ICEM12- 12th International Conference on Experimental Mechanics
29 August - 2 September, 2004 Politecnico di Bari, Italy

ROUND ROBIN EXERCISE FOR OPTICAL STRAIN MEASUREMENT

D.-A. .Mendels[a], E. Hack[b], P. Siegmann[c], E. Patterson[c], L. Salbut[d], M. Kujawinska[d], H.R. Schubach[e], M.M. Dugand[f], L. Kehoe[g], C. Stochmil[h], P. Brailly[h], M. Whelan[i]

[a] *NPL Materials Centre, National Physical Laboratory, Queens Road, Teddington, TW11 0LW, UK, david.mendels@npl.co.uk*
[b] *EMPA, Swiss Federal Laboratories for Materials Testing and Research, Ueberlandstrasse 129, CH-8600 Duebendorf, Switzerland, erwin.hack@empa.ch*
[c] *University of Sheffield, Dept of Mechanical Engineering, Mappin Street, Sheffield, S1 3JD, UK e.a.pattenson@sheffield.ac.uk*
[d] *Warsaw Technical University, Institute of Micromechanics and Photonics, 8 Sw. A. Boboli St., Warsaw 02-525, Poland, m.kujawinska@mchtr.pw.edu.pl*
[e] *Dantec-Ettemeyer AG, Nersinger Strasse 12-16, Elchingen 89275, Germany, reinhard.schubach@dantec-ettemeyer.com*
[f] *C.R.F. Società Consortile per Azioni, Tecnologie innovative di pordotto – Ottica, Strada Torrino 50, Orbassano 10043, Italy, mariemarguerite.dugand@crf.it*
[g] *Optical Metrology Innovations Ltd., 2200 Cork Airport Business Park, Cork, Ireland, liam.kehoe@omi.eu.com*
[h] *SNECMA, Materials and Processes Dept, Site de Villaroche, Rond Point René Ravaud, Moissy Cramayel 77550, France, carole.stochmil@snecma.fr, philippe.brailly@snecma.fr*
[i] *Joint Reseach Centre, IHCP, Via Enrico Fermi, 1, Ispra, 21020, Italy, maurice.whelan@jrc.it*

ABSTRACT
Pre-normative research in the area of strain measurement using optical techniques is proposed. These techniques use a non-contacting approach to the assessment of engineering artefacts subject to in-service loading. The EU-funded project 'SPOTS' addresses the lack of standards and reference materials that are necessary for the full benefit of the new technology to be realised. An initial round robin exercise was conducted in order to establish the sources and levels of variability in results arising from a lack of standardisation and unified methodologies. The two main results of the exercise are presented here, namely a standard data format for robust exchange of optical strain measurements between different parties, and an overview of experimental results for a tensile coupon of complex geometry.

1. INTRODUCTION
It generally assumed that there are two main drivers for standards users. The first one is carrying-out a measurement that is conform to the rules of quality assurance, without the need to revise the test conditions and methodology. The second is the trust at all levels, from the experimentalist to the lead scientist and the designer, that the value measured is adequate for the use in another environment (e.g. different laboratory, companies, etc...). In order to fulfil these requirements, optical strain measurement techniques need to be defined in terms of the uncertainty associated with the equipment, with data processing, and finally with the measurement itself. This is one of the goals of the EU-funded project 'SPOTS', which

particularly addresses the lack of standards and reference materials that are necessary for the full benefit of optical strain measurement methods to be realised [1].

A round robin exercise was conducted to establish the sources and levels of variability in results arising from a lack of standardisation and unified methodologies. A tensile coupon with an intricate geometry was used to compare a wide range of optical strain measurement techniques. Electronic Speckle Pattern Interferometry (ESPI), moiré (grating) interferometry, thermoelasticity, digital photoelasticity, and image correlation techniques were used with varying degrees of success.

In the following, the geometry of the round-robin coupon and the experimental conditions are presented, together with the challenges faced by the consortium. The results are further discussed in terms of their two main outputs: a standard data format for the consistent exchange of results between partners, and an inter-comparison of experimental results from two methods (photoelasticity and ESPI).

