# DEVELOPMENTS IN INVERSE ANALYSIS FOR IN-SITU FLAW DETECTION IN COMPOSITE MATERIAL STRUCTURES

A.D. Nurse, J.M. Huntley, D.C. Panni,
J.N. Petzing, P.J. Sherratt, and J.R. Tyrer

Department of Mechanical Engineering, Loughborough University,
Loughborough, U.K., LE11 3TU, a.d.nurse@lboro.ac.uk

## ABSTRACT

This paper explores some of the fundamental issues surrounding inspection techniques by inverse analysis. Current research projects by the authors are presented to illustrate the advantages and flexibility of inverse techniques. The use of whole-field optical methods to determine a large data set is proving important to the capability of the techniques for detecting damage.

## INTRODUCTION

One of the problems limiting the structural integrity of laminated fibre-matrix materials is the possibility of delamination flaws, porosity and other forms of ‘damage’ that may have been introduced during manufacture and/or service. Many flaw detection methods are laboratory based requiring components to be taken out of service ultimately at high cost to the user. As an alternative, the use of “inverse analysis” has been introduced as a means of detecting damage from experimental data whilst the components are in-situ. This was first used in civil engineering applications for system identification of framework structures where reduced stiffnesses would be used to identify flawed members.

The Department of Mechanical Engineering at Loughborough University has a large research group using advanced optical techniques for the investigation of internal flaws in aerospace composite structures. The surface-based information collected, usually in the form of displacements or displacement gradients under a known loading regime, can be used to make predictions on the internal structure of the material using inverse analyses. Through a series of unequivocal static tests enough information may be gathered to solve unknown (internal) stiffness parameters that characterise the condition of the material through a mathematical model normally based on the finite element method. Typically, the stiffness values of potentially damaged material will deteriorate due to the existence of porosity in fibre-matrix composites, and may be zero in the presence of a delamination flaw. The same finite element mesh may then be used with actual in-service loads to predict the residual strength of components.

The paper will start with a brief review of techniques developed for the calculation of member stiffnesses in framework structures. A discussion follows on how these techniques might be used for inspection of composite structures where the component is discretised into a finite element model. Some examples of inverse analysis for flaw detection are presented to demonstrate the wide-ranging capabilities of the techniques involved.

## FUNDAMENTALS

Inverse techniques are being applied to the study and characterisation of delaminations within composite structures, which develop as a result of poor manufacturing techniques or foreign object impacts. The ability to determine the residual properties of components containing delamination defects allows decisions to be made on whether the component must be taken out of service, repaired or scrapped. In order to help with this decision there currently exist a number of non-destructive techniques for damage inspection, such as ultrasonic C-Scan, and finite element (FE) modelling techniques for prediction of the residual structural response. However, if composites are to be further accepted in a wide range of industries, more cost-effective tools that integrate the detection of delaminations in complex real-life structures with the estimation of the residual structural strength and performance are needed. Current research work is focussing on inverse techniques to meet this requirement.

The theory of the inverse approach under study is that by physically loading a component. under a known static test regime, the experimentally measured output responses may be used to automatically update a mathematical model of the component to characterise the damage. This model, usually based on FE analysis, then fully describes the delamination in terms of location, and size, etc. Furthermore, it can be used subsequently to determine the actual response of the structure under in–service loads. The advantages of inverse techniques are that they may be performed in-situ and the result is a mathematical characterisation of the damage. Most other inspection techniques require components to be taken into the laboratory and the data has to be subsequently interpreted to formulate the nature of the damage.

In an inverse analysis it is assumed that certain information about the problem is known *a-priori*. Such information includes the geometry of the component so that a FE model can be constructed and the material properties of the undamaged composite specimen. Mathematically, the inverse approach to damage inspection can be described as; "*Minimising an objective function that represents the difference between the response of the actual model containing delamination damage and the finite element model*". The challenge is to determine the most efficient way of applying static tests and updating the mathematical model so that damage is detected as accurately as possible with minimum effort. This requires five major issues to be considered.

(I) What loading conditions should be used for the testing so that the damage can be fully characterised?

(II) How is the damage described mathematically?

(III) What output data is collected and how is it measured?

(IV) How is the objective function formulated?

(V) How is the objective function to be minimised?

The first two issues represent *a priori* information that is necessary for the results of the inverse analysis to be accurate and unique. They represent reasonable engineering knowledge about the structure and the nature of the damage, which constrain the solution to physically admissible solutions.

