SAND2019-2039C

Validation of Finite-Element Models using Full-Field Experimental Data

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Keywords: Finite-Element Model; Verification and Validation; Digital Image Correlation (DIC)

INTRODUCTION

Verification and validation (V&V) of finite-element (FE) models are critical to building credibility and confidence in model predictions for engineering design analysis. Historically, experimental data for validation studies was limited to either global data (e.g. resultant applied force) or point data (e.g. strain gauges and thermocouples). Such data, however, often misses important details about local deformation. The maturation of techniques for measuring full-field deformation of test pieces, such as Digital Image Correlation (DIC), have opened the door for richer experimental data for validation studies. *Qualitative* comparisons of field data between FE simulations and experimental DIC deformation data are simple and can provide valuable information to the design engineer in the beginning stages of FE model development. *Quantitative* comparisons, however, require that several inconsistencies between the two sets of field data be addressed, including different: data filtering, coordinate systems, grids of nodes or meshes, strain calculation methods, and spatial resolutions.

In this presentation, we present a method to address the above differences by using a stereo-DIC simulator. The simulator uses the FE mesh and FE displacements from the surface of the model to synthetically deform an image of a DIC speckle pattern. These synthetically deformed images can then be processed through the DIC software using the same user-defined parameters as for the experimental DIC images. By leveling the FE data to the experimental data, both sets of data have the same filtering, spatial resolution, and strain calculation method. We demonstrate the necessity and efficacy of the proposed method using synthetic data with a known solution. We show that when the DIC simulator is neglected and FE data is compared directly to DIC data, false negatives can occur in the validation process. When the simulator is utilized, correct validation conclusions are drawn.

BACKGROUND

An integral concept throughout this work is the generation of synthetically deformed speckle images for DIC, based on FE nodal information, which we call FE-DIC. The image deformation procedure is detailed in [1], while the extension to stereo-DIC is reported in [2]. The stereo-DIC simulator has been implemented in the FE Deformation module of the commercial software MatchID. Here, we briefly repeat the basic underlying principles, which are shown schematically in Figure 1. First, a finite-element simulation is performed yielding a mesh with corresponding nodal locations in the reference (unloaded) configuration. This mesh is then aligned onto an actual DIC speckle pattern captured by the left stereo DIC camera (annotated camera 0). Nodal displacements of various deformed configurations generated by the FE solver can be invoked to retrieve grey values at non-integer pixel locations: (x+u,y+v), with (u,v) determined from the shape functions of the element in which the pixel belongs. Next, a set of intrinsic and extrinsic camera parameters – as derived in a true experiment – project the FE nodal locations from the camera 0 sensor plane to the sensor plane of camera 1, yielding grey values at non-integer pixel locations (x+u+q, y+v+r), with (q,r) the additional projection displacements. The actual numerical

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images with grey values at integer pixel locations are then constructed based on these non-integer pixel location maps. These synthetically-deformed images can then be processed using the same DIC software, with the same user-defined parameters, as the experimental images. In this way, the FE data has been leveled to the experimental DIC data, and both data sets have the same data filtering, coordinate systems, grids of nodes or meshes, strain calculation methods, and spatial resolutions.

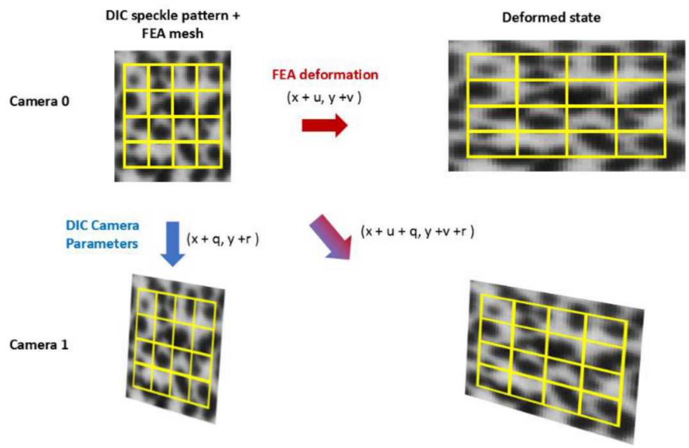

Figure 1: Schematic representation of the FE-DIC procedure used to synthetically deform a DIC speckle pattern according to the nodal displacements from a finite-element analysis.

