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A hybrid VFM-FEMU approach to calibrate 3D anisotropic plasticity models for sheet metal forming

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Abstract. Recently, inverse methods such as the Virtual Fields Method (VFM) or the Finite Element Model Updating (FEMU), coupled with a full-field measurement technique, have been distinguished as efficient strategies for the calibration of complex plasticity models [1]. The use of heterogeneous strain fields, in fact, offers a larger amount of material information compared to the classical standard test, enriching the identification process and, in general, reducing the experimental effort for the calibration [2]. Here, an inverse identification framework is proposed for the calibration of a full-scale anisotropic plasticity model. The inverse identification procedure employs full-field information from two main experiments: a tensile test on double notched specimens for the calibration of the coefficients expressing the planar anisotropy, and an innovative Iosipescu-like test for the through-thickness shear ones. A hybrid approach is used with the VFM employed to identify the planar coefficients and the FEMU for the through thickness ones.

Introduction

Sheet metals are characterized by an anisotropic behavior which plays a crucial role in the prediction of their plastic deformation and failure. Generally, their constitutive response is modeled and calibrated by mainly considering the in-plane material behavior, while the through-thickness one is often neglected based on the plane stress assumption. However, in some applications - for instance the sheet metal forming of complex geometries - the state of stress can deviate from the plane stress assumption and a complete 3D description is necessary [1].

Over the years, several testing protocols have been developed to capture in detail the complex mechanical response under different types of loading conditions and to infer a comprehensive description of the material deformation. Traditionally, the common material testing approach relies on the use of quasi-homogeneous tests, where the relation between stress and strains can be directly obtained from experiments properly designed; on the other side, the application of full-field techniques to material testing has allowed to analyze and simultaneously exploit multiple stress and strain conditions produced through heterogenous tests [2,3].

However, mechanical data from heterogeneous tests cannot be directly used in the calibration process, and are generally coupled with inverse methods. Inverse methods have been already used to identify, for instance, the plastic behavior of metals by resorting to numerical simulations [4,5]: the method is often referred as Finite Element Model Updating (FEMU) since, essentially, performs the identification by iteratively changing the constitutive parameters of a numerical simulation of the test until the difference between the numerical and experimental results, in terms of loading force and strain fields, is minimized. Other examples for the identification of the hardening behavior can be found in [6,7] using an energy balance approach called the Virtual Fields Method (VFM) [8]. The VFM has been applied also to anisotropic plasticity [9-11] and to investigate multiaxial loading conditions such as cruciform specimens [12] and the bulge test [13].

However, experimental procedures to calibrate full 3D anisotropic plasticity models of sheet metals are still not well addressed. The aim of this work is to demonstrate that such calibration can be effectively carried out using inverse methods and simple experiments.

Methods

The aim of this paper is the identification of a full 3D anisotropic model trying to reduce the experimental effort and the number of tests required to make the identification. A similar problem was already tackled in [14] by Denys et al., who introduced a double drilled specimen employed for the full calibration of the Hill48 yield surface, by means of the FEMU approach. However, especially for sheet metals, often it is not possible to perform a hole along the thickness of the specimen, so the previous method can only be applied to thick materials.

A different approach is used here, employing specimens that can be easily machined from a sheet metal blank and tested using a standard uniaxial machine, so that the experimental procedure can be readily implemented in almost each material testing lab. The proposed method also requires the use of a full-field optical measurement technique, e.g. digital image correlation (DIC), to obtain the strain field in a region of interest (ROI) of the specimen, following the Material Testing 2.0 logic [2].

Virtual experiments are used to verify the feasibility of the developed procedure; the three-dimensional anisotropic behavior of the material was reproduced using the Hill48 yield function:

$$f(\boldsymbol{\sigma}) = \sqrt{F(\sigma_y - \sigma_z)^2 + G(\sigma_z - \sigma_x)^2 + H(\sigma_x - \sigma_y)^2 + 2L\tau_{yz}{}^2 + 2M\tau_{xz}{}^2 + 2N\tau_{xy}{}^2} \quad (1)$$

where F,G,H,LM and N are constants that must be identified from experiments, in particular, in this case, we set L=M so that the shear behavior through the thickness in the *y-z* plane is equal to the one in the *x-z* plane. The hardening was described by a Swift law:

$$\sigma_{eq} = k\left(\varepsilon_0 + \varepsilon_{eq}\right)^n \quad (2)$$

where σ_{eq} and ε_{eq} are the equivalent stress and strain, respectively, and k, ε_0 and n are parameters that must be identified. Summarizing, to fully characterize the three-dimensional anisotropic behavior of the material, it is necessary to identify a total of 8 parameters, 5 for the yield function and 3 for the hardening law.

