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CLASSIFICATION OF OPERATIONS AND PROCESSES IN OPTICAL STRAIN MEASUREMENT

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ABSTRACT

The development of a structure for classifying the steps within optical techniques of strain measurement is described in the context of a set of physical and virtual reference materials for the calibration of optical systems including both hardware and software elements. The classification is intended to be applicable to all techniques of strain measurement and to assist in the development of a unified set of reference materials for the techniques. The work forms part of project, SPOTS (Standardisation Project for Optical Techniques of Strain measurement) which is in part funded by the European Union and is being conducted by eleven partners.

STATE OF THE ART

Optical methods of strain measurement are a generic technology, which support life cycle performance, safety and reliability assessments, and design optimisation of products, components, and machines varying in scale from micro-machines to ships. However, the quality of the data generated is strongly dependent on the procedures employed and the set-up of the instrumentation. There are no standards or universally accepted guidelines relating to optical methods of full-field strain and displacement measurement. So, there is a significant need to provide standards, including reference materials both for procedures and instrumentation in order to provide traceability, to facilitate data fusion, and to promote the compatibility of systems. Reference materials allow measurement systems to be calibrated, i.e. compared to a secondary or local standard which is traceable to a primary standard, through an unbroken chain of comparisons all having stated uncertainties. Standardised tests, on the other hand allow the fitness for purpose of a system to be assessed using agreed criteria.

A project [1] funded in part by the European Union was established in January 2003 with objectives that included the development of a unified set of reference materials which would be applicable to the complete range of optical techniques of strain measurement. The project is organised around a consortium that includes partners from all stages of the innovation chain from University laboratories involved in developing novel techniques, small companies involved in product development, manufacturing and marketing of the associated systems and end-users from the aerospace, automotive and electronics industry as well as national laboratories with responsibilities for standards. The task of developing a unified reference material for optical techniques of strain measurement is ambitious and the consortium has recently undertaken to design standardised tests as well. The philosophy underpinning the unified approach to these developments is outlined below. More details relating to the reference material is given elsewhere [2] and the issues surrounding traceability are discussed by Hack and Sims [3]. Whilst it is intended that the work should be applicable to all full-field optical techniques, the consortium has focussed on a subset which is industrially relevant.

A FRAMEWORK FOR STANDARDS

The development of reference materials and standardised tests that are applicable across the spectrum of optical techniques of strain measurement is a major challenge. The first step of this task was to identify the common elements of systems used for optical strain measurement. This has required the sub-processes within the techniques to be identified and classified using a common structure. A single process map is presented in Figure 1 which can be used to describe the processes involved in all optical techniques used for measuring strain. The map starts at the top with a test object subject to strain and the process is completed at the bottom with the distribution of strain experienced by the test object. In between are a series of intermediate stages at which data is generated in various forms (shown in the ellipses in Figure 1). The processes that are used to generate these data forms are shown in the rectangular black boxes and maybe executed by a physical device or a piece of software. Clearly, not all optical techniques involve all these stages and a summary is provided for a number of techniques in Figure 2.

In metrology it is usual to calibrate an instrument using a physical reference material that provides traceability to a primary standard. This

