Cellular material behavior characterization

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Abstract: Cellular materials such as polymeric foams are often used for the development of composite materials as core in sandwich structures. Their use in the aircraft, naval, or automotive industries does not cease increasing by the way of their lightness and their great capacity to absorb energy. Generally used under a large range of strain rates the behavior of these materials must be identified in experiments before being integrated in finite element codes. The structural response of these foams strongly depends on their density, their cell structures, and the solid material properties. The viscoelastic nature of the solid polymer is, such as the gas trapped in the closed-cells, responsible of the sensitivity of the foam behavior. A viscoelastic Split Hopkinson Pressure Bar (SHPB) apparatus is used to perform tests at high strain rates.

Key words: Split Hopkinson Pressure Bar, Polymeric foams, Compression behavior, Strain rate sensitivity

1. INTRODUCTION

In order to optimize structures filled of cellular materials as core, it is necessary to observe and understand the response of these materials at their closest conditions of use. Often subject to crash or impact during their service life, an experimental characterization is then essential at a great range of dynamic loadings. The identified response by testing, allows us to provide models implemented in finite element codes that are able to predict the dynamic behavior and dissipation energy of such structures submitted to impacts.

Nowadays, the mechanical properties of these types of cellular materials are well known under quasi-static compression. The behavior of these foams is characterized by three stages: i) a linear elastic behavior, ii) a stress plateau, iii) and a final stage which consists of foam densification [1]. A conventional testing machine was used for quasi-static tests. For dynamic tests (strain rates up to 3500 s⁻¹), a Split Hopkinson Pressure Bar (SHPB) can be used. Mainly developed by Kolsky [2], this device is widely used to characterize metallic materials [3, 4, 5], and also to characterize other materials such as: concrete [6], rocks [7], composites [8], and metallic cellular materials (honeycomb, aluminum foam...) [9, 10]. Firstly developed to characterize metallic materials, the Hopkinson bar apparatus has been modified to test all type of materials, and particularly, for this study compliant materials such as polymeric foams [11, 12, 13] and polymers [14]. Because of the high acoustic impedance mismatch between polymeric cellular materials and the bars, usual metallic bars have been adapted using hollow bars or lower impedance bars [15]. For this study, the bars have been replaced by viscoelastic bars (Nylon bars) in order to reach the best test results [16, 17].

The aim of this study is to characterize the behavior of EPP cellular materials under dynamic compression loadings and also to highlight the influential parameters on the response of the foams, such as density and microstructure (morphology, thickness and cell diameter...).

2. STUDIED MATERIAL

The foam chosen for this study is an expanded polypropylene foam (EPP) that is mainly used in automotive industry as crash-box according to their high energy absorption or door panel for side impact protection. These foams also present a particular microstructure due to their manufacturing processes. The first step of this process consists in the pre-expansion of small polypropylene granulates into low density polypropylene beads of 30 to 50 kgm⁻³. These expanded plastic foam beads are injected into a steam chest mold, where individual beads are fused together under steam heat and pressure. The gas generates the expansion of these beads of a few millimeters that agglomerated together to constitute the structure of the foam. The micrographs (“Fig. 1”) show the multi-scale structure of the foam and reveal that micro-closed cells of variable diameters constitute each polygonal bead.

The size of these beads and cells varies due to the manufacturing process but a mean diameter of these beads could be considerate of about 3 to 4 mm and the cell diameter of about 0.1 to 1.5 mm. An analysis of the SEM investigation (“Fig. 2”) reveals that the repartition of the cell area observed on 300 cells is 0,01 up to 1,5 mm². So according to these observations the foams show a random multi-scale structures that do not present any particular orientation at macro or microscopic scales and it seems that isotropic compression behavior could be supposed. This hypothesis was verified by preliminary compression tests [18].

