MECHANICAL BEHAVIOR OF INNOVATIVE SANDWICH MATERIALS

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Abstract: *Foams are an important element in the dimensioning calculations of sandwich composite structures for nautical applications. Their standardized tests don't lead to establishing an intrinsic mechanical behavior. The aim of this paper is to study and characterize the elastic mechanical behavior of a reference foam of polyvinyl chloride (PVC) and those of recycled polyethylene terephthalate (PETr) substitute foams. Compression and shear tests, instrumented by a Digital Image Correlation method, were conducted on different shapes and dimensions of PVC and PETr foams in order to identify the mechanical parameters and thus, lead to measurements of apparent properties. Following the compression tests, PVC and PETr foams are found to be transversely isotropic. Using these experimental results, the elastic mechanical behavior of PVC and PETr foams is identified based on a finite element model updating method, using Abaqus and Matlab, by minimizing the difference between the simulated modulus, and the experimental apparent elastic one.*

Keywords: Sandwich materials; PVC; PETr; FEMU method.

1. Introduction

The use of fiber reinforced composites has increased in naval construction due to their favorable physical properties in particular their specific modulus, ease of fabrication and excellent mechanical behavior in the marine environment. As such, sandwich materials, composed of two laminated facings and a polymer foam core, are the first-choice materials for the design of light and rigid superstructures for the vessels. The mechanical behavior of sandwich materials made of recycled and bio-based materials (biopolymers reinforced by low environmental impact fibers) seems suitable for the nautical construction since these materials can offer equivalent specific mechanical properties compared with traditional composites, however, while having better environmental credentials [1][2][3][4]. The purpose of the study is to establish a homogenized behavior of a sandwich material. In order to do so, the work is divided into two parts: the characterization of the foam and then of the bio-based composite. The first part consists of studying the mechanical behavior of a reference foam of polyvinyl chloride (PVC) and those of recycled polyethylene terephthalate (PETr) substitute foams. The evaluation of the behavior of a foam-model is complicated as a result of the anisotropy induced by the process and the structural heterogeneity at the scale of laboratory tests [5][6][7][8]. This work is devoted to studying the elastic mechanical behavior of polymer foams subject to compression and shear tests. PVC and PETr foams were chosen as materials for this study. Unlike the shear tests, the standardized compression tests carried out are structural tests, hence the use of a numerical interpretation of the tests associated with a Finite Element Model Updating method of the test. Based on the experimental results of compression tests and on the mechanical behavior of the PVC and PETr foams, a three-dimensional finite element model has been implemented in a user-

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defined material subroutine built on ABAQUS/Explicit linked to an optimization method on Matlab to predict the intrinsic elastic behavior of these polymer foams.

2. Materials and methods

In order to predict a material substitution by materials related to sustainable development, two different types of foam were used as materials for this work:

- PVC foam which is the reference material, has a density of 80 kg/m^3 and a commercial reference “AIREX C70”.
- PETr foam which is the substitute material, has a technical commercial reference "ArmaForm Core", and where two different densities were used (80 kg/m^3 and 115 kg/m^3). Recycled PET, which is more sustainable than the reference PVC foam, aims to replace this last in terms of performance.

The information in the table 1 below is taken from the datasheets of these foams.

Table 1: Mechanical properties of PVC and PETr foams

Foam type	Density [kg/m^3]		Compressive modulus [N/mm^2]		Shear modulus [N/mm^2]
PVC	80	DIN 53421	Average: 104 Minimum: 80	ASTM C393	Average: 30 Minimum: 24
PETr	80	ISO 844	57	ISO 1922	16
PETr	115	ISO 844	90	ISO 1922	26

Using the mechanical saw, the samples were cut from large sheets of rigid closed-cell foams with a thickness of 15mm.

Compression and shear tests were performed using an MTS testing machine in order to characterize the apparent physical properties of these polymer foams. These different tests are instrumented by a digital image correlation (DIC) technique [9]. Moreover, the implementation of the camera allows the visualization of real-time compression, shear progression, and the measurement of full-field displacement of specimens during the compression and shear tests.

