Development of new experimental test for sheet metals through-thickness behaviour characterization

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Abstract. The present work proposes a new testing system to evaluate the through-thickness shear behaviour of anisotropic sheet metals, that can be employed in identification methods such as the Virtual Fields Method (VFM) and the Finite Element Model Updating (FEMU). In fact, only the planar components of anisotropy are usually considered due to assumption of plane stress condition, and the through-thickness shear behaviour can be relevant in the prediction of failure models and plastic instabilities in such industrial applications where localized shear occurs during metal forming processes.

The new experimental protocol is based on the application of Unnotched Iosipescu test to large strain plasticity, using DIC for the thickness surface displacement measurement. Here, a first configuration of the experimental set-up is tested employing specimens obtained from S355 steel blank. Then, the test performed is used to identify the anisotropy shear parameter in the thickness plane of constitutive model Hill48 via FEMU method.

1. Introduction

Sheet metals often exhibit preferential orientations in their texture due to rolling production process, that plays, also, a really important role in subsequent metal forming applications. Although only the planar components in the RD-TD plane (Rolling and Transverse directions) of anisotropy are usually considered in constitutive modelling due to assumption of plane stress condition, the through-thickness shear behaviour can be relevant in the prediction of failure modes and plastic instabilities. Several 3D anisotropic plasticity models were developed among the years [1–4], and their calibration is getting increasing interest from the research community, working on methodology and design of appropriate specimens. For example, in [5] a general procedure to retrieve material parameters for the 3D Hill48 model using the VFM on numerical data is described; also, Denys et al. [6] reported an application of stereo-DIC for the identification of 3D Hill48 yield surface through FEMU technique, where a double perforated specimen with a 10 mm thickness is introduced. However, when these 3D material models are employed on metal sheets, it is often a common procedure to assume the through-thickness parameters equal to the isotropic case, and then to calibrate the others.

The main propose of this work, thus, is to assess the feasibility of a new experimental protocol for testing through-thickness anisotropic shear behaviour of sheet metals. The idea took place extending the Unnotched Iosipescu test [7, 8] to large strains, using 2D-DIC for the thickness surface displacement measurement.
Here, a first set-up configuration is analysed, performing the through-thickness shear test on S355 steel metal sheet specimens. Therefore, the obtained results are used to identify the Hill48 anisotropy shear parameter in the thickness plane using the Finite Element Model Updating (FEMU) technique.

2. Description of the test

Iosipescu test [9, 10] is nowadays a common standard for studying the shear properties of composite materials in the field of linear elastic anisotropy, and in literature several applications [10,11] are reported. This kind of test involves a V-notched specimen with appropriate fillets that is hold on one side by a fixed jaw while the other is clamped by a second jaw that can move only vertically, permitting to generate a bending and shear load on the specimen. Also, a second version was proposed by Pierron et al. [7,12], where the two notches are removed from the specimen.

Starting from these basics, this shear test is redesigned considering, first, the subsequent design requirements:

- The experimental apparatus must contain thin metal sheet specimen;
- Large deformation regime must be reached, taking care of clamping system effects on strain localization due to bending moment;
- The measurement area must guarantee enough field of view for the full-field technique (in this case 2D-DIC).

Therefore, the clamping system is adapted to hold thin metal sheet specimens, following the set-up scheme displayed in Figure 1. In this first configuration, the field of view length $L_v$ is equal to 25 mm.

![Specimen geometry](image)

**Figure 1.** Sheet metals through-thickness shear test scheme and specimen geometry specifications.

The specimen employed in the test is obtained from a 2 mm thick blank of S355 steel, following the geometry specifications listed in Figure 1. Displacement and strain fields on the specimen surface are retrieved using a 2D-DIC set-up composed by a $2048 \times 2048$ CCD camera equipped with telecentric lens to prevent experimental uncertainties due to the out of plane movement of the specimen surface. MatchID software ([www.matchidmbc.be](http://www.matchidmbc.be)) is employed for the correlation analysis, setting a subset size of 41 pixels and a step size of 4 pixels, while strain derivation is calculated imposing a filtersize of 15 points. The measured Hencky strain fields are depicted in Figure 2-3-4 respectively for the last measurement step, where the maximum vertical displacement achieved by the moving grip is $d = 12.82$ mm. Here, the $xx$ subscript indicates the RD, while the $zz$ subscript refers to the normal direction ND.
Figure 2. DIC measured $\varepsilon_{xx}$ strain field.

Figure 3. DIC measured $\varepsilon_{zz}$ strain field.

Figure 4. DIC measured $\varepsilon_{xz}$ strain field.