2. SPOTS ROUND-ROBIN COUPON

A specific Aluminium coupon (EN-AW-6082 T4) was machined by spark erosion from CAD drawings. The main idea of the geometry was that it did not allow for an easy evaluation of the strain field by other means than an optical strain measurement method (Fig. 1), which ensured a 'blind' test over the panel. Furthermore, a complex strain field with large variations in all measurable components is generated upon application of a tension along the specimen. Within the area to be measured, three openings were introduced: a "S" slit with a double curvature, and two holes of 1 and 2 mm diameter respectively. The "S" slit was chosen because:

- it did not allow for a precise measurement of the specimen dimensions, and therefore prevented the accurate manufacturing of 'dummies' and/or FE modelling;
- it introduced an asymmetry, and therefore rigid-body motion, in the present case a rotation, which is known to introduce some problems with sensitive optical strain methods, and systematic errors in the extraction process;
- the strain field generated is complex, and presents both small and large gradients, which should further reveal the limitations of the methods.

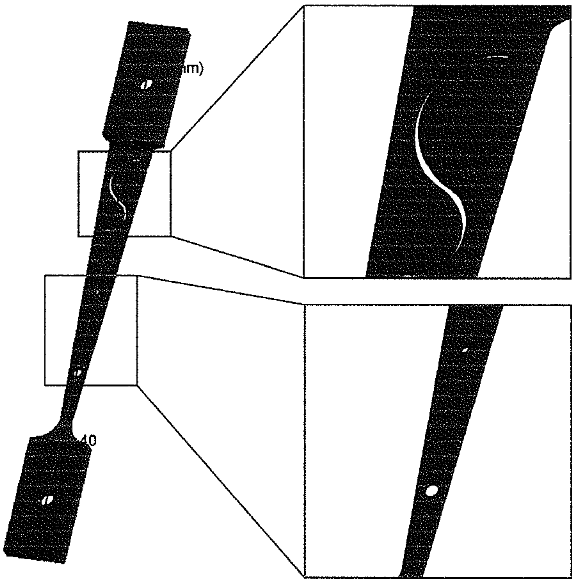

Fig. 1: Geometry and FE mesh of the SPOTS round-robin coupon

Additionally, the thickness of the specimen (1 mm) was chosen to be small enough to permit large displacements in a tensometer with limited load capacity (maximum 1 kN). The main disadvantage of such a low thickness is that the specimen could be subjected to out-of-plane bending if it was not well aligned in the tensile grips.
Studies of the stress-strain behaviour of the specimen where also carried-out by finite elements, using ANSYS8.0. A full 3-D rendering of the coupon was generated from the CAD Drawing, and meshed with 3-D 10-node tetrahedral structural solid elements (SOLID187). These elements allow for an elasto-plastic behaviour with strain hardening, i.e. plasticity was fully accounted for in the analysis. The material properties are given in Table 1.
Allowing for an elasto-plastic behaviour was needed as the loads were not specified to the participants, and only a load range was indicated: because the various methods under consideration involved a wide range of sensitivities, each participant was left with the option of choosing the loading range that suited best his method. In terms of modelling, the force levels corresponding to the loads applied by the partners were applied at the nodes located on the $y = 0$ plane on the inside surface of the top hole, while the bottom was held with a zero-displacement condition. Because the specimen was left free to rotate in the plane, a weak-spring reaction force of 0.01 μN was added at the bottom left corner of the specimen, in order to facilitate representation in the deformed state (it was checked that the load did not have any influence on the numerical values obtained, being 8 orders of magnitude smaller than the applied loads).
The round robin concentrated on the analysis of displacement/strain results along the y-axis of the specimen, defined as passing through the centres of the 4 holes in the specimen (Fig. 1).

Table 1: Properties of Aluminium EN-AW-6082 T4

Property	Value
Young's modulus	69 GPa
Poisson's ratio	0.33
Density	2770 kg/m^3
Tensile Yield Stress	110 MPa
Compressive Yield Stress	110 MPa
Tensile Ultimate Stress	205 MPa

3. RESULTS

In a first step, the qualitative agreement of strain maps was considered. The methods did not show major differences between each other, and most agreed with the trend of the FE simulation. This was followed by a quantitative assessment of the data and comparison between similar methods. To do so, the first step is to exchange robust data that can be dealt with irrespective of the measurement method. As such, one of the benefits of the exercise was certainly the establishment and refinement of the standard data format used by the participants to report strain results.