PVC foam was assumed to be transversely isotropic, in-line with many preliminary experimental results and information from the literature on foam manufacturing processes [10] as well as the work of [5]. For the compression tests, the guidelines within the ISO 844 standard were followed. Consequently, the test specimens in this standardized test cannot be considered in the context of uniaxial compression which is a theory requiring a ratio of 2 at least, between the height and the width of the sample to be considered in uniaxial compression. Therefore, these compression tests are structural tests since the size of the sample would remain limited and not representative of its microstructure. And that is why a Finite Element model is needed to identify the intrinsic elastic parameters**.**

Compression tests on 15x15x15mm^3 cubic specimens were conducted along with two directions, longitudinal ($\vec{z}$ axis) and transversal (axis $\vec{x}$ or $\vec{y}$). Hence, these tests do not lead to

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the determination of the intrinsic elastic parameters of the foam, and therefore, these tests have the sole purpose of confirming the transverse isotropy assumption.

Afterward, the intrinsic elastic behavior is identified by recalibrating a FE model of the tests, i.e., the need to carry out compression tests on larger specimens in order to experimentally determine the apparent properties of the material which will be considered as initialization parameters to apply the FE recalibration method. Compression tests along the $\vec{z}$ axis direction were then carried out on specimens of dimensions 30x30x15mm^3 and 60x60x15mm^3 respectively. On the other hand, a series of shear tests following the ISO 1922 were carried out on the foams in subject with the aim of determining the shear coefficients.

3. Experimental tests

3.1 Compression tests

According to ISO 844 standard (Rigid cellular plastics - Determination of compression properties), three sets of specimen's dimensions were tested in order to obtain the apparent elastic properties of the foams in compression. As shown in Figure 1, the cubic specimens compressed along two directions ($\vec{z}$ and $\vec{y}$ axis) are intended to validate the theory of transverse isotropy by calculating the ratio between the apparent stiffness modulus and the apparent transverse contraction coefficient corresponding to each test.

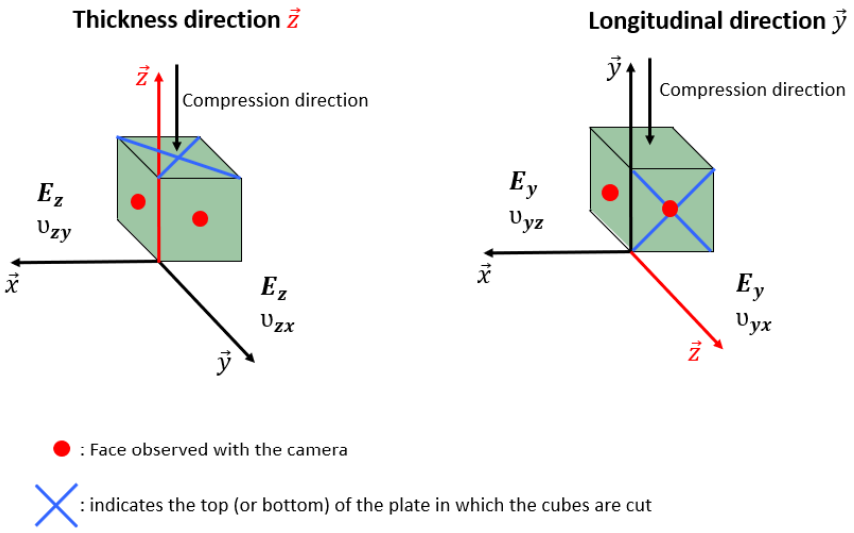


Figure 1: Compression tests in two directions

For each type of foam and for each set of dimensions 10 specimens were tested. Figures 2 and 3 show the apparent stiffness modulus $E_z$and the apparent transverse contraction coefficient υ_{zx} for the 10 cubic specimens of PVC80 as well as their average value.

Knowing that the equation that verifies transverse isotropy is:

$$-\frac{\upsilon_{zx}}{E_z} = -\frac{\upsilon_{xz}}{E_x} = -\frac{\upsilon_{yz}}{E_y} \quad (1)$$

Based on the experimental results obtained and using Eq. (1) which can let us validate the transverse isotropy theory, the ratio found is equal in the two directions ($\vec{z}$ and $\vec{y}$ axis).

