Design of Reference Materials and Standardised Tests for Optical Strain Measurement

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Abstract

The need for standards in optical methods of strain measurement has been discussed previously and attention has switched to the creation of reference materials and standardised tests. Reference materials provide a means of calibrating a measurement system by comparison to a standard that is traceable to an international standard. In other words there is an unbroken chain of comparisons between the measurement system and the international standard with defined uncertainties in each comparison. A standardised test allows the performance of the measurement system to be assessed against a number of known quantities and such tests should be as challenging as the applications for which the measurement system has been designed. The preliminary design of a reference material for optical techniques of strain measurement are presented. Results obtained from the preliminary design using digital image correlation, ESPI, grating (moiré) interferometry, LDVTs, photoelasticity, strain gauges and thermoelasticity support the design hypothesis and have aided the refinement of the design. It is worthy of note that the first set of results produced with the new design showed remarkable correlation despite being obtained independently in four different laboratories in four different countries using six different techniques. Initial designs for a set of standard tests have also been created and some preliminary results will be presented. The set of tests incorporate boundaries, strain discontinuities, strain reversal, rotation of the principal direction and a strain concentration within three test materials. The concept of virtual standardised test materials has been introduced to allow the performance of the algorithms within a measurement system to be assessed so that a standard and comprehensive diagnostic and evaluation framework will be available to system designers, manufacturers and end-users.

Introduction

In recent years there has been a burgeoning of new optical techniques for measuring deformation and strain. However, there has not been a corresponding increase in usage of these techniques by industry. The reasons for the poor level of adoption by industry are complex and associated with both economic and technical factors. However one technical factor cited in discussions with industrialists has been the lack of reference materials and certification procedures available for full-field methods of optical strain measurement. Reference materials are required for the calibration of an instrument and allow the comparison of the measurement results with a working standard and subsequently via a chain of comparisons to a primary or national standard. A consortium consisting of eleven partners from eight countries was established in Europe [1] and partly funded by the European Commission to develop reference materials for optical strain methods and is known as SPOTS (Standardisation Project for Optical Techniques of Strain measurement). The consortium includes university research laboratories, national laboratories, instrument designers, manufacturers, vendors and end-users from the aerospace, automotive and electronics industries. A rational decision making process [2] was employed to guide the development process and this involves identifying the essential and desirable attributes of the design which in this case was achieved through consultations with the experimental mechanics community as well as through discussions within the consortium. This process lead to the identification of two needs: first, for calibration materials and procedures that would allow the certification of instruments and complete systems; and second, for standardised tests that permit the performance of an instrument to be evaluated. Calibration is important within a regulatory regime and for quality assurance whilst evaluating performance is important in the development of new systems, for purchasers of strain measurement systems, and for suppliers and end-users during the setting-up and maintenance of systems. The requirements of calibration imply that the reference materials should be simple to allow repeatable and reproducible measurements and straightforward comparisons in which uncertainty is minimised. The evaluation of performance implies more demanding test materials which will allow the capabilities of a measurement system to be assessed. The development of both a reference material and a standardised test are described here and some preliminary results from the former are presented. The SPOTS project began in January 2003 and is scheduled to finish in December 2005 after which it is anticipated that the preparation of an international standard could begin based on the work of the project.

Design of Reference Materials

The rational decision making process [2] was utilised to design the reference material. In this process, the essential and desirable attributes of the design are identified and a number of options or alternative designs are generated. The extent to which each alternate possesses the attributes is assessed in order to highlight the designs which best fit the requirements. This approach is intended to allow a large search space so that many widely different solutions can be considered and to avoid the inappropriate dominance of previously utilised solutions. In this case, consortium members and the wider experimental mechanics community were asked to identify attributes and to assign levels of importance to each attribute. Five essential attributes were identified: easy optical access, lack of hysteresis, an in-plane strain field, traceability to international standards and utilisation of the length standard for traceability [3]. Twenty-four desirable attributes were also defined and used to guide the choice of preliminary design. A number of brainstorming sessions lead to a short-list of candidate designs including a disc subject to compression along one diameter, a Hertzian contact pair and a beam subject to four point bending. The latter choice was preferred for a variety of reasons including: use in previous standards associated with optical measurements [4], simplicity of geometry and the perceived suitability of the strain field for calibration.