3. FEMU Inverse Identification

The performed test is employed, thus, to identify the shear constitutive parameter of a traditional anisotropic plasticity model, the Hill48 [13]. According to its formulation, the equivalent stress, expressed in terms of deviatoric stress $S$, is:

$$\bar{\sigma}(S) = \left[ f(s_{yy} - s_{zz})^2 + g(s_{zz} - s_{xx})^2 + h(s_{xx} - s_{yy})^2 + ls_{yz}^2 + ms_{xz}^2 + ns_{xy}^2 \right]^{1/2}$$

where four coefficients can be obtained from the ratio between the transverse strain and the through-thickness strain from uniaxial tensile test (R-value [14]) at different directions, such that:

$$f = \frac{1}{1 + \frac{R_0}{R_{00}}}; \quad g = \frac{1}{1 + R_0}; \quad h = \frac{R_0}{1 + R_0}; \quad n = \left( \frac{1}{2} + R_{45} \right) \frac{R_0}{R_{00}},$$

while the two shear coefficients are often imposed equal to the isotropic case, viz:

$$l = m = \frac{3}{2}.$$  \hspace{1cm} (3)

Since the aim of this paper is to verify the feasibility of the proposed experimental protocol, here the FEMU method is used as diagnostic tool, focusing the inverse identification of Hill48 parameter $m$. Therefore, a Finite Element model reproducing the introduced shear test was built using ABAQUS/Standard. Following the FEMU technique framework, the identification is achieved performing iteratively numerical simulations till a certain cost function is minimized. In particular, the cost function $\Psi$ is defined as the root mean square error (RMSE) between the force-displacement curve measured during the experiment and the one resulting from the FE analysis, so:

$$\Psi = \sqrt{\frac{1}{n} \sum_{i=1}^{N_{\text{step}}} \left( F_{\text{exp}}[d(i)] - F_{\text{num}}[d(i)] \right)^2}$$

The through-thickness shear test was reproduced employing a 2D model, assuming plane strain stress state. The model is composed by three main parts: the two jaws, the right one fixed while the left one capable of translating vertically, modelled both with discrete rigid wires; the sheet metal specimen represented by a deformable planar shell, whose material orientation is assigned accordingly to the tested specimen. The anisotropic behaviour is described by the Hill48 material model, while the plastic behaviour by the stress-strain curve obtained from uniaxial tensile test.
at $0^\circ$ with respect to the RD (Figure 5). It is worth noting that, for this preliminary study, the investigation is focused only on the material parameter $m$, while the remaining Hill48 coefficients are considered isotropic. Albeit this represents a quite strong assumption, it can give an insight on the test sensitivity with respect to the shear anisotropy in the thickness plane.

Concerning the contact interactions between the three parts, a frictional contact was included in the model, assuming the typical frictional coefficient between steel-steel dry surfaces ($\mu_s = 0.7$). All numerical model specifications are summarised in the table contained in Figure 5.

![Figure 5](image)

**FE model characteristics**

| Element type      | CPE4          |
|-------------------|---------------|
| Number of elements| 7720          |
| Number of nodes   | 8127          |
| Hill48 yield function | Isotropic hardening |

*Figure 5.* Uniaxial true $\sigma$-$\varepsilon$ curve obtained from standard tensile test at $0^\circ$ and FE model characteristics.

The minimization of cost function $\Psi$ is performed using MATLAB® Optitool function *fmincon* [15]. Exploiting a standard computers equipped with an Intel® Core™ i7-7700HQ CPU @ 2.80 GHz, 16 MB RAM, the FEMU identification procedure took an average time of 5h20m to achieve the optimization convergence, employing the isotropic case ($m = 3/2$) as starting point of the minimization. Figure 6 depicts the comparison in terms of measured Force-Displacement curve between the experimental data and numerical data obtained with the isotropic plasticity case and Hill48 material model, where the optimized value given by FEMU is $m = 9.98$.

![Figure 6](image)

*Figure 6.* Comparison between the experimental Force-Displacement curve with the isotropic case and the resulting one from FEMU identification.
4. Conclusion
This paper contains a first design proposal of new experimental test for sheet metals through-thickness behaviour that can be employed in identification methods such as the VFM and FEMU. In particular, here, the FEMU is used as a diagnostic instrument to assess the feasibility of new testing procedure. Basically, the aim is to extend the Unnotched Iosipescu test to large deformations, considering that the apparatus must contain samples obtained from a thin sheet metal and it must guarantee an adequate field of view for the optical measurement.

This investigation motivates the development of such testing protocol, showing a relevant dependence between the shear anisotropy Hill48 parameter $m$ and the measured force, albeit the anisotropy in the RD-TD plane is not considered. Moreover, this preliminary study suggest several improvements and future developments: first, in this configuration, the distance between the two jaws $L_v$ is too wide, making the bending condition predominant on the pure shear; secondly, a more accurate characterization of the material model must be provided. Also, the FEMU cost function can be enhanced including strain field data from full-field measurement on the thickness surface of the specimen.

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