A LETTERS JOURNAL EXPLORING
THE FRONTIERS OF PHYSICS

OFFPRINT

Energy absorption in a bamboo foam

A. LE GOFF, L. COURBIN, H. A. STONE and D. QUÉRÉ

EPL, **84** (2008) 36001

A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

November 2008

EPL, **84** (2008) 36001
doi: 10.1209/0295-5075/84/36001

www.epljournal.org

Energy absorption in a bamboo foam

A. LE GOFF[1], L. COURBIN[2], H. A. STONE[2] and D. QUÉRÉ[1(a)]

[1] *Physique et Mécanique des Milieux Hétérogènes, UMR 7636 du CNRS, ESPCI - 75005 Paris, France, EU*
[2] *School of Engineering and Applied Sciences, Harvard University - Cambridge, MA 02138, USA*

received 31 July 2008; accepted in final form 16 September 2008
published online 15 October 2008

PACS 68.03.-g – Gas-liquid and vacuum-liquid interfaces
PACS 47.55.D- – Drops and bubbles
PACS 47.57.Bc – Foams and emulsions

Abstract – We discuss the ability of soap films to absorb the energy of an impacting projectile. If the impact velocity is large enough, solid objects or water drops pass through the films without breaking them. However, during each impact a small part of the original kinetic energy is extracted, which is revealed by considering collections of parallel films (so-called bamboo foams). Then, the impacting object is observed to stop after crossing numerous films. The total energy absorbed by the foam is found to be the total energy of distortion of the films, integrated over the multiple crossings. The case of inclined films is also considered, and found to affect the trajectory of the projectile.

Introduction. – Systems which have the ability to absorb the kinetic energy of projectiles are of interest for protecting internal contents, as well as people, precious objects, etc. It can also be a matter of public safety, and it is believed that foams might be used to absorb the sound, the kinetic energy and the particles generated by the explosion of a bomb [1]. Foams are particularly attractive for such a purpose: they are light, simple, fast to form, and cheap. To the best of our knowledge, kinetic energy absorption by foams is undocumented in the research literature. We present here an experimental study of the energy absorption properties of a model system, the so-called bamboo foam, consisting of regularly spaced and parallel soap films [2]. We first discuss the impact of a solid particle on a single lamella and the associated energy transfer, which slows down the particle. Then we show how the particle can be brought to rest in a bamboo foam, by characterizing its penetration in this multi-layered device. We conclude by analyzing the effect of the film inclination on the trajectory of the projectile.

In order to introduce some of the basic ideas, we first recall that a solid or liquid body does not necessarily cross a soap film (and more generally an interface [3]) as it hits it. In a recent study, we showed that below some threshold velocity, the solid bounces on the elastic membrane as if it were a trampoline, which eventually leads to its capture by the film [4]. For millimeter-size objects, this threshold velocity is of the order of 10 cm/s, which corresponds to a release height of a few millimeters above the film. We shall describe here much more violent impacts, with velocities V in the range of 1 to 3 m/s. For larger velocities, the projectile might irreversibly damage the film [5].

The evolution of the position of a solid sphere during the impact and subsequent crossing of the film, as captured with a high-speed camera, is displayed in fig. 1. The solid deforms the film, which rapidly becomes highly stretched. When the distance between the sphere and the unperturbed part of the film becomes of the order of the sphere radius, the film pinches off, but does not break! We could expect that a hole might form and grow provided that the size of the projectile is of the order (or larger) than the film thickness (that is, about one micrometer) [6], but this hole never forms. Instead, a cavity appears and grows, and closes above the projectile, so that the continuity of the film is always preserved.

