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Numerical Simulation of Non-Standard Tensile Tests of Thin Metal Foils

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Abstract. The evolution of the fracture processes occurring in thin metal foils can be evidenced by tensile tests performed on samples of non-standard dimensions. The load versus displacement record of these experiments does not return directly the local stress-strain relationship and the fracture characteristics of the investigated material. In fact, the overall response of thin foils is sensitive to local imperfections, size and geometric effects. Simulation models of the performed tests can support the interpretation of the experimental results, provided that the most significant physical phenomena are captured. The present contribution focuses on the role of modelling details on the numerical output that can be obtained in this context.

INTRODUCTION

A growing number of technological applications are made of laminates constituted by thin metal foils coupled to polymer layers [1–4]. The performances of these material systems rely on the metal ply, which provides a significant contribution to the overall strength and stiffness of the composite, represents the conductive layer in flexible electronics [1], protects against light and oxygen penetration in beverage packaging [3].

A crucial problem consists of determining the mechanical and fracture properties of these laminates in a reliable manner. In fact, their characteristics are substantially modified with respect to the corresponding bulk materials by the lamination processes, which reduce the thickness to the micron scale.

In the usual range of interest (1–100 μm thickness), the metal foils and their composites present a rather brittle failure mode [5–8]. Their mechanical characteristics are usually inferred from the output of tensile tests performed on narrow material strips, with large length to width (*L/W*, see Fig. 1) ratio [9]. However, these geometries do not permit to calibrate the fracture properties since failure is provoked by an almost instantaneous material separation. Different aspect ratios and pre-notched material samples have been therefore considered in order to follow the fracture evolution and the relevant crack propagation processes [10, 11].

On the other side, wrinkling phenomena are frequently observed in wide samples and affect the interpretation of the experimental output [10–13]. These disturbances can be detected by three-dimensional digital correlation techniques [14, 15] and potentially reproduced by finite element analysis. However, numerical models based on slightly different assumptions can lead to rather different conclusions. This contribution presents the observed discrepancies between the phenomena occurring in real and simulated uniaxial tensile tests of the thin aluminum foils employed in beverage packaging.

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PROBLEM FORMULATION AND MODELLING ASSUMPTIONS

The present investigation focuses on the thin aluminum foils (9 μm nominal thickness) that are usually employed in beverage packaging. The mechanical characteristics of this material have been evaluated on the basis of the results obtained from non-standard uniaxial tensile tests, performed under displacement control on the material samples sketched in Fig. 1. The assumed dimensions are $2W = 100\ mm$ width and $2L = 250\ mm$ length. Two symmetrical notches with $a = 10\ mm$ depth are introduced in one of the considered configurations, shown in Fig. 1(b).

The main features of the experimental setup and the most significant output of the tests are described in [13–15].

The experiments have been simulated by a widely used finite element commercial code that implements both material and geometrical non-linearity [16]. Large plastic deformation with small elastic strains have been taken into account. An additive decomposition of the total strains into the elastic and plastic components is thus introduced.

The classical elastic-plastic constitutive law based on Hencky-Huber-von Mises yield criterion with associative plastic flow rule describes the metal response. Isotropic hardening is assumed, initially governed by an exponential rule. A saturation limit is introduced beyond $\varepsilon_s = 10\%$ overall strain. The corresponding uniaxial stress-strain relationship is schematically represented in Fig. 2, while the main model parameters are listed in Table 1. The realism of these assumptions was validated in a former contribution [3].

Some preliminary 2-dimensional (2D) finite element analyses were performed in order to simulate the structural response of the considered material samples with plane stress conditions. Results show that the wrinkles observed in the real experiments are the likely consequence of compression stresses acting orthogonally to the loading direction [13]. In fact, geometric instability can arise despite the small amplitude of these stresses due to the extremely low bending stiffness of the thin metal foils.

Wrinkles can be potentially reproduced by 3-dimensional (3D) finite element models. Further discretization of the aluminum foils was therefore implemented in the present study, considering either shell or membrane elements that share the same in-plane geometry and formulation. An initially flat configuration was assumed in all cases. Quasi-static analyses were carried out, introducing a small damping factor as numerical stabilizing factor to improve convergence.

