

Developing Standards for Optical Methods of Strain Measurement

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ABSTRACT

In 1999 under the auspices of VAMAS, an international Technical Working Area on Full-field Optical Methods of Strain Measurement (TWA26) was formed. TWA26 was charged with coordinating pre-normative research that would ultimately lead to the development of international standards in this area. In 2003 a consortium of eleven organizations from eight countries began an EU-funded research project to develop reference materials for optical techniques of in-plane strain measurement. This research will be completed at the end of 2005 and will generate a draft Technology Trend Assessment (TTA) which will be reviewed by VAMAS TWA26 before being submitted to ISO for publication. This will represent a major step towards the development of an international standard in the field of optical strain measurement and hence will provide a certification route for those interested in using such methods to validate simulations and to quantify uncertainty. Progress to date includes the design of a reference material for the calibration of optical systems for strain measurement, routes for traceability to the international standard for length, standardized tests for evaluation of sub-systems within the optical systems and draft standard guides for the application of electronic speckle interferometry, image correlation, geometric moiré, grating interferometry, photoelasticity and thermoelasticity.

INTRODUCTION

The strain gauge is the ubiquitous device for measuring strain at a single location, however a plethora of optical techniques have been developed for measuring strain over an entire field of view. The latter approach appears to provide a significantly more powerful methodology yet is not widely used outside of the experimental mechanics community. The reasons for this lack of popularity seem to be novelty and uncertainty about the reliability of these sophisticated techniques. A Technical Working Area (TWA 26¹) on Optical Methods of Full-Field Strain Methods was established under the auspices of VAMAS² (Versailles Agreement on Materials and Standards) in order to address the issues around the uncertainty concerning this group of methods. VAMAS is an unfunded mechanism for international co-operation and so in Europe a consortium was formed to fund and perform pre-normative research. The objectives of this research program were:

- the investigation and development of candidates for both physical and virtual reference materials that allow traceability, validation, and transparent comparability of full-field optical methods of strain measurement;

¹ www.twa26.org

² www.vamas.org

- the optimization of methodologies for full-field optical techniques for strain measurement; and
 - a contribution to standardization activity for full-field optical methods for strain measurement.
- This paper reports on some of the work towards these objectives performed by the consortium known as SPOTS³ (Standardization Project for Optical Techniques of Strain measurement) which includes: university research laboratories active in the development of techniques; instrument manufacturers and suppliers; end-users from the aerospace, automotive and electronic industries; and national laboratories responsible for the maintenance of standards.

METHODOLOGY

The consortium has worked in a number of modes including round-robins, brainstorming sessions followed by design and experimentation. The rational decision making model (1) was employed to allow a wide and unbiased design space to be considered for the reference materials. The world-wide experimental mechanics community was surveyed to establish the perceived desirable attributes for the reference materials. Mailing lists were used from the optical techniques division of the Society for Experimental Mechanics and for the attendees at the Advanced Techniques in Experimental Mechanics in Nagoya Japan in 2003. This data combined with input from the eleven SPOTS consortium members from eight countries resulted in twenty-three attributes being considered in the preliminary design stages. Information from an initial round robin performed by the SPOTS consortium (2) identified the over-riding importance of reproducible boundary conditions in generating comparable data.

Examination of the data from the community led to the identification of two principal needs: for calibration of instruments for optical strain measurement; and for evaluation of the instruments. Calibration is a necessary step in certification procedures required in many industries such as aerospace and includes identification of the uncertainty included in the measurements. Whereas evaluation is associated with assessing the fitness for purpose of a particular technique or system for making measurements and might be part of a technique selection process, instrument set-up procedure or purchase decision. At the moment there are no standards to allow either calibration or evaluation to be performed against an internationally recognized norm. Calibration involves comparing a locally performed measurement against a local standard which forms the first part of continuous chain of traceability to a primary (international) standard. The prerequisite to make comparisons implies that a relative simple strain field should be considered and a beam in four-point bending was selected to satisfy this need. The length standard was selected as the primary standard due to the direct relationship between length and strain and the desire to avoid defining a new international standard measure for strain. The use of the length standard implied the use of displacement loading in which the applied displacement could be measured using a calibrated instrument. When these features were combined with the desire to control the boundary conditions, then the concept of a beam loaded within a monolithic frame, as shown in figure 1, was produced.