This deformation process is similar to the instability of a soapy catenoid stretched above its critical height, studied by Chen and Steen [7]. Then, it pinches off, and the mechanism and dynamics of this process was described by Eggers [8]. However, our experiment is slightly different: although there is an axis of revolution in the direction of the fall, the cavity has no equatorial symmetry as a catenoid: on one side the surface is attached to the solid sphere, while it meets the surface of a much larger film on the other one. This explains why the pinch-off occurs very close to the sphere rather than in the middle of the

(a) E-mail: david.quere@espci.fr

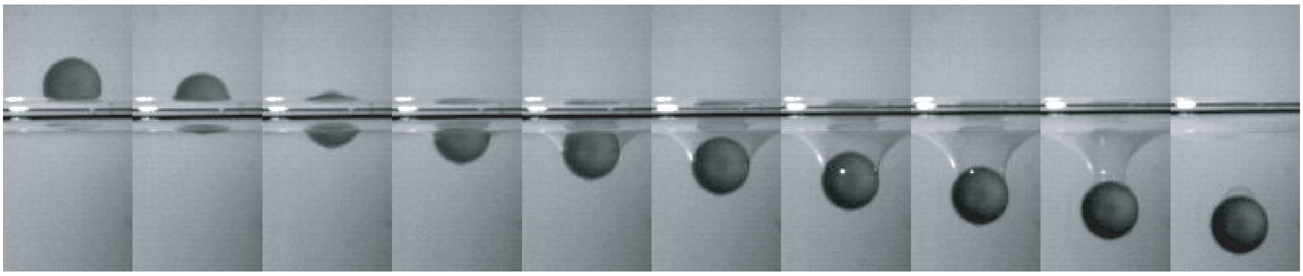

Fig. 1: Position of a plastic (delrin) sphere of radius $R = 1.6$ mm passing through a soap film. The velocity of impact and time between two consecutive images are, respectively, $V = 1.9$ m/s and 0.8 ms. The film heals after the passage of the sphere, which brings with it a small bubble at its top. A straight line can be traced through the centers of the spheres, which implies a very small slowing-down as the sphere crosses the film.

cavity. It is also responsible for the rearrangement of the film after the crossing: most of the liquid relaxes upwards, except a very small bubble, which remains attached to the solid, as described by Thoroddsen *et al.* [9]. This healing property is particularly relevant in the context of energy absorption, since it allows a foam to collect new particles once some have penetrated it. The situation is different if impact occurs with hydrophobic particles (*e.g.*, Teflon beads or metallic solids coated with a silicone oil), for which the film generally bursts during the passage of the particle, as reported in the antifoaming literature [10].

The time interval between two pictures (about 1 ms) is constant in fig. 1, which allows us to monitor directly the temporal variation of the position of the sphere, by tracing a line passing by its bottom. This altitude is observed to vary linearly with time, which means that the velocity remains (nearly) constant during this short interval of time. In particular, this impact with a single film does not produce a significant variation in the velocity of the projectile, which shows that the quantity of energy transmitted to the film during this event is very small compared to the kinetic energy of the impacting solid. However, we also notice that the film vibrates after impact and before returning to its initial flat and quiescent state, which illustrates that some energy was transferred by the particle to the film. In order to characterize this energy exchange, we "magnified" the system by considering the impact of rigid spheres onto multiple parallel films, as reported in the next section.

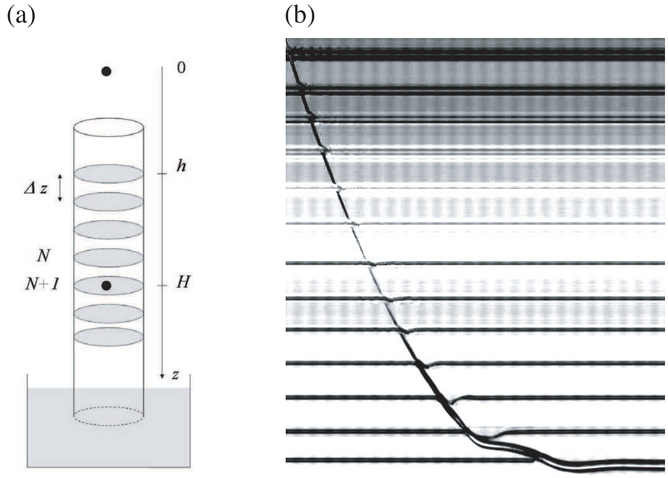

Fig. 2: (a) Experimental set-up for the impact in a bamboo foam. The sphere is released from a height h above the first film, and we denote H as the distance where it gets entrapped after having crossed N films. (b) Spatio-temporal diagram showing the trajectory of a projectile through the foam. The horizontal axis is time, and the z-axis is the vertical position of the drop. The release height is $h = 1.6$ mm, two films are separated by 0.6 mm, and the sphere radius is $R = 0.8$ mm. The slope of the trajectory is changing, which demonstrates that the vertical velocity is decreasing. The bead eventually stops after making the last film oscillate. At the right of each impact position, the interface is blurred due to the vibrations of the film.

