6th International Conference
ðComputational Mechanics and Virtual Engineeringð
COMEC 2015
15-16 October 2015, Braşov, Romania

A COMPARATIVE EXPERIMENTAL STUDY OF IMPACT DAMPING USING HIGHLY COMPRESSIBLE POROUS MATERIALS IMBIBED WITH FLUIDS

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Abstract:*An innovative solution for damping of residual energy after the impact of a bullet on a protective vest, based on the flow of a fluid through a porous material that is placed under the protective Kevlar layers, has been recently proposed. The fluid flow through the open pores is produced by the compression of the porous material, during impact, i.e. the deformation of the Kevlar layer under the impact with the bullet. The simulation of the impact is done using a pendulum test rig that with a spherical cap. The acceleration and force under impact is analyzed on the impacted body that is protected by the porous material. Combinations of candidate porous materials and fluids were tested. The comparison is done in terms of peak-acceleration and peak-force but also in combination with the thickness and the porosity of the material. The best combination of porous material and fluid was determined. The experiments were also focused on the evaluation of various sealing (encapsulating) membranes necessary for bulletproof application.*
Keywords:*damping, impact, porous, Kevlar, lubrication*

1. INTRODUCTION

Hostile-Aggressive behaviors and the politics of some countries opened new threats and intensified armed or bomb attacks. In this circumstance, protection is a matter of major interest in situations where different constructions, transportation vehicles or human lives (civilian or military) are subjected to high energy transfer phenomena, like explosions or high speed impacts of projectiles, bullets, shrapnel etc. The effectiveness of a protective system depends not only on the capability to stop the penetration, but also on blunt trauma protection – the blow suffered by the body from the impact of the bullet/ projectile/ explosive with the protective system. For personnel involved in high risk operations, blunt trauma can be a matter of life or death.

During the last decade the development of improved protection equipment for human personnel which contains an encapsulated, highly compressible porous layer imbibed with a liquid,has been analyzed. Placed in the backing of a bulletproof vest, it will absorb the energy left after the bullet's impact and reduce the risk to injury due to blunt trauma.

Viscous friction of a fluid that flows through the pores of a highly compressible material shows great potential in shock absorbers applications. The fluid flow is produced by the compression of the porous material, with open pores, under the action of external loads.The first mention of this mechanism was in 2000,by Prof. Mircea D. Pascovici [1], under the name of Ex-Poro-HydroDynamic (XPHD) lubrication. It is based on the interaction between the fluid and the porous structure, coupling the effect of the compression of the material with the flow of the fluid through its pores. During compression, the porous material is highly deformed, the porosity decreases, and so, the permeability. As a consequence, the resistance to flow increases and generates high pressures.Impact damping based on XPHD lubrication mechanism is difficult to study, with few experimental investigations so far.

The experimental studies found in literature are scarce, with very different approaches, and reduced significance. Regarding the porous materials used and imbibing fluids, there is an extremely wide variety of solutions, but very few were considered experimentally. Dawson studied theoretically and experimentally the force generated by squeezing in dynamic conditions reticulated foam imbibed with high viscosity glycerine [2]. The results show, that when compressing the foam up to 50%, the fluidinside has an important contribution to the lift force.

Later, Vossen [3] studied the behaviour of polyurethane foams imbibed with cells of glycerine as application for motorcycle helmets.
This paper presents the experimental work done to find a compatible combination of porous material and fluid that provides the best damping capacity relative to the volume occupied.

2. EXPERIMENTAL SET-UP

Experimental set-up of shooting bullet-proof vests can be very expensive and time consuming, which is why, for analyzing the behavior of the porous material imbibed with fluid, the Kevlar layersdeformed by the bullet was associated with a sphere of a larger radius (Fig. 1).

