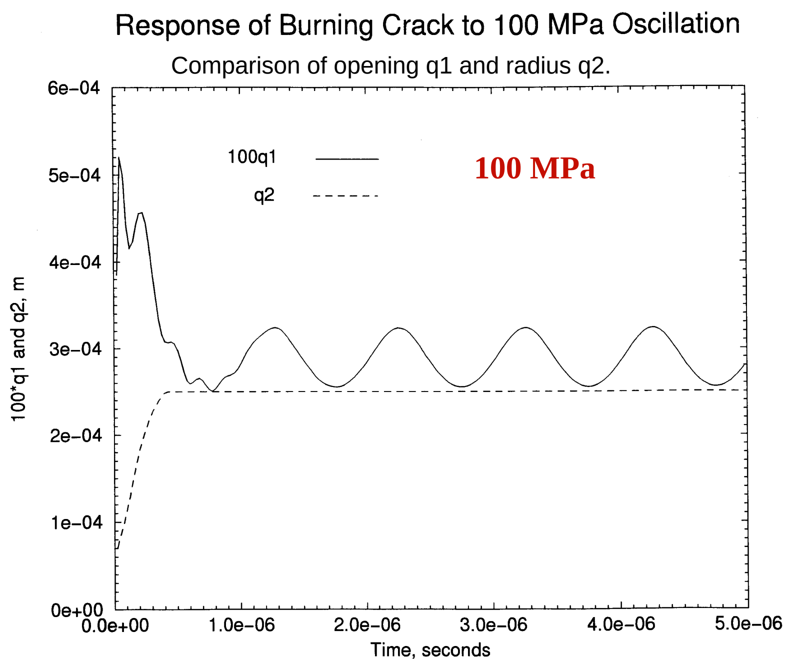
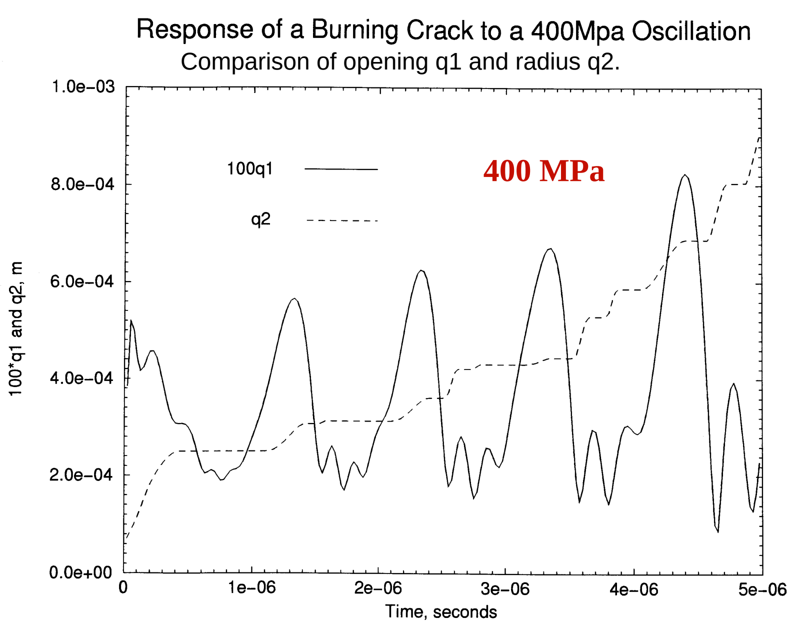
Statistical Crack Mechanics: Recent Progress and Prospects for the New Millennium

John K. Dienes

In the ductile state, large deformations of materials can be modeled with a relatively simple rule relating stress and strain rate. However, no corresponding rule is known for brittle behavior, and it seems unlikely that one exists since the defects responsible for brittle behavior are unstable*. In Statistical CRAck Mechanics (SCRAM) we simulate brittle behavior by combining the response of various sets of defects (cracks) whose individual behavior is understood. In addition, SCRAM shows that it is valid to combine different kinds of material behavior, including brittle, viscoelastic, porous, and ductile deformation, as well as the high-pressure equation of state. An ad hoc superposition principle of this kind has been used since the thirties to combine elastic and plastic flow, but the one used in SCRAM is more general in several respects: it has been derived from first principles, it is valid for arbitrarily large deformations, and it applies to many kinds of material behavior, not just the small elastic-plastic deformations originally envisioned by Prandtl and Reuss. The current SCRAM effort involves both formulation of the theoretical basis for our materials algorithm and application to practical problems of brittle behavior, including the dynamics of ceramic armor and the sensitivity of explosives. Both of these have resisted standard theoretical treatments. The ultimate goal is to take SCRAM from a feasibility study to a robust, self-consistent algorithm suitable for three-dimensional calculations of complex material flow and failure.





In the first versions of SCRAM, crack behavior was represented by a quasi-static theory, and crack growth was prescribed at a rate known from empirical rules. In more recent work, crack dynamics is represented by a pair of Lagrange equations with crack opening and size as the generalized coordinates and internal pressure and far-field stress as the generalized forces. These equations provide behavior in agreement with conventional fracture theory, including the transition from stable to unstable crack behavior, and they account for the variation in crack speed with stress in both the dynamic and creep regimes. These equations form a part of the new SCRAM algorithm.

One of the principal applications of SCRAM has been to provide an understanding of the sensitivity of explosives to low-speed impact. Though we have predicted that interfacial crack friction is the probable initiation mechanism since the 70s, only recently has this become accepted by experimentalists. Following ignition, explosives burn. Recently, we have accounted for the burn in crack interiors using a classical multiphase treatment akin to flame theory. Some confirmation of the SCRAM algorithm with burn has been obtained by comparisons of computed material velocities with very accurate measurements in a reactive multiple-shock experiment. These velocity histories indicate shock coalscence and burn, but not detonation.

Crack burning is a very complex process involving both crack dynamics and multiphase chemistry. Rather than attempt a full finite-difference simulation we have modelled the process with the Lagrange equations and a one-dimensional burn model that assumes heat flow perpendicular to the crack plane, as described above. This algorithm can be introduced into multi-dimensional hydrocodes to represent the behavior at the mesoscale without an unrealistic computational burden. The behavior of an isolated crack is highly nonlinear, as illustrated by a comparison of the response to driving pressures of 100 and 400 MPa in the figures. The former shows a stable response while the latter is highly unstable. Thus, slow burn in cracks does not cause a violent reaction because the rate of crack growth is normally so high that the pressure in the crack interior rapidly drops to a level at which the burn rate is negligible. Hence, our tentative conclusion is that crack interactions are responsible for violent explosions caused by certain low-speed impacts rather than isolated cracks acting as hot spots.

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There has been considerable emphasis in recent years on the ability to compute three-dimensional processes. In recognition of this, a three-dimensional version of SCRAM has been developed and tested as a stand-alone package. We are planning to incorporate it into the three-dimensional CFDLIB, PRONTO, and EPIC codes. Simplified versions have previously been incorporated into DYNA and CTH.

A major outstanding question is: how much theory is necessary to deal with the practical issues that face us? We are continuing to examine the underlying tensor theory of deformations, though the main demand seems to be for quick, practical results and, consequently, scalar theories are sought and favored by many users. Nevertheless, it seems likely that in the long run tensor theories will be predictive, while scalar theories will not.

*The simplicity of the flow rules for plasticity arises from the stability of dislocations which are responsible for ductile flow. Since brittle failure is due to unstable cracks, it is not possible to construct a theory akin to thermodynamics or standard statistical mechanics wherein the degrees of freedom are in some kind of equilibrium.

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jkd@lanl.gov