Experimental set-up. – We achieve a bamboo foam, made of series of parallel films in a cylindrical tube. Our foaming solution is made of 120 mL of water, 10 mL of dishwashing liquid (from the French brand Paic) and 20 mL of glycerol (in order to slow down the aging of the soap films [11]). The surface tension of this solution was measured using the classical ring method, and found to be 24 mN/m. We dip a glass (or plexiglas) tube (diameter of 0.6 to 3 cm) in this solution, so that a single film forms at the end of the tube. The tube is then held vertically, the film being a the top, which makes it slide down along the wall. When it reaches a mark drawn on the tube, we stop the film by blocking the bottom end of the tube and repeat the operation until the column of foam is long enough (typically 50 films). The distance Δz between successive films is constant in a given bamboo foam, and we studied foams with different Δz between 5 mm and 1 cm. The tube is then placed in a bath of water (fig. 2a), allowing us to prevent a gravitational descent of the films. The presence of this reservoir also contributes to limit the evaporation of the foam.

We used various solid particles, including aluminum, stainless steel and plastic spheres (density range

1.2–7.8 g/cm^3, radius range 0.4–0.8 mm). These beads are smaller than the capillary length, which allows them to float on the films, if gently deposited upon it (the force of gravity is dominated by surface tension; otherwise, the beads would systematically cross the films owing to their weight). The beads are then dropped on the bamboo foam, and observations are made through the transparent walls of the tube. The spheres slow down as they cross the films until they eventually get entrapped [4]. We count the number N of films crossed by each projectile before it gets stopped (in a typical experiment, $10 < N < 30$). The experiment then consists of reporting the position of this $(N+1)$-th film as a function of sphere radius, density and impact speed.

We can also extract from the high-speed movies a diagram of the spatio-temporal evolution of the solid. We display in fig. 2b an example of such a diagram: horizontal lines indicate the film positions (and thus the scale, two films being separated by 0.6 cm), and the black oblique line the position of the sphere. The slope of this line gives the bead velocity, which is observed to decrease (slightly) after each film crossing. This decrease becomes obvious as the velocity approaches the entrapment threshold, and the bead eventually stops: on the last film, we see damped oscillations, which correspond to small rebounds and to the arrest of the sphere on this film. We also notice in the same diagram the healing capacity of the films after each crossing: there is an oscillation in the horizontal line (due to the film stretching and retraction), followed by a plain horizontal line which illustrates that the film survived its crossing by the projectile.

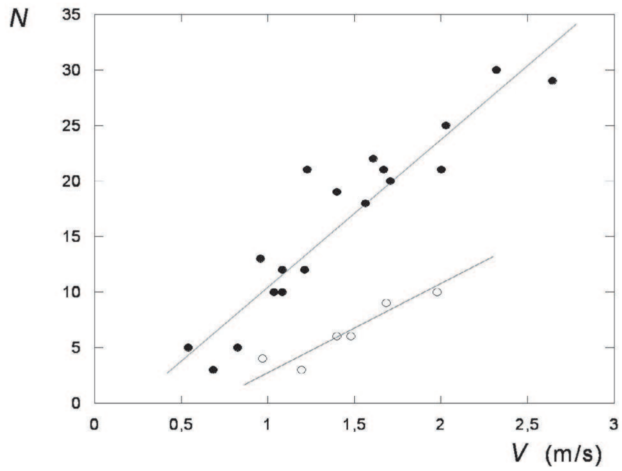

Fig. 3: Variations of N with the velocity of the impacting spheres ($R = 0.8$ mm): the number of films crossed by the sphere increases with the impact velocity. Heavier beads cross more films as well, as seen from a comparison between aluminum beads (•) and delrin or acrylic ones (○).

