ADVISE project
FP7-SST-2007-RTD-1 Safety and security by design
GRANT AGREEMENT SCP7-GA-2008-218595

Deliverable D3.7

Specification of 'non-linear' reference material published on website

Partners involved: EMPA, AUK, DD, JRC, LTSM-UP, MSU

Author: Eann Patterson, MSU

Date: November 2011

Introduction

A reference material is defined as a material, sufficiently homogeneous and stable with respect to one or more specified properties, which has been established to be fit for its intended use in a measurement process [1]. Reference materials provide a simple definition of the measured quantity that can be traced to an international standard and can be used to assess the uncertainty associated with a measurement system. In the ADVISE project, efforts have been oriented to provide reference materials for calibration of systems capable of measuring three-dimensional deformation fields induced by dynamic loading. The purpose of this document is to describe a Reference Material that will allow the calibration of full-field optical systems that are used to capture dynamic, non-linear deformation fields. Here, non-linearity is taken to mean that the relationship between applied loading and resultant deformation is not linear. In related documents, reference materials for cyclic loading and transient loading cases are specified (Deliverables D3.4 and D3.5, respectively).

Calibration of full-field optical deformation measurement systems is an essential step in providing traceability and promoting confidence in relation to displacement and strain distributions obtained from experiment. Calibration is also highly desirable when the full-field experimental data is used to validate computational models employed in engineering design. Formally, calibration is defined as an '*operation that, under specified conditions, in a first step establish a relation between the quantity value with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step uses this information to establish a relation for obtaining a measurement result from an indication'*[1].

Design concept

The aim was to design, manufacture, and demonstrate a physical Reference Material that generates a known and reproducible displacement/strain field in a defined gauge-zone, as a function of an applied dynamic load. An iterative design process has been followed involving analytical, computational, and experimental mechanics techniques in order to reduce possible sources of experimental uncertainty and to simplify the manufacturing process. The rational decision making model[2] was employed to guide the definition and development of the Reference Material, as already performed in the design of SPOTS reference material[3]. In this process, essential and desirable attributes of the Reference Material that would facilitate an effective calibration procedure were identified. Then, a set of candidate designs were created. The extent to which each design possessed the attributes was assessed in order to highlight the designs which best fitted the requirements. This approach allowed a large search space so that many widely differing solutions could be considered and the inappropriate dominance of previously utilised solutions could be avoided. As a first step, a comprehensive set of possible attributes were proposed and used as a basis of an ADVISE questionnaire to engage the engineering community in the weighing of these attributes. The surveyed communities included ADVISE partners and participants of the Society for Experimental Mechanics 2009 Spring Conference (Albuquerque, NM). Contributors were asked to weigh the attributes provided and to propose any extra attributes that they felt should be included. Attributes were divided into those associated with the displacement field the Reference Material should generate, and those

[1] ISO/IEC guide 99:2007, International vocabulary of metrology – Basic and general concepts and associated terms (VIM)

[2] Cross N., *Engineering Design Methods* (John Wiley & Sons, London, 1989)

[3] *Guidelines for the Calibration and Evaluation of Optical Systems for Strain Measurement, SPOTS,* www.opticalstrain.org

associated with the general embodiment of the Reference Material. Four essential attributes for the displacement field were identified: presence of a range of displacement values inside the area of calibration; presence of out-of-plane & in-plane displacements; possibility of in situ verification of the performance; and in case of cyclic loading: data extraction throughout a cycle. Three essential attributes for the physical embodiment were identified: boundary conditions are reproducible; system is portable; and robust. Sixteen desirable attributes were also defined and used to guide the choice of a preliminary design. Some additional attributes were suggested during the survey and these were: i) the displacement field comprises both out-of-plane and in-plane displacement components, ii) the start and end conditions of the calibration process have to be well-defined in transient loading, iii) the magnitude of displacements should be variable, and iv) the Reference Material could be manufactured from a viscoelastic material. The weighted attributes formed the basis of a set of design constraints.

The next step in the rational decision making model was to put these constraints aside, and to brainstorm the widest possible set of candidate designs conceivable to the ADVISE partners. Subsequently these design concepts were tested against the essential attributes and those designs that did not possess all of these were rejected. As a result of this filtering process, nine quite different candidate designs were left. The designs selected were then evaluated once more, this time against the desirable attributes, which led to the identification of two preferred candidate designs. These two candidate reference materials have been explored by detailed embodiment of the designs and the production of prototypes. First, a rectangular membrane contained in a monolithic frame, which is intended for use in calibration when cyclic deformation is of interest, has been developed via two prototypes and is described in a companion document (ADVISE deliverable D3.4: Specification of a Cyclic Reference Material). Second, and the subject of this document, a design based on a simple cantilever has been specified for use in the calibration of optical systems for measuring transient and non-linear deformations. The specification of this design for use in transient but linear applications is described in a sister document: ADVISE deliverable D.3.5: Specification of 'Transient' Reference Material.

The ADVISE consortium restricted the Reference Material development to a planar case, but when tilting the Reference Material, a displacement in a non-orthogonal direction can be generated. This approach appears reasonable, since in practice at the moment, most optical measurements of strain result in data relating to two-dimensions.

Design specification

The preferred design candidate for the transient and non-linear deformation cases is based on a simple cantilever as shown in figure 1. The design is parametric and can be manufactured in any homogeneous, isotropic material that is free of residual stress. The Reference Material consists of a cantilever of length 20T and width 5T where T is the thickness, with at one end an enlarged portion of thickness 3T and length 10T, giving an overall length of 30T. The fillet radius at the junction between the cantilever and the enlarged portion should be as small as it is practical to manufacture, in order to minimise the effect of the strain distribution in the cantilever.