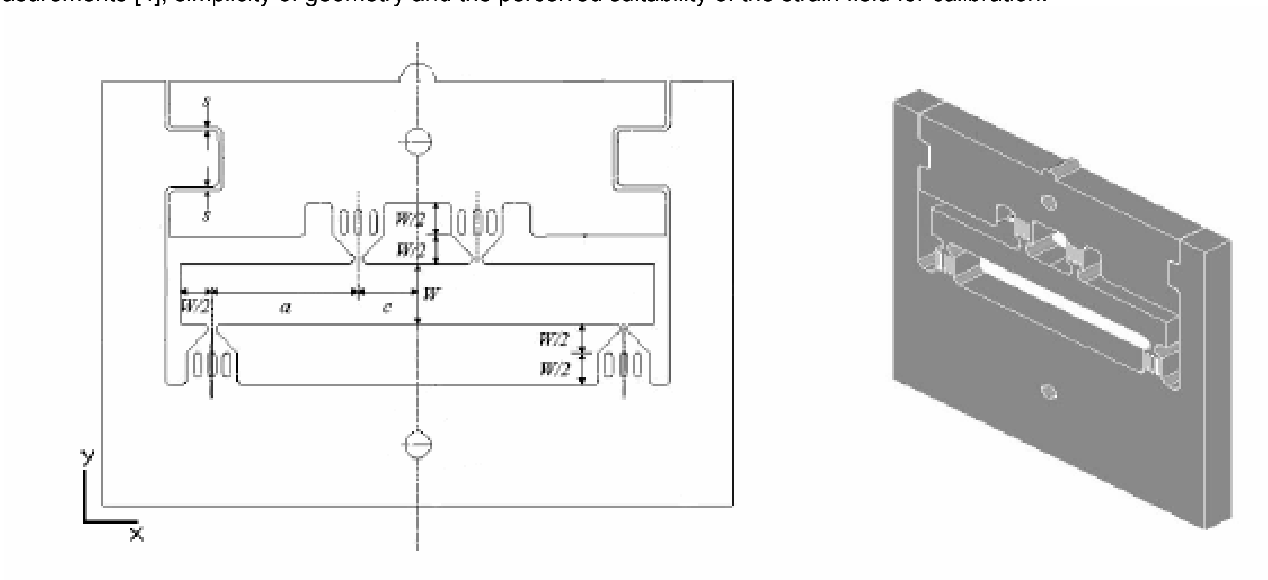

Figure 1: Schematic and solid-model drawings of the monolithic reference material with some important dimensions shown.

A preliminary round robin test within the SPOTS consortium [5] on a tensile specimen with some geometric features had revealed the difficulties associated with generating reproducible results from different optical systems in laboratories located in different countries even when the test specimens were manufactured and supplied from one source and many laboratories used the same model of loading frame. The crucial importance of a reproducible loading system became apparent and lead to the concept of a test specimen and loading frame contained with a single monolithic design. The preliminary design is shown in figure 1 and consists of a central horizontal beam loaded in four-point bending via an outer loading frame. The outer loading frame is designed to eliminate mis-alignment and positioning errors whilst allowing either compressive or tensile loading. The means of application of load is unrestricted and could be dead-weight loading or via a loading machine. The loading frame is massive relative to the test specimen and contains an interlock in the top left and right corners to protect the test beam from over-loading and plastic deformation. In compressive loading, the bottom surface of the frame can located on a platen and the load applied through the half-cylinder on the top surface to ensure alignment. In tension alignment is achieved by loading on pins through the two holes located on the centre-line of the frame. It is intended that displacement loading should be applied to permit traceability to the international standard for the metre and so in the second prototype design (figure 2) a series of teeth in the top corners allow the use of a variety of types of displacement transducers with either the internal or external surfaces. The choice of displacement transducer will be a decision for the user but is likely to be influenced by the availability of calibrated transducers and the scale of the test specimen. The monolithic frame dictated that knife-edges could not be used at the loading points on the beam and an alternative mechanism was required that would transmit a load but not a moment. A set of whiffle-trees was selected which maintain the continuity between the test specimen and the loading frame but minimise the transmission of lateral and rotational forces.

