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Optical Techniques and Automatic Fringe Analysis for Composite Materials

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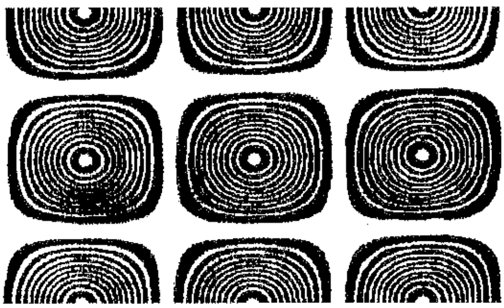

Optical techniques and automatic fringe analysis for composite materials

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Abstract

The use of some optical techniques combined with automatic analysis is presented and discussed. Some results achieved by means of moire' interferometry are read and analysed using different computer procedures. A comparison between the different algorithms is made.

Sommario

Vengono presentate delle procedure di misura basate sull'uso di tecniche ottiche e dell'analisi automatica. Alcuni interessanti risultati (quadri di frange), ottenuti con la moire' interferometria, vengono trattati con diversi algoritmi. Viene infine presentato un confronto fra i diversi risultati.

Introduction

For several years different research groups of the Mechanical Engineering Department in Cagliari have been involved in studying the structural behaviour of composite materials made of carbon fibers and polymeric matrix.
For the analysis of static and dynamic behaviour of such materials different experimental approaches have been adopted. The present paper reports some results, obtained by means of optical techniques. In particular, four techniques have been used: one grid technique [1,2] with a microscopic vision, moire' interferometry [3], holographic moire [4] and holographic interferometry [5]. All these optical methods are well known and in previous papers both the optical set-ups and the analytical problems have been amply described [6,7]. Here some significant results are reported and the different problems in reading and analysing fringe pattern pictures are also taken into account. Fig. 1 schematically depicts the general procedure applied in our laboratories in Cagliari to validate specimens made of composite materials, using optical techniques.

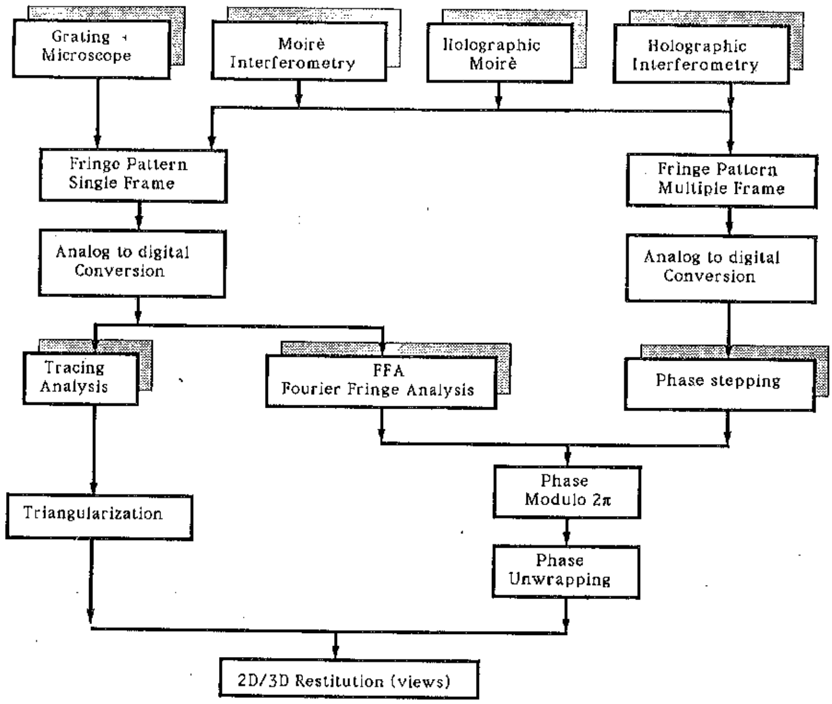


Fig. 1 - Scheme of the automatic procedures.

With reference to the above figure the fringe pictures are transformed into one numerical matrix which is then read and analysed by different procedures: both the tracing and the FFA (Fourier Fringe Analysis) methods work on the basis of a single fringe frame, while phase shifting requires multiple frames allowing easy and automatic analysis of the overall results.

Problems concerning materials and techniques

As is well known, under static and dynamic loads laminates of composite material show very complicated mechanical behaviour. When even a small load is applied a macroscopic assessment of the material structure grows and it determines small fracture both in the matrix and in the fibers.

