XII International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XII
E. Oñate, D.R.J. Owen, D. Peric and B. Suárez (Eds)

EXPERIMENTAL CHARACTERIZATION AND COMPARISON OF PLANAR AND CORRUGATED ALUMINUM SHEETS

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Key words: Computational Plasticity, Forming Process, Anisotropy, Finite transformations, corrugated, Finite elements.

Abstract. To evaluate the effect of the corrugation [1] on the mechanical behavior of aluminum plates, a corrugated sheet on aluminum alloy Al1050 is characterized under tensile mechanical tests at room temperature. To characterize anisotropic behavior of the material, tensile experiments are carried out in three different tensile directions i.e. 0, 45 and 90° with respect to the rolling direction. All experiments are performed until final failure using both planar and corrugated sheets for comparison issues. Concerning the experimental supplies, a tensile testing machine is used which can handle forces until 5 kN and can perform monotonic tensile as well as cyclic displacement and force controlled tests. The tensile machine is connected with a digital image correlation background. The measurement apparatus is equipped with two cameras for the detection of displacement fringes. The equipment is able to detect transversal and longitudinal displacements and calculate strain values at also virtual rectangular gauges or along straight lines. The responses of both planar and corrugated plates are compared in the macroscopic level within the force-displacement curves, damage localization zones and macroscopic crack propagation paths. The experimental data for Al1050 is quite interesting because it will be used for the material parameters identification of anisotropic elasto-plastic models combined with mixed hardening and isotropic damage [2]. The implemented models are validated later by comparisons between finite element simulations of Marciniack tests in the FE code Abaqus® and complementary experimental data.

1 INTRODUCTION

Corrugation is an interesting manufacturing process for formed metals. Corrugated parts are widely used for covering roofs or walls, aerodynamic accessories, chain guards, side stands, mud guards, sheet metal accessories such as simulated fuel tanks, etc. the required and attractive aspect of these corrugated parts are mainly compliant behaviour in one direction and stiff behaviour in the other directions [3] as well as higher bending strength which made it widely used for automotive applications. Corrugation process is mainly realized after cold or hot rolling process in order to introduce an additional stiffness and a constrained state to the sheet [4]. This gives an interesting aspect of the mechanical behaviour of the corrugated profile.

2 EXPERIMENTAL PROCEDURE

Tensile and bending tests are conducted into rolled Al1050 specimen at both planar and corrugated configurations. The tensile and bending plate specimen are cut in 0, 45 and 90° with respect to the rolling direction. All the tests are performed until failure at room temperature with an imposed displacement rate of 6mm/min which considered as relatively high tensile speed. All the experiments are reproduced 5 times in each anisotropy angle for repeatability issues. The tensile machine used for the mechanical tests can hold a maximal force up to 5 kN and large displacement. All the tensile strains and displacements measures are computed using a digital pictures correlation procedure. The measurement apparatus is equipped with two digital cameras able to take measures on three directions. For the tensile tests, an acquisition frequency of 1 picture/sec is considered. Moreover, 10 points are registered every second for the displacement force responses. The strains and displacements results are extracted form 13 gauges in a fixed study zone as illustrated in Figure 1.

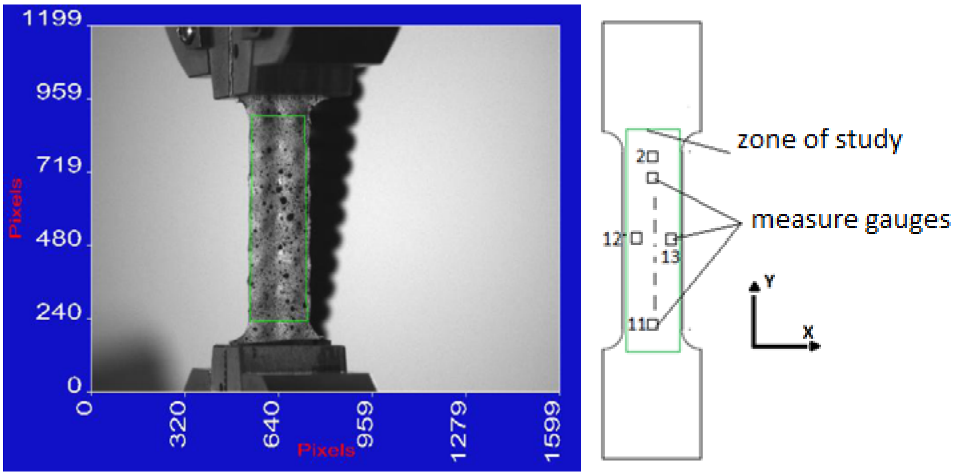


Figure 1: Configuration of the tensile corrugated specimen and emplacement of the measure gauges.