A two-steps identification process was developed using a double notched (DN) specimen to identify the in-plane anisotropic properties and the hardening law, i.e. parameters F, G, H, N, k, ε_0 and n; and a through-thickness shear (TTS) test to identify the shear behavior along the thickness, i.e. parameter L.

FE models of the two tests were developed using ABAQUS and used to generate synthetic data that replicate the load history and the strain maps obtained during a real test. The synthetic data were accordingly used as input for the identification procedure.

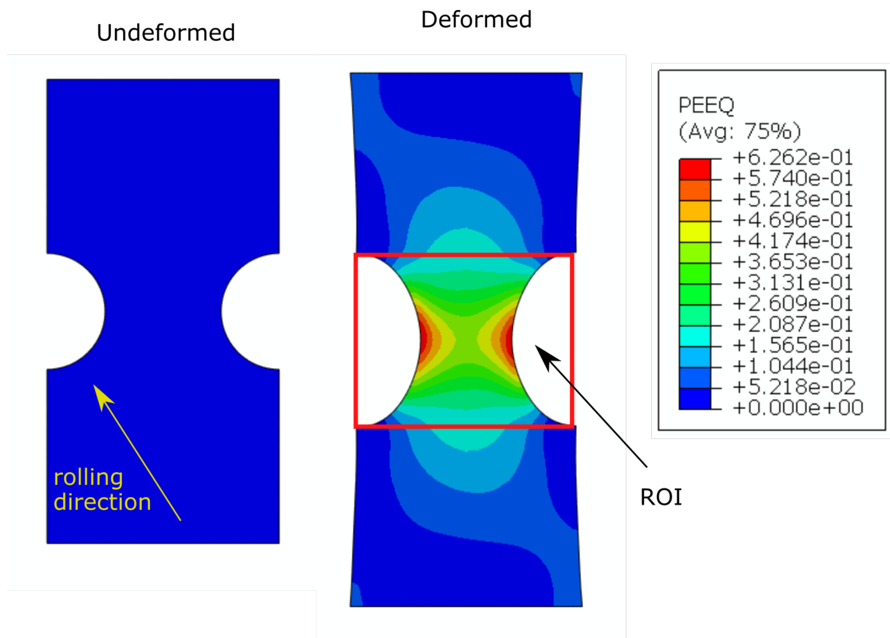

Fig. 1. Double notched specimen used to evaluate the in-plane properties.

Fig. 1 shows the geometry of the DN specimen and the ROI where the full-field strain measurement is performed through DIC. In this case, the FEM data were used to simulate a DIC measurement with 151 × 51 strain points in the ROI. The rolling direction of the material was inclined with an angle of 22.5° with respect to the force direction.