The static test conditions to be used for the testing do not need to be those experienced by the component in-service but do need to be carefully selected. It was found by Hajela and Soeiro [1] during their experiments to evaluate damage in truss structures, that for certain loading conditions their algorithms failed to locate significant damage in some members. It is important that any loading condition be selected so that it 'activates' the damage and results in an appreciable change in the measured response output. This is further researched and discussed in an accompanying paper [2].

The response output data to be collected in an inverse problem will be determined by the topology of the component to be tested, limited physical access to the component and on the measurement technique adopted. Previous studies on 2D truss structures [1,3-7] have identified damage in members using nodal displacements or element strains as the experimentally determined data. For simple trusses, access is generally not restricted in any way and the small number of degrees of freedom mean that it is practical to measure displacement responses at all degrees of freedom (DOFs). In the case of 3D structures is not possible to directly measure response at internal degrees of freedoms, leaving only surface DOFs to be measured. (In composite materials it may be possible to access internal DOFs using embedded sensors such as fibre optics, however this is beyond the scope of the present discussion). As a result, obtained output for 3D structures will always be incomplete. In 2D structures, strain measurements taken at discrete points using strain gauges may be sufficient to determine the response of the structure but 3D structures require full-field structural response data to be obtained if the damage is to be determined to the required resolution.

As stated, the key to the inverse problem is the mathematical minimisation of an objective function. This objective function describes the difference in response between the physically obtained data and that predicted by the numerical model. In the case of 2D truss structures two principle forms of objective function have been utilised – the output-error and the equation error functions. In the output error approach the objective function is formulated in terms of the difference in output at given nodes between the analytical and theoretical models, Eqn.(1) below. Where, $y_m$ is a vector of system output measured experimentally, $y_a$ is the corresponding vector of system output determined from the analytical finite element model. Superscripts $i$ and $j$ refer to the component of the system output vector and the load condition respectively [1].

$$E = \sum_i \sum_j (y_m^{ij} - y_a^{ij})^2 \qquad (1)$$

The equation-error approach formulates the objective function in terms of the left and right hand sides of the system equilibrium equation, Eqn.(2) below:

$$E = \sum_i (\sum_j K_{ij} . x_{mj} - f_i)^2 \qquad (2)$$

where $f_{\mathrm{i}}$ denotes the $i^{\mathrm{th}}$ load component and $x_{mj}$ is the $j^{\mathrm{th}}$ component of the measured static displacement vector[1]. $K_{ij}$ is the stiffness matrix for the model and contains the unknowns to be determined. Another formulation has been proposed in which the difference in stored strain energy between the analytical and FE models is used as an objective function [8].

Solution of the unknowns in the output-error approach are found by continually solving the forward FE problem using iteratively updated data until the objective function is minimised. The equation error-approach avoids this decomposition of the stiffness matrix and is considered by some authors to be more computationally efficient. Both approaches are capable of handling incomplete data.

Many authors have adopted the above procedures with respect to damage in 2D truss structures. The objective functions being described as unconstrained optimisation problems and the damage resolved using a variety of iterative routines. These mathematical approaches can be computationally inefficient due to determining and storing derivatives of the equilibrium equations.

## ISSUES RELATED TO DAMAGED COMPOSITES

There are many ways in which damaged composite structures differ, in general, from the civil-engineering frameworks for which early studies in inverse analysis were aimed. A laminated fibre-matrix composite material is inherently three-dimensional with orthotropic properties whereas framework members tend to be one-dimensional. Line/bar elements are typically used to construct framework FE models with only a single value of *E* to characterise the element stiffness. However, the three-dimensional nature of a composite permits the FE formulation to have more degrees of freedom and to work with two- or three-dimensional elements. One problem is that there must be sufficient (static test) data available to be able to solve a given set of unknowns and this may be a function of the number of elements in the mesh. This is both useful, one may size the elements to resolve defects of a certain scale at pertinent locations, or may be hazardous, inexperienced users may 'blur' certain forms of damage through over-sized elements. Therefore, there is a requirement to use whole-field experimental techniques to provide the quantities of test data needed to perform the inverse analysis.