2.1 Tensile tests results

Z-displacement franges are illustrated in Figure 2 for a corrugated 45°-loaded specimen. As shown in this figure, there is a folding mechanism which occurs progressively in the beginning of the tensile tests until 50 seconds. The folding mechanism is obseved also in the case of the other anisotropy angles. for all the anisotropy directions, the folding mechanism is traduced in the displacement- force responses by the presence of two loading ramp. the first loading ramp correspond to the folding and the second ramp to the high plastic deformation process. In the other hand, the displacement-force responses plotted in Figure 3 show a high dispersion especially at 0° when the force reaches a maximum value of 560 N. At 45 and 90°, the tensile responses appear to be much more repeatable than those in 0°. During the loading at 45°, the first 4 tests present a much less dispersion (less than 10 N). The force takes an ultimate value of 520 N. finally, for the tensile responses in the transversal direction, the maximal force does not exceed 510 N. the displacement at failure take an average value of about 18 mm for all tests.

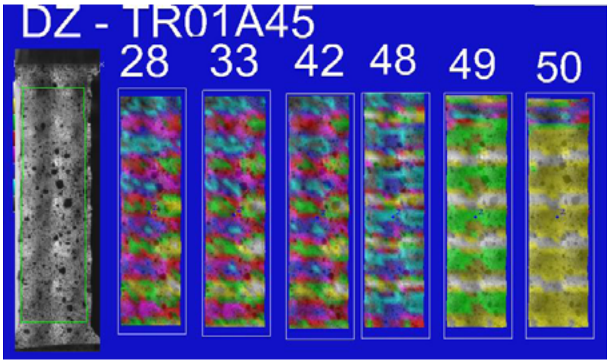


Figure 2: Folding mechanism occurring in successive periods of time.