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3. EXPERIMENTAL DEVICES

3.1. Quasi-static device

Quasi-static compression tests were carried out using an electromechanical device. The samples tested for this study have been carefully measured and their densities are 35, 75 and 85 kg/m$^3$. To check the repeatability of the mechanical properties of the foam, several compressions were carried out at a crosshead speed of 1.44 mm.min$^{-1}$ on cubic samples of 24 mm side. An initial strain rate of 0.001 s$^{-1}$ has been carried out. In order to evaluate the foam behavior, the engineering stress $\sigma = F/S_0$ and true strain $\varepsilon = \ln(1+\Delta l/l_0)$ have been chosen for two main reasons: concerning the stress, for this material, the evolution of the section is not perceptible, the Poisson ratio $\nu$ is close to zero and therefore the real stress $\sigma = F/S$ is close to $\sigma = F/S_0$; secondly, since the foam is submitted to a large range of deformation, the engineering strain $\varepsilon_{\text{eng}} = \Delta l/l_0$ cannot be used, the strain definition $\varepsilon = \ln(1+\varepsilon_{\text{eng}})$ is more appropriated.

3.1. Dynamic device

To carry out compression tests with Hopkinson bars, the tested sample has to be placed between two hurled bars. A projectile strikes the free face of the first bar (input bar). A compression wave is then initiated and transmitted along this bar. It crosses the sample and a part of this wave is finally transmitted to the second bar (output bar). The “fig. 3” below represents the device (projectile, input bar, sample and output bar). The associated Lagrange diagram details the space-time evolution of the stress waves in the bars:

At the initial stage: before the contact, the bars are at rest, stresses $\sigma$ and particulate velocities $\nu$ are zero, whatever in the bars or in the projectile. The projectile is launched on the input bar and induces a stress wave generating a deformation $\varepsilon_i$ in the bar.

Stage 2. This elastic compressive wave $\varepsilon_i$ is propagated towards the sample at a speed $C_B$ equal to the wave velocity in the bar (elastic bars) $E$ and $\rho$ are respectively the Young modulus and the density of the bars. The first gauge bridge measures the deformations generated by the passage of this wave. The duration $\Delta t$ of this stress is proportional to the length of the projectile and for its intensity it is related to the impact speed.

Stage 3. The wave $\varepsilon_i$ is at the interface bar/sample, a part of this wave crosses the sample, starts to load it whereas the other part of this wave is reflected due to the impedance rupture. The reflected wave $\varepsilon_i$ is then created.

Stage 4. The transmitted wave in the sample is propagated until the other interface bar/sample (output interface) and reflected against this one. This wave loads the sample again whereas the other part is transmitted into the output bar. A reverberation effect settles then in the sample and gradually brings it in a compression state.

Stage 5. The multiple reverberation phenomenon enables to "build" the transmitted wave gradually $\varepsilon_i$ in the output bar. The second gauges bridge then measures the strains generated by the passage of this wave.

Incident, reflected and transmitted waves measurement allows obtaining the characteristics of the test, such as the imposed force $F_{\text{input}}$ and $F_{\text{output}}$ on the sample and its deformations. In the case of traditional elastic bars, a simple equation setting of the system makes it possible to determine the physical quantity $F$ and $\nu$:

\[
\begin{align*}
F_{\text{input}}(t) &= SE\varepsilon(t) + SE(\varepsilon(t) - \varepsilon_i(t)) \\
F_{\text{output}}(t) &= SE(\varepsilon_i(t) - \varepsilon_i(t)) \\
\varepsilon_{\text{input}}(t) &= SE(\varepsilon_i(t) - \varepsilon_i(t)) \\
\varepsilon_{\text{output}}(t) &= SE(\varepsilon_i(t) - \varepsilon_i(t))
\end{align*}
\]

However, this usual bars (metallic bars) cannot be used to identify the light expanded material behaviour. Indeed the material stiffness is too weak compared to that of the usual metal bars, thus it is necessary to resort to bars less stiff made of viscoelastic materials.
Material characterization using Hopkinson bars is based on the stress wave measurement on the input and the output bars. The amplitude of these waves strongly depends on the samples to be tested. On the one hand, the measurement of the incidental wave can be done without any problem because its amplitude depends directly on the impact intensity. On the other hand, transmitted wave amplitude depends on the response of the material tested. In the case of cellular material, incident and transmitted wave are strongly attenuated. The use of viscoelastic bars is then necessary. However the use of viscoelastic bars involves acoustical dispersion of waves [19]. To take into account this dispersion $\gamma(\omega)$ and attenuation $\alpha(\omega)$, it is then essential to carry out an accurate numerical transport of the waves from their measurement point to the sample. This dispersion is characterized by a propagation coefficient $\gamma(\omega)$ which is determined experimentally for each bar, $\omega$ being the angular frequency related to the frequency $f$ by $\omega=2\pi f$:

$$\gamma(\omega)=\alpha(\omega)+ik(\omega)$$

Then, in the Fourier’s domain, relations which describe the force $F(x,\omega)$ and the velocity $v(x,\omega)$ in a section $x$ of the bar can be resumed by:

$$F(x,\omega)=\frac{\rho So^2}{\gamma^2}(\tilde{P}(\omega)e^{-i\gamma x}+\tilde{N}(\omega)e^{i\gamma x})$$

$$v(x,\omega)=-\frac{i\omega}{\gamma}(\tilde{P}(\omega)e^{-i\gamma x}-\tilde{N}(\omega)e^{i\gamma x})$$

$S$ denotes the section of the bar, $\tilde{P}(\omega)$ and $\tilde{N}(\omega)$ the Fourier’s transforms of the incident and retrograde wave (respectively $\varepsilon_i$ and $\varepsilon_r$). Supposing that the stress and strain states are homogeneous in the sample height $h$, the stress $\sigma$ and the deformation $\varepsilon$ are then given by the relations as below:

$$\sigma=\frac{F_{input}}{S} \quad \varepsilon=-\ln\left(\frac{u_{output}-u_{input}}{h}\right)$$

The Split Hopkinson Pressure Bar used for these experimentations is made of nylon PA6 of 3 m length for the input bar and 2.5 m length for the output bar. Their diameters are 40 mm and an air compressor allows throwing the striker bar to the speed of 1 to 40 ms$^{-1}$. For these experiments the striker bar of 55 mm length (diameter 40mm) and 500 g was through with an air pressure of 30 bar transmitting it an impact speed of 25 ms$^{-1}$. The tests parameters are sum up on the Table 1.

### 4. RESULTS AND EXPLOITATION

The “Fig. 4” sum up the typical stress-strain responses of the quasi-static tests performed at 0.001 s$^{-1}$ and of the dynamic tests performed at nearly 3000 s$^{-1}$ on the three densities of 35, 75 and 85 kgm$^{-3}$. Tests parameters and sample dimensions are presented in the Table 1.

![Fig. 4. Experimental results.](image)

The “classical” foam behavior can be identified [1] by an initial linear elastic behavior followed by a stress plateau. In a care of presenting the final stage that consists of the foam densification is not plotted.

Theses tests on the three densities reveal a dynamic hardening effect that is raised with respect to density.

<table>
<thead>
<tr>
<th>Strain rate</th>
<th>Number of samples</th>
<th>Dimensions</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasistatic</td>
<td>0.001 s$^{-1}$</td>
<td>4 24×24×24±0.02 mm</td>
<td>35±1 kgm$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>0.001 s$^{-1}$</td>
<td>4 24×24×24±0.02 mm</td>
<td>75±3 kgm$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>0.001 s$^{-1}$</td>
<td>4 24×24×24±0.02 mm</td>
<td>85±2 kgm$^{-3}$</td>
</tr>
<tr>
<td>Dynamic</td>
<td>3000±200 s$^{-1}$</td>
<td>4 8×φ38±0.02 mm</td>
<td>35±1 kgm$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>3000±180 s$^{-1}$</td>
<td>4 8×φ38±0.02 mm</td>
<td>75±3 kgm$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>3000±170 s$^{-1}$</td>
<td>4 8×φ38±0.02 mm</td>
<td>85±2 kgm$^{-3}$</td>
</tr>
</tbody>
</table>
4.1. Density and strain rate effects

In order to highlight the density effects and the strain rate influence on the mechanical response of these foams at compression, the evolution of the Young’s modulus, Yield stress and the plateau stress modulus of these foams is plotted on the following Figures.

