

involving uniaxial and biaxial traction, uniaxial and biaxial compression and pure and simple shear, going beyond the elastic limit in all cases, over a unique specimen loaded using a conventional test device.

In the last decade, multiple geometries have been designed to achieve this objective; the present study focuses on specimen geometries adapted to uniaxial tensile loadings. For instance, Marek et al. tested a notched specimen [6], Kim et al and Jones and al. designed more complex geometries: a “ Σ ”-shape and a “D”-shape [7,8]. Finally, Barroqueiro et al. used topological optimization to generate a more complex specimen shape [9]. The present work focusses on the notched specimen only.

3.2 FEM model

To simulate tensile tests and analyse the stress states generated in the elements that reach plasticity, we use the *Z-set* finite element software. The material behaviour is modelled using the constitutive equations and the associated material parameters identified previously. All simulations are performed using plane stress hypothesis. The elements are linear triangular shells with full integration with an average size of 0.5mm. The simulation stops when an element reaches an equivalent plastic strain, ϵ_p , of 0.15.

3.3 Synthetic images generation and DIC

To take into account biases encountered with full-field measurement, synthetic test images are generated based on the finite elements simulations. The algorithm initially implemented by Bouda et al [10] uses the position of the pixel inside the deformed element (x_d, y_d) . Then, it projects the pixel in the reference configuration (x_0, y_0) using isoparametric coordinates (ξ_i, η_i) of the pixel inside the element to define its grey level (Fig. 3). In this study, the grey level of the pixel is interpolated from the grey levels of a set of real pictures of a speckle pattern. The deformed pictures have been taken in the same configuration as for real tests (lightening, camera and pattern application technique). This helps make synthetic images closer to real images considering the grey levels range and the sensor noise.

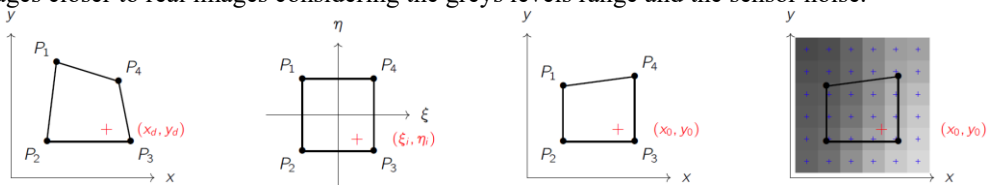


Fig. 3. Principle of finite element based image deformation process

The next step is to compute the displacement fields using a DIC software. In this study, the algorithm *folkID*, developed by ONERA [11] is used. The strain fields are smoothed spatially and temporally using Gaussian filters with a window size of 20 pixels for spatial smoothing and 3 time steps for temporal smoothing. Finally the data close to the edge (less than the half of the smoothing window) is reconstructed by extension of the latest known value. The stress field and the equivalent plastic strain are obtained by calling the same routine than in the FEM model using the *Zmat* tool.

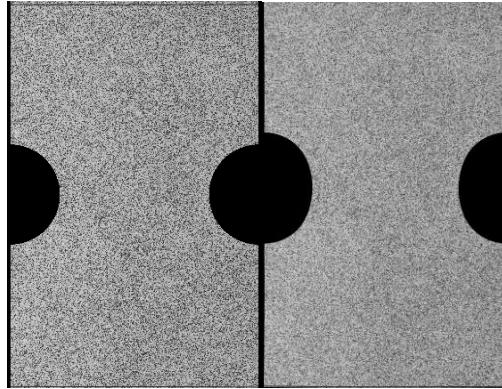


Fig. 4. Synthetic images of a tensile test on a deep-notched specimen (initial and deformed stages) simulating images with spatial resolution of 4320 x 2868 pixels

4 Results

To analyse the heterogeneity of the stress field from FE results, the generated stress states are projected on the yield surface. **Fig. 5** shows the equivalent plastic strain and the projection of the stress states over the yield surface computed by FE simulations at the final time step. The elements where the equivalent plastic strain is zero are coloured in light grey and the stress states inside those elements is not projected on the yield surface. The numerical simulations shows that a notched specimen can generate uniaxial tension and stress states close to biaxial tension and simple shear in elements that reach plasticity.

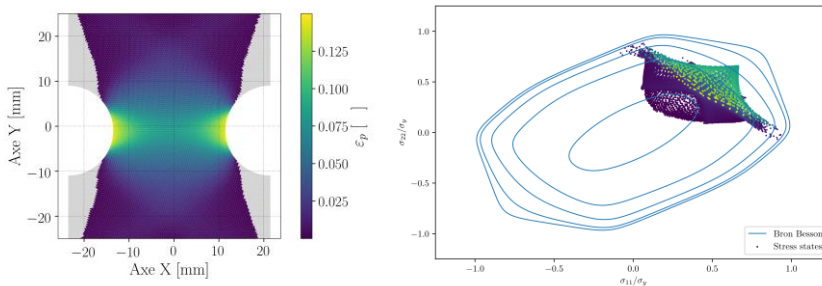


Fig. 5. Cumulated plastic strain field and stress states for a notched specimen

The same analysis is presented for the synthetic images of the notched specimen (**Fig. 6**) after computing the stress fields with the DIC results (i.e. including measurement biases). At the same time step, the regions that reach plasticity are the same than the reference FE simulation, except close to the edges, where reconstructed data generates plasticity while the simulation does not. The stress states thus obtained, in the region where the plastic strain is greater than 0.01, are similar to FE simulation ones, i.e., are mainly characteristics of uniaxial tension, with a tendency of expansion towards biaxial tension and simple shear. The inclusion of full-field measurement biases on synthetic images leads to the computation of stress states between pure and simple shear, which are not present in the reference FE simulation. As they are not real mechanical states, these biased stress states can cause errors in identification of the material parameters.

