Experimental proof of squeeze damping capacity of imbibed soft porous layers subjected to impact

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Abstract: During last decade a series of theoretical studies revealed the high pressures generated in highly porous soft materials imbibed with fluids and subjected to compression, with possible application to impact damping. The mechanism, named eXPoroHydroDynamic (XPHD) Lubrication, combines the resistance to flow inside the porous matrix with its variable (decreasing) permeability during compression. Early experimental results obtained on falling ball and pendulum tests, at low velocity (V<6m/s), were promising. This paper reports preliminary experimental results obtained at medium impact velocity and high energy, for circular, flat contact surface, performed on a gas gun test rig. Specimens ("damping cells") made by encapsulation of a porous material and glycerine have been tested in various impacted structures. It is shown that the maximum contact force is reduced up to 50\% when the impacted structure includes the proposed specimens. Visual inspection of impacted specimens clearly shows that for medium velocity the impact was supported by high squeezing pressure generated inside the porous layer. The experiments have also shown that the presence of a bullet-proof vest does not change significantly the impact force variation. Comparison with the XPHD model for disc configuration shows satisfactory agreement for velocity V < 17m/s.

1. Introduction

Best impact protective systems for personnel are based on a multilayer structure with complementary functions. Next to hard or high tensile strength materials, a soft material is used to make the body armor comfortable. This layer is also designed to reduce armor deformation produced by perforation resistance and to protect against blunt trauma. This paper analyses an innovative solution for this deformable protective layer based on encapsulated porous materials imbibed with fluids (named "damping cells").

During last decade a series of theoretical studies demonstrated high squeezing pressures generated when compressing highly porous soft materials imbibed with fluids. This mechanism, named eXPoroHydroDynamic (XPHD) lubrication, combines the effect of fluid flow through a porous layer with the variation of permeability due to compression between two rigid surfaces.
Pascovici et al. [1,2] demonstrated the high lifting forces generated when a soft porous layer imbibed with a fluid is subjected to an impact with a rigid, spherical body or a flat disc. Later, other configurations have been theoretically studied: inner contact cylinder-on-cylinder - Ilie et al. [3], cylinder-on-plane - Radu [4, 5]. All these models assumed planar squeeze flow of a Newtonian fluid in a thin layer of porous material and neglected the contribution of the solid matrix to load support.

Several experimental studies have been performed to prove the validity of the models but they were restricted to low compression speed and their results were mostly qualitative. Radu and Ciccone [6] used a pendulum to impact various porous materials imbibed with water to define best candidates for impact damping. They were evaluated using force and acceleration of the impacted structure recorded during impact with low velocities (V<2m/s). Similar tests have been reported by Radu et al. [7] for different other fluids. These experiments have been performed on the same pendulum test rig but also on a falling ball testing arrangement, where the impact velocity was up to V_{\text{max}}=6m/s.

Dawson et al. [9] reported similar studies in which a reticulated, elastomeric foam (polyurethane with high porosity $\epsilon=0.99$) imbibed with glycerol is subject to dynamic loading. The envisaged application was ballistic protection against projectiles or blast waves. The proposed model includes the contribution of the porous matrix but proposes a very simple Darcy model for the flow of the fluid inside porous structure, assumed with constant permeability. Experiments have been made on standard tension-compression testing machine at low compression speed, respectively a drop-tower for higher speed, and showed good agreement with predicted results.

Similar investigations have been reported by Vossen [10] who was interested in the damping effects of polyurethane foams to improve impact performance for motorcycle helmets with low impact energy. He proposed annular damping cells with centrally placed reservoirs of glycerine. His studies were focused on the optimum size and space arrangement of these partially filled cells. For experiments he used a drop tower and the impact mass was 7.2 kg. The impact velocity was set to 6 m/s, resulting in an impact energy of approximately 130 J.

This paper reports some preliminary experimental results obtained at medium impact speed ($V=12m/s\div26m/s$) on a gas gun test rig.

2. Experimental Setup
The tests were performed on a horizontally oriented, gas gun (Fig. 1a), using a 60mm dia. cylindrical projectile. The flat face aluminium projectile of mass $m=521$grams impacts the target placed at 200mm far from the end of the gun. The speed of the projectile can be varied by the pressure in the compressed air tank, using a pressure regulator. The target consists of the damping structure which includes the tested specimen placed on a high-speed load cell, rigidly attached on the frame of the testing facility. The load cell is based on a preloaded piezoelectric load washer (KISTLER 9051A) with the measuring range $0\div120$kN. A high speed (max. 20.000fps) video system (PHOTRON) records the motion of the projectile before, during and after impact.

