On the validation of finite element models through stereo digital image correlation measurements in a bulge test

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Abstract. The aim of this paper is to investigate the experimental validation of finite element (FE) models using Digital Image Correlation (DIC). One of the key objectives of the work is to rigorously isolate the effects of DIC errors to identify the potential model errors. For the former, we rely on the use of a Digital Twin (DT) to push the FE data through the same filter as the experimental ones. One practical difficulty though is to establish a realistic noise floor for the random DIC errors. After this step, the remaining errors should be attributed to model discrepancies such as material properties, geometry and/or boundary conditions. Another key objective is to analyse such error maps to help the user identify the nature of the potential model discrepancies. The topic is explored here through a simple bulge test on a metallic plate loaded in its elastic regime.

Introduction

The use of finite elements as a numerical modeling paradigm dates back to the early 1940s [1]. Since then, FE modelling has been always a center of attention in engineering sciences, refined and developed through the contribution of numerous researchers in the field. It has proven to be an incredibly powerful tool, providing data-rich information to solve a wide range of engineering problems for several decades. To this day, FE modelling remains a dynamic area of research, with continual efforts aimed at further enhancing its credibility, precision and functionality. Hence, the validity of FE models is usually a subject of investigation, commonly established by benchmark testing. This is generally carried out by quantitative comparison with real-world experiments. This objective assessment helps to determine how well the FE model performs in representing the actual physical system.

The experimental application of point-wise sensors on deformation measurements may be traced back to the same era as FE with the development of strain gauges and accelerometers [2,3]. Nevertheless, contact extensometers were first introduced in the late 19th century [4]. They have been widely integrated into the metrology systems and are still commonly in use in a vast variety of engineering applications to measure the surface deformation of an object. However, there are a number of intrinsic limitations associated with point-wise sensor metrology systems, preventing them to appropriately afford validation of FE models. For instance, they can not capture the full field distribution of the measurand on the surface of the test specimen and the accurate determination of sensor positions on the surface of the FE model is quite a challenging task.

In the last decade, the use of digital cameras has soared in industry. In the field of deformation measurements, the most popular technique is Digital Image Correlation. It is a non-contact white light optical technique used in mechanical testing to measure the surface deformation of the materials in a full-field sense. The information-rich nature of DIC has the potential to revolutionize structural testing. It has shifted the focus away from traditional point-wise sensor metrology systems (strain gauges, extensometers, accelerometers) towards camera-based ones. Matching the full-field information-rich characteristic of FE, DIC also serves as a touchstone to assess the validity of finite element models. However, quantitative validation of FE models still remains significantly challenging. There is currently a lack of comprehensive methodologies for achieving this, despite the availability of DIC data. One of the difficulties lies in the fact that DIC suffers from some intrinsic limitations such as noise and limited spatial resolution. A recent paper addressed this issue by introducing DIC-levelling approach that involves generating FE-based synthetically deformed images [5]. Nevertheless, experimental validation is still lacking. The next step involves analysing difference maps to identify the origin of potential inconsistencies; namely boundary conditions, material behaviour and/or geometrical imperfections.

The present work looks into this topic through a bulge test on a metallic plate loaded elastically. The primary emphasis is to comprehensively distinguish between errors originating from DIC measurements and those resulting from inaccuracies in the FE model.

