The Dynamic Fracture of Rocky Bodies: Applications to Planetary Impact Problems

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Improvement to our understanding of the mechanics of earthquakes and planetary cratering by asteroids depends upon ongoing research on the failure of brittle geological materials. For example, the ability to predict the fragment size of such materials after the formation of an impact crater will provide new constraints on the collisional evolution of the asteroid belt. To first order, higher strain rates yield smaller fragment sizes. As Fig. 1 shows, the relationship is really more complex.

As a first step toward better understanding the failure of geological materials at fairly moderate strain rates—more akin to what a planetary body typically encounters during a planetary-scale impact—we embarked on an experimental investigation to probe the response of a model geological material (single-crystal quartz) under uniaxial compression.

Dynamic compression experiments were conducted using a Kolsky bar, which allowed a detailed history of the stress–time response on the microsecond time scale to be obtained. Ultra-high-speed photography recorded the evolution of damage and the propagation of cracks. Experiments also were done at quasi-static loading rates to further determine the effect of loading rate. Again, images detailing the evolution of the failure process were recorded. An increase in compressive strength was observed with increased loading rate. In specimens that were not loaded to (catastrophic) failure, significant crack growth was observed during the mechanical unloading of the specimen. The mechanism (or mechanisms) responsible for generating and propagating these "unloading cracks" is currently under investigation.

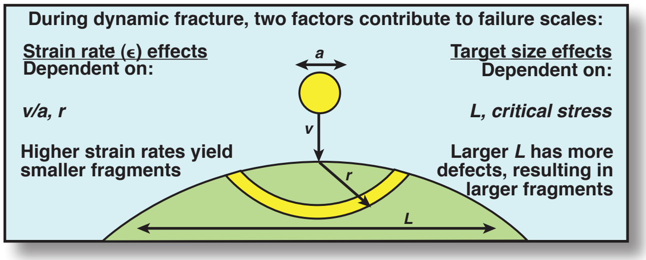

Figure 1. Factors that contribute to the failure of materials on the basis of classical dynamic fracture mechanics. Most of the region cratered by a bolide actually undergoes moderate rather than high strain rates, which result in different mechanical and failure behaviors of the impacted body.

A parallel modeling effort is in progress (Fig. 2). Impacts initiate dynamic fracturing on macro- and micro-scales, and the resulting fragmentation can be related to strain rate. Dynamic fracture has been directly observed at low strain rates ($\sim 10^{-2}$ to 10^{-3} s^{-1}, during earthquakes) and at high strain rates ($\sim 10^{5}$ to 10^{6} s^{-1}, during laboratory-scale hypervelocity impact experiments). On the basis of first-order estimates of the strain rate in the event (approximate impact velocity/projectile diameter) and numerical results such as those shown, the strain rates encountered in a typical planetary-scale impact range from $\sim 10^{0}$ to 10^{2} s^{-1}. These intermediate values lie within a strain rate regime that can be observed with the Kolsky bar, but are not easy to observe during typical small-scale hypervelocity (<2 km/s) impact experiments. Combining our numerical simulations with new dynamic fragmentation models derived from Kolsky bar experiments, we have begun to

