where \( \delta \) is the corresponding phase change that resulted from the change of optical path of the two neighboring points on the surface. This second image is now available for subtraction from the first/reference image yielding the following result as the difference in intensity of the two images:

\[ I_\Delta = 4A^2 \left[ \sin \left( \alpha + \frac{\delta}{2} \right) \right] \sin \frac{\delta}{2} \] (3)

Further processing of the digitized image (its intensity expressed by equation 3), that is by assigning digitally values of grey level from 0 (black or darkest) to 255 (white or
brightest), visible fringes are displayed superimposed on the image of the surface of the object under test. It is thus possible to observe the behaviour of the surface of the object under test, at real or almost real time conditions. A number of fringes \((N)\), that appear superimposed on the image of the surface of the object under test, are lines of constant gradients of out-of-plane surface displacements, along the direction of the shear or lateral shift created by tilting one of the mirrors of the modified Michelson interferometer. The out of plane displacement gradients can be quantified as shown \(^7\) by the following expression

\[
\frac{\partial \delta p}{\partial x} = \frac{\lambda N}{2S}
\]

where \(\lambda\) is the wave length of the laser, \(N\) is the number of fringes observed, and \(S\) is the lateral shear imposed. Clearly the sensitivity of the instrument depends on the amount of tilt of the mirror and hence the magnitude of shift \(S\).

The process of identification of defects or flaws from the fringe anomalies is quite effortless and is possible even to the untrained eye. However quantitative interpretation of the fringe anomalies, with regard to the defect size and depth from the surface, requires a more involved process and has been the subject of considerable work by many researchers in the field. Even the most cursory literature survey indicates that it is unlikely that we can obtain a closed form solution for the problem but rather rely on turn key solutions to individual situations.

Although shearography was initially developed for direct surface strain measurements it has been proven as a viable non-destructive testing technique particularly attractive because it is a whole field and non-contacting technique. It does rely on light intensity interference, making it nominally sensitive and accurate to the order of the wave length of the laser light used. Being a “single” beam interferometer it is less stringent to the requirement of environmental stability during a test procedure than many other optical interferometric techniques such as for example holography, electronic speckles pattern interferometry etc. It is further claimed in Hung at all \(^8\) “Whilst conventional shearography uses a small image shearing device to give displacement gradients on the object surface, deliberate use of large scale shearing device enables direct measurement of surface displacements. Thus, shearography may also be perceived as an optical technique that measures both surface displacements and surface strains, depending on the amount of image shearing used in the set-up”.

With the advantages listed above, shearography is a prime candidate as a practical non-destructive testing tool which should enjoy wide acceptance by NDT practitioners and industry alike. There is evidence of shearography being used routinely by the tire industry \(^9, 10, 11\); however the use of it in the testing of aircraft composite structures appears to be sporadic. For example the testing of the helicopter blades, by the French manufacturer Eurocopter S.A \(^12\) manufactured as composite, with foam or honeycomb materials as the core of the blade and covered on the outside with one or more layers of fiber reinforced plastics. Another example is the testing of the thermal protection parts
of the new European Ariane launcher, which are made of carbon, reinforced composite materials using honeycomb structure core.

There is of course a large collection of work that is performed by researchers in academic institutions, research laboratories and industry aimed at expanding the range of applications of shearography. The work is performed on optical tables in laboratories, or using dedicated fixed position equipment for specific applications in industry and with light weight portable systems like the one developed at the University of Cape Town as shown in figure 3. It appears that shearography is rapidly approaching the state of wide acceptance by industry (being the subject of this paper); provided steps are taken for the final hurdle, i.e. the validation of the technique for given applications or even better the establishment of an International Standard.

![Figure 3. UCT’s portable Digital Shearography system comprises of the Head as shown containing the shearing optics, phase stepper, camera and diode laser, mounted on a tripod. The image on the right obtained using the equipment, is depicting impact damage on a wing of an unmanned aerospace vehicle.](image)

### 3.0 Benchmarking

It has been stated that “Benchmarking is a powerful management tool because it overcomes ‘paradigm blindness’..... The way we do it is the best because this is the way we’ve always done it” [Wikipedia](#).

Benchmarking of Digital Shearography as a non destructive testing procedure, means we are dealing with the criterion by which we measure and compare the technique against other techniques, in testing several products and applications. This implies competitive benchmarking with industry accepted norm, in other words the comparison with existing and long standing accepted techniques. Such process is perhaps too large, very complex and perhaps unmanageable. It can be argued that is better to select one task or application at a time and carry on with the benchmarking process, which appears to have worked with the two examples, the helicopter blades and the thermal protection parts, mentioned earlier.
The technical report by Erne et al\textsuperscript{1} prepared for the U.S. Army Tank-Automotive Command attempted to assess technology available to be applied to composites destined for use in the Composite Armored Vehicle (CAV). The information gathered through literature survey, direct contacts with academia, research laboratories etc. lead to a useful discussion regarding real time in-process inspection techniques. The report is complimentary about Shearography in that it classifies it as a mature technology requiring very little modification for use in the CAV application and “especially sensitive to near surface delaminations and disbonds”.

