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CANDIDATE REFERENCE MATERIALS FOR OPTICAL STRAIN MEASURMENT

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ABSTRACT

The lack of standards and reference materials related to optical methods and devices is hindering the uptake of modern optical strain measurement technology by industrial end-users. The lack of reference materials also makes it difficult to calibrate an instrument or to compare different instruments and methods. The aim of this study is the development of a set of physical and virtual (digital) reference materials that can be used to both calibrate an instrument and assess its performance. A rational decision making approach was employed and involved the identification and weighting of desirable attributes and the subsequent evaluation of candidate designs. Essential attributes for physical reference materials included easy optical access, no hysteresis, in-plane capability and traceability to international standards via length. An innovative monolithic design of a four point bend test was proposed as a prototype physical reference material suitable for instrument calibration. Features include inherent alignment of specimen and loading axes, displacement controlled deflections ensuring traceability to length standards and the possibility of easily machining specimens of a wide range of sizes from different materials.

1. INTRODUCTION

Optical methods of strain measurement have been widely used in the experimental mechanics community for many years. They are continually gaining importance in industry where optically derived strain or displacement data is used in the design process to analyse the stresses in new components or validate numerical models. The availability in recent times of affordable, quasi turn-key optical strain measurement systems has also encouraged the uptake of optical technologies by industrial end-users. As optical instrumentation is further integrated into product design and manufacturing processes, however, a significant problem has arisen. The lack of standards and reference materials, specifically related to optical methods and devices, has hindered the acceptance of optically derived data by certification authorities because it is impossible to trace an optical strain measurement to any primary standard. On a more practical front, the lack of standards and reference materials makes it difficult to reliably calibrate an instrument or to accurately compare the performance of different instruments and methods.

This study involves eleven collaborating partners from around Europe, including optical instrumentation manufacturers, end-users and academic and government research laboratories, brought together under the EU-funded SPOTS project [1]. A central aim of the project is the development of a set of physical and virtual (digital) reference materials that can be used to calibrate and characterise instruments both during manufacture and while in-service. Ultimately these reference materials should provide a basis for i) calibration standards that are traceable to existing international standards via length and ii) standardised tests that validate the performance of an instrument or measurement protocol. By first devising a single generic process flowchart [2] that is applicable to ESPI, image correlation, moiré, photoelasticity, shearography and thermoelasticity, it is possible to define a set of reference materials that can be used to evaluate or calibrate each sequential process or operation performed during a measurement, from the acquisition of a raw intensity image to the calculation of a strain map. Thus such a reference set should have a wide relevance and appeal and be a useful tool to the majority of practitioners in the optical strain measurement field.

2. THE DEVELOPMENT PROCESS

A rational decision making model [3, 4] was used to guide the development of the physical and virtual reference materials. This approach comprised a number of steps that included naming and weighting of desirable attributes, identification of essential attributes, development of candidate designs, evaluation of candidate designs and selection and embodiment of preferred designs.

2.1 Physical reference materials

A number of desirable attributes for physical reference materials were proposed by all project partners and the complete list (30 attributes in total) was subsequently weighted according to perceived importance (i.e. 1 - unimportant, 2 - preferred, 3 - important, 4 - highly desirable, or 5 – essential). In addition, the views of a wider experimental mechanics community were sought through the distribution of a questionnaire to members of the Optical Division of the Society for Experimental Mechanics and to attendees of the International Conference on Advanced Techniques for Experimental Mechanics in Nagoya, Japan (ATEM 03).

The list of desirable attributes and the results of the weighting exercise are shown in Fig.1. It can be seen that the differences between the project partners (spots average) and the wider experimental mechanics community (average) was very small. The essential attributes were identified as those with an average weighting from the whole community of greater than the mean plus a standard deviation of the average weightings. Five essential attributes were identified for physical reference materials (Fig.1), namely, they should provide easy optical access, exhibit no hysteresis, have in-plane capability and be traceable to international standards, via length.