Results. – If the foam is sufficiently dense, we observe that a millimeter-size solid sphere is always stopped by a finite number of films denoted as N. For example, an aluminum bead hitting the first film at a velocity $V = 1$ m/s will be stopped after crossing about 30 films. We report in fig. 3 the value of N as a function of V, for different materials and a given sphere radius. It is logically found that the higher V, the larger N. It is also observed that N increases with the mass of the projectile: metallic beads penetrate further in the foam than plastic ones. We finally varied the viscosity of the foaming solution by a factor of 10 by using glycerol. We found that N is independent of the film viscosity, which is not really surprising, owing to the small thickness of the fluid layer crossed by the particle.

Therefore we neglect viscous effects and rationalize our results by comparing surface and mechanical energies. The total energy injected by the projectile (of mass m) in the foam is the mechanical energy $E_p = mgH$, corresponding to the *total* height of descent H until arrest. This energy is transferred to the foam, since crossing requires the deformation of N films.

For each crossing event, a cavity forms above the moving bead (fig. 1), which for surface energy purposes is modeled as a cylinder of radius R (the solid radius) and height L, the length below the film for which pinch-off occurs. Experiments (not shown here) indicate that for each type of sphere L depends very weakly on the impact velocity and remains close to $6R$. The surface energy ε_S needed to form one cavity is then $2\pi RL\gamma \approx 12\pi R^2\gamma$, where γ is the surface tension of the film. Balancing the total energy $E_S = N\varepsilon_S$ transferred in film distortion with the energy E_p injected by the projectile in the bamboo foam can be written:

$$12\pi N\gamma R^2 \approx mgH. \tag{1}$$

This equation relates two measurable quantities, namely N and H, where H itself is a function of $N (H = N\Delta z + h$, where h is the distance traveled by the bead before the first film, and Δz is the distance between two films). We thus get a prediction for the depth of penetration in the foam, characterized by the number N (generally much larger than 1):

$$N = (mgh - 12\pi\gamma R^2)/(12\pi\gamma R^2 - mg\Delta z). \tag{2}$$

This description is in good agreement with most of our data, as seen in fig. 4. The depth of penetration of the projectile inside the bamboo foam is described as a function of both the initial velocity and the nature of the bead (contained in the quantity E_S): most data are indeed found to approximately collapse onto a single curve. Equation (1) is drawn as a full line without any adjustable parameters in the same figure, and it is observed to describe the majority of the data points. We can also notice some scatter of the data. In particular, some projectiles stop earlier than expected ($E_S < E_p$). These projectiles are often seen to be localized along the tube walls and trapped by the Plateau borders, which are thick compared to the films and thus efficiently slow down the solids. This observation supposes that these

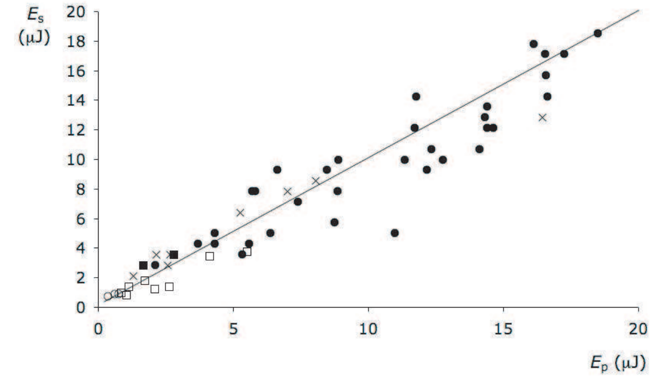

Fig. 4: Total surface energy $E_S = 12\pi N\gamma R^2$ "dissipated" by the distortion of the Ncrossed soap films, as a function of the total mechanical energy $E_p = mgH$ injected by the projectile in the foam. The symbols correspond to different sizes and materials: empty circles: aluminum with $R = 0.4$ mm; filled circles: aluminum with $R = 0.8$ mm; empty squares: delrin with $R = 0.8$ mm; full squares: acrylic with $R = 0.8$ mm; cross: stainless steel with $R = 0.35$ mm. Equation (1) is drawn as the solid line.

