CMMT(MN)056

The Use of Electronic Speckle Pattern Interferometry for Determining Non-Uniform Strain Fields

Summary

This Measurement Note illustrates the use of laser speckle interferometry (ESPI) for monitoring and measuring non-uniform full strain fields at high resolution. The technique was assessed for its ability to validate and provide confidence in analysis techniques for loaded components.

The note describes the principle of a full field measuring technique which allows deformations under mechanical and thermal loads to be measured. Comparisons of experimental data and Finite Element Analysis (PEA) predictions agreed well for five different examples. The technique provides valuable and necessary experimental validation of numerical analysis.

This initial evaluation confirmed the potential of this technique for assessing strain fields and validating analytical techniques. It has several advantages including its ability to measure local deformation, with a resolution of 0.1 microns, equivalent to 10 micro strain.

The work reported forms part of the research programme at NPL under the title of "Composites Performance and Design" (CPD1).

J. Niklewicz and G. D. Sims

November 1999

Introduction

Finite element analysis is well established for predicting strain fields in components under load, however, there is continuing concern regarding particularly the results around stress concentrations.

Techniques used for validation do not normally have sufficient precision or resolution of strain fields in stress concentrated areas. A technique for evaluating such areas is explained, with five examples shown.

Electronic speckle pattern interferometry (ESPI)

Electronic speckle pattern interferometry (ESPI) was developed in 1969 [1], to determine the full displacement field and thus the strain at any surface or point of a diffuse reflecting object. In contrast to holographic interferometry, where interference is produced by two interfering wave fields from an object having small speckles, speckle interferometry uses speckles sufficiently large to be resolved by a video system. The fringe patterns are similar to those in holographic interferometry, but with more speckle noise. For this reason no more than 20 fringes can be achieved, thus limiting the applications of this process. The improvement of ESPI [2], with computing power for image analysis using new techniques of phase shifting, have allowed more detailed information to be achieved. The main advantage of this technique is that fringe patterns can be generated instantly without recourse to a photographic process. This makes ESPI useful for many applications such as validation of finite element methods (FEA).

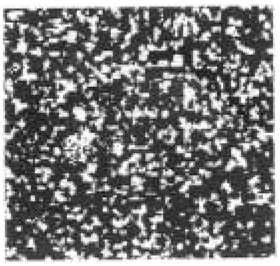
Principle of the measurement technique

ESPI is a non-contact full field measurement system which measures the deformations under mechanical and/or thermal loads along three perpendicular axis (for a 3D system). Deformations can be measured on samples with relatively large dimensions and aspect ratios, such as test specimens or even components. The current set-up at NPL can measure areas of between 25 mm^2 to 600 mm^2. Samples require little or no preparation.

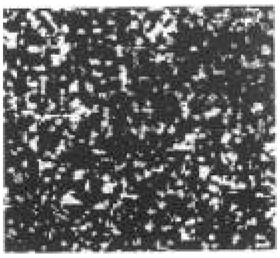
A speckle effect is produced by the interference between the reflected rays when a surface is illuminated with a laser beam. The image of the object is recorded by a video camera. The light waves reflected from the objects surface interfere and produce a variable pattern known as speckle.

The pattern is defined by the microscopically rough topography of the sample surface. Any deformation of the surface results in a change of the speckle pattern. This speckle pattern and deformed object state is stored by the image processor.

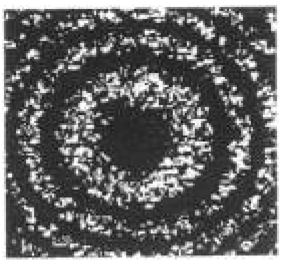
When the sample deforms the speckle pattern changes. Correlation fringes are created by comparing the speckle pattern for the object in a reference state and then in a deformed state (Figure 1). These fringes represent the deformation of the object's surface in the applied direction. Evaluation software then analyses and counts the correlation fringes and transforms them into a quantitative set of deformation and strain data.



