Delamination blisters: statics and dynamics.

The deposition of thin films on a solid substrate is of paramount importance in a wide range of industrial processes: paint, microelectronics, packaging, or adhesives. Adding a thin coating layer is indeed a standard strategy to improve the mechanical, thermal, electrical, optical or chemical properties of materials. The efficiency of the protective layer may however be greatly reduced by a mechanical instability, the delamination of the layer: under the action of compressive mechanical constraints (due to thermal, chemical or electrical loading), the thin layer rebounds and buckles into blisters. A common phenomenon is the propagation of anisotropic undulating blisters (Fig. 1) under isotropic stress. Despite their importance for the stability of industrial layers, the mechanisms that select these surprising but ubiquitous “telephone cord” patterns are still poorly understood.

![Image of delamination blisters](image)

**Fig. 1:** Delamination of a thin carbon layer (200nm) deposited on a quartz substrate (G.Gille & B.Rau, 1984).

From a fundamental point of view, the propagation of blisters indeed raises challenging issues because it results from the interaction of two complex phenomena: the out-of-plane buckling of the blister (geometrical non-linearties) and the fracture-like process of rebounding. Driven by technological applications, experimental studies were largely devoted to thermally induced delamination of nanometric films. The characterization of the mechanical properties of the films, the control of the applied constraints, and of the geometry of boundary conditions are very difficult to achieve. Moreover, the micro-blisters may only be observed through AFM or SEM techniques, which may be difficult to use *in situ*, and thus only allows for *post mortem* observation. This forbids the characterization of propagation dynamics.

**Experimental techniques.**

To circumvent these difficulties, we propose new experimental strategies that take advantage of modern microfabrication technology. We will use thin elastomeric films (different thicknesses are obtained with standard spin-coating techniques) deposited on a thick substrate. The film is not chemically bound to the substrate, and adhesion is reversible. Adhesion energy can be tuned by vapour phase chemical treatment (e.g. grafting of fluorinated trichlorosilane molecules). More importantly, the use of stencil masks obtained by standard UV lithography will provide spatially modulated adhesion properties. Preliminary tests show that using an appropriate range of elastic modulus and adhesion properties, the blister can be scaled from submicronic to millimetric size, which then allows for fast and precise optical detection.
Two strategies are proposed to apply biaxial stresses to the thin film:

- The swelling (dilation up to a factor 3) of the elastomeric film by a good solvent of the polymer develops isotropic compressive stress. (e.g. polar solvents for silicon elastomer, Figure 2a).
- Direct mechanical compression of the substrate using a biaxial compression device that we are currently designing. This homemade device will also allow for anisotropic biaxial loading on centimetric samples.

As a whole we believe that these qualitatively different experimental approaches will provide the necessary experimental results for a significant advance in the modelling of delamination.

Fig. 2: a- Image sequence showing the dynamics of propagation over a channel (image credit: D.Bartolo). b- Steady-state delamination under biaxial compression of a macroscopic elastic sheet.

2.1 Statics of blister shapes.

The description of the blister requires solving an elasticity problem with variable boundary conditions. In line with one of our previous work restricted to small displacements, we propose to begin with a much simpler problem by imposing the shape of the blister’s boundaries (Fig. 3). We will study the buckling transition upon biaxial loading of a thin elastic sheet strongly bound to a substrate with holes of chosen geometry. The resulting buckled shapes will then be compared to the one obtained for a proper delamination experiment where the thin film lies on a substrate where the holes will be replaced by a selective coating chosen to impose a finite adhesion contrast.

Figure 3: Left: the boundaries of the blister are fixed. Right: the blister adapts its shape on a heterogenous surface.
First, we will focus on the formation of telephone cord blisters, using substrates patterned with stripes of different widths. This will allow to study whether adhesion induces qualitative differences in the final blister morphology. Then, we will tackle the more difficult problem of the crumpling induced by biaxial loading of extended films, see (Fig. 4-b). The shape of the folds will be compared to the one extensively studied for crumpled paper (Fig. 4-a). Eventually, an interesting perspective concerns a new system in solid state physics, at a completely different scale: graphene sheets made of a single layer of carbon atom. The typical topography of a graphene sheet adhering on solid substrate is shown on Fig. 4-c and reveals a similar pattern of ridges. Our results on the ridges distribution in crumpled delaminated sheets may be used to understand crumpled graphene patterns.

2.2 Blister dynamics.

This second study concerns the dynamics of delamination blisters through propagation of the rebounding front.

Before studying the forward propagation of the telephone cord fingers, we will first focus on a simpler two-dimensional problem, where elastic non-linearities are greatly simplified. When subject to uniaxial mechanical compression, preliminary experiments show that a blister nucleates and grows conserving a cylindrical shape. This simplified situation will allow the testing of theoretical ideas and the characterization of the adhesion properties of the considered materials.

We will then investigate the forward propagation of a single blister. Enforcing the formation of a single telephone cord on a striped substrate we will monitor the propagation dynamics of the debounding front. Preliminary experiments on swollen elastomeric thin films (Figure 2a) revealed that the tip of the blister does not follow a trajectory defined by its final pattern but rather adopt a complex sliding motion that we aim to understand.

The next step will naturally concern the study of the collective dynamics of multiples blisters. Guided by the fracture-fracture interaction in elastic solids, leading for instance to the well know desiccation patterns, we will investigate the patterns resulting from the ‘collision’ between multiple blisters, Figure 5. We will first tackle a simplified problem,
taking advantage of micropatterning techniques to control the blister’s trajectory: study isolated blisters collisions on T shaped patterns.

**Figure 5 Left:** Dessication patterns on drying latex suspension [Couder et al., 2002]. **Right:** A network of telephone cord blister on a delaminated Silicon Nitride film (acrylate susbstrate) [Abdallah et al., 2006].

To conclude the presentation of this research program, we would like to emphasize on the similarity of the experimental and theoretical tools for the two projects. Most of experimental data will be obtained from image processing (edge detection to study shapes, image correlation for measuring the strain fields, space-time diagrams for dynamical phenomena) and direct force measurements. These techniques have already been partly developed in the PMMH lab with great success. The theoretical description will be developed simultaneously. In order to obtain the fastest feedback between theory and experiments, a scaling physical approach will be first proposed and then followed by a more detailed description including numerical simulations. We have already experienced this type of methodology.