

Measurement Note

DEPC-MN 032

Development of an Integrated Multi-Axis Loading and Strain Mapping Facility

This Measurement Note details work carried out to demonstrate the capability and use of the NPL multi-axial strong floor test machine, in conjunction with a number of full-field strain mapping techniques.

Two case studies were undertaken; (i) an open-hole tension (OHT) specimen loaded transversely via a pin fitted into the hole and (ii) an aluminium bolted T-joint loaded at 45°. For both case studies measured strain data was compared to strain maps predicted using finite element modelling and theoretical analyses. The strain mapping techniques used were; (i) strain gauges, (ii) electronic speckle pattern interferometry (ESPI) and (iii) digital image correlation (DIC).

The results of the case studies have shown that the multi-axial strong floor has been used with some success in conjunction with DIC and strain gauge techniques. However, the balance between spatial and strain resolution when using the DIC technique, means that the technique is limited in its ability to measure strains near to the edges of a component or strain concentrators such as holes. It was not possible to use the ESPI technique on the strong floor due to the sensitivity of the equipment to vibration. However, results from tests undertaken on a uniaxial test machine have shown that the technique compares favourably with DIC and strain gauge measurements.

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November 2005

INTRODUCTION

The vast majority of composite components experience multi-axial loading during their service life. Existing composite material test standards for measuring mechanical design data are predominantly uniaxial in scope, and although several European laboratories are proposing standard methods for multi-axial characterisation, there is currently no standard protocol in place. There are several methods of creating multi-axial loads, including the use of axial forces and pressure (internal/external) using tube specimens, bi-axial plate or cruciform type biaxial configurations and full rig systems applying combinations of axial, bending and/or twisting loads. Currently, the biaxially loaded cruciform specimen has been identified as of most interest. In addition to test method/standard development, to further increase the confidence of designers, manufacturers and end-users in the use of composite materials for safety critical applications, it is important to be able to apply realistic “service-loading” to components and structures as opposed to just testing simple coupons.

As a consequence of the drivers discussed above, NPL has recently acquired a multi-axial test facility, which will be used for test method development plus loading of components. In conjunction with a number of

full-field, non-contact strain mapping techniques including electronic speckle pattern interferometry (ESPI) and digital image correlation (DIC), the aim is to use the facility to validate predicted strain distributions obtained using finite element analyses and check for strain uniformity in coupon specimens.

This measurement note details recent work undertaken to demonstrate the applicability, capability and use of the multi-axial and strain mapping facilities using two cases studies. The following sections outline the multi-axial test facility, strain measurement techniques used and results of the case studies.

NPL’S MULTI-AXIAL TEST FACILITY

The multi-axial strong floor facility set-up consists of a tee-slotted cast iron strong floor, upon which can be mounted up to four hydraulic actuators (axes 1-4), each with a dynamic rating of ± 50 kN. Each of the hydraulic rams has a stroke of ± 50 mm and can be positioned on the strong floor independently, providing, for example, the flexibility to configure the facility from four single-axis test rigs, to a bi-axial loading arrangement for cruciform test components. Figure 1 shows the set-up as would be used for bi-axial testing of a cruciform specimen geometry.

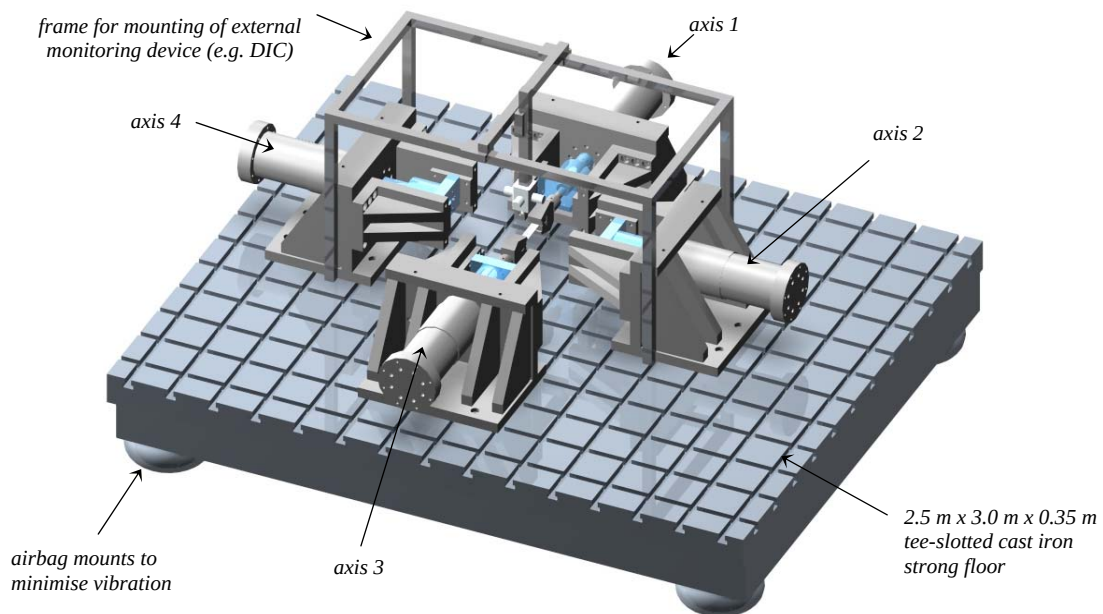


Figure 1 - Schematic of NPL’s multi-axial strong floor test facility

STRAIN MAPPING TECHNIQUES

Three techniques have been used to measure in-plane strain in the two case studies selected for the development of the integrated multi-axial strain mapping facility. These are; (i) bonded strain gauges, (ii) electronic speckle interferometry (ESPI) and (iii) digital image correlation (DIC). Background on all three techniques and a brief description of the systems used by NPL are given in the following sections.

Strain Gauges

The use of bonded electrical resistance strain gauges is a commonly used technique for measurement of local strain when a specimen or component is loaded, either mechanically or thermally. The basic principle upon which a strain gauge functions is that when it undergoes strain, its electrical resistance changes. If the relationship between strain and change in resistance is known for a particular gauge (defined as the gauge factor) then the strain can be measured by monitoring the change in resistance resulting from loading. The change in resistance that needs to be measured is usually very small.

Strain gauge instruments usually employ a Wheatstone bridge as the primary sensing circuit. The bridge circuit consists of four resistive components (R_1 - R_4) or bridge arms connected in a series-parallel arrangement, and an excitation voltage source (V_E) - see Figure 2. The connections where pairs of bridge arms are joined to the lead wires from the excitation voltage are referred to as input

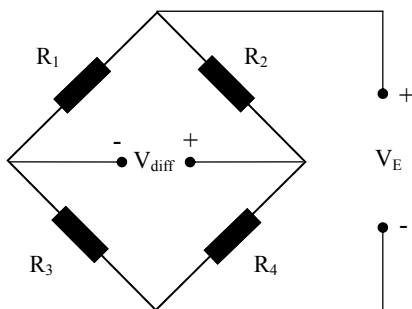


Figure 2 - The Wheatstone bridge circuit

corners of the bridge. A differential output voltage (V_{diff}) is measured at the two remaining bridge corners. By ensuring that the bridge arms are resistively symmetrical about an imaginary centre line drawn through the bridge output corner, V_{diff} will be zero regardless of the value of excitation voltage. In this condition the bridge is resistively balanced. If the bridge is not balanced, a differential voltage will be present at the output corners and the magnitude of the output voltage will be proportional to the amount of unbalance.

If a strain gauge is used as one of the resistive arms of the bridge circuit (i.e. a quarter-bridge Wheatstone bridge circuit) and resistors of the same resistance as the gauge are used in the other three arms, the bridge will be balanced when the gauge is in an unstrained state. When a strain is applied to the gauge, its resistance changes and therefore the voltage in the strain gauged arm of the circuit changes causing an unbalance. By measuring this voltage unbalance, the change in resistivity of the gauge and therefore the strain can be calculated. In the work detailed in this measurement note, a quarter-bridge Wheatstone bridge circuit was used for all strain gauge installations.

Electronic Speckle Pattern Interferometry

Electronic speckle pattern interferometry (ESPI) offers very precise measurement of the elastic properties and thermal expansion coefficient of composite specimens with relatively large dimensions and aspect ratios, such as plates or entire components, or locally within a larger specimen or part. It is a full-field measurement method with which deformations under mechanical and thermal loads can be measured along three perpendicular axes without contact with the test piece [1-5]. Sample preparation is easy and requires a minimum of handling [6].

