PhyCracks – Final publishable summary report

From microstructural to macroscopic properties in material failure

Bridging material microstructure and heterogeneities with their macroscopic failure properties is a major challenge in both pure and applied science: today, there is no consistent theory relating the microstructure of a solid with its resistance or lifetime, in spite of its important potential applications in the design of composites with improved failure properties.

But integrating the effect of material microstructure into predictive models of material failure is not a simple task: material failure result from the propagation of a crack, the behavior of which is extremely sensitive to the response of a small region in the vicinity of its tip. As result, microscale heterogeneities have dramatic effects on the failure properties of materials that classical approaches which models materials by effective homogeneous media do not capture. In addition, for some materials referred to as quasi-brittle solids, crack propagation occurs by the nucleation, growth and then coalescence of a large number of small cracks developing at the microstructure scale that interact together producing rather unexpected and largely unexplained failure behaviors. If bridging microscale properties of solids with their macroscale failure properties is a formidable scientific challenge, it is also a unique opportunity to control the resistance of solids by designing adapted microstructures. The objective of this project is to tackle these fundamental and difficult questions and benefit from the ideas emerging from these works to design systems with improved failure properties.

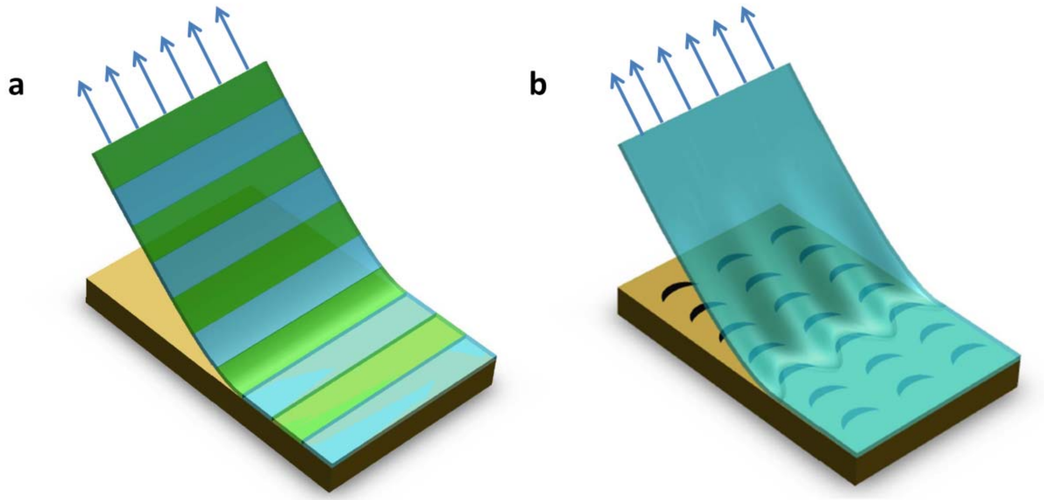

Fig. 1: Heterogeneous adhesive tapes with (a) elastic and (b) adhesive heterogeneities. While the first type of adhesives allows a dramatic enhancement of the stickiness of tape, the second one induces exceptional directionality so that the adhesive can be much more resistance when peeled from left to right as shown on the image than in the other direction.

These ideas have been explored first in the context of thin film adhesives. Can we improve the resistance of adhesive tapes by introducing a ‘microstructure’, i.e. using patterned thin films as shown in Fig. 1 with heterogeneous elastic or adhesion properties? The response is yes. At first, Laurent designed these new types of adhesives, and studied their peeling properties. He showed that elastic heterogeneities could lead to a dramatic toughening of the adhesives, resulting into resistance to peeling up to ten times larger than homogeneous tape. This study has demonstrated that the strength of tapes depends not only of the quality of the glue used in the adhesive layer, but also on the deformation processes that accompany peeling.

He went then further than heterogeneous adhesives with improved effective strength, and investigated the role of heterogeneities of adhesion energy at the interface between the substrate and the tape. Using specific pattern such as the one used on Fig. 1b, he was able to produce exceptional strength anisotropy: these tapes can be up to twice more resistance if peeled from left to right than in the other directions. This example illustrates here again how microscale properties can help engineer to manipulate and control failure properties at the macroscale. These ideas illustrated here on the peeling properties of adhesive tape and the theoretical tools developed in this context during the Marie Curie project opens formidable perspectives for the development of a new generation of thin film adhesives with exceptional properties, but also for the design of 3D brittle solids with improved resistance. It also shows many promises for other systems (*e.g.* magnetic thin films in microelectronic) where the motion of interfaces and their pinning by designed heterogeneities could play a central role.

The second aspect of the Marie Curie project was devoted to the role of damage and microcracking on the behavior of solids. Laurent studied first the role of these mechanisms on the way ceramics deform when submitted to external solicitations. Through a careful experimental investigation, he showed that they present a highly hysteretic and reversible behavior under compressive and cyclic loading. In other words, the material can deform and come back to its initial state, but dissipated a large part of the mechanical energy that has been provided. This property opens the door to the use of this type of materials as energy absorber or shock actuator for structures susceptible to undergo high impacts. Laurent developed then a micromechanical model that captures quantitatively this behavior, based on the description of the friction and crack sliding during the unloading and reloading of the ceramics.

Finally, Laurent investigated the role of these microcracks on the overall failure behaviors of solids, and focused on PMMA - commonly referred to as Plexiglas – to develop predictive theoretical tools. His approach can capture the macroscopic failure properties of PMMA resulting from the interplay between a large number of microcracks, from the detailed description of the failure mechanisms (microcrack nucleation and growth, coalescences…) at the microscale. This study opens the door to the improvement of macroscopic failure properties of quasi-brittle solids – and in particularly Plexiglas widely used as a impact protection material - by a careful design of their microstructure.

The last paragraph of this report is devoted to the benefits of the Marie Curie project to Laurent’s scientific career. Laurent arrived at the California Institute of Technology as a young and promising physicist. He is now a well established and recognized young researcher in the field of Solid Mechanics, while keeping a high level of expertise in Statistical Physics, his PhD thesis speciality. Very recently, he has been hired by the CNRS for a permanent researcher position, and he is currently developing his own research group. This future shows already many promises, since he was granted recently two fellowships for hiring a PhD and a post-doctoral scholar, and received the integration grant from the Marie Curie program through the project 'Toughbridge'. In the coming years, he will certainly capitalize on his experience at the California Institute of Technology, both pursuing the line of research developed during the Marie Curie “Phycracks” project and going on his successful collaboration with his colleagues from Caltech.