XXV AIAS NATIONAL CONFERENCE
INTERNATIONAL CONFERENCE ON MATERIAL ENGINEERING
Gallipoli - Lecce, 4-7 September 1996

Speckle interferometry applied to 3D mechanical characterisation of composite samples

A. Di Tullio, P. Jacquot*, F. Ginesu**, F. Bertolino***

*Laboratory of stress analysis, Swiss Federal Institute of Technology, CH - 1015 Lausanne

**Department of Mechanical Engineering, Engineering Faculty, University of Cagliari

KEYWORDS: Speckle interferometry, 3D displacement measurement, structural analysis, composite material characterisation.

ABSTRACT

The scope of this work is to present a speckle interferometry method suited to the measurement of three-dimensional displacements over the surface of a plane object subjected to strain. The measurement of the three dimensional displacement components is made possible through the combined use of a coplanar optical system using collimated beams and a specially designed loading system. The latter is capable of a ninety degree rotation around an axis perpendicular to the sample surface leading the measurement of the third component. The images obtained are then processed by a PC in order to recover the whole-field displacement allowing the possibility for extended measurements. This set-up has been used for the characterisation of composite sample under a four point bending deformation.

The details of the system are presented in the paper, along with experimental verifications of the mains possibility of the approach.

Further applications of the arrangement for structural analysis are also outlined through the example of a five-holed shaped disk under compression.

INTRODUCTION

Speckle interferometry[1] is an optical method that performs non invasive and non destructive testing for measurements of parameters such as shape, displacement and strain.

This technique has a high theoretical accuracy (approximately 1/100 of the wavelength of the light used), but requires that the elements of the interferometer are perfectly stable during the measurement. However, a complete surface displacement analysis requires knowledge of displacement in all three dimensions: this means that, at least, three different and independent measurements must be performed involving three non-planar viewpoints or illumination directions[2,3].

The first technique is very complex because it requires three different cameras and software for the correction of parallax effects in the different images. The second system usually consists of three non planar illumination directions with uncollimated beams. Commercially available systems belong to this category. However, the sensitivity is not uniform over the field. Therefore, to the best of our knowledge, there is no proper recover of 3D information.

The proposed system utilises two symmetric planar collimated illumination beams and an in-line reference beam. In-plane displacement measurement is permitted when two illumination beams are used and out-of-plane measurement when one object beam and the reference beam are used. The second in-plane measurement required in order to obtain the third dimension is reached with the ninety degree rotation of the specimen and loading system. The rotation control is possible within the mounts itself, looking at the rotation fringes arising from a real time image subtraction with a reference image

OPTICAL CONFIGURATION

The schematic drawing of the set-up is shown in Fig.1. A beam of a Krypton laser, operating at 647 nm, is split into a reference and an object beam. The object beam is then divided into two collimated beams symmetrically illuminating the object. The image of the object is acquired by a CCD camera and processed by a PC.

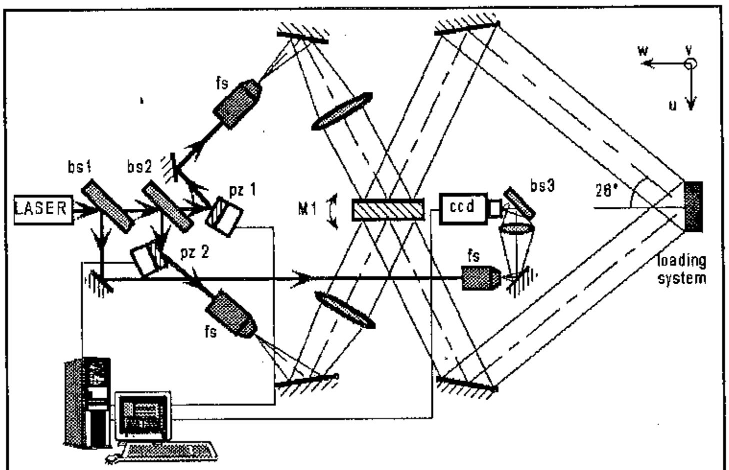


Figure 1: set up.