The speckle effect is produced by the interference between the reflected rays when a non-specular, dispersing surface is illuminated with a laser beam [1]. The pattern is defined by the microscopically rough topography of the specimen surface. Any deformation of the surface results in a change of the speckle

pattern. A correlation between the speckle patterns for an object in a reference state and in a deformed state gives information on the deformation of the object's surface. This is typically done by gray level difference of two digital video interferograms and some additional digital image analysis. For each interferogram, three or four images of the interference pattern are taken with a phase shift of the laser beam of 120° or 90° respectively, and they are combined to give a phase image, which holds information not only on the amount, but also on the direction of the deformation.

The ESPI installation used in this study (Dantec Ettemeyer, Germany) consists of an ESPI head, a hardware control and data acquisition system, and an image analysis facility. The software Istra $\text{\textcircled{R}}$ v.3.3 was used for the image processing. A compact unit, illustrated schematically in Figure 3, allows the quasi simultaneous measurement of in- and out-of-plane displacements. The in-plane displacements are given by the relative phase shift of two imaging beams. The out-of-plane displacements, i.e. parallel to the optical axis, are obtained from the amount of phase shift of an imaging beam with respect to a reference beam. One can thus measure the 3-D deformation of an object under a load.

The integrated ESPI head includes the laser source, mirrors, piezos, shutter, and video camera. The measurement sensitivity of the system, defined as the amount of relative

displacement giving rise to an additional interference fringe, is

$$\text{out-of-plane: } s_z = \frac{\lambda}{2}$$

$$\text{in-plane: } s_{x,y} = \frac{\lambda}{2 \sin \theta}$$

where λ is the wavelength of the laser and θ the angle between the imaging beams and the optical axis as shown in Figure 3. The speckle interferometer uses near infrared laser diodes ($\lambda = 0.780 \mu\text{m}$), giving an out-of-plane measurement sensitivity of $0.390 \mu\text{m/fringe}$. The distance between the front mirrors forming the imaging beam sources was 140 mm and the distance to the object was held at 265 mm as shown in Table 1. Table 1 presents details of the configuration used with NPL's set-up, and indicates the in-plane measuring sensitivity for both in-plane axes. Since information on the displacement gradient is carried by the entire phase image, and not just by the fringes, the effective in-plane sensitivity is about an order of magnitude better. The limiting factor of the sensitivity is the inherently high noise of the method resulting from the speckle pattern.

Images were recorded with a 752×582 pixel built-in CCD camera operating at 25Hz. A set of Pentax Cosmimar $\text{\textcircled{R}}$ macro lenses was used on the front end of the viewing system, giving an imaging field presented in Table 1. The resulting calibration of the monitor screen in the x and y-directions, together with the lateral

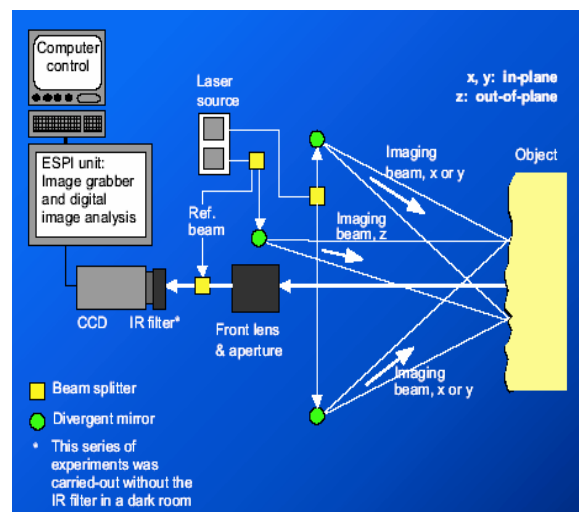


Figure 3 - Layout of the ESPI deformation measurement system

Table 1 - Optical Configurations of the ESPI Set-Up

Lens	Distance to object (mm)	Imaging field (mm x mm)	Resulting calibration (mm/pixel x mm/pixel)	s_x, s_y $\mu\text{m}/\text{fringe}$
12 mm F*8	265	57.03 x 33.20	0.128 x 0.123	0.738

resolution achieved are also given in Table 1. The time required for a measurement, determined by the frequency of the video camera and the speed of the shutters and phase shifting piezo devices, was approximately a third of a second for each axis.

Figure 4 illustrates the speckle pattern of an epoxy rod strained and measured in the x-direction, before and after the strain was

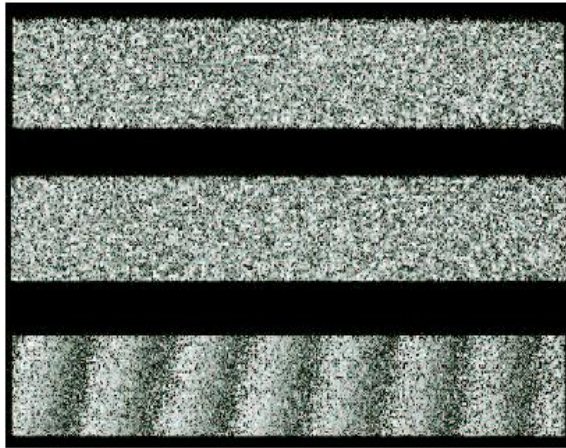


Figure 4 - Speckle pattern in the undeformed state (top), under 4×10^{-4} axial strain (middle) and the resulting typical fringe pattern from the difference of the two images (bottom).

applied to the sample. It also shows the image of displacements obtained through the difference of the two images of the deformed and undeformed state. A measure of displacements typically produces parallel fringes in an isotropic material without any defects from which quantitative values of displacements and deformations are obtained through the sensitivity by unwrapping the fringe pattern.

Digital Image Correlation

Digital Image Correlation (DIC) is a non-contact full field strain measurement technique. The basic concept of DIC is to compare two images of a component before and after deformation.

A LaVision[®] system was used to map 2D and 3D strain distributions. Displacements and strains are determined by correlating the position of pixel subsets or blocks in the original and deformed image, normally based upon contrast i.e. grey intensity levels. The size of the pixel block can be varied, thus allowing many random patterns to be correlated. In order to identify if there is any movement between the two blocks there must be sufficient detail for it to be considered

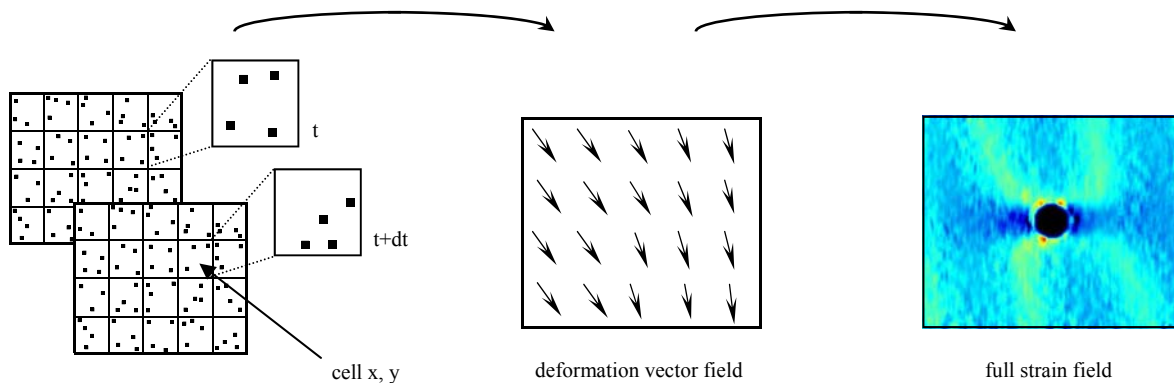


Figure 5 - The principle of digital image correlation [7]

unique. It may be the case that the specimen or component already has a suitable level of surface features which can be imaged directly, but if not, some form of spray paint or coating or scratches on the surface can be used. For best results a good distribution of intensity values must be obtained. The deformations of the specimens are then calculated by correlating the positions and displacements of pixel subsets or blocks in the original and deformed image to produce a vector map. This is then processed further to produce a full field strain map, shown schematically in Figure 5.

Figure 6 shows a high magnification image of a spray coated specimen, showing a good range of pixel grey level intensities, separate (8 x 8) pixel blocks and the corresponding vector calculation points.

