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Dynamics of cracks in disordered materials

Dynamique des fissures dans les matériaux désordonnés

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ABSTRACT

Predicting when rupture occurs or cracks progress is a major challenge in numerous fields of industrial, societal, and geophysical importance. It remains largely unsolved: stress enhancement at cracks and defects, indeed, makes the macroscale dynamics extremely sensitive to the microscale material disorder. This results in giant statistical fluctuations and non-trivial behaviors upon upscaling, difficult to assess via the continuum approaches of engineering.
These issues are examined here. We will see:

- how linear elastic fracture mechanics sidetracks the difficulty by reducing the problem to that of the propagation of a single crack in an effective material free of defects;
- how slow cracks sometimes display jerky dynamics, with sudden violent events incompatible with the previous approach, and how some paradigms of statistical physics can explain it;
- how abnormally fast cracks sometimes emerge due to the formation of microcracks at very small scales.

RÉSUMÉ

Prévoir quand les matériaux cassent constitue un enjeu majeur dans de nombreux domaines industriels, géologiques et sociétaux. Cela reste une question largement ouverte : la concentration des contraintes par les fissures et défauts rend en effet la dynamique de rupture à l'échelle macroscopique très sensible au désordre de microstructure à des échelles très fines. Cela se traduit par des fluctuations statistiques importantes et des comportements sous homogénéisation non triviaux, difficiles à décrire dans le cadre des approches continues de l'ingénierie mécanique.
Nous examinons ici ces questions. Nous verrons :

- comment la mécanique linéaire élastique de la rupture contourne la difficulté en ramenant le problème à la déstabilisation d'une fissure unique dans un matériau effectif « moyen » sans défauts ;
- comment la fissuration lente présente, dans certains cas, une dynamique saccadée, composée d'événements violents et intermittents, incompatible avec l'approche précé-

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dente, mais qui peut s'expliquer par certains paradigmes issus de la physique statistique ;
– comment des fissures anormalement rapides émergent parfois du fait de la formation de microfissures à très petites échelles.

1. Introduction

Under loading, brittle materials[1] like glasses, ceramics, or rocks break without warning, without prior plastic deformation: their fracture is difficult to anticipate. Moreover, stress enhancement at defects makes the behavior observed at the macroscopic scale extremely dependent on the presence of material heterogeneities down to very small scales. This results in large specimen-to-specimen variations in strength and complex intermittent dynamics for damage difficult to assess in practice.

Engineering sidetracks the difficulty by reducing the problem to the destabilization and subsequent growth of a dominant pre-existing crack. Strength statistics and its size dependence are captured by the Weibull's weakest-link theory [1] and Linear Elastic Fracture Mechanics (LEFM) relates the crack behavior to few material constants (elastic moduli, fracture energy and fracture toughness). This continuum theory provides powerful tools to describe crack propagation as long as the material microstructure is homogeneous enough and the crack speed is small enough. Conversely, it fails to capture some of the features observed when one or the other of these conditions stop being true. In particular:

- slowly fracturing solids sometimes display a so-called crackling dynamics: upon slowly varying external loading, fracture occurs by intermittent random events spanning a broad range of sizes (several orders of magnitude);
- in the fast-fracturing regime, the so-called dynamic fracture regime, the limiting speed is different from that predicted by LEFM theory (see [2,3] for reviews).

These issues are discussed here. Section 2 will provide a brief introduction to standard LEFM theory, the different stages of its construction, its predictions in term of crack dynamics, the underlying hypothesis and their limitations. Crackling dynamics in slow cracks will be examined in section 3. Experimental and field observations reported in this context evidence some generic scale-free statistical features incompatible with the continuum engineering approach (section 3.1). Conversely, it will be seen how the paradigm of the depinning elastic interface developed in non-linear physics can be adapted to the problem (section 3.2). This framework has, e.g., permitted to unravel the conditions required to observe crackling in fracture (section 3.3). Section 4 will focus on dynamic fracture and the various mechanisms at play in the selection of the crack speed. Will be seen in particular that, above a critical velocity, microcracks form ahead of the propagating crack (section 4.1), making the apparent fracture speed at the macroscale much larger than the true speed of the front propagation (section 4.2). It will also be seen that, at even larger velocity, the crack front undergoes a series of repetitive short-lived microscopic branching (microbranching) events, making LEFM theory not applicable anymore (section 4.3). Finally, the current challenges and possible perspectives will be outlined in section 5.

2. Continuum fracture mechanics in a nutshell

2.1. Atomistic point of view

Here is how strength would be inferred in a perfect solid. Take a plate pulled by an external uniform stress σ_{ext}. This plate is made of atoms connected by bonds (Fig. 1A). As depicted in Fig. 1A′, the bond energy, U_{bond}, evolves with the interatomic distance, ℓ, so that the curve presents a minimum, γ_b, at a given value, ℓ_0. This ℓ_0 gives the interatomic distance at rest. To estimate the way the plate deforms under σ_{ext}, recall that stress is a force *per* surface and, hence, relates to the pulling force F_{bond} via $\sigma_{\text{ext}} = F_{\text{bond}}/\ell_0^2$. Recall also that strain, ϵ, is a relative deformation and, as such, relates to ℓ via $\epsilon = (\ell - \ell_0)/\ell_0$. Recall finally that U_{bond} is a potential energy (analog to the potential energy of a spring) and, as such, relates to F_{bond} via $F_{\text{bond}} = -\text{d}U_{\text{bond}}/\text{d}\ell$. The so-obtained stress–strain curve is represented in Fig. 1A″. By definition, its maximum is the sought-after strength, σ_*.

[1] In contrast with brittle fracture, ductile fracture is preceded by significant plastic deformation. Ductile fracture is always preferred in structural engineering since it involves warning. Note that the brittle or ductile nature of the fracture is not an intrinsic material property. Among others, it depends on temperature: all materials break in a brittle manner when the temperature is smaller than their so-called ductile-to-brittle transition temperature. Many catastrophic failures observed throughout history have resulted from an unforeseen crossing of this transition temperature. The sinking of the *Titanic*, for instance, was primarily caused by the fact that the steel of the ship hull had been made brittle in contact with the icy water of the Atlantic. The loading rate is also an important parameter: rocks behave as brittle materials under usual conditions, but deform in a ductile manner when the loading rate becomes very small. This is, e.g., observed in the convection of the Earth's mantle at the origin of the plate tectonic.