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Modern Stress and Strain Analysis

A state of the art guide to measurement techniques

BSSM

BRITISH SOCIETY FOR STRAIN MEASUREMENT

Eureka

BSSM Technical Editors: J. Eaton Evans, J.M. Dulieu-Barton, R.L. Burguete

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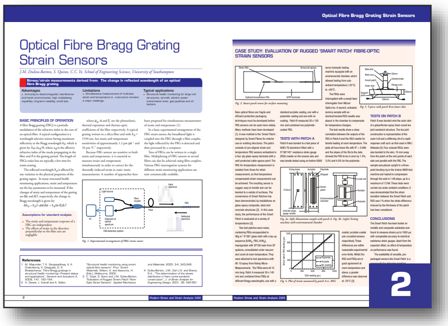

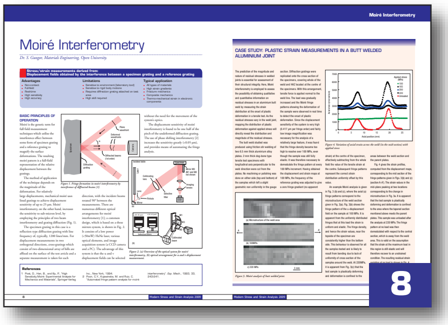

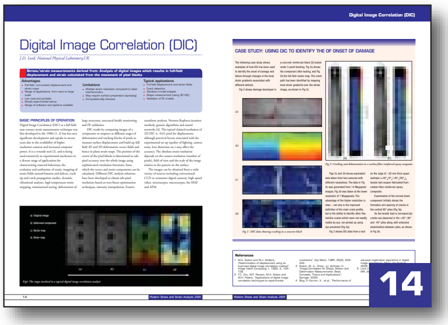

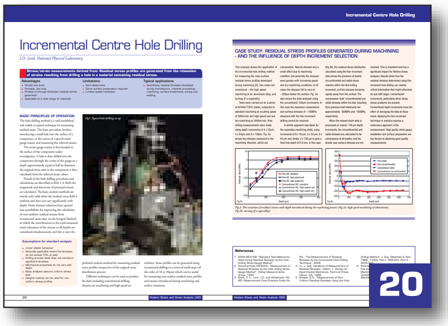

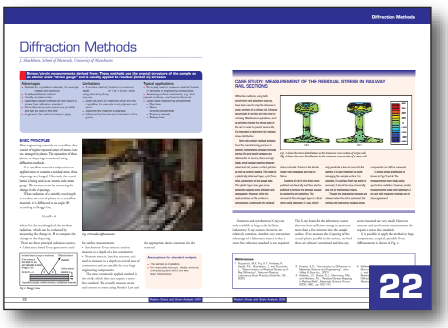

Capturing the State of the Art

MAKE MEASUREMENTS LESS OF A STRAIN

The field of engineering is complex; the range of applications for engineering products is huge. And yet, despite this complexity, the basics remain the most important things.

Engineers encounter stress and strain regularly as they progress their latest designs. But what they may not be so familiar with are the ways in which these parameters can be measured. Perhaps the most familiar device will be the strain gauge, but it's not the only approach: a range of techniques is available to provide engineers with exactly the information they require.

Eureka is pleased to join with the British Society for Strain Measurement to provide its readers with an update on the 'state of the art'. A combination of technical briefings and case studies will allow readers to acquaint – even re-acquaint – themselves with a range of techniques and their application.

We encourage you to find out more about these techniques by using this handbook and by contacting the BSSM's member companies.

Graham Pitcher,
Group Editor, Findlay Media

Why experimental mechanics is becoming ever more accessible.

'Experimental mechanics' can be defined as the investigation by experimental means of the mechanical behaviour of engineering systems subjected to load. The system can be a structure, a material, soft matter such as human tissue or a fluid structure coupling – the list is practically endless.

Implicit in the definition is that some kind of measurement system is used to capture a quantity that describes the system's behaviour. The main attributes conventionally associated with experimental mechanics are the deformation and the mechanical strain. These can then be related to a failure parameter by deriving the stresses from the strains by knowing the material constitutive relationships.

Experimental mechanics approaches that provide a measure related to the strain are therefore very important design tools. Many of these techniques have been available for decades, but recently have been gaining popularity because of the advances in computing power and decreasing hardware costs.

More importantly, from the design perspective, the necessity for experimental data to validate numerical models of systems manufactured from complex nonlinear inhomogeneous materials, such as fibre reinforced polymer composites, is ever increasing. Experimental mechanics approaches have much to offer and it is the purpose of this booklet to provide an overview of the range of application and operation of the techniques.

This booklet has been produced by the British Society for Strain Measurement (BSSM), supported by its members through expert contributions. The thrust is to capture the State of the Art in the field of experimental mechanics within an accessible guide targeted at the non-expert.

A primary role of the BSSM is to educate and disseminate leading edge advances in experimental mechanics. The partnership with Eureka has provided a much greater reach, with the target to attract a new generation of engineers and scientists to the field of experimental mechanics, as well as to update and inform more experienced practitioners of what is currently available. The funding for this booklet has been provided by sponsorship, mostly from BSSM Corporate members, and the BSSM is grateful for their ongoing support in ventures such as these.

The booklet is split into two sections. The first section concentrates on the techniques – ranging from single point sensors to full-field optical techniques. Each contribution contains a concise overview of a technique, followed by a short case study. The BSSM is grateful to the authors of each section for taking the time to prepare the excellent and easy to read articles. The second section is the sponsors' section, where companies provide information on their products, range of use and exemplar case studies that demonstrate the capabilities of their equipment.

We hope that this booklet will convey readers on a journey of exploration through the range of modern experimental stress and strain measurement techniques currently available. We hope that the guide is useful in finding solutions to existing problems or in providing the inspiration to pursue new avenues of investigation.

Dr James Eaton-Evans,
University of Oxford
Professor Janice Dulieu-Barton,
University of Southampton
Dr Richard Burguete,
Airbus

Optical Fibre Bragg Grating Strain Sensors

J.M. Dulieu-Barton, S. Quinn, C.C. Ye, School of Engineering Sciences, University of Southampton, UK.

Stress/strain measurements derived from: The change in reflected wavelength of an optical fibre Bragg grating

Advantages

- Immunity to electromagnetic interference and harsh environments; high multiplexing capability; long-term stability; small size

Limitations

- Simultaneous measurement of multi-axis strain and temperature in a structure remains a major challenge

Typical applications

- Structural health monitoring for large civil structures, aircraft, electric power transmission lines, gas pipelines and oil tankers

BASIC PRINCIPLES OF OPERATION

A fibre Bragg grating (FBG) is a periodic modulation of the refractive index in the core of an optical fibre. A typical configuration is a wavelength-selective mirror having maximum reflectivity at the Bragg wavelength λ_B, which is given by: $\lambda_B = 2n_{eff}\Lambda$, where n_{eff} is the effective refractive index of the mode propagating in the fibre and Λ is the grating period. The length of FBGs varies, but is typically a few millimetres for strain sensing.

The reflected wavelength λ_B is affected by any variation in the physical properties of the grating region. In many structural health monitoring applications, strain and temperature are the key parameters to be measured. If the changes of strain and temperature of the grating are $\Delta\varepsilon$ and ΔT, respectively, the change in Bragg wavelength is given by:

$$\Delta\lambda_B = \lambda_B(1-\rho\alpha)\Delta\varepsilon + \lambda_B(\alpha+\xi)\Delta T$$

where ρ, α and ξ are the photoelastic, thermal expansion and thermo-optic coefficients of the fibre respectively. A typical grating written in a silica fibre and with $\lambda_B \approx$ 1550 nm, has strain and temperature sensitivities of approximately 1.2 pm $\mu\varepsilon^{-1}$ and 10 pm $°C^{-1}$ respectively.

Because FBG sensors are sensitive to both strain and temperature, it is essential to measure strain and temperature simultaneously in order to correct for the thermally induced strain in static strain measurements. A number of approaches have been proposed for simultaneous measurement of strain and temperature [1].

In a basic experimental arrangement of the FBG strain sensor, the broadband light is coupled into the FBG through a fibre coupler, the light reflected by the FBG is detected and then processed by a computer.

Tens of FBGs can be written in a single fibre. Multiplexing of FBG sensors in several fibres can also be achieved using fibre couplers. Various FBG interrogation systems for different strain monitoring applications are now commercially available.

Assumptions for standard analysis:

- The strain and temperature response of an FBG are independent
- The effects of strain in the direction perpendicular to the fibre axis are negligible

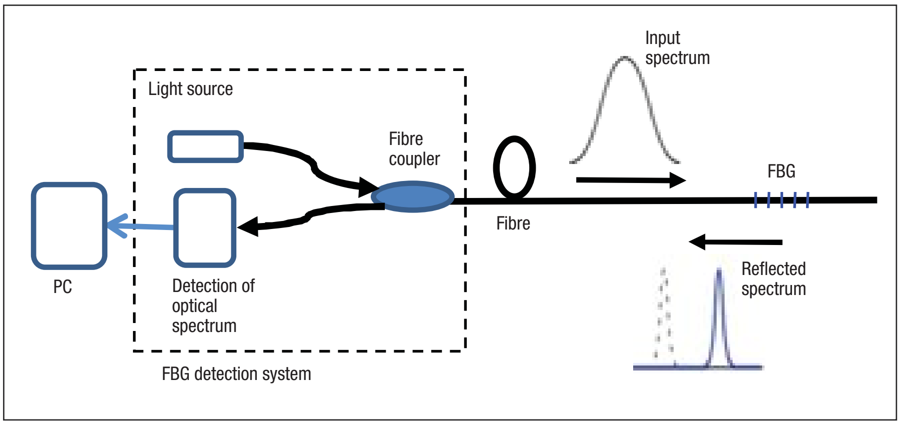

Fig. 1. Experimental arrangement of FBG strain sensor

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CASE STUDY: EVALUATION OF RUGGED 'SMART PATCH' FIBRE-OPTIC STRAIN SENSORS

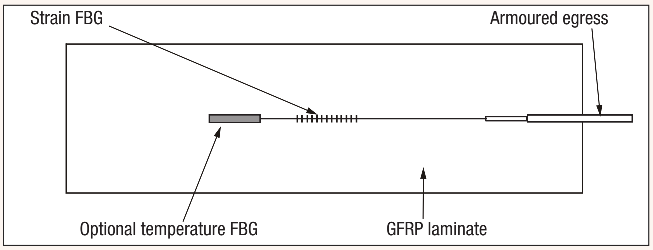


Fig. 2. Smart patch sensor for surface mounting

Bare optical fibres are fragile and efficient protection packaging techniques must be developed before FBG sensors can be used more widely. Many methods have been developed [1]. A new method is the 'Smart Patch', designed by Smart Fibres for exterior use on existing structures. The patch consists of pre-aligned strain and temperature FBG sensors embedded in a four ply glass-epoxy laminate with a well-protected cable egress point. The FBG for temperature measurement is isolated from those for strain measurement, so that temperature compensated strain measurement can be achieved. The resulting sensor is rugged, easy to handle and can be bonded to a variety of surfaces. The convenience of Smart Patches has been demonstrated by installations on glass-epoxy composite, steel and concrete structures [2]. In this case study, the performance of the Smart Patch is evaluated at a variety of temperatures [3].

Two test patches were made, containing FBGs encapsulated in 90g m^{-2} 0°/90° glass cloth with a lay-up sequence {0/90_2, FBG, 0/90_2}, impregnated with SP106 resin from SP systems, consolidated under vacuum and cured at room temperature. They were attached to test specimens with AE-10 epoxy from Vishay Micro-Measurements. The FBGs were all 10 mm long. Patch A measured 50 x 145 mm and contained three FBGs at different Bragg wavelengths, one with a standard acrylate coating, one with a polyimide coating and one with no coating. Patch B measured 20 x 150 mm and contained one polyimide-coated FBG.

TESTS WITH PATCH A

Patch A was bonded to a test piece of 6083-T6 aluminium fitted with a 0°/90°/45° resistance strain gauge (RSG) rosette on the reverse side and was tensile tested using an Instron 8800 servo-hydraulic testing machine equipped with an environmental chamber, which allowed testing from sub-ambient temperature (-25°C) to +80°C.

The FBGs were interrogated with a swept laser interrogator from Micron Optics Inc. A second, unloaded, dummy sample with an identical bonded RSG rosette was placed in the chamber to compensate for temperature changes.

The test results show a close correlation between the outputs of the FBG in Patch A and the RSG rosette for tensile loading at room temperature. The plots all have linear fits with $R^2 > 0.999$ and the slopes of the fits to the data showed the FBG to be in error by 1.4%, 3.5% and 4.0% for the polyimide-coated, acrylate-coated and uncoated sensors respectively. These differences are within reasonable experimental error limits. Whilst the RSG and FBGs are in good agreement at room temperature and above, a greater difference was observed at -25°C [3].

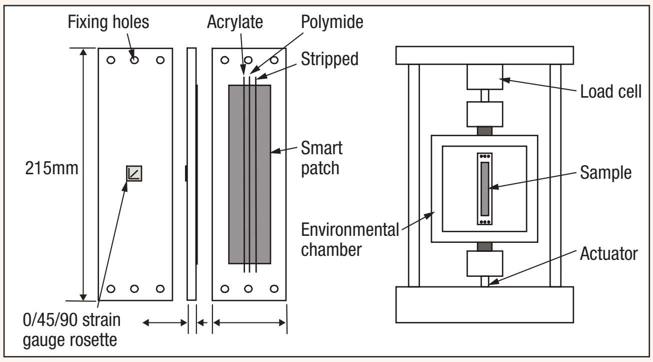


Fig. 3a. (left) Aluminium sample with patch A. Fig. 3b. (right) Testing machine with environmental chamber

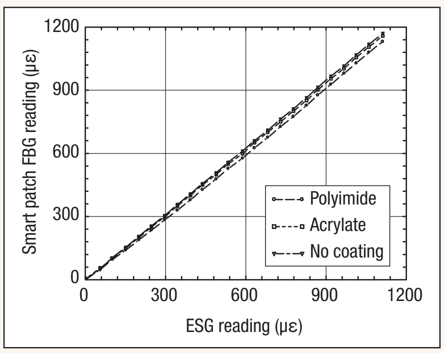


Fig. 4. Plot of strain measured by patch A vs. RSG

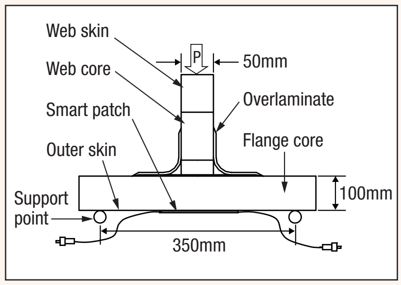


Fig. 5. T-piece with patch B on lower skin

TESTS ON PATCH B

Patch B was bonded onto the outer skin of a glass/Kevlar-epoxy foam-cored tee joint sandwich structure. The tee joint construction is representative of the outer hull and a stiffening rib of a rapid response craft such as that used in RNLI lifeboats [4]. Four uniaxial RSGs were also bonded to the skin, 10 mm away from the patch at the mid-points of each side and parallel with the FBG. The sample was placed upright in a three-point bending rig in the Instron 8800 test machine and loaded in compression through the web in 1 kN steps, up to a maximum of 13 kN. These tests were carried out under ambient conditions. It was demonstrated that the strain deviation between the Smart Patch and RSG was 1% when the strain difference induced by the thickness of the patch had been considered.

CONCLUSIONS

The Smart Patch has been tested on metallic and composite substrates and found to measure strains up to 1600 με with comparable accuracy to electrical resistance strain gauges. Apart from the expected offset, no effect of temperature on performance was found.

The availability of versatile, pre-packaged sensors like Smart Patch is a prerequisite for delivering practical systems to customers since it enables tailored measurement solutions to be put together quickly and efficiently from off-the-shelf parts.

Electrical Resistance Strain Gauges

G. Mordan, BSSM, UK; E.G. Little, Dept. of Mechanical and Aeronautical Engineering, University of Limerick, Ireland.

Stress/strain measurements derived from: The change in resistance of a conductive material when it is stretched

Advantages
- Mature technology
- Low cost
- Commercial instrumentation readily available
- Very accurate (down to 0.1μmicro metre/meter)
- Small mass and volume
- Remote monitoring possible, including wireless instrumentation
- Measures tension and compression
- Capable of elastic and post yield measurements
- Good frequency response
- Easy to attach
- Usable on a wide range of materials

Limitations
- Not full field
- Measures at a point (user must know where to place the gauge)
- Some skill needed to install and interpret result
- Strain averaged over grid length of gauge
- Three measurements required for complete stress state
- Limited to approx 20% elongation

Typical applications
- Stress analysis of engineering components and structures
- Sensing element for many types of transducer

BASIC PRINCIPLES OF OPERATION

An electrical resistance strain gauge consists of a conductor in the form of a resistance element attached to a thin insulating backing.

The resistive element is usually in the form of a foil grid. However, for some applications – particularly high temperature measurements – the conductor may take the form of a wire element. Occasionally, semiconductor material may form the resistive element.

To make a measurement, the strain gauge must be bonded to the component or structure under test and this means the quality of the bonding procedure is a critical factor in ensuring faithful transmission strain into the gauge grid.

The change of resistance of a bonded gauge is related to the strain by the following equation:

$$\frac{\Delta R}{R} = K\varepsilon$$

where:

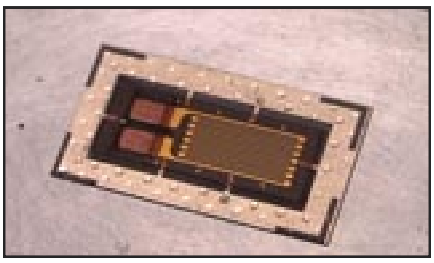
ε = Strain along the gauge axis
R = Initial Strain Gauge Resistance
ΔR = Resistance change due to strain
K = Gauge Factor (a property of the grid material quoted by the strain gauge manufacturer).

Since the strains experienced in most structures and components are small (μm/m), so are the resulting resistance changes in the strain gauge (μohms/ohm). To measure these very small changes, a Wheatstone Bridge is used.

In an application where the direction of principal strain is known, a single gauge with its axis lined up in this direction can be bonded to the structure to form one arm of the Wheatstone Bridge, the remaining three arms being provided by the measuring equipment.

This single active gauge arrangement is known as a quarter bridge and is most effective when used with a three lead wiring system.

If the principal strain direction is not known, a gauge configuration known as a rosette must be used. A rosette consists of a number of independent gauge grids – normally three – mounted on a common backing.



Independent readings are taken from each grid and, by using the known angles between the grids and a suitable datum on the component, the value and direction of the principal strains can be computed.

In a transducer application, is it normal to use a full bridge where all arms employ active strain gauges arranged on the transducer sensing element so that the resistance changes are additive.

Taking readings from a strain gauge involves the measurement of very small changes of resistance therefore a suitable signal conditioning system is required.

There are many commercial systems available, ranging from small portable units to large multi channel systems covering both static and dynamic measurements.

As well as providing the necessary signal amplification, the conditioning system should have the facility to enable three lead quarter and half bridge inputs to be completed internally, provide accurate and stable excitation to the strain gauge bridge together with facilities to balance or null any initial offsets from the strain gauges.

In addition, a shunt calibration and filtering facility would be very desirable.

CASE STUDY: 3D STRAIN ROSETTES FOR ANALYSIS OF STRAINS IN CEMENT MANTLES SUPPORTING HIP PROSTHESES *IN VITRO*

There are approximately 250 000 hip replacement surgeries in the USA annually. A significant problem with hip replacements is loosening induced, for example, by breakdown of the cement that secures the prosthesis to the bone. It is important to have an understanding of the strains in the cement mantle *in vitro*. To measure these strains for comparison with finite element analyses it is necessary to use large scale models (Fig. 1) and embed 3D strain rosettes (Fig. 2) into the model of the cement mantle to establish the engineering strains (ε_x, ε_y and ε_z) and the shearing strains (γ_{xy}, γ_{yz} and γ_{zx}). The model is made from materials, with a stiffness ratio to one another based on the laws of dimensional analysis, although the anisotropy of bone is not modelled. Large scale models are necessary to minimize the effects of strain gradients since these can have adverse effects on the results.

The 3D rosettes are made by mounting three separate rosettes onto an epoxy carrier, which is then mounted in a steel die. The same type of epoxy is then cast into the die embedding the carrier. After curing the resulting plug is machined to fit into cavities in the model of the cement, also made from epoxy. Recent investigations have shown that the plugs should be square or rectangular and embedded into similar shaped cavities in the model so they cannot rotate, thereby maintaining the direction cosines of each gauge as measured before the plug was embedded.

A special purpose computer programme analyses the results from the 3D rosettes giving the mean and standard deviation of the engineering and shearing strains derived from the model.