Since the early days of Shearography (by its inventor, Hung 1974) a considerable amount of research and development has taken place regarding the applicability of the technique to strain and displacement measurements and nondestructive inspections. The technique has been enhanced by sophisticated software and advancement in technology, enabling phase stepping when acquiring the required images to produce the interferograms. Besides the visual enhancement of the location of the defects by vivid colours and filtering of the images, as exemplified in figure 4, phase stepping has opened the way for automatic quantitative fringe measurements. This will not only confirm the size of the defect as depicted by the fringe pattern but also indicate its position below the surface.

Figure 4. Typical examples of shearographic image enhancement depicting defects below the surface of a composite of GFRP skin and Monex core: (a) and (d) intensity images, (b) and (e) phase stepped images, (c) phase stepped with colour image and (f) phase stepped filtered image.
The filtered phase stepping fringe patterns shown in figure 4 above readily reveal the presence of the defect; furthermore the direction of the displacement gradient can also be seen via the direction of the grey-scale gradient.

UCT’s Digital Shearography 03 system has the ability to perform phase stepped inspections. In addition, a software project has just been completed which complements the existing software by unwrapping the phase fringes into a displacement gradient map. The following text and images are the results of the inspection process where a single de-lamination was identified and serve as an example of the system’s capabilities.

To make the evaluation as user friendly as possible the phase map (figure 5a) depicting the characteristic double bull’s eye, needs to be unwrapped (figure 5b), where each grey-scale value represents a unique displacement gradient level.

![Phase Map (a) and Unwrapped Image (b) of Defect](image)

**Figure 5. Phase map (a) and unwrapped image (b) of defect.**

The phase unwrapped image was manipulated using the Matlab “mesh” function in order to produce a 3D map of the intensity of the unwrapped image (figure 6).

![Matlab 3D Visualisation of the Unwrapped Phase Image](image)

**Figure 6. Matlab 3D visualisation of the unwrapped phase image**
Finally the grey-scale image is subjected to a reconstruction routine. The result of this image processing routine can be seen in figure 7 below. Here the presence and location of the defect can clearly be seen as the white circular section indicating a larger displacement than the immediate surrounding due to the weakened structure. This image was also subjected to the Matlab “mesh” function and is illustrated in figure 8 alongside. Here the presence of the defect is identified by the conical section in the centre of the image protruding from the rest of the surface.

Digital Shearography although featuring distinct advantages over other NDT methods, namely full field view, non-contacting and real time evaluation, and proven in a vast number of applications in the laboratory/field/factory environment, surprisingly does not yet have a standard, like for example an ISO International Standard.

The International Organization for Standardization (ISO) is a worldwide federation of national standard bodies, numbering in excess of 100 countries, aiming at facilitating technology transfer, enhancing reliability of methodology and ease of maintenance.

Particularly in the field of non-destructive investigations the ISO has a standing technical committee known as TC 135, Nondestructive Testing. The activity of this committee is divided among subcommittees at a lower level associated with the activities say Acoustical Methods SC3, or SC8 on Infrared Thermography etc. six in total. In the web site of ISO 14, there is a guideline of how to go about developing a standard, a process which encompasses three main phases.

The need for a standard is communicated by an industry sector to the national body which proposes the work to ISO. The first phase involves the definition of the scope of the future standard generally carried out by the working group of the parties interested in the matter. The second phase comprises negotiations regarding the specifications in the standard and finally the third phase is the formal approval of the draft standard before publication as an ISO International Standard.
Typical example of the above is a committee draft ISO/CD 21648, establishing the design, material selection, fabrication, testing, and inspection etc. of the flywheel module in unmanned space systems. Among the materials selection there is a section on composite materials and polymeric materials and the proposed inspection techniques to determine non-uniform or broken fibers, cracks or delaminations etc. Digital Shearography features among the recommended techniques to detect and characterize critical defects.

Perhaps the example above which focuses on a particular structure is not the way to keep validating or standardizing Shearography because invariably it leads to duplicating the effort and of course adds to the slowness of the process in its entirety.

A consortium including representatives operating at all stages of the process, from fundamental research, to manufacturers, suppliers and end users could be formed with view to communicate to ISO, preferably through a national member body, the need for the standard. Once the need for the standard has been recognized the consortium could proceed with the formulation of the technical scope of the envisaged standard. The second stage of the process would involve the detailed specifications within the standard such as the standardized test materials, the minimum requirements of the optical system, the methodology of testing etc. all of which need verification and traceability with the stake holders and industrial case studies. The final stage would require the formal approval of the draft of an ISO Technology Assessment, being a 75% approval vote by the members of the ISO standard development process, before it is published as an ISO International Standard.

It is clear that a substantial effort is involved toward standardization and as an ISO general rule all standards should be reviewed within five year intervals, however the move would assist equipment manufacturers by providing a strong basis for marketing, and more importantly, for the end users it would alleviate uncertainty and lead to more innovative and efficient designs lowering costs and above all, failure rates.

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