Uncertainty quantification for DIC-based model validation: the influence of undermatched lens distortions

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Abstract. The goal of this research is to review some specific challenges associated with the full-field validation of Finite Element (FE) models using Digital Image Correlation (DIC) measurements. A key aspect of an effective validation process is not only generating difference maps in a quantitative manner, but also accurately interpreting these differences to distinguish the errors based on their nature and origin. The current study explores the model validation problem through an out-of-plane bending case study, highlighting the importance of additional sources of uncertainty that are often overlooked, particularly in cases involving small strains.

Possible Sessions

Model validation, Optical and DIC Techniques

Introduction

Over the last few decades, Digital Image Correlation (DIC) has gained significant attention amongst image-based full-field deformation measurement techniques. It provides many orders of magnitude more data than the conventional pointwise sensors, essentially matching the data-rich nature of numerical simulations. This feature makes DIC an ideal tool to experimentally assess the validity of mechanical models, often provided by the Finite Element (FE) method. Such an integration nevertheless remains very much an emerging field with limited literature. Most existing studies on this topic originate from the research group of Prof. E. A. Patterson [1, 2, 3]. They have used the so-called "shape descriptors" as low-pass spatial filters and relied on the Uncertainty Quantification (UQ) arising from a four-point bending test on a beam [4]. This approach is however too simplistic, as the linear displacement distribution in bending tests does not adequately challenge the low-pass filtering effect of DIC.
A more recent approach involves using the displacement field derived from the FE model to numerically deform the reference speckle pattern, creating a Digital Twin (DT) [5]. These images can then be processed with the same DIC machinery as the experiment to allow for a point-to-point comparison in the form of a validation map. This so-called "DIC-levelling" approach pushes the model through the same regularization level as the experiment to eventually deliver the map of differences between FE and DIC. This methodology has been recently validated in elaborate studies on fragmentation [6], anisotropic plasticity [7] and constitutive model fitness assessment [8]. However, these studies did not systematically address UQ in model validation. Peshave *et al*. [9] recently explored UQ in model validation, emphasizing the necessity of Digital Twins. They listed different sources of uncertainty and categorized them based on their identification approach. Their work suggests that, while most errors can be addressed through Digital Twins or stationary images, others are either too difficult to budget for (heat haze, camera heating, specular reflection), or require further investigation (calibration errors). Yasmeen *et al.* [10] examined the sensitivity of in-plane strains to calibration parameters under large out-of-plane specimen rotations. While they assessed the impact of intrinsic and extrinsic calibration parameters on strain maps, they did not consider lens distortions.
The present study investigates the influence of lens distortions on strain maps through a practical case study, incorporating uncertainty quantification in the context of model validation.

Experimental setup

Fig. 1. illustrates the experimental setup. The test sample is clamped at one end and subjected to a gravitational force (by hanging weights) applied at a small point at the other end, thus providing cantilever loading. To complexify the test, a notch and a hole, acting as geometrical strain concentrators, have been created near the clamping end. The deformation field was measured using stereo-DIC. An FE model was developed based on the elastic properties obtained from a monotonic tensile test. Ideal boundary conditions were initially adopted for modelling, constraining all degrees of freedom at the clamp and coupling a point load to the contributing nodes at the other end. This model was then used to synthetically deform the reference experimental image via the FEDEF tool within the commercial software MatchID. The synthetically deformed images were then pushed through the same DIC engine as used for the experimental images, creating a one-to-one DT that mimics a chunk of the uncertainties associated with DIC [9]. Full-field error maps were generated by subtracting the DT from the experimental results. The error maps encompass the model errors, yet are contaminated by "stationary images covered" random errors as well as the other "uncovered" errors [9]. A model is considered fully validated when these error maps contain only high-frequency random errors within the bounds of DIC uncertainty, as evaluated by the stationary images.

Results

Fig. 2. presents the longitudinal strain obtained from the test (DIC), the model (DT), and the difference between the two. It is important to note that the model errors had already been minimized by enforcing the DIC measured boundary conditions as well as the geometry. The focus of this study was to investigate the errors mainly arising from the lens distortions; an aspect which is not covered in previous research.

Figure 1 – Experimental setup.

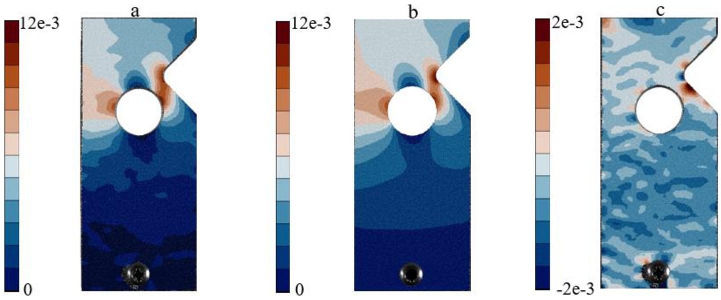

Figure 2 – Longitudinal strain, comparison between the DIC (a) and DT (b), delivering the difference map (c).

One can see that the error distribution does not directly correspond to the actual strain distribution. Additionally, a residual error appears near the clamping end, suggesting that the enforced boundary conditions may not have been measured precisely with the test. One possible explanation for this could be the nature of radial lens distortions, which analytically tend to increase as one moves away from the optical centre towards the edges of the image plane, where the boundary conditions are measured.

To assess the sensitivity of strain measurements to lens distortions, a reference DT was created using the experimentally derived calibration parameters and the displacement field from the FE model with ideal boundary conditions. The influence of radial lens distortions was then examined by individually increasing or decreasing each distortion parameter by ±5% from the reference value, on each of the two cameras. Fig. 3. shows that the longitudinal strain is particularly sensitive to variations in the first radial distortion parameter.

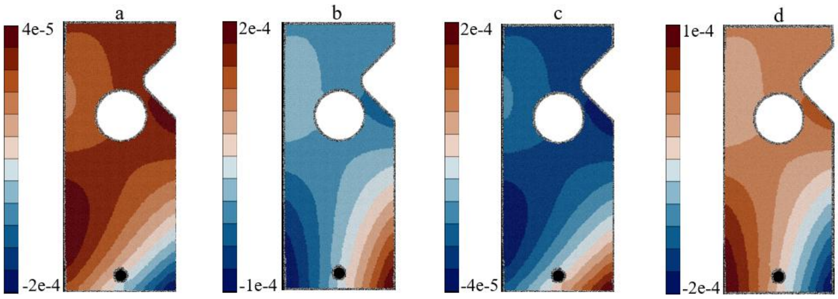

Figure 2 – Longitudinal strain sensitivity to variations in the first radial distortion parameter, with 5% increase for camera-0 (a) and camera-1 (c), and 5% decrease for camera-0 (b) and camera-1 (d).

This study represents an initial step towards evaluating the errors introduced by lens distortions. The approach will then be extended to cover the other calibration parameters, which will be further discussed in the presentation.

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