Speckle pattern of undeformed surface



Speckle pattern of deformed surface



Difference of the two speckle patterns

Figure 1: Principle of speckle measuring technique [3]

Dual Illumination Method

The dual illumination method produces a speckle pattern by simultaneous illumination of the sample with two laser waves symmetrically about the observation direction (Figure 2).

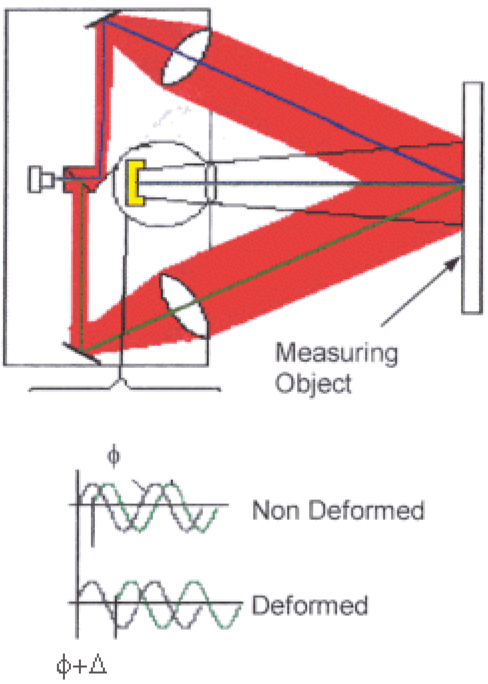


Figure 2: Dual illumination method

The resulting speckle pattern represents the phase difference ϕ between the two light paths from the laser via the object surface to the camera. This speckle pattern is stored as a reference.

Movement of the object produces a change in the two light paths relative to one another and creates a new phase relation $\phi + \Delta$. This creates a new speckle pattern.

The difference Δ between both patterns is represented by correlation fringes. By counting the number of fringes at every object point the deformation of the objects surface is obtained. The measuring direction is orthogonal to the viewing direction and is produced in plane to the two illumination directions.

The measuring sensitivity can be calculated from:

$$d = \frac{N\lambda}{2\sin\left(\frac{\alpha}{2}\right)}$$

where:

- d is the deformation component of the object point in the measuring direction
- N is the fringe order at the measuring point
- λ is the wavelength of the laser light (i.e. 780 nm)
- α is the angle between the two illumination directions

Phase Shifting Technique

Phase shifting is used to evaluate the correlation fringes quantitatively. In the phase shifting method, the phase of one beam is shifted relative to that of the other. Up to four interference patterns are then recorded at appropriate different phase shift values to calculate the phase differences [4]. The phase change, calculated for every point in the recorded intensity pattern, yield a resulting phase fringe pattern. Under a reference load, a first phase fringe pattern is recorded, when the load is changed a second phase fringe pattern is recorded and electronically subtracted from the reference pattern, to produce a resulting phase fringe pattern. This procedure is repeated at gradually increasing load levels. The recorded phase fringe patterns can then be added by phase summation [5] to achieve a phase fringe pattern which represents the full load range.

By differentiating the phase fringe pattern within a known area, the full field strain measurement can be evaluated.

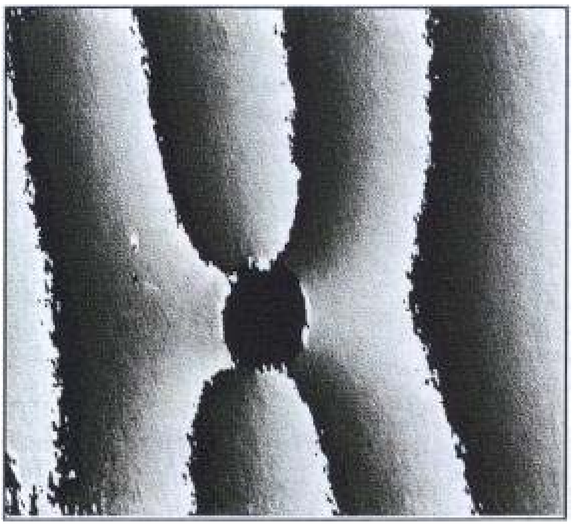


Figure 3: Phase fringe pattern of an open hole specimen

a) Comparison of Strain Data between FEA and Speckle Interferometry.