A delamination in a composite material is a separation of the material between adjacent plies and can be considered to have a zero thickness. It is proposed that, using the finite element method, a delamination can be modelled between two adjacent laminae in two ways [2]. In the first instance a "glue-layer" of negligible thickness is introduced into the model and the material properties of this glue-layer reduced to zero. In the second instance the damage can be represented by de-equivalencing of nodes of adjacent element nodes between the laminae. On-going research aims to compare the results obtained using both these formulations to evaluate which most accurately represents delaminations.

## RESEARCH IN PROGRESS

Within the department there are a number of different industrial-based projects being undertaken using inverse techniques for the detection of damage or internal flaws in composite structures. One of the key contributions has been the development of in-plane shearing interferometry [9-11]. This enables whole-field maps of in-plane strain partial derivatives to be obtained which are not affected by out-of-plane displacement components. Shearing interferometry was indeed invented at the Department of Mechanical Engineering, Loughborough University, some decades ago [9]. It may be applied to any object or structure with an optically rough surface that generates the 'speckle' effect. Electronic subtraction of data collected before and after loading enables displacement gradients to be measured in the whole-field sense (Fig.1).

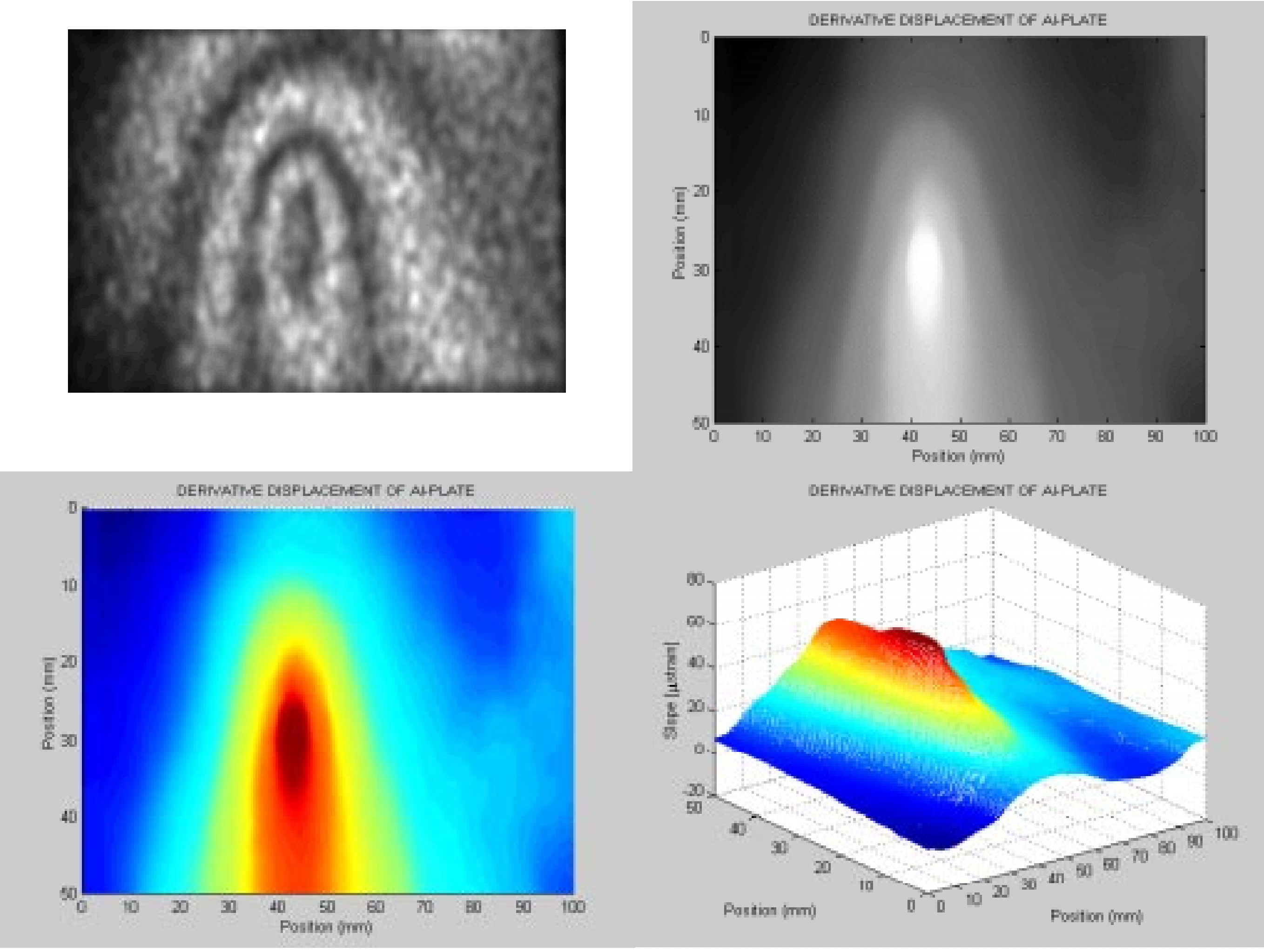


Fig.1: Shearing interferometry results for a boron repair patch applied to aircraft skin: (a) Fringe pattern data; (b) Unwrapped data; (c) Displacement derivative data; (d) Displacement derivative surface plot.

The flexibility of the experimental technique has led to a multitude of applications and it is only possible to mention below a few wide-ranging examples. In selecting these for presentation it is to be noted that the phrase "inverse analysis" may be interpreted in a different manner. However, in each case information is revealed regarding the internal state of the structure that is at the heart of the analysis.