TABLE 1. Model parameters

Young's modulus (MPa)	Poisson's ratio (-)	Initial yield limit (MPa)	Hardening coefficient (-)
46000	0.3	35	0.015

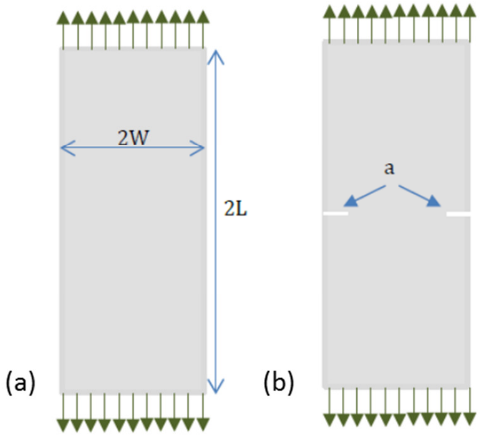

FIGURE 1. Schematic geometry of the material samples and testing conditions.

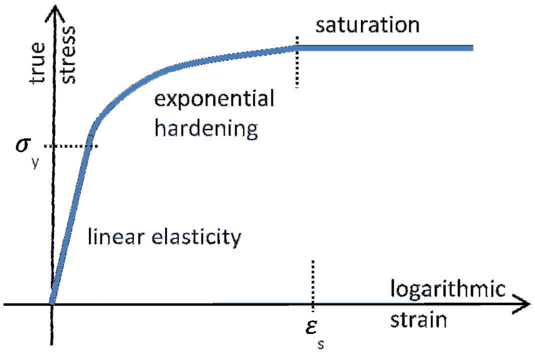

FIGURE 2. Schematic uniaxial stress-strain response.

SELECTED RESULTS

The simulation of the tensile tests of the initially flat material samples represented in Fig. 1 returned automatically the corrugation of the foil surface when finite element models based on shell elements were implemented. The phenomenon is represented in Fig. 3 for the un-notched aluminium specimens. The graphs evidence the influence of the apparently marginal input details like the numerical stabilization (damping) factor (df) on the distribution and amplitude of the wrinkles.

The stabilization factor influences also the macroscopic material response recovered from the 3D numerical analyses. The computed engineering (nominal) stress-strain curves are represented and compared with the corresponding experimental output (dots) in Fig. 4. The results are almost insensitive to the stabilization factor for $df \leq 0.001$. In this range, the numerical curves represent the envelope of the experimental ones.

The simulated overall response of the notched material samples is represented in Fig. 5. Convergence is lost for the lower values of the damping factors, but reasonable agreement with the experimental output is found up to the peak load.

The nominal stress-strain curves obtained from simulations based on 2D (plane stress) and 3D (shell and membrane elements) are compared in Fig. 6. In the same conditions (e.g., for $df = 0.01$ or for $df = 0.001$) the membrane model returns an intermediate value of the maximum load and a rather different post-peak response, which reflects a different evolution of the inelastic deformation. The graphs in Fig. 7 evidence that both 2D plane stress and 3D shell models suggest the formation of shear bands as the likely failure mode. On the contrary, membrane elements predict the localization of plastic strain in correspondence of the ligament where fracture eventually occurs, but out-of-plane displacements are ruled out.

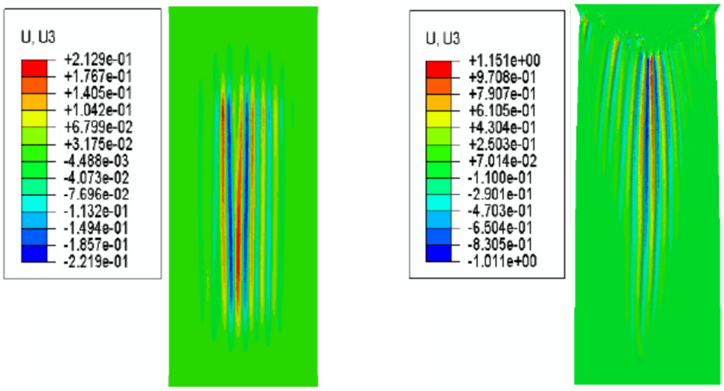

FIGURE 3. Out-of-plane displacement (U3) distribution in the final numerical configuration for damping factor $df = 0.001$ (left) and $df = 0.01$ (right).

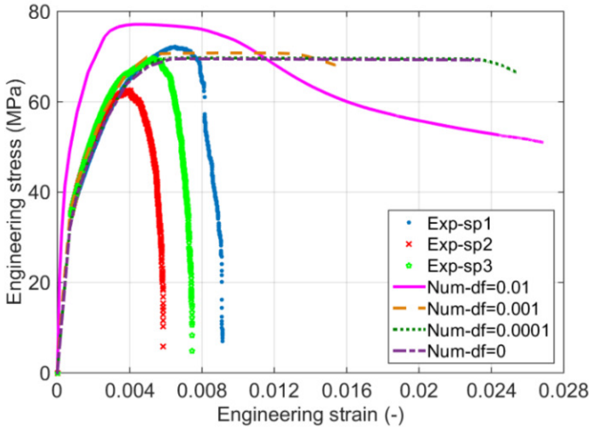

FIGURE 4. Nominal stress-strain curves recovered from the 3D simulations of a plain metal sample: experimental (dots) versus numerical results obtained by means of shell elements.