A 36 mm E-glass-fibre/epoxy cross-ply [Oo/90ohs laminate with a centrally drilled 6 mm hole was loaded up to 16 kN. The strain distribution was determined using speckle interferometry. Figure 4 shows the output strain map for the sample. The results of analysing the strain map for the longitudinal strains perpendicular to the hole compared favourably with FEA analysis as shown in Figure 5.

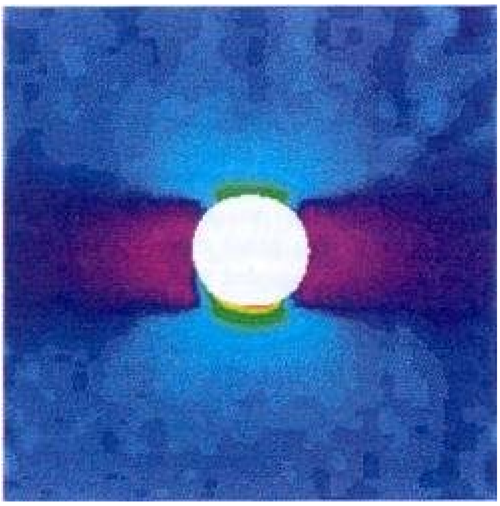


Figure 4: Strain map of specimen

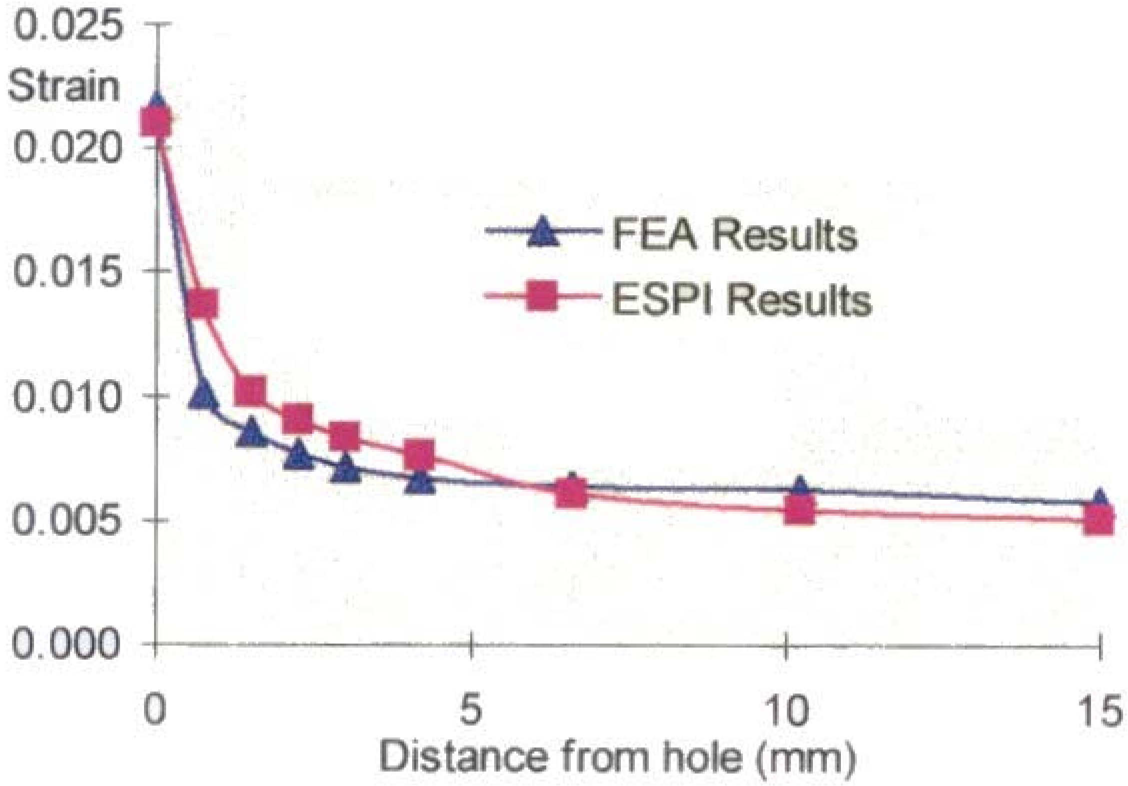


Figure 5: Comparison of strain data

b) Evaluation of stress concentrations of Titanium notched Alumna tensile specimens

Speckle interferometry was carried out in conjunction with Imperial College/GEC Alsthom to validate FEA modelling on a TiAl tensile specimen as shown in Figure 6.