Fig.1: Hip under test

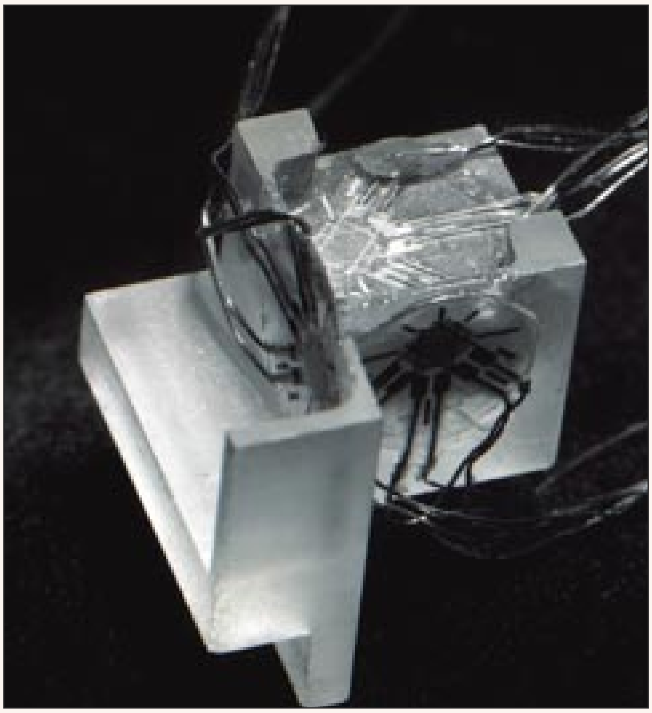


Fig.2: 3D strain rosette

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Standardisation Project
for Optical Techniques of Strain Measurement (SPOTS)

R. Burguete, Airbus, UK, and E. A. Patterson, Michigan State University, USA.

A programme of pre-normative research for a range of optical strain measurement techniques

Advantages
- A rigorous and consistent approach to the application of optical methods
- Practical and viable methods for assessment and comparison of optical techniques and systems

Limitations
- Standards developed only for commonly used techniques
- Calibration of an optical system or sub-system, not individual components

Typical application
- Calibration methods described for the following techniques: Photoelasticity; Moiré Methods; Thermoelasticity; Digital Image Correlation; Laser Speckle; and Interferometric Methods.

SUMMARY TABLE

Standardisation of full field optical techniques aims to increase the acceptance and use of these methods. It will increase the market benefiting system providers and stimulate investment by academic and industrial end users.

PROJECT OBJECTIVES

1. The development of physical reference materials for speckle techniques, shearography, Moiré, photoelasticity, and thermoelastic stress analysis.
2. The design and construction of simulated, virtual reference materials to include: simulated data, and synthesised fringe patterns with and without random or systematic noise.
3. Definition of recommended data formats for image data, numerical data, and processed data for full-field optical techniques of strain measurement.
4. Optimisation of methodologies for the use of unified reference materials and for the practical application of speckle techniques, shearography, Moiré, photoelasticity, and thermoelasticity.
5. Liaison with international bodies to ensure recognition of the measurement procedures and reference materials developed.
6. Identification of routes for traceability of calibrations.

PROJECT DESCRIPTION

A unified approach was required for all optical techniques. It was quickly appreciated that there are two needs, namely for calibration of optical instruments and independently for evaluation of instruments and their sub-systems. Calibration requires traceability to an international standard which implies a simple reproducible strain field. A beam subject to four-point bending was selected to generate the strain field in the reference material (Fig. 1). The beam was enclosed in a monolithic frame to eliminate the influence of boundary conditions and to provide a route for traceability to the standard for length.

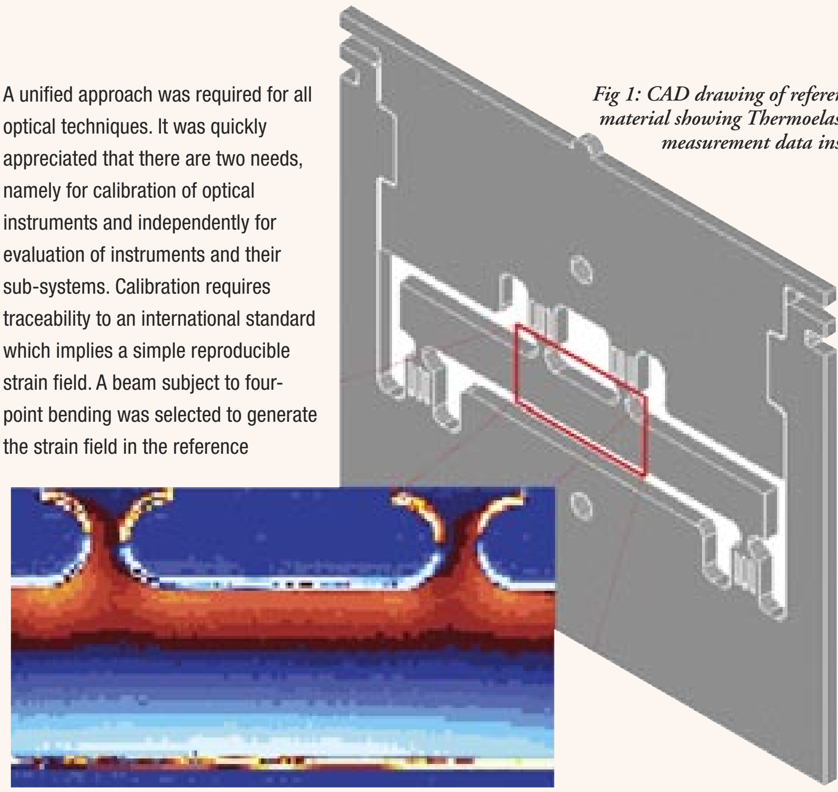

Fig 1: CAD drawing of reference material showing Thermoelastic measurement data inset.

A set of standardised test materials (STMs) have been designed to allow evaluation of both complete systems and sub-systems or algorithms. STMs are intended to allow the 'fitness for purpose' of a

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Selected Publications

1 Burguete, R.L., Hack. E., Kujawinska, M., Patterson, E.A., "Classification of operation and processes in optical strain measurement", Proc. 12th Int. Conf. Exptl. Mechanics, Advances in Experimental Mechanics, Pappalettere, C. (ed), McGraw-Hill, Milano, 697-8, 2004.

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3 Whelan, M.P., Albrecht, D., Hack, E., Patterson, E.A., "Calibration of a speckle interferometry full-field strain measurement system", Strain, 2008, 44(2), 180-190.

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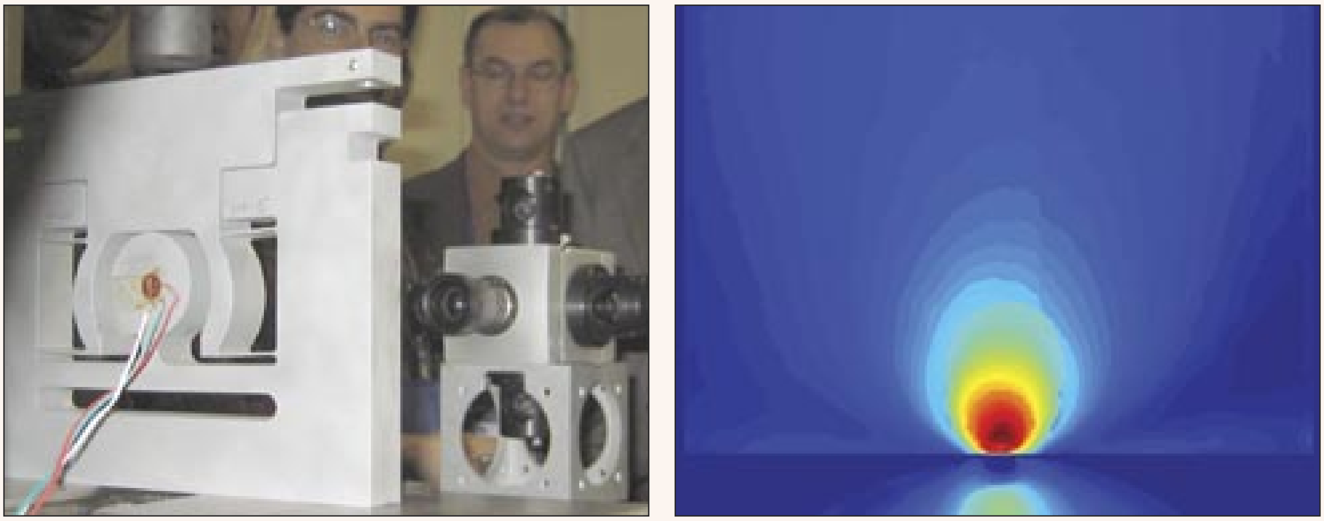

Figure 2: Standardised Test Material (left) and measured data (right) by Photoelastic analysis.

system to be assessed and to enable diagnostic investigations in the most sophisticated instrument. This implies that STMs must contain complicated strain fields that offer challenging problems for analysis. Two geometries have been proposed: a disc in contact with an elastic half-space (Fig. 2) and the interference fit of a pair of rings. In addition, standard data sets are needed for the input and output from each step in an analysis process. The concept of functional pathways has been developed to allow the generation of standard data sets (SDS) from an analytical description of the strain field in the STM. Pathways have been created for ESPI, grating interferometry, image correlation, Moiré, photoelasticity and thermoelasticity. The final report of the project and the draft proposed standard are available at **www.opticalstrain.org**.

OUTCOMES

1. A recommended format for full-field optical strain data.
2. Draft standard guides on ESPI, geometric Moiré, grating interferometry, image correlation, photoelasticity, and thermoelasticity.
3. Completion of two round robins and a set of industrial case studies as part of the verification process.
4. Reports on routes for traceability and on feasibility of full-field data comparisons.
5. A SPOTS standard for the calibration and assessment of optical strain measurements including the design and methodology for use of a reference material and a set of standardised test materials.
6. Draft proposed ISO TTA submitted to VAMAS TWA26 (**www.vamas.org** and **www.twa26.org**).
7. Project final report (January 2006) available on project website: **www.opticalstrain.org**.

Moiré Interferometry

S. Gungor, Materials Engineering, The Open University, UK.

Stress/strain measurements derived from:
Displacement fields obtained by the interference between a specimen grating and a reference grating

Advantages
- Non-contact
- Full-field
- Real-time
- High sensitivity
- High accuracy

Limitations
- Sensitive to environment (laboratory tool)
- Sensitive to rigid body motions
- Requires diffraction grating attached on test area
- High skill required

Typical application
- All types of materials
- High strain gradients
- Fracture mechanics
- Composite mechanics
- Thermo-mechanical strain in electronic components

BASIC PRINCIPLES OF OPERATION

Moiré is the generic term for full field measurement techniques which utilise the interference effect between some form of specimen grating and a reference grating to magnify the surface deformations. The resulting Moiré pattern is a full-field representation of the relative displacement between the gratings.

The method of application of the technique depends on the magnitude of the deformation. For relatively large displacements, mechanical Moiré uses lined gratings to achieve displacement sensitivity of up to 25 μm. Moiré interferometry, on the other hand, increases the sensitivity to sub-micron level, by employing the principles of two beam interferometry and grating diffraction (Fig. 1).

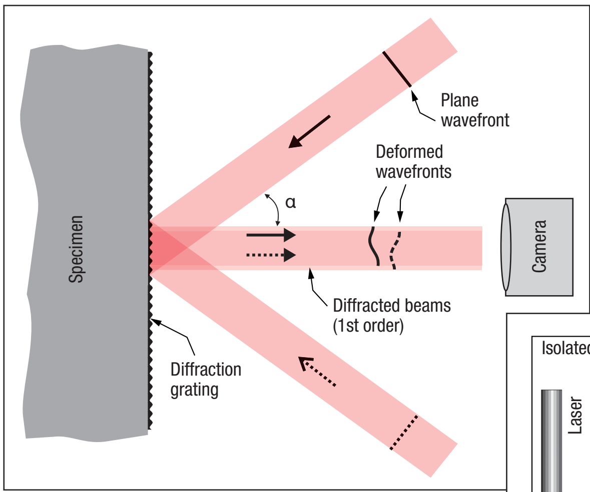

Figure 1. Fringe formation in moiré interferometry by interference of diffracted beams [1].

The specimen grating in this case is a reflection type diffraction grating with line frequency of, typically, 1200 lines/mm. For displacement measurements in two orthogonal directions, cross-gratings which consist of two-dimensional array of hills are affixed on the surface of the test article and a separate measurement is taken for each direction, with the incident beams rotated 90° between the measurements. There are numerous different optical arrangements for Moiré interferometry [1]; a common design, which is based on a three mirrors system, is shown in Fig. 2. It consists of a low power (<50mW) HeNe laser, various optical elements, and an image acquisition system (a CCD camera and a PC). The advantage of this system is that the u and v displacement fields can be selected without the need for the movement of the system's optics.

The displacement sensitivity of Moiré interferometry is found to be one half of the pitch of the undeformed diffraction grating. The use of phase shifting interferometry [2] increases the sensitivity greatly (<0.05 μm), and provides means of automating the fringe analysis.

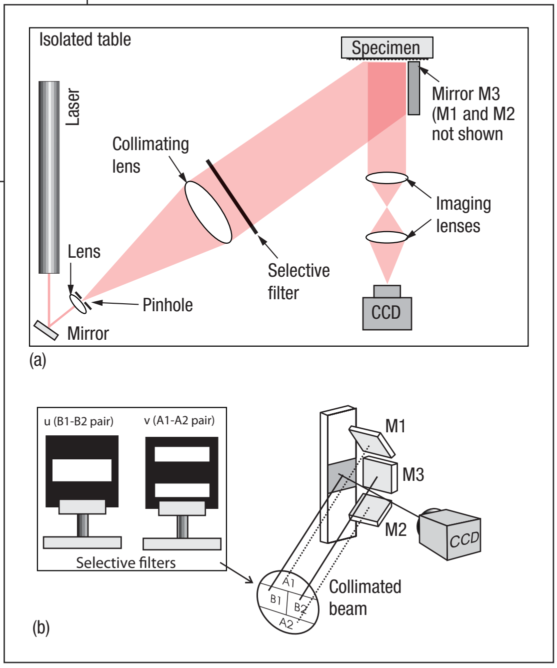

Figure 2. (a) Overview of the optical system for moiré interferometry, (b) optical arrangement for u and v displacement measurement.

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CASE STUDY: PLASTIC STRAIN MEASUREMENTS IN A BUTT WELDED ALUMINIUM JOINT

The prediction of the magnitude and nature of residual stresses in welded joints is essential for assessment of their structural integrity. Here, Moiré interferometry is employed to assess the possibility of obtaining qualitative and quantitative information on residual stresses in an aluminium butt weld by measuring the strain distribution at the onset of plastic deformation in a tensile test. As the residual stresses vary in the weld joint, mapping the distribution of plastic deformation against applied stress will directly reveal the distribution and magnitude of the residual stresses.

The butt weld studied was produced using friction stir welding of two 6.5 mm thick aluminium alloy plates. 2 mm thick dog-bone type tensile test specimens with longitudinal axis perpendicular to the weld direction were cut from the plates. No machining or polishing was done on either side (top and bottom) of the samples which left a slight geometric non uniformity in the gauge section. Diffraction gratings were replicated onto the cross section of the specimens, covering the whole of the weld and HAZ located at the centre of the specimens. With this arrangement, tensile force is applied normal to the weld line. The load was gradually increased and the Moiré fringe patterns showing the deformation of the sample were observed in real time to detect the onset of plastic deformation. Since the displacement sensitivity of the system is very high (0.417 μm per fringe order) and fairly low image magnification was necessary for the analysis of a relatively large feature, it was found that the fringe density became too high to resolve over 100 MPa, even though the sample was still fully elastic. It was therefore necessary to demodulate the fringe pattern at every 100 MPa increment. Having obtained the displacement and strain maps at 100 MPa, the frequency of the reference grating was adjusted to give a zero fringe gradient (no

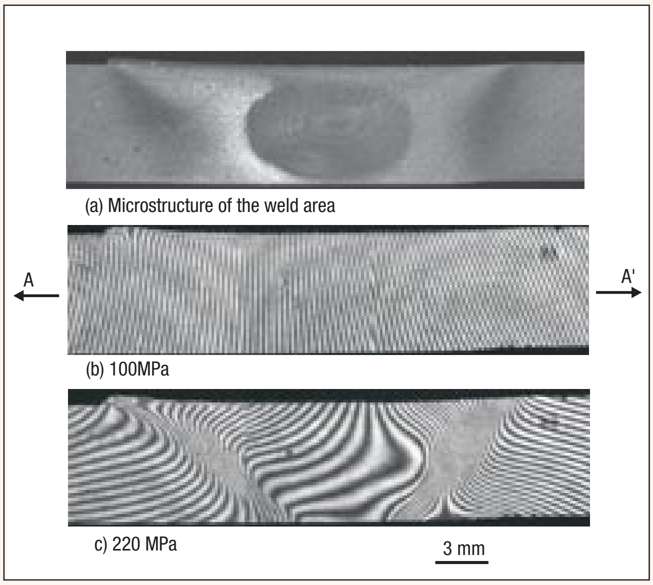

Figure 3. Moiré analysis of butt welded joint.

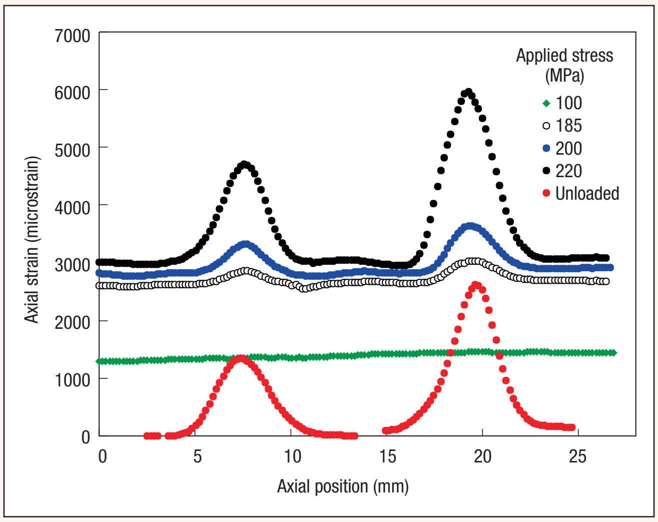

Figure 4. Variation of axial strain across the weld (in the mid-section) with applied stress

apparent strain) at the centre of the specimen, effectively subtracting from the whole field the value of the tensile strain at the centre. Subsequent fringe patterns represent the correct strain distribution uniformly offset by this value.

An example Moiré analysis is given in Fig. 3 (b) and (c), where the axial (u) fringe patterns correspond to the microstructure of the weld section given in Fig. 3(a). Fig. 3(b) shows the fringe pattern of the u-displacement field on the sample at 100 MPa. It is apparent from the uniformly distributed fringes that at this load the strain is uniform and elastic. The fringe density, and hence the strain values, near the topside of the specimen are consistently higher than the bottom side. This behaviour is observed for all the samples tested and is likely to result from bending due to lack of uniformity of cross section of the samples around the weld. At 220MPa, it is apparent from Fig. 3(c) that the test sample is plastically deforming and deformation is confined to the areas between the weld section and the parent plates.

Fig. 4 gives the strain profiles, computed from the displacement maps, corresponding to the mid section of the fringe patterns given in Figs. 3(b) and (c) (section A-A'). The strain values in the mid-plane peaking at two locations corresponding to the change in microstructure in Fig. 3a. It is apparent that the test sample is plastically deforming and deformation is confined to the area where the tapered section mentioned above meets the parent plates. This sample was unloaded after the analysis at 220 MPa. The fringe pattern at no load was then demodulated with respect to the central section, which is away from the weld area. This is valid on the assumption that the strain at the maximum load in this region is still elastic and will therefore recover to an unstrained condition. The resulting residual strain variation at no load is shown in Fig. 4, which allows inferences to be made about the magnitude and distribution of residual stress.

Photoelastic Stress Analysis

V.N. Dubey, School of Design, Engineering and Computing, Bournemouth University, UK.

Stress/strain measurements derived from: Fringe patterns generated in a photoelastic coating applied to a stressed components and viewed under polarized light

Advantages
- Non-contact
- Full-field
- Direct method
- Stress or strain data
- Portable

Limitations
- Requires a source of light
- Operates under the temperature range of 0-60 degrees C
- Stress level may saturate
- Calibration of coatings required for accurate measurement

Typical applications
- Immediate identification of stressed area
- Component/structure stress analysis
- Stress visualization
- Static/dynamic tests

BASIC PRINCIPLES OF OPERATION

Photoelasticity is an optical technique for experimental stress analysis. It is based on the principle of temporary birefringence (i.e. double refractive index) of certain non-crystalline transparent materials [1]. Under external or internal stress the material exhibits birefringence, which splits the incident light into two components travelling at different speeds. At emergence, the two beams are out of phase and the difference in phase is dependent on the value of stress at that point. This retardation or the temporary state of double refraction o f photoelastic materials is used for surface stress analysis.

The technique can be implemented in transmission or reflection mode depending on the application requirement. Fig. 1 shows the arrangement of optical elements in a plane polariscope in transmission mode, where the incident polarized light (after passing through the polarizer) is split into two components at the stressed photoelastic model with a relative retardation. When these components pass through the analyzer, they recombine and interfere to produce coloured fringes.