3.1 Standard Data Format

The standard data format was primarily established to allow direct and automated extraction of the results. The main difficulties were encountered while trying to establish a format that suited most methods, and afterwards in establishing the location of the optical axis system as opposed to the specimen's natural axis system. For convenience, an ASCII file format was used (files compressed in the ZIP fomat were allowed to facilitate electronic exchange). The file is built on two distinct parts, namely one heading section describing the nature of the measurement and all informations needed to characterise the values reported, followed by the data itself. It was agreed that the first three lines would be used to describe the measurement and describe the quantity measured (measurand and unit of data reported). The next four lines are defined by the optical system including any mask used, i.e. the number of pixels in each row and columns reported later do not correspond obligatorily to that of a CCD camera chip. The pixel pitch represents the scale factor by which a length measured in pixels on the picture needs to be multiplied in order to be expressed in meters. The next two lines indicate the origin of the specimen's axis system on the picture, and is therefore given in pixels. This is followed by the global transformation matrix, comprising both translation and rotation, to obtain the global axis system, i.e. that of the specimen, from the local system, i.e. that of the picture. The measurement results are enclosed between the 'EOH' (end of header) and 'EOF' delimiters. An example of the data format is given in Table 2.

Table 2: Example data format

Photoelasticity data, L1= 100N, L2= 350N	*File descriptor*
Shear strain	*Measurand (e.g. intensity, phase, displacement, strain)*
m/m	*units of measurand (AU-arbitrary units for intensity)*
5	*no. of pixels in each row*
10	*no. of pixels in each column*
±0.001E±00	*pixel pitch at sample plane in row (in metres)*
±0.012E±00	*pixel pitch at sample plane in column (in metres)*
0 0 1 0 0 -1	*co-ordinates (in pixels by row then column) of local origin, point on local x-axis, point on local y-axis*
1 1 1 0	*transformation matrix for local to global axes* $r_{11}\ r_{21}\ r_{31}\ t_1$
1 1 1 0	$r_{12}\ r_{22}\ r_{32}\ t_2$
1 1 1 0	$r_{13}\ r_{23}\ r_{33}\ t_3$
0 0 0 1	*Fixed last line of transformation matrix*
EOH	*End Of Header*
±0.000E±00 NAN ±0.000E±00	*Data in rows with single space delimiters. Masks indicated by 'NAN'. Origin defined at bottom left corner.*
EOF	*End Of File*

3.2 Round-Robin Results

Because a large number of measurand were encountered, it was not possible to compare the all the methods on the same plot, since different measurand are prone to different sources of

error. Ideally, the accuracy of each experimental method should be plotted against the field of view, for a similar measurand.
As in all inter-comparison exercises, results of various qualities were obtained:

- good to excellent: quantitative data agrees within 10% with the FE model
- average: quantitative data are representative, but sources of error are found and can be isolated
- poor: the method does not permit that kind of measurement within a reasonable accuracy, or the data is not representative, or the scale (e.g. measurement of the value of the pitch) is wrong. In particular, some methods were too sensitive to rigid body movements and results would need to be adjusted to be comparable to other methods.

The participants identified a number of problems and/or difficulties with the test method, namely:

- optical accessibility of specimen in tensometer: due to the wide range of techniques examined it was not found possible to fix the dimensions of the specimen so that it suits all measurement apparatus. This limitation is being handled in another part of the 'SPOTS' project: standard reference material;
- operation of the tensometer: the handle was not balanced, and its weight could induce creep of the specimen;
- specimen holders: the excessive clearance of guide on posts could permit out-of-plane displacements;
- specimen holders: excessive out-of-plane displacement due to the weight of the holders could occur;
- torsion of the specimen, due to its small thickness;
- rigid body motion (rotation and translation): this effect was voluntarily introduced with the "S" slit.

Most of the problems arising in this round robin were therefore linked to the use of a tensometer, because the specimen was not self-contained in the device applying the displacement, and the experimentalist had therefore a non-negligible influence on the quality of the results. These remarks call for a self-contained, monolithic device, which could not be produced for an initial round robin.