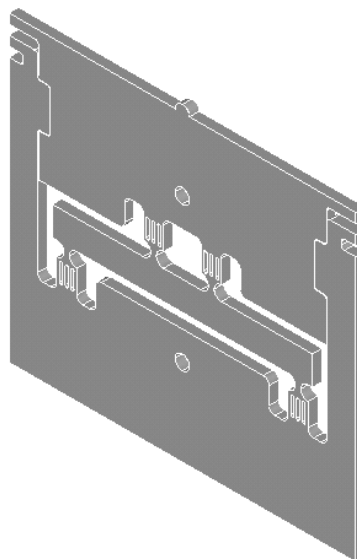


Figure 1 – 3D view of prototype reference material (EU Community Design Registration No. 000213467)

³ www.opticalstrain.org

This reference material can be loaded in either tension or compression using any device available. In a recent exhibition, a simple lever mechanism was employed and a person stood in a stirrup to apply dead-weight loading. Interlocking teeth in the upper portion of the frame protect the beam, or gauge section from overloading. The applied displacement can be measured using the flats provided in the top corners of the frame. The specimen is scaleable from millimeters to meters though the calibration will only be valid for the scale at which it is performed.

Similar concepts concerning loading arrangements and measurement were extended to the design of a standardized test sample for evaluating the performance of a system or technique. The need to evaluate the fitness for purpose of a strain measurement system implies that this sample should contain a strain field with features that will represent challenges to the system. The feedback from the community suggested that the following features should be included: a strain concentration; a variation in strain direction; a reversal of sign of strain; a discontinuity in strain distribution; and a physical boundary. The reversal in sign of strain is present in the beam subject to four-point bending in the reference material in figure 1 and so is not essential in the standardized test sample. Most of the remaining features are present in the prototype design shown in figure 2.

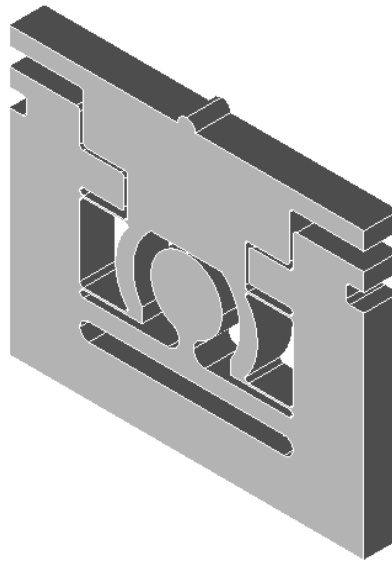


Figure 2: 3D view of prototype standardized test material (EU Community Design Registration No. 000213467)

The area for strain measurement is the central disc subject to compression and its contact with the upper half of the sample. The sample is monolithic by virtue of the two pairs of leaf springs which offer a negligible resistance to loading but ensure that the contacting pair remain connected and aligned. In this case only compressive loading is viable and again the gauge section is protected from over-loading by interlocking teeth. The applied displacement can be measured at the flats in the top corners. The disc is supported by a flexible beam in order to generate larger and thus more readily measurable displacements. The dimensions of the standardized test material are scaleable from millimeters to meters.

In evaluating the performance of a measurement system it is often desirable to be able to identify the performance of its sub-systems since many systems will consist of multiple operations and devices. The aim was to design a unified set of reference materials and standardized tests that would be applicable to the complete range of optical techniques of strain measurement. To aid this process considerable attention was given to classifying the individual stages in each technique using a single classification system [3] shown on the right in figure 3 in which devices or processes are represented by rectangles that generate data sets represented by ellipses. Not every technique will include every device or process; in fact speckle interferometry is perhaps the only technique to utilize every stage in the classification system. The classification system highlights the need for standardized data sets that would allow the efficacy of each device or process, usually embedded in an algorithm, within the measurement system to be evaluated. The standardized test material only provides a basis for evaluation of the complete system. Therefore, the concept of standardized data sets connected by analytical theory as shown schematically on the left in figure 3 was developed.