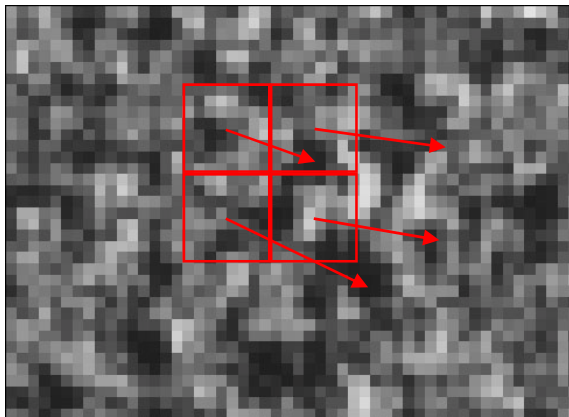


Figure 6 - Spray coated specimen showing range of pixel intensities, an 8 x 8 interrogation window and vector calculation points

A key issue with DIC is the size of the interrogation window i.e. the size of the pixel subset used for the correlation during data processing. The effect on accuracy of changing the size of the interrogation window on the calculated vectors and strain data can be seen in Table 2 and is illustrated in Figures 7 and 8. Although a small interrogation window size (e.g. 16 x 16) offers good spatial resolution, the strain resolution is poor (see Table 2). For a larger window size (e.g. 128 x 128) the spatial resolution is poor, but the error in the strain resolution is much lower. Careful consideration must be given to the size of this window as it has important implications on the spatial resolution and accuracy of the measurement.

Table 2 - Summary of Estimated Uncertainties and Accuracies of Strain Measured Using DIC [7]

Size of interrogation window in pixels	Accuracy of calculated vectors in pixels	Accuracy of calculated strain values
128 x 128	0.01 to 0.03	0.094%
64 x 64	0.02 to 0.05	0.3%
32 x 32	0.05 to 0.2	1.25%
16 x 16	0.1 to 0.3	5%

It is clear from the images and information detailed above that a compromise is needed between:

- High spatial resolution (small interrogation window size)
- High strain resolution and accuracy (large interrogation window)

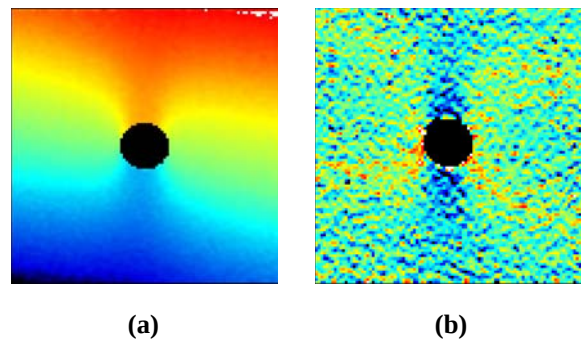


Figure 7 - (a) vector plot and (b) strain map calculated from a 16 x 16 interrogation window

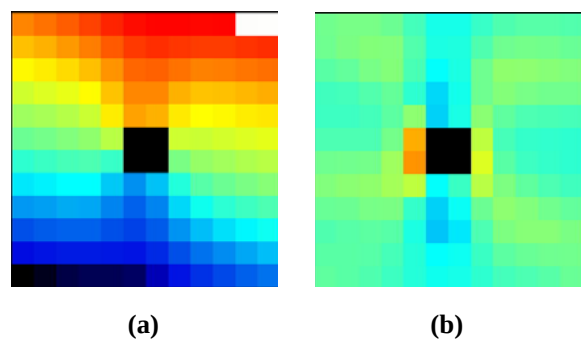


Figure 8 - (a) vector plot and (b) strain map calculated from a 128 x 128 interrogation window

The decision on what size window to use depends on the particular application, expected strain field and data required. The interrogation window sizes used for each case study will be detailed in the relevant sections.

CASE STUDIES

Two case studies were chosen in order to complete the installation of, and demonstrate the use of the multi-axial test facility in conjunction with the strain mapping techniques previously described.

Case Study 1- Experimental Programme

The first case study to be undertaken looked at using the multi-axial facility to test a simple open hole tensile coupon in three different modes: (i) open-hole tension (OHT); (ii) filled-hole tension (FHT), and (iii) side pin loading in tension. These loading modes are shown schematically in Figure 9. It is noted that the OHT and FHT configurations were only loaded in uniaxial tension (P_{axial}), whilst the pin side loaded configuration was subject to a transverse load via the pin (P_{side}) in addition to the uniaxial tensile load (P_{axial}). This case study was chosen for two reasons: (i) the data generated in the OHT and FHT modes can be directly compared to data obtained using a uniaxial test machine and (ii) the side pin loading in tension is a simple multi-axial test set-up through which good practice and experience of using the test facility multi-axially could be gained.

All of the tests conducted were based on the procedures recommended in ISO New Work Item 712 [8] for open-hole and filled-hole tensile strength measurements of fibre-reinforced plastic composites, which is similar to ASTM D 5766 [9], EN 6035 [10] and AIMT 1.007 [11]. Specimens of a woven glass

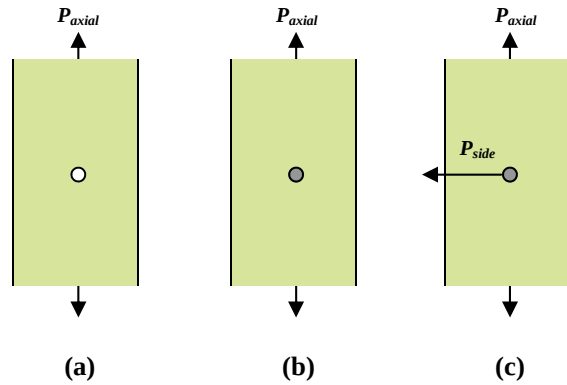


Figure 9 - Loading configurations used in case study 1: (a) open-hole tension (OHT); (b) filled-hole tension (FHT); and (c) pin side load

fibre-reinforced/epoxy material of ~3.6 mm thickness, were machined to dimensions recommended in [8] as detailed in Table 3.

The multi-axial test rig was configured so that axes 1 and 3 (Figure 10) were aligned opposite each other and axis 4 was positioned perpendicular to the specimen longitudinal axis and mid-way between axes 1 and 3. Mechanical wedge action grips were used to grip the ends of the specimens axially and a side loading arm was attached to axis 4 in order to apply a side load via the pin in the specimen.

For this case study, strain gauges and DIC were used to produce a map of the strain concentration around the hole. It was not possible to use ESPI due to the sensitivity of the technique to vibrations transmitted through the strong floor. However, ESPI was used to record strain for OHT specimens tested on a uniaxial test machine for comparison with the subsequent strong floor tests.

Table 3 - Material and Specimen Details Tested in Case Study 1

Material	Specification	Specimen dimensions (mm)			
		Thickness	Length	Width	Hole diameter
Woven glass-fibre/epoxy	Permaglass 22FER28	~3.6	240	36	6

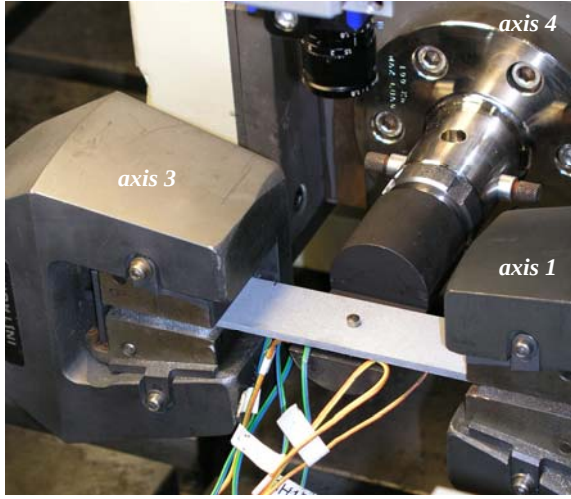


Figure 10 - Pin side loaded tensile test undertaken on the NPL multi-axial test facility using DIC strain mapping.

Four biaxial strain gauge rosettes (2 mm transverse and longitudinal gauges) were bonded onto the surface of specimens at various locations around the hole (see Figure 11). The gauges were connected to a data logger and strain data was recorded throughout the tests. On the opposite side of the specimen (to the strain gauges), a white/grey/black speckle pattern was sprayed onto the specimen for the DIC measurements. Low and high resolution cameras were used to record images throughout the test and processed using the DIC software. For all sets of recorded DIC data, a 64 x 64 interrogation window size was used to process the deformation vector plots from which strain data was calculated.