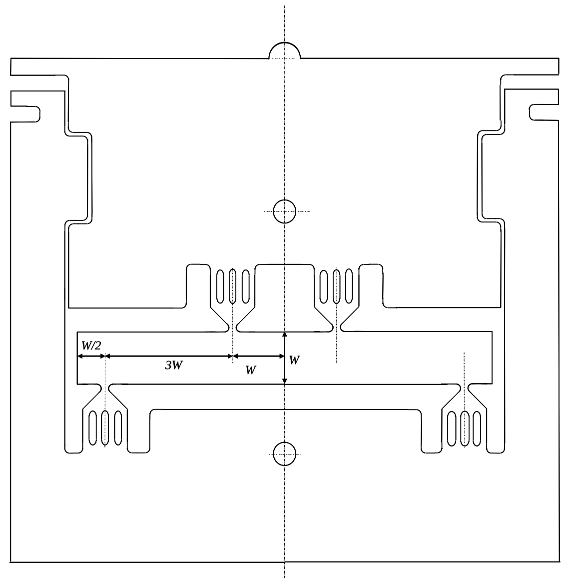

Figure 2: Schematic drawing of second prototype design of reference material with more flexible whiffle-trees and flats in top corners for displacement measurement.

The design is parametric based on the beam width, W, in the direction of the load and this should allow the calibration material to be manufactured from a range materials and scales from micro to macro. The design is two-dimensional because the SPOTS consortium decided to focus on the simpler two-dimensional problem as an initial step and this was believed to be reasonable since in practice most optical measurements of strain are conducted in two-dimensions at the moment. The central section of the test beam between the two inner loading points forms the gauge section of the reference material. The simple theory of bending can be employed to describe the strain field in this region and expressions can be obtained to describe the Cartesian strain components as functions of the distance, y from the neutral axis of the beam and the applied displacement load, d:

$$\varepsilon_{xx} = \frac{-yd}{6W^2} \qquad \varepsilon_{yy} = \frac{-\upsilon yd}{6W^2} \qquad \varepsilon_{xy} = 0 \tag{1}$$

where υ is Poisson's ratio. In order, to simplify the reporting of results and to allow the assessment of uncertainty and repeatability, it is proposed that the results should be reported as the derivative of strain with respect to distance from the neutral axis and the derivative of this quantity with respect to displacement load, i.e.

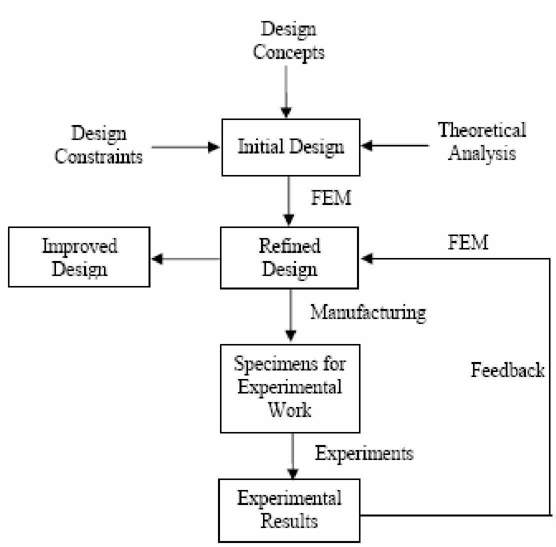

Figure 3: Design flow-chart for reference materials

$$\frac{\partial e_{xx}}{\partial y} = \frac{d}{6W^2} \qquad \frac{\partial e_{yy}}{\partial y} = \frac{\upsilon d}{6W^2} \tag{2}$$

and

$$\frac{\partial}{\partial d}\left(\frac{\partial e_{xx}}{\partial y}\right) = \frac{1}{6W^2} \qquad \frac{\partial}{\partial d}\left(\frac{\partial e_{yy}}{\partial y}\right) = \frac{\upsilon}{6W^2} \tag{3}$$