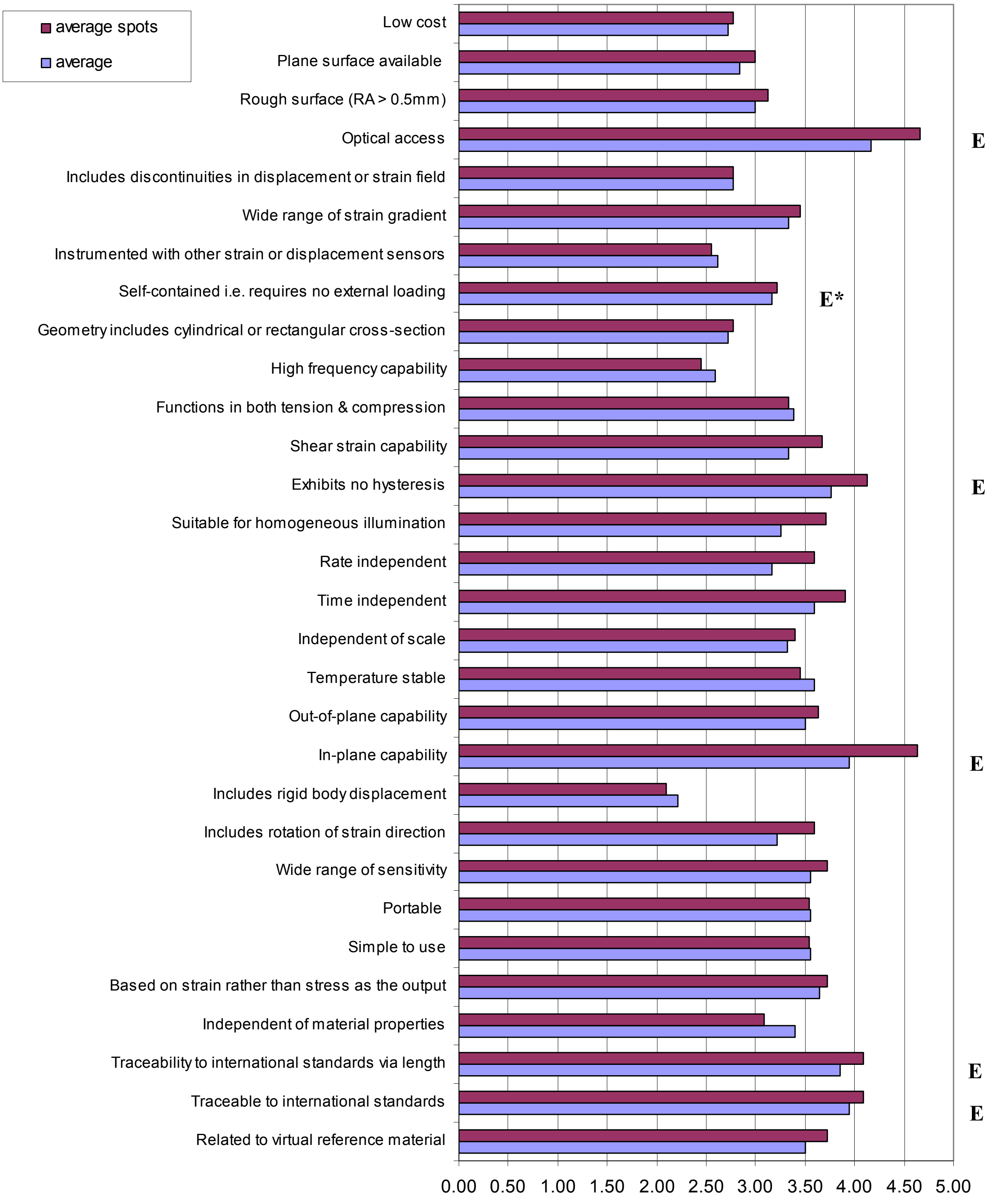

Fig.1. Attributes and their weightings for the physical reference materials. Essential attributes are identified as those marked as '**E**'.

At subsequent brain-storming sessions, sixteen candidate physical reference materials were proposed, as presented in Fig.2. Five of these sixteen were judged as lacking one or more of the essential attributes and thus were rejected (Fig.2). Evaluation of the remaining candidates against the twenty-five desirable attributes was found to be too daunting in the time available. Instead, the candidate materials were classified into four groups and their suitability for application with the various optical techniques of relevance was considered, as shown in

Fig.2. In addition, based on the experience gained during a first round robin trial conducted within the project, it was decided to attach more importance to having a self-contained reference material (marked ‘E*’ in Fig. 1). This was due to the fact that one of the main sources of uncertainty and variation in the results from the round robin was due to the lack of repeatability and reproducibility in the method of load application and specimen constraint. At the conclusion of this process, the candidate physical reference materials selected for further consideration were a four-point bending geometry, a modified Brazilian disk and a Hertzian contact-pair were.