Figure 7 shows that the strain map results compare favourably with FEA as shown in graphical form in Figure 8.

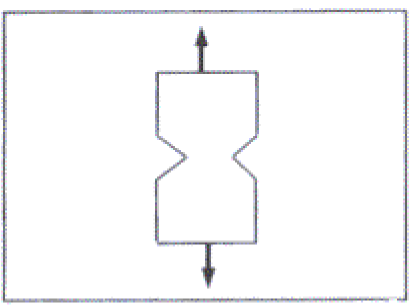


Figure 6: TiAl Specimen

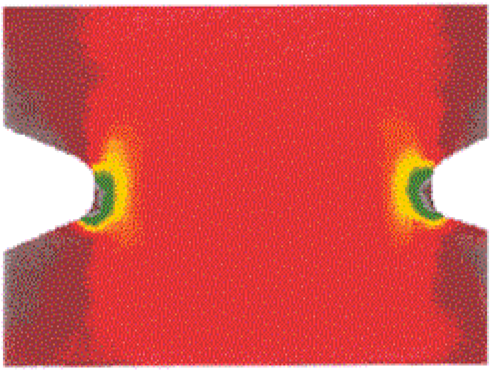


Figure 7: Strain map of TiAl Specimen 14 14 kN

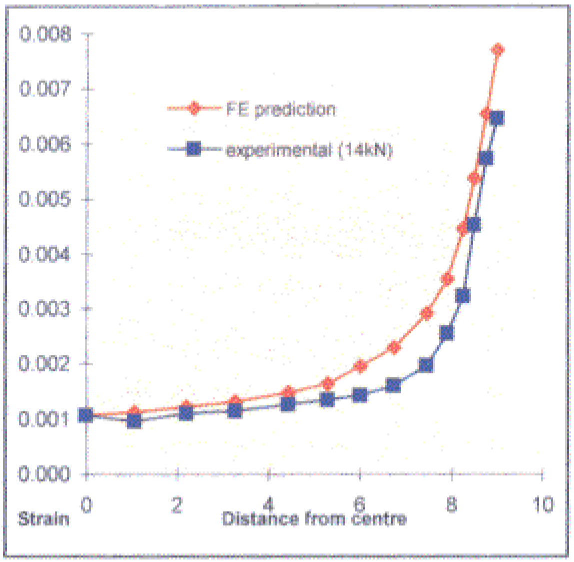


Figure 8: Comparison of FEA to strain map

c) Evaluation of shear modulus of a glass-fibre epoxy matrix insulator

Speckle interferometry was used to determine out the shear modulus of an E-glass-fibre/epoxy composite which was resin transfer moulded between two copper coils. Sections of the coils were machined into test pieces as shown in Figure 9.

To measure the shear strain in the specimen, a 20 head was used which measures displacement and strain in the x and y directions. This was rotated at 45° in the x/y plane so that the total shear strain could be calculated. This was calculated by combining the measured strains from both directions using:

$$\gamma_i = |\varepsilon_{+45}| + |\varepsilon_{-45}|$$

Where

γ_i	is the total shear strain
ε_{+45}	is the normal strain in the x direction
ε_{-45}	is the normal strain in the y direction

Figure 10 shows a 3D plot of the normal strain distribution of the specimen at 4.8 kN in the x direction.

Plotting the average shear strain versus the average shear stress (Figure 11) gives an approximation of the through-thickness shear modulus.

The value measured, 5.1 GPa, compares favourably with coupon test specimens of similar lay-up and composition.