Methods

Measurements were conducted on a fully clamped, circular SAE 304L stainless steel plate subjected to uniform pressure on one of its faces. Prior to loading and after the stereo calibration, a set of static images were captured and correlated with the DIC engine. Resultant data was then analysed statistically to evaluate the noise floor attributed to the Quantities of Interest (QOI), here, displacements and strains. The spatial standard deviation of the QOIs in the stationary state was determined as the spatially uniform noise floor from a single pair of images. In this case, the noise floor was considered identical for all data points in the region of interest. On the other hand, temporal standard deviations of the QOIs were evaluated to determine the local noise floor, assuming heterogeneous distribution of variance across the data points in the region of interest. A series of modifications were made to the DIC test setup to explore the impact of light intensity and ambient temperature on the reproducibility of the temporal noise floor. The Sum of Square of Subset Intensity Gradient (SSSIG) [6] was calculated for each subset in the region of interest to assess the effect of the local grey level gradient and speckle pattern quality on the spatial variation of the local noise floor. A finite element model of the test specimen was then created, incorporating the specimen's geometry and material properties, as well as the specified boundary conditions at the loaded state. The FE generated data was validated through full-field comparison to DIC data, using both direct-subtraction and the DIC-levelling approach. In the latter, FE data was processed through the same DIC machinery to build a digital twin, while in the former, only spatial interpolation was used to coincide data points. Both uniform and spatially varying noise floors were considered in the validation (Fig. 1). Synthetically deformed images were generated using a stereo DIC simulator and validated in the same way as the real experimental images. These images were artificially corrupted with a realistic copy of the grey level noise to simulate the experiment. The resulting validation maps for both "truly-deformed" and "synthetically-deformed" images were analysed to illustrate the impact of potential model errors.

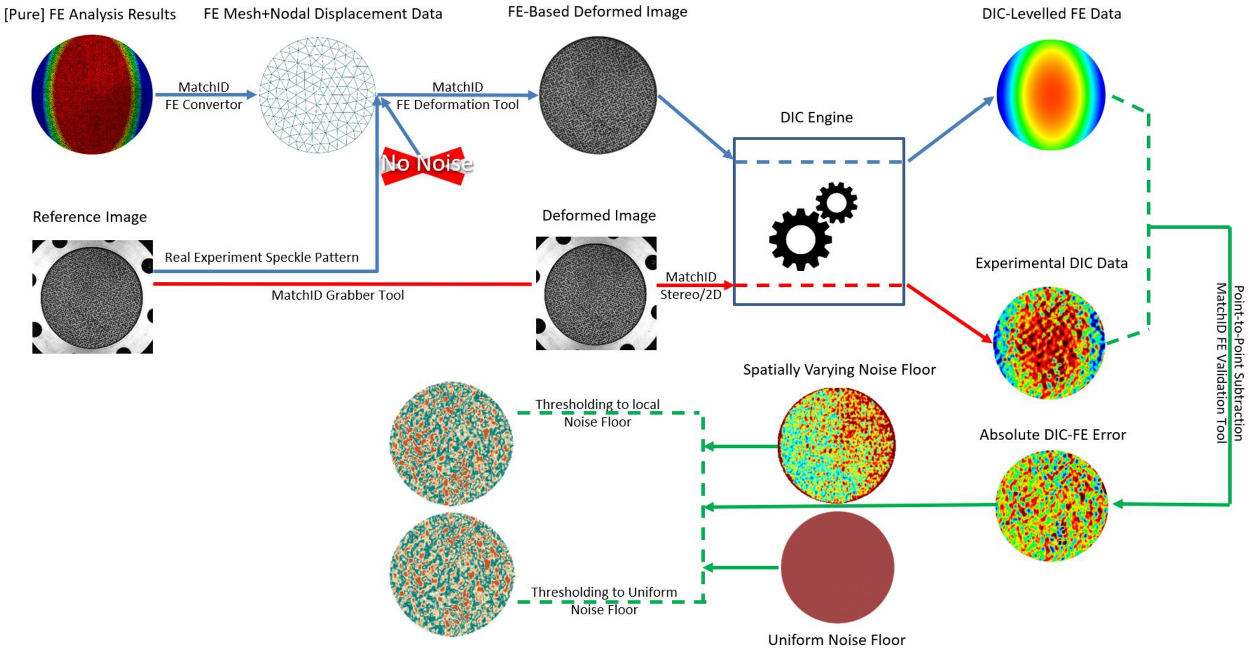

Figure 1. FE validation roadmap

Conclusions

This work shows that the use of the FE-levelling approach is essential in the validation of structural models with DIC as otherwise, it is impossible to separate the effects of the DIC measurements from that of potential model errors. One of the key conclusions is also that the random noise floor is underestimated from stationary images, and that a better approach must be established, even though the use of a point-wise noise floor is already an improvement. The presentation will provide some more hindsight into this.

References

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