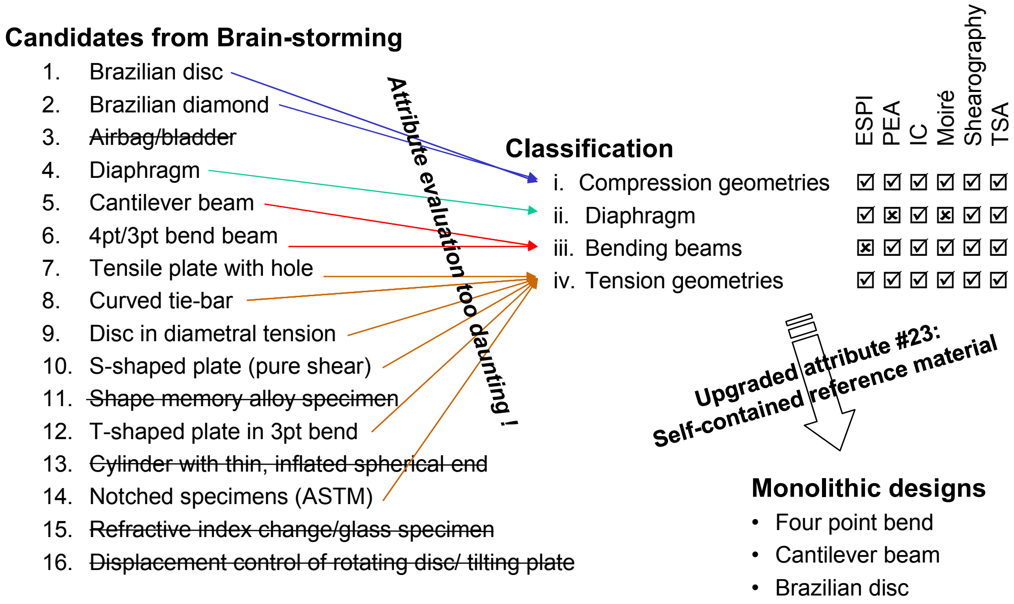

Fig.2. Schematic diagram showing the decision making process for the development of physical reference materials. The list of sixteen candidates is shown on the left with those lacking the essential attributes having a line through them. The remaining candidate PRMs were classified into the groups shown in the top right-hand corner. These classes were assessed for their suitability ☑ or not ☒ for application with the core techniques of interest in the project. Experience based on the first round robin led to the concept of a self-contained reference material being promoted as an essential attribute. A four-point bending geometry, a modified Brazilian disk and a Hertzian contact-pair were selected for further consideration.

2.2 Virtual reference materials

The attributes for the virtual reference materials were identified and weighted in exactly the same manner as described above for the physical reference materials. A total of 16 desirable attributes were distributed for scoring and the results obtained are shown in Fig.3. Basically the virtual reference materials were required to cover a wide range of strains, possess in-plane capability and be traceable to international standards.

Attention then turned to proposing a set of candidate virtual reference materials that could be examined against the essential and desired attributes. However, the problem arose that being virtual (digital), a plethora of possible candidates existed that could satisfy the favoured attributes. Also, unlike physical reference materials where it was clear at what stage in the measurement process they would be used, virtual reference materials could be utilised at various steps in the image (signal) processing chain. Initial work focused, therefore, on defining first their function and position in the measurement procedure by developing a process map and flow chart applicable to all techniques under consideration [2]. The map and flowchart represent the first attempt to formulise in a unified framework the processes associated with measurements of displacement and strain using full-field optical techniques.

