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Levelling of Finite Element Models for Material Model Calibration using Digital Image Correlation

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ABSTRACT – Finite element model updating (FEMU) is an inverse technique used to identify material model parameters based on experimental data. These experimental data, often in the form of full-field deformation measurements, may cause a bias in the calibration procedure as a result of systemic filtering effects of the measurement technique used. Thus, a method to eliminate this filtering-induced mismatch is necessary for an accurate calibration. It is shown in this work that this can be achieved through appropriate levelling of the finite element model results. Levelling here refers to applying the same significant biases that occur in the experimental measurements, often digital image correlation (DIC), to the finite element model. We show through synthetically-derived data that DIC-levelling of the finite-element model eliminates errors in the calibrated parameter results that would otherwise occur if no leveling were performed. Moreover, the leveling process removes sensitivity of the calibration results to user-defined DIC settings such as subset shape function, step size, and virtual strain gauge size.

KEYWORDS – Digital Image Correlation, Finite Element Model Updating, Virtual Strain Gage, Material Model Calibration, DIC-Levelling

INTRODUCTION – To properly perform FEMU, the user must ensure compatibility between the experimental data and computational model. This is because the strain is often calculated differently between the experimental analysis and finite element model. In order to directly capture the errors present in an experiment, one would have to reproduce the biases caused by these three groups:

1. Image-induced errors such as pattern-induced bias (PIB), discrete truncation of grayscale values [1], and subpixel interpolation bias [2].
2. Systematic DIC related errors such as shape function attenuation bias (SFAB) [3] and strain attenuation which is a similar filtering error as the SFAB [4], and different strain formulations or calculation methods between DIC and FEM.
3. Experimental errors such as image noise, heat haze [5], pattern delamination, alignment, registration, or specimen fixturing issues that cannot necessarily be predicted or measured.

The authors in [6] created software that can create FEM-based synthetically deformed (F-SID) images based on output from commercial FEM software to approximate the biases in groups 1-2. A software module, in MatchID called Finite-Element Deformation (FEDEF), was used in [6] to compare full-field strains from DIC to those from the FEM software. They showed that if different length-scales and spatial resolutions of the two sets of data are not rectified, false errors may appear. These errors may be mistaken for an error in the FEM, when in actuality, they are caused by different filtering applied to the experimental data by the DIC engine.

With this new F-SID capability, it is possible to “level” the FEM strain by taking the FEM strain as the DIC-measured strain from the F-SID images. This ensures that both the FEM and DIC data have the same filtering applied and have the same spatial resolution. In this way, meaningful comparisons of the field data can be made. Building from this work, we show here that DIC-leveling of the FEM data is critical for material model calibration using FEMU. However, instead of using the complete leveling process of performing DIC analysis of F-SID images created through the FEM, we posit that the DIC errors in group 1 are often inconsequential in the model calibration process compared to the systemic biases in group 2 and group 3 (the latter of which should be minimized at the experimental level). By simplifying the leveling process to

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analytically performing filtering of the FEM data similar to that of DIC, we are able to implement it in-house without specialized software, and we improve the computational efficiency.

Additionally, we show it is possible to perform FEMU using heavily levelled FEM strain and still obtain a unique and accurate set of material parameters. To validate this hypothesis, we created a set of "experimental" images using the FEDEF module in MatchID with a deformation state based on a FEM of a known material. Then we performed FEMU with different levels of DIC-levelling of the FEM data, using different DIC settings. The results of only one of these analyses are shown in the Results section.

METHODS – F-SID image sets were formed using the FEM simulation described below in conjunction with MatchID's FE image deformer module (FEDEF) [6] with a global bicubic spline interpolant. This module takes the ABAQUS odb file and applies the deformation to a given image, in this case the rotated noise-free reference image from the DIC Challenge 2.0 [4]. Two image pairs were created in total, one without noise, and one with a unique instance of heteroscedastic noise to each the reference and deformed image. The camera noise was based on a FLIR (formerly PointGrey) 5-Megapixel camera (GRAS-50S5C-C) and is the same noise model the DIC Challenge 2.0 uses.

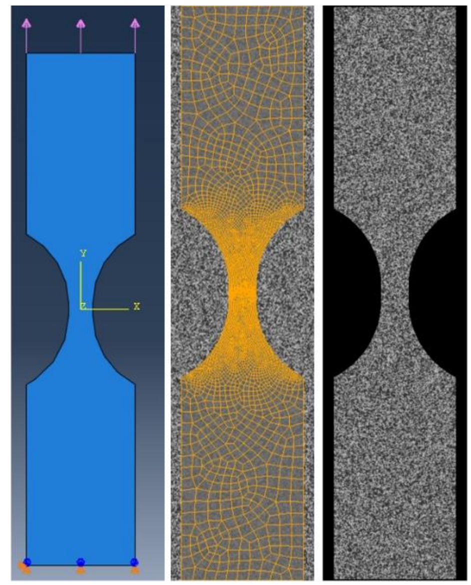

Fig. 1 Left) FEM used in our experiment with applied boundary conditions. Center) FEM mesh overlaid on the rotated DIC Challenge 2.0 image serving as our reference image. Right) the deformed image using MatchID's FEDEF module.