The “Fig. 5” highlights the Young’s modulus sensitivity to strain rate for three densities. This elastic modulus seems to be increased by strain rate. A low influence is observed on the low density, 35 kgm$^{-3}$, and the modulus increase from 1.6 to 6.94 MPa whereas at high density, 85 kgm$^{-3}$, the modulus in more than six times increased (from 6.9 to 43.2 MPa). This strong sensitivity to strain rate at high density can assign to the large influence of the solid constitutive material, polypropylene (PP) to the elastic compression phenomenon that is mainly ruled by the elastic bending of cell walls and compression mechanisms.

Fig. 5. Evolution of the Young modulus at quasi-static and dynamic strain rate.

Nevertheless, for an accurate analysis, these results must be carefully noticed. Indeed it is very difficult to get precise measurements with the Hopkinson bars at the early time measurement, special experimentation with carefully analysis must be proceeded [Zhao and Gary 1996] in order to reach these data.

Concerning the evolution of the collapse stress its evolution plotted on the “Fig. 6” follows the same tendency: a large increase in this threshold stress at high density for high strain rate and a low increase at low density. The mechanism responsible of this hardening is mainly due to inertia effects during the cell edge buckling which is stronger at high strain rate.

Fig. 6. Evolution of the collapse stress at quasi-static and dynamic strain rate.

The evolution of the plateau stress modulus, defined as the slope of the stress-strain curves in the plateau region between 0.1 and 0.6 of strain, is an increasing function with respect to density and slightly seems to depend on strain rate, “Fig. 7”. Concerning dynamic tests, the level of the standard deviation is quite large and do not make it possible to determine an accurate evolution of the plateau stress at high density. Indeed, the mechanical phenomenon settled during this phase is more complicated than in the elastic stage. During this phase, the collapse of the cell edges is combined to the compression of the trapped air in closed cells.

Fig. 7. Evolution of the plateau stress modulus at quasi-static and dynamic strain rate.

To conclude, the density effect increases the global mechanical response of the foam. Indeed, higher foam density involves thicker cell’s walls and higher polypropylene contribution. The effect of strain rate is obvious on the evolution of the Young’s modulus and the collapse stress and the magnification phenomenon for high foam density implies an important microstructural response on its behavior.

4.2. Localization effects

The global behavior of the expanded polypropylene foam is identified in quasi-static and dynamic experiments. However in order to better understand the failure mechanisms of the cellular material and also to define the local behavior of the cellular structure, compression tests performed with the viscoelastic Hopkinson bars at a strain rate of 2800 s$^{-1}$. These tests have been filmed at 80000 frames per second with a high speed cam (Phantom V7). The “Fig. 8” shows on one of the stress strain response of these tests the solicitation state corresponding to the optical measurements.

Fig. 8. Evolution of uniaxial stress strain response of the filmed sample.
To summarize the evolution of this compression test five pictures have been chosen: before the material compression, one picture in the elastic phase at 3.3% of strain, one after the collapse stress at 11.9% of strain and two other in the plateau stress at 27.7 and 35.9% of strain "Fig. 9".

During the elastic step (“Fig. 9” at 3.3% of strain) the strain field is obviously very small and seems to be quite homogeneous. On the contrary during the plateau stress phase, at 27.7% of strain for example, a strong localization band occurs. The strain field is not homogeneous in the foam, two large layers on the left and the right near the input and output bars seem undamaged. Then, this localization band seems to progress and as it is nearly dense, compress the others layers of the sample “Fig. 9” at 35.9% of strain. For all the dynamic compression tests at high strain rate this phenomenon of a collapse foam damage band was noticed in contrary to quasi-static tests where strain field is much more homogeneous.

5. CONCLUSION

Dynamic compression tests at high strain rate have been achieved showing the classical cellular material response, an elastic behavior followed by a plateau stress behavior.

These tests using a viscoelastic Hopkinson bar make it possible to highlight the hardening phenomenon that occurs at high strain rate compression. The density effect on the compression behavior have also been identified so as to the increase of this phenomenon with respect to high foam densities.

Then the inhomogeneous strain field during high compression tests has been highlighted. A compression damage band appears perpendicular to the loading direction and that the microstructure of the foam is mainly responsible of these non-homogeneous phenomenon.

REFERENCES