Explicit 3D Continuum Fracture Modeling with Smooth Particle Hydrodynamics

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Impact phenomena shaped our solar system. From the accretion of the planetesimals 4.6 billion years ago to the comparatively recent spallations of meteorites from their parent bodies, which take them to Earth, this ceaseless process has left no bit of solid matter untouched.

As usual for most solar system processes, the scales are far different than we can address directly in the laboratory. Impact velocities are often much higher than we can achieve, sizes are often vastly larger, and most impacts take place in an environment where the only gravitational force is the mutual pull of the impactors. Laboratory studies are limited to disruptive impacts with typical velocities ≈ 3 km/s, and typical target diameters ≈ 6 cm, in an imposed terrestrial gravitational environment. We must extrapolate from these data by upwards of five orders of magnitude before we reach the size range of asteroids, comets and planetesimals.

It is unlikely that analytical scaling relations for disruption can be extrapolated meaningfully by so many orders of magnitude, since fracture processes are nonlinear and complex. To experiment far beyond laboratory scales, numerical models are the only real alternative. Of course, numerical models are not without problems and limitations either. The first obvious difficulty is to accurately integrate the hydrodynamics and the fracture physics in three spatial dimensions, which by itself is not a totally trivial task! In addition, the predictive power of these models relies upon the limited data available concerning rate-dependent strengths for relevant materials, and upon good equations of state. In any case, it is essential that this tool be properly tested. For this, reproducing laboratory experiments is certainly a necessary condition.

The Smooth Particle Hydrodynamics (SPH)[1] technique has been applied in the past to the simulations of giant impacts[2]. In these simulations, the colliding objects were so massive (at least a sizeable fraction of the Earth's mass) that material strength was negligible compared to gravity. This assumption can no longer be made when the bodies are much smaller. To this end, we have developed a 3D SPH code that includes a strength model [3,4] to which we have added a von Mises yielding relation for stresses beyond the Hugoniot Elastic Limit. At the lower stresses associated with brittle failure, we use a rate-dependent strength based on the nucleation of incipient flaws whose number density is given by a Weibull distribution. Following Grady and Kipp[5] and Melosh *et al.*[6], we introduce a state variable D ("damage"), $0 \leq D \leq 1$, which expresses the local reduction in strength due to crack growth under tensile loading.

Unfortunately for the hydrodynamics, Grady and Kipp's model predicts which fragments are the most probable ones and not the ones that are really formed. This means, for example, that if a given laboratory experiment is modeled, the fragment distribution obtained from the Grady-Kipp theory would be equivalent to a ensemble average over many realizations of the experiment. On the other hand, the hydrodynamics itself is explicit and evolves not an ensemble average but very specific fragments. Hence, there is a clear incompatibility with the deterministic nature of the hydrodynamics equations and the statistical approach of the Grady-Kipp dynamical fracture model. We remedy these shortcomings by making the incipient flaw distribution explicit, i.e. particles carry activation strains which are distributed at random with a probability of occurence given by the Weibull distribution. If the local principal axis strain exceeds this limit, damage starts to grow. By growing explicit cracks together with statistical cracks (damage) at the sub-particle scale, we ensure that material strength and fragmentation is independent of model resolution.