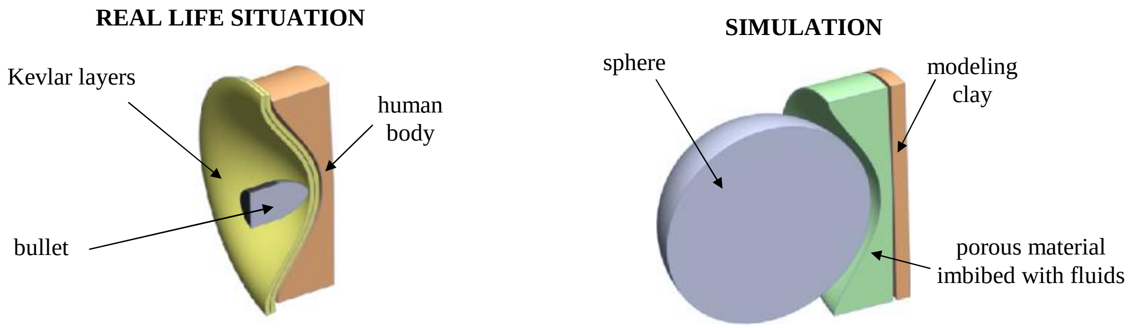

Figure 1: Analogy between real life situation and simulations of a bullet's impact

Two sets of simulating experiments have been performed:
(a) Tests done on a instrumented pendulum test-rig.

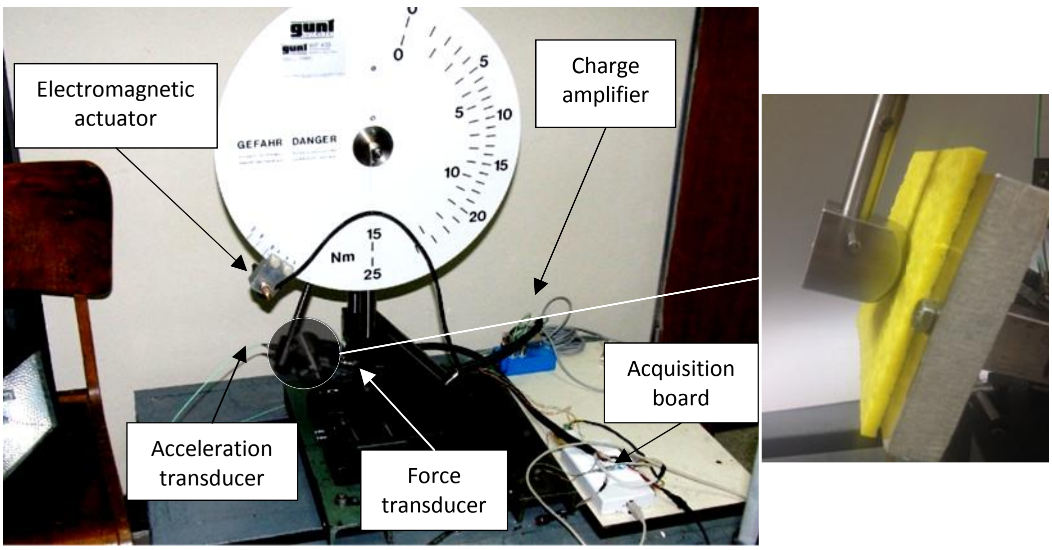

Figure 2: Pendulum test-rig

The experimental test-rig(Fig. 2) is composed of a pendulum with a spherical cap (radius 25 mm), that drops from a certain height *H*, on a rigid plane where the porous material is fixed [4]. An uni-axial acceleration piezoelectric sensor (KISTLER 8274A5) of maximum 20000 m^2/s screwed on the impacting body, tangent to the trajectory at the point of impact, and a force transducer (KISTLER 9301 B) of maximum 2500N, screwed in the middle of a bracket supporting the impacted body, record the two main characteristics of the impact through a data acquisition system. The bracket is free to slide against the force transducer and is inclined with an angle calculated to ensure that the line of contact is tangent to the pendulum trajectory, in the point of impact. The results presented in this paper are focused only on the sphere-on-plane configuration. A series of three tests have been done in the same experimental conditions in order to check the repeatability of the results.

(b) Falling-ball drop tests were made in a second series of experiments.
A 30mm dia sphere drops from *H* over a witness material that replaces the human body: water-based modeling clay. Each test is made on a different sample of clay which solidifies after 24 hours.