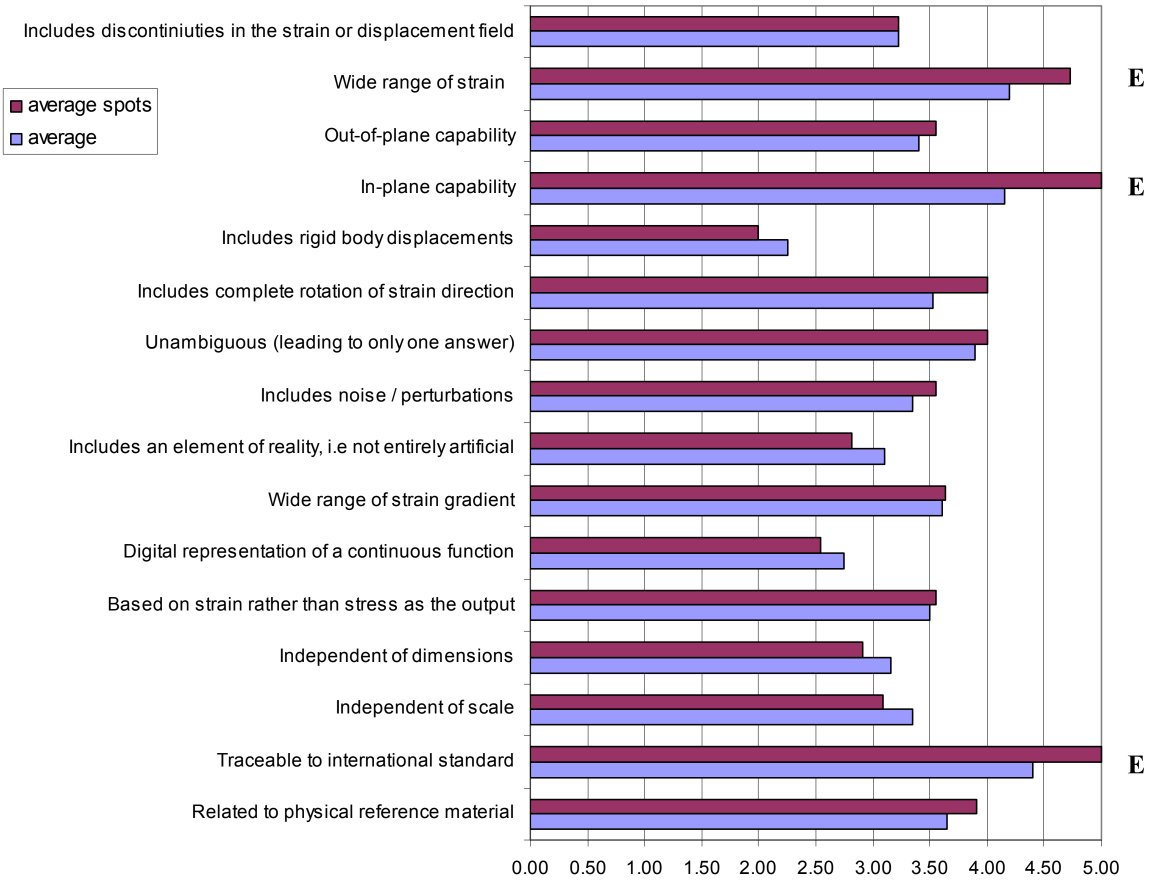

Fig.3. Attributes and their weightings for the virtual reference materials which were processed as for the physical reference materials. Essential attributes are identified as those marked as '**E**'.

Although more precise definitions of the function of virtual reference materials and the stages at which they would be used helped to reduce the number of possibilities, it was decided to introduce two new essential attributes to restrict the choice of candidates further. Firstly, it was proposed to limit candidates to those based on analytical solutions to known problems in mechanics since this would allow complete 2D maps of strains and other calculated quantities to be easily generated (attribute - 'analytical solution'). It was also felt that this would make the proposed reference materials more appealing and intuitive to the end-user community. Secondly, in order to have the possibility to link physical and virtual reference materials, extending the traceability chain, another essential attribute was defined as the viability of physically reproducing the analytical strain field represented by the virtual reference material (attribute – 'physically reproducible'). The set of ten candidate virtual reference materials that were subsequently proposed are given in Table 1, together with the evaluation of the candidates against the two new essential attributes. The salient features of the strain fields associated with the virtual reference material candidates are also indicated in Table 1.

Table 1. The ten candidate virtual reference materials proposed, evaluated against the two new essential attributes (✓signifies 'yes', ✓* signifies 'yes with some reservation', × signifies 'no' and '?' signifies 'not sure'). Also shown are the salient features of the strain field associated with each candidate.