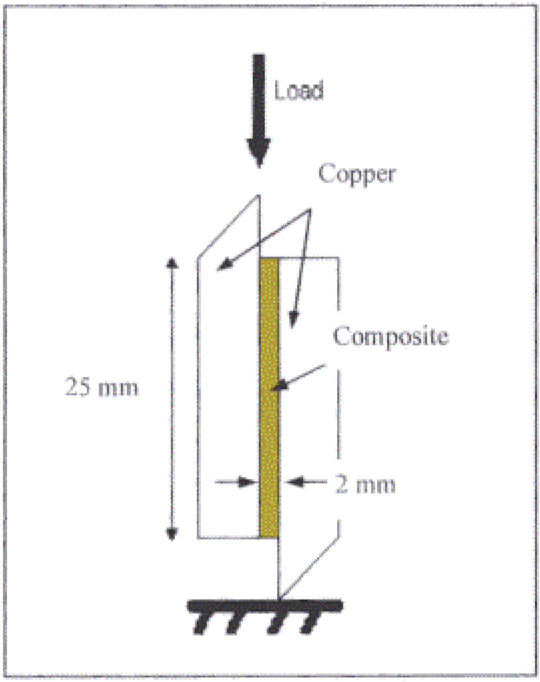


Figure 9: Diagram of composite specimen

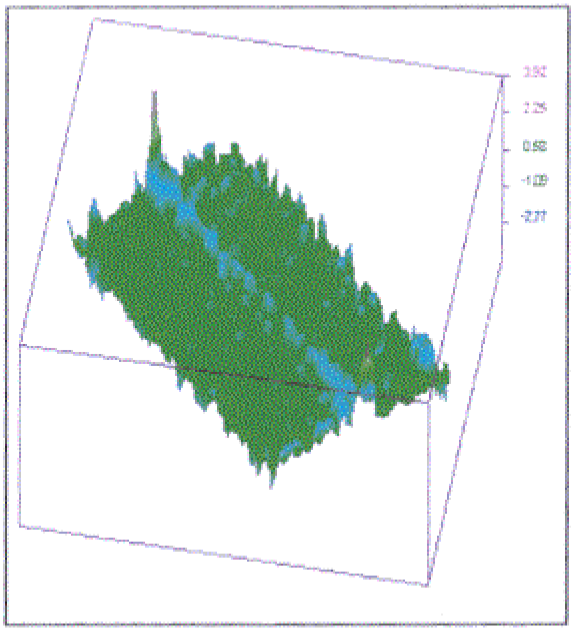


Figure 10: 3D strain contour of copper composite specimen

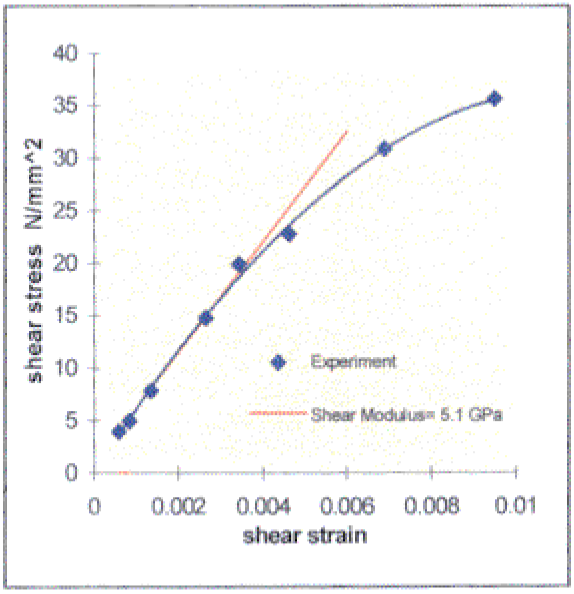


Figure 11: Shear stress/strain curve of copper/composite specimen

d) Double-lap shear joint with large adhesive fillet

A quantitative and qualitative study was carried out on a unidirectional carbon-fibre epoxy double-lap joint specimen with large fillet region as shown in Figure 12.