***Fundamental Developments***

An advantage of adopting full-field data gives the flexibility of allowing the FE mesh to be changed without requiring additional tests to be performed. Current work in the department uses automated reflection photoelasticity techniques [12] to obtain full-field strain responses on the surface of a 1.5mm thick carbon fibre-reinforced cross-ply specimen containing known delamination defects. These specimens are manufactured using compression moulded unidirectional prepregs and the delaminations artificially introduced into the specimen by inserting a release film at the required location prior to curing. As an alternative to the traditional approaches work is being conducted to resolve the damage using genetic algorithms. These are particularly suited to solving problems in which the unknowns of a problem can be described in terms of discrete values as is the case when trying to resolve delaminations, (A delamination either exists or it doesn't exist). This avoids the physically-inadmissible situation where negative Young's moduli may otherwise be calculated.

### *Aircraft Tyre Inspection*

That non-destructive techniques are applied to inspect aircraft tyres is a requirement of the regulatory aircraft bodies. Fig.2 shows results of inspecting tyres using shearing interferometry where the presence of the flaw is revealed by the fringe patterns. The characteristics of possible defects make the use of vacuum conditions most suitable. A comparatively unknown phenomena occurs when results such as shown in Fig.2(d) are viewed over short but finite time differences. The response of the defect changes when the results are viewed as a sequence over time giving the observer the opportunity to 'see' the flaw being revealed. This sequence and the timescale of the event are currently being used to size and locate flaws within the tyre's compound.