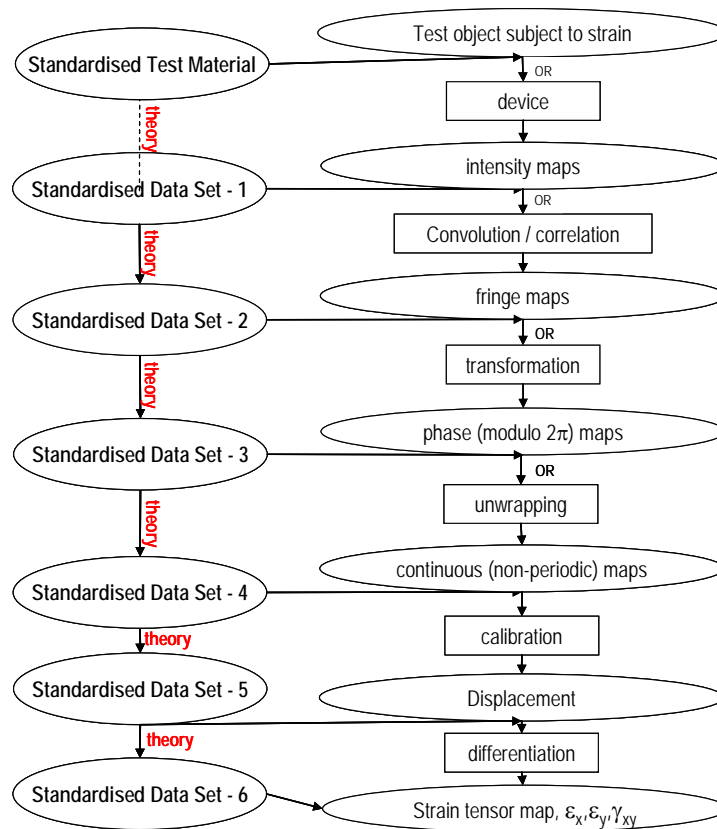


Figure 3: A schematic illustrating the classification of processes within an optical strain measurement system (right) and the connection to standardized data sets (left).

The generation of standardized data sets can be achieved using, what have been named, functional pathways. These pathways can be written for each optical technique and are independent of the strain field being considered. They define the mathematical route from an analytical description of an arbitrary strain field in terms of its tensor to each standardized data set. An example for geometric moiré is shown in figure 4 and further ones are available for other techniques such as moiré, photoelasticity, speckle interferometry and thermoelasticity.

The final step is to replace the physical standardized test material by an analytical representation. Classical solutions exist for a disc subject to compression across a diameter [4] and for a cylinder contacting an elastic half space [5]. These descriptions can be used to generate the strain tensor map that is equivalent to the 'standardized data set 6' in figure 3 and form the starting point for the functional pathways such as the example in figure 4. The geometry of the gauge section in physical standardized test material shown in figure 2 does not include one of the desired features identified in the data collected from the experimental mechanics community, namely a discontinuity in the strain field. Consequently, a second standardized test material in the form of a pair of interference fit discs has been proposed. This second material only exists in a virtual form, i.e. there is no physical specimen and all the standardized data sets including the intensity data (standardized data set 1) are generated using a functional pathway and the analytical description of the strain tensor (standardized data set 6). The latter is readily obtained from Lamé's equations [6].

RESULTS

The reference material shown in figure 1 was initially designed based on analytical descriptions of its strain field and predicted elastic deformation. It was subsequently modeled using the finite element method to refine the design³ and simultaneously tested using a variety of optical strain techniques including ESPI, image correlation, photoelasticity and thermoelasticity. A number of incremental improvements in the design have been generated from analyses of these results and further tests performed [7]. At the time of writing a final design, which incorporates some minor refinements, is undergoing test. However, the work so far demonstrates the good reproducibility is achievable with the minimum of effort using this approach.