The object and the loading system are integral with a micrometric rotation stage possessing a large load capacity and providing a full 360° range of rotation.

Firstly, the speckle images are stored in their primary state: they are the reference interference patterns. A new set of images is then acquired after deforming the object: the two image sets are then subtracted by pairs to show the fringe patterns corresponding to the increment of deformation.

Without rotation, it is possible to obtain three different measurements: an in-plane measurement and two out-of-plane measurements. Combined with the ninety degree rotation, the set-up therefore allows six different measurements. A typical 3D measurement is composed of two out-of-plane and two in-plane measurements.

The first ninety degree rotation is controlled through the micrometric scale of the rotation stage, the opposite rotation is controlled instead by looking at the real time difference between the live image and a reference image recovered and stored before the first rotation. The rotation stage itself is used as the reference object to determine the absolute rotation. In-plane and out-of-plane configurations are possible for this process. Moreover, imperfect repositioning leads to a type of inaccuracy involving a linear additional phase, easily removable by a software option available in the fringe analysis program. Measurements of pure rotation of a metallic plate controlled by a self-collimating lens show that one rotation fringe is approximately 1.5″ in in-plane configuration and 3″ in out-of-plane configuration

The displacement vector components are obtained from the analysis of a fringe pattern at each state of rotation as follows:

$$\begin{aligned} &\text{out-of plane 1} && L_u \sin\alpha + L_w(\cos\alpha + 1) = d_1 \\ &\text{out-of plane 2} && -L_u \sin\alpha + L_w(\cos\alpha + 1) = d_2 \\ &\text{in-plane} && 2L_u \sin\alpha = d_3 \end{aligned} \quad (1)$$

where $L_{u,w}$ are the displacement vector components, α is the angle between the illumination and observation directions and $d_i = n_i\lambda$, with n_i the fringe order and λ the laser wavelength. Indeed, d_1, d_2 and d_3 of equations (1) are obtained through the automatic computation of the phase of the corresponding interferograms by means of a classical three phase stepping technique[4].

The three displacement components are:

$$\begin{aligned} L_u &= \frac{\lambda n_3}{2\sin\alpha} = \frac{\lambda(n_1 - n_2)}{2\sin\alpha} \\ L_v &= \frac{\lambda n_6}{2\sin\alpha} = \frac{\lambda(n_4 - n_5)}{2\sin\alpha} \\ L_w &= \frac{\lambda(n_1 + n_2)}{2(\cos\alpha + 1)} = \frac{\lambda(n_4 + n_5)}{2(\cos\alpha + 1)} \end{aligned} \quad (2)$$

where the parameters (n_4, n_5, n_6) are homologous to (n_1, n_2, n_3) of eqns. 1 and are also acquired with phase calculation after the ninety degree rotation of the loading device.

Redundancy in eqns. 2 allows the removal of uncertainties in absolute fringe orders.

In addition to the displacement, the rotating mirror M1 present in the set up, means that contouring measurements are also possible.

SIMULATION OF DISPLACEMENT MEASUREMENT

An example of a rotation test to simulate displacement is shown in figure 2. The original position of the rotating stage is shown in figure 2(a). Two images are stored at this position: a phase speckle reference image and figure 2(a), that is the speckle reference image for the rotation control. After the ninety degree rotation, another phase speckle reference image is stored, a small rotation is made and a phase speckle image is stored. When the rotation is made in the opposite direction real time fringes are visible on the monitor (figure 2(b)). The last phase speckle image is then stored. The two fringe patterns are obtained by making the phase subtraction in pairs. They are shown in figure 2(c) and 2(d).