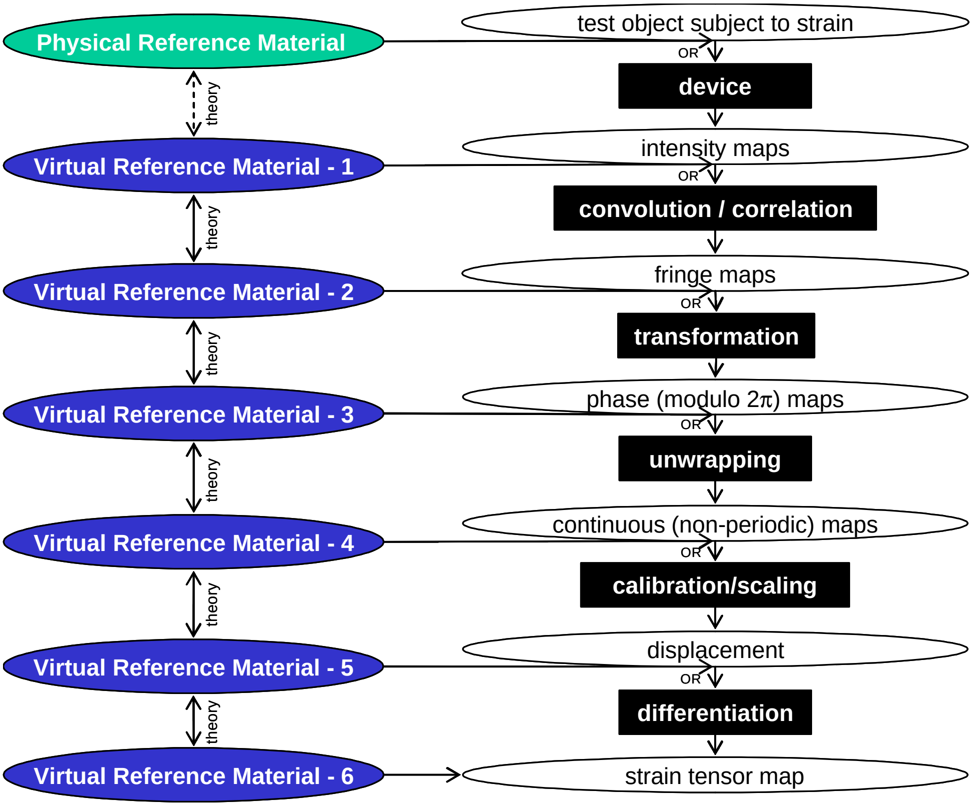

Figure 1 – Generic process map for full-field optical techniques of strain measurement showing operations as black boxes and data maps as white ellipses (*right*) with the relationship of reference materials (*left*) shown.

approach is possible for the first stage in process map in Figure 1, i.e. the collection of intensity maps from the test object using an appropriate (physical) device. However, most or all of the remaining sub-processes are associated with algorithms for transforming intensity and, or phase data and could be termed virtual processes. To calibrate these processes requires reference materials that are appropriate to virtual processes, i.e. *virtual reference materials*. Consequently to validate and verify the processes involved in strain optical techniques both physical and virtual reference materials are required as shown on the left side of the process flow chart in Figure 1. It is intended that the virtual and physical reference materials can be used to calibrate an optical technique either as a complete system or the individual processes within the system. This implies that there should be traceability through the virtual reference materials from the bottom of the chart in Figure 1 to the physical reference material at the top and from there to an accepted primary standard. Traceability to the international standard metre seems appropriate when making strain measurements due to the association of strain to displacement. It is the intention that there should be a continuous chain of comparisons from the virtual reference material for the strain map at the bottom of Figure 1 to the standard metre. The means of achieving this goal is described in detail by Burguete et al [2].

DESCRIPTION OF FLOW CHART

The flow-chart in Figure 1 is intended to be largely self-explanatory however some explanation is provided here within the context of the strain analysis around the crack tip in the compact tension (CT) specimen shown in Figure 3(a). The CT specimen was 24mm thick with a geometry that followed ISO12737 and was manufactured from 2024 T315 aluminium alloy. A Dantec Ettemeyer 3D ESPI system (Figure 3(b)) was used to analyse the strain induced around a 3mm long fatigue crack when the specimen was subjected to a load of 15.2kN [4]. The CT specimen represents the test object in the top left corner of Figure 1 whilst the physical head of the ESPI system (Figure 3(b)) represents the device used to record the map of intensity shown in Figure 3(c) which is only one of several recorded during a measurement sequence. When these intensity maps are combined by the software of the system fringe maps are generated such as the in-plane *y*-displacement fringes shown in Figure 3(d). This process has been termed ‘convolution or correlation’ in the process map and is followed by a ‘transformation’ process which involves the generation of modulo 2π phase maps (Figure 3(e)) from the fringe pattern. Each phase map is subsequently unwrapped to generate a continuous map shown in Figure 3(f) for this example and following ‘calibration or scaling’ becomes a map of displacement (Figure 3(g)). Finally, a ‘differentiation’ process is required to produce maps of the components of the strain tensor such as the map of in-plane *y*-direction or vertical strain shown in Figure 3(h).

ESPI was chosen for the above description because it involves all of the processes described in the black boxes in Figure 1. However, in many techniques some of the processes are integrated/combined or simply omitted. This is illustrated in the flow-chart in Figure 2. For instance, shearography, photoelasticity and thermoelasticity do not generate maps of displacement but strain data is generated directly following calibration; and similarly thermoelasticity produces a continuous contour map without the need for convolution, transformation and unwrapping.