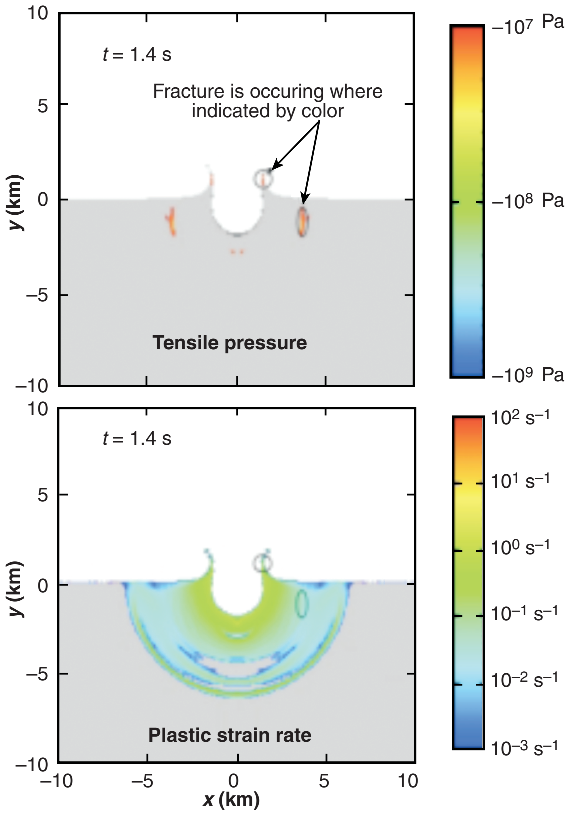

Figure 2. Numerical calculations for a 1-km bolide striking the Earth at 20 km/s showing the regions of fracture and strain rates experienced within a planetary-scale crater.

investigate how strain rates generated during large-scale impacts might influence fragmentation during planetary-scale cratering. We will calibrate our models to the geological materials used in our Kolsky bar experiments, and these models will then be tested with new high-resolution visible and thermal imaging obtained from ongoing missions at the Moon.

Some preliminary results are shown in Fig. 3. We compare the classical Grady–Kipp fragmentation model to a more recent Zhou–Molinari–Ramesh (ZMR) model. The Grady–Kipp model assumes that the kinetic energy of the impact goes entirely into fracturing, with higher kinetic energy and strain rates resulting in smaller fragments. It provides reasonable estimates of fragment sizes generated by very high strain rates typical of laboratory-scale hypervelocity impact experiments (Fig. 3, green region).

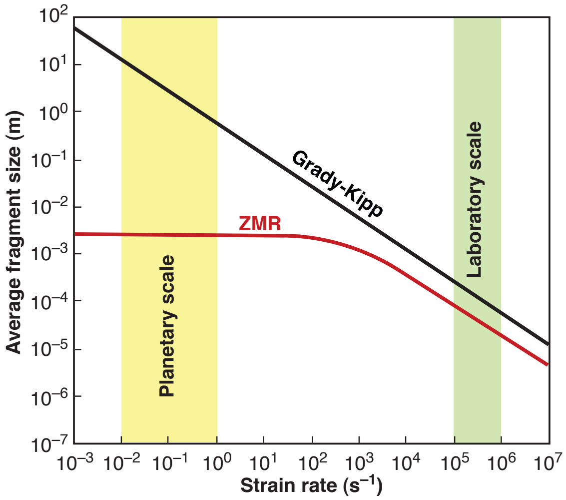

Figure 3. Predictions of the average fragment size as a function of strain rate for two impact cratering models.

The ZMR model partitions the kinetic energy of the impactor into fragmentation, strain energy and propagating waves that travel through the fragments. This more complex and realistic model yields a larger number of fragments for both low- and high-strain rate relative to the Grady–Kipp model. Its results compare favorably with Kolsky bar data using ceramics and hypervelocity impact experiments. Once geological materials are considered, this ZMR model might provide a viable explanation for the large amount of fines observed at lunar and other planetary craters.

These initial results support improved fragment size predictions: planetary-scale impacts occur at significantly lower rates than laboratory impacts. The ZMR model predicts fragment sizes that are several orders of magnitude smaller than those predicted by Grady–Kipp, and these smaller fragment predictions agree with the vast number of fine particles observed at lunar craters. Smaller fragment size also affects the number and size of possible secondary craters. The results also provide the framework for additional activities currently supported by NASA. Portions of this research were presented at the 2008 and 2009 Lunar and Planetary Science Conferences. Future plans include measurement of the impact strength of relevant geological materials and meteorites, development of scaling arguments to apply laboratory experiments to full-scale impacts, and direct incorporation of our fragmentation models into existing shock physics codes.

For further information on the work reported here, see the references below or contact olivier.barnouin@jhuapl.edu.

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