This design was selected using the rational decision making process and the detail embodiment generated using theory of elasticity to perform the appropriate analyses. The complete design was subsequently refined using finite element analysis to investigate the locations of stress concentrations prior to manufacturing and testing a prototype. This process is outlined in the schematic flow-chart shown in figure 3 and the detailed analyses can be found on the SPOTS website [1].

Design of standardised tests

The same design process has been employed for the standardised test specimen where the requirement was for a test that would allow validation of the performance of a system. Traceability was not a requirement since this would be provided through the calibration process using the reference material. In order to be useful for development and diagnostic work it is necessary to provide opportunities to validate each stage of a measurement process and hence each sub-section or algorithm of a system. The objectives of the SPOTS project are to create a unified set of materials that are applicable to all full-field optical methods of strain measurement. Since the spectrum of optical techniques includes many different approaches to strain measurement, this objective represents a significant challenge. One of the first steps in meeting this challenge was to develop a process flow-chart that was applicable to all techniques. This is shown in figure 4 together with data from around a crack in a compact tension specimen obtained using ESPI [6] and which is included as an exemplar. Only a few techniques use every process included in the flow-chart but each technique uses a different combination of these process. However a standardised test would need to contain standardised data sets (SDS) that would allow validation of the output from each process. In addition, the rational decision making process identified the possession of the following features in the strain field as desirable attributes: specimen boundaries, strain discontinuity, sign reversal in the strain distribution, strain concentration and rotation of the principal strain directions. Again, brain-storming sessions were used to generate possible solutions including: a notch, a Brazilian disc, a simple beam subject to bending, a diaphragm, a compound beam, a pair of interference fit rings, a compound Brazilian disc, a tensile plate with central hole, a Hertzian contact pair and a Mode I crack. The list of attributes was used to evaluate the suitability of these solutions and the interference-fit rings and the Hertzian contact pair were selected for more detailed design. It is intended that the interference-fit rings will not have a physical manifestation but will exist only as a virtual standardized test or a set of functions from which standardized data sets can be generated in order to validate algorithms. Photoelasticity has been chosen as an exemplar and the functions required to generate the SDS are shown in figure 5. Similar sets of functions and pathways are available for ESPI and thermoelastic stress analysis and are being developed for grating interferometry, image correlation, and moiré. These will be available from the SPOTS website [1].