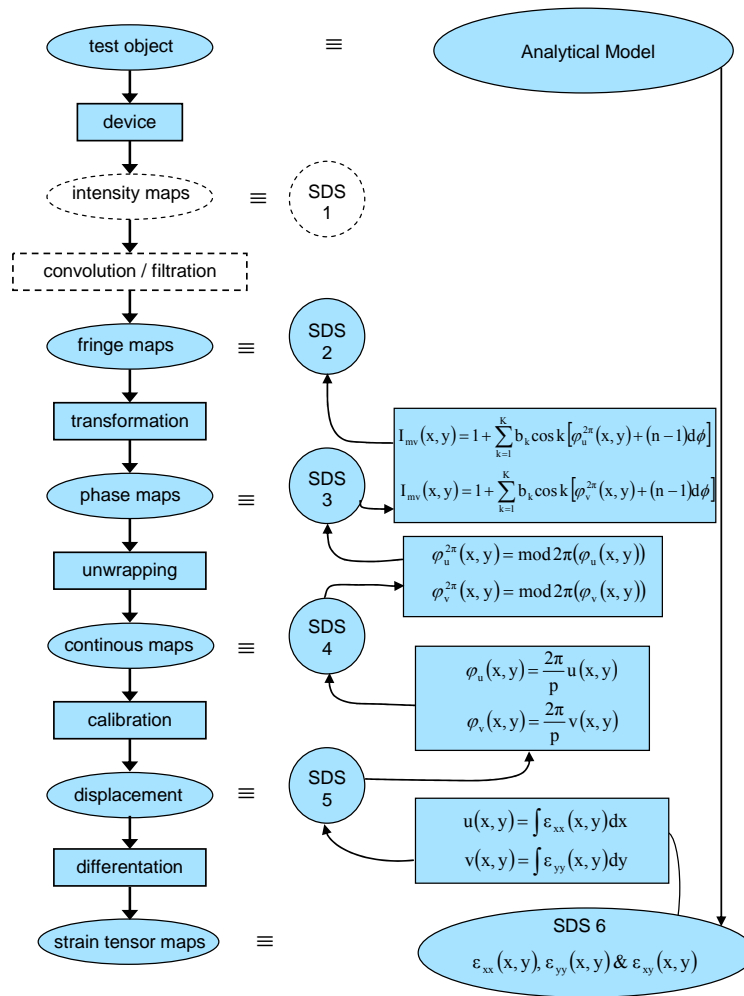


Figure 4: Functional pathway for geometric moiré illustrating the route from an analytical description of the strain field and subsequently the strain tensor (standardized data 6) to all the standardized data sets.

A round robin within the SPOTS consortium is being conducted using the design of the physical standardized test material shown in figure 2. Scales from a disc diameter of 4mm to 100mm are being considered using three different materials and six optical techniques. The study is being performed by nine laboratories in six different countries and is due to be completed in late 2005.

DISCUSSION

The work described above forms part of a three-year program jointly funded by the European Commission and due for completion at the end of 2005. One output from the program will be a draft ISO Technology Trend Assessment (TTA) which includes the detailed designs of the reference and standardized test materials; methodologies for their use including the functional pathways for a wide range of optical techniques for strain measurement. The approval process for this TTA will involve internal review within the SPOTS consortium, followed by a wider international review under the auspices of TWA26 followed by submission for approval to VAMAS and finally ISO. This process is likely to take a year or two and so following review at each stage the draft document will be available at the SPOTS³ and TWA26¹ websites.

In addition to the work described above the TTA will also include information on evaluating the uncertainties associated with the calibration and hence with measurements performed with the calibrated instrument as well as recommendations for making full-field comparisons between data sets. The latter is particularly important when

evaluating the performance of a system or sub-system using the standardized data sets. Often, a reference material is purchased in a protective case with documentation detailing its deviation from a standard and the uncertainties associated with its use. In this case the end-user is able to manufacturer the reference material and, hence before use, must establish these uncertainties and the deviation from the standard.

The current work is restricted in scope to static and two-dimensional strain fields. This restriction was imposed at the beginning of the program in the light of the limited time period in which it was intended to generate a unified approach for all optical techniques of strain measurement. Extension of the concepts to three-dimensions and dynamic loading would require substantial further work. However a system calibrated for a static, two-dimensional case and used in a three-dimensional and, or dynamic situation is probably still preferable to an uncalibrated one.

CONCLUSIONS

Work towards a set of reference materials and standardized test materials that will allow the calibration and evaluation respectively of optical systems for full-field strain measurement is described. Calibration implies a chain of comparisons leading to an primary or international standard and this requirement for traceability imposes a need for simplicity and reproducibility in the design of the reference material. A beam subject to four-point bending contained within a monolithic loading frame is proposed. Conversely, evaluation of sophisticated strain measurement systems implies the need for challenging strain fields that can be generated reproducibly. A contacting pair consisting of a disc and elastic half-space within a monolithic frame is proposed. In both cases, the specimens are scaleable, displacement loading is employed and the applied displacement is measured using a device calibrated against the international standard for length. A classification for the processes or steps within the measurement procedure that leads from intensity data to a strain tensor has been developed for all optical techniques. This classification is used as a basis for evaluating the performance of sub-systems within a measurement system. Methodologies for reporting the calibration and the associated uncertainties are being prepared based on experience gained from tests performed by the SPOTS consortium. The final results will be published as a draft ISO TTA in early 2006 by the consortium³ prior to submission to VAMAS and ISO.

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