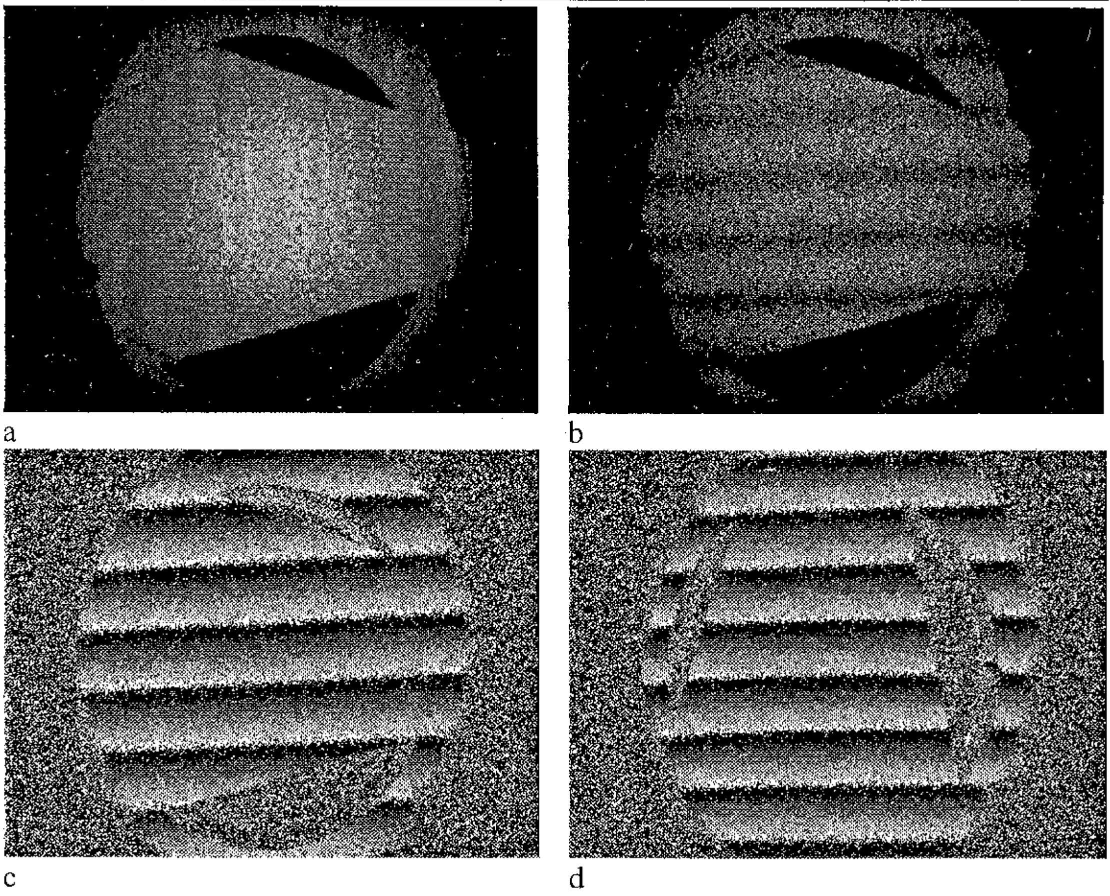


Figure 2: displacement measurement images

3D DISPLACEMENT ON A FIVE-HOLED SHAPED RUBBER DISK

In order to show an example of the adopted technique for a 3D displacement measurement, a five-holed shaped rubber disk was tested. The specimen was compressed between two plates along the horizontal diameter. The interferograms related to all the components of displacement were obtained and the resulting filtered phase maps are shown in figure 3.

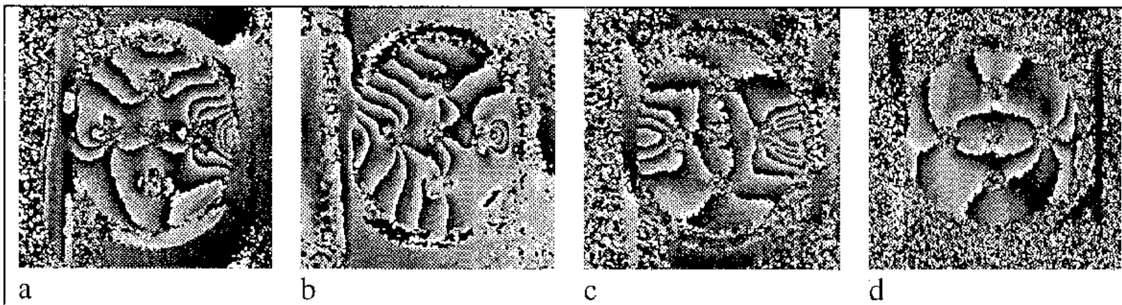


Figure 3: phase maps of rubber specimen: the two symmetrical out-of-plane (a and b), the horizontal sensitive in-plane (c) and the vertical sensitive in-plane (d).