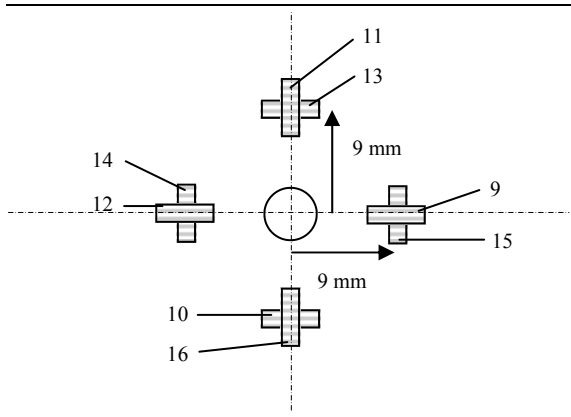
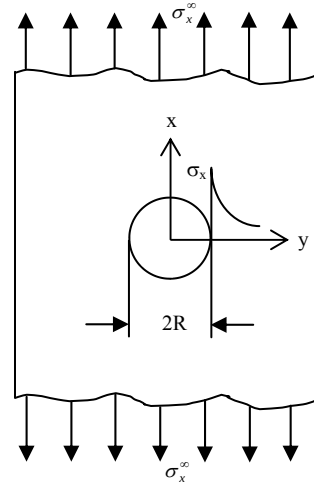


Figure 11 - Pin side loaded tensile test undertaken on the NPL multi-axial test facility using DIC strain mapping.

For the OHT and FHT tests, specimens were loaded to 15 kN in tension, which was within the elastic region of the material. For the pin side loaded tests, specimens were first loaded to 15 kN in tension and then a 3 kN side load was applied.

Case Study 1 - Theoretical and FEA Analyses

In order to demonstrate the validity of the strain maps measured using the DIC and ESPI strain mapping techniques, an analytical solution was calculated for the strain distribution in the OHT case, and FEA solutions were produced for the OHT, FHT and side loaded cases. The analytical solution was calculated using theory for an infinite orthotropic plate containing a circular hole [12] and the FEA modelling was performed using LUSAS Composite. The FEA models were all two dimensional (2D) plane strain analyses and used the same loads as in the experimental work.



$$\sigma_x(0, y) = \frac{\sigma_x^\infty}{2} \left\{ 2 + \left(\frac{R}{y} \right)^2 + 3 \left(\frac{R}{y} \right)^4 - (K_T^\infty - 3) \left[5 \left(\frac{R}{y} \right)^6 - 7 \left(\frac{R}{y} \right)^8 \right] \right\}$$

$$\text{Where } K_T^\infty = 1 + \left\{ 2 \left[\left(\frac{E_x}{E_y} \right)^{1/2} - \nu_{xy} + 0.5 \frac{E_x}{G_{xy}} \right] \right\}^{1/2}$$

Figure 12 - σ_x along the y axis for an infinite orthotropic plate containing a circular hole subject to a uniform stress [12]

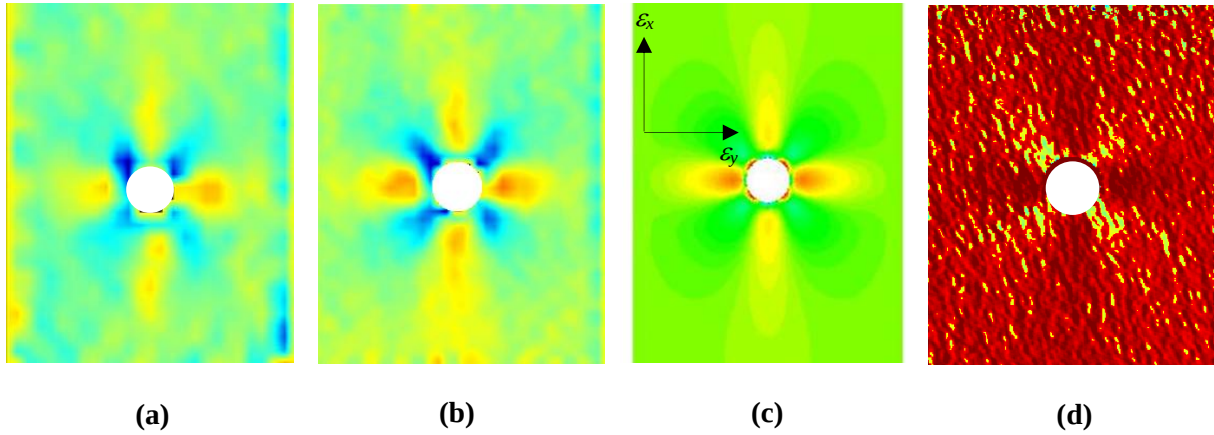


Figure 13 – ϵ_y strain distribution around hole in an open-hole tensile coupon by;
(a) DIC low resolution; (b) DIC high resolution; (c) FEA (LUSAS) and (d) ESPI (uniaxial)

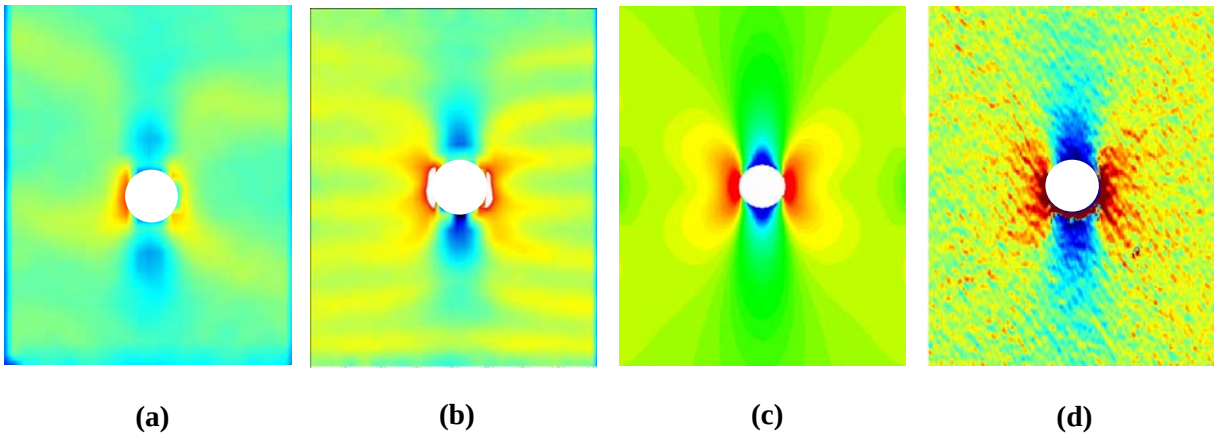


Figure 14 – ϵ_x strain distribution around hole in an open-hole tensile coupon by;
(a) DIC low resolution; (b) DIC high resolution; (c) FEA (LUSAS) and (d) ESPI (uniaxial)

Case Study 1 - Results

The results of the OHT, predicted and measured strains are shown in Figures 13 to 15. Measured ϵ_y strain maps from tests undertaken on the multi-axial strong floor and using the DIC technique with low and high resolution cameras are shown in Figures 13a and 13b. Corresponding ϵ_x strain maps are shown in Figures 14a and 14b. Strain maps predicted using 2D FEA LUSAS models and also measured strains using the ESPI technique on a uniaxial electro-mechanical test machine are given in Figures 13c, 13d, 14c and 14d, respectively. It was not possible to use the same contour levels for the DIC, FEA and ESPI techniques and therefore regions of equal strain level do not correspond in terms of colour. However, closer inspection of Figures 13 and 14 shows that the strain

distributions measured using DIC and ESPI techniques agree reasonably well with that predicted using FEA.

In order to show the degree of correlation between measured and predicted strain distributions, in Figure 15 ϵ_x strain has been plotted against distance along a line extending from the edge of the hole to the edge of the specimen (as in the theoretical analysis shown in Figure 12). Figure 15 shows that the strain level predicted using the 2D FEA and exact theoretical solutions agree very well as expected. The DIC results using low and high resolution cameras are in reasonably good agreement with each other, the predicted results and strain gauge values measured in tests undertaken on both uniaxial and strong floor machines. It is noted that the DIC results near to the edge of the hole do not show good