Candidates Proposed	**Analytical Solution**	**Physically Reproducible**	**Features of Strain Field**
Notch	?	✓	1,4,5
Brazilian disc	✓	✓*	(1),4, (5)
Simple beam	✓	✓	(1), 3, (4)
Diaphragm	✓	✓*	1,4
Compound beam	✓	✓*	(1),2,3,(4)
Compound cylinders	✓	×	1,2,3,4
Compound brazilian disc	?	✓*	(1),2,(3),4,5
Hole in tensile plate	✓	✓	1,4,5
Hertzian 2-disc contact	✓*	✓*	1,(2),4,5
Mode I crack	✓	✓*	2,4,5

Code to features of strain fields:
1-Boundaries, 2-Discontinuities, 3-Sign reversal, 4-Variation in principle direction, 5-Concentration.

3. Prototype physical reference material for calibration purposes

The first steps in the development process led to the selection of a four-point bending geometry, a modified Brazilian disk and a Hertzian contact-pair as the favoured candidate physical reference materials. As mentioned above, however, lack of repeatability and reproducibility in the constraint of the reference material and the method of load application had to be avoided in as far as possible. This concern led to the concept of a monolithic design incorporating both the loading frame and reference specimen to which a uniaxial displacement load would be applied either in compression, between two platens, or in tension through two pins. The monolithic design ensured alignment through the specimen geometry and traceability to the length standard by the closure of a defined gap in the structure upon loading. The design was restricted to be two-dimensional so that it could be manufactured by different techniques and at a range of scales, from the micro to macro.

It was decided to first concentrate on producing a prototype reference material suitable for calibration of an optical strain measurement device, rather than a reference material fit for a standardised test. The four point bend test was preferred for this purpose since the basic geometry has been used in existing standards for optical measurements [5, 6]. A schematic diagram of the design developed for production of the prototype is shown in Fig.4. A monolithic construction eliminates most slip and friction effects and helps to ensure good alignment. The flat platen on the lower surface facilitates alignment with compression loading fixtures and a central half-cylinder on the otherwise flat upper surface ensures centrally aligned loading in compression. Two holes are present on the vertical axis of symmetry to facilitate tensile loading. The top and bottom beams of the monolithic frame and the side sections are relatively massive in order to resist bending deformations both in compression and tension. The monolithic design is completely parametric in that every dimension is related back to the width of the beam. Thus varying the width (*w* in Fig. 4) scales the complete specimen proportionally. The region of the reference material intended for use in a calibration procedure is located in the central section of the beam, between the two inner loading points (*ROI* in Fig.4).

Significant attention was given to the design of the joints between the monolithic frame and the beam at the loading points. The ideal case would be loading through a knife-edge but this was not believed to be practically possible within the constraints of a monolithic design. Instead the use of whiffletrees was favoured because of their ability to avoid the transmission of lateral loads. The thickness and length of the strut elements in the whiffletree were chosen to minimise the generation of lateral forces and moments at the joints while avoiding any buckling in compression. The upper beam of the loading frame was designed to incorporate a simple interlock feature on both sides that served to limit the maximum deflection of the beam in both tension and compression. Variation of the gap size can be used to limit the maximum strain occurring in the test section.