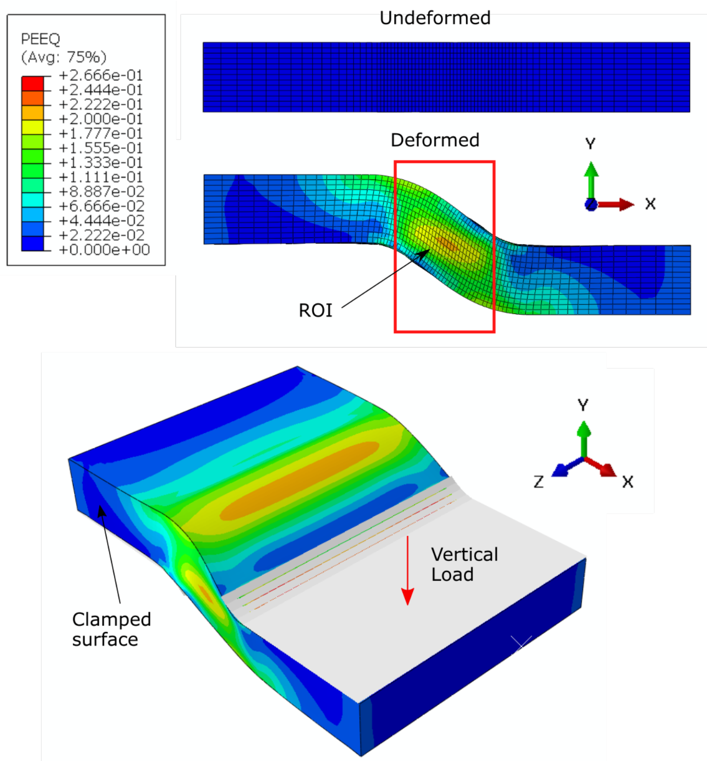

Fig. 2. Through-thickness shear test.

Fig. 2 illustrates the TTS test used to identify the parameters governing the through-thickness shear behavior. In this case, the ROI was placed along the thickness surface with 200 × 200 simulated measurement points, see Fig. 2. For both tests, the thickness of the sheet metal is 2 mm.

The identification of the constitutive parameters was performed using a hybrid VFM-FEMU approach, where the VFM was used with the DN specimen to identify 7 parameters and the FEMU was used with the TTS test to identify 1 parameter. Indeed, the VFM cannot be employed on the TTS test because the problem is three-dimensional and the plane stress or plane strain assumption is not valid, i.e. the strain measured along the thickness surface with DIC is different from the strain inside the material.

The advantage of combining the two methods is that VFM is usually less computationally expensive, so it can be used to quickly identify 7 parameters while FEMU is restricted to the identification of 1 parameter. The hybrid procedure is sequential, first the VFM is applied and then the FEMU using different cost functions, this is possible because the behavior of the DN specimen is not influenced by the parameter L, which is subsequently identified with FEMU. Theoretically, VFM and FEMU could also be put in the same optimization loop, using a common cost function, but such approach will be more complex and less efficient. Test design is essential to develop tests that are uncoupled with respect to different parameters, in order to simplify the identification procedure.

Both methods are implemented in Matlab using the in-built minimization functions to solve the inverse problem. A brief description of the two methods is given below, more details can be found in the references.

VFM Approach

The Virtual Fields Method (VFM) is an inverse method based on the weak form of the equilibrium through the Principle of Virtual Work (PVW) and allows to identify the coefficients of a given constitutive model starting from full-field kinematic and loading data. In the case of quasi-static problems where the body forces are neglected, the VFM is generally expressed for large deformations using the following cost function:

$$\Psi(\boldsymbol{\xi}) = \sum_{i=1}^{N_{vf}} \sum_{j=1}^{N_{step}} \left| \int_V \boldsymbol{T}_j^{1PK} : \delta \boldsymbol{F}_i^{\bullet} dV - \int_{\partial V} \left(\boldsymbol{T}_j^{1PK} \boldsymbol{n} \right) \cdot \delta \boldsymbol{u}_i dS \right| \tag{3}$$

where $\mathbf{T}_j^{1PK}$ indicates the 1st Piola-Kirchhoff stress tensor, $\delta\mathbf{u}_i$ is any kinematically admissible virtual displacement field, $\delta\mathbf{F}_i^{\bullet}$ is the corresponding virtual displacement gradient tensor, V is the volume of the inspected solid, ∂V is the boundary surface and **n** the surface normal. The first integral term represents the Internal Virtual Work, where the stress tensor is calculated from the full-field strain data of the test according to the model constitutive parameters ξ; the second integral indicates the External Virtual Work and accounts for the loading condition on the boundaries. The cost function is evaluated for all the N_{step} timesteps of the test and for all N_{vf} virtual fields introduced. In this study, the constitutive behaviour is described by a non-linear relation, therefore, the identification is achieved through the minimization of the cost function $\Psi(\xi)$ until the equilibrium equation of the PVW is satisfied. The method is widely described in the literature and more details can be found in the book and papers cited in the introduction see [6-13].