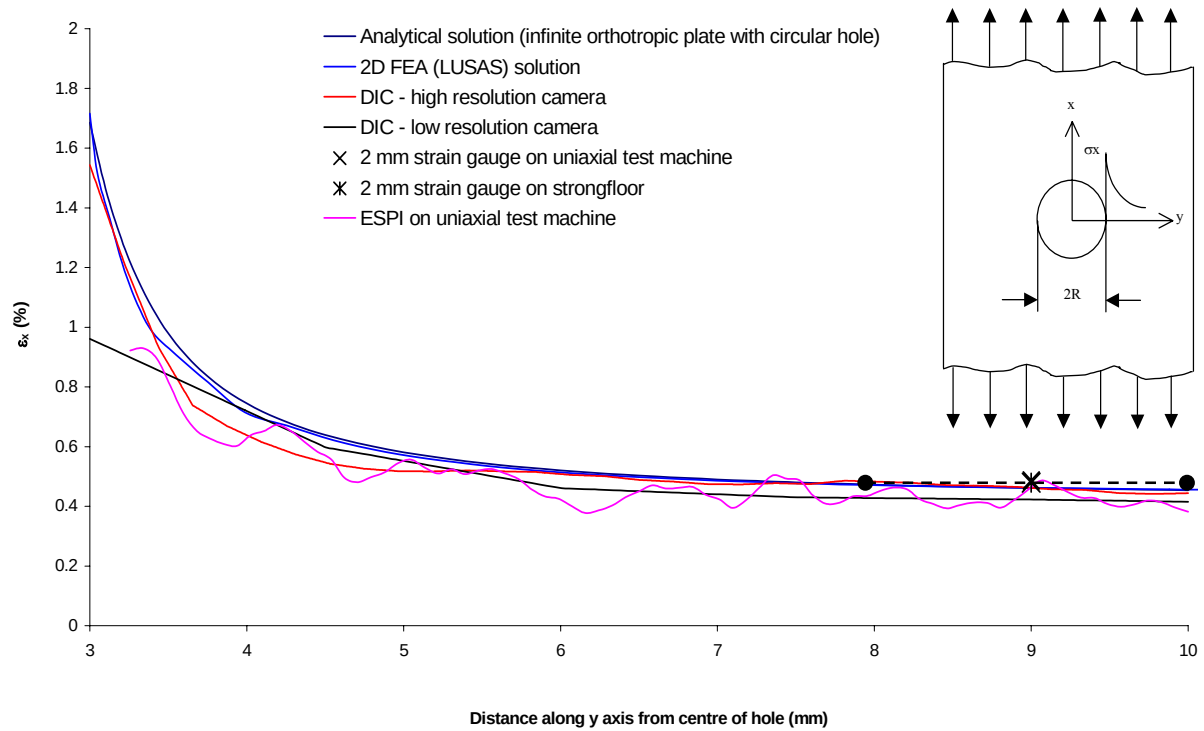


Figure 15 - Percentage ϵ_x versus distance from centre of the hole - OHT configuration

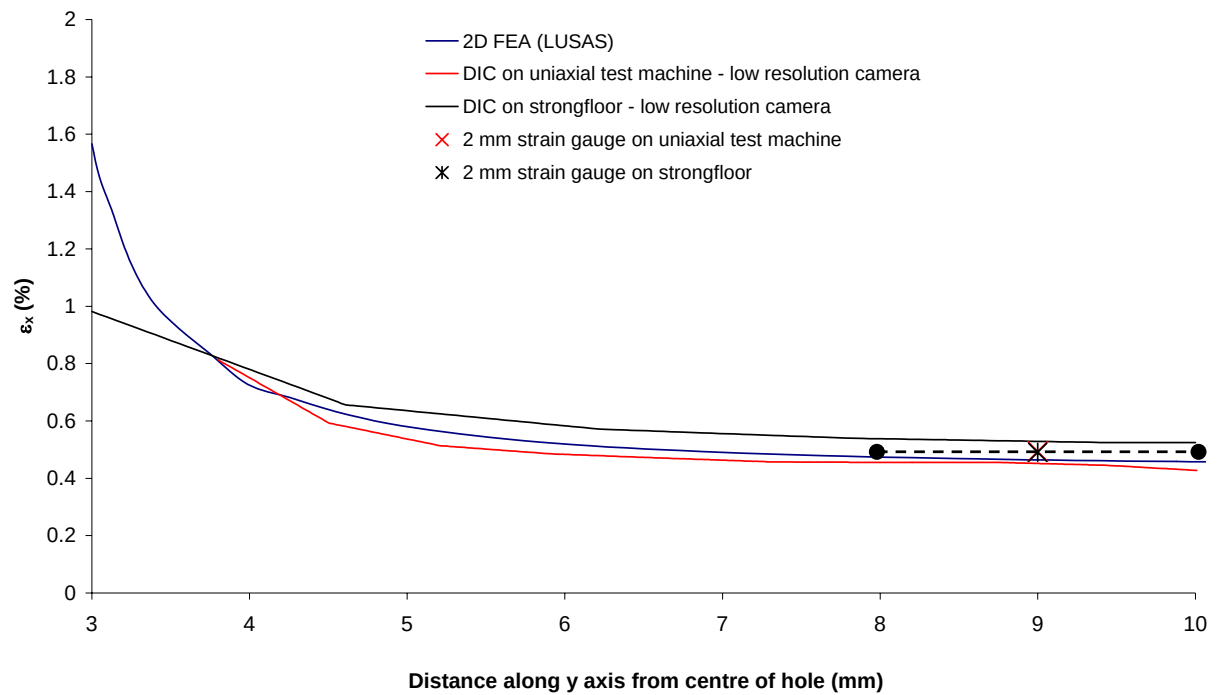


Figure 16 - Percentage ϵ_x versus distance from centre of the hole - FHT configuration

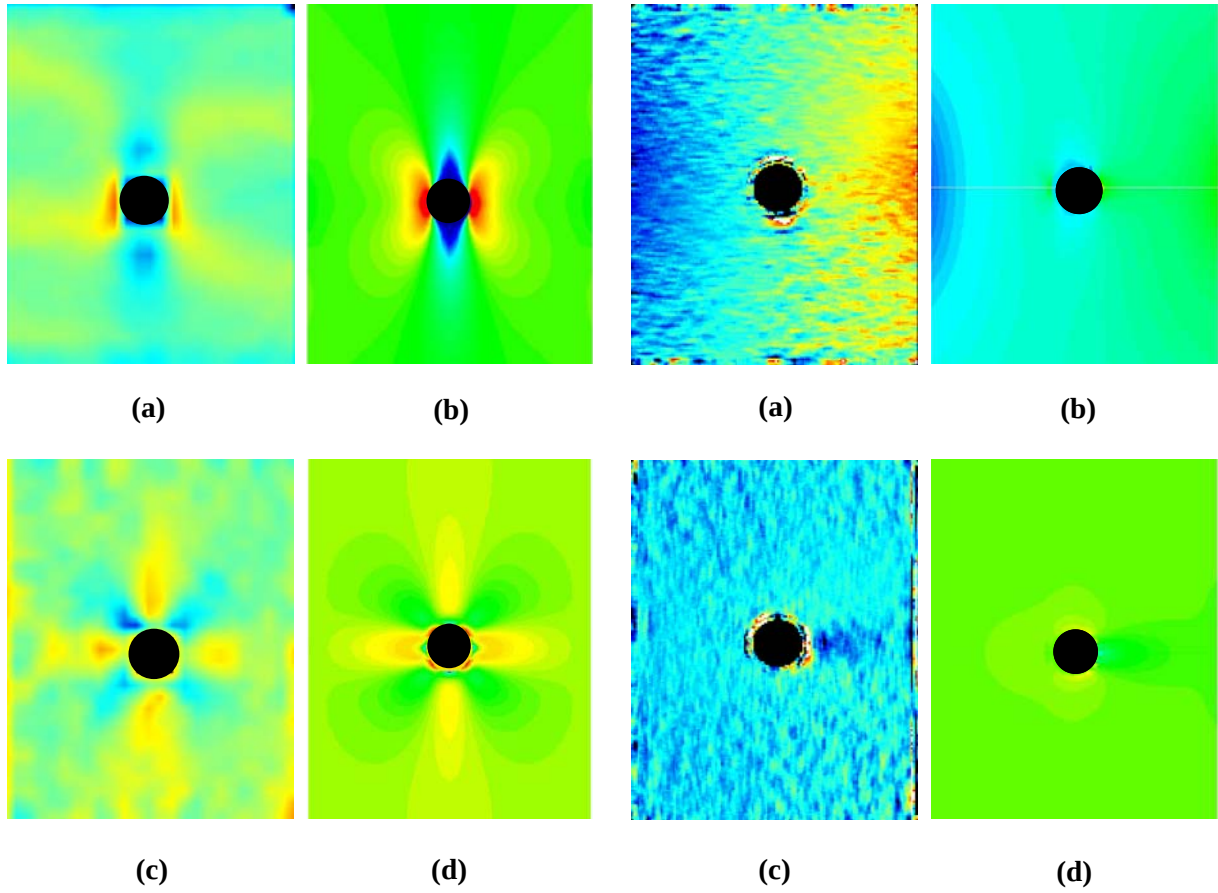


Figure 17 - strain distribution around hole in a filled-hole tensile coupon; (a) ϵ_x by DIC; (b) ϵ_x by FEA; (c) ϵ_y by DIC and (d) ϵ_y by FEA

Figure 18 - strain distribution around hole in a side loaded tensile coupon; (a) ϵ_x by DIC; (b) ϵ_x by FEA; (c) ϵ_y by DIC and (d) ϵ_y by FEA