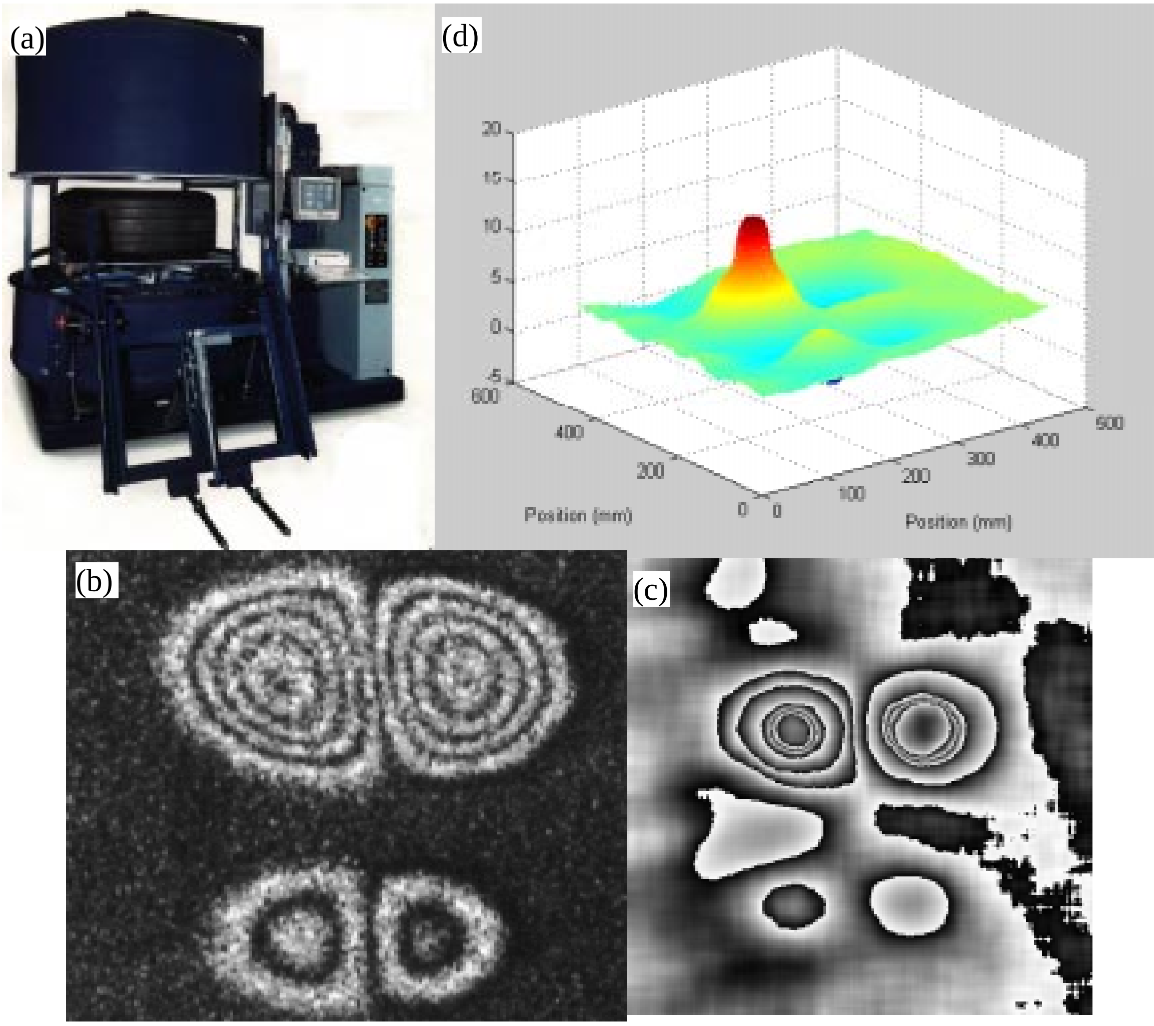


Fig.2: Non-destructive inspection of aircraft tyres: (a) test equipment; (b) shearing interferometry data; (c) unwrapped data; (d) Surface plot of displacement gradients.

### *Aircraft Skin Panel Delaminations*

Shearing interferometry data may also be used to reveal delamination flaws in carbon-fibre composite aircraft skin panels (the resulting fringe patterns are not dissimilar to that shown in Fig.2b). In a programme of research currently in progress inverse analysis is being used to size and locate flaws in skin panels loaded by a vacuum. Use will be made of neural network techniques to classify fringe patterns from shearing interferometry data of flaws in terms of size and depth to enable rapid detection to be made of these panels in-situ by the aviation industry.

Alternatively, (boron) patches may repair aircraft skins subjected to damage (Fig.1). It is just as important that these are assessed for structural integrity. Inverse techniques of a slightly different nature may be used to determine the degree in which the problem has been rectified. That is, the repair patch must take up some of the load and this may be measured quantitatively by an inverse analysis that records the response of the component both before and after the repair has been made. A simple algebraic difference in the response may be sufficient to determine if the problem has been rectified. A simple example is demonstrated in the next section.

### *Human Bone Implants*

Whilst human bones are indeed constructed of a 'composite' compound the use of a foreign implant is now a common practice to improve the structural integrity of ageing bones. In an inverse analysis, interferometric data was obtained before and after the implant was introduced to a damaged femur and the algebraic difference determined (Fig.3). This validates the function of the implant that is to reinforce the structure.