Between the impacting sphere and the modeling clay was placed one or two layers of the tested specimen (porous material imbibed with fluid). Some tests include also the presence of the Kevlar layer(s) in order to simulate better the real situation.

3. TESTED SPECIMENS

The experiments presentedin this paper were done on different porous materials, commercially available for purposes like: cleaning, clothing, filtering etc., imbibed with various fluids All of the materials are highly compressible (deformable),homogeneous, with open pores. The structure of the solid materials can differ, having either ordered or disordered fibbers, consolidated or nonconsolidated.
The main **candidate materials** (Fig. 3) that meet the necessary characteristics were:

- Textile materials:
  - *Woven materials*(T03, T04);
  - *Unwoven materials*(NT01, NT03, NT04);
- Reticulated Polyurethane foams(F133);
- 3D spacer (S3D), a double wall woven fabric interconnected with yarns perpendicular to the walls.

Prior to experiments all these materials have been characterized in terms of structure (morphology) thickness h_0, and initial porosity, ε_0.

Figure 3: Candidate materials

The fluid imbibed in the porous material can be any liquid adhering to the surface of the pores and/or absorbed in the fibbers (water, glycerine, oil, pastes, gels etc). They can be more or less viscous, Newtonian or non-Newtonian. The possibilities of combinations of porous materials and fluids are endless, considering the variety of products commercially available. Of course, many of these combinations are not compatible because of the particular properties of the materials, such as chemical or physical incompatibilities (e.g. hydrophobia), or large porosities that cannot sustain low viscosity fluids.

4. EXPERIMENTAL RESULTS

Generally, the damping capacity of materials[5], can be evaluated using different methods:

- Peak acceleration of the impacting/impacted body;
- Peak force on the impacting/impacted body;
- Deformation of the impacted body (footprint);
- Vibration damping after impact;
- The evaluation of the rebound of the impacting body (restitution coefficient).

Experiments on the pendulum test-rig were done from a height of H=200mm, that gives a velocity of approximately 2m/s at impact.A comparative study (Fig. 4) for different materials imbibed with fluids was done in order to establish the best pair that has the lowest peak acceleration and force. The materials are compared in terms of peak-value of acceleration (a_{max}), and peak-value of force (F_{max}).To overcome the difference in thickness and porosity of the materials, two relative indicators have been proposed, using thickness h and fluid fraction, $h \cdot \varepsilon$, respectively.

The best damping capability of the materials is there obtained by the following criteria:

- lowest values of peak-acceleration $a_{\max}$, relative acceleration$a_{\max} \cdot h$ and $a_{\max} \cdot h \cdot \varepsilon$;
- lowest values of peak-force$F_{\max}$, relative force $F_{\max} \cdot h$, $F_{\max} \cdot h \cdot \varepsilon$

The results show that the foam F133 imbibed with tooth paste has the lowest values in the measured parameters, but taking into account the relative indicators, the S3D material imbibed with paste seems to be a better choice.