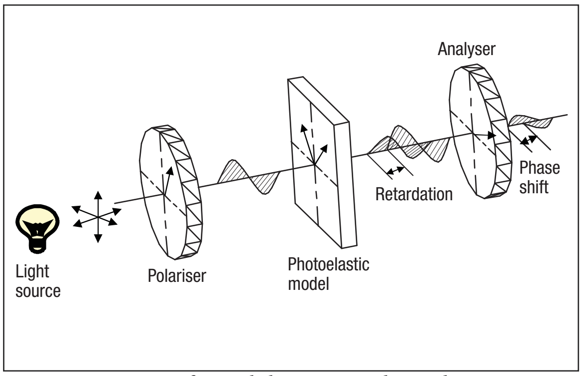

Fig. 1. Arrangement of optical elements in a plane polariscope in transmission mode

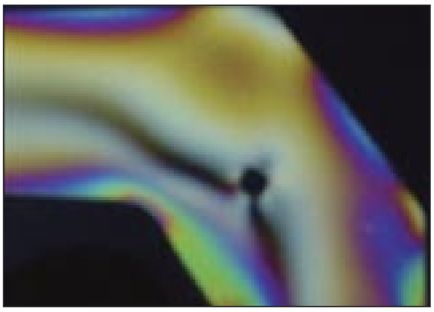

Fig. 2. Fringe patterns in a stressed photoelastic model with a hole obtained in reflection mode

This is the measure of difference of principal stresses at that point and is given by:

$$(\sigma_1 - \sigma_2) = \frac{N}{t}\,\frac{E}{(1+\nu)}\,\frac{\lambda}{K} \qquad (1)$$

where E is modulus of elasticity, ν is Poisson's ratio, K is strain optic co-efficient of the material, t is the coating or model thickness and λ is the wavelength of light used. The band of fringes represents different stress zones which are designated by distinct fringe orders N. The fringe orders can be estimated from the colour of the band and can be used to find the principal stress difference at the test points.

METHODS AND APPLICATIONS

This technique involves applying a thin epoxy coating to a metal, glass or plastic component or even a model of a component. When the component is loaded, strains are transmitted into the coating and when viewed under polarised light, the photoelastic fringes can be observed and analysed to determine shear stresses (difference of principal stresses). This is a powerful stress analysis technique for direct visualization and determination of the stress field on loaded components or structures. This technique is complementary to Finite Element Analysis (FEA) for direct measurement of the stress field. It is also widely used for measuring residual stresses in transparent materials such as glass.

The classical manual procedure of analysis was very tedious and time consuming and required skilled and experienced personnel [2]. With the advent of fast computing, developments in digital image processing and high speed cameras, the whole process of stress analysis can be automated. There are commercial systems available that offer semi-automated [3] and fully automated stress analysis on coated parts [4]. Digital imaging is the basic requirement in all photoelastic techniques used for stress analysis.

The most commonly used photoelastic techniques are RGB calibration and phase-shifting methods. RGB calibration is a simple technique which provides isochromatic

Assumptions for standard analysis:

- linear elastic loading
- material is homogenous isotropic
- adiabatic conditions
- mechanical properties of material are independent of small changes of temperature
- constant ambient temperature

CASE STUDY: STRESS VISUALISATION IN BOEING 767 MAIN LANDING GEAR

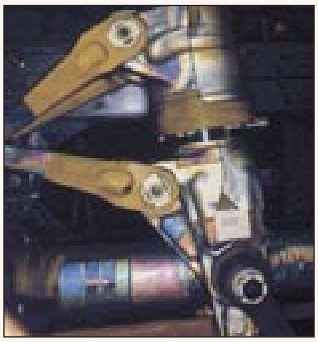

Fig. 3. Fringe pattern on Boeing 767 main landing gear

The landing gears for nearly all modern aircraft are stress analysed by covering the entire gear surface with coating. Landing gears are fabricated from forged and machined high-strength steel. The gear is a complex assembly of parts subjected to various static and shock loadings. Occasionally, certain parts are exposed to as many as six different loading conditions. Because the landing gear is used only twice during a flight and represents dead weight the remainder of the time, any weight reduction is of great benefit. At the same time, safety is obviously of paramount importance; large safety factors must be employed unless the stress distribution is accurately known for all significant modes of loading. After a thorough survey and analysis of the surface strain distribution on all structural components is completed (Fig. 3), an additional analysis is performed to establish acceptance criteria prior to manufacture of the actual landing gear.

RESIDUAL STRESSES

A metal fan hub was failing in service where the hub shaft support was welded to the flange. Analytical studies predicted low stress levels during the dynamic loading sequence. Strain gauge measurements near the weldment supported this prediction.

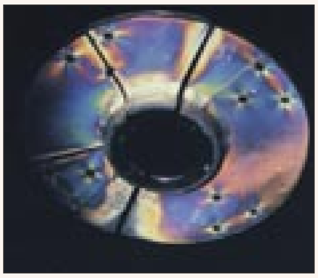

Fig. 4. Residual stresses in a metal fan hub

Several of the fan hubs were fabricated for test purposes, and coatings were contoured and bonded over the surface area. After application of the coating, the hubs were cut through, releasing the internal forces (residual stresses) developed by non-uniform heating during the welding process. The fringe patterns shown in Fig. 4 revealed locked-in residual stresses, which were of very high magnitude in the welded area. The modest cyclic stresses, superimposed upon the high residual mean stresses, were sufficient to produce field failures.

COMPOSITE MATERIAL

A fibreglass plate and an aluminium plate of similar dimension were coated with a bifringent material and tested in uniaxial tension. The resulting strain patterns that developed around the holes in both plates were similar in geometry, demonstrating a definite correspondence in the gross strain distribution in homogeneous and heterogeneous materials. However, the fringe patterns appeared as smooth unbroken lines for the homogeneous material (aluminium) as shown in Fig. 5, while for the heterogeneous material (fibreglass), they were discontinuous, with a more or less scotch plaid appearance as shown in Fig. 6.

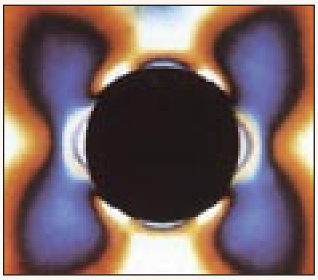

Fig. 5. Stress pattern on a composite (homogeneous) material plate with a hole

Fig. 6. Stress pattern on a composite (heterogeneous) material plate with a hole

(stress) information in terms of fringe order. The technique requires generation of a look up table (LUT) with colour information against fringe order. During analysis the RGB triplet value of test points can be compared to the LUT values using the least squares method thus fringe order can be determined and stress analysis can be performed using Eq. (1).

Phase shifting, on the other hand, is the most promising multi-image technique providing both isoclinic (direction) and isochromatic information. It is based on acquisition of phase stepped images of photoelastic models at different orientations of optical elements. Intensity equations from these images are used for the determination of isochromatics and isoclinics. Special algorithms are required for phase unwrapping of the data obtained from these equations [5].

Fig. 2 shows the full-field view of stress patterns generated on a section of a stressed model under white light. The coloured fringes represent the principal stress difference and the technique is used to determine regions of high stress or over-loading of fabricated components.

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Digital Speckle Pattern Interferometry

F. Pierron, LMPF, ENSAM, France.

Stress/strain measurements derived from: interference fringes at the specimen surface

Advantages
- Non-contact
- Full-field
- High sensitivity
- High spatial resolution
- Three deformation components

Limitations
- Sensitive to vibrations
- Requires a diffusive surface
- Large rigid body motions
- Not adapted to large deformation

Typical applications
- Heterogeneous materials (welds, bonded joints)
- Metals, polymers, composites, ceramics
- In-plane or bending tests

BASIC PRINCIPLES OF OPERATION

Speckle interferometry [1] is based on the interference between two coherent light rays (laser). In the simplest set up, the laser light is separated in two by a beam splitter. One of the beams (reference) goes to the camera and the other illuminates the specimen. If the surface is diffusive, some of this light is reflected back to the camera and recombines with the reference beam giving a reference phase map. When the specimen undergoes some out-of-plane deformation, the specimen beam has to travel longer to reflect back to the camera. This path difference creates a set of fringes related to the out-of-plane displacement.

Assumptions for standard analysis:

- Surface is diffusive (spray white powder before test)
- Displacement between load steps is less than speckle size (to avoid decorrelation)
- Flat or near-flat surface (can be extended to moderately curved surfaces)

An important concept is that of sensitivity vector. In Fig. 1, the sensitivity vector $\vec{g}$ is the difference between vectors $\vec{k_e}$ and $\vec{k_0}$. The displacement is measured in this direction (here, out-of-plane). It is possible to combine two vectors to build up an in-plane sensitivity vector, as in Fig. 2. The displacement associated to one fringe (sensitivity) is:

- $\dfrac{\lambda}{2\cos(\alpha/2)}$ for the set-up in Fig. 1;
- $\dfrac{\lambda}{2\sin\theta}$ for the set-up in Fig. 2.

Commercial systems usually provide the three components of the displacement field at the surface by using sets of mirrors to toggle the illumination to different directions.

The spatial resolution is one pixel (typically from 15 µm to 1 mm), with fields of view ranging from centimetre to metres. The displacement resolution is typically 1/100th of a pixel in-plane and 1/300th of a pixel out-of-plane. Strains down to 10^{-5} can be measured.

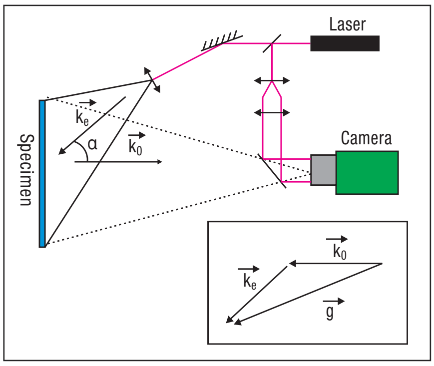

Fig. 1 - Out-of-plane sensitivity arrangement

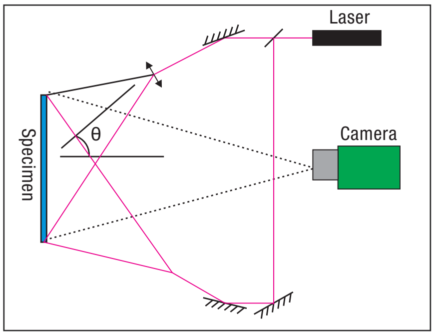

Fig. 2 - In-plane sensitivity arrangement

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CASE STUDY: STRAIN LOCALIZATION IN FSW WELDS

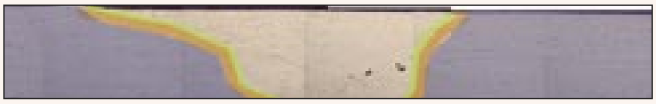
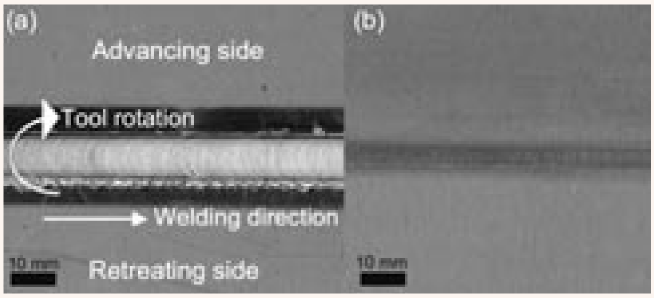


Fig. 3a (above). FSW magnesium weld (through-thickness view of the weld nugget). Fig 3b (right). Top view of the weld (a) Top surface (b) Bottom surface



Welding is a very important industrial joining process. However, the mechanical behaviour of the weld zone is extremely complex as a consequence of the fact that the microstructures created by the welding process vary rapidly within the weld zone. In order to assess the mechanical behaviour of such joints, full-field deformation measurements bring considerable insight into the plastic deformation localization. This type of information can even be used to identify local elasto-plastic laws as in [2].

The present case study concerns the measurement of the strain field in a magnesium Friction Stir Weld (FSW). Views of the weld are given in Figs. 3a and 3b (from [3]).

Tensile specimens have been tested in the plane of the weld, for both the top and bottom surfaces. The reason why speckle interferometry (SI) was used instead of digital image correlation (DIC, the most popular full-field measurement technique at the moment) was spatial resolution. Indeed, with DIC, an independent displacement measurement is obtained for windows of typically 15 x 15 pixels, hence, 225 pixels. The resolution is usually 1/100th of a pixel at the very best. With SI, one independent displacement measurement is obtained for each pixel, hence, 225 more measurement points than with DIC, with about the same displacement resolution. Therefore, SI will pick up very localized strain concentration over a large field of view which DIC will struggle to measure.

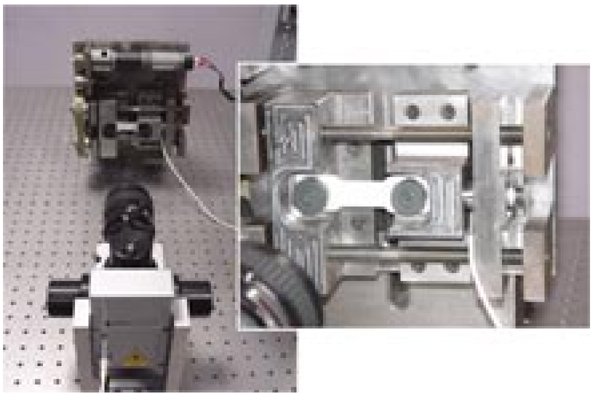


Fig. 4 – Experimental set-up

A commercial system was set up on an optical table to limit the effects of parasitic vibrations. A small table top in-house designed tensile test machine was used to apply the load. The experimental set-up can be found in Fig. 4. The specimen was sprayed with a white powder to make the surface uniformly diffusive.

The load was applied through a number of steps (typically about thirty steps). The three components of the displacement were measured at each step. The measurement time is about 1s for each step. Therefore, the test was stopped at each load step to allow for the measurement. The raw data consists of about 1.3 million data points for each load step. To calculate in-plane strains from these displacement maps, a specific smoothing technique was applied. It consists of fitting a local second order polynomial with a particular weighing function (the procedure is known as diffuse approximation, see [4]).

The longitudinal strain field at the end of the test for the bottom surface is shown in Fig. 5. One can see that there is a very strong localization just outside the nugget, together with bands (right hand side) originating from the nugget. This very complex and highly localized strain field could only be measured with such a high resolution technique. It also clearly shows how essential full-field measurements are to the understanding of such behaviour.

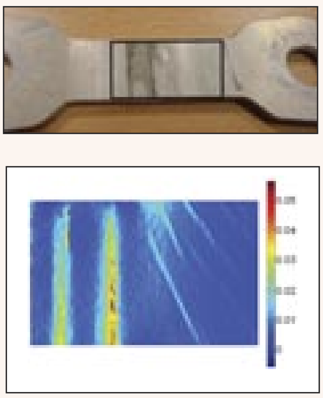


Fig. 5 – Specimen and longitudinal strain field (bottom surface)

The complexity is even worse when considering the fact that the nugget is not homogeneous through the thickness of the specimen, as shown in Fig. 3a. This results in a very awkward out-of-plane deformation pattern as shown in Fig. 6, where the nugget rotates forward along a horizontal axis whereas the base material bends backwards along a vertical axis. This will generate very high through-thickness shear strains.

Finally, Fig. 6 (lower image) shows the longitudinal strain field from the top side where the ripples caused by the shoulder (and easily seen on Fig. 3b) were sandpapered off before the test, leaving a flat surface. The strain localization in circular bands following the original surface pattern is very striking (and the shear bands on the right are also present).

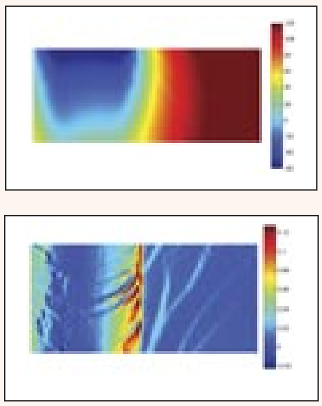


Fig. 6 Out-of-plane displacements (bottom surface) and longitudinal strain field (top surface).

Digital Image Correlation (DIC)

J.D. Lord, National Physical Laboratory, UK.

Stress/strain measurements derived from: Analysis of digital images which results in full-field displacement and strain calculated from the movement of pixel blocks

Advantages
- Full field, non-contact displacement and strain maps
- Range of applications, from nano to large scale
- Low cost and portable
- Simple experimental set-up
- Range of software and systems available

Limitations
- Modest strain resolution compared to laser interferometry
- May require surface preparation (spraying)
- Computationally intensive

Typical applications
- Full field displacement and strain fields
- Crack detection
- Vibration/modal analysis
- Shape measurement (using 3D DIC)
- Validation of FE models

BASIC PRINCIPLES OF OPERATION

Digital Image Correlation (DIC) as a full field non-contact strain measurement technique was first developed in the 1980s [1, 2] but has seen significant development and uptake in recent years due to the availability of higher resolution cameras and increased computer power. It is a versatile tool [3], and is being used extensively in experimental mechanics in a diverse range of applications for characterising material behaviour, the evolution and uniformity of strain, mapping of strain fields around features and defects, crack tip and crack propagation studies, dynamic vibrational analyses, high temperature strain mapping, miniaturised testing, deformation of large structures, structural health monitoring and FE validation.

DIC works by comparing images of a component or testpiece at different stages of deformation and tracking blocks of pixels to measure surface displacement and build up full field 2D and 3D deformation vector fields and hence in-plane strain maps. The position of the centre of the pixel blocks is determined to sub-pixel accuracy over the whole image using sophisticated correlation functions, from which the vector and strain components can be calculated. Different DIC analysis solutions have been developed to obtain sub-pixel resolution based on non-linear optimisation techniques, intensity interpolation, Fourier transform analyses, Newton-Raphson iteration methods, genetic algorithms and neural networks [4]. The typical claimed resolution of 2D DIC is ~0.01 pixel for displacement, although practical factors associated with the experimental set up (quality of lighting, camera noise, lens distortion etc.) may affect the accuracy. The absolute strain resolution depends on the camera resolution (number of pixels), field of view and the scale of the image relative to the pattern on the surface.

The images can be obtained from a wide variety of sources including conventional CCD or consumer digital cameras, high-speed video, microscopes, macroscopes, the SEM and AFM.

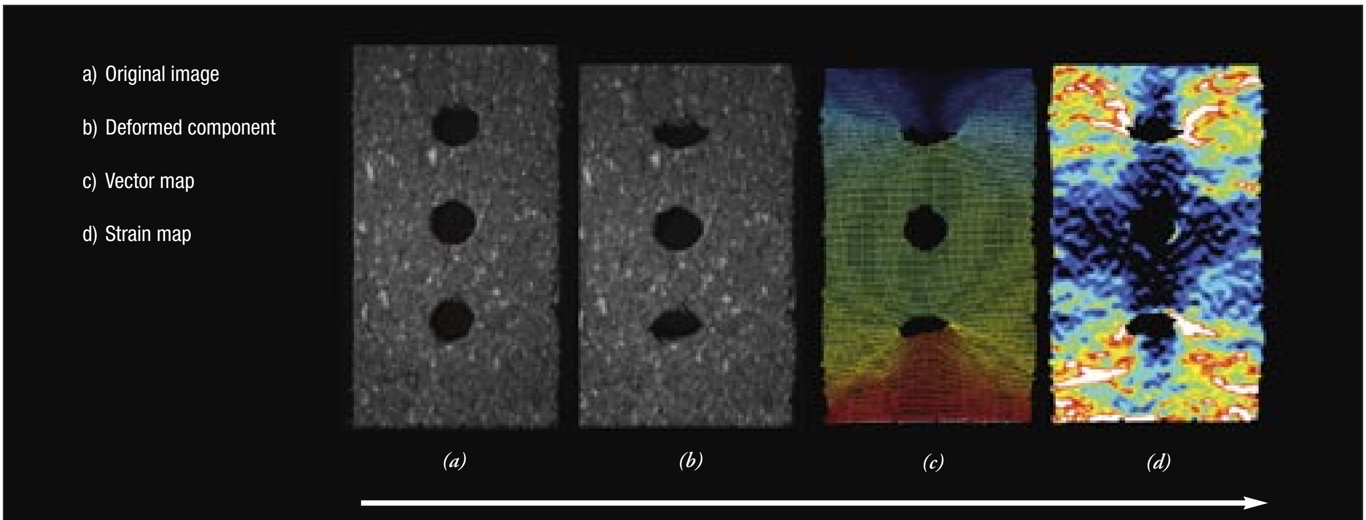


Fig1: The stages involved in a typical digital image correlation analysis

CASE STUDY: USING DIC TO IDENTIFY THE ONSET OF DAMAGE

The following case study shows examples of how DIC has been used to identify the onset of damage and failure through changes in the local strain gradients associated with different defects.

Fig 2 shows damage developed in a concrete reinforced block [5] tested under 3-point bending. Fig 2a shows the component after testing, and Fig 2b the full field vector map. The crack path has been identified by mapping local strain gradients over the whole image, as shown in Fig 2c.