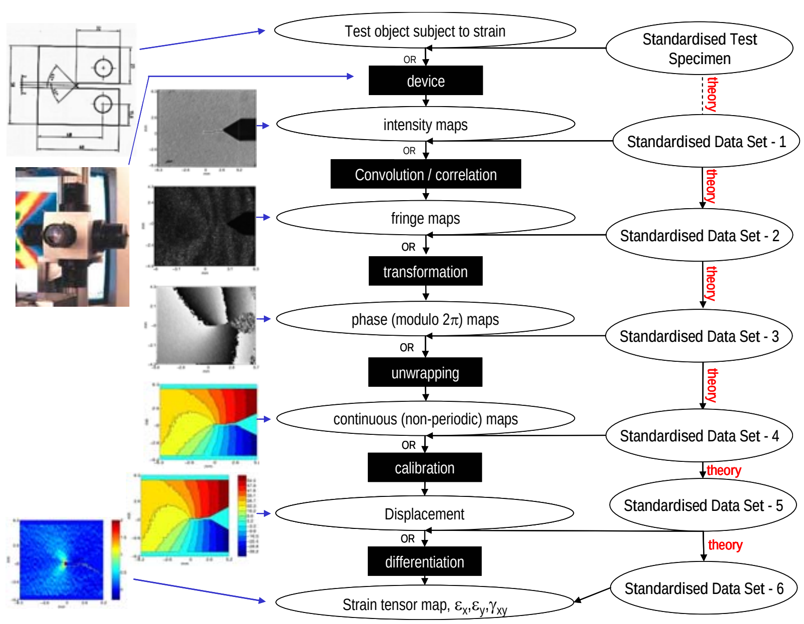

Figure 4 – A schematic illustrating the generic measurement process (*centre*) for optical strain measurement systems and the relationship to the proposed standardized test and data sets (*right*). The ovals represent data sets and the rectangles represent components of the system. The process is exemplified (*left*) using measurements of the y-direction (vertical) strain in a cracked compact tension specimen from EPSI [6].

The Hertzian contact pair has been developed as a physical test specimen with a corresponding set of functions and pathways. A disc in contact with an elastic half-space was chosen as the contacting pair as shown in figure 6. The physical specimen incorporates the monolithic design in order to reap the advantages of reproducible loading but in this case a pair of leaf springs is included on each side of the test specimen in order to achieve the integrity of the monolithic design. These leaf springs also provide resistance to out-of-plane deformation. The same design process as shown in figure 3 is being followed in this case although progress is less advanced than for the reference material. The design analyses are complete and will be available on the SPOTS website [1]. At the moment physical specimens are being manufactured for testing by the partners in the consortium.