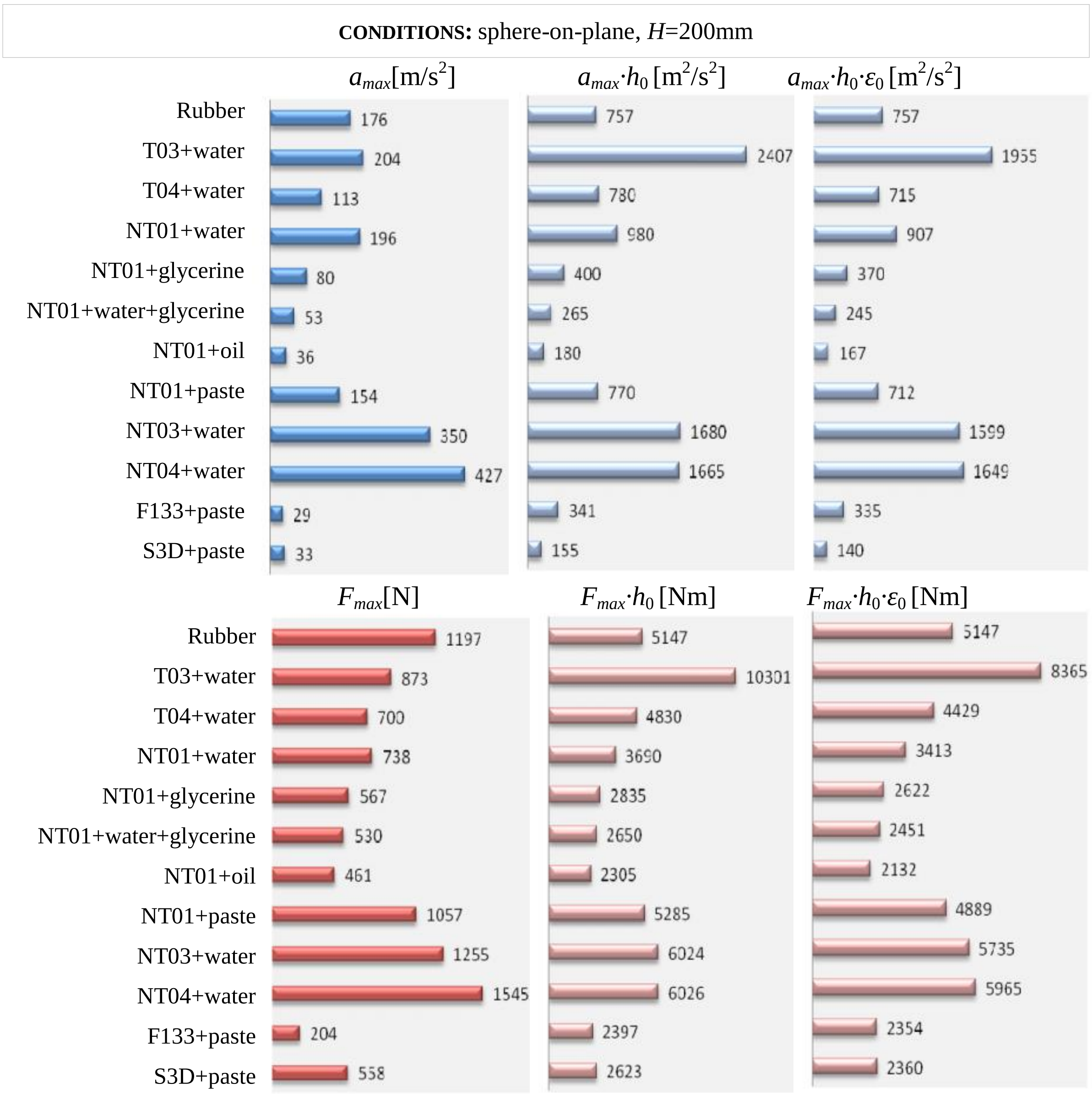

Figure 4: Comparative study of impact behaviour of different porous materials imbibed with fluids

Since from the comparative study, the F133 material has the most promising results, therefore, it was used for further experiments in an encapsulated form (with plastic wall). In Fig. 5 to Fig. 8 are presented the acceleration and force variation in time for different materials. Comparing Fig. 5 and Fig.6, one can observe that adding a layer of Kevlar, increases the reactions on the impacted body. This can be explained by the fact that the Kevlar layer, which is not compressible, acts as an external layer of the sphere, increasing its radius. Hence, a larger zone is deformed. This doesn't imply that the Kevlar is harmful, because currently it is the strongest layer known that can decrease the velocity of the bullet.

By comparing Fig. 6 and Fig. 7, we can demonstrate that the presence of the glycerin in the porous material can decrease the acceleration by 60% and the force by 30%, a very conclusive result that demonstrates the effectiveness of the XPHD mechanism. Fig 8.demonstrates that two layers of porous material are very efficient in damping the impact.