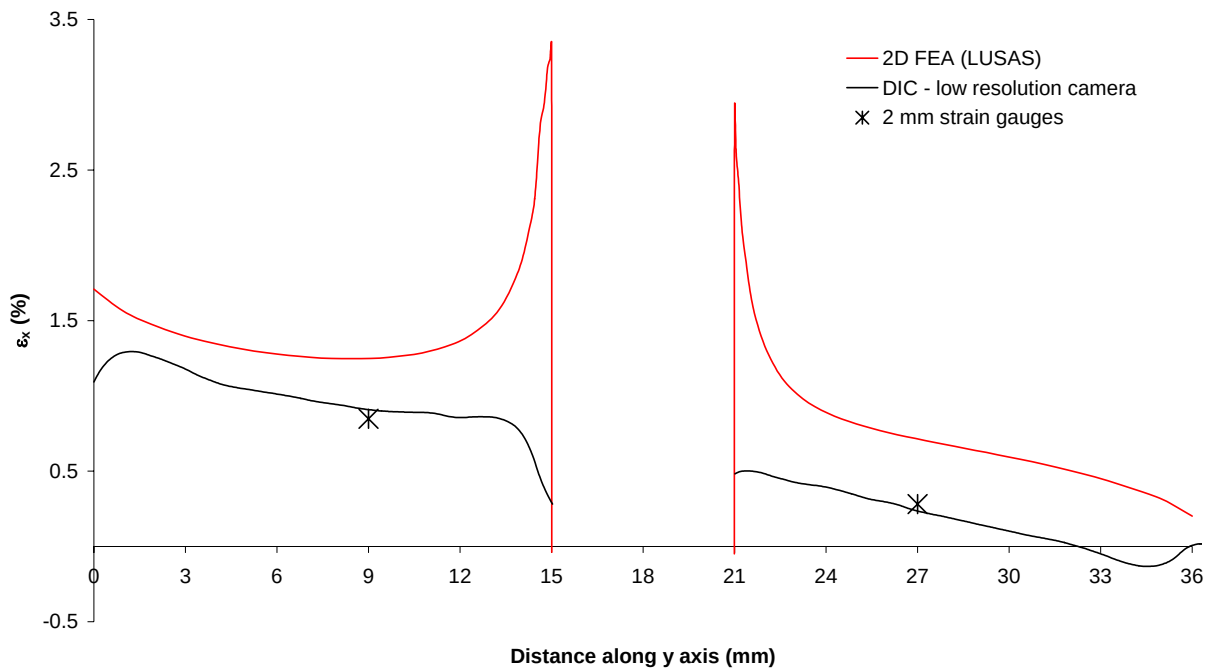


Figure 19 - Percentage ϵ_x versus distance across specimen width - pin side load configuration

agreement with the predicted strain. This is due to the size of the interrogation window used and the resulting compromise between spatial and strain resolution. The ESPI results from tests on the uniaxial machine show reasonable agreement with the DIC, strain gauge and predicted results. The waviness of the ESPI plot in Figure 15 is due to the data being raw and unsmoothed.

Figure 16 shows a similar plot for the FHT configuration and the results show that the strain distribution away from the edge of the hole are in good agreement for strain gauges, DIC and FEA. Results from uniaxial and strong floor test machines also agree well. The strain maps for ϵ_x and ϵ_y are shown in Figure 17. As for the OHT results, the DIC data is poor near to the edge of the hole.

Figure 18 shows the strain maps for ϵ_x and ϵ_y for the side loaded tension configuration. A plot of ϵ_x against distance across the width of the specimen for DIC, FEA and strain gauges is shown in Figure 19. The DIC results agree well with the two strain gauge results but the correlation to the FEA prediction is poor. This disagreement is considered to be due to

possible errors in the FEA model concerned with modelling the contact of the pin with the hole in the specimen.

Case Study 2- Experimental Programme

Within a previous project [13] that developed design procedures for bonded and bolted aluminium and glass-fibre reinforced plastic (GFRP) T-joints, a series of direct pull-off and lateral loading tests were undertaken and the results compared to 3D-FEA predictions. The pull-off and lateral loading tests were undertaken on a uniaxial machine. This case study has been undertaken to measure the global stiffness of, and local strain distribution in an aluminium bolted T-joint loaded at 45 degrees to the supporting base plate. The multi-axial strong floor has been used for these tests as it was not possible to arrange the required loading configuration on a uniaxial machine. The test set-up is shown in Figure 20. The T-joint is clamped at both ends of its base plate to a reaction plate mounted on the strong floor. The bolts in the joint were torqued to 20 ft-lbs. The loading actuator was connected to the specimen web plate via a clamping arrangement (Figure 20). The

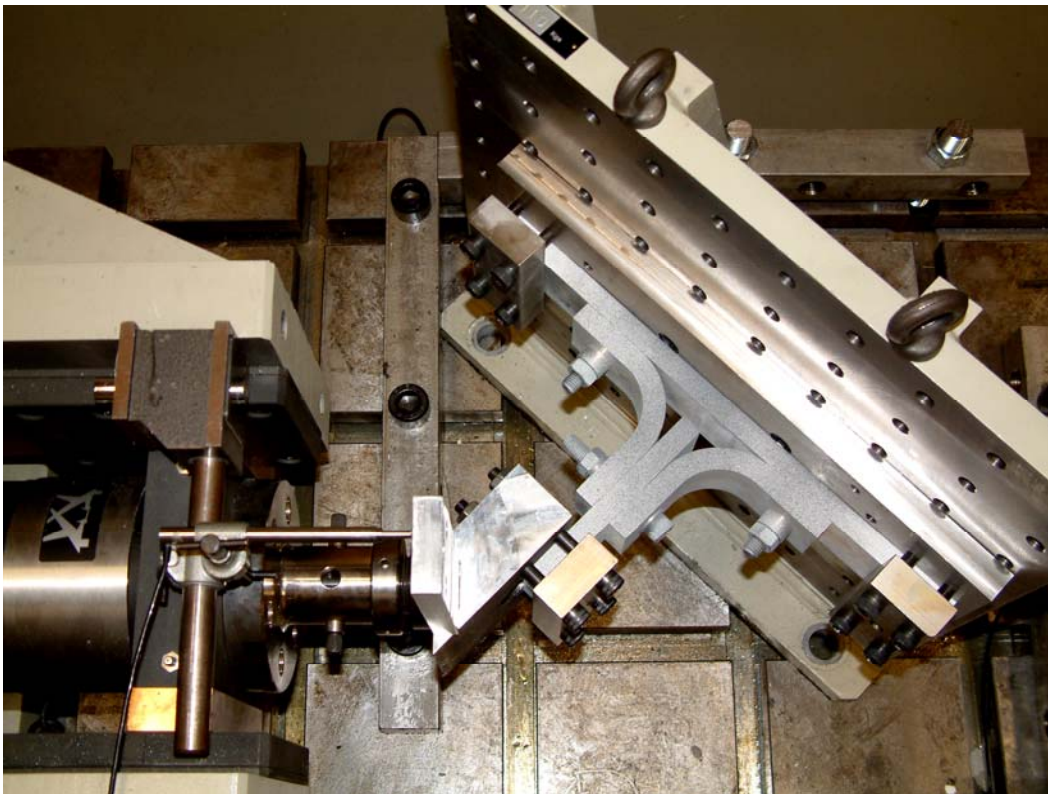


Figure 20 - Test set-up for an aluminium bolted T-joint loaded at 45° to the base plate

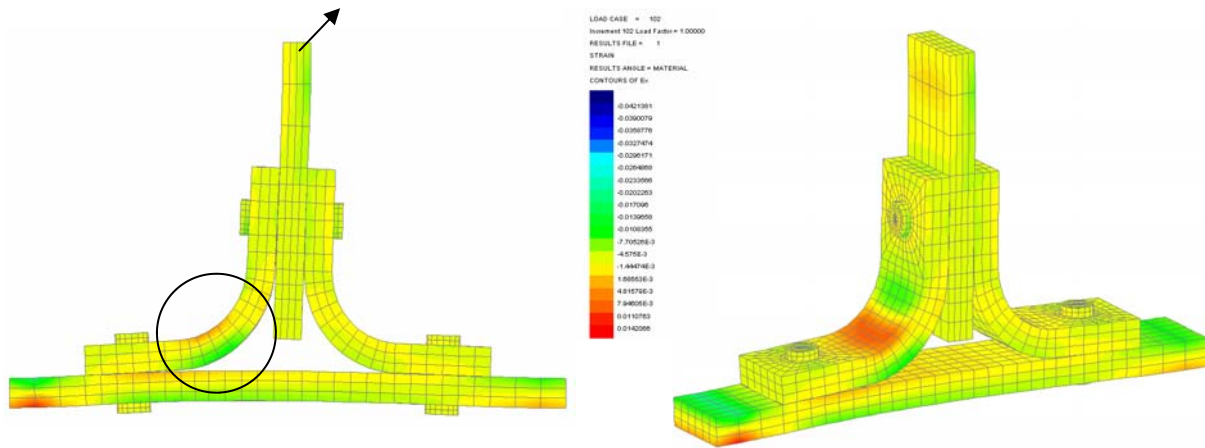


Figure 21 - FEA results (ϵ_x) for an aluminium bolted T-joint loaded at 45° to the base plate