When a perfect laminate is loaded in its plane, the resulting stress distribution consists of plane stress in each layer, with a complex, three-dimensional stress distribution at any free edges. Edge stresses, which involve interlaminar normal and shear stress, may become very large. This stress distribution indicates several possible modes of initial failure. Away from the edges, a laminate may fail either in a fiber mode, implying rupture or buckling of fibres, or in a matrix mode, implying cracking parallel to the fibers. At the edges the interlaminar stresses may produce delamination as the initial fracture.

As opposed to metals, the direct measurement of fatigue limit is difficult for these materials. Repeated loading cycles can cause failure and the composites do not seem to show an endurance limit.

Angle-ply laminates, in particular, show highly nonlinear stress-strain tensile behaviour mainly due to the presence of transverse matrix cracking and delaminations. After unloading, which essentially follows a linear law, the composites show large permanent strain. The strain field observable on the lateral surface of the specimen during the loading cycle is generally nonuniform because of the presence of cracks and of the different behaviour of the layers.
It is therefore important to use experimental techniques that can both detect faults in, and characterize, such materials. Knowledge on the microstructural behaviour of composite laminates is required to predict the influence of defects on the overall strength of the material.
Optical techniques must allow us to distinguish from among the different fractures those capable of determining failure of the structural element. It is not easy to discriminate between local defects of the grating,which are always present, and anomalies of the fringe patterns due to fractures and overstresses.

The different techniques reported in fig. 1 were used keeping in mind their advantages and disadvantages.

The grating technique was recently used by the Authors for observing the strain field on the lateral surface of a specimen subjected to mainly static, but also fatigue, loading. The technique is based on observations with an optical microscope and subsequent monitoring a phase grating printed on the lateral surface of the composite specimen. The in-plane displacements and strains can be calculated from the pitch variation measurements. The frequency of the grating was 150-300 lines/mm.

The moire'-interferometric technique was used at different stages of load. This technique is very powerful in real time and very sensitive to microstructural defects. It was used in our application with a virtual pitch of 0.0005 mm.

The holographic moire' was used with an original disposition of optical components in the holographic bench [4]. The method is useful and easy in double exposure. The big advantage of this technique is the possibility of changing the sensitivity with the same grating.

Holographic interferometry is very powerful and handy, does not need a grating and is very sensitive. Some problems arise when knowledge of in-plane displacements is important; the optical set-up is more complex and the localization of fringe pattern may become difficult. Here the technique was always used to check models in composite, out-of-plane deformed.

Automatic fringe analysis

The introduction of high performance image processing systems and cheap powerful computers has enabled researchers to develop various techniques for the analysis of interference fringe patterns. As shown in fig. 1, fringe tracing, phase stepping and FFA (Fourier Fringe Analysis), which are among the most popular techniques in use today, were used here in Cagliari. The application dictates which method is most suitable for use.
The most natural approach in fringe analysis consists of their identification and tracing through the image. This technique is completely general, does not require previous knowledge of the fringe characteristics and allows a simple and immediate validation of the algorithm. Several algorithms have been proposed [8-10]. With a software code made in Cagliari, several techniques can be used to suit the specific conditions. One of the first techniques was a semiautomatic one and consisted of reading fringe pattern systems under operator supervision. It allows images of very poor quality to be read and analysed.

The algorithm requires the assistance of the operator at the beginning when the search for the different lines starts and when a noisy area is present. At the end of this process a certain number of points describes the lines and a triangular frame is then provided automatically. This frame behaves as a finite element model: the shapes of the elements are optimized and the values of the displacements can easily be calculated for the whole model by simple interpolations. In case of need numerical difference between two reconstructed images, the undeformed and the deformed grating for example, permits the point-by-point calculation the in-plane displacements.

One of the main problems with this technique is the fringe orders. Fringes can easily and interactively be ordered with the assistance of an operator with a knowledge of the problem under study. Sometimes a carrier fringe pattern can be introduced to obtain an equidistant fringe system and facilitate the reading stage. In this case the fringe order increases by one unit, fringe by fringe, allowing an automatic numbering procedure.
Fringe tracing techniques that take into account only maxima and minima of brightness intensity are not always the most suitable in microscopic analysis where only fractional fringe orders on the whole field can be observed. Using the fringe system as a continous function, this drawback can easily be overcome.