ESPI was used to validate FEA aimed at reducing the stress concentration at the end of the laps and therefore increasing the strength of the joint.

Initial FEA runs predicted the stress concentration in the adhesive in the wrong areas as shown in Figure 12. Testing with ESPI showed (Figure 13) that the build up of the stress concentrations were at the top edge of the adhesive close to the tip of the reverse taper.

Once modifications were made to the FEA model, it agreed closely to the ESPI test. With the FEA model validated for this simple case, more complicated models were created, in the knowledge that these models could predict the failure load and mode with confidence.

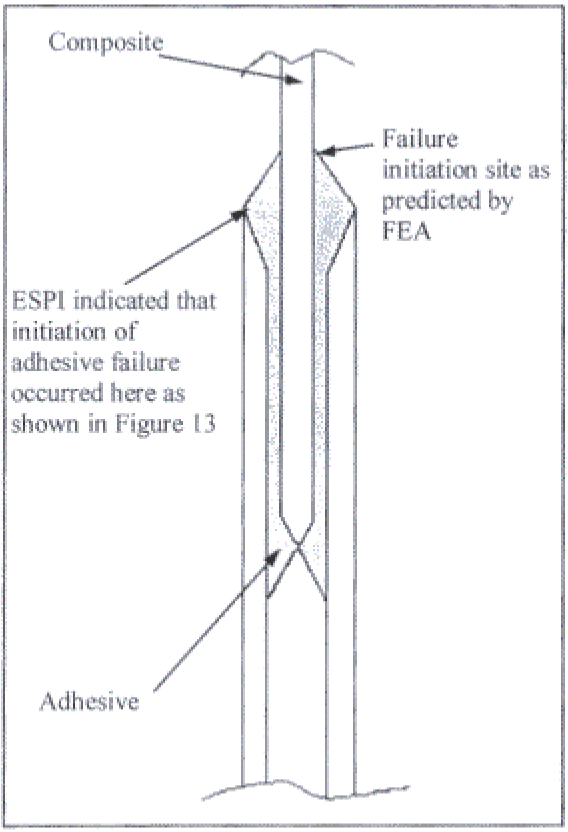


Figure 12: Diagram of double lap joint

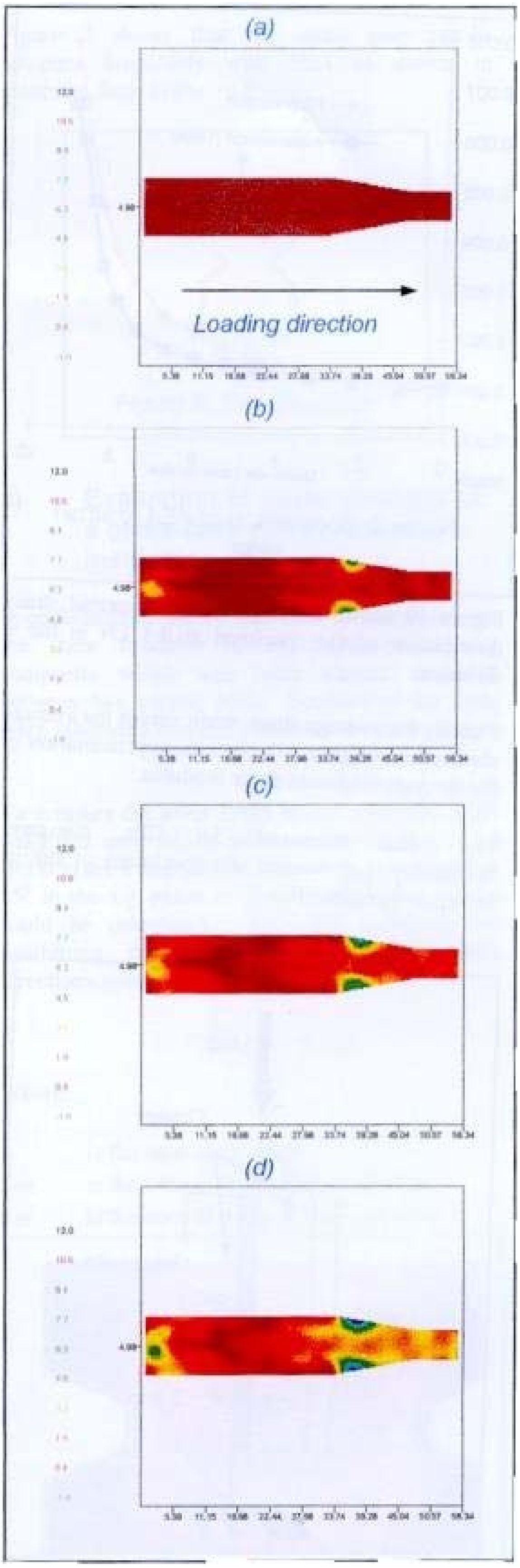


Figure 13: Strain distribution in double lap joint at different loads (a) 2.5 kN (b) 10 kN (c) 15 kN (d) 20 kN

e) Development of new method in predicting adhesive properties

It is notoriously difficult to evaluate material properties of adhesives, particularly for film adhesives. Most current methods involve stacking individual film plies which have been cut into a dumbbell shape, placed into a mould and then cured. The method is time consuming and can produce specimens which contain a large amount of voids.