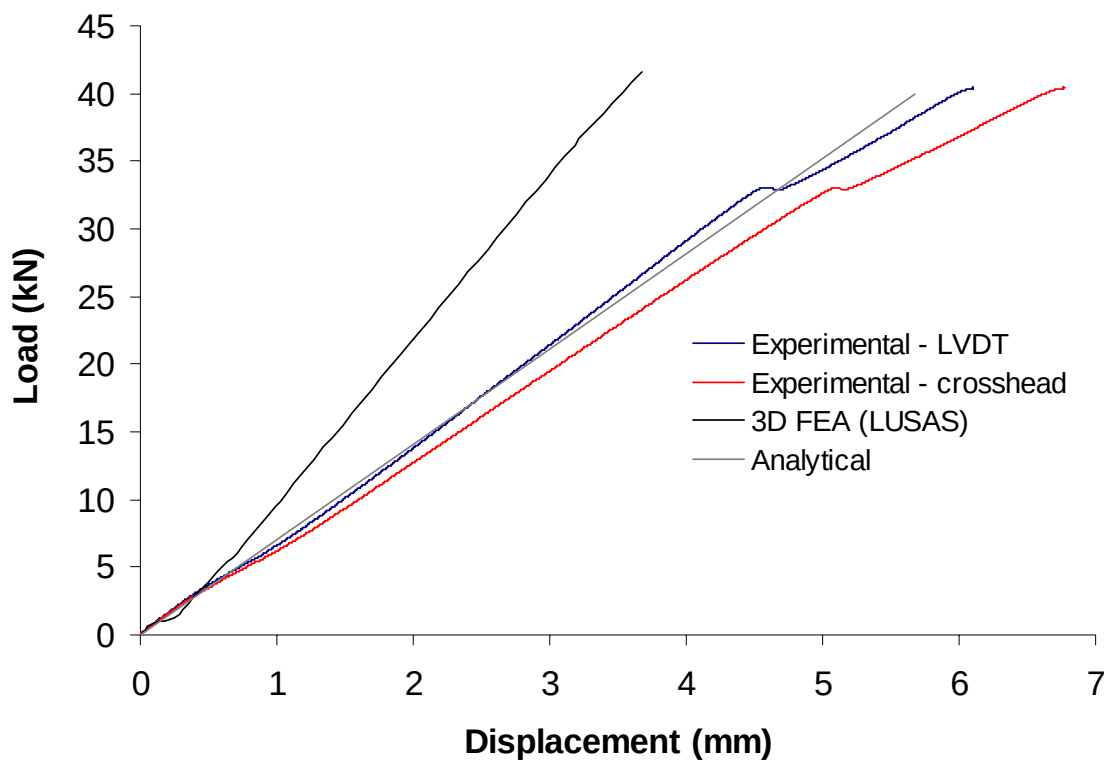


Figure 22 - Load versus displacement for an aluminium T-joint (45 degree load)

deflection of the specimen web plate was recorded using a linear variable differential transducer (LVDT). The side of the bolted T-joint was sprayed with a speckle pattern so that DIC measurements could be made. The specimen was loaded at 1.3 kN per second to a maximum load of 40 kN which was below the predicted yield load of the joint. The DIC technique was used to measure the local strain distribution in the left hand flange of the joint, which was a region that FEA predictions showed had a high concentration strain (see Figure 21).

Case Study 2 - FEA analysis

3D-FEA analyses of bolted and bonded joints were undertaken in a previous project [13]. The bolted analyses were performed using LUSAS and provided predictions of the joint global stiffness and strain distributions throughout the joint geometry.

In addition, a theoretical analysis was also used to predict the global stiffness of the joint.

Case Study 2 - Results

The global stiffness results for the aluminium T-joint are shown in Figure 22. This figure shows results predicted from FEA and theoretical analyses and also measured results using the machine crosshead and LVDT to record the joint deflection. It is clear that the FEA analysis tends to give a higher global stiffness than that measured from experiments or predicted using the closed-form solution. This was reasoned to be due to the fact that the FEA model uses supports of infinite stiffness when in practice the supports have a finite stiffness. In addition, in the experiments undertaken the 45 deg load is applied to the

specimen via a bulky clamping block whereas in the FEA model the load is applied to the end surface of the web plate. It is noted that the use of an LVDT to record deflection gives a slightly higher stiffness compared to the crosshead measurement due to the compliance of the loading rig. The slight drop in the measured load deflection traces was due to slipping of the joint in one of supports.

Figures 23 and 24 show the predicted and measured (DIC) local ϵ_x and ϵ_y strains in the left hand flange of the joint. Figure 25 provides a profile plot of ϵ_x and ϵ_y along the section A-B (Figure 23) through the thickness of the flange from the inner to the outside surface. From

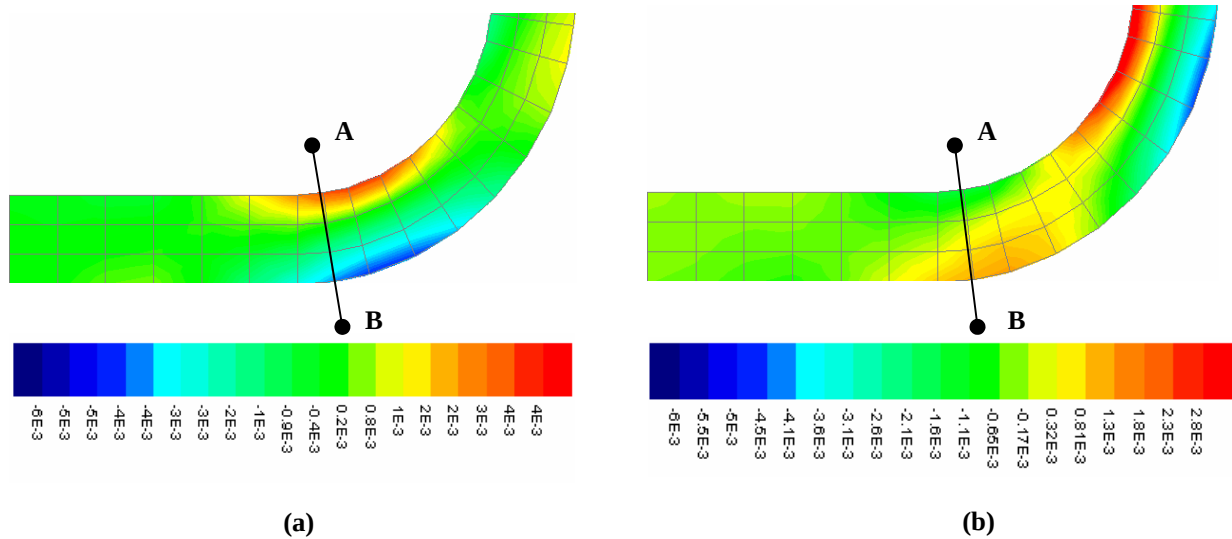


Figure 23 - (a) ϵ_x and (b) ϵ_y (mm/mm) in the left angle flange for an aluminium bolted T-joint