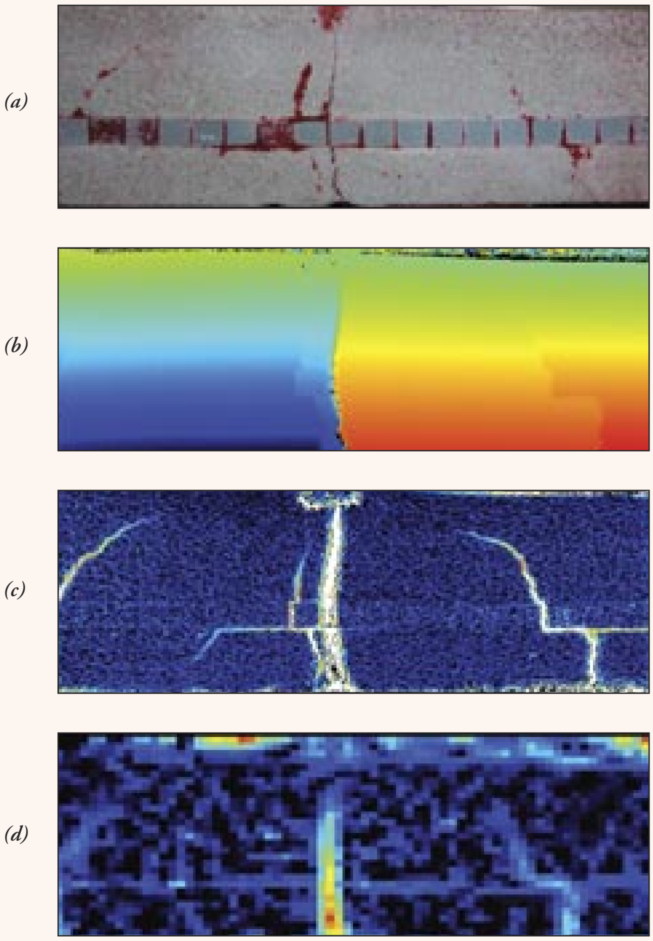


Fig 2 : DIC data showing cracking in a concrete block

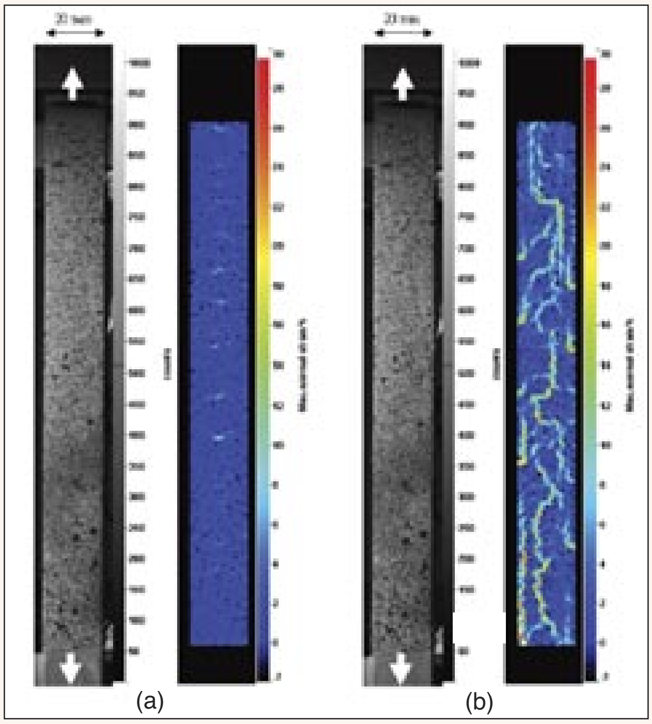


Fig 3: Cracking and delamination in a carbon-fibre reinforced epoxy composite

Figs 2c and 2d show equivalent data taken from two cameras with different resolutions. The data in Fig 2c was generated from 14 Megapixel images; Fig 2d was taken at the lower resolution of 1 Megapixel. The advantage of the higher resolution is clear – not only in the improved definition of the main crack profile, but in the ability to identify other fine hairline cracks which were not readily visible by eye, nor picked up using dye penetrant (Fig 2a).

Fig 3 shows DIC data from a test on the edge of ~20 mm thick quasi-isotropic $(+45°_8/0°_8/-45°_8/90°_8)_s$ tensile test coupon fabricated from carbon-fibre reinforced epoxy composite.

Examination of the normal strain component initially shows the formation and opening of cracks in the central 90° plies (Fig 3a).

As the tensile load is increased ply cracks are observed in the +45°, 90° and -45° plies along with extensive delamination between plies, as shown in Fig 3b.

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Acoustic Emission Testing

K. Holford and R Pullin, School of Engineering, Cardiff University, UK.

Crack detection/location derived from: Detection of stress-waves generated as a crack front propagates

Advantages
- Global and local monitoring
- Extremely sensitive
- Portable
- Location of damage

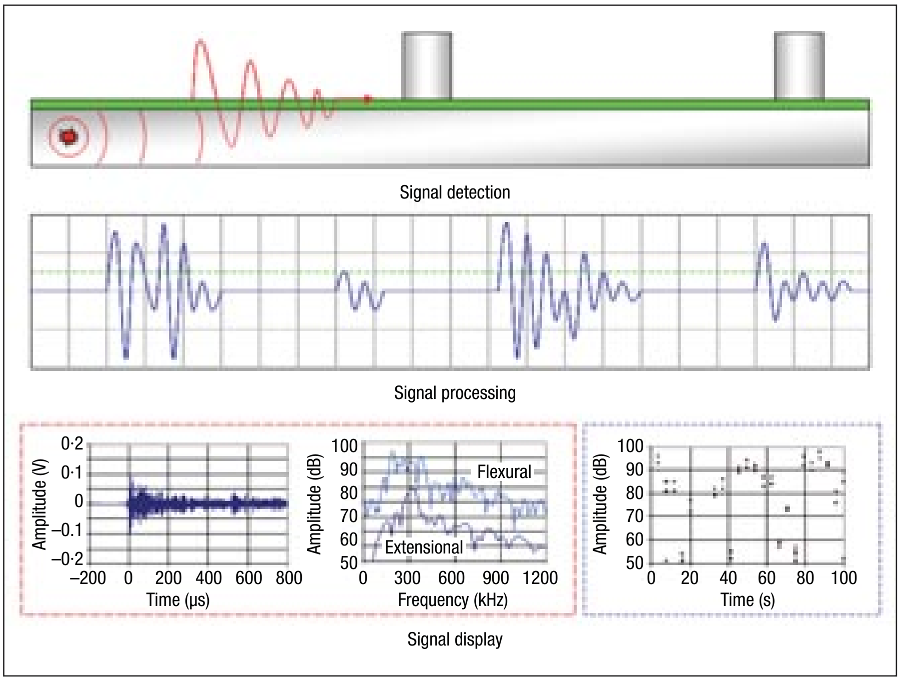
Limitations
- Contact required
- Loading of structure required
- Characterisation of damage is complex
- Only active damage can be detected
- Sizing of cracks difficult

Typical applications
- In general; metallic, concrete and composite materials
- Commercially; Metallic and concrete reinforced bridge structures, aircraft landing gear and aerospace components, pipelines, pressure vessels and storage tanks

BASIC PRINCIPLE OF OPERATION

Acoustic Emission (AE) is the elastic energy that is released by a material when it undergoes deformation or fracture [1]. Most AE sources appear to function as point source emitters that radiate energy in spherical wavefronts. Early AE systems acquired the raw radio frequency (RF) signal through analogue processing, however a rapid advancement in computer technology has lead to systems moving away from the recording of the RF signal towards acquiring smaller data files by pre-processing.

Sources of AE include many different mechanisms of deformation and fracture whilst the detection process remains the same. As a crack grows, a number of emissions are released. When the AE wavefront arrives at the surface of a test specimen, minute movements (ηm) of the surface molecules occur. The function of AE sensors is to detect this mechanical movement and convert it into a useable electric signal.



Assumptions for standard analysis:
- Location techniques assume single wavespeed [2]

The collected waveforms can then be displayed in two ways, either as a function of waveform parameters or as the collected waveform and its associated FFT. Most AE tests currently only record the waveform parameters and ignore the collected waveform, mainly due to the large amount of computing memory it uses.

The automated source location capability of AE is perhaps its most significant attraction as a non-destructive testing (NDT) technique. The predominant method of source location is based on the measurement of time difference between the arrivals of individual AE signals at different sensors in an array.

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CASE STUDY: ACOUSTIC EMISSION TESTING OF A LANDING GEAR COMPONENT

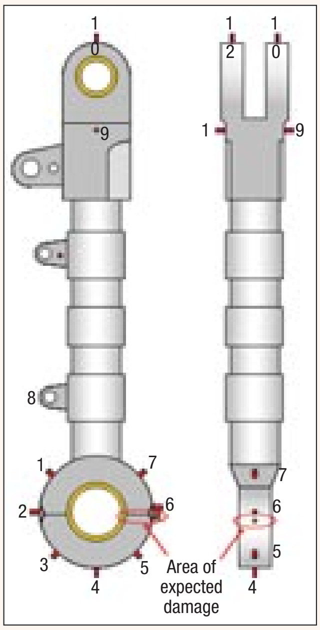


Fig. 1. Test specimen with sensor positions shown.

Messier-Dowty is a world leader in the design and manufacture of aircraft landing gears. Each design requires certifying for flight by the airworthiness authorities. NDT is used to confirm the integrity of the landing gear structure at key stages in the fatigue test regime.

The NDT inspection requires the test to be stopped to allow the structure to be dismantled, this can account for 25% of the total testing time. It is proposed that AE can be used to monitor the landing gear during the certification test in order to reduce the down time caused by NDT inspections.

Fig. 1 shows a drawing of the component indicating the region of expected damage. The component is tested for 500 cycles before the bearings are re-greased and the test re-started. After 2,000 cycles the component was removed for NDT inspection. The AE investigation was implemented after 83,000 cycles had been completed and the test had been in commission for over four years. Several blocks of 2,000 cycles were monitored using AE. This case study presents the findings of the final 2,000 cycles.

The investigation was completed using a PAL MISTRAS system. Twelve resonant sensors were mounted to the component (Fig. 1) and secured in position using aluminium clamps adhered to the component. Grease was used as a couplant.

The history of the detected AE signals is shown in Fig. 2. The plot shows an increase in the rate of detected activity. This suggests the presence of damage within the component. The increase in rate of detected signals occurred at approximately 910 cycles.

Fig. 3 shows the linear location of the detected signals, a photograph of the specimen has been superimposed to indicate the relevant position of the activity compared with the actual position on the link. There is a defined peak of activity of hits in close proximity to the grease pin.

Plots of planar location of signals at 0-500 cycles, 500-1000 cycles 1000-1500 cycles and 1500-2000 cycles showed that prior to the change in the rate of activity there were only small amounts of activity around the grease pin, however after the change in rate of

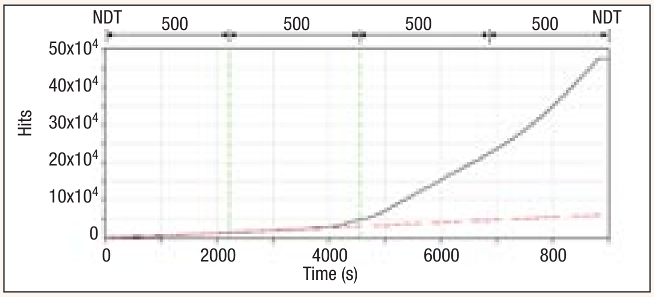


Fig. 2. History of detected signals

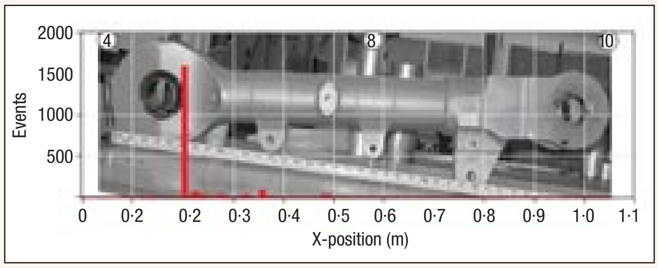


Fig. 3. Linear location of detected signals

detected activity many more sources are detected. This not only shows that there is damage in the component but by examining the rate of change of activity it is possible to identify the onset of damage.

A planar location of all detected signals is presented in Fig. 4. The location plot shows that there is a source of AE in the region where the grease hole meets the bearing.

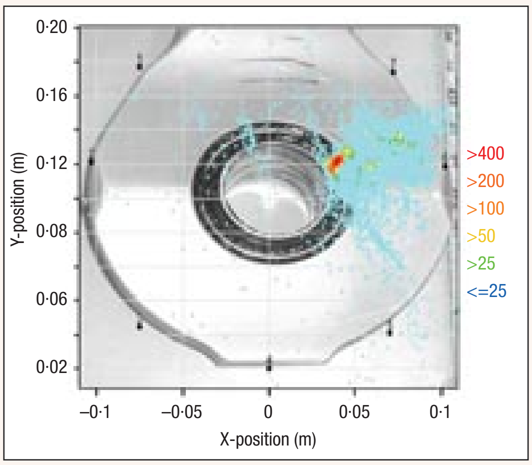


Fig. 4. Planar location of detected signals for 2000 cycles with photograph of specimen superimposed

Fig. 5 shows a photograph of a dye penetrant test taken after the completed AE investigation. The photograph shows that there is damage in the component around the greasing hole and was attributed to fretting of the bearing housing on the component, validating the AE location results. This fretting may have lead to the initiation of a fatigue crack and demonstrates that AE could have been used to monitor the structure from the outset.

Acoustic emission was successfully used to monitor an aluminium landing gear component. An increase in the rate of detected activity indicated damage present within the component. A planar location plot showed the exact location of the damage, which was confirmed by other NDT techniques to be fretting of the bearing housing on the component.

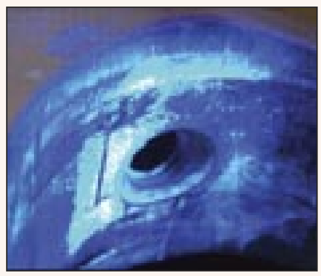


Fig. 5. Dye penetrant test of specimen revealing regions of damage

Thermoelastic Stress Analysis

J. Eaton-Evans, Dept of Engineering Science, University of Oxford, UK; D. Crump and J.M. Dulieu-Barton, School of Engineering Sciences, University of Southampton, UK.

Stress/strain measurements derived from: Small temperature changes on the specimen surface that are related to the thermoelastic effect

Advantages
- Non-contact
- Full-field
- Small scale analysis
- Can be used to examine material phase change behaviour

Limitations
- Cyclic load required
- Linear elastic loading only for standard application
- Difficult to compensate for large motion affects

Typical applications
- Most engineering materials, e.g. metals, polymers
- Composites materials
- Damage detection

BASIC PRINCIPLES OF OPERATION

Thermoelastic Stress Analysis (TSA) [1] is an experimental stress analysis technique that is based on the well-documented thermoelastic effect, e.g. [2, 3]. It uses a highly sensitive infra-red detector to measure small temperature changes (in the order of mK) that can be directly related to changes in the stresses in the component.

A schematic of the typical TSA equipment arrangement is shown in Fig. 1. The test specimen is cyclically loaded within its elastic range to minimise heat transfer in the specimen sufficiently in order to obtain an adiabatic response. This can be achieved for most applications at frequencies <20 Hz, but intensity of the stress gradients and

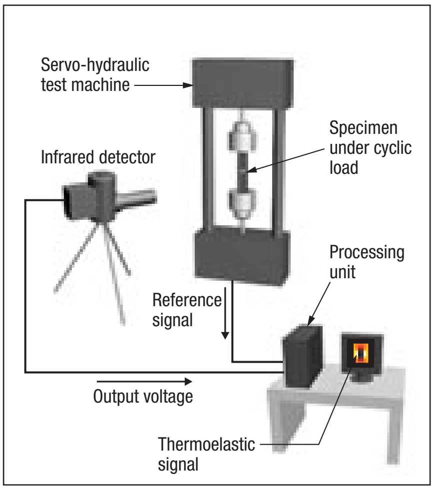


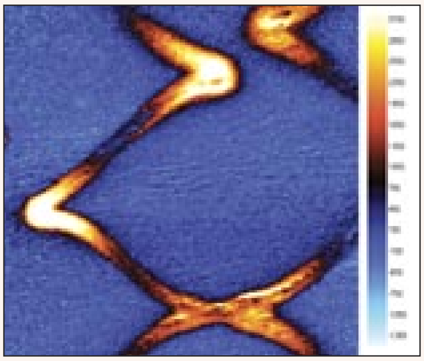
Fig.1 Experimental arrangement for TSA

CASE STUDY: HIGH RESOLUTION ANALYSIS OF MEDICAL DEVICES

Intravascular stents are small medical devices used in the treatment of arterial disease. They are cylindrical in shape and are composed of a fine mesh like structure. Thermoelastic measurements can be obtained from this type of structure using a zoom infra-red lens that increases the spatial resolution of the detector. Current off the shelf technology can achieve a resolution of 85 pixels/mm, where each pixel corresponds to a discrete temperature measurement.

In a study conducted by Eaton-Evans et al. [5], it was shown that thermoelastic measurements could be obtained from the structure of vascular stents. A loading system was designed to apply a cyclic radial load to the device to facilitate an analysis using TSA. The stent was constructed from a NiTi alloy, known for its superelastic and shape memory properties. These capabilities are derived from material phase change that results in a nonlinear mechanical response, which complicates the application of any experimental stress analysis technique, including TSA. It was shown that TSA was suitable for analysis of this type of structure, but strict temperature control is required to control variation in the material properties and a high frequency loading is required to obtain an adiabatic response at this level of resolution.

NiTi stent



High-resolution TSA image of stent struts

conductivity of the test material are important factors.

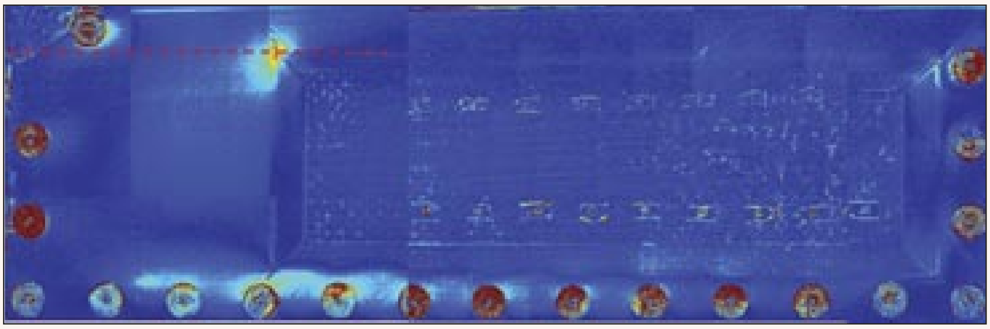
Temperature measurements are obtained from the specimen surface and correlated with the loading using a reference signal from the test machine. The voltage output from the infra-red detector is converted to a digital output and plotted as a full-field map on the computer monitor.

The displayed output is known as thermoelastic signal (*S*) and can be directly related to the change in the sum of the

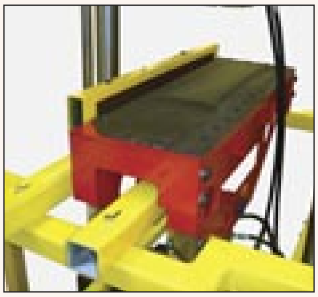
CASE STUDY: FULL-FIELD MEASUREMENT OF COMPOSITE AIRCRAFT PANELS

Composite sandwich structure is increasingly used for aircraft skin panels; the weight saving over traditional aluminium structure is important to improve fuel efficiency. However, the lengthy and complicated manufacturing process for composites is expensive. The use of a lower cost process has been shown to significantly reduce the cost premium [4], but before processes can be adopted into use in the aerospace industry, a lengthy certification process is required.

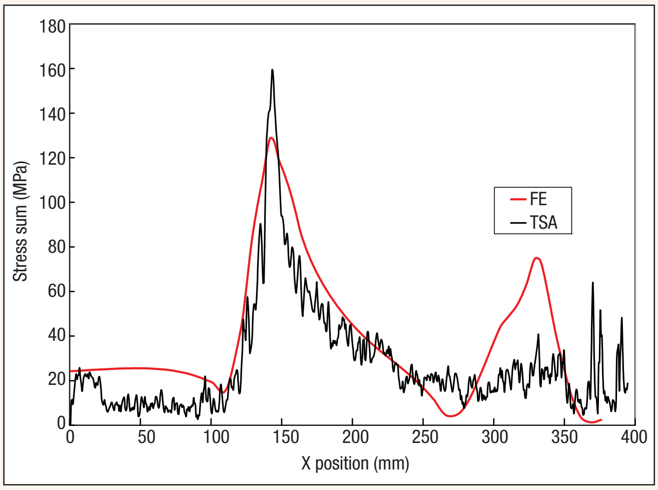
To fully assess the use of a complex material in a complicated loading situation, full-scale testing is used together with full-field TSA imaging of the surface. Panels are tested under a pressure load on a custom designed test rig. Thirty two TSA images are taken to analyse the response of the whole surface of the panel. The data is 'stitched' together and calibrated to give a full-field plot of the stress sum. The stress sum can be compared to processed data from a finite element (FE) model of the panel. The processed full-field TSA and FE data show excellent correlation, both in position and value of the stress concentrations.