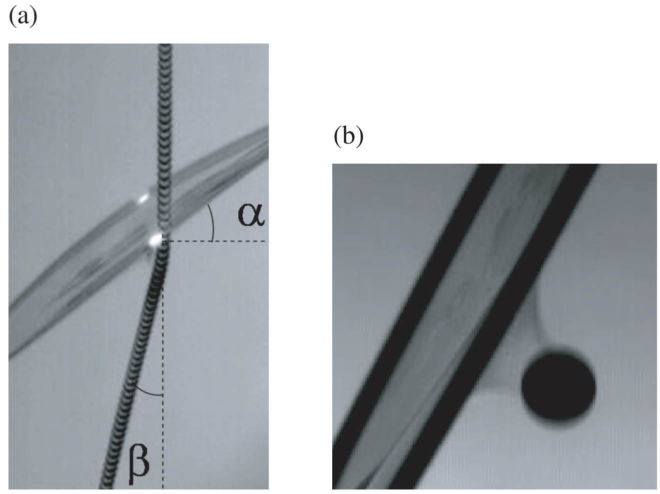

Fig. 5: (a) Trajectory of a stainless-steel sphere of radius $R = 0.7$ mm impacting a soap film, which is tilted by an angle $\alpha = 37°$ ($V = 0.36$ m/s). The bead is deflected by an angle $\beta = 21°$ towards the direction of the film. (b) Maximum deformation of the film during the crossing. Later, the cavity pinches off, as described above.

projectiles either are thrown with some initial angle, or that they deviate from the vertical. We shall see later that any deviation from a normal impact is amplified as the projectile crosses the film, which may explain why a large number of crossings has the ability to drive the projectile off the center of the films, towards the tube walls.

Equation (2) also gives a necessary condition for stopping the sphere: the energy $12\pi\gamma R^2$ transferred to a film must be larger than the kinetic energy $mg\Delta z$ gained between two consecutive films. This result gives a rationale to what we call a "sufficiently dense" foam. The minimum density required for stopping the particle provides an upper limit for Δz of the order of $9\gamma/\rho g R$ (where ρ is the bead density), of about 2 cm for a millimeter radius bead of density comparable to that of water.

There is also a minimum distance Δz for being able to achieve a bamboo foam. If the parallel films are too close to each other, then the basic bamboo structure becomes unstable and there is a transition to a so-called "staircase" state, in which films rearrange in a nearly 3-dimensional fashion, giving them different orientations [12]. A projectile impacting such a foam is observed to stop after crossing a number of films comparable to the one found with a bamboo foam, without modifying the arrangement of the staircase. However, the trajectory of the projectile is observed to deviate considerably from the vertical direction, following a zig-zag path. We now comment on the origin of these biased trajectories.

Oblique impacts. – We consider here the impact of projectiles on inclined soap films. Using a high-speed camera, we observed the trajectory of beads released on an oblique soap film, with impact velocities large enough to allow the solid to cross the film. Figure 5a shows such a trajectory: the film is tilted by an angle α of about 30°, and the bead leaves the vertical direction after crossing the film (which also heals in this case), being deflected by an angle β of the order of 25°. Varying sphere diameters and impact velocities, we found that β increases with the film inclination α, and decreases with both the particle size R and the impact velocity V.

These experimental facts can be understood by examining the deformation of the soap film during the crossing (fig. 5b). There again, a cavity forms, with its direction normal to the film surface. We can thus assume that surface tension acts like an elastic force in this direction, with a magnitude scaling as $\pi R\gamma$. Newton's law projected on the x-axis can be written dimensionally (for small α and β):

$$m(V/\tau)\beta \sim \pi R\gamma\alpha, \tag{3}$$

where τ is the characteristic time for crossing. Since the maximal extension of the cavity is $L \sim 6R$, we can set $\tau \sim 6R/V$. Hence we get, for small angles:

$$\beta We \sim 9\alpha, \tag{4}$$

where we introduced the Weber number $We = \rho RV^2/\gamma$, which compares inertial and capillary effects (with ρ the solid density). As observed, high velocities (*i.e.* large We) imply a (nearly) vertical trajectory: in such a limit, eq. (4) predicts a negligible β, whatever the value of α.