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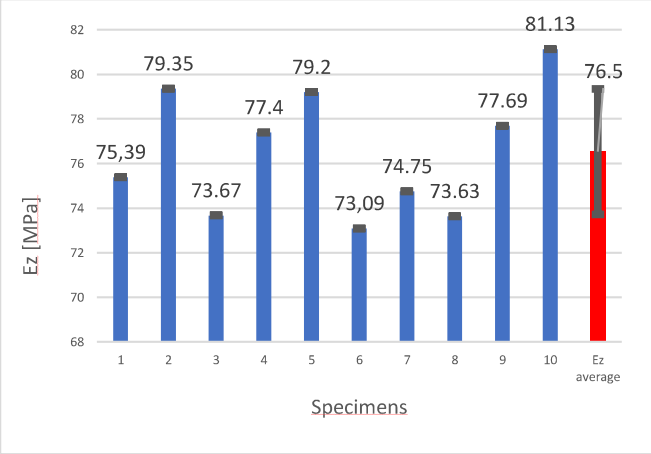


Figure 2: Apparent stiffness modulus E_z

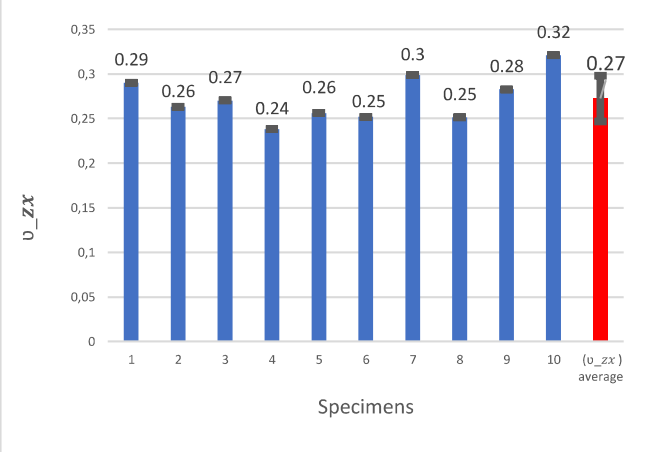


Figure 3: Apparent transverse contraction coefficient υ_{zx}

Results for the PVC80:

$\overline{E_z}$ = 76.5 MPa and $\overline{\upsilon_{zx}}$ = 0,272 => Ratio $= -\frac{\overline{\upsilon_{zx}}}{\overline{E_z}} = -\frac{0,27}{76,5} = -0,0035$

$\overline{E_y}$ = 50.05 MPa and $\overline{\upsilon_{yz}}$ = 0,188 => Ratio $= -\frac{\overline{\upsilon_{yz}}}{\overline{E_y}} = -\frac{0,19}{50.05} = -0,0038$

Using the same approach for the recycled PET80, this foam is also found to be transversely isotropic.

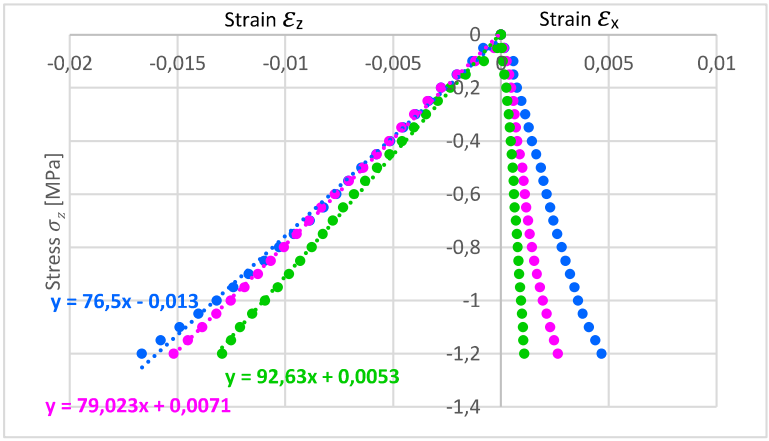


Figure 4: Experimental results PVC80 - Compression tests (3 specimen's dimensions)

Figure 4 shows the envelope of stress-strain curves obtained from the average of 10 different samples for each set of dimensions investigated (15x15x15 mm³, 30x30x15 mm³, 60x60x15 mm³) for the thickness direction. Accordingly, for the same material, PVC80 in this case, we have different apparent modulus for each set of dimensions (76.5 MPa, 79.023 MPa, and 92.63 MPa) which is proof that we are not in the case of uniaxial compression. And that is why a Finite Element model is needed to identify the intrinsic elastic parameters.