The experimental studies are dedicated to damping effects of a soft porous material imbibed with fluids. During previous experiments [6,7,8] there were found some good candidates for porous materials and the filling fluid. For the present tests the selected porous material was a special fabric known as 3D spacer (SPACETEK™ from Heathcoat Fabrics). It is a knitted fabric made of 100% polyester yarns with an average diameter $d=0.145$mm. The thickness of the material was $h_p=6.5$mm with the average porosity $\epsilon=0.95$. 

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The fluid was a solution of glycerine with 7.5% Zeosil, which demonstrated good compatibility with the porous material and compliance to personnel protective equipment. The viscosity of the fluid was about 1Pa-s, a value which is influenced by the ageing of the glycerine.

A disc of radius $R=24\text{mm}$ cut from the porous material and imbibed with the fluid was encapsulated with a multilayer polyethylene-polyamide-polyethylene membrane bonded by ultrasonic welding (Fig. 1b). This pack is what we name from this point forth a *specimen* or "damping cell". The manufacturing of these specimens makes difficult a complete imbibition of the porous matrix. Weighting the cells after encapsulation it was found a level of imbibition between 75%-80%.
Multiple series of tests have been performed with different structures impacted with velocities up to \( V_{\text{max}} = 26 \text{m/s} \). Single specimen or a pack of two specimens, covered by 4-8 layers of Kevlar knitted fabric were tested to find the influence of the layers. The layers of Kevlar were used also to limit the glycerin splashing after impact. Tests were also performed with light bullet-proof vests (19 layers of Kevlar) with and without specimens behind (Fig. 1c).

After each test the damaged specimens were marked and further visual analysis was performed. Force variation on the impacted structure was recorded for each test; based on a simple integration procedure the total impulse was also calculated. The exact impact speed was calculated using the slow-motion movies recorded during each impact.

3. Results and discussions

The first objective of the experiments was the analysis of the reproducibility of the tests. As fine adjusting of the air pressure does not ensure an accurate control of the impact velocity and the specimens are not perfectly identical it was found necessary to make tests in apparently similar conditions to characterize the dispersion of the results. Fig. 2 presents the results of three consecutive similar impacts on a pack of two damping cells. The differences in maximum force as well as in terms of impulse are very small and justified by the difference in impact velocity. Similar conclusions can be drawn from Fig. 3 were the results of three impacts on a single specimen are presented. In both cases the specimens were covered with 4 layers of Kevlar. The same excellent reproducibility was obtained when the impact was on a bullet-proof vest and a single specimen (Fig. 4).

A second objective of the tests was the analysis of the influence of the impact speed on the force variation during the impact. Fig. 5 shows the comparison of three tests made with the same impacted structure (one specimen covered by 4 layers of Kevlar). The results confirm the expectations: the maximum impact force is almost proportional with the impact velocity of the projectile. This important remark can be better seen from Fig. 6, where all the results, in terms of maximum impact force versus impact velocity are represented. The maximum forces, when impacting one specimen, are distributed along a straight line with a R-squared factor 0.95.
Figure 4. Reproducibility tests - bullet-proof vest with one specimen

Figure 5. Impact on a single specimen with various velocities

Figure 6. Maximum force variation with impact velocity

Figure 7. Force variation at impact on bullet-proof vest

The third objective of these preliminary tests was the analysis of the damping effect of the specimens when placed behind a bullet-proof vest. Three consecutive tests have been performed: first the impact was on the vest with no other layer behind, then a specimen was placed behind the vest and finally, a pack of two overlapping specimen was placed behind the vest. Fig. 7 shows a drop with almost 50% of the maximum force when using a specimen behind the vest and close to 66% reduction if two specimens are overlaid. However, we can conclude that two layers of specimens are less effective in terms of damping / weight ratio. This is probably the most important results of this session of tests.