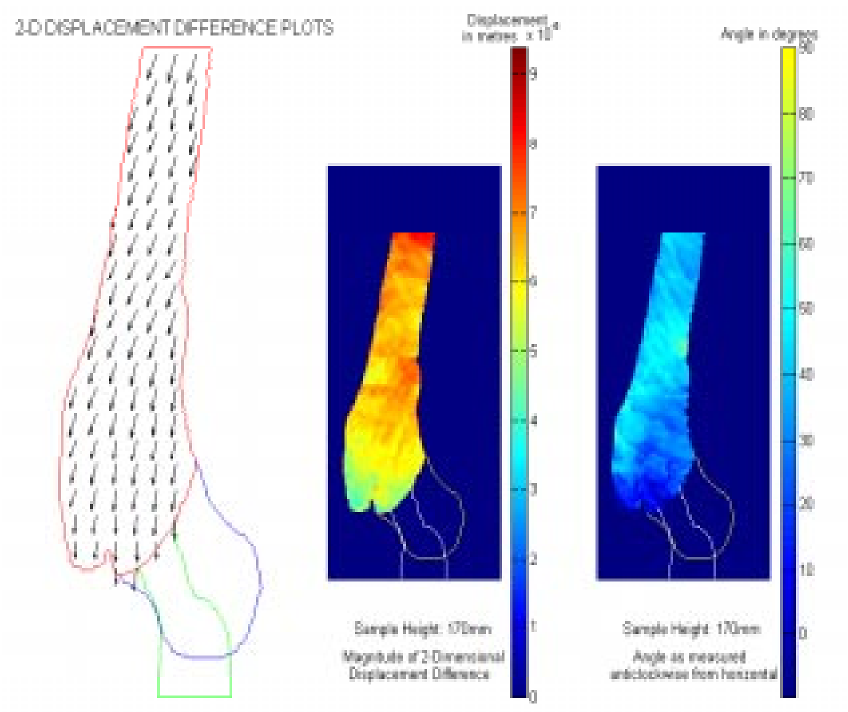


Fig.3: Analysis of human femur repaired by metallic implant (shown upside). Contours represent the result of the inverse analysis, i.e. the difference in response before and after the implant was introduced. Displacement magnitude is shown on the right, angle of displacement on the right.

## CONCLUDING REMARKS

A strain analysis based upon actual performance of the object, under normal loading, in its host environment, is the only true test of a structure's capability. If materials are weakened by the presence of flaws or damage they must respond accordingly to load and be revealed by a reduction in stiffness. Inverse techniques when fully realised will be able to quantify the severity of flaws since they are 'active' in contrast to traditional forms of non-destructive techniques that are 'passive'. A practical benefit of this approach is that it can distinguish between benign and malignant defects. If the aims of an inverse analysis are set at a realistic level then an optimistic future for techniques incorporating whole-field optical methods lies ahead.

## REFERENCES


1. Hajela, P., and Soeiro, F.J., (1990) "Recent Developments in Damage Detection Based on System Identification Methods", *Structural Optimization*, **2**, pp1-10

2. Sherratt, P.J., Panni, D.C., and Nurse, A.D., (2000), "Inverse analysis of a box-section composite beam with impact damage", To be presented at the 13th ECF, San Sebastien, 6-9 Sept.

3. Hajela, P., and Soeiro, F.J., (1990) "Structural Damage Detection Based on Static and Modal Analysis", *AIAA Journal*, **28**, pp1110-1173

4. Liu, P.L., and Chian, C.C., (1997) "Parametric identification of truss structures using static strains", *J.Struct. Eng*., **123**, pp.927-933

5. Sanayei, M., Imbaro, G.R., Mcclain, J.A.S., and Brown, L.C., (1997) "Structural model updating using experimental static experiments", *J. Struct. Eng*., **123**, pp792-798

6. Sanayei, M., and Saletnik, M.J., (1996) "Parameter estimation of structures from static strain measurements: I Formulation", *J.Struct. Eng*., **122**, pp555-562

7. Sanayei, M., and Onipede, O., (1991) "Damage assessment of structures using static test data", *AIAA Journal*, **29**, pp1174-1179

8. Sherratt, P.J., Panni, D.C., and Nurse, A.D., (2000), "On the inverse analysis of damage in laminates composites using inverse analysis", Proc. 3rd Int. Conf. Composite Structs. & Technology, Durban, SA, 11-13 Jan 2000, pp435-440

9. Leendertz, J.A., and Butters, J.N., (1973) "An image shearing speckle-pattern interferometer for measuring bending moments", *J. Phys. E: Sci. Inst.*, **6**, pp1107-1110.

10. Tyrer, J.R., and Petzing, J.N., (1997) "In-plane electronic speckle pattern shearing interferometry", *Opt. Lasers Engng.*, **26**, pp395-406.

11. Huntley, J.M., (1998) "Automated fringe pattern analysis in experimental mechanics: a review," *J. Strain Analysis*, **33**, pp105-125.

12. Ekman, M.J., and Nurse, A.D., (1998) "Completely automated determination of two-dimensional photoelastic parameters using load stepping", *Opt. Engng*., **37**, pp1845-1851.