COMPOSITE MATERIAL MEASUREMENTS

Composite materials were tested in a four point bending configuration[5]. The material used was a sixteen layer carbon-fibre composite, with all layers at +75 degree to the long axis of the specimens. Each specimen had dimensions of 200mm×20mm×2mm and was tested in two systems. Two type of observation were done: one looking at the front side and one looking at the thin side. Four point bending was realised by means of two pairs of parallel cylinders, the outer pair being fixed and the inner pair serving to apply the load. The first system for monitoring the front surface of the specimen consisted of four 5mm diameter cylinders (figure 3), the outer pair were separated by 120mm and the inner pair, behind the specimen, were separated by 100mm. The second system for monitoring the edge of the specimen consisted of four 1.5mm diameter cylinders, the upper pair were separated by 12mm and the lower pair, below the specimen, were separated by 5mm.

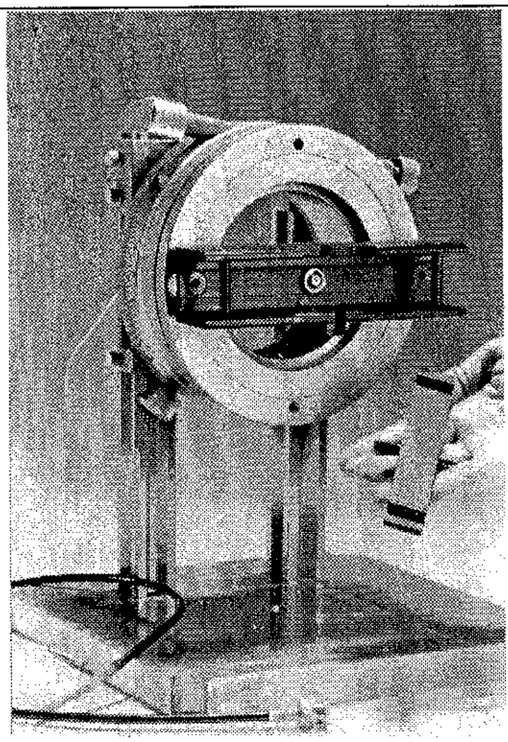


Figure 4: loading system.

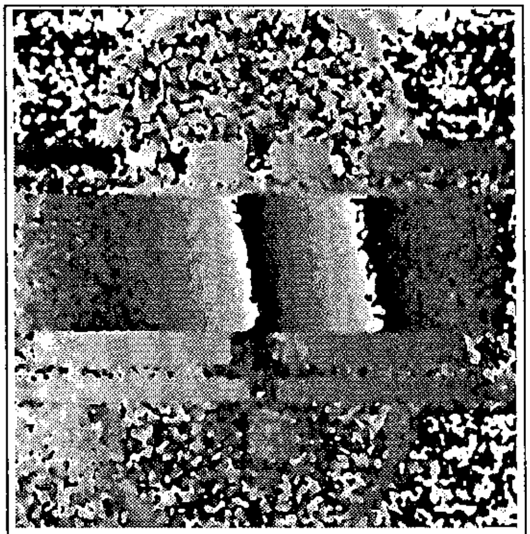
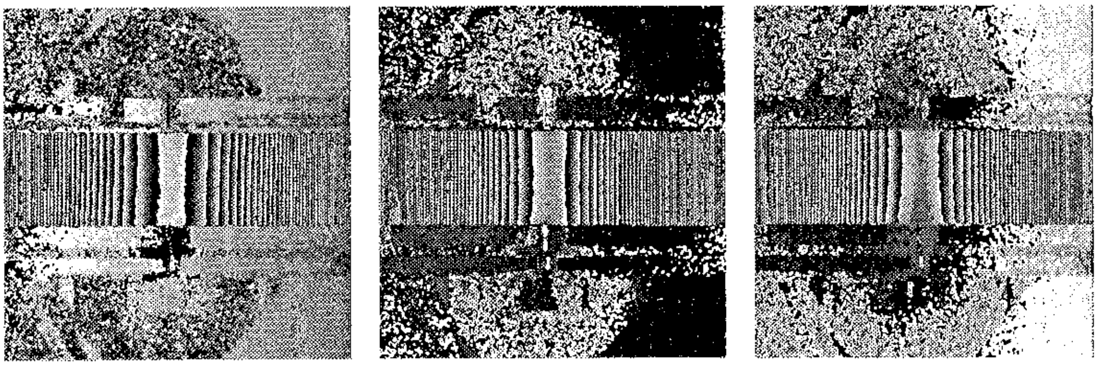