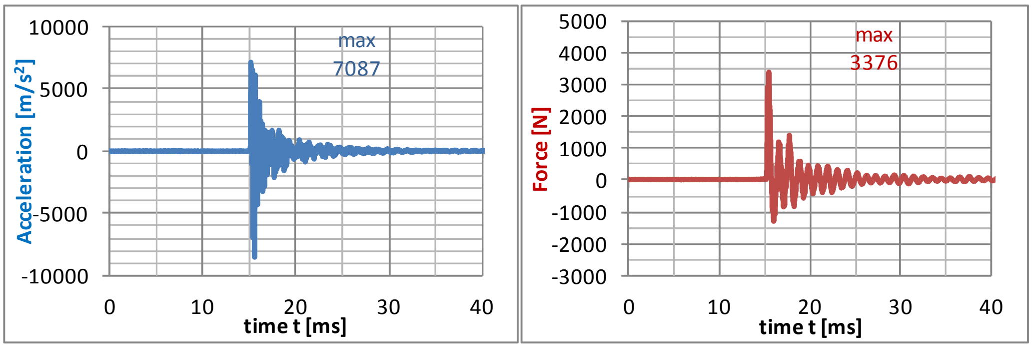

Figure 5: Acceleration and force variation in time of an impact using one layer of encapsulated dry F133

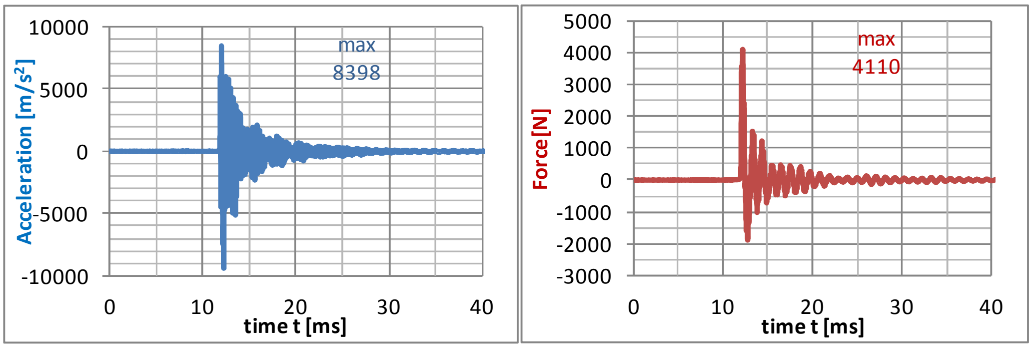

Figure 6: Acceleration and force variation in time of an impact using one layer of encapsulated dry F133 and a layer of Kevlar

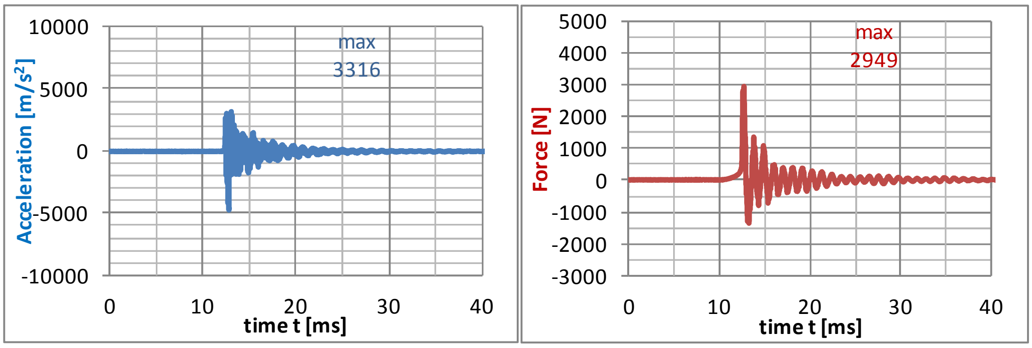

Figure 7: Acceleration and force variation in time of an impact using one layer of encapsulated F133 imbibed with glycerin and a layer of Kevlar