For the material model, we used an isotropic linear-elastic model with isotropic hardening based on a simplified Johnson-Cook model shown by Eq. 1.

$$\sigma_y = \sigma_0 + B(\epsilon^p)^n \quad (1)$$

The material model parameters σ_0 , B, and n are included in Table I below along with the initial guess of the FEMU optimization. The traction was applied vertically with a magnitude of 117 MPa.

Table I. Parameters used in the finite element model.

	E (GPa)	ν	σ_0 (MPa)	B (MPa)	n
Nominal	200	0.29	339	1,070	0.645
Initial Guess	200 (fixed)	0.29 (fixed)	305.1	1,177	0.5805

DIC was performed in MatchID using a subset size of 21 pixels, step of 7 pixels, quadratic shape function, and an approximated normalized sum of squared difference criterion. The strain was then calculated by applying an affine shape function to a set of DIC points with an area defined by the virtual strain gage (VSG). The coefficients of the shape function were then used to analytically calculate the Green-Lagrange strain. Several sizes of virtual strain gages (VSGs) were investigated, ranging from 0.4 mm to 2.0 mm in 0.4 mm increments, to simulate different levels of the DIC filtering. The full-field y-strain is shown in Figure 2 as an example of the DIC results.

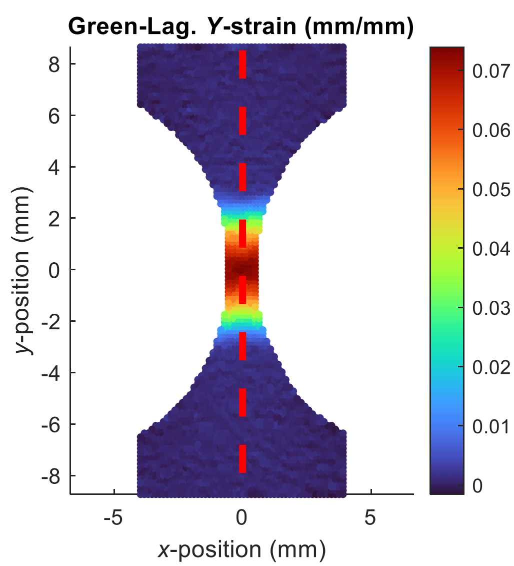

Fig. 2 DIC y-strain results for the smallest VSG 0.4 mm.

The spatial resolution of the strain signal is dependent on the size of the VSG. Figure 3 shows a linecut of the y-strain across the center of the specimen in Figure 2 for several different VSG sizes. The second plot in Figure 3 more clearly displays the strain attenuation from the larger filtering. This under-estimation of the strain can cause errors in the FEMU calibration as will be shown in the next section.

RESULTS – In the first calibration, the effect of levelling the FEM to the DIC results is studied for both the noisy and noise free images. The unlevelled FEMU results (shown by the blue crosses in Figure 4) were identified by optimizing the ABAQUS strain output, which is an integrated strain measure, to the DIC-measured Green-Lagrange strain, which is a different strain measure and spatial resolution. For both the noise free and noisy image calibrations, the unlevelled FEM models failed to provide

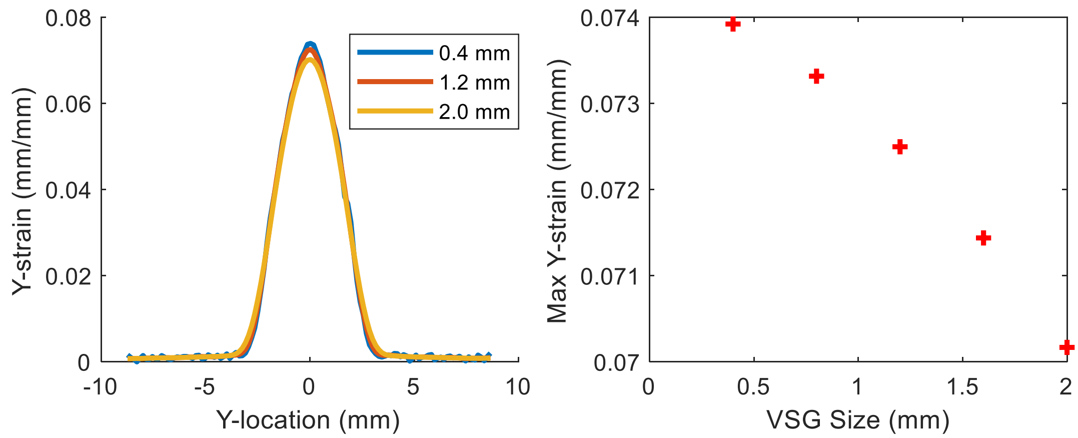

Fig. 3 Left) y-strain line samples for the noise free image. Right): The maximum *y*-strain measured for each VSG. The larger strain gages attenuate the strain more and can cause a disparity between the experimental measure of strain a higher resolution FEM-measured strain.