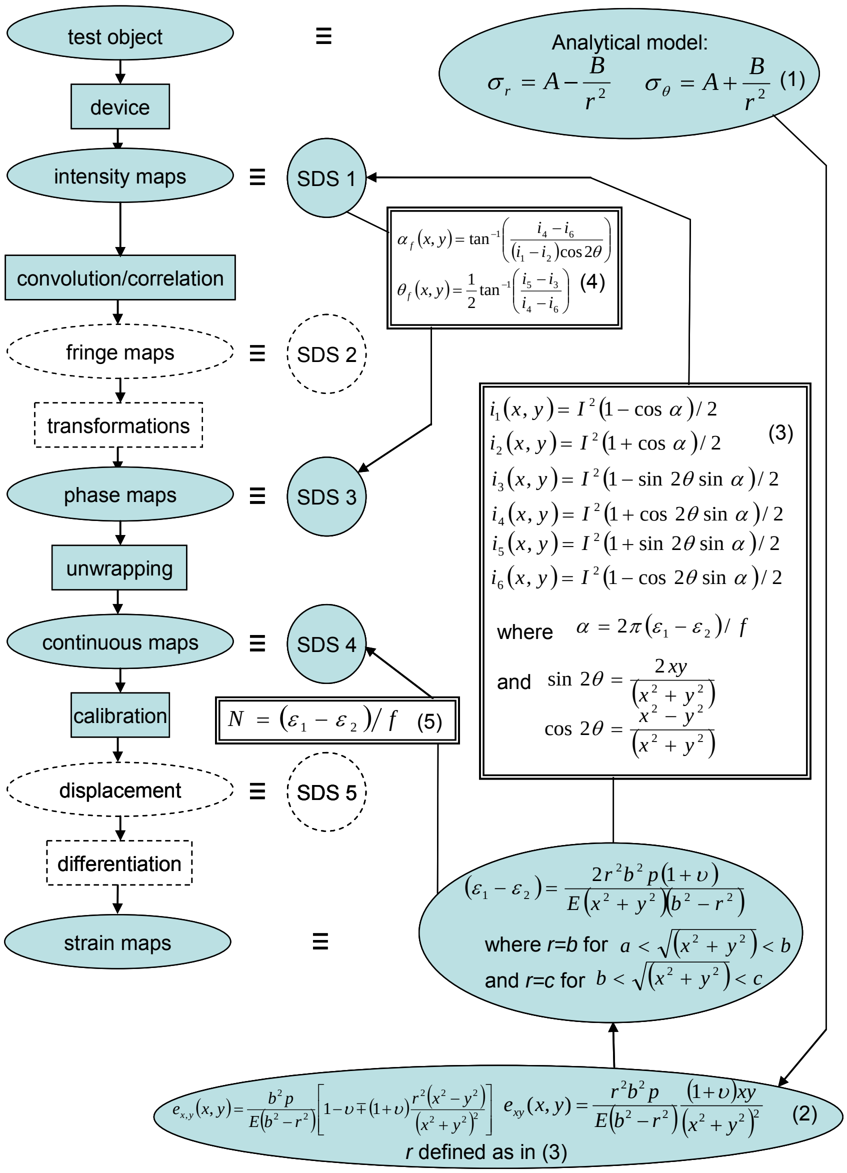

Figure 5 – Schematic diagram based on figure 4 showing the virtual standardized test (interference-fit rings) using digital reflection photoelasticity as the exemplar. The dotted boxes and ovals show data operations and sets which do not exist in digital photoelasticity using phase-stepping. The boxes with a double frame show the functions required to generate the standardized data sets.

Initial experiments

Three specimens based on the design in figure 1 have been manufactured from aluminium plate of thickness equal to the beam width, W where W was 20mm in two cases and W was 29mm in the third case. The specimens were manufactured by two partners and distributed to other partners for testing using a range of optical techniques as well as strain gauges and displacement transducers. The objectives of these first tests were to compare the strain field in the gauge section to the analytical solution and to assess the degree of reproducibility achieved by the monolithic design. Figure 7 shows one of the specimens set-up for analysis using ESPI and figure 8 shows a comparison of results from a strain gauge rosette bonded to the underside of the gauge-section with results from finite element analyses carried out independently by separate laboratories with the analytical solution. Figure 8 shows results from ESPI, image correlation and strain gauges plotted together with the finite element results and analytical solution in the form of the derivative in expression (2) as a function of the applied displacement. It is clear from these results that both close proximity to theory and reproducibility have been achieved. However, data from photoelasticity and thermoelasticity plotted in terms of stresses in figure 9 suggest that there are some differences relative to the analytical result although there is close agreement with the finite element results. These findings imply the boundary conditions on the test beam do not correspond perfectly to those assumed by the simple bending theory and as a consequence the whiffle-trees have been re-designed to reduce their stiffness as shown in figure 2. Samples of the revised design have been manufactured and are being tested at the moment.

Conclusions

Research in progress to develop a set of reference materials and standardized tests for optical methods of strain measurement is reported. A reference material for the calibration of optical systems has been designed and is being refined, however the preliminary tests have already demonstrated that its use across several laboratories in different countries and using different techniques is reproducible to a remarkably high degree. Strain data analysed as a function of applied displacement (load) shows good agreement with the analytical solution. Consequently the prototype design appears to offer excellent prospects as an easy-to-use and reliable reference material. The design of a set of standardized tests for the evaluation of systems for optical strain measurement and the validation of sub-sections, including algorithms, within the systems is in progress and the conceptual framework is in place. It is anticipated that this work will lead eventually to internationally accepted standards for the calibration and evaluation of the full optical techniques of strain measurement.