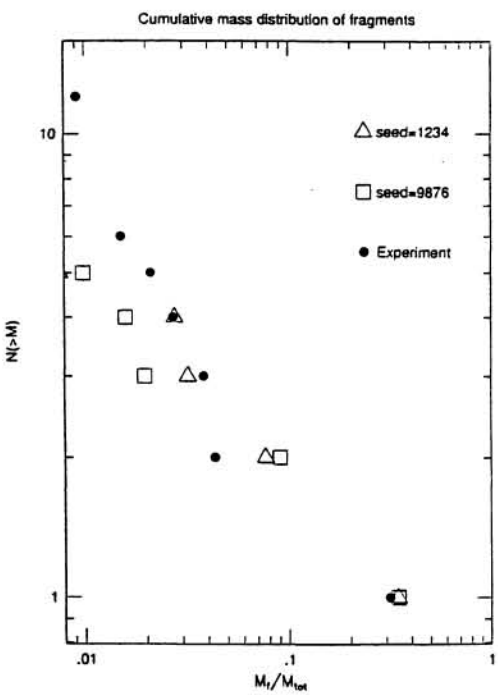
We tested our scheme by simulating laboratory impact experiments on basalt spheres[7]. In these experiments, a 0.2g nylon bullet impacts a 3cm radius basalt sphere off-axis at about 3 km/s and results in core-type fragmentation and extensive spallation. (Our simulation is shown in Fig. 1 at t=4ms.) Since these experiments have been recorded on two high-speed cameras, information about the dynamics of the debris can be obtained from the analysis of the recording. For example, Nakamura *et al.* were able to reconstruct quantities like spatial velocity and angular momentum of the flying

SPH Fracture Model: W. Benz and E. Asphaug

debris which we use in addition to the fragment mass spectrum to check the numerical results. These comparisons show that the numerical results are a close match to the experiments. In particular, our largest fragment is found to be a core with a mass of 34% of the initial target mass, a result within 6% of the experimental value. In addition, the core's spatial velocity as well as the other fragment velocities are found to be well within the observational error bars. Fig. 2 shows the experimental fragment mass distribution of the largest fragments together with the experimental result, using two different random seeds for the Weibull flaws. These are the explicit fragments shown in Fig. 1.

Our model reproduces laboratory experiments in some detail; we shall therefore present its application to the simulation of colliding asteroids.

References: (1) Benz, *Comput. Phys. Comm.* **48** 1990; (2) Benz, Slattery and Cameron, *Icarus* **66** 1986; (3) Libersky and Petshek (preprint) 1992; (4) Wingate and Fisher (preprint) 1991; (5) Grady and Kipp, *Int. J. Rock Mech. Min. Sci. and Geomech. Abstr.* **17** 1980; (6) Melosh, Ryan and Asphaug, *JGR* **97** 1992; (7) Nakamura and Fujiwara, *Icarus* **92** 1991.



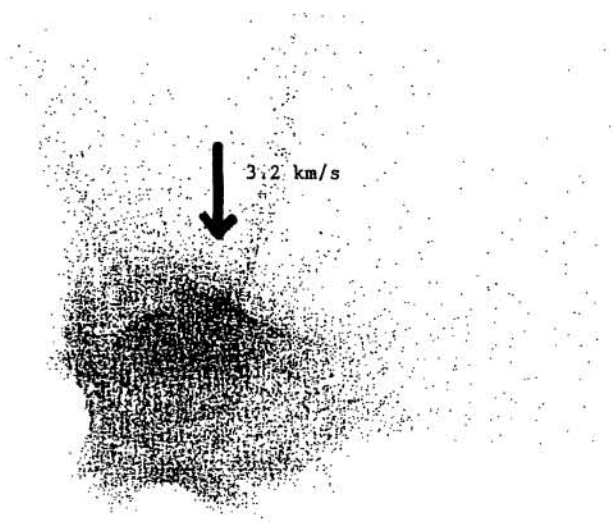


Fig. 1: A core-type fragmentation event modeled with our 3D SPH fragmentation code. Note the sizable core and the large surface spalls. The time is 4000 μs after impact, extrapolated from a hydrocode completion time of 60 μs. The original basalt target was 6cm in diameter, impacted at 3.2 km/s.

Fig. 2: Cumulative mass distributions for the several largest fragments. Two simulations with different random seeds (at t=60μs) are compared with experiment. The largest fragments ($M_f/M_{tot} \sim 0.3$) are cores. In both simulations, the largest spall failed to break into two pieces; otherwise the distributions are in good agreement.