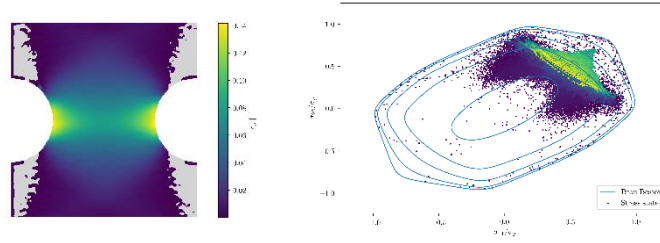


Fig. 6. Cumulated plastic strain field and stress states for the notched specimen computed from DIC results on synthetic images

A quantification of the biases induced by the measurement can be computed from the quantification of the mechanical field heterogeneity. A first approach can be based on the exploitation of strain fields, following the indicator suggested by Souto et al. (6) [12]. On the one hand, the strain states heterogeneity is expressed with the standard deviation, $Std(\epsilon_2/\epsilon_1)$, and the range, $(\epsilon_2/\epsilon_1)_R$, of the ratio between minor and major strain. On the other hand, the range of plastic strain is analysed with its standard deviation, $Std(\epsilon_p)$, its average value, $Av(\epsilon_p)$, and the maximum plastic strain reached for specific loadings (7). Each element is normalized by an absolute coefficient, w_{ai} , and weighted by a relative coefficient, w_{ri} . The coefficient values used in this work are reported in **Table 2**.

The results of the heterogeneity indicator and its components are reported in **Table 3**. Concerning the strain state ratio, DIC results increases the standard deviation. Moreover, some pixels with a major strain close to zero have caused the strain ratio range to explode. As this value is much higher than the other elements, it may not be relevant for computation of I_T with experimental results. Therefore, the relative coefficient w_{r2} was set to zero. The results also show that the maximum value of equivalent plastic strain has decreased. This is mainly due to the measurement biases close to the edges that underestimate the deformation (extension of the last know value). Also the shear observed with the synthetic images (**Fig. 6**) is reflected by the increase in the coefficient $\epsilon_p^{Max}_{shear}$. Finally, for the same test, the value of the heterogeneity indicator has significantly increased. So it is possible to quantify the measurement biases using its variation.

$$I_T = w_{r1} \frac{Std(\epsilon_2/\epsilon_1)}{w_{a1}} + w_{r2} \frac{(\epsilon_2/\epsilon_1)_R}{w_{a2}} + w_{r3} \frac{Std(\epsilon_p)}{w_{a3}} + w_{r4} \frac{\epsilon_p^{Max}}{w_{a4}} + w_{r5} \frac{Av(\epsilon_p)}{w_{a5}} \quad (6)$$

$$\epsilon_p^{Max} = \frac{\epsilon_p^{Max}_{test} + \epsilon_p^{Max}_{tensile} + \epsilon_p^{Max}_{shear} + \epsilon_p^{Max}_{plane} + \epsilon_p^{Max}_{biax.} + \epsilon_p^{Max}_{comp.}}{6} \quad (7)$$

Table 2. Coefficients used to compute the heterogeneity indicator

w_{r1}	w_{r2}	w_{r3}	w_{r4}	w_{r5}
0.3	0.0	0.2	0.4	0.1
w_{a1}	w_{a2}	w_{a3}	w_{a4}	w_{a5}
1	4	0.25	0.15	0.15

Table 3. Values of the heterogeneity indicator and its components for the notched specimen

	$Std(\epsilon_2/\epsilon_1)$	$(\epsilon_2/\epsilon_1)_R$	$Std(\epsilon_p)$	$\epsilon_p^{Max}_{test}$	$\epsilon_p^{Max}_{tensile}$	$\epsilon_p^{Max}_{shear}$	$\epsilon_p^{Max}_{plane}$	$\epsilon_p^{Max}_{biax.}$	$\epsilon_p^{Max}_{comp.}$	$Av(\epsilon_p)$	I_T
FE	0.240	0.775	0.029	0.150	0.017	0.0	0.119	0.0	0.0	0.022	0.237
DIC	0.668	104.0	0.031	0.142	0.020	0.014	0.126	0.0	0.009	0.030	0.383

5 Conclusions and future work

In this study, the objective was to quantify the influence of DIC measurement biases on the selection procedure of a specimen geometry to identify material parameters of an anisotropic yield criterion. To that end, synthetic images are used to investigate the effect of DIC measurement biases on the stress states range and on strain-based indicators. It reveals that the use of DIC can be the source of several biases that may affect the indicators for the selection of a heterogeneous states and the identification results, especially the occurrence of biased stress states.

Future work will aim at consolidating the use of criteria to quantify measurement induced biases. Then, this method will be used on several specimen geometries to compare their robustness to measurement biases. Then, real tests will be performed with several geometries to validate the selection procedure described in this paper.

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