Among all the results, it is useful to give two examples to illustrate some of the problems that have arisen. In the present paper, only results from photoelasticity and ESPI are shown. Grating interferometry and image correlation data were also obtained during this round robin, and led to conclusions similar to those described below.
It must be noted that no correction was applied to the results of the participants by the organiser. The method used was the automated extraction of the results from the data file sent by the partner, and representation versus corresponding FE data. In the following, in order to test the variability of test methods, strain results obtained for different loads were normalised by the maximum strain obtained by FE. This allowed the representation of the results of different load ranges on the same plot for easier comparison.
Figure 2 shows a good match both between experimental results obtained by photoelasticity and with numerical ones. Although the strain features are well captured around the two holes, the largest mismatch is obtained around the "S" slit, i.e. in the y-range 15 to 40mm. The reason is essentially that, although the displacements are large in this region, their gradient is small, and the accuracy of the photoelasticity method is limited by the small strain value.

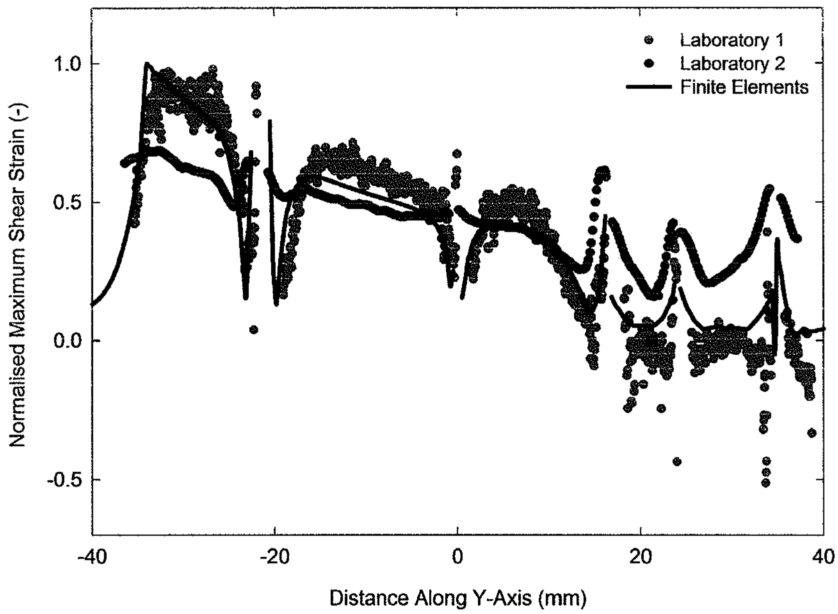

Fig. 2: Normalised maximum shear strain along the y-axis, obtained by photoelasticity

Nevertheless, all the strain concentrations are present, and given the normalisation applied it is believed that results of similar accuracy would be obtained on the two halves of the specimen provided different loads are used to probe each half separately. The results from Laboratory 2 are also degraded by an out-of-plane bending due to the weight of the sample holder in the tensometer.

The next example illustrates some of the difficulties associated with rigid body motion (RBM) and vibrations. Three laboratories completed the exercise using ESPI, and results could be compared following the procedure introduced. Firstly, all the measurements agreed well qualitatively, and quantitatively are relatively close to each other, apart from one (Laboratory 3). The measurement carried-out by Laboratory 1 was in good agreement with the numerical results, even in the region of the "S" slit. However, the accuracy was limited close to the holes and the edges of the "S" slit, due to the choice of the mask, and uncontrolled rigid body motion of the specimen in the tensometer (both out-of-plane bending and in-plane rotation were present). These effects are maximised close to the openings in the specimen, in particular when strains are considered, as they reach high values in these locations. In fact, the measurement would show smaller deviation from the numerical values if the data were not smoothed and differentiated, as was observed on the displacement data. The measurement carried-out by Laboratory 2 was quantitatively better as RBM was negligible, although its accuracy in the high strain concentration regions was limited by the choice of the mask and a slight out-of-plane misalignment of the specimen. However, it must be remarked that ESPI captured with a relatively good accuracy the strain value in the middle of the "S" region ($y \sim 30$mm). On the other hand, the measurement carried-out by Laboratory 3 was prone to a large noise associated with poor isolation of the system from vibrations. This was also due to a different method of capturing the data. Contrarily to Laboratory 3, Laboratories 1&2 used a multiple load step procedure where the strain maps are summed, which resulted in lower signal to noise ratios.