The selection of the virtual fields (VFs) directly affects the identification results since they activate and weight the constitutive information contained in each material point. For this reason, the definition of the VFs employed in the cost function minimization is not trivial. Different approaches can be found in literature [15, 16] which, basically, classify the VFs in manually defined VFs and automatically generated VFs. In this work, we adopt the latter approach, where the virtual kinematic fields are produced starting from the sensitivity of the computed stress field to the single material parameter:

$$\delta \boldsymbol{T}_{(i)}^{1TPK}(\boldsymbol{\xi}, t) = \boldsymbol{T}^{1TPK}(\boldsymbol{\xi} - \delta\xi_i, t) - \boldsymbol{T}^{1TPK}(\boldsymbol{\xi}, t) \tag{4}$$

in other words, by perturbing the material parameter ξ_i, it is possible to highlight the material points where ξ_i effectively affects the stress calculation; the sensitivity distribution can be used as $\delta\mathbf{F}_i^{\bullet}$ and can be integrated to get the $\delta\mathbf{u}_i$ through a piecewise approach, as discussed in detail in [17].

FEMU Approach

The FEMU is based on the minimization of a cost function that represents a weighted difference between the numerical and experimental results. In this particular case, the compared results are the vertical load force applied by the tensile machine (see Fig. 2) and the full-field strain map measured in the ROI. In a real test, the boundary conditions (BC) are a critical factor, in fact possible misalignments or sliding on the clamping zone of the specimen can influence the deformation history. To reduce the bias due to BC, the FEMU is conducted only on a portion of the material within the ROI, see Fig. 3. The boundary conditions are applied using the displacement measured by the full-field measurement at the border. The central zone is not subjected to friction and the vertical load force measured by the machine can always be obtained from the FE model as sum of the nodal reactions along the vertical direction.

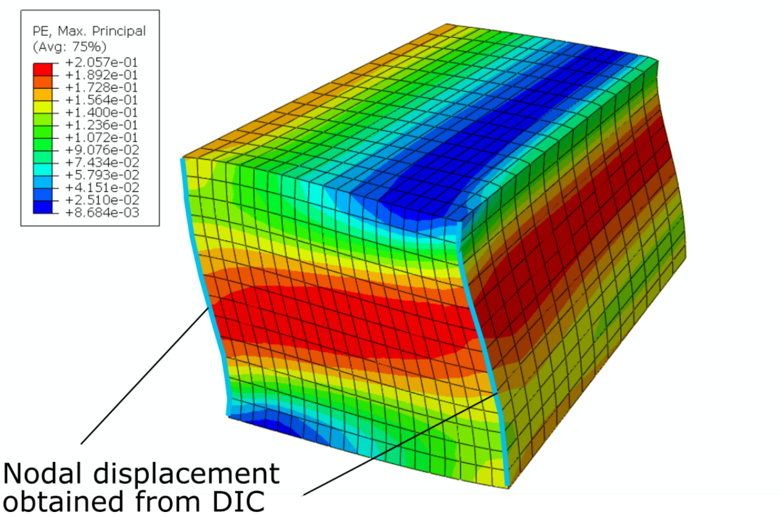

Fig. 3. Portion of the specimen used in the FEMU.

Results and Discussion

The results of the identification are listed in Table 1 in terms of identified parameters and percentage error. The reference parameters are the ones input in the FE model used to create the simulated experiment and can be viewed as the ground truth of the inverse problem. The identification is reasonably good except for parameter ε_0, however it is well known that this parameter has a minor impact in the description of the hardening curve. Moreover, often, the sole parameter identification error is not a proper criterion to evaluate the accuracy of the identification method, instead, it is preferable to verify the results in terms of plastic behavior, i.e. yield surface and hardening curve.

Table 1. Reference and identified parameters.

	VFM							FEMU
	K	ε_0	n	F	G	H	N	L=M
Reference	1000	0.02	0.5	0.3819	0.3125	0.6875	1.389	2.5
Identified	1041	0.0123	0.4846	0.3980	0.3308	0.6692	1.4033	2.66
Error %	-4.1	38.5	3.0	-4.2	-5.8	2.6	-1.03	-6.4

Fig. 4 shows the results in terms of yield surface and hardening curve. Since it is not possible to represent a 6-dimensional anisotropic yield surface, Fig. 4a shows the yield surface in terms of the normal stress components, i.e. σ_x σ_y σ_z, and Fig. 4b shows the yield surface for the shear stress components, i.e. in-plane (τ_{xy}) vs out of plane (τ_{xz} or τ_{yz}). Finally, Fig. 4c illustrates the identified hardening curve. It is worth noting that the computation was performed on a workstation and the VFM algorithm took around 20 seconds to solve the inverse problem while FEMU more than 5 hours. Such huge difference is due to the fact that each iteration of FEMU needs to run a complex three-dimensional FE simulation, on the other hand, parameter L can only be identified with FEMU. Moreover, the hybrid approach allows to simplify the FEMU part since only 1 parameter needs to be identified, reducing the computational effort of the minimization algorithm.