METHODS

We generated synthetic "experimental" DIC data of the cover plate of a pressure vessel, as shown in Figure 2. The cover plate was clamped via bolt connections along the plate circumference. Both the bolt and the central tube connection resulted in local strain concentrations. A FE analysis was performed in Abaqus, using an isotropic linear hardening plasticity model. The nodal displacements were exported from Abaqus and used to generate synthetic DIC data using the FE-DIC procedure. This synthetic DIC data was then treated as if it came from a validation experiment independent of the FE. By creating synthetic experimental data in this way, with a known reference solution from FE, the effect of the DIC simulator on the validation results can be investigated.

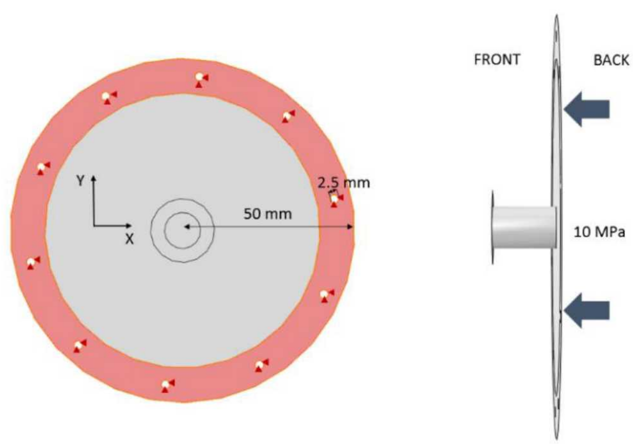

Figure 2: Geometry and loading of the pressure vessel cover.

RESULTS AND DISCUSSION

Figure 3 presents the original FE major principle strain and the "experimental" DIC principle strain computed using three different virtual strain gauge (VSG) sizes. As expected, the larger VSG sizes decreased noise in the DIC results, while simultaneously smoothing over sharp strain gradients near the bolts and central connection tube. The third column shows the strain error maps when the "experimental" DIC strains were directly subtracted from the FE strains, and then normalized by the DIC noise floor for each VSG. Since synthetic "experimental" data, which encoded the exact FE displacements with no model form error, was used, one expects that this trivial validation study would show a positive validation. Instead, we observe misleading negative validation results, which suggest that the "experimental" data does not agree with the FE data. Moreover, the validation results are dependent on the VSG size used in the DIC processing. These results highlight the fundamental issue with directly comparing FE strains and DIC strains. Namely, the DIC machinery acts as a low-pass filter, reducing strains in localized regions of high strain gradients. If this filtering is not accounted for in the FE strain data, an apparent model error is found during the validation studies.