Figure 5: in-plane wrapped phase.



a b c

Figure 6: the out-of plane wrapped phase (a, b and c) for increasing increment of 8μm for one direction.

The first test consisted in observing the specimen with two out-of-plane measurements and an in-plane measurement along the specimen. The calculated in-plane displacement in the short axis direction (0.738μm) was, in fact, too small for the sensitivity in that direction. The displacement applied to the lower pair of cylinders was 24μm. The displacement in the out-of-plane direction was far bigger than in the in-plane direction, for this reason the two out-of-plane measurements were made in twelve different steps. The phase recovering was made for three groups of four images. To each image a Kernel filter of dimension three was applied. Three wrapped phase images were obtained for each out-of-plane measurement. The results for the in-plane test are shown in figure 4, and for one of the out-of-plane motion in figure 5.

In the second test only an in-plane measurement in the long axis direction was made. A section of the wrapped phase is shown in figure 6 and a section of the unwrapped phase in figure 7.

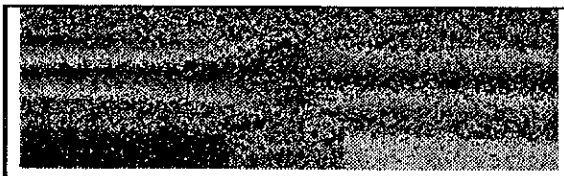


Figure 7: wrapped phase of the edge.

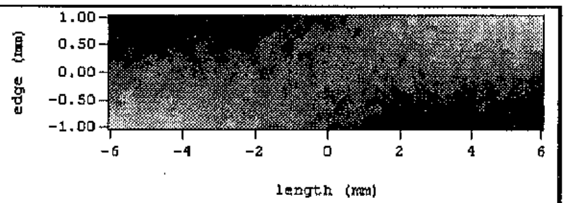


Figure 8: unwrapped phase of the edge.

CONCLUSIONS

A simple technique for 3D displacement measurement has been presented. It utilises a planar collimated beam system providing the third dimension measurement with a high precision reversible rotation of the loading stage. Some examples of rotation and 3D deformation are shown. The rotation of the loading stage requires, of course, a compact loading system and a longer time for measurement but allows the use of a simple collimated beam system.

REFERENCES

[1] R. Jones, C. Wykes: Holographic and Speckle Interferometry, Cambridge University Press (1983).

[2] M. Maas: Phase Shifting Speckle Interferometry, PhD thesis, Delft University (1991).

[3] S. Winther: 3D Strain Measurements Using ESPI, Optic and Lasers in Engineering, **8** (1988) 45-57.

[4] D.W. Robinson, G. T. Reid: Interferogram Analysis, Institute of Physics Publishing, Bristol and Philadelphia (1993).

[5] D. Cuche: Determination of the Poisson's ratio of filled epoxy and composite materials, Proc. SPIE **1212**, 315-324 (1990).

CORRESPONDING AUTHOR

Alma Di Tullio: Laboratory of stress analysis, Swiss Federal Institute of Technology, CH - 1015 Lausanne, E-mail: ditullio@imac.dgc.epfl.ch.