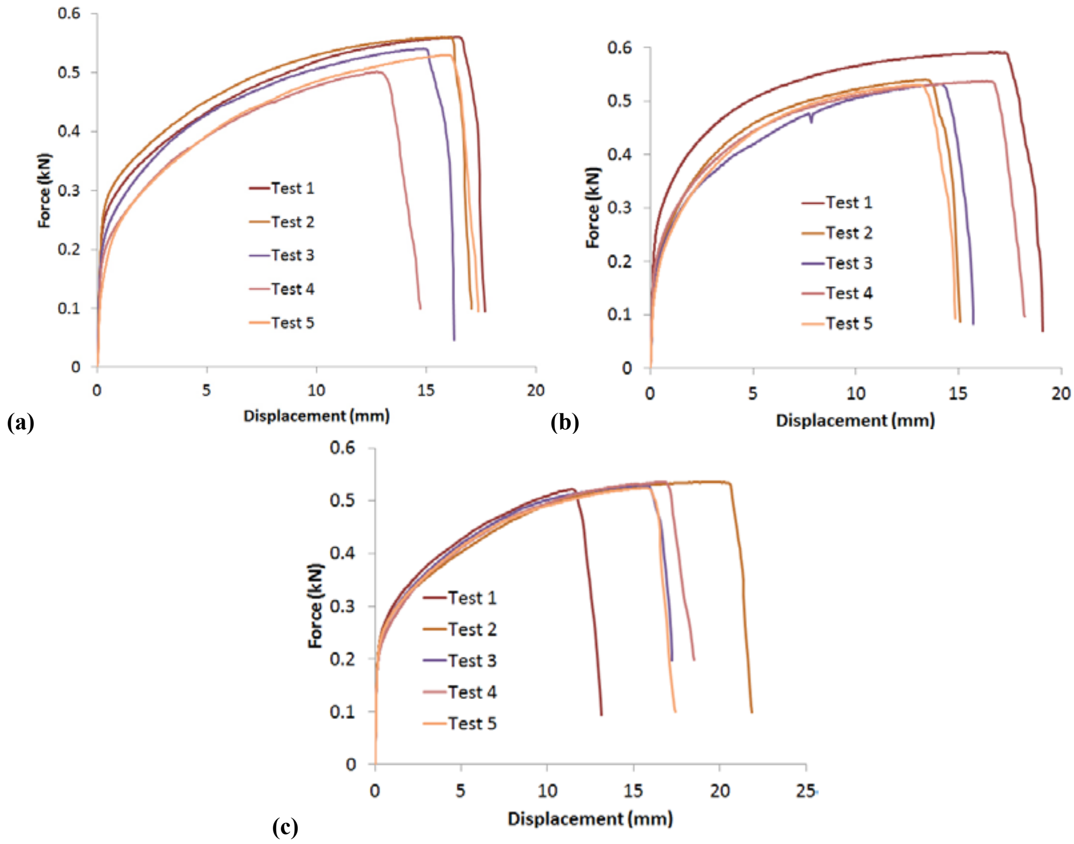
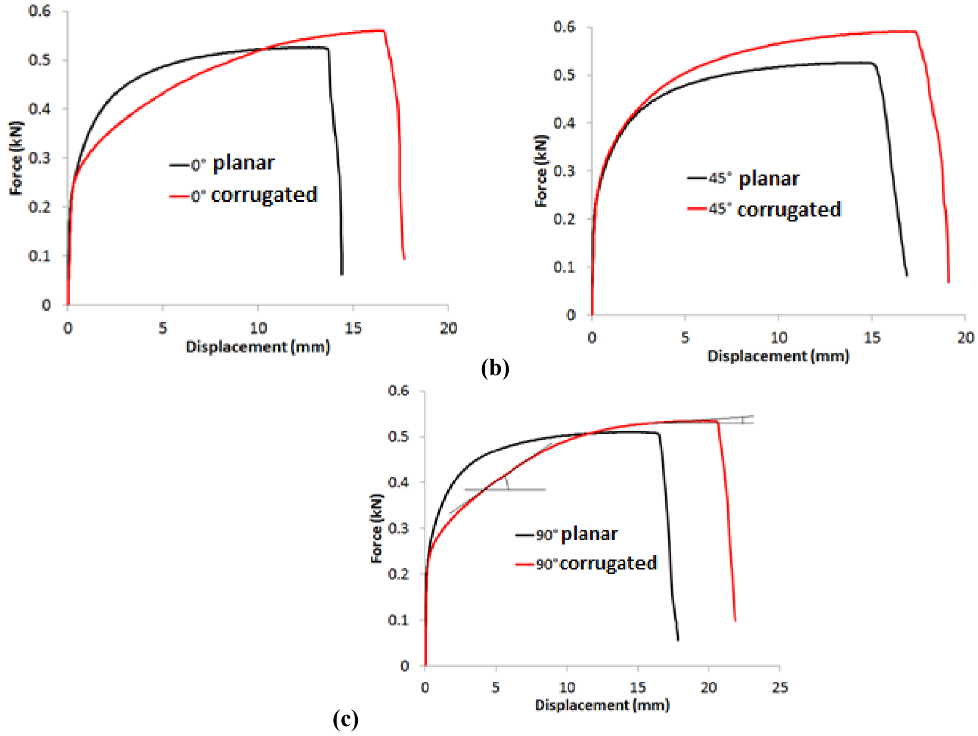


Figure 3: Tensile responses of corrugated sheets at various anisotropy angles.

A comparison of the average tensile behaviour for both planar and corrugated sheets have been made in the three anisotropy angles. the results which are presented in Figure 4, show a higher ultimate force obtained in the corrugated case. this improved mechanical beahvior of the corrugated sheets is associated with an increase of the displacement to failure which often exceed 50% making a quasi-constant gap of 5 mm with respect to the planar configuration.

the saturation of the force is reached more faster in the case of planar sheet because the material is homogeneously loaded earlier.



(a) (b) (c)

Figure 4: Comparisons of the average tensile responses of planar and corrugated sheets at various anisotropy angles.

2.2 bending tests results

The bending test consists on flexural load imposed to the 200 mm length Al1050 plate. The plate is placed on two supports spaced of 40 mm. A total displacement of 240 mm is imposed to the punch. The displacement-force curves are recorded. Dispersive responses can be observed in Figure 5. the maximal force obtained is about 7.5 N. the oscillations observed at the second half of displacement-force curves are due to the slip mechanism which happens between the corrugated plate and the maintaining support.