3.2 Shear tests

According to ISO 1922 standard (Rigid cellular plastics - Determination of shear properties) shear tests were conducted on the different types of foams in the $(\vec{x}, \vec{z})$ plane as in Figure 4 below in order to identify the last elastic parameter G_{xz} using the Digital Images Correlation (DIC method) [9].

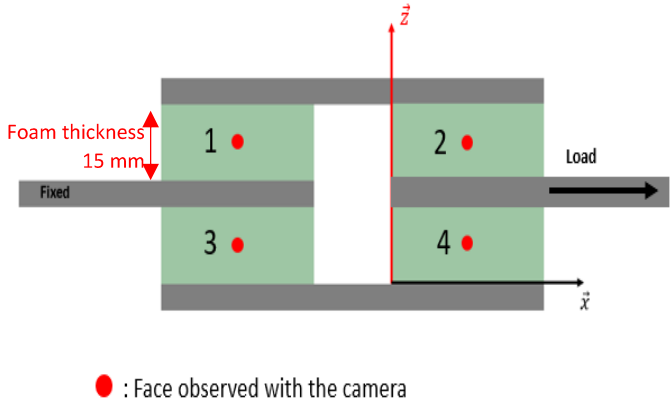


Figure 5: Shear test : $(\vec{x}, \vec{z})$ plane

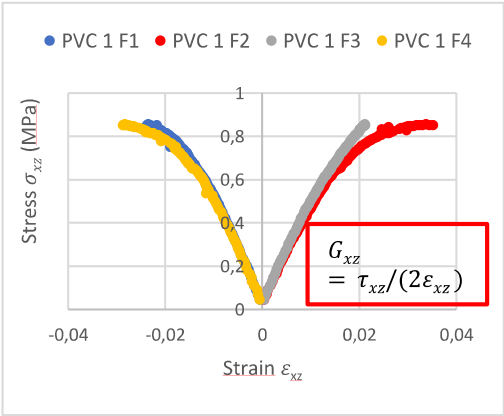


Figure 6: Experimental results PVC80 Shear tests (4 faces) - specimen 1

Based on the stress-strain experimental graphs shown in Figure 6, we determined the shear modulus G_{xz} for the different faces observed for each specimen. They are almost equal with an average of 24.35 MPa as shown in Table 2.

Table 2: Experimental results -Shear modulus G_{xz} (specimen 1)

Face	1	2	3	4
G_{xz} [N/mm^2]	24.71	23.09	24.02	25.56

Table 3 shows the different experimental results of the Shear modulus G_{xz} for the three types of foams. These results are similar to those shown in the datasheets for each foam (Table 1).

Table 3: Experimental results - Shear modulus [N/mm^2] Gxz for the different types of foams

Specimen	PVC 80	PETr 80	PETr 115
G_{xz} [N/mm^2] (Average)	27.04 (SD = 2.33)	12.19 (SD = 1.69)	21.89 (SD = 0.67)

Unlike the compression tests, the modulus G_{xz} calculated is an intrinsic parameter. The proof is shown on the graph below (Figure 7). The strain evolution profile is continuous all over the specimen. Accordingly, there is no need for a Finite Element model for this test.