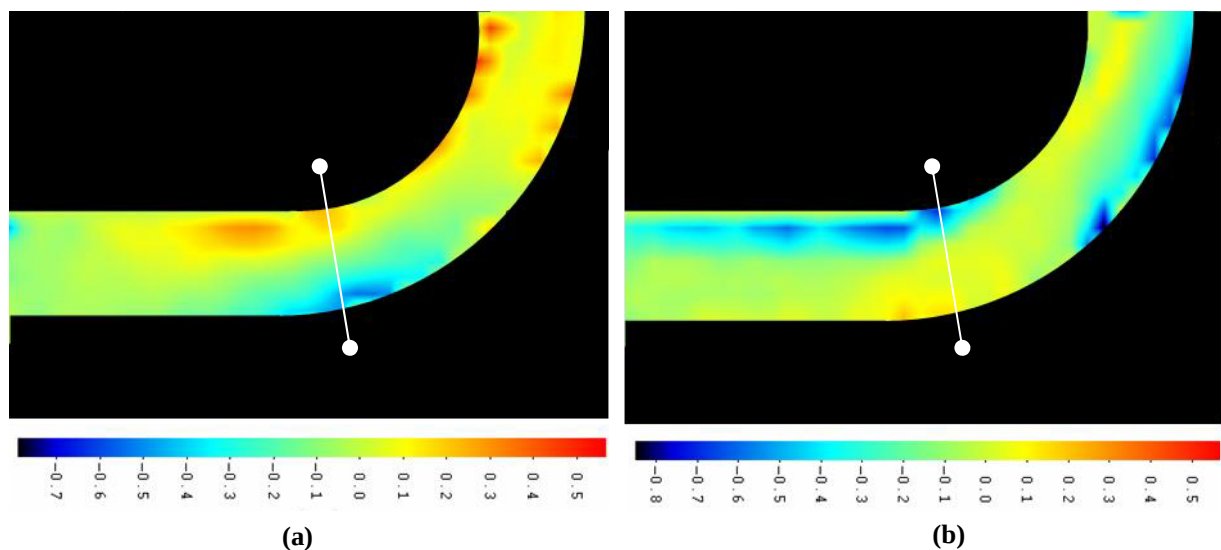


Figure 24 - (a) ϵ_x and (b) ϵ_y (%) in the left angle flange for an aluminium bolted T-joint

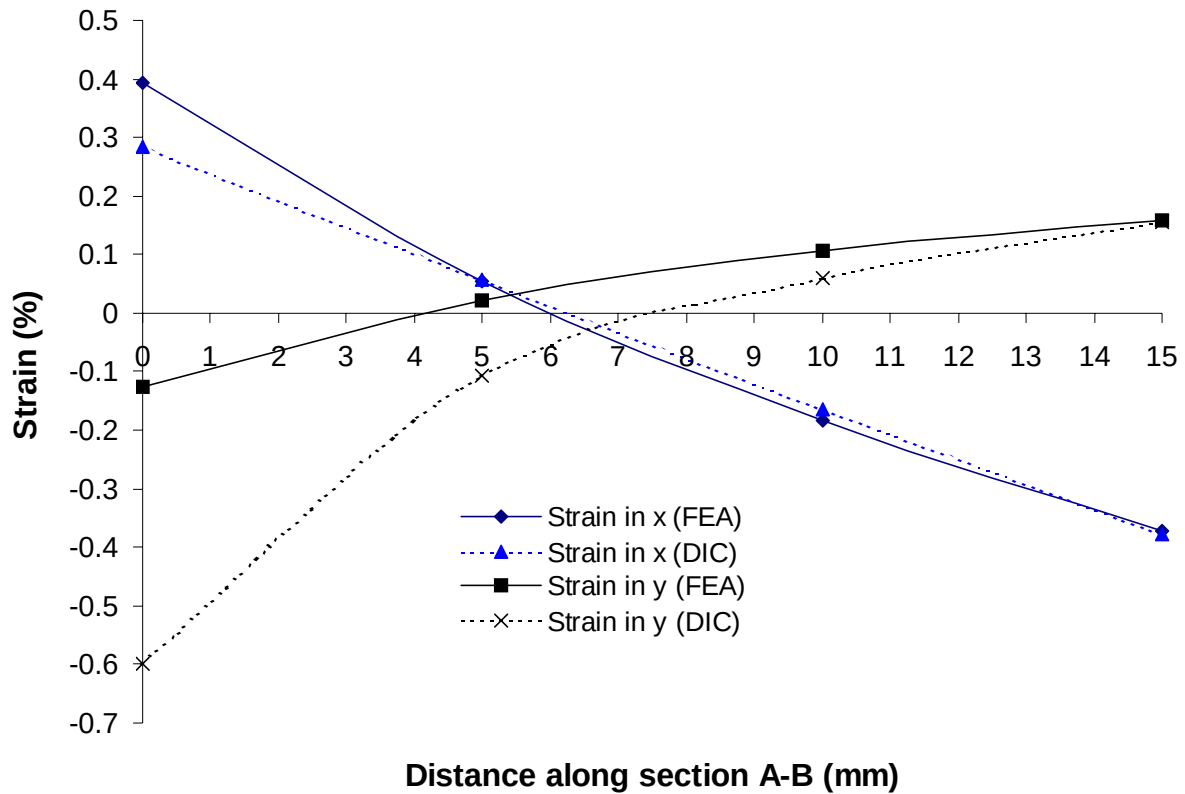


Figure 25 - FEA results (ϵ_x) for an aluminium bolted T-joint loaded at 45° to the base plate

Figures 23 to 25 it can be seen that the predicted and measured ϵ_x strain shows good agreement across the A-B section. The agreement for ϵ_y is generally poor near to the inner surface of the flange, but improves towards the outer surface. The poor agreement near to the inner surface is again due to the size of the interrogation window used and the resulting compromise between spatial and strain resolution near to the edges of the component.

CONCLUSIONS

The results of this study have demonstrated the use of a number of strain mapping techniques in conjunction with the multi-axial strong floor. A number of salient conclusions can be drawn from the work undertaken:

- It is currently not possible to use the ESPI technique on the strong floor due to the sensitivity of the equipment to vibration. However, results from tests undertaken on a uniaxial machine have shown that the technique compares favourably with DIC and strain gauge measurements.

- The DIC technique has been used with some degree of success to measure strain in the two cases studies especially as the levels of strain in both cases studies were quite low and near to the minimum levels currently able to be detected using DIC. However, the balance between spatial and strain resolution, means that the technique is limited in its ability to measure strains near to the edges of a component or strain concentrators such as holes. However, the technique does provide full-field strain maps as opposed to strain gauges which only provide an averaged strain value over a relatively small area.
- The strong floor has been used successfully in both cases studies as comparisons to uniaxial machine test data has shown.

The work detailed in this measurement note is the first attempt to use the multi-axial test machine in conjunction with various full-field strain mapping techniques. Further case studies will be carried out in order to further develop expertise.

REFERENCES

1. J.A. Leendertz. Interferometric displacement measurement on scattering surfaces utilizing speckle effect. *J. Phys. E.: Scientific Instruments*, 3:214-218, 1970.
2. O. Lokberg. Electronic speckle pattern interferometry. *Physics in Technology*, 11:16-22, 1980.
3. R. Hofling and P. Aswendt. Interferometric studies on thermal expansion behaviour of carbon fibre-reinforced composites. *Measurement*, 12:85-93, 1990.
4. P. Kim, S. Toll and J.-A.E. Manson. Measuring the thermal expansion of polymers and composites by speckle pattern interferometry. In *ICCM'10*, Vancouver, Canada, 1995. Whistler.
5. P. Kim, S. Toll, and J.-A.E. Manson. Characterisation of the dimensional stability of thermoplastic matrix composites by speckle pattern interferometry. In A. Miravete, editor, *ICCM'9*, pages 333-340, Madrid, Spain, July 12-16 1993. Woodhead Publishers.
6. P. Kim. The dimensional stability of fiber-reinforced thermoplastic composites. PhD thesis, No 1427, Ecole Polytechnique Federale de Lausanne, 1995.
7. LaVision Strainmaster Manual, October 2003 and website (<http://www.lavision.de>)
8. ISO New work item 712 - UK lead - Fibre-reinforced plastic composites - Determination of the open-hole (notched), and filled-hole, tensile strength (similar to ASTM D5766, EN6035 and AITM 1.0007)
9. ASTM D 5766 - Standard Test Method for Open Hole Tensile Strength of Polymer Matrix Composite Laminates.
10. EN 6035 Aerospace series - Fibre reinforced plastics; Determination of notched and unnotched tensile strength.
11. AITM 1.0007, Fibre Reinforced Plastics - Determination of notched and unnotched tensile strength
12. J.M. Whitney & R.J. Nuismer, "Uniaxial Failure of Composite Laminates Containing Stress Concentrations", *Fracture Mechanics of Composites*, ASTM STP 593, 1975.
13. Broughton, W.R.B, Crocker, L.E., Gower, M.R.L. Gower and Shaw, R.M., "Assessment of Predictive Analysis for Bonded and Bolted T-Joints", NPL Report DEPC-MPR 002.

ACKNOWLEDGEMENTS

The research reported in this Measurement Note was carried out at NPL as part of the 2004/2005 Materials Interim Programme funded by the United Kingdom Department of Trade and Industry (National Measurement System Directorate). The authors would like to express their gratitude to the Industrial Advisory Group, and colleagues Jerry Lord, David Mendels, Bill Broughton and Nick McCormick.

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