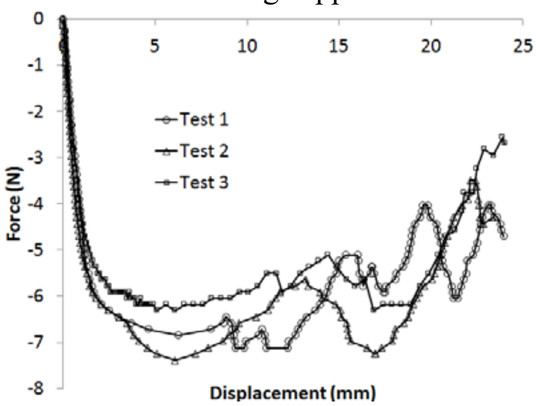


Figure 5: Comparisons of the tensile responses of planar and corrugated sheets at various anisotropy angles.

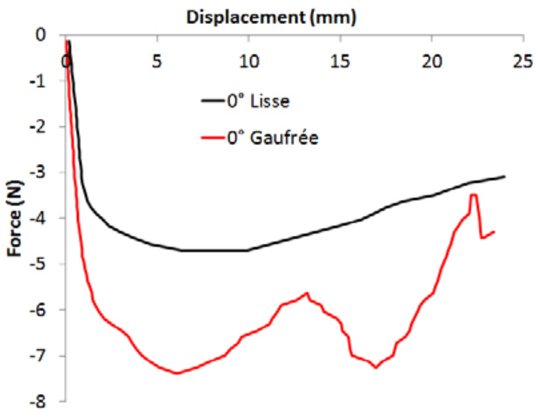


Figure 6: comparisons of the average bending responses of planar and corrugated sheets at 0°.

A comparison is also made in figure 6 between planar and corrugated average bending behavior. In the case of corrugated plates, it can be observed that there is higher resisting force which is greater by a factor of 1.5. The increase in force is due not only to the contact nature between the support and the plate but also to higher stiffness of the corrugated sheet.

3 FE MODELING OF THE TENSILE BEHAVIOR OF CORRUGATED SPECIMEN

In order to use the geometric model of the corrugated specimen, a 3D scan with a tridimensional measure machine (TMM) is realized in a 20×20mm corrugated sheet. The attractive feature of the TMM is that complex profiles can be scanned easily in three directions. The machine precision is 10 µm and the scanning increment is 0.1 mm.

After scan, the corrugated profile appears to not be symmetric which is due essentially to the rolling process. The shell thickness is also not constant and varies linearly from 0.36 mm in the peaks to 0.54 mm in the sides. The thickness variation and some approximations on the profile have to be taken into account to ensure the modeling task.

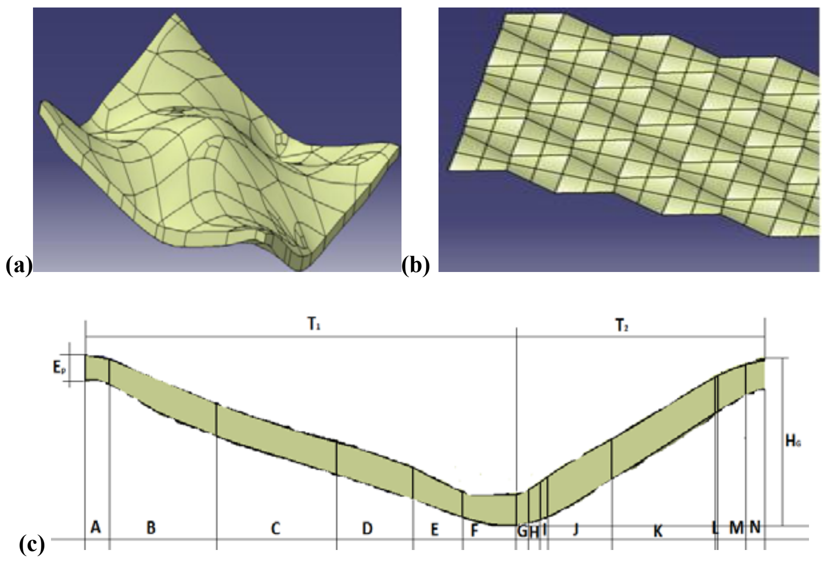


Figure 7: TMM scanned profile of a 3D corrugated pattern.