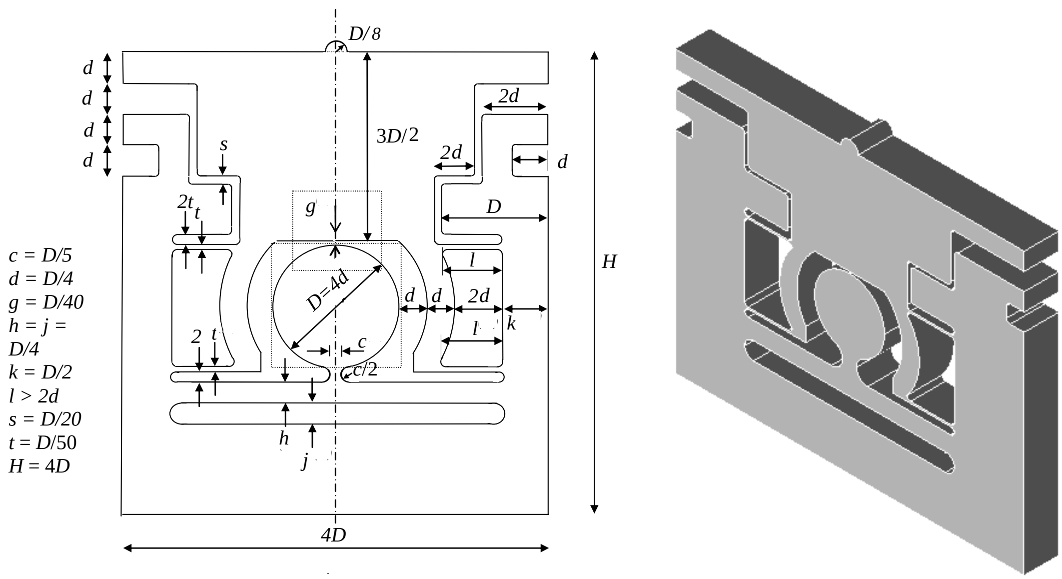

Figure 6: Schematic and solid-model drawing of the prototype standardized test specimen.

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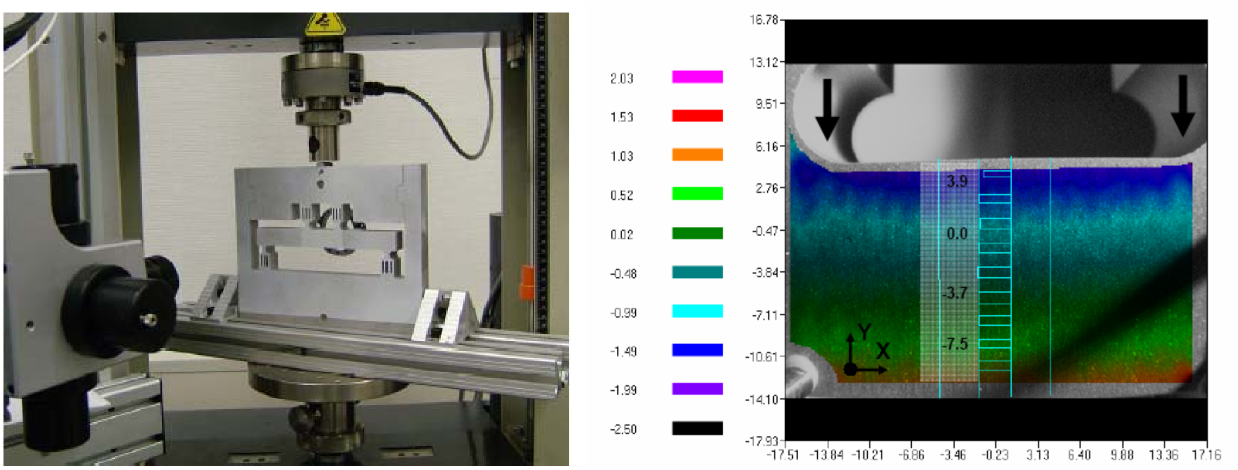

Figure 7: Reference material set-up for analysis using ESPI system (*left*) and results (*right*) for ε_{xx} in the gauge-section.