One important development of automatic fringe analysis is the phase-shifting method [11]. By means of micro-displacements of light phase and the recording of a certain number of frames, phase can be calculated over the whole field. For each pixel the phase value and the correlated meaning are known. No doubt exists about concavity or convexity, static noisy is eliminated and precision is greater here than that given by fringe tracing techniques. The program code allows the use of this technique with 3, 4 or 5 images.

Recording some frames at different times is the main drawback of phase shifting and limits both measurement and analysis. When a single image is achieved, some analysis methods, which spatially apply the temporal phase measurement, work properly.
These methods mainly consist of using a tilt of the fringe pattern such that the information is provided by the deviation of fringes from rectilinearity. This tilt can be obtained either tilting a mirror in the optical set-up or adding a linear function to the numerical matrix of fringes.

The Fourier transform method of fringe analysis was originally described by Takeda et al [12]. They developed a one-dimensional technique that adds phase which is a linear function of the coordinates to the interferogram. In this case by filtering the carrier component from the image in the Fourier plane, it is possible to obtain automatically complete information about the deformations due only to loads.

The fringe frame can be expressed as:

$$g(x,y) = a(x,y) + b(x,y)*\cos[2\pi f_0 x + \phi(x,y)] \quad (1)$$

where the phase f(x,y) is proportional to the required displacements, while f_0 is the carrier frequency. The Fourier transform function along the sensitivity direction (x) of the grating can be expressed as:.

$$G(f,y) = A(f,y) + C(f-f_0,y) + C^*(f+f_0,y) \quad (2)$$

Because spatial variations of a(x,y), b(x,y), and f(x,y) are slow compared with f_0, the function G(f,y) will be a trimodal function with peaks at $-f_0$, f_0, and the origin. The function $C(f-f_0,y)$ can be isolated using a filter centered at f_0. The carrier frequency can be removed by shifting $C(f-f_0,y)$ by f_0 to the origin to give C(f,y). The inverse transform of C(f,y) with respect to f yields

$$c(x,y) = 0.5*b(x,y)*\exp[i*\phi(x,y)] \quad (3)$$

From which the phase $\phi(x,y)$ can easily be found:

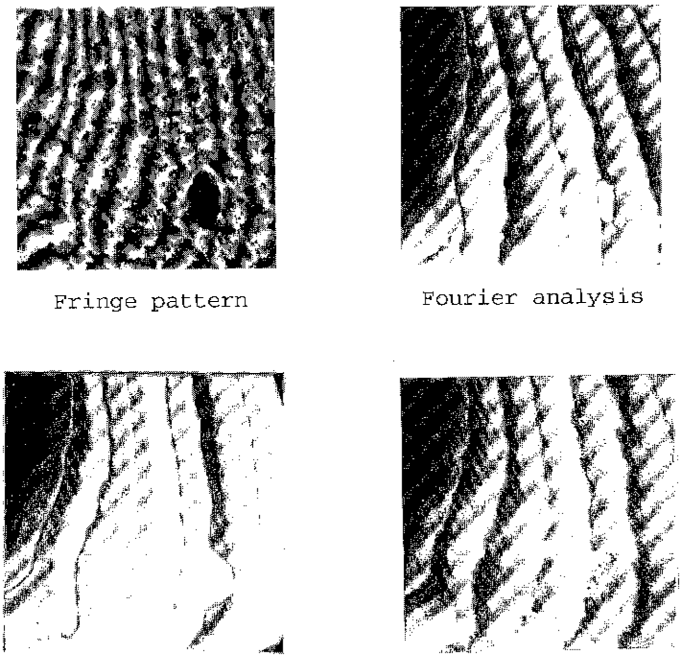
$$\phi(x,y) = \tan^{-1}\{Re[c(x,y)]/Im[c(x,y)]\} \quad (4)$$

where Re[c(x,y)] refers to the real part and Im to the imaginary part of c(x,y).
The phases obtained from Eq. (4) are undetermined to a factor of 2π because the arctangent is defined over a range from $-\pi$ to π. Phase unwrapping [11-19] is therefore required to restore the unknown multiple of 2π to each pixel. This is normally achieved by working along each row in turn: when the phase difference between a pixel and its predecessor is greater than π, 2π is either added to or subtracted from the remaining pixels in the row. The process is then repeated along the columns. This approach is computationally efficient but has poor noise immunity. It is disadvantaged by the fact that any erroneous data in the phase will cause problems locally, and will also propagate, causing damage globally.