Calibrated TSA image of panel under pressure loading



Full-scale pressure test rig



Comparison of TSA to FE model through the stress concentration

principal stresses, $\Delta(\sigma_{11}+\sigma_{22})$, on the specimen surface as follows [2]:

$$\Delta(\sigma_{11}+\sigma_{22}) = AS$$

where A is a calibration factor that can be derived by:

1. Calibration using detector/material properties. The calibration constant, A, is related to the radiometric properties of the detector, system variables and surface emissivity and the thermoelastic constant of the material
2. Calibration against a calculated stress. The thermoelastic signal is related to a known applied stress, produced by a known applied load.
3. Calibration against an independent measure of stress. Typically measured using a strain gauge.

Assumptions for standard analysis:

- Linear elastic loading
- Material is homogenous isotropic
- Adiabatic conditions
- Mechanical properties of material are independent of small changes of temperature
- Constant ambient temperature

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Incremental Centre Hole Drilling

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Stress/strain measurements derived from: Residual stress profiles are generated from the relaxation of strains resulting from drilling a hole in a material containing residual stress

Advantages
- Simple and quick
- Portable, low cost
- Profiles of through thickness residual stress generated
- Applicable to a wide range of materials

Limitations
- Semi-destructive
- Some surface preparation required
- Limited spatial resolution

Typical applications
- Quantifying residual stresses developed during manufacture, material processing, machining, surface treatments, joining and welding

BASIC PRINCIPLES OF OPERATION

The hole drilling method is a well-established and widely accepted technique for measuring residual stress. The basic procedure involves introducing a small hole into the surface of a component, at the centre of a special strain gauge rosette and measuring the relieved strains.

The strain gauge rosette is first bonded to the surface of the component under investigation. A hole is then drilled into the component through the centre of the gauge to a depth approximately equal to half its diameter; the original stress state in the component is then calculated from the relieved strain values.

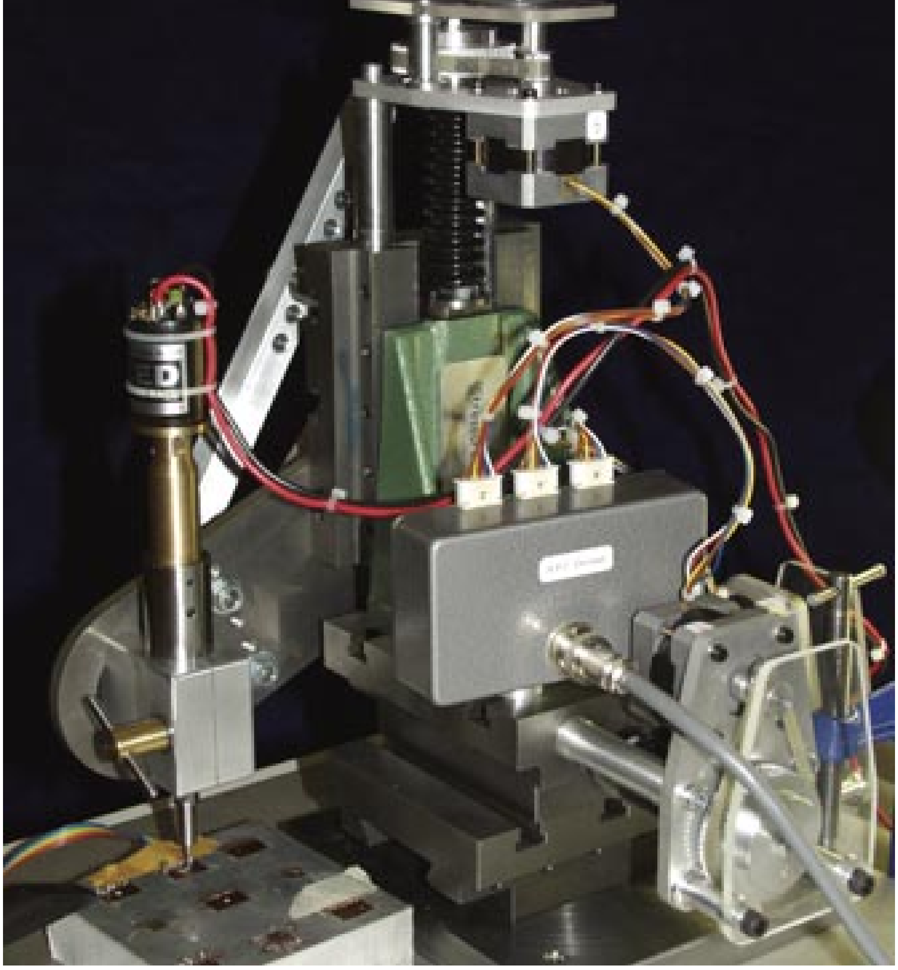
Details of the hole drilling procedures and calculations are described in Refs 1-4. Both the magnitude and directions of principal stresses are calculated. The basic analysis methods are strictly only valid when the residual stress field is uniform and does not vary significantly with depth. Finite element solutions have opened new possibilities for improving the calculation of non-uniform residual stresses from incremental strain data via the Integral Method in which the contributions to the total measured strain relaxation of the stresses at all depths are considered simultaneously, and this is now the preferred analysis method for measuring residual stress profiles irrespective of the original stress distribution present.

Different techniques can be used to produce the hole including conventional drilling, abrasive jet machining and high speed air turbines. Stress profiles can be generated using incremental drilling in a series of small steps (of the order of 10 to 30µm) which can be useful for measuring near surface residual stress profiles and stresses introduced during machining and surface treatment.

Assumptions for standard analysis:

- Linear elastic behaviour
- Generally applicable where the stresses do not exceed 70% of yield
- Drilling process itself does not introduce significant stresses
- Mechanical properties do not vary with depth
- Basic analyses assume uniform stress field
- Integral method can be used for non-uniform stress profiles

Fig1: Typical hole drilling set up



CASE STUDY: RESIDUAL STRESS PROFILES GENERATED DURING MACHINING - AND THE INFLUENCE OF DEPTH INCREMENT SELECTION

This example shows the application of the incremental hole drilling method for measuring the near-surface residual stress profiles developed during machining [6]. Two cases are considered – the high speed machining of an aluminium alloy, and the turning of a superalloy.

Tests were carried out on a series of Al7449-T7651 plates, subjected to standard machining at a cutting speed of 300m/min and high speed wet and dry machining at 3000m/min. Hole drilling measurements were made using depth increments of 4 x 32µm, 4 x 64µm and 8 x 128µm. Fig. 2a shows the stresses measured in the machining direction, which are compressive. Results showed only a small effect due to machining condition, but generally the stresses were greater with increasing speed and dry machining conditions. In all cases the stresses fell to zero at ~200µm below the surface. Fig. 2a also shows the data analysed using the conventional 128µm increments. In this case the maximum compressive sub-surface stresses of ~150MPa observed with the fine increment drilling cannot be resolved.

A similar approach was taken for the superalloy machining study, using increments of 6 x 16 µm, 5 x 32 µm, 6 x 64 µm and, finally, 2 x 128 µm to give a final hole depth of 0.9 mm. In this case (Fig 2b), the residual stress distribution calculated using the fine-increment data shows the presence of tensile circumferential and radial stress maxima within the first drilling increment, and the stresses decaying rapidly away from the surface. The compressive 'bulk' circumferential and radial stresses within the disc (resulting from previous heat treatment) are approximately -300MPa and -100MPa, respectively.

When the relaxed strain data is processed at 'coarse' 128 µm depth increments, the circumferential and radial stresses are calculated to be compressive at all depths, and the tensile near surface stresses are not resolved. This is important and has a significant impact for lifetime stress analyses. Results show how the residual stresses determined using fine increment hole drilling can resolve critical information that might otherwise be lost with larger, 'conventional' increments, particularly when sharp stress gradients are present. Conventional depth increments have the effect of averaging the data at these levels. Applying the fine increment technique in practice requires a meticulous approach to the measurement. High quality strain gauge installation and surface preparation are key factors to obtaining good quality measurements.

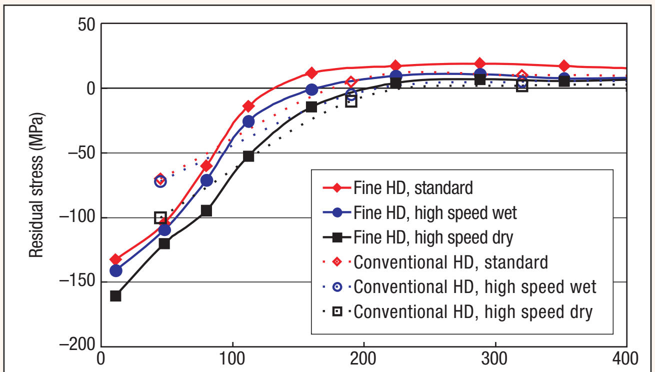


Fig 2a

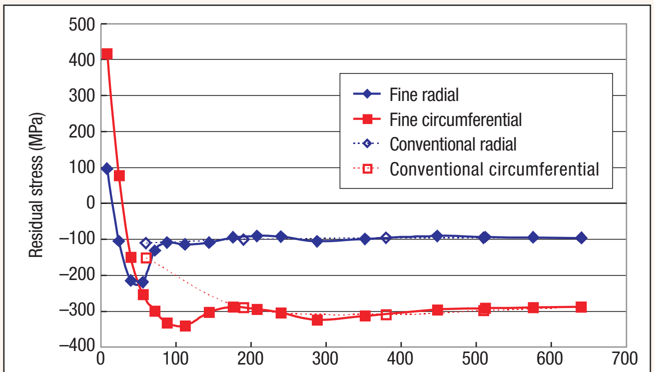


Fig 2b

Fig 2: The variation of residual stresses with depth introduced during the machining process (Fig 2a: high speed machining of aluminium; Fig 2b: turning of a superalloy)

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Diffraction Methods

J. Shackleton, School of Materials, University of Manchester, UK.

Stress/strain measurements derived from: These methods use the crystal structure of the sample as an atomic scale "strain gauge" and are usually applied to residual (locked in) stresses

Advantages
- Suitable for crystalline materials, for example metals and ceramics
- A well-established method
- Usually non-destructive
- Laboratory based methods do not require a stress free calibration standard
- Some laboratory instruments are portable and can be used in the field
- In general, the method is easy to apply

Limitations
- A surface method, limited to a maximum depth of 1 to 1.5 mm, when using laboratory X-ray sources
- Does not work on materials which are not crystalline, for example most polymers and wood
- Assumes the material is isotropic
- Influenced by the size and orientation of the grains

Typical applications
- Principally used to measure residual 'locked-in' stresses in engineering components
- Assessing surface treatments, e.g. shot peened surfaces, machined surfaces etc
- Large scale engineering components:
  – Pipe lines
  – Gears
  – Aircraft components
  – Pressure vessels
  – Railway lines

BASIC PRINCIPLES

Most engineering materials are crystalline; they consist of a regular repeated array of atoms, ions etc. arranged in planes. The separation of these planes, or *d*-spacing, is measured using diffraction methods.

If a crystalline material is subjected to an applied stress or contains a residual stress, these *d*-spacings are changed. Effectively, the crystal lattice is being used as an 'atomic scale strain gauge'. We measure strain by measuring the change in the *d*-spacings.

When radiation of a suitable wavelength is incident on a set of planes in a crystalline material, it is diffracted to an angle (*θ*) according to Bragg's law,

$$2d\sin\theta = \lambda$$

λ is the wavelength of the incident radiation and is known. Consequently, if the change in θ is measured then the change in the *d*-spacing can be calculated.

There are three principal radiation sources,

- Laboratory based X-ray generators: used for surface measurements
- Synchrotron X-ray sources: used to measure to a depth of a few centimetres
- Neutron sources, (nuclear reactors, etc): used to measure to a depth on several tens of centimetres and are suitable for very large engineering components.

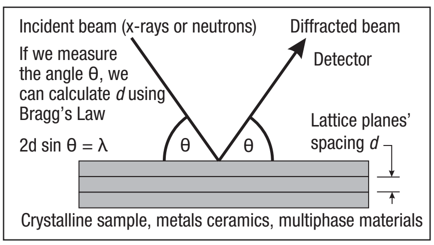

Fig. 2 Portable diffractometer

The most commonly applied method is the $\sin^2\psi$, which does not require a stress free standard. We actually measure strain and convert to stress using Hooke's Law and the appropriate elastic constants for the material.

Assumptions for standard analysis:

- The sample is crystalline
- It's reasonably isotropic, ideally randomly orientated grains which are less than 100 microns

CASE STUDY: MEASUREMENT OF THE RESIDUAL STRESS IN RAILWAY RAIL SECTIONS

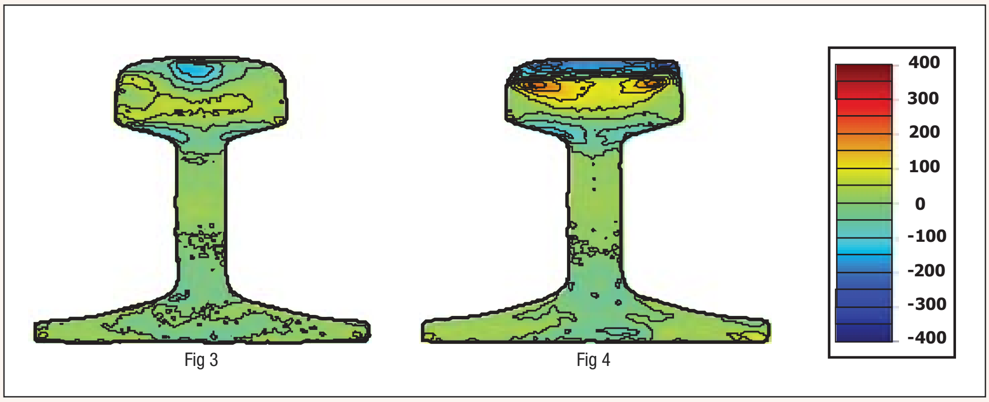

Fig. 3 shows the stress distribution in the transverse cross-section of virgin rail. Fig. 4 shows the stress distribution in the transverse cross-section of a worn rail

Diffraction methods, using both synchrotron and laboratory sources, have been used to map the stresses in cross-sections of a railway rail. Stresses accumulate in service and may lead to cracking. Maintenance operations, such as grinding change the stress state of the rail. In order to predict service life, it's important to determine the residual stress distribution.

New rails contain residual stresses from the manufacturing process. In general, compressive stresses increase service life and tensile stresses are detrimental. In service, there are high loads, small contact patches between wheel and rail, uneven contact patches as well as uneven loading. This leads to a plastically deformed layer, up to 3mm thick, particularly on the gauge side. This plastic layer does give some protection against crack initiation and propagation. However, while the residual stress on the surface is compressive, underneath the residual stress is tensile. Cracks in the tensile region may propagate and lead to failure.

Sections of rail (5 mm thick) were polished mechanically and then electro-polished to remove the damage caused by sectioning and polishing. The removal of this damaged layer is critical when using laboratory X-rays, which only penetrate a few microns into the sample. It is also important to avoid damaging the sample surface. For example, if a surface finish (eg paint) is removed, it should be done chemically and not by mechanical means.

Though the longitudinal stresses are relieved when the rail is sectioned, the vertical and transverse residual stress components can still be measured.

A typical stress distribution is shown in Figs 3 and 4. The measurements were made using synchrotron radiation. However, similar measurements made with laboratory X-ray and with magnetic methods are in close agreement.

Neutrons and synchrotron X-rays are only available at large scale facilities. Laboratory X-ray sources, however, are relatively common. Another very convenient advantage of a laboratory source is that a stress free reference standard is not required. The X-ray beam for the laboratory source does not have sufficient energy to penetrate more than a few microns into the sample surface. If we measure the *d*-spacing of the crystal planes parallel to the surface, we find these are (almost) unstrained and that any errors incurred are very small. However, neutron and synchrotron measurements do require a stress-free standard.

It is possible to apply the method to large components; a typical, portable X-ray diffractometer is shown in Fig. 2.

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Electromagnetic Stress Measurement

B. Dover, Dept. of Mechanical Engineering, University College London, UK.

Stress/strain measurements derived from: Application of a stress to a metal will change the magnetic properties of the metal. Monitoring the magnetic properties of the metal allows prediction of the change in stress

Advantages
- Non-contact
- Manual/robotically deployed
- Retro-fitted
- Measures stress distributions
- Stress monitoring

Limitations
- Ferritic materials only
- 2D stress measurement

Typical applications
- Offshore structures
- Mooring chains
- Pipelines
- Wind turbines
- Pressure vessels
- Bridges, rail

BASIC PRINCIPLE OF OPERATION

The technique is based on the practical use of piezomagnetism, which describes the interaction between stress and magnetic fields. Application of a stress to a metal will change the magnetic properties. Monitoring the magnetic properties allows prediction of the change in stress [1-3]. There is no theoretical solution for predicting the change in properties and, hence, the application of this method relies on calibration for each material.

The technique uses an AC current (5kHz) to examine stresses measured in a thin surface layer: in essence, to provide a 2D stress distribution. Interpretation of shaped electrical fields has made it possible to make measurements of individual components of the stress field.

Electromagnetic techniques respond to material strain and so can be considered analogous to a 'non-contacting strain gauge' – but with important differences. It is not possible to apply strain gauges to a loaded structure and determine the load.

Furthermore, strain gauges cannot be installed through coatings without damaging the coating itself. Magnetic techniques can however be used to measure the response of the steel through coatings up to 5mm in thickness, depending on the probe. While this technique only works with magnetic material, it is possible to bond or insert magnetic material onto a non-magnetic material and obtain meaningful data.

CASE STUDY: BI-AXIAL STRAIN MEASUREMENTS ON A STEEL PIPELINE

Pipeline operators need to monitor the combination of pressure and axial load to ensure safe operation. Often, in remote geologically active regions, operators periodically expose a long section of a pipeline to perform a strain relief operation. These are expensive activities; if a tool can establish the need for such a dig by taking readings on the external surface of the pipe in a bell hole, it would provide significant cost savings. An electromagnetic approach – StressProbe has been used for this purpose.

In order to interpret service data, a biaxial calibration is needed. A calibration of the StressProbe tool under biaxial loading has been performed and comparison of strain gauge data and StressProbe readings have been obtained for a variety of biaxial stress states [4]. The tests were carried out in the axial and hoop directions using a test frame that could apply internal pressure and compressive or tensile axial loads simultaneously.

A series of StressProbe and strain gauge measurements have been made on a buried pipeline during bell hole digs and subsequent excavation for stress relief. The plots not only indicated that axial strain relief was achieved, but also showed an excellent correlation between the two data sets. This case study demonstrates that the StressProbe correctly monitored the changes in strain during an excavation. Other work has shown that the StressProbe can give the pipeline strains in a bell hole, thus avoiding the need for a full excavation.

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Video Extensometry

K. Potter, Dept. of Aerospace Engineering, University of Bristol, UK.

Stress/strain measurements derived from: Images captured from a video camera

Advantages
- Non-contact
- Time and cost savings compared to using strain gauges
- Increased capability over strain gauges and extensometers
- Scale insensitive (by changing the lens)
- UKAS certified
- Quick and easy to set up and use
- Video of entire test can be recorded and re-analysed to make new measurements even if the sample has been destroyed

Limitations
- For single camera systems, the test sample must be planar
- Special approaches are needed to allow for solid body rotations

Typical applications
- Batch testing of material properties (coupon testing)
- Suitable for virtually all materials including composites, metals, plastics, rubbers, biological & food samples
- Testing of very small or delicate samples
- High & low temperature testing
- Testing in difficult or aggressive environments

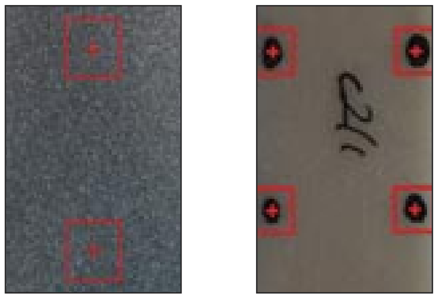
BASIC PRINCIPLES OF OPERATION

Video Extensometers operate by accurately tracking the position of features in video images. When the test sample is strained, the features will move in the image. By measuring those movements, displacements and strains can be extracted.

Early Video Extensometers required precise markings to be applied, whereas the best current technology uses patented pattern matching techniques that do not require specific markings. These modern systems are much more accurate, robust and flexible.

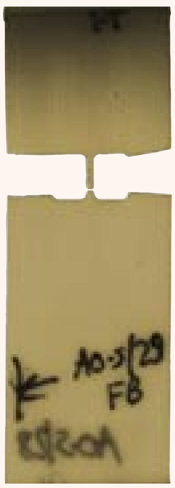
A typical set-up for materials testing would consist of a sample mounted as normal in a test frame. The sample is usually prepared by painting on a speckle pattern using spray paint or applying a set of suitable spots. After mounting the specimen, the video camera is positioned to look squarely at the face of the specimen. The operator then selects a number of target points in the image. As load is applied, the target points will begin to move and the Video Extensometer precisely tracks these movements in order to calculate displacements and strains.