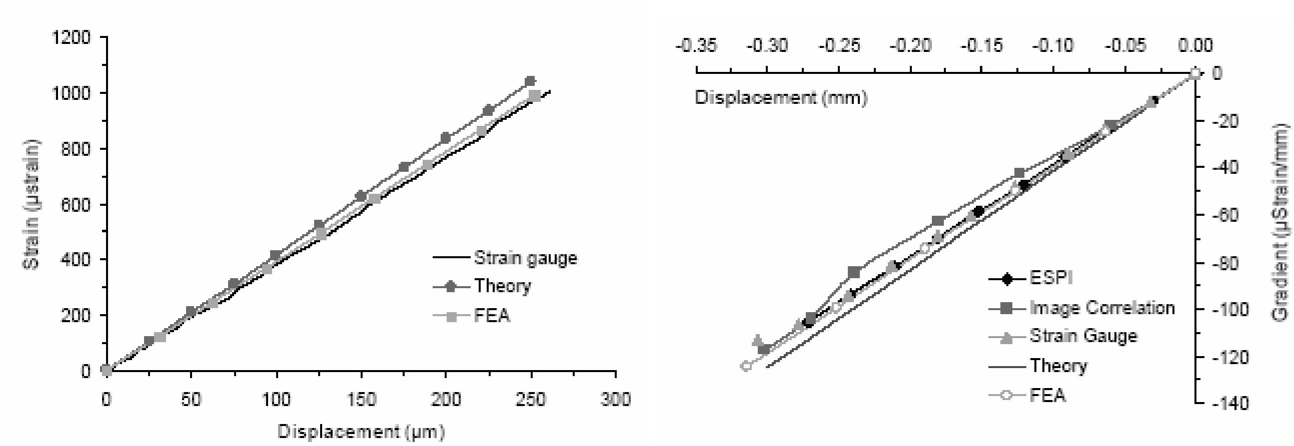

Figure 8: Experimental results from the reference material showing a comparison (*left*) of strain gauge and finite element results with theory of elasticity for the underside of the gauge-section and the relationship (*right*) between the strain gradient across the width of the gauge-section as a function of applied displacement obtained using ESPI, image correlation, strain gauges and finite element analysis.

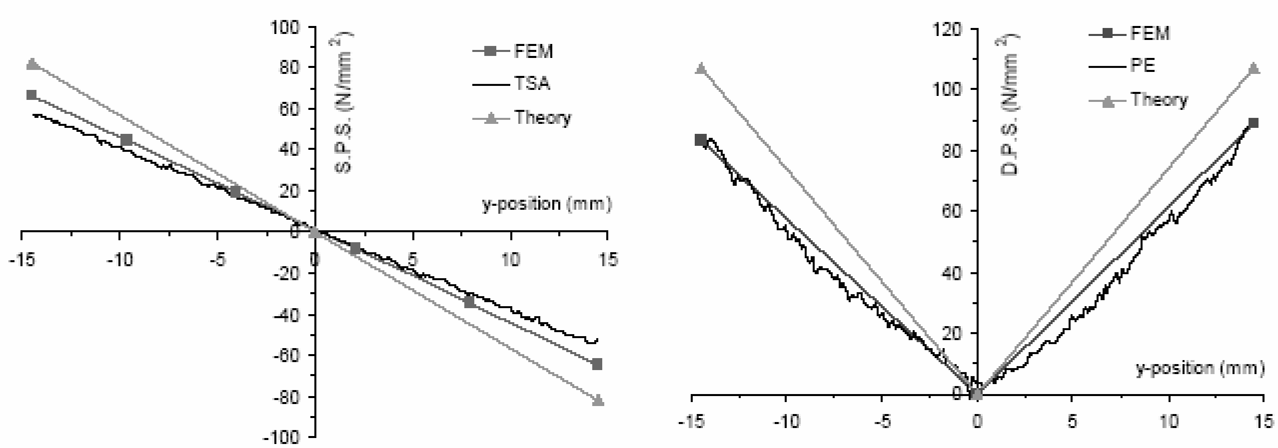

Figure 9: Experimental results from thermoelastic stress analysis (*left*) and photoelasticity (*right*) for the sum (SPS) and differences (DPS) respectively of the principal stresses with results from finite element analysis and theory of elasticity for comparison.