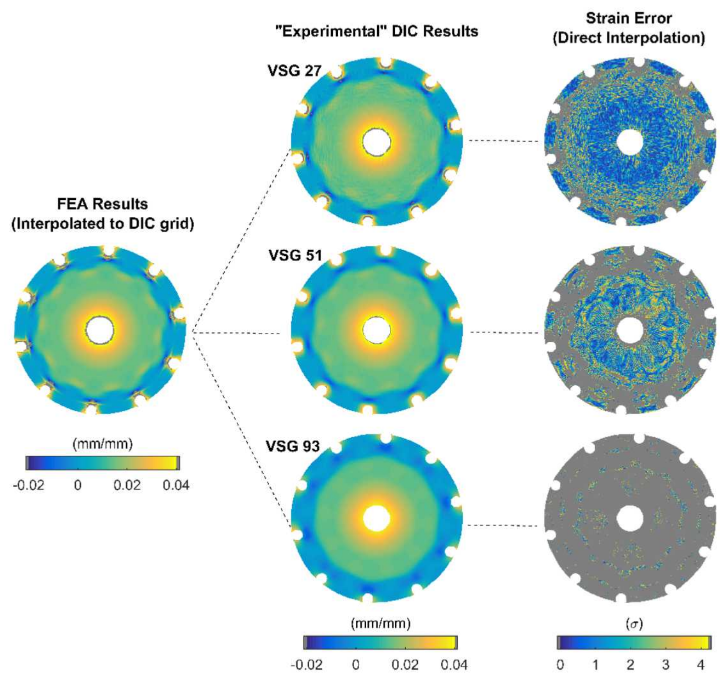

Figure 3. False negative validation results when the synthetic "experimental" DIC data is compared directly to the FE results, without taking into account the different spatial resolutions of the two sets of data and the low-pass filter effect of the DIC machinery.

Figure 4 presents the leveled FE strain – where the FE data was processed through the DIC machinery using the FE-DIC procedure – and the "experimental" DIC strains, again for three different VSG sizes. Additionally, the strain error maps are shown, where the "experimental" DIC strains were subtracted from the leveled FE strains, and then normalized by the DIC noise floor for each VSG. From the contours of the strain fields, we observe qualitatively that both the FE-DIC strain and the "experimental" strain fields have the same filtering applied as the VSG size increases. Despite this change in filtering, the validation maps all show predominant agreement between the "experimental" data and the FE model. Thus, the FE model is correctly validated. This result is in direct opposition to the false negative validation result shown in Figure 3, when the DIC strains were directly subtracted from the FE strains.

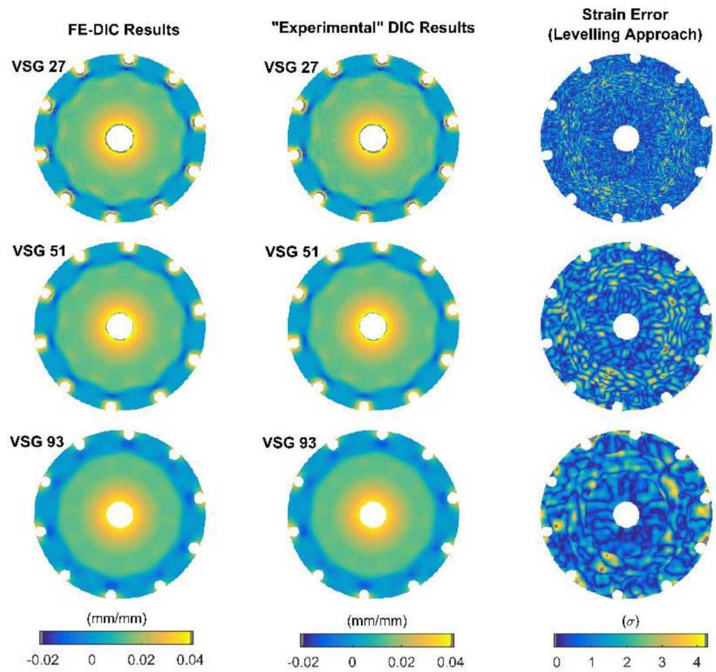

Figure 4. Accurate validation results, that are insensitive to the VSG size, when the FEA data is first leveled to the “experimental” DIC data, by processing it through the FE-DIC procedure.

CONCLUSION

Before using full-field DIC data for quantitative model validation, it is important to level the FE data to the experimental DIC data, to ensure that both sets of data have the same filtering, coordinate systems, grids of nodes or meshes, strain calculation methods, and spatial resolutions. We accomplish this leveling by synthetically deforming a DIC speckle pattern according to the nodal displacements from the FE analysis, and then processing these synthetically-deformed images through the same DIC software with the same user-defined parameters as were used for the experimental images. If this leveling step is ignored, false validation results can occur, leading to confusion about whether or not the FE model agrees with the experimental data. When this levelling step is employed, however, the validation results become independent of the VSG size, and accurate validation results are obtained.

ACKNOWLEDGEMENTS

This work was supported in part by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security administration under contrast DE-NA0003525.

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