Many target points can be tracked enabling multiple simultaneous displacement and strain measurements. Standard material properties such as Modulus and Poisson's ratio can also be automatically measured.



(a) (b)

Images from the video camera showing (a) a specimen with speckle pattern applied and (b) a specimen with spots. The target points chosen by the operator are shown in red. The two targets chosen in (a) enable longitudinal strain to be measured. The four targets chosen in (b) enable longitudinal and lateral strains and Poisson's ratio to be measured.



CASE STUDY: MEASURING SIZE EFFECTS IN THE STRAIN TO FAILURE OF CAST ADHESIVE SAMPLES

Cast adheshive test sample: The narrow part in the middle is the actual test piece measuring just 0.75mm wide, 0.5mm thick and 3mm gauge length.

Peak strains in adhesive bonds are highly localised. To predict failure in bonded joints the effect of changing the volume of stressed material on the strain at failure must be found. To do this three sample sizes were taken and the failure strain had to be measured for each one.

The smallest samples were far too small for strain gauges or conventional extensometers (0.75mm wide, 3mm gauge length, 0.5mm thick). Strain gauges also influence the results as the gauge is much stiffer than the adhesive. Strain gauges and extensometers also give premature failure due to stress concentrations. Video Extensometry allowed the size effect in strain to failure to be established (and also allowed Poisson's ratio to be measured at each size out to high strain values). Adhesives are strain rate sensitive materials so the measurements had to be performed in real time without stopping the test at any point.

This is a case in which the unique characteristics of Video Extensometry, (scale insensitive, non-contact, real time and multipoint strain measurements) ideally matched the requirements of the task to be undertaken with minimal effort required to achieve excellent results and demonstrate previously unrecognised aspects of material performance.

THE BSSM MEASUREMENT SYSTEM BUYER'S GUIDE

A strain or stress measurement system is often a large and important capital investment. For this to provide a good return, it should be fit for purpose and deliver results in accordance with the expectations you set. To help ensure that such systems meet these requirements, it is suggested that the following guidance will maximise the benefit derived from a new purchase. It should, however, be emphasised that this is not an exhaustive list of guidelines nor a guarantee, so before you buy, you should at least consider the following.

TEST SPECIMENS

Is the measurement system compatible with the component(s) and material(s) under consideration? Namely size, shape (flat or curved, continuous), colour (shiny or matt), temperature (are tests carried out at room temperature?) and can it measure the desired strain range?

SOFTWARE AND DATA ANALYSIS

The requirement for data handling can vary enormously depending on the type of application. You should consider if the system has the right level of flexibility (can you change all the parameters affecting the data processing that you require?) or do you require simple operation avoiding complicated set-up routines, which lead to a poor consistency. Will the data output be in the right form? Can the data be post processed adequately by the system's software? Is this even required, as you may post process data in other ways using generic tools. How do you propose to compare the data obtained from measurements with other data (CAD, simulations, theory or analytical results) and will you need to transform co-ordinate systems, scaling, etc.?

SYSTEM

The performance of the system will usually be the principal concern, Does it have the right attributes for the tests you will perform? Does the system have suitable resolution, accuracy, data capture rate and storage capacity? Can the system be configured and used in all situations and environments envisaged? The main concerns could be portability, compatibility and connectivity with other systems (test machines).

DATA INTEGRITY

Do you have a requirement to show traceability of the data to accepted national or international standards? Do you have any statutory or conformance requirements that are imposed on you to ensure that your analysis and measurements are reliable? Will the system be able to meet these needs?

PRODUCT SUPPORT

Post sale product support and training should be appropriate to your needs and should allow you to use the system effectively within a few weeks of first acquisition assuming you have made some effort to use the system. A minimum of 30 to 40 hours' use will be required to achieve basic competence. Support should be readily and quickly available over the phone, by email or via the supplier's web site. You should also consider local servicing and maintenance arrangements.

If there is to be one golden rule, it is to ask for a demonstration of the equipment in your laboratory, using some of your specimens and test machines. Demonstrations should therefore be relevant and fit for purpose. You should determine what the typical problems are which you are going to tackle and ensure that at the demonstration stage you can perform a measurement with the demonstrated system in your laboratory on your equipment.

To ensure satisfactory function of your system after purchase, you should not use the system for purposes that it was not designed for without checking first with the manufacturer. Ensure that all users are adequately trained prior to using the system. If in doubt, seek help and advice from those more experienced than yourself (manufacturer, fellow users and the BSSM).

Finally, you should always satisfy yourself that you have done everything in your power to acquire all the relevant information relating to your purchase. The BSSM hopes that, as a result of having followed the advice above, you get many years of productive use out of your new measurement equipment.

BSSM COURSES AND PUBLICATIONS

The BSSM organises seminars, exhibitions, conferences and workshops throughout the year. Most events are open to BSSM members and non-members. Rates for BSSM members are significantly discounted

The BSSM also organises a series of training courses and exams for strain gauge personnel. Training courses are aimed at technicians who use strain gauges to make measurements. The courses are also aimed at senior personnel who specify strain gauge installations and are responsible for the analysis of measurement data

For more information, visit:

www.bssm.org/training

The BSSM certification scheme promotes good practice in strain measurement and confirms the competence of a strain gauge user by awarding a formal qualification. The scheme operates at three levels consistent with the European Standard EN473:2005, General Principles for Qualification and Certification of NDT Personnel.

For more information, visit:

www.bssm.org/certification

For a list of all BSSM events, please visit:

www.bssm.org/events

BSSM PUBLICATIONS

The BSSM produces various publications, including the 2009 issue of the BSSM Code of Practice for the installation of Electrical Resistance Strain Gauges. The new handbook, which contains the latest procedures, has been produced following consultations with the most experienced practitioners in the field.

For further information on this and other publications, visit:

www.bssm.org/publications

FURTHER INFORMATION

For more information about the British Society for Strain Measurement:

call 0845 1668 382 from the UK or
+44 1525 712779 from overseas.
info@bssm.org or ***www.bssm.org***

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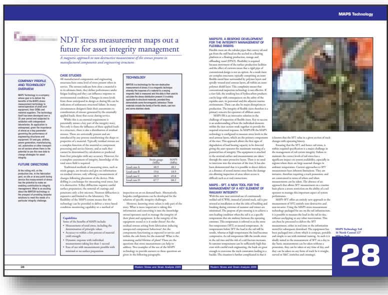

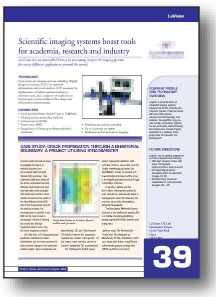

NDT stress measurement maps out a future for asset integrity management

A magnetic approach to non destructive measurement of the stresses present in manufactured components and engineering structures

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

MAPS Technology is a company whose goal is to deliver the benefits of the MAPS stress measurement technology to owner/operators of plant and equipment, their OEMs and material suppliers. The technology itself has been developed over a 20 year period and subjected to validation with independent laboratories. Its application is widespread, given the importance of stress as a key parameter governing the performance of engineering structures and equipment. Oil and gas, utilities, power generation, manufacturing, rail, automotive or other transport are all sectors where there is the potential to use this new data to change strategies for asset integrity.

FUTURE DIRECTIONS

At the rolling mill, on the production line, in the fabrication yard, on site or at any point during service the measurement of stress has the potential to make an enabling contribution to integrity management. What is so exciting about the MAPS® technology is the prospect of providing bespoke solutions to meet the needs of a particular integrity challenge.

CASE STUDIES

All manufactured components and engineering structures have some level of stress present when in service. The stresses indicate how close a material is to its ultimate limit, they define performance under fatigue loading and they can influence response to environmental conditions. Changes in stress levels from those anticipated in design or during life can be indicators of unforeseen structural failure. In many circumstances designers limit their assessments to consideration of stresses generated by the externally applied loads; those that occur during service.

Whilst this is an essential requirement it potentially misses a key part of the integrity story. Not only is there the influence of these applied loads in a structure, there is also a distribution of residual stresses. These are universally present and are introduced by any process transforming the shape or properties of a material. Typically residual stresses are a complex function of the material or component processing and service history, and as such they cannot be determined by calculation or predicted from first principles with any accuracy. However, for a complete assessment of integrity, knowledge of the total stress field is required.

Traditional methods of measuring stress, such as strain gauges, are invasive and give no information on residual stresses, only offering a measurement of changes following placement of the device. Hole drilling is a technique for measuring total stress, but it is destructive. X-Ray diffraction requires careful surface preparation, the removal of coatings and penetrates only a few microns. Neutron diffraction is expensive and limited to the laboratory. The flexibility of the MAPS system means that the technology can be provided to deliver a stress based condition monitoring capability or a method of inspection on an on demand basis. Alternatively, bespoke configurations can be developed for the solution of specific integrity challenges.

However, knowing stress values is only part of the story. What is more important is taking this information and converting it into the knowledge owner/operators need to manage the integrity of their plant and equipment. Is the integrity of the equipment sound or is it under threat? Are the residual stresses arising from fabrication inducing unexpected component behaviour? Are the components functioning as expected in service and within the safe limits for the material? What is the remaining useful lifetime of plant? These are the questions that stress measurement can help to address. Two examples of the use of the MAPS technology to provide answers to these questions are given in the following paragraphs.

Capabilities

Some of the benefits of MAPS include:

- Measurement of total stress, including the determination of principal values
- Accuracy to within a few percent of material yield strength
- Dynamic response with individual measurements taking less than 1 second
- Ease of use with measurements possible with minimal or no surface preparation

TECHNOLOGY

MAPS® is a technology for the non-destructive measurement of stress. It is a magnetic technique whereby the response of a material to a varying magnetic field is measured and this data is then used to calculate the stress distribution present. It is widely applicable to structural materials, provided they demonstrate some ferromagnetic behaviour. These materials include the family of ferritic steels, cast iron and some stainless steels.

	Strain gauge (MPa)	MAPS (MPa)
Load case A	48.9	48.1
Load case B	19.6	18.9
Load case C	48.9	49.8
Load case D	67.7	68.2

MAPS-FR, A BESPOKE DEVELOPMENT FOR THE INTEGRITY MANAGEMENT OF FLEXIBLE RISERS

Flexible risers are the tubular pipes that convey oil and gas from the well head on the sea bed to a floating platform or a floating production, storage and offloading vessel (FPSO). Flexibility is required because movement of the surface production facilities and the effect of currents mean that a rigid pipe of conventional design is not an option. As a result risers are complex structures; typically comprising an inner flexible metal liner surrounded by polymer layers and spirally wound steel armour layers, all within an outer polymer shield layer. This complexity means that conventional inspection technology is not effective. If a riser fails, the resulting loss of hydrocarbon products can be large with consequences on the safety of the topsides asset, its personnel and the adjacent marine environment. There can also be major disruptions to production. The integrity of flexible risers therefore is a primary concern for operators of offshore assets.

MAPS-FR is an innovative solution to the challenge of inspection of flexible risers. Key to success is an understanding of how the individual elements within the riser section work together to provide the required structural response. In MAPS-FR, the MAPS technology is configured to measure stress levels in the steel armour layers, which are the primary components of the riser. This approach allows the first signs of degradation of load bearing capacity to be detected giving the asset operator the maximum warning of a potential loss of integrity. The equipment is attached to the external surface and measurements are taken through the outer protective layers. There is no need to intervene into the structure of the riser. It has also been demonstrated that it is possible to detect defects at a distance of several metres away from the damage site allowing inspection of areas where access is difficult such as at end connections.

MAPS – SFT, A NEW TOOL FOR THE MANAGEMENT OF A KEY ELEMENT OF RAILWAY INTEGRITY

With the now near universal use of continuously welded rail (CWR), instead of jointed track, rail is pre-stressed at installation so that the risks of buckling and breaking during extremes of summer and winter are minimised. The purpose of pre-stressing is to achieve a zero loading condition when the rail is at a specific temperature that sits midway between the operating extremes. This temperature is referred to as the stress free temperature (SFT) or neutral temperature. At temperatures below SFT the load in the rail will be tensile, whereas at high temperatures the load becomes compressive. As rail temperature falls the tensile stress in the rail rises and the risk of a rail fracture increases. In summer temperatures can be sufficiently high that even with careful track engineering, the loads are great enough to overcome the track constraints leading to a buckle. The situation is further complicated in that it is known that the SFT value in a given section of track changes with operating history.

Ensuring that the SFT, and hence rail stress, is within required specification is a major challenge in the management of rail system integrity. Failure to maintain the correct levels of rail stress has a significant impact on system availability, especially in regions where there are large seasonal changes in ambient temperature. Current approaches to SFT measurement have inherent limitations. They are intrusive, therefore requiring a track possession, and are constrained in terms of where and when measurements can be taken. The absence of an approach that allows SFT measurement on a routine basis places a severe restriction on the ability of a rail operator to manage this important aspect of system performance.

MAPS-SFT offers an entirely new approach to the measurement of SFT, entirely non-destructive and non-invasive. Using the MAPS stress measurement technology packaged for use on the rail infrastructure, it is possible to measure the load in the rail in-situ, without unclipping or any other intervention. This can then be processed to deliver the SFT measurement, either in real time or the information stored for subsequent download. The equipment has been packaged into a form which is compact, portable and simple to use with minimal training. As such it is ideally suited to the measurement of SFT on a day to day basis; measurements can be taken without a possession, they can be taken at any time of day, and they can be taken on any form of track be it straight, curved or S&C (switches and crossings).

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Taking the stress out of strain measurement

Dantec's Q-400 strain measurement system uses the optical full field method of digital image correlation

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

Dantec Dynamics is a Danish company providing optical and laser based measurement solutions to fluid and solid mechanics applications. Its strain measurement products have evolved from the former German Ettemeyer company. Complementing these products is a range of laser shearography products – a qualitative method for defect detection or NDT. Dantec provides strain measurement products and services to major industrial customers in the UK Aerospace, Automotive, Wind Energy, Formula 1, Nuclear, Medical and Military sectors as well as supporting university research.

FUTURE DIRECTIONS

With the continuing rapid development of both CCD cameras and computer power, aligned with the ever reducing costs of these electronic products, the potential for growth of Digital Image Correlation capabilities is large. The technique is still in its early years and many applications are still to be discovered. Increases in accuracy, measurement areas as well as portability and ruggedness of systems can be expected.

CASE STUDIES

Digital Image Correlation systems are already widely used to quickly identify the strain distribution on a 3D surface to verify object behaviour for FEA validation or to complement strain gauge applications. These systems can be applied to static and dynamic deformation and strain measurements on all kinds of materials and objects.

To understand the basics of Digital Image Correlation (DIC) a simple application will be described first. One of the most widely used materials tests is a tensile test. DIC can be applied to this to produce full field, 3D results, gaining all required information from one quick test. The basic hardware setup has two high resolution monochromatic CCD cameras, mounted on a rail in a stereoscopic setup. The rail also positions the dedicated illumination source, the HILIS, designed and manufactured by Dantec. Lighting can play a key role in the accuracy of DIC and the HILIS provides a cold and homogenous illumination giving an even intensity distribution while not heating your specimen. Dantec's latest generation software ISTRA4D allows fully integrated setup of the hardware as well as acquisition and evaluation of the data. A similar setup can be seen in Fig 1. To allow the DIC algorithms to work, a stochastic pattern needs to be applied to the specimen. There are many ways to do this; one of the simplest is to use spray paints to create a speckle pattern. A prepared specimen can be seen in Fig 2. This was mounted in a tensile test rig for the measurement.

ISTRA4D features integrated algorithms to quickly focus the cameras and optimise the lighting to make full use of the grey scale available in the pattern. Calibration of the cameras is obviously critical in gaining accurate results. The software needs to know the properties of each camera; ie intrinsic values including aperture and focal length and also the extrinsic values, including the relationships between the two cameras, angle and distance. The Dantec system uses an automatic calibration process where a chessboard-like plate is positioned in front of the cameras and moved through different positions. The plate is automatically tracked in real time and images are acquired by the software instantly, an indicator of calibration quality is constantly shown on screen. This unique calibration process is the basis to allow every value of strain or displacement at a point calculated by the software to have a discrete accuracy. The next stage in the measurement process is to acquire the images. In its simplest form two pairs of images are needed to perform an evaluation, a before and after. In this case the first pair of images taken were the unloaded reference images then 20 loading steps were acquired throughout the test.

Once all images have been captured they have to be evaluated to give the full field strain and displacement data. ISTRA4D's dedicated high accuracy DIC algorithm takes the millions of pixels in the images and forms small facets of pixels, typically 12-17pixels square, but they can be as low as 4 or 5. Each facet is then located in each camera view and then tracked

Capabilities

Full field, 3D measurement of:

- Strain
  - Tangential X, Y & Shear
  - Principal Strain 1&2
- Displacement/deformation

TECHNOLOGY

Dantec's main strain measurement product uses the optical technique of Digital Image Correlation (DIC) to give full field strain and displacement information. This uses a minimum of two cameras in a stereoscopic setup to track small scale movements of a component with a stochastic speckle pattern applied. If the application requires accuracies beyond DIC, Dantec can also offer similar products utilising the Electronic Speckle Pattern Interferometry (ESPI) technique.

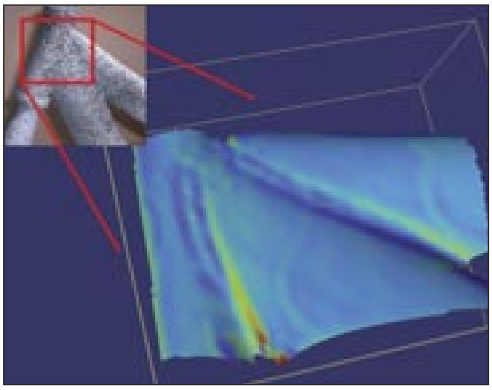
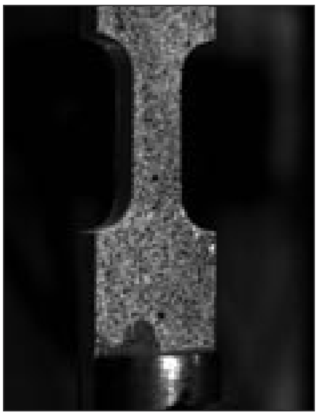


Fig. 4: Strain distribution along the welding seams of a bike frame.

through the loading steps to compute displacement data. As with any full field data, for comparison with other results, the definition of the axis system is critical to the interpretation of results. The ISTRA4D system has the unique ability to define the axis on the measured object surface. The overlay of the surface texture onto the 3D results enables the definition of the axis system, by clicking within the software on the axis origin and the x direction to quickly transform the coordinate system. These markers can also be used to define exact positions for FEA correlation. The full field maximum principal strain of this test is shown in Fig 3. As mentioned earlier, the accuracy of each calculated facet is given as a plus-minus number (or standard deviation), thus effectively giving a full-field accuracy plot for each kind of data. The accuracy of any DIC result is affected by the pattern, camera setup (focus, camera angle, no. of pixels) and lighting. The minimum strain variation detectable by any DIC algorithm is around 100 microstrain or 0.01% local strain. This can be improved by smoothing and averaging data, however strain resolution will be lost in this case. The accuracy of displacement however is determined by the number of pixels and measurement field of view. In this tensile test example, the field of view was about 30 mm and 1.3 Megapixel cameras were used to give a displacement accuracy in the range of 0.2 - 0.3 microns. ISTRA4D can import 2D and 3D images sets from any source and also uses open raw data formats, compatible with software such as MatLab and Excel.



Dantec technology has been successfully applied to many UK industrial sectors as well as playing a key role in university based research. Fig. 4 shows the strain distribution along welding seams of a bike frame. Fig. 5 shows the strain field caused by a wrinkle (manufacturing defect) in a composite section of a wind turbine blade.

Digital image correlation is proven to be a valuable strain measurement tool that provides enhanced measurement capabilities not possible with other techniques, whilst serving as an excellent complementary technique for existing methods.Apart from the applications described here, recent UK applications have included large scale deflection on wind turbine blades and aircraft wings, FEA correlation in the aerospace and Formula 1 industry and materials research in the aerospace and nuclear industry. The flexibility of this technique is leading to an ever widening range of exciting applications.

Written by: Rob Wood, Application Specialist, Dantec Dynamics.

Fig.1 (above): Dantec's complete Q-400 system.
Fig. 2 (left): Typical DIC speckle pattern on tensile test specimen
Fig 3 (below): full field strain results – Principal strain 1

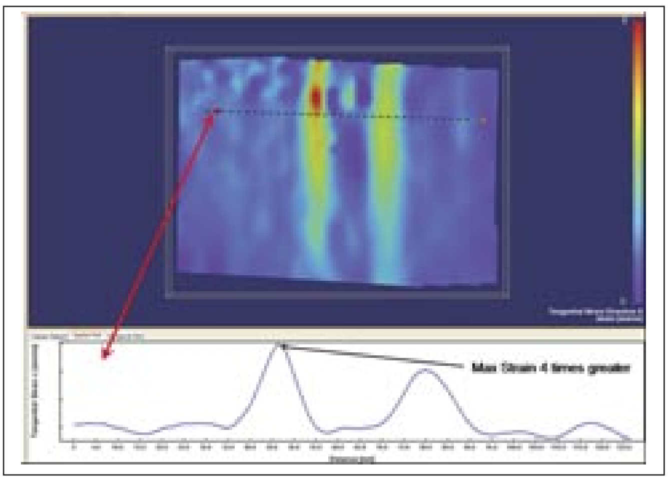
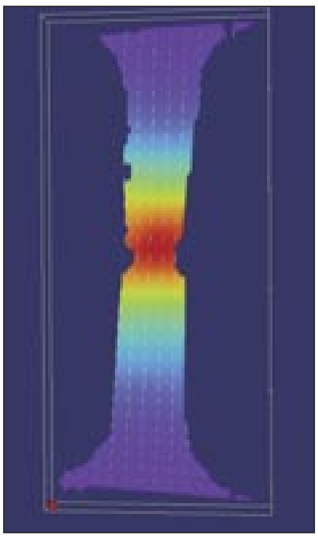


Fig 5: Strain field caused by a wrinkle in a section of a wind turbine blade



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Which strain gauge is better: optical or electrical?