The enlarged portion is used for clamping the cantilever to a rigid, immovable body, and experiments have shown that the behaviour of the cantilever is independent of the clamping method and force providing there is no relative movement between the enlarged end of the Reference Material and the rigid, immovable body.

The design is scalable and the dimensions and materials should be chosen so that deformations are comparable to those it is expected to measure with the calibrated measurement system; in addition, the Reference Material should occupy the majority of the field of view of the optical arrangement set-up for the planned experiments.

Traceability is achieved by measuring the tip deflection δ of the cantilever using a calibrated displacement transducer. The choice of transducer is not specified; however, a non-contacting sensor such as a proximity probe is recommended . The measurement of the tip displacement can be related to the displacement in the cantilever, using theory of elasticity for which standard expressions are available in Roark[4].

For all loading cases, i.e. cyclic, transient and non-linear the Reference Material should remain in the elastic loading regime so that the process is reproducible. Non-linear loading occurs for $\delta/L > 0.35$ which implies that the material will need to have a low modulus of elasticity and high yield strength, e.g. high density polyethylene (HDPE).

Although designed for transient and non-linear deformation cases, this design of Reference Material can be used also for cyclic loading. Any appropriate form of excitation can be used for cyclic loading and by restricting data collection to a single excursion from equilibrium, transient loading conditions can be represented. In these circumstances, the natural frequencies can be found analytically as[5]

$$f_i = \frac{\lambda_i^2}{2\pi L^2}\left(\frac{EI}{m}\right)^{1/2}$$

where the modal shape is defined as

$$y_i\left(\frac{x}{L}\right) = \cosh\frac{\lambda_i x}{L} + \cos\frac{\lambda_i x}{L} - \sigma_i\left(\sinh\frac{\lambda_i x}{L} + \sin\frac{\lambda_i x}{L}\right)$$

and, where the dimensionless natural frequency parameter, λ_i can be computed from

$$\cos\lambda\cosh\lambda + 1 = 0$$

Alternatively, the tip of the cantilever could be subjected to a single, reproducible impact and data acquired during the first excursion from equilibrium of the cantilever for transient loading, and possibly non-linear loading. Non-linear loading could be achieved by static loading of the cantilever to an appropriate displacement followed by its sudden release and acquiring data over the first oscillation.

[4] Young, W.C., Roark, R.J., Budynas, R.G., 2002, *Roark's formulas for stress and strain*, McGraw-Hill
[5] Blevins, R.D., 2001, *Formulas for natural frequency and mode shape*, Krieger Pub. Co.,

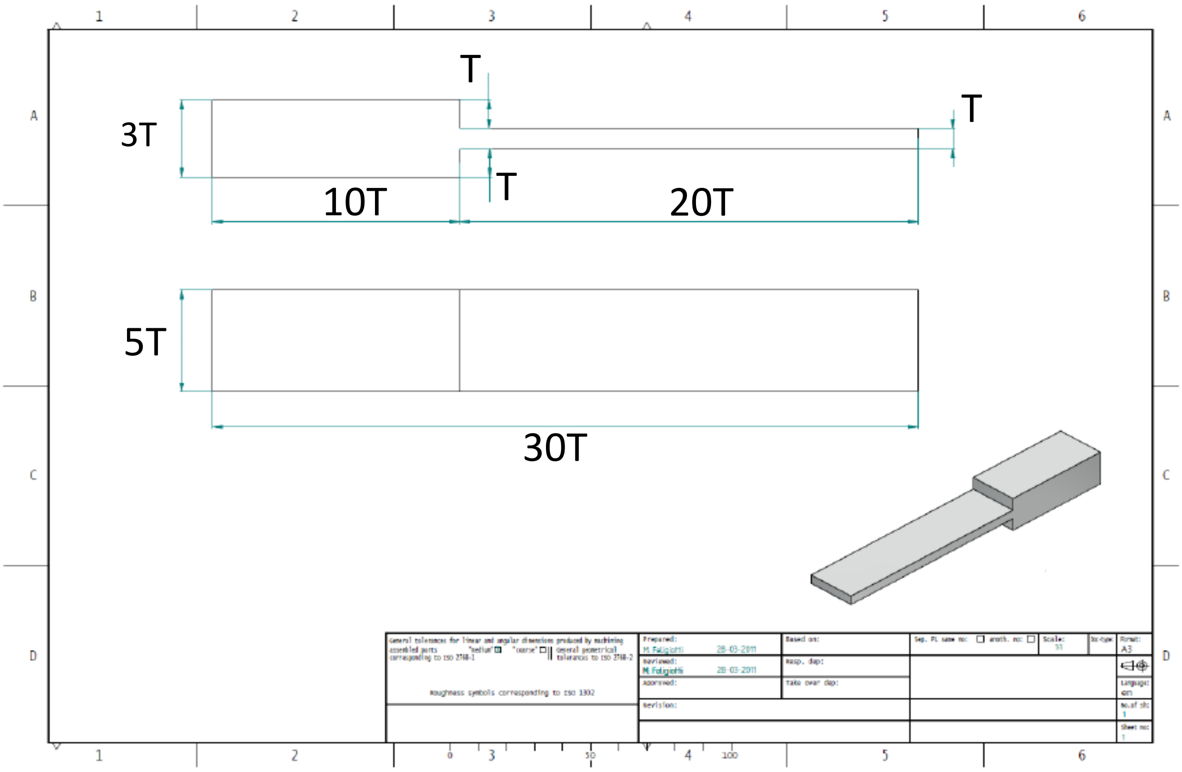

Figure 1: Drawing and three-dimensional rendering of the candidate Reference Material