A method developed at **NPL** can predict the shear modulus and therefore the Young's modulus (as the material is isotropic) without having to use dumbbell specimens.

The procedure uses a small thick adherend shear test specimen (TAST) as shown in Figure 14. The specimen is loaded in compression using a similar fixture to that specified in ASTM D 384 [6]. The specimen is supported along its entire length to minimise out-of-plane deformation [7].

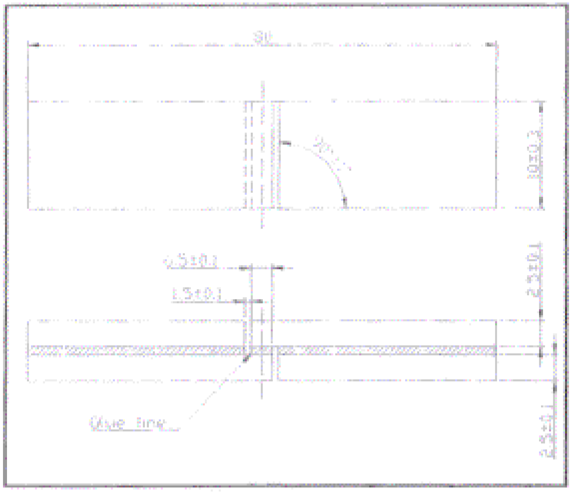


Figure 14: TAST specimen [6]

Rather than trying to measure the strain distribution in the bond the displacement of the adherends is measured between two points as shown in Figure 15. Once these points are known, the total strain in the adhesive can be calculated from:

$\tan \theta = d/l$

Where $\tan \theta$ is taken as the total strain, *d* is the measured thickness of the adhesive and *l* is the displacement between the two points.

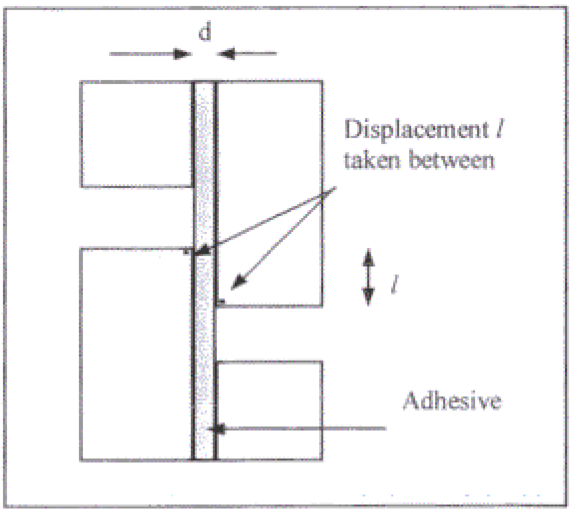


Figure 15: Measurement technique of double notch specimen

The lap shear strength is given by:

$\tau = P/bL$

Where *p* is the load, *b* is the joint width and *L* is the joint overlap length.