Making the correct choice of strain gauge can be critical and usually depends upon the application

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

HBM is a world market leader in weighing technologies, test and measurement. Its high-quality, innovative products are globally renowned for their precision. HBM's extensive product portfolio includes strain gauges, transducers, precision amplifiers and signal conditioning electronics, data acquisition systems and measurement software.
A number of optical strain gauges (based on the Bragg grating) can be connected via a single glass fibre to a measuring instrument called an interrogator.

HBM has 27 offices in Europe, the Americas and Asia. It is represented in a further 40 countries worldwide and has R&D and production facilities in Darmstadt, Germany; Marlborough, USA and Suzhou in China.

HBM constantly strives to achieve high-quality standards. It was the first company in Germany to be awarded ISO 9001 certification and, in 1996, received ISO14001 certification.
HBM is a wholly-owned subsidiary of Spectris plc.

FUTURE DIRECTIONS

At present, optical strain gauges are only available as linear strain gauges. However, rosettes with three measuring grids are a requirement for classical experimental stress analysis. HBM will continue to develop a rosette using three Bragg gratings to increase the flexibility and range of suitable applications for this technology.

HBM will also seek to develop Bragg gratings for use in force sensors that could benefit applications in potentially explosive atmospheres as this would then be easy to implement.

The increased use of optical strain gauges based on fibre-Bragg technology means that design engineers can become confused about whether they replace or complement traditional electrical strain gauges.

Essentially there are four key questions that need to be considered about optical strain gauges:

- How do the sensors work?
- What are their advantages?
- Where are they best used?
- Are electrical strain gauges obsolete?

Background

There are millions of electrical strain gauges used in experimental stress analysis and in the manufacture of transducers.

Since being invented in 1938, electrical strain gauges have been consistently improved through numerous trials and in various tests.

The electrical strain gauge, also called the metal foil strain gauge, is now a technically mature product. Its specifications, installation, application areas as well as its advantages and disadvantages are established and comprehensively documented.

By contrast, sensors based on the so-called fibre-Bragg gratings are relatively new, although they are increasingly being used in a wider range of applications. This is particularly true when the sensors are developed in the form of optical strain gauges.

A typical strain gauge application is in the manufacture of sensors

Reduced wiring

One major advantage of the technology is that several Bragg gratings can be inscribed in single piece of glass fibre to reduce the overall time and cost of wiring the strain gauges into position. When, for example, 10 Bragg gratings are inscribed into glass fibre, the wiring effort is greatly reduced because every electrical strain gauge that might have been used would have to be individually wired with separate connection cables.

Electrical strain gauges are particularly useful for experimental stress analysis

A secondary benefit of this is that there is a reduced cabling weight when using glass fibre instead of copper connection cables. In some applications the weight of the connection cables may distort any experimental test results.

There are other advantages for design engineers when using Bragg gratings that include:

- Insensitivity to electromagnetic fields because light is used for measurement
- Suitability for use in highly explosive environments because of the very small laser power requirements.

Fitting developments

When Bragg gratings were initially developed, they were installed by applying adhesive to both right and left of the actual Bragg grating.

However, this method requires that the glass fibre is pre-stressed so that both tensile and compressive strain can be measured. Without pre-stressing, the glass fibre will simply bulge when placed under compressive strain because the actual Bragg grating is not guided or installed over the whole surface.

Pre-stressing limits the compressive strain that can be measured to the maximum pre-stressed value.

To overcome these challenges HBM has developed an optical strain gauge that provides an elegant

TECHNOLOGY

Optical strain gauges are based on fibre Bragg gratings that are inscribed into glass fibre and can be used for measuring mechanical strain. Multiple optical strain gauges can be fitted in one glass fibre, several of which are connected to an interrogator to measure the strains.

solution; the Bragg grating is symmetrically embedded in plastic compound. This design enables both tensile and compressive strain to be introduced into the Bragg grating. The dark areas (see figure) at either end of the strain gauge enable tensile strain, up to 10,000 µm/m, to be measured by the Bragg grating without any loss. The lighter area in the centre enables compressive strain to be measured without pre-stressing the fibre.

A substantially larger measurement range – both of tensile and compressive strain – can be measured compared with a pre-stressed glass strain gauge.

This can be clarified by a simple example. If, for example, the maximum elongation – or measuring range – of a glass fibre Bragg grating is ±10,000 µm/m, then the glass fibre would need pre-stressing of some 5,000 µm/m to enable the measurement of compressive stresses.

This would limit the measurement range to only ±5,000 µm/m because a tensile strain of 10,000 µm/m would reach the measurement range's limit at 5,000 µm/m. Hence, using pre-stressed systems, half the measurement range is effectively wasted.

Since HBM's latest optical strain gauge is not pre-stressed to enable measurement of compressive stresses, then, using the same example, the full measurement range of ±10,000 µm/m would be available. HBM has applied for a patent for this solution.

HBM tests its optical strain gauge to meet VDI/VDE2635 – the standard for testing the relevant characteristics of electrical strain gauges – because there is no agreed standard of optical strain gauge characteristics. HBM's optical strain gauge is installed using the same method and materials as an electrical strain gauge. This includes adhesives and any covering agents required for protecting the measuring points.

More advantages

Optical strain gauges display substantially higher stability against alternating loads than electrical metal foil strain gauges. With a defined strain of ±3,000 µm/m over 107 load cycles can be attained giving a maximum zero offset on completion of less than 60 µm/m. To attain 107 load cycles using electrical strain gauges would, by comparison, limit the defined strain to about 1,000 µm/m.

However, comprehensive tests have shown that strain gauge adhesives presently available are the limiting factor rather than the characteristics of the optical strain gauge. Adhesive limitations also affect the maximum elongation; at present it is specified at nearly ±10,000 µm/m.

This substantially higher stability against alternating loads makes optical strain gauges the best choice for new materials that are under development such as fibre-reinforced plastics. In many cases, the introduced strain is higher with fibre-reinforced plastics than with conventional, metal structures.

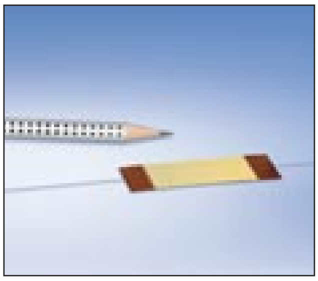
Fibre Bragg gratings are affected by temperature variations. Any temperature-dependent output signal is relatively high because of the so-called temperature coefficient of the index of refraction. The output signal comprises the actual temperature coefficient of the index of refraction (about 8 µm/m/K) and the free temperature dilatation of the component under test.

This temperature effect can be compensated for either through calculation or by using a compensating circuit comprising two optical strain gauges. One of these is installed on the component under test and the other one on identical material that is not subject to mechanical stress, but is affected by identical temperature variations.

Usually the compensating strain gauge is installed as close to the measuring strain gauge as possible and corresponds to the classic quarter bridge circuit with a compensating strain gauge used with electrical strain gauges.

With its latest generation of optical strain gauges, HBM provides users with an easy-to-use product that will not replace electrical strain gauges but will be better suited to new application fields.

Author: Dirk Eberlein is HBM's Product Manager for strain gauges and experimental stress analysis.



Top: A number of optical strain gauges (based on the Bragg grating) can be connected via a single glass fibre to a measuring instrument called an interrogator.
Above: HBM's optical strain gauges are about 30 mm long.

CAPABILITIES

- Insensitivity to electromagnetic fields because light is used for measurement
- Suitability for use in highly explosive environments because of the very small laser power requirements.
- Reduced wiring requirements compared to electrical metal foil strain gauges because several Bragg gratings can be inscribed in one fibre
- Reduced weight when using one glass fibre instead of several copper connection cables with metal foil strain gauges
- Optical strain gauges have a substantially higher stability against alternating load than electrical metal foil strain gauges
- No new installation routines: optical strain gauges are installed using the same method and materials as metal foil strain gauges.

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Improved determination of yield stress for sheet metal

Using GOM's digital image correlation technology to characterise plastic behaviour in detail

MEASUREMENT SYSTEM: ARAMIS

Long before the production of components and vehicles, simulation models are used to optimise the process. Only after variant types have been calculated and characteristics compared will prototypes be produced.
In order to achieve a good simulation, the materials need to be understood. Faulty data will most likely lead to poor performance of product – either wrong form or worse still material worked beyond its capability leading to thinning or cracks. Therefore the material characteristics of the sheet metal material to be used have to be determined precisely and reproducibly in a test laboratory.
An important determination is the yield stress which indicates the point at which a material passes from the elastic state to the stage of plasticity and deforms permanently.

FUTURE DIRECTIONS

GOM realises that there are multiple industrial sectors and applications where the use of optical technology will contribute greatly, and push heavy resource into developing improved mathematics and hardware integration. GOM has developed a live 3D displacement and optical strain gauge. Keen areas of interest are those where its products combine to achieve hitherto not practicable results. Higher speed hardware, process calculation and a simplified work flows are a permanent aspiration.

It is important that simulation models use good quality data. Accurate simulation requires accurate material characterisation. The use of erroneous data during the design phase of sheet metal products can lead to the poor performance of a product – either it being the wrong shape or, worse still, material failing where over-worked. Therefore, reliable material data that characterises accurately the yielding behaviour of the sheet metal is required

DETERMINING THE YIELD STRESS

The tensile test specified in DIN EN 10002-1 specifies particular specimen geometries and test parameters. During the test active force, strain and cross section are measured continuously. The strain is integrated via the measuring length of the strain gauge.

As the load increases, local necking of the specimen is initiated. From this stage, conventional tactile gauges cannot accurately be used when considering the cross-section since the longitudinal change is averaged over the entire measurement length.

Using ARAMIS, however, which is a full-field measurement device capable of collecting the local deformations in both surface directions, it is possible to determine the complete distribution of deformation. The necking area can be investigated in more detail and local changes in the cross-section of this area can be measured.

Fig. 1 shows the global strain characteristic determined by a tactile strain gauge as a function of time. This is compared to the measurement from ARAMIS in the necking area.

It is clear that although the deformations are small, the values generally correlate well, just prior to failure there is a large deviation. This effect is related to the fact that the tactile gauge integrates the strain over its entire length and is unable provide peak values. Once local necking starts, the deformation is concentrated in that area whilst elsewhere on the sample there is minimal deformation.

The optical system ARAMIS is capable of achieving high accuracy measurement data over a short measurement length. Fig. 2 shows the ARAMIS positioned in front of a tensile test machine.

MEASUREMENTS IN THREE DIMENSIONS

The system also provides the capability to evaluate the complete deformation behaviour of the specimen by using stereo cameras. Multiple camera arrays can also be used simultaneously to evaluate more complex components, with these data from each source reported as a single project.

Fig.3 shows a schematic of an experimental arrangement used to determine the biaxial yield stress by means of the hydraulic bulge test. A thin sheet metal board is clamped between blank holder and stamp and pressurised oil is used to load the plate to failure. Due to the biaxial state of stress, failure occurs considerably later than during a tensile test, and so considerably higher forming degrees can be used.

The ARAMIS 3D system combined with a conventional sheet metal test machine is an ideal

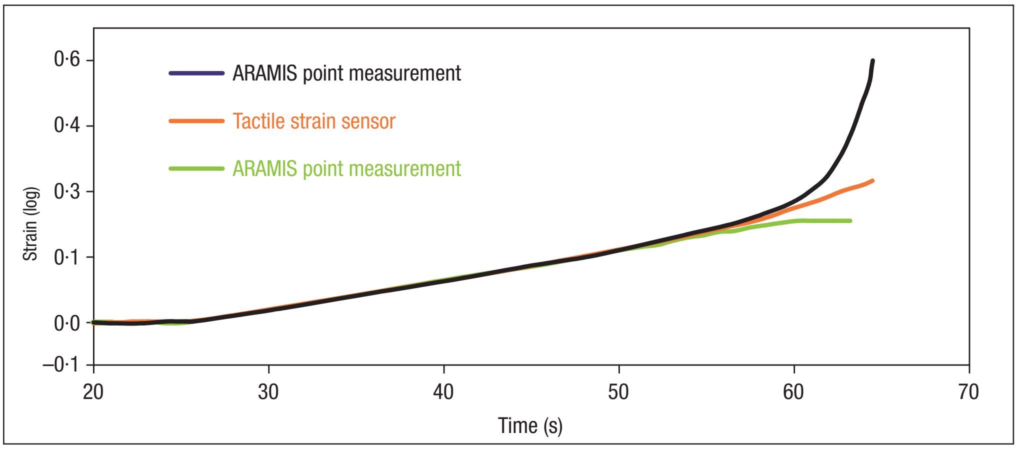

Figure 1. Shows the global strain characteristic determined by a tactile strain gauge as a function of time. This is compared to the measurement from ARAMIS in the necking area.

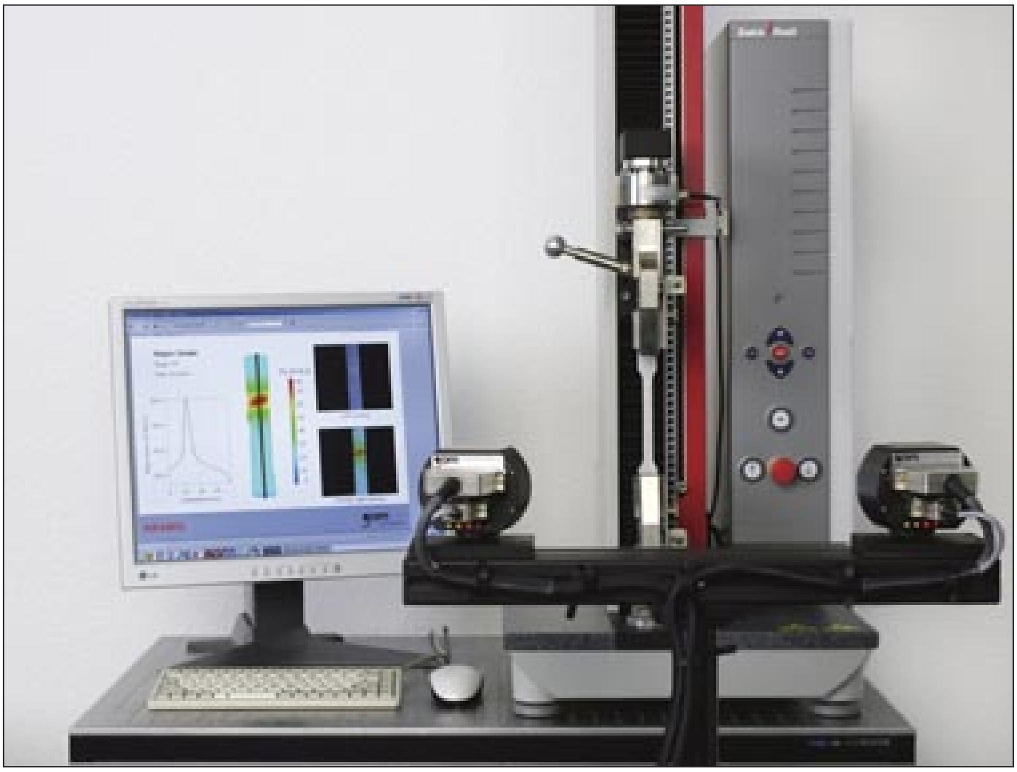

Figure 2. Shows the ARAMIS positioned in front of a tensile test machine.

method to improve the determination of yield stress for simulation calculations.

DETERMINATION OF DEFORMATION

ARAMIS uses black /white image detection and triangulation principles to compute strains in three dimensions. In the bulge test, the effective material load (yield stress) is determined by the current shape of the specimen, the equivalent strain at the top of the dome and the current oil pressure.

The ARAMIS reporting software allows movies and multi image reports to be generated to graphically document the deformation process.

In addition to the determination of biaxial flow curves, ARAMIS can easily be used for determining Forming Limit Curves using the same experimental arrangement. However, in this case a mechanical stamp, rather than using oil pressure, is used to load the specimen.

In both applications, ARAMIS allows high-resolution, easy and precise recording and evaluation of deformation tests. The measurement data is displayed graphically and converted to current material characteristics. In addition, local effects are captured and represented thus allowing for a complete understanding of the local material behaviour during the forming process.

These characteristics can be used to precisely calculate the material behaviour during the forming process, so that optimum tool designs can be generated with the simulation. In addition, the newly determined characteristic values allow a precise forecast of the crash behaviour of the formed sheet metal structures.

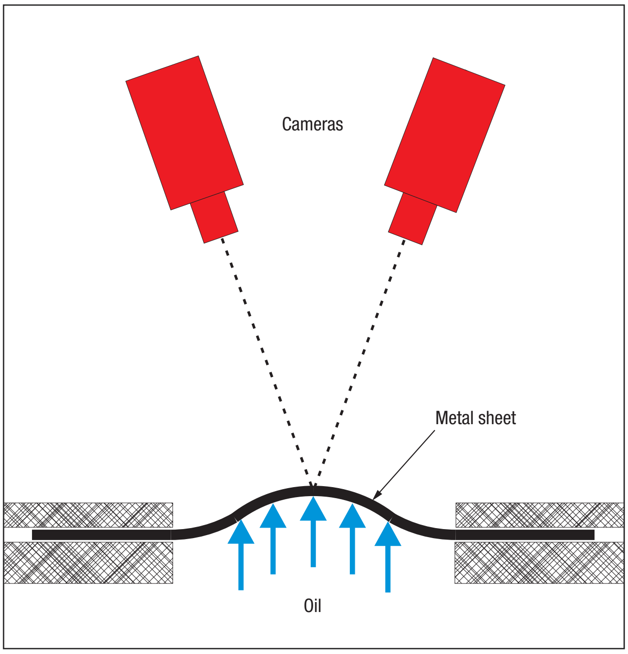

Fig 3. The ARAMIS system combined with a conventional sheet metal test machine is an excellent method to improve the determination of yield stress for simulation calculations.

By courtesy of Alcan Technology & Management Center, Neuhausen, Switzerland, Novelis Technology AG , Neuhausen, Switzerland and Hydro Aluminium Deutschland GmbH, Bonn, Germany

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Strainstall
The world of load measurement and stress analysis

CrackFirst™ fatigue sensor for welded joints

Designed for steel structures to provide advanced warning of the rate at which the design life is being consumed

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

Strainstall UK Ltd has over 40 years experience in the field of stress analysis and structural monitoring, and are specialists in both short and long term monitoring of complete structures such as bridges, plant and building, as well as structural monitoring of components of large marine vessels, road and rail vehicles and aero structures. The services provided in the field of experimental stress analysis cover a wide range of potential clients, and include static and dynamic testing using strain gauges and other sensors, investigations into the residual stress states of structures and components, as well as fatigue life estimates.

FUTURE DIRECTIONS

In order to reduce any access tests associated with collecting data, a wireless transmitter network is being developed for launch in 2009.

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TECHNOLOGY

CrackFirst™ Sensor

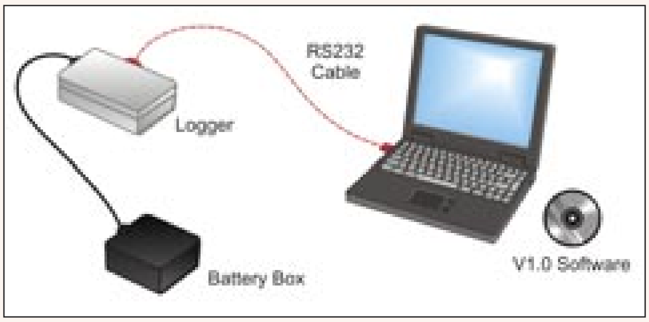
A fatigue sensor for welded joints in steel structures, capable of providing advanced warning of the rate at which the design life is being consumed. Unlike a typical strain gauge which monitors the amount of strain at the point where it is attached to the structure, CrackFirst™ senses the actual amount of fatigue damage a structure has suffered. The CrackFirst sensor consists of a steel shim 0.25mm thick which is attached to the target structure close to a critical joint.

Under the action of cyclic stress in the structure a fatigue pre-crack at the centre of the shim, introduced during manufacture, extends by fatigue crack growth.