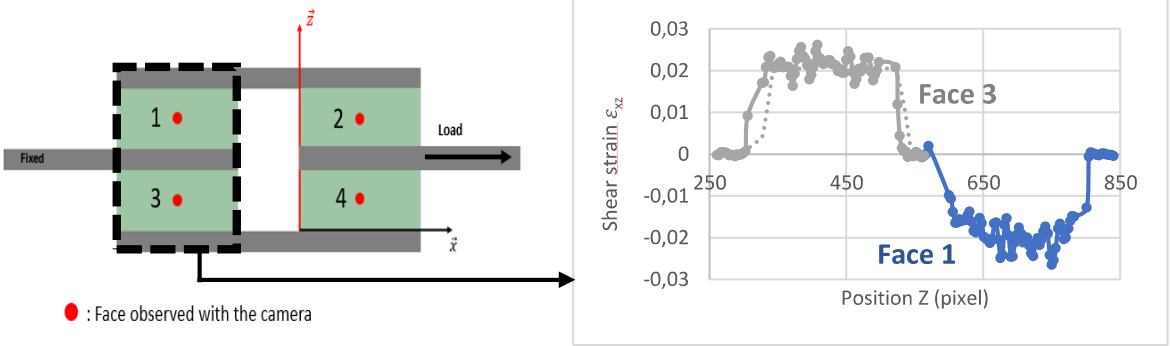


Figure 7: Strain evolution profile - specimen 1

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4. Numerical simulations

4.1 Boundary conditions

As previously mentioned, we are not in the conditions of uniaxial compression. Therefore, in order to create a model which is as close as possible to the experimental test we imposed the following boundary conditions for the compression test in the thickness direction (Figure 8):

- Displacement Uz on the top face
- Displacement Ux = Uy on the sides
- Blocking the z displacement on the bottom face
- Applying two symmetries (along $\vec{x}$ and $\vec{y}$ axis)

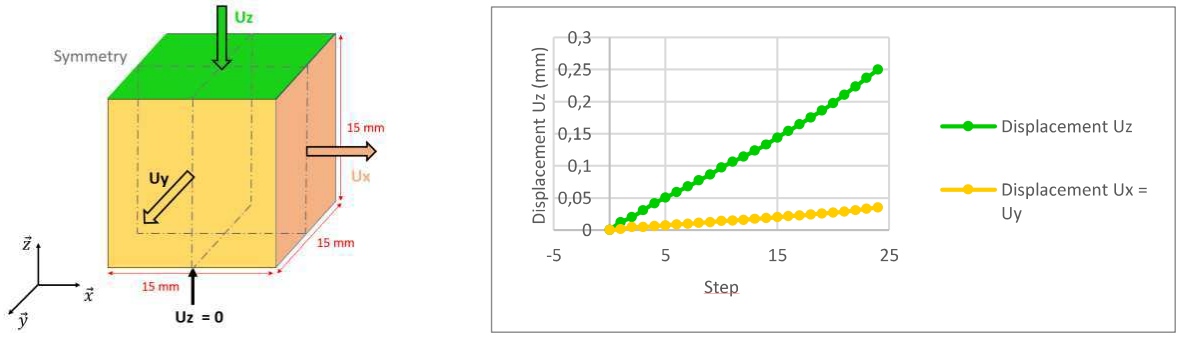


Figure 8: Boundary conditions for PVC80 - 15x15

Following the same concept, we imposed the boundary conditions for the compression test in the longitudinal direction ($\vec{y}$ axis).

4.2. Minimization

The method used to identify the intrinsic elastic behavior of the foam is based on a Finite Element Model Updating Method. An interface on Matlab linked to Python is created to link between the Finite Element model on Abaqus and the adjusting method on Matlab (Figure 9). This adjusting method, which already exists in Matlab's library, consists in minimizing the error between the experimental results and the simulated ones. As such, this error minimized is the average of the errors of the different compression tests in both the thickness and the longitudinal direction. Accordingly, the optimized elastic parameters (intrinsic) are those corresponding to the smallest error.

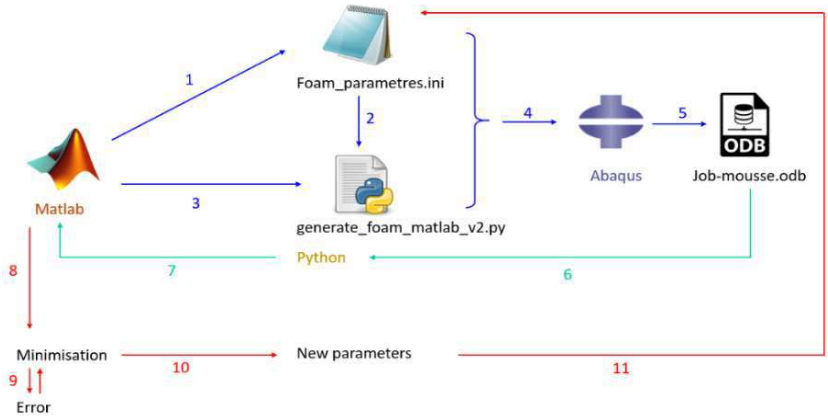


Figure 9: Interface Abaqus-Matlab-Python

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5. Results and discussions

Figure 10 shows the different results of compressions tests conducted on 30x30x15 mm^3 specimens. The blue, green, and red graphs indicate the experimental, numerical before minimization (apparent), and numerical after minimization data respectively (optimized).