A comparison of two impacts on a specimen, first covered by 4 layers of Kevlar and second covered by the bullet-proof vest shows a slight difference in maximum force and time of impact (Fig. 8). One can note that the smaller maximum force in the case of bullet-proof vest is also the result of a lower impact velocity: \( V=24.4 \text{m/s} \) instead of \( V=25.4 \text{m/s} \) for impact on the sample without vest.
Figure 8. Force variation during impact with and without bullet-proof vest

Figure 9. Porous material (a) before and (b) after impact with $V=12\text{m/s}$

Visual inspection of the porous material after tests shows that for low impact velocity ($V \approx 12\text{m/s}$) the material is not affected so much by the impact (Fig. 9). The broken fibers which can be remarked in Fig. 9b can be attributed to the high pressure of the squeezed fluid. This is probably the most concluding evidence of the existence of XPHD lubrication mechanism. The same conclusion can be drawn if we analyse Fig. 10b, showing the porous disc after a $V=25\text{m/s}$ impact on a bullet-proof vest with a specimen behind: the material is more damaged but the porous matrix is still evident. However, a test made at the same impact velocity but directly on the specimen destroyed completely the porous matrix (Fig 10b); this shows that the presence of the bullet-proof vest, even if it does not reduce sensibly the maximum impact force, makes the contact of the projectile with the backing specimen more uniformly distributed on the contact surface. This conclusion endorses the beneficial effect of damping cell placed behind a bullet-proof vest.
4. Comparison with theory

The experimental maximum impact force can be compared with predicted values using the model proposed initially by M.D. Pascovici et al. in 2009 [1], modified with an improved assumption by M. Radu [11]. According to this model, the maximum impact force generated when a flat, rigid disk of mass $M$ and radius $R$ impacts with the velocity $V$, a layer of a soft porous material (with initial porosity $\varepsilon_0$ and initial thickness $h_0$) imbibed with a fluid of viscosity $\mu$, is:

$$F_{\text{max}} = \frac{\mu NR^4}{Dh_0} \cdot \frac{\pi}{8} \left( \frac{1-\varepsilon_0}{H-(1-\varepsilon_0)} \right)^3 \left(1 - \tilde{M} \frac{\pi}{16} \left(1-\varepsilon_0\right)^2 \left[ \frac{1}{H-(1-\varepsilon_0)} - \frac{1}{\varepsilon_0^2} \right] \right)$$

(1)

After differentiation and cumbersome algebra, one can find the closed form equation of the maximum force:

$$F_{\text{max}} = \frac{\mu NR^4}{D} \cdot \frac{\pi}{8} \left( \frac{1-\varepsilon_0}{H-(1-\varepsilon_0)} \right)^3 \left[ \frac{48\tilde{M}}{4800\tilde{M}} \frac{\varepsilon_0^2}{\sqrt{5}} + 3\pi (1-\varepsilon_0)^3 \right]^{5/2}$$

(2)

where

$$\tilde{M} = \frac{DVM}{\mu R^4}$$

is the dimensionless impulse and $D$ a complex permeability constant in Kozeny-Carman permeability-porosity correlation.

The latter parameter can be experimentally determined or approximated with the formula:

$$D = \frac{d^2}{16k}$$

(3)

where $d$ is a characteristic dimension of the porous structure (fiber diameter in our case) and $k$ is a correction factor taking values usually in the range $k=5...10$.

Equation (2) has been used to calculate the maximum force produced by XPHD effects for various velocity impact corresponding to experiments assuming the complex permeability parameter $D=1.3\cdot10^{-10}$ m² (value obtained for $k=10$). Fig. 11 presents the variation of the maximum force with impact velocity from both experiments and theoretical model. One can see a very good agreement for
low velocity (V < 17 m/s). However, for greater impact velocities, the analytical model predicts forces much greater, up to twice the measured one. This shows that at higher impact velocity the squeezing process is limited by the complete compression of the porous matrix. From this moment forth, the solid matrix of the porous material contributes also to impact support.

![Image](image.jpg)

**Figure 11.** Force variation with impact velocity - Experiment versus XPHD model

5. Conclusions

The paper presents original experimental data to evaluate the damping capacity of original "damping cells" made of soft, porous materials imbibed with glycerine. The experiments, made on a classical gas gun were performed at medium velocity impact (V < 26 m/s) but high energy, up to 170 J.

It was shown that the proposed damping cells reduce with up to 50% the maximum impact force when directly impacted or when the impact is on bullet-proof vest with a damping cell behind.

Visual inspection of the impacted specimens shows clearly that the squeezed fluid at high pressure is at the origin of specimen destruction.

The experiments have also shown that the maximum impact force is quasi proportional with the impact velocity.

The comparison of the maximum impact force with a predicted value based on a simplified, analytical model, shows very good agreement for low velocity impact (V < 17 m/s).

6. References

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