CAPABILITIES

- Provides an accurate record of cumulative damage
- Indicates the portion of design life consumed
- Provides design and development engineers with valuable information
- Improves maintenance scheduling
- Optimises operational efficiency

CASE STUDY: A FATIGUE MONITORING SYSTEM FOR A REFURBISHED MULTI-PURPOSE CARGO VESSEL



Unlike a typical strain gauge which monitors the amount of strain at the point where it is attached to the structure, CrackFirst™ senses the actual amount of fatigue damage a structure has suffered. The sensor design is such that the extent of crack growth in the shim is related to the cumulative fatigue damage for a welded joint subject to the same loading.

Originally developed by The Welding Institute (TWI), the sensor has been designed for use on most common steel structures which see cyclic loading, such as ships, earth moving machines, bridges and cranes. As the sensor provides information on the rate at which the fatigue design life is being expended, it can be used to set inspection levels according to usage rather than elapsed time. The physical change of condition of the sensor is permanent and irreversible, so sensors remain serviceable for many years. It is also not necessary to install sensors on a structure from new, as installation part-way through life is feasible, provided the prior service is taken into account. It is of most benefit for structures in which fatigue is the primary limit state, especially in situations where inspection and repair are difficult or impossible, or where structural failure would have significant consequences with respect to safety and/or financial loss.

A CrackFirst™ sensor system was recently installed onto a general cargo vessel operated by the international transport department of British Nuclear Group Sellafield Ltd. Originally built as a vehicle carrier, the ship was extensively refurbished in 2001 and is now used to transport used research reactor fuel and MOX fuel as well as being chartered to transport non-nuclear materials.

Strainstall were commissioned by James Fisher & Sons plc (shipping agents to BNFL) to install four CrackFirst™ sensors with enclosures onto the vessel. They were required as part of the re-fitting of the vessel so that the chief engineer could set up regular checking of the sensors and record the sensor display on the indicator provided as part of the fatigue monitoring system.

Each sensor is interrogated using an on-board electronics unit that regularly checks the sensor status and records in memory the date/time of each crack increment. Data is then downloaded to a laptop PC, and the information used by engineers to confirm that the fatigue levels are within predefined levels and that the vessel is still fit for purpose.

Finite elements or strain gauges or both? – It's a question of confidence

Strain gauging and FEA are both powerful technologies; however, in practice, the two methods are most powerful when combined

AV Technology Ltd has long recognised the increased power of combining practical strain gauge work with theoretical Finite Element Analysis (FEA). Whilst FEA models can produce important predictions of stress, displacement and frequency, often actual in-service loading conditions are unknown and so results can be unreliable unless validated using actual in-service data.

Conversely, whilst strain gauge data can yield vital accurate information about stress amplitudes and fatigue, they are normally limited to measurements at a few positions and therefore do not give a complete 3D picture of the modal behaviour of a structure.

Once an FEA model has been validated in this way, it gives greater confidence in any subsequent 'what-if' analysis during design optimisation. Often the hand-in-hand relationship between FEA and practical strain measurement is more entwined than this: often it is necessary to use an FEA approximation to decide the best locations for the strain gauges.

CASE STUDY

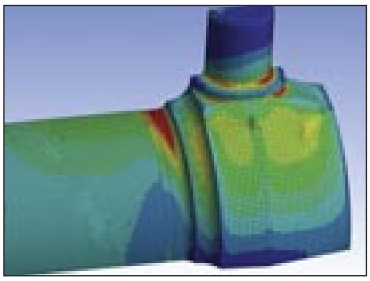
Many of AVT's customers are benefiting from the combined capability of 'Measurements and Predictions'. Edbro, a leading manufacturer of hydraulic truck tipping hoists and waste management equipment, is one such company. With more than 90 years' experience, Edbro has developed a range of products offering high levels of safety and efficiency to customers worldwide.

Tipping cylinders operate in challenging and often harsh environments, where long term reliability is paramount. Therefore changing design parameters is not something to be undertaken lightly. When Edbro decided to design a new hydraulic cylinder base tube, aimed at reducing manufacturing costs and weight, it needed to optimise the design to ensure structural integrity was maintained. Although much of the new design was based on proven technology and experience, Edbro opted for the powerful twin approach of strain gauge measurements and FEA predictions, utilising out-sourced expertise from AVT.

The Edbro project started with AVT establishing a model of the existing cylinder using ANSYS Workbench software. This highlighted 'hot spots', where predicted peak stress levels would occur. Using this data, under the guidance of AVT, Edbro engineers placed a series of strain gauges on the cylinder to check the predictions on the existing cylinder design during pressure and load testing. Data from the strain gauges were also analysed by AVT using specialist fatigue analysis software to determine the fatigue life and provide a bench mark for the new design.

The process of comparing measured stresses with theoretical went through a number of iterations and involved changes to the FEA model constraints to improve agreement with 'real life behaviour'.

Once the basic format was established, AVT progressed to changing the model to incorporate the new cylinder criteria. Based on information from Edbro, theoretical side loads, end loads and internal pressure loading were applied to the model, individually and in combination, to evaluate worst-case operational scenarios and the critical features of the design.



Edbro is developing a new hydraulic cylinder base tube in association with AV Technology.

Working closely with Edbro, AVT carried out several design iterations of the new cylinder to minimise weight and aid manufacture, whilst ensuring stress levels prevailing in the existing proven design were not exceeded. After several iterations, an acceptable design was achieved and Edbro has moved to manufacture a prototype cylinder assembly for final strain gauge validation. (Having validated this first FE model, Edbro is extending its product development to include other cylinders using in house FE and solid modelling tools, referring back to AVT when necessary.)

AVT EXPERTISE PROVIDES REAL VALUE

Given the specialised nature of measurement work and because such projects are not everyday requirements, many companies simply do not have the necessary in-house expertise for on-site measurements. Therefore it is all too easy to over-rely on un-validated FEA results, which although they may look attractive and professional are, in practice, totally meaningless. This is the area where specialist companies such as AVT can provide real value, not only through their extensive experience in the design, selection and application of strain gauges and other sensors for measuring the behaviour of all types of structures and machines under 'real-life' operational conditions, but also in the integration of combined strain measurement and FEA technologies.

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

AV Technology is a leading industrial consultancy established in 1976. Core competences include: structural monitoring, strain gauging, noise and vibration, condition based monitoring, lubrication management, remote visual inspection, thermography, facilities management. AVT also provides a range of specialist sensors and instrumentation for measuring acoustic emission and vibration. Services are supplied across a wide range of industries including civil engineering, iron and steel, chemical, nuclear, petro-chemical, offshore oil and gas, pharmaceutical, food and beverage, utilities and power generation, automotive and aviation. Major customers include: British Energy, AMEC, Royal Dutch Shell, Diageo, Cadburys, JCB, Basell, Doosan Babcock, Bomel, Rio Tinto and Corus.

FUTURE DIRECTIONS

As for the past few decades, the fundamental practice of installing strain gauges is unlikely to change significantly in the foreseeable future. The best practice techniques proposed by the BSSM have proven to be extremely rigorous and will endure for decades to come. The main advances will come in the form of signal conditioning and data acquisition in particular wireless technology.

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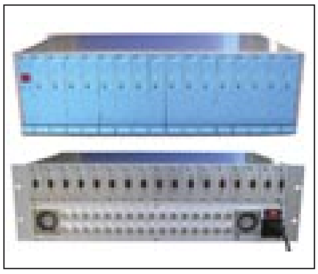
Balanced constant currents take the strain

A strain gauge technology for dynamic measurement has high sensitivity and requires no balancing



COMPANY PROFILE AND TECHNOLOGY

Fylde Electronic Laboratories Ltd has specialised in the design and manufacture of analogue instrumentation since 1964. Our signal conditioning products concentrate on the link between the transducer and the data acquisition system. We have innovative solutions for conditioning most types of transducer, and work with engineers of all disciplines who demand the best at a realistic price. We offer standard, configured standard and specially designed products to ISO9001 quality standard. Our instruments are used by aerospace for flight applications and in ground based testing, in gas turbine testing and monitoring, in automotive testing and development and find applications in many universities and development agencies.

FUTURE DIRECTIONS

The constant current Dynamic Strain Gauge technique has potential in gas turbine blade strain gauging, where the system cable tolerance brings great advantages.

It is possible to use, for example, Mineral Insulated cables whose resistance may be many tens of ohms whilst still maintaining accuracy in the measurement, even in the presence of high temperature effects on the characteristics of the cable. Flight versions of the equipment are in development and, in this instance, the amplifiers are miniaturised, ruggedised and powered from (aircraft) 28VDC supplies.

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TECHNOLOGY

Single and multi-channel Dynamic Strain Gauge systems using precisely balanced and metered constant current sources enable a single gauge to deliver twice the signal of a conventional Wheatstone Bridge at the same gauge power and strain level. Low noise signal processing with programmable band pass filtering.

CAPABILITIES

- Strain measurements from <1Hz to >150kHz.
- Requires no balancing.
- Requires no completion.
- Delivers higher signals for a given gauge power (x2 typ.)
- Simple cabling two wires per channel.
- High temperature gauge and cable applications with no loss of calibration.

CASE STUDY: DYNAMIC STRAIN GAUGE MEASUREMENT HELPS MONITOR VIBRATION IN GAS COMPRESSOR PLANTS

Advantica is using the FE527SGA, the 2u 'blue panel' presentation of the system, in vibration monitoring of onshore and offshore gas compressor plant.

With gauges installed in hazardous areas, the use of the constant current Dynamic Strain Gauge equipment yields advantages over other methods in being easy to connect and calibrate, whilst being economic in the use of zener barrier protection devices. Because monitoring may be of many months' duration, the high stability inherent in the technique over time and temperature is vital.

The system has proved to be robust and reliable, with no major shortcomings evident. Strain gauge failure due to damage or degradation, if it occurs during the monitoring period, is detectable by changes in the strain gauge signal characteristics, and also directly indicated by the equipment itself.

Advantica has commented 'the constant current strain gauge instrumentation offers high accuracy with good noise performance, and is simple to set up as there is no bridge type circuit for each channel'.

In this application, the gauges are energized at 10mA and the use of precise constant current means that irrespective of the cable length or barrier resistance, the exact voltage across the gauge depends only on the resistance of the gauge itself. Unlike normal DC constant current systems, the dynamic constant current compliance voltage has a very fast response to delta R of the gauge. The signal is picked off by a balanced differential AC coupled amplifier with very high common mode rejection, giving great immunity to interference and noise, even though the data acquisition is up to 300m distant from the gauges.

(Fylde would like to thank Advantica Ltd for their assistance with this article, and for permission to feature plant photographs).

Scientific imaging systems boast tools for academia, research and industry

LaVision has an unrivalled history in providing integrated imaging systems for many different applications around the world

TECHNOLOGY

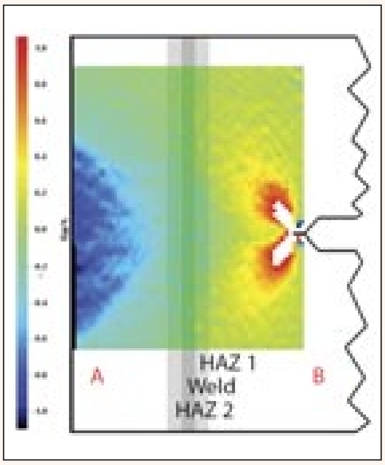
State-of-the-art imaging systems including Digital Image Correlation (DIC) for materials deformation and strain analysis. DIC measures the displacement of surface patterns between a reference state, and a sequence of loaded states. Stereoscopic systems enable surface shape and deformation measurements.

CAPABILITIES

- Local precision better than 0.01 pix or 50 μStrain
- Global precision better than 3μStrain
- Cameras up to 16MPix
- Frame rates >5kHz
- Imaged area <0.5mm up to almost unlimited maximum
- Simultaneous analogue sampling
- Up to 6 cameras per system
- Simultaneous flow & material imaging

CASE STUDY: CRACK PROPAGATION THROUGH A BI-MATERIAL BOUNDARY. A PROJECT UTILISING STRAINMASTER

A recent study focused on crack propagation through a bi-material boundary in a pre-cracked steel Compact Tension (CT) specimen. Two materials (A&B) were joined of the same composition but with different heat treatments, thus one had higher yield strength. The steels were electron beam welded to minimize the width of the Heat Affected Zone (HAZ). Due to the temperature cycle of the welding process, the microstucture is modified in the HAZ but the macro scale is unchanged. Section B (having the crack) was the high toughness steel in test 1, but the lower toughness in test 2.



Strain distribution in Compact Tension welded steel specimen

DIC data from a 2D setup gave good qualitative indications of strain distributions, but the more accurate 3D data resolved changes in the specimen surface height. Good comparison was seen between DIC and Finite Element (FE) results, however the experiment revealed less uniform crack growth. For this reason crack shielding cannot be ruled out despite the DIC showing none.

The challenge for the DIC was to extract high spatial resolution with sufficient precision around the crack tip. Simple smoothing (not a default in StrainMaster) should be avoided as it masks local phenomena, but the group is investigating smart innovative FE type interpolation schemes.

In parallel, LaVision and the University of Manchester continue to push boundaries, and recently tested a new approach aimed at increasing DIC precision by an order of magnitude, with promising results.

The Manchester Materials Science Centre is at the forefront of applying DIC to complex engineering problems, having employed LaVision systems over many years.

LaVision would like to thank Alex Forsey from The University of Manchester for his contribution to this case study, who in turn would like to acknowledge project funding form EPSRC and Serco Assurance.

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

LaVision is at the forefront of integrated imaging systems manufacture for the scientific and industrial markets. Products include ultra-fast CCD cameras, measurement technologies, and software. Amongst the range we offer turnkey and custom systems for non-destructive material testing. Our mission is to provide imaging solutions via a customer driven programme of innovation and development.

FUTURE DIRECTIONS

LaVision has an exciting programme of product development including :

- Ultra high accuracy modes with order of magnitude improvements in strain precision
- Increased Digital Volume Correlation (DVC) for volumetric images (3D 3C)
- Fluid-Structure interaction capabilities for multi-parameter analysis: PIV + DIC

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Listen and learn

Acoustic emission tells you what is happening inside your materials in real-time

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

Physical Acoustics has provided AE products and services worldwide since 1978. AE application requires a multi-disciplinary approach, and Physical Acoustics' experience together with a partnership approach has resulted in hundreds of applications and led many to become established codes and standards. The use of AE monitoring during material and component testing is a major application area. For example monitoring metal and composite aircraft structure during static and fatigue test, including the SAAB JAS39, VC10, Lynx, and ARIANNE. In the civil structures area AE is used on both concrete and metal bridge structures, both in the laboratory and the field, earning the PAL-Cardiff University partnership an 'engineering excellence' award from the Royal Society. Success of AE is largely due to its ability to identify in real-time any micro-fracture or overstress occurring anywhere in the component or structure, using a few stationary sensors.

FUTURE DIRECTIONS

AE technology continues to develop as new signal analysis methods are applied to extract the maximum information from the signal waveform. These include: moment tensor information from the fracture events, the use of neural networks and SPR, and improved damage location capability through improved understanding and application of wave propagation models.

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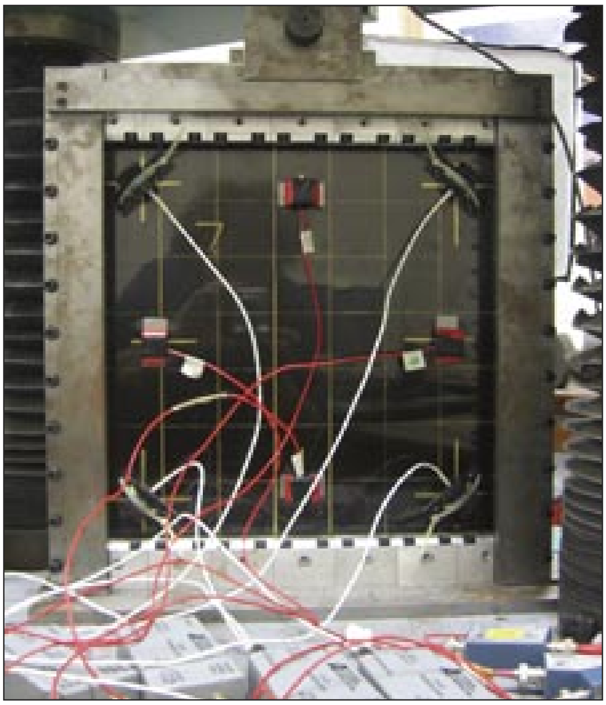
TECHNOLOGY

Acoustic Emission (AE): AE is the high frequency acoustic stress wave which occurs due to the rapid release of energy in a material. Dislocation slip resulting from yielding or phase transformation, and micro-fracture and macro-fracture events from any material, all release AE.

CAPABILITIES

AE is used to monitor materials under stress, in order to identify changes to the microstructure and cracking. Micro-electronics, human joints, spacecraft, bridges, vessels and offshore platforms make use of AE. Sensitive high-frequency piezo-electric sensors are used for detection, AE is like seismology, on a small scale, and at high frequency.



AE sensors monitoring a buckling test, photo courtesy of Cardiff University.

CASE STUDY: FATIGUE ANALYSIS OF FIGHTER JET SEAT

The SAAB JAS39 Gripen is a lightweight single seat fighter with CFRP wings and vertical stabiliser. During the full size static qualification test loads are applied in many orientations to simulate service conditions. These loads are applied using computer controlled jacks and a "wiffle tree" arrangement to apply the load to the structure via loading pads. Strain data is obtained to allow comparison of theoretical stress/strain with measured values on the structure, to validate the design model. Once all service load cases were applied the loads were increased in the main cases of interest, and eventually an ultimate case was taken through to failure. It is vitally important not to put damage into the structure prior to the final load cases, otherwise subsequent test cases will not provide the correct data, and another test article would be needed, losing many months of development time. For this reason AE was used to identify the early onset of sub-critical damage in real-time, both to protect the structure at moderate load levels, and to provide information on damage levels under different loading conditions. This information is important as it means if an aircraft is overloaded in service, the probable location and extent of damage will be known. AE monitoring saved the structure on two occasions, one a result of loading pads being too small, causing local crushing risk, and the second when a loading pad became displaced. Each AE sensor monitored a radius of about half a metre, providing 100% volumetric monitoring, something not possible with strain gauges. AE was used during the fatigue test to monitor the metallic wing attachments and joints for fatigue cracking. Whilst no cracks developed at these locations, cracking induced by a testing tool was successfully identified in an adjacent area. [Ref: ASIPP99 Dan Lindahl, Markku Knuuttilla, CSM Materialteknik]

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sales@techni-measure.co.uk, www.techni-measure.co.uk

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

Techni Measure offer a large range of sensors, to measure strain, force, load, pressure, vibration, displacement, orientation, temperature and torque, along with instrumentation to go with them, and wireless systems where required. The TML range of strain gauges offers a wide choice of standard gauges for experimental measurements or sensor manufacture, most available from stock. Their range also includes standard and high temperature weldable gauges, as well as various adhesives, coatings and lead wires.

TECHNOLOGY

Supply of, and advice on strain gauges, transducers, and instrumentation.

Photron

Photron (Europe) Ltd, The Barn, Bottom Road
West Wycombe, Bucks HP14 4BS, Tel: +44 (0) 1494 481 011
Fax: +44 (0) 1494 487 011, europe@photron.com

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

With 30 years experience designing and manufacturing high speed imaging systems for research and industry, Photron has become known for its products' performance, reliability and ease of use, backed up by excellent support in Europe and overseas.
The high quality – low noise images captured by Photron cameras make these systems ideally suited for integration with 3rd party software and hardware for use with dynamic measurement techniques including Motion Analysis and Digital Image Correlation (DIC)

TECHNOLOGY

High-Speed digital imaging cameras for materials research and for integration with dynamic DIC systems

iMETRUM

NON CONTACT PRECISION MEASUREMENT

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University Gate East, Park Row, Bristol. BS1 5UB
Tel: 0117 9878012 or 01305 852881 Mobile: 0780 171 7126
john.brewster@imetrum.com, www.imetrum.com

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

Imetrum's patented software, which has been developed over the last 15 years, can track up to 100 strain or displacement points to an accuracy of 1/500th of a pixel, using a standard computer and CCD camera to view a material test sample or structure. The amount of available data is higher while preserving the real time capabilities of the system. Simply, the system allows the user to perform their tests more quickly, cost effectively, and accurately, while also providing more data, compared to traditional contact methods.

TECHNOLOGY

The patented software enables highly accurate measurement of strain and displacement in materials and structures

LMS®

ENGINEERING INNOVATION

LMS Engineering Innovation, Rye Hill Office Park,
Birmingham Road, Allesley, Coventry, CV5 9AB
Tel: 02476 408120, www.lmsintl.com, info@lmsintl.com

COMPANY PROFILE AND TECHNOLOGY OVERVIEW

LMS is an engineering innovation partner for companies in the automotive, aerospace and advanced manufacturing industries. LMS enables its customers to get better products faster to market and turn superior process efficiency to their strategic competitive advantage. LMS offers a unique combination of virtual simulation software, testing systems and engineering services. Through our technology, people and over 25 years of experience, LMS has become the partner of choice for most leading discrete manufacturing companies worldwide.

TECHNOLOGY

- In field durability testing
- Durability data analysis
- Durability simulation (fatigue life prediction)
- Life cycle testing