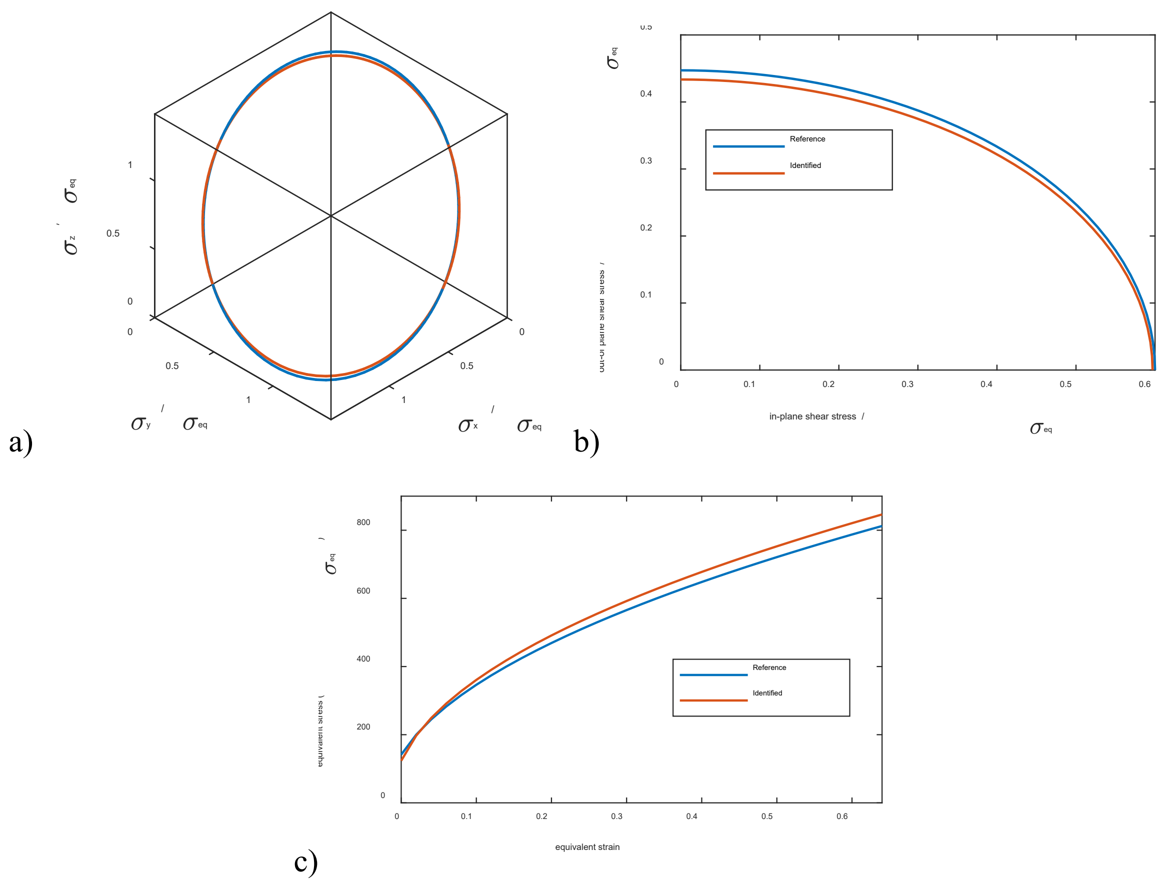

Fig. 4. Comparison of the identification results: a) yield surface for the normal stress components, b) yield surface for the shear components, c) hardening law.

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Summary
In this paper an inverse identification procedure to characterize the 3D anisotropic behavior of a metal is proposed and validated through simulated experiments. Two tests are used to identify 8 constitutive parameters combining two well-known inverse methods, i.e. the VFM and FEMU. The identified parameters provides an accurate description of the plastic behavior, with an average error below 5%. In the future, an experimental validation will be conducted and the possibility of identify more complex 3D constitutive model will be evaluated.

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