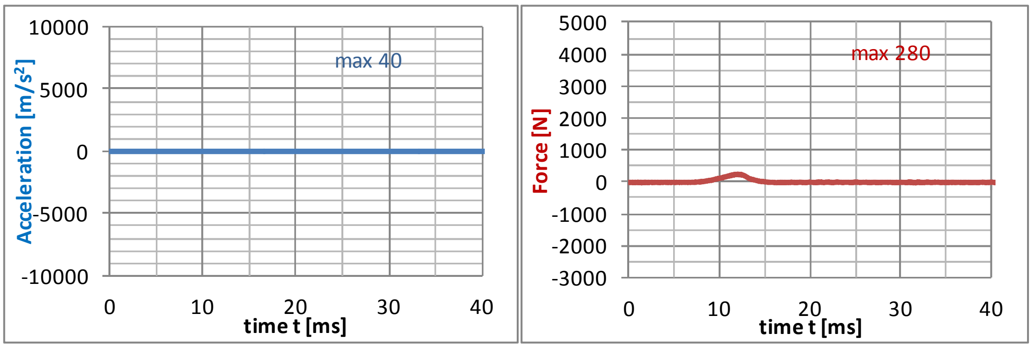

Figure 8: Acceleration and force variation in time of an impact using two layers of encapsulated F133 imbibed with glycerin and a layer of Kevlar

Three tests were done by dropping a ball from H=4.91mthat gives a velocity of 9.8m/s at impact:

- A - undamped;
- B - damped with one layer of F133 imbibed with glycerin;
- C - damped with one layer of F133 imbibed with glycerin and with four layers of Kevlar on top.

The 3D scans of the three clay samples are presented in Fig. 9.

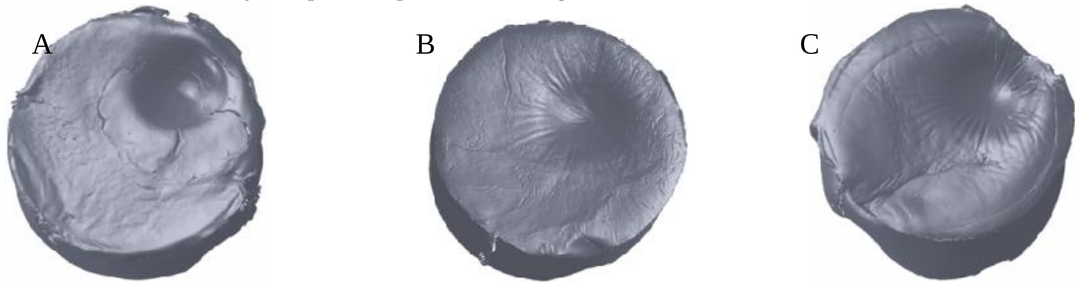

Figure 9: 3D scans of modelling clay after impact of a sphere: A, B and C

The footprint was evaluated with three methods: by measuring the mass of water or wax that can be placed inside the footprint and calculating the mass and by using a software calculation of the 3D scan.
The results, presented in Table 2, are very close.

Table 2: Porosity measurement results

Method	Volume of sample A [mm^3]	Volume of sample B [mm^3]	Volume of sample C[mm^3]
Water	2513	1759	3015
Wax	3011	2444	3322
Software	3150	2355	3358

The footprint of the sample B is smaller than the one of sample A, which is a clear proof of the damping capacity of the glycerin. Also the increased footprint of sample C with respect to sample B shows that the Kevlar layer acts like a cover of the impacting sphere.

3. CONCLUSION

This experimental study is relevant and constitutes an important basis for further studies on XPHD lubrication, as two types of impact tests validate the lift force generated and confirms the damping capacity of this mechanism. The low energy impact, with velocities under 2m/s, can be completely damped and show great effectiveness when compared with a contact without any material interposed between the impacted bodies. The tests done with and without fluid prove that the damping effect is produced by the viscous friction generated by the flow of the fluid and not the elasticity of the material, although this has its contribution. Also, the results in terms of peak acceleration and peak force are smaller in comparison with classical damping materials (like rubber).
Testing the impact behavior of HCPL material imbibed with different fluids proved to be a quick approach for comparison in terms of damping capacity, due to the simplicity of the experimental stand and time required for experiments. The best pair of HCPL + fluid tested was reticulated polyurethane foam imbibed with tooth paste, but a lot of other combinations (based on Newtonian fluids) have promising results.

ACKNOWLEDGEMENT

This work was partially supported by MEN-UEFISCDI Partnership Program PN-II Contract No 287/2014 (PROTHEIS). The 3D scans were realized by SPECTROMAS S.R.L.

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