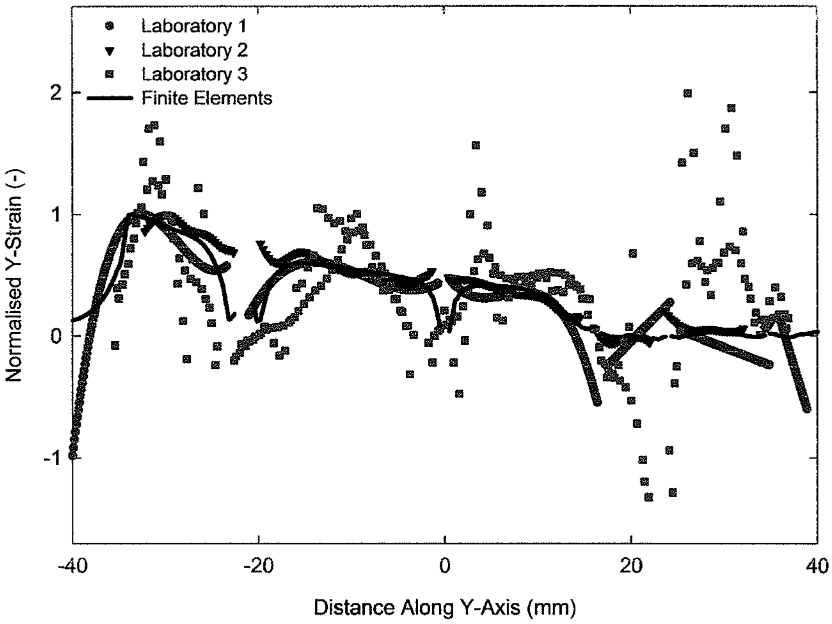

Figure 3: Normalised strain in the *y*-direction along the *y*-axis, obtained by ESPI

From this first exercise, we could as well conclude that the test method should be revised in order to have:

- reduced influence of the experimentalist skills on the test result;
- increased optical access: this could be achieved by tailoring the dimensions of the specimen to suit the needs of each method, where the specimen can be scaled easily;
- reduced freedom given to the experimentalist in terms of load.

Furthermore, in order to enable direct comparison between methods, it is recommended that the partners use the same measurand where possible, and similar procedures in the load application. It must be remarked that the direct comparison of methods is not the primary goal of the 'SPOTS' project, nor was it the goal of this inter-comparison exercise. The ultimate goal of these inter-comparisons is to determine traceability routes and confidence intervals for the various techniques based on experimentally determined uncertainties in order to provide easy access to these technologies.

4. CONCLUSIONS

In conclusion, the results of this first inter-comparison exercise have met the expectations, allowing the determination of a large number of weaknesses in the data format, the test method and the interpretation of the results. All of these have been corrected, which has allowed direct comparison of results between different groups. Most of the results were good enough to allow an engineering interpretation and direct comparison to each other or to numerical results; the source of failure of the others has been determined and understood.

A number of limitations of the test method used during this exercise were found while exploiting the results. In particular, there have been a lot of difficulties for some partners associated with the dimensions of the specimen. In order to eliminate this concern for the second inter-comparison exercise, it seems necessary to produce a device that can be scaled easily, while retaining all its essential features. Also, in order to simplify the analysis, a simpler device could be used, which allows only a limited number of load (or displacement) steps. Finally, in the second round robin, the geometry could also be simplified to a large extent, so that an analytical solution is available. In this case, the results are generally of better quality, and would permit the establishment of a map of the accuracy of the methods for a given field of view, for example.

In order to gain additional information on the reproducibility between experiments of the same kind, it is also envisaged to involve a larger panel of laboratories through VAMAS activities [2] and the technical working area (TWA) 26 [3]. The technical drawings of the specimen are available in electronic format from the author or the chairman of the TWA26.

BIBLIOGRAPHY

[1] see http://www.opticalstrain.org

[2] the Versailles Project on Advanced Materials and Standards (VAMAS); information available from the website http://www.vamas.org, or from the VAMAS secretary (e-mail martin.rides@npl.co.uk)

[3] VAMAS TWA26: Full Field Optical Stress and Strain Measurement; information available from the website http://www.twa26.org, or from the TWA's chairman richard.burguete@bae.co.uk

ACKNOWLEDGEMENTS

The work presented forms part of the SPOTS project (G6RD-CT-2002-00856), which is funded through the GROWTH programme of the European Union.