Kreis et al. [20] developed a model that interprets the phase image 2π modulus as a graph, the pixels being the nodes and the arcs the connections between neighbouring pixels. Demodulation proceeds along paths where the variations in phase values are minimum. Along these paths the probability of an erroneous phase is minimum.
The latter technique has been implemented and worked on our program code, but is highly computational intensive (time and memory).
Some tests were performed with fringe patterns generated by computer codes.

Applications

The different procedures for reading and analysing fringe patterns are compared here by taking into account one system obtained by means of the moire'-interferometric technique.
The fringes represent the in-plane displacements of one tensional loaded specimen made of carbon fiber and a peek matrix.
These fringes were read, transformed into a numerical matrix and then analysed by means of the three algorithms, tracing analysis, Fourier fringe analysis (FFA) and phase shifting, set in the procedure code shown in fig. 1.
Fig 2 shows the pictorial results, which are in good agreement both qualitatively and quantitatively.

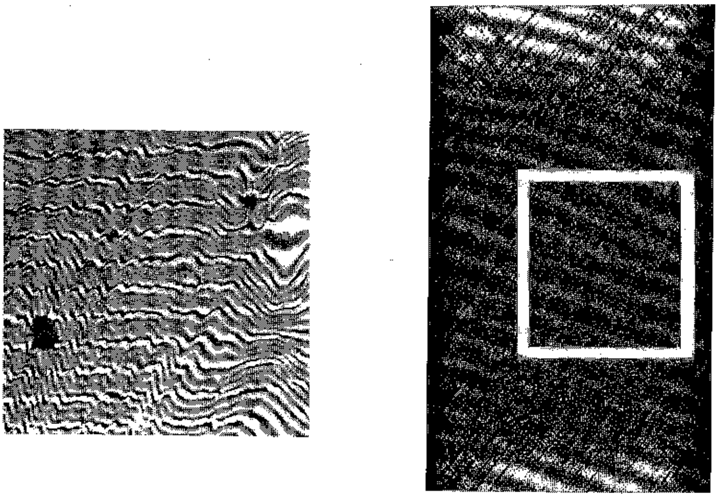


Fringe pattern — Fourier analysis — Tracing algorithm — Phase shifting

Fig. 2 Phase algorithms comparison.

The mean relative error is about 3-5%.
Even though the average values are equal, the three functions of displacements, achieved by the algorithm of computer analysis, have different slopes and gradients.
In particular, the tracing algorithm shows a step behaviour due to the triangular mesh used.

Fig. 3a shows the fringe pattern image of a composite specimen similar to the one previously reported. From this pattern some oblique failures present in the model are evident and manifest important structural damage. Picture b shows a x-ray test made on the same sample where the tested area is highlighted.