All the quantities in eq. (4) are measurable, allowing us to compare this simple model with experimental data. As observed in fig. 6, where we plotted βWe as a function of α, all the data collapse on the same curve, in fair agreement with the expected behavior. We superimposed to the data a straight line whose slope is 10, close to the value expected

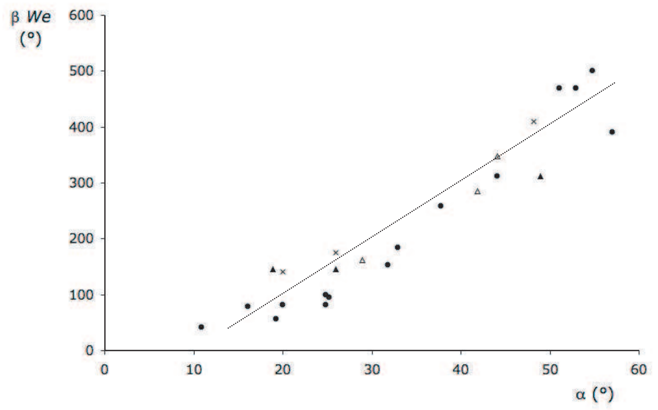

Fig. 6: Variations of the quantity βWe (where $We = \rho RV^2/\gamma$ is the Weber number associated with impact), as a function of α. Both angles are expressed in degrees, and the Weber number corresponding to these experiments is typically between 10 and 50. Symbols stand for: aluminum, $R = 0.8$ mm (circles); glass, $R = 0.45$ mm (empty triangles); copper, $R = 0.4$ mm (full triangles); stainless steel, $R = 0.35$ mm (crosses).

from eq. (4) (note however that the line drawn in fig. 6 does not exactly intercept the origin).

Conclusion. – In this experimental study, we have demonstrated how a model foam can retard and eventually stop a projectile thrown on it. Interestingly, the crossing does not induce the bursting of the films, which helps to maintain the structure of the foam and can serve as barriers to more impacts. The healing is made possible by the pinch-off of the films as they are stretched, which preserves their continuity as a function of time. Owing to the presence of multiple interfaces, there is an efficient transfer of kinetic energy into distortion energy of these interfaces, as the projectile crosses them, which then oscillate and ultimately see these oscillations damped by viscosity. We could thus predict the depth of penetration of the projectile in the foam, restricting to the case of a bamboo foam, which consists of many parallel soap films. The comparable case of a staircase foam was also investigated, and it was shown that the main effect concerns the trajectory of the bead, which is deflected by the oblique films, provided that kinetic energy and surface energy are of the same order. The next step naturally consists of investigating energy absorption with real foams, where preliminary experiments indicate strong absorption. Then, beads are larger than the cells of the foam, and we expect the laws for the dissipation to be very different, owing to the special rheological properties of foams [13]. However, the mechanisms explored here might be relevant in the context of explosions, which produce many fragments, both smaller and larger than the foam cells.

* * *

We thank C. Clanet for useful suggestions and discussions. LC and HAS thank the Harvard MRSEC (DMR-0213805) for support.

REFERENCES

[1] Clarck C. J. and Bennet E. M., U.S. Patent No. 4 (1986) 589, 341.
[2] Weaire D. and Hutzler S., *The Physics of Foams* (Oxford University Press) 2001.
[3] Pitois O., Moucheront P. and Weill C., *C. R. Acad. Sci. Paris, Série IIb*, **327** (1999) 605.
[4] Courbin L. and Stone H. A., *Phys. Fluids*, **18** (2006) 091105.
[5] Zheng R. and Witten T. A., *Phys. Rev. E*, **74** (2006) 051602.
[6] Taylor G. I. and Michael D. H., *J. Fluid Mech.*, **58** (1973) 625.
[7] Chen Y. J. and Steen P. H., *J. Fluid Mech.*, **341** (1997) 245.
[8] Eggers J., *Rev. Mod. Phys.*, **69** (1997) 865.
[9] Thoroddsen S. T., Takehara K., Etoh T. G. and Hatsuki Y., *J. Fluid Mech.*, **530** (2005) 295.
[10] Denkov N., *Langmuir*, **20** (2004) 9463.
[11] Kellay H., Wu X.-L. and Goldburg W. I., *Phys. Rev. Lett.*, **74** (1995) 3975.
[12] Reinelt D., Boltenhagen P. and Rivier N., *Eur. Phys. J. E*, **4** (2001) 299.
[13] Höhler R. and Cohen-Addad S., *J. Phys.: Condens. Matter*, **17** (2005) R1041.