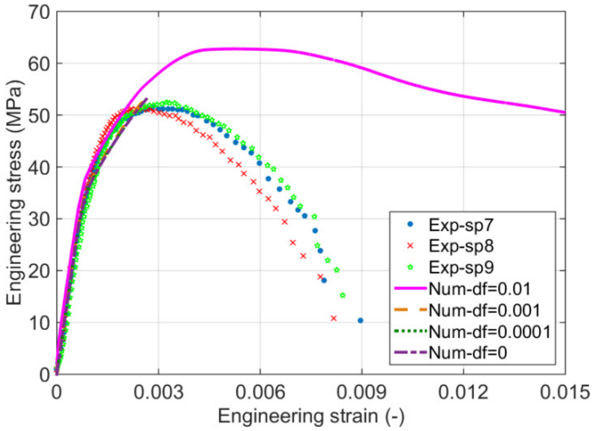

FIGURE 5. Nominal stress-strain curves recovered from the 3D simulations of the notched metal sample: experimental (dots) versus numerical results obtained by means of shell elements.

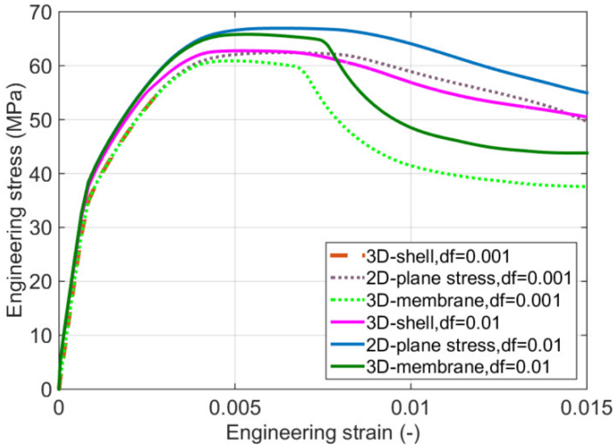

FIGURE 6. Nominal stress-strain curves recovered from the 2D and 3D simulations of the notched metal sample ($df = 0.001$ and $df = 0.01$).

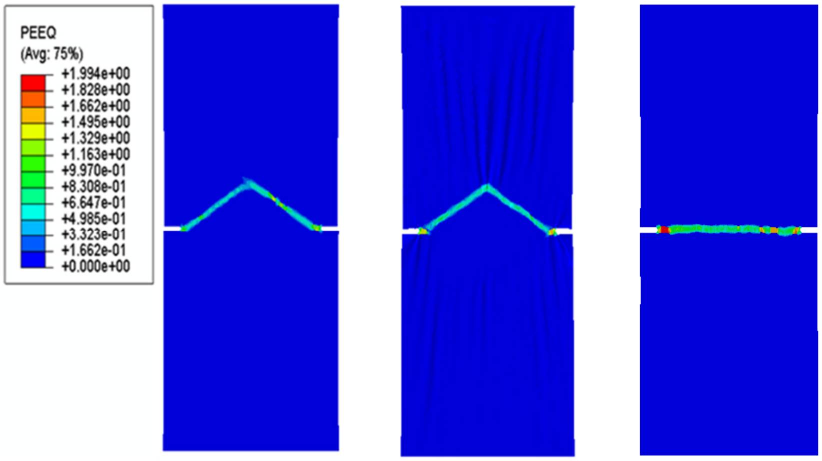

FIGURE 7. The plastic strain distribution obtained from the simulations based on plane stress (left), shell (center) and membrane (right) elements at 1.5% nominal strain for $df = 0.001$.

CLOSING REMARKS

Non-standard tensile tests have been proposed to follow the fracture processes that develop in metal foils [10, 11]. The problem involves both geometrical instability and strain localization phenomena emphasized by the thinness of the considered material samples.

The experiments have been simulated in a finite element context, considering different 2D and 3D models that share the same in-plane formulation. The results presented in this contribution show that the output of the numerical analyses is rather sensitive to details like the finite element type or the damping factor introduced to improve convergence. These factors may play the role of the physical imperfections, which explain the discrepancies between experiments and simulations in similar applications [17, 18].

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