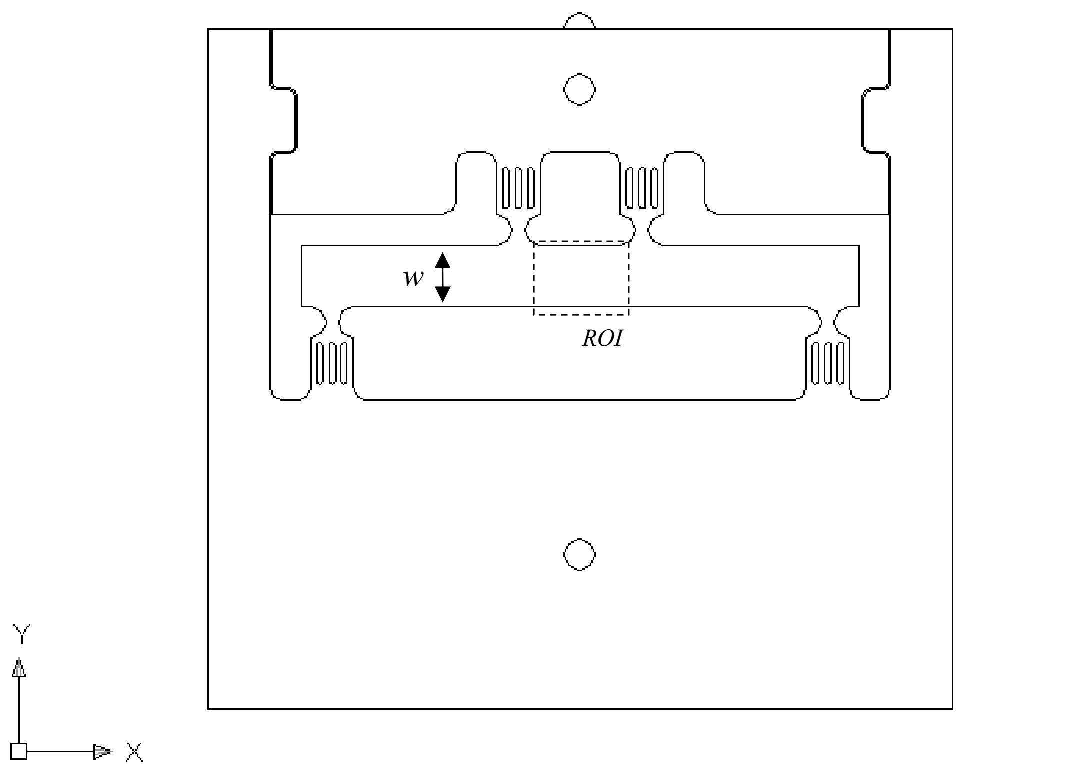

Fig.4. Monolithic design of four point bend test proposed for the first prototype of a physical reference material for calibration of optical strain measurement systems (*w* – width, *ROI* – region of interest).

A very preliminary test was carried out on the prototype reference material to qualitatively assess the nature of the displacement (strain) field in the calibration zone (*ROI* in Fig. 4). The specimen was placed on a flat rigid base-plate and a weight was applied to the top beam using a simple loading fixture. The displacement field in the vertical (*Y* axis in Fig.4) direction was measured using an Electronic Speckle Pattern Interferometry (ESPI) system. A wrapped phase-map recorded during the process is shown in Fig.5, superimposed on the geometry of the specimen. As can be seen, the displacement field is highly regular and indicative of a strain field produced by pure bending. Obviously these results are only qualitative and incomplete. Future activities will focus on rigorously assessing the overall performance of the prototype and analysing the strain distribution. Protocols will also be developed on how to use the specimen to calibrate an optical strain measurement instrument.

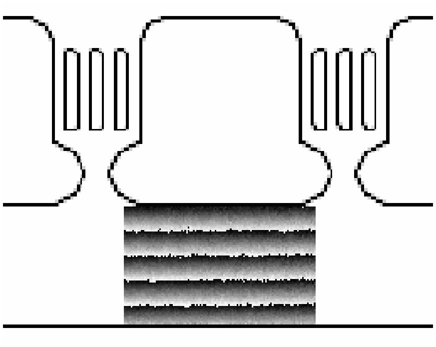

Fig.5. Wrapped phase-map associated with vertical displacements in the calibration zone of the reference material specimen, acquired using an Electronic Speckle Pattern Interferometry system.

5. CONCLUSIONS

This report has described the initial stages of the development of a set of physical and virtual (digital) reference materials for optical strain measurement instruments and procedures. Two classes of reference material are being considered namely those that can be used to calibrate an instrument and those more suited for the validation of an instrument or measurement procedure (i.e. determine fitness for purpose). A rational decision making approach was employed which involved the identification and weighting of desirable attributes and the subsequent evaluation of candidate designs. The desire is to develop reference materials that can be traced to international standards, via length. An innovative parametric design of a monolithic four point bend test was presented whose features include inherent alignment of specimen and loading axes and negligible friction and slip. Specimens can be manufactured by different techniques and at a range of scales using the same design. Preliminary results obtained with ESPI show the displacement field to be is highly regular and indicative of a strain field produced by pure bending. Future activities will concern the rigorous assessment of the mechanical performance of the prototype and the detailed nature of the strain field in the calibration zone. Protocols on how to use the specimen to calibrate different optical strain measurement instruments will also be devised.

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