a) Moire' interferometry   b) x-ray test

Fig. 3 Failures on a graphite-PEEK specimen

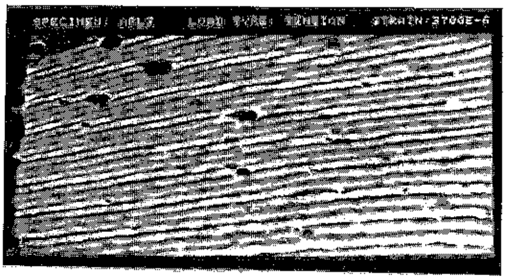
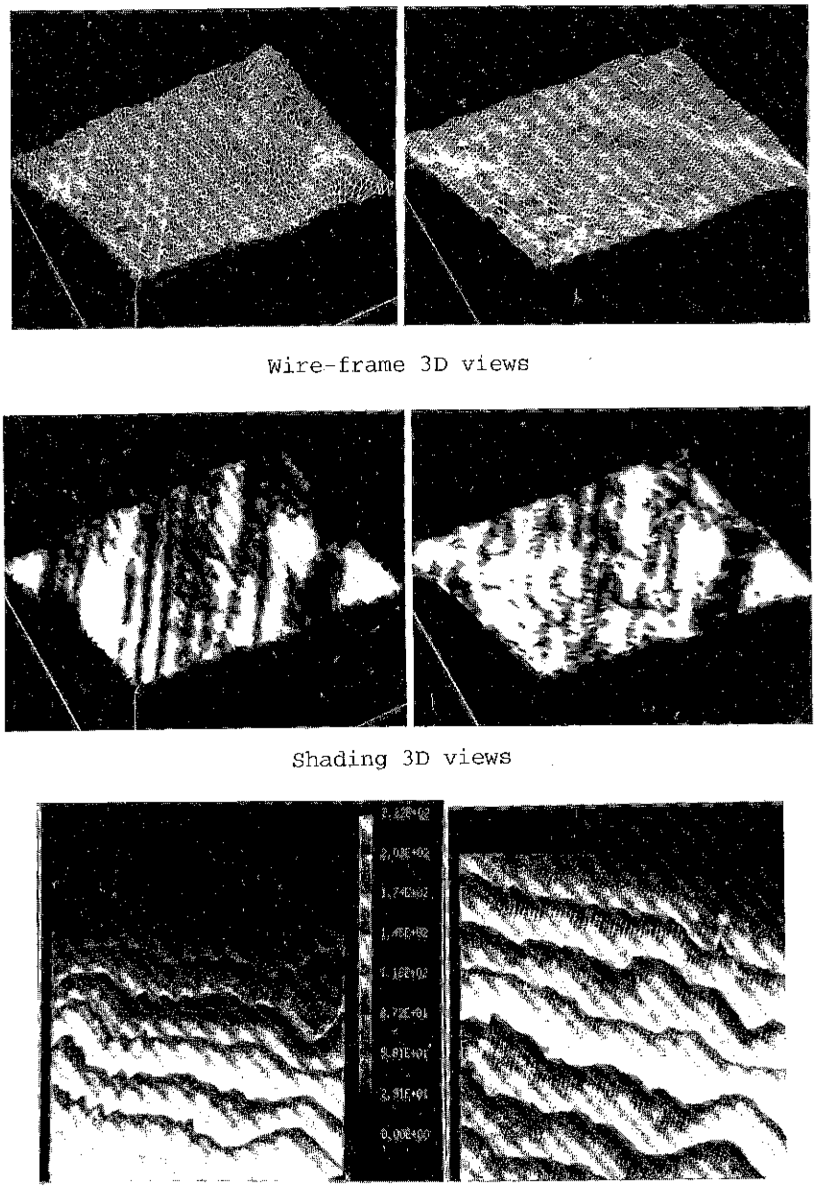


Fig 4. Superficial failures effect

Fig. 4 shows another fringe pattern system obtained on a specimen with the same characteristics. Here some failures, visible on the surface, have not succeeded in changing the mechanical behaviour of the model.
The moire' technique can discriminate among all fractures present in the specimen those which are important for the structural behaviour of the tested component.

Tracing FFA



2D map of displacement values

Fig.5 Analysis of fringe pattern reported on fig. 3

In fig. 5 the same failures underscored in fig. 3 are analysed and evidenced by means of the tracing and the FFA techniques, which are respectively to left and right in the figure. Three different representation are shown: both wire-frame and shading 3D reconstructions, and a 2D plot with values of displacements, are reported.
The failure effect seems more evident with the tracing results, even though the values are quite similar from a quantitative point of view.

Fig. 6 depicts the first-derivative (strains) of the tracing results and strongly underlines the failure effect. but local gradients of strains are present and sometimes interfere with the overall analysis of results.

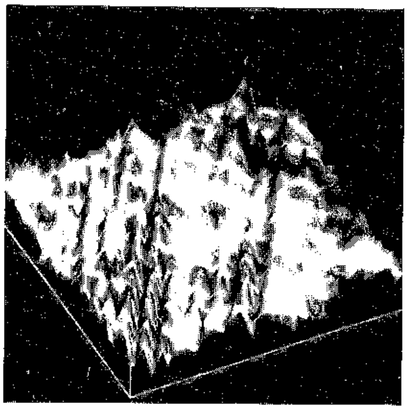


Fig.6 First derivative of tracing-algorithm results

Conclusions

From an analysis of the different results presented here and many others, it can be stated that optical techniques in conjunction with automatic data analysis, give a sensitive, quick and reliable study of the mechanical behaviour of industrial components. In particular, this procedure has allowed the analysis of several composite specimens and yielded essential information about their failure mechanism in a short time.

The fringe pattern in fig. 4 points out the oblique fractures with sharp variation in fringe behaviour. This variation can be studied in the frequency domain where its contribution can be isolated.

At present, most efforts are aimed at achieving consistent results in this field. The authors are now investigating ways to achieve quantitative hints on fracture-risk from Fourier spectrum analysis and, in particular, from the analysis of its variation due to abrupt change in fringe-lines.

Aknowledgments

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