Shear modulus is obtained using:

$G = \tau / \gamma$

where:

$\gamma = \tan \theta$

Initial work was carried out using FEA to evaluate the method. This was followed by validation using ESPI. Figure 16 shows a displacement plot for a unidirectional carbon-fibre epoxy TAST specimen bonded with Araldite 2007® epoxy adhesive.

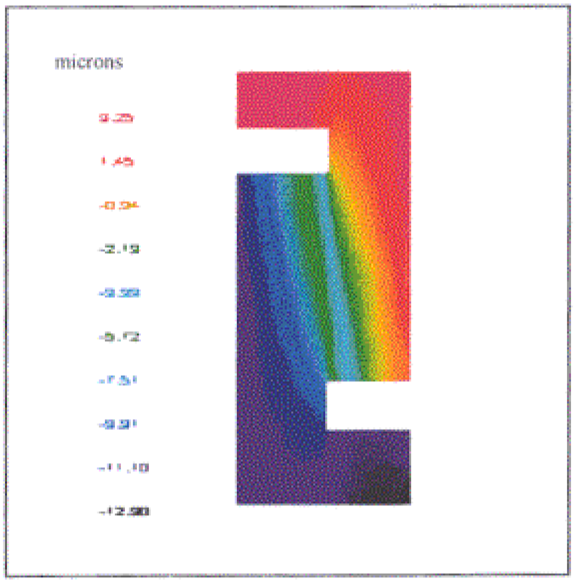


Figure 16: Displacement contour of carbon-fibre epoxy adherends and Araldite 2007® Epoxy resin loaded at 650 N

Conclusions

The use of the speckle interferometer as illustrated by the examples has the following advantages:

- full field deformation of 0.1 microns of the surface can be measured in all three directions
- can measure local strain values to 1 O~ microD strain accurately
- needs little specimen preparation
- able to measure non-linear deformation
- there is no contact with specimen
- capable of evaluating stress concentrations
- ability to validate FEA and other analysis predictions

The use of speckle interferometry has shown major advantages over other techniques for "mapping" strain fields with increased resolution. Its use gives greater confidence for validating predictions using finite element analysis and numerical modelling of complex strain fields in composite materials and other structures.

References

1. Leendertz J.A., "Interferometric displacement measurement on scattering surfaces utilizing speckle effect", J. Phys. E: Sci. Instrum., Vol. 3, pg.214, 1970
2. Lokberg O.J. & Slette-moen G.A., "Interferometric comparison of displacement by electronic speckle pattern interferometry", Appl. Opt., Vol 20, pg. 2630,1981
3. Ettemeyer GmbH Promotional Compact Disk
4. Flemming *T.,* Hertwig M. & Usinger R., "Speckle interferometry for highly localized dis-placement fields", Meas. Sci Technol., Vol. 4, pg. 820, 1993
5. Floreux T ., "Improved fringes using an ESPI system" Opt Laser Technol. I 993
6. ASTM D 3846-94, "Standard test method for in-plane shear of reinforced plastics", Vol. 8.02, ASTM Standards, 1 999, 99477-479
7. Broughton W. R & Mera R. D., "Report 7: Environmental degradation of adhesive joints, Accelerated testing", NPL Report CMMT(A) 197, 1999

Acknowledgement

This work is part of the research programme at NPL under the title of "Composites Performance and Design", financed by the UK Department of Trade and Industry, Engineering Industries Directorate [CPDI T3M2]. Thanks are also due to several collaborators for contributing case studies.

For further information contact:

Mr J Niklewicz
Centre for Materials Measurement and Technology
Tel: 020 8943 6034
Fax: 020 8943 6177
Experts Link to Expert

National Physical Laboratory
Queens Road
Teddington
Middlesex
United Kingdom
TW11 0LW

Tel: 020 8977 3222
Fax: 020 8943 6458
Email: materials@npl.co.uk

CMMT(MN)056

The Use of Electronic Speckle Pattern Interferometry for Determining Non-Uniform Strain Fields

November 1999