Two principal assumptions have been made for the FE modeling. We suppose first that the profile is symmetric so it can be fitted to a sinusoidal profile and the entire tensile specimen geometry can be reproduced (Figure 7(a)). Then, the profile is flattened as shown in Figure 7(b). The two kinds of profile are compared respectively in 3D solid and 3D shell structural level to the experimental data using finite element computations.
The finite elements simulations are started using the identified parameters for the Al1050. A finite strains elastoplastique model coupled with damage is considered. For anisotropy description, a Hill48 yield criterion is adopted. The behavior model is predefined in the FE code Abaqus. The thickness at the nodes is updated in the input file. It takes a value of 0.36 in the peaks and 0.57 in the middle. The material orientation is defined here as 0° with respect to the tensile direction.

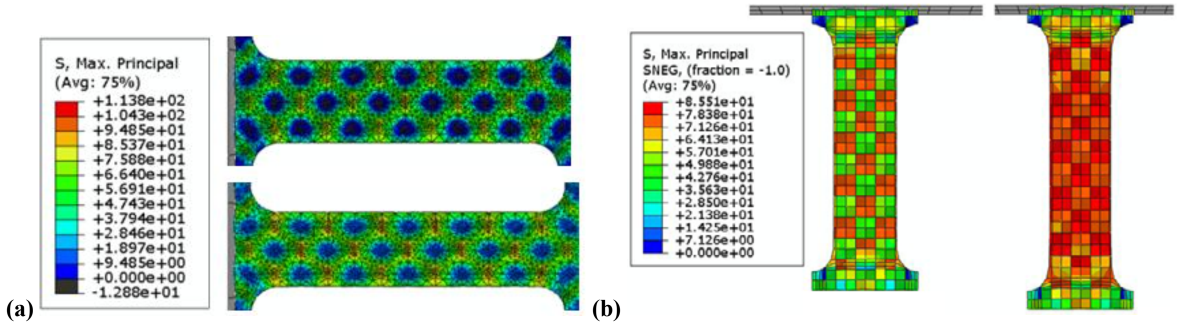


Figure 8: FE simulations on (a) fitted and (b) flattened profile of the tensile corrugated specimen.

Figure 8(a) shows the FE results for the sinusoidal profile. Tensile and compressive stresses are observed alternatively in the peaks. In the other hand, the flattened specimen with updated section thicknesses shows the same stress distribution but it appears that a folding process is generated first, followed by an entirely tensile stress distribution in specimen. To validate the flattened model, the numerical displacement-force curve is compared to the experimental one using respectively different element types and various shell thickness distributions. The comparison works are performed using Abaqus material due to the fact that user material definition is unsupported for two kinds of element type which are S4RS and S4RSW.

3.1 Effect of the element type

In this step, the taken element size is 2.5 mm. The considered thicknesses are 0.36 mm in the peaks nodes and 0.5 mm in the middle nodes. Four element types are evaluated as shown in figure 9. The element types predefined in Abaqus are finite strains, full integration quadratic element (S4), finite strains reduced integration quadratic element (S4R), small strains reduced integration quadratic element (S4RS) and a small strains reduced integration quadratic element with wrapping consideration (S4RSW). Following the curves trend, some differences exist between numerical and experimental data especially in the beginning of the tensile response. Among the factors that can be referred to this difference is the neglecting of the effect of the corrugation process on the initial state of the material. In fact, the corrugated sheet presents a constrained state once corrugated and responses to tensile test will differ from those of a non corrugated material. Moreover, for the most element types, no folding process is really viewable in the tensile responses in spite of his existence in the experimental data.

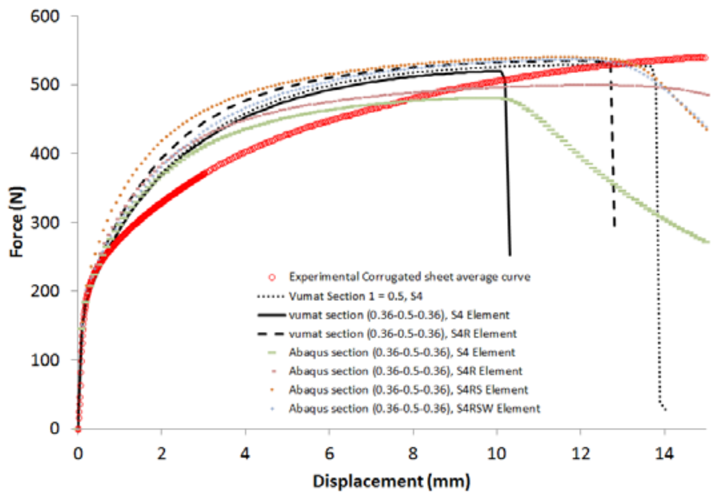


Figure 9: Numerical displacement-force responses issued from various element types.