accurate calibrations for any VSG size. This error increased with increasing VSG size due to the disparity in spatial resolution, exceeding 10% for σ_0, 18% for B, and 22% for n for the largest VSG size employed. The difference in the error between noisy and noise free results was negligible as the error was mainly dictated by the disparity in spatial resolution.

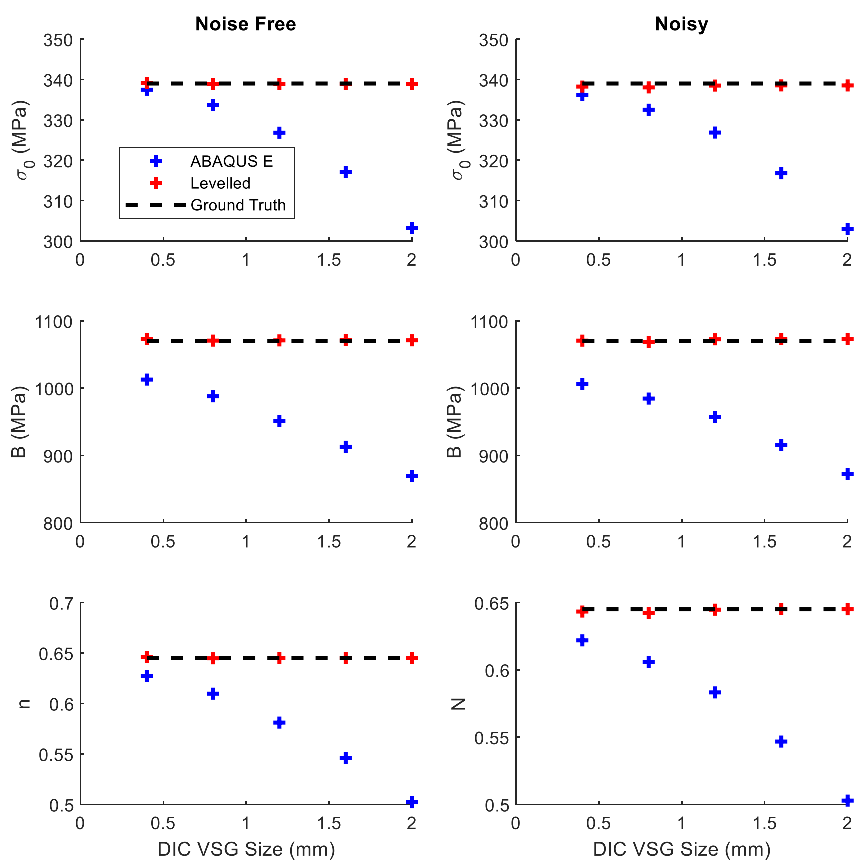

Fig. 4 Found parameters for the FEMU calibration between the DIC measured strain and the levelled and unlevelled FEM strain. The FEMU results using the levelled FEM model were accurate for all VSG sizes, where the unlevelled FEM was not.

For the next calibration, the FEM strains were leveled by computing them using the same affine strain shape function and VSG size as was used in the DIC strain computation. In this way, both the FEM and DIC strains have the same filtering and same spatial resolution. The levelled calibrations (red crosses) were all successful in acquiring the correct parameters. For the noise free images, all parameters were calibrated to within 0.3% of the ground truth value (black dashed line) for all VSG sizes. Disparities between this calibration and the nominal value can be explained by the biases introduced by the images, namely image discretization errors, pattern induced bias, small amounts of shape function attenuation bias, and subpixel interpolation bias (i.e. group 1 errors), among other things. The calibration of the noisy images was also successful in that the final parameters were calibrated to approximately 0.5% or less of the nominal values despite the bias introduced by the added noise.

CONCLUSIONS – We have shown when using full-field data such as from DIC for material model calibration via FEMU, it is critical to take into account the disparities of filtering, length scale, and spatial resolution between the two data sets. If these differences are not accounted for, incorrect calibration results are identified, with errors up to 22% in the presented exemplar. Moreover, the errors depend on the user-defined VSG size used in the DIC processing, making it difficult to objectively and consistently determine appropriate user-defined parameters. To address this issue, we have shown that by consistently levelling the finite element model results, so that both the FEM and DIC data have the same filtering and same spatial resolution, the correct material model parameters can be identified regardless of the VSG size. Moreover, this levelling can be done without the use of F-SID images, which require extra computation and access to specialized software.

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