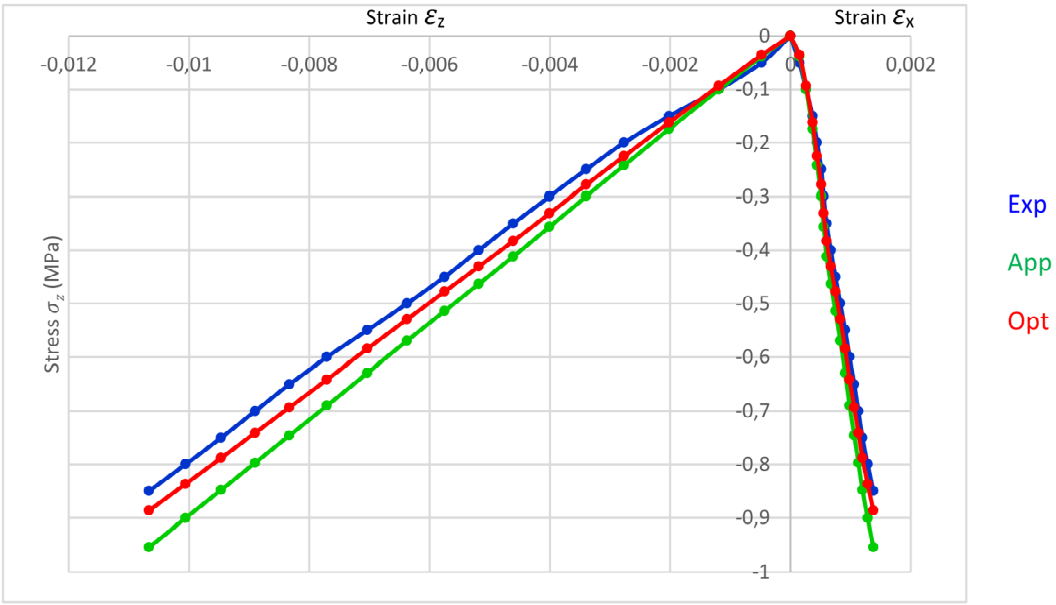


Figure 10: Numerical results - PVC80 (dimension specimen 30x30x15 mm^3)

The table 4 below shows the adjusted parameters obtained for the PVC80 and the PETr80 foams by minimizing the total error between the experimental and the numerical results for the different compression tests in parallel. By looking at the datasheets and the adjusted parameters, the datasheet Ez values are higher than the adjusted ones for both foams and the PETr80 always has a smaller Ez modulus than PVC80. Thus, as mentioned earlier, the values in the datasheets are based on standardized tests which are not following the theory of uniaxial compression, therefore, this FEMU method allows the determination of the intrinsic elastic parameters of the foams.

Table 4: Adjusted elastic parameters (compression tests)

Foam	Ey [N/mm²]	Ez [N/mm²]	υ_{xy}	υ_{yz}
PVC80	48.12	74.45	0.36	0.18
PETr80	19.14	42.95	0.32	0.15

6. Conclusions and perspectives

In this paper, an original method combining compression and shear tests, Digital Image Correlation (DIC) technique, and a Finite Element Model Updating Method (FEMU) was developed to characterize and predict the mechanical elastic behavior of PVC and PETr foams. The results analysis of the conducted compression tests showed that the PVC80 and the PETr80 foams represent a transversely isotropic behavior and the material parameters calculated are

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considered apparent properties. DIC technique was successfully used to detect the surface strain for each compression and shear tests. Based on these experimental results, it has been confirmed that the conducted compression tests don't respect the theory of uniaxial compression. Therefore, a numerical model (on Abaqus) is developed by linking it to an optimization interface on Matlab which allowed us to adjust the material parameters by comparing the experimental and numerical properties in order to evaluate the real intrinsic elastic parameters of the foams (Young Modulus, Poisson's ratio …). This study will be complemented by establishing a statistical morphological model of the foam through a morphological analysis.

Acknowledgements

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