We just can see that for the computations performed with a S4RSW element type, a folding process occurred at the beginning which means that this type of element is the most adequate for representing the folding step.

3.2 Effect of the variation of the nodal thicknesses

Henceforth, all the computations in this section are performed using the S4RSW element type thanks to its ability to reproduce better the sheet folding. However, the values of the nodal thickness are customized in the peaks and in the middle of the corrugation plane. We start the simulations by an element size similar to the element used for the previous section i.e. an element size of 2.5 mm. the nodal thicknesses are then 0.36 mm in the peaks and 0.5 mm in the corrugation plane. Then, we have refined the mesh to have four elements instead of two between two peaks. The same values of nodal thickness are still unchanged in this case. A third simulation is conducted with another refined mesh (6 elements between peaks). Two nodal thicknesses of 0.4 mm and 0.55 mm are retained in the middle nodes. Another underestimating simulation is carried out with 0.4 mm thickness in the middle nodes and finally, a realistic simulation is realized considering the real values of the shell thickness in the corrugated profile shown in figure 7. The set of performed calculations are summarized in table 1. The aim of all realized simulations is first to see if we can simplify the computations by considering only two or three nodal thickness or have to take all the real nodal thickness. Second, these assumptions can be interesting in the mesh and computation time viewpoints for the next FE simulations of the forming process of corrugated sheet metals and especially complex automotive parts.

Table 1: the set of FE tensile simulations realized to study the effect of mesh and nodal thickness.

N° Case	Thickness (mm)		Number of elements
	In the peaks	In the middle	
1	0.36	0.5	2
2	0.36	0.5	4

3	0.36	0.4 and 0.55	6
4	0.36	0.4	6
5	0.36	0.38 – 0.42 – 0.46 – 0.5 – 0.54 – 0.56	6

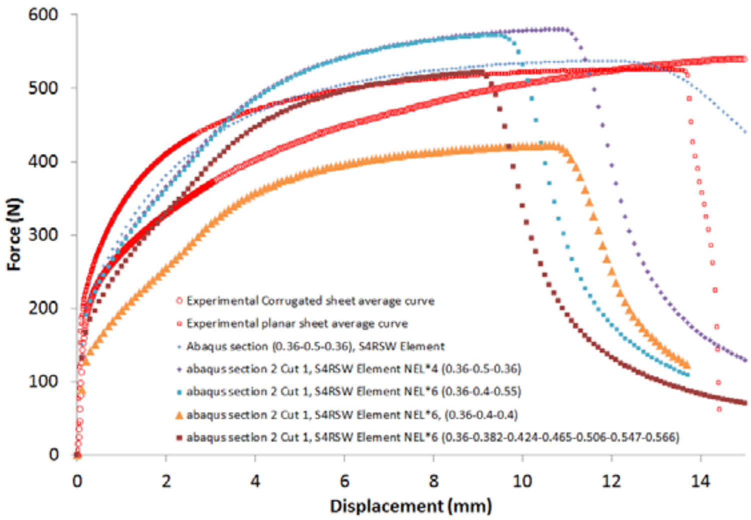


Figure 10: Numerical displacement-force responses issued from different thickness distributions.

It is obvious that the values of thickness in the nodes have a consequent influence on the mechanical behavior of the corrugated sheet. Looking to the folding process, the force response decreases or increases proportionally to the nodal thickness. But the nearest response is that of the realistic nodal thickness entered and it is not as dramatic as we can expect. Thereby, the saturation appears to be reached close to the experimental saturation force. Merely, failure prediction has to be slightly calibrated through the ductile damage model in order to extend the average value of the stress at failure.

4 CONCLUSIONS

- Corrugated sheet exhibits substantially better mechanical behavior than planar sheet either in tension or bending conditions thanks to the hardened state obtained by the resulting manufacturing process of corrugation.
- The tensile tests on corrugated specimen show a folding process which occurs at the beginning of the loading followed by a global tensile state of stress.
- Finite elements simulations of the tensile test are performed and show that the S4RSW element type is used successfully to describe folding phenomena in corrugated specimen.
- The displacement-force responses are very sensitive to the nodal thickness but every time the thickness values at the nodes are realistic, the numerical displacement-force responses are then closer to the experimental data.

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