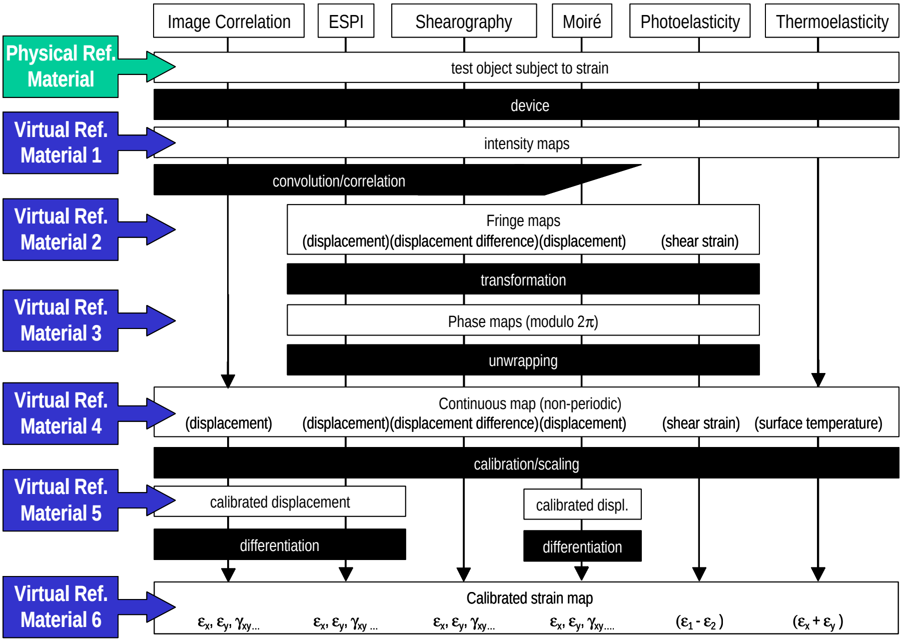

Figure 2 – Process flow chart for image correlation, ESPI, shearography, moiré, photoelasticity and thermoelasticity showing the appropriate route through the map in Figure 1. Operations are shown as black boxes, data as white boxes and the corresponding reference materials as coloured boxes (*left*).

CONCLUSION

A process map and flowchart for all optical techniques for strain measurement have been presented. The map contains all the stages or processes involved in an optical technique of strain measurement as well as all of the intermediate data between the intensity measurements obtained from the test object which is subject to strain to the map of strain that is the final output. Not all optical techniques include all of these processes or forms of data and the flow-chart summarises the situation for a wide range of techniques including: image correlation, ESPI, shearography, photoelasticity, thermoelasticity and moiré. Together the process map and flow chart provide a framework for the design and development of appropriate reference materials and standards for full-field optical techniques of strain measurement. These reference materials will be both physical and virtual since the processes involved in strain measurement include both physical and virtual or electronic data. It is intended that the reference materials will allow calibration of optical systems of strain measurement through providing a continuous chain of comparisons to the international standard for the metre.

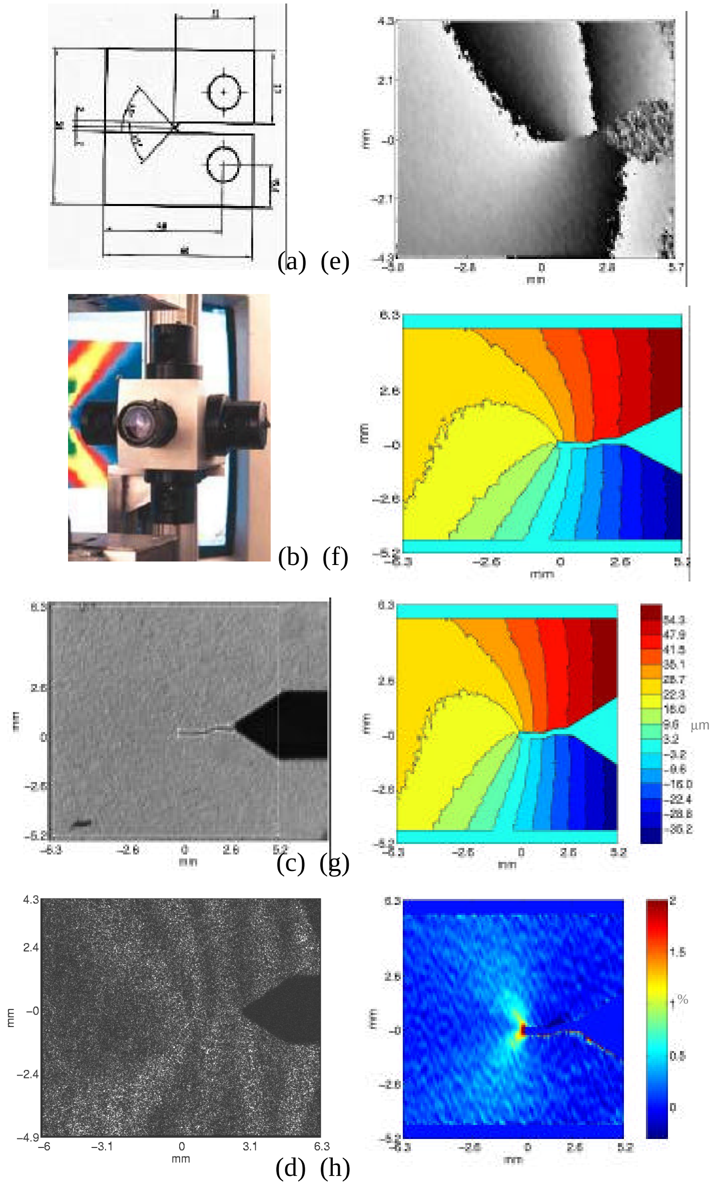

Figure 3 – Stages of analysis of the strain field around (a) a compact tension specimen using (b) an ESPI system. The stages or processes in the analysis are illustrated by (c) a recorded intensity distribution; (d) the fringe pattern related to the in-plane *y*-displacement; (e) the phase map for the in-plane *y*-displacement; (f) the corresponding unwrapped phase map; (g) the distribution of in-plane *y*-displacement and (h) the distribution of strain in the *y* or vertical direction. This data can be related to the process map shown in Figure 1.

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