THE DYNAMIC STRENGTH OF BASALT UNDER GENERAL STRESS STATES: EXPERIMENTS FOR IMPACT MODEL DEVELOPMENT AND VALIDATION.

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Introduction: Properly benchmarked and validated computational models provide powerful tools for furthering our understanding of impact processes at large scales. In order to understand the physics occuring following an impact, accurate and realistic material models must be incorporated into numerical codes. In recent years, significant advances in material modeling have been made for these problems, including e.g. phase transformations [1], fracture [2], and porosity effects [3-4]. However, many current models do not incorporate dynamic effects on material strength and failure. Significant improvements in undertanding impact processes can come from physically-based (rather than phenomenological) models for the dynamic response of materials under general stress states.

Rock mechanics experiments show that the yield stress is a function of confining pressure, temperature, strain rate, strain, porosity, and sample size [e.g., 5]. The onset of material failure is typically defined to occur when a scalar measure of stress in the material, such as principal stress or equivalent (Mises) stress, reaches a critical value (e.g., the material strength). It is important to note that there are a multitude of “strengths” for a given material that may arise from different loading conditions (stress states). For example, most rocks exhibit significantly higher strength under compression than tension. Thus, even if a scalar measure of strength could be used, determining the appropriate measure to use is not trivial.

Traditionally, descriptions of material strength have followed from ideas derived from isotropic plasticity modeling: a single scalar value of strength exists beyond which the material will fail. For example, dislocation movement under shear stress drives failure in ductile materials. Following impact, however, material failure will occur in an evolving, multi-axial stress state, and a scalar measure may not be able to accurately capture the complex behavior in a brittle solid, illustrating the need for a direction dependent (tensor) description of damage. This description relies on accurate measures of dynamic strength under general states to develop predictive damage models for implementation into hydrocodes.

Analyzing damage and deformation following an impact provides a useful means to validate numerical models of impact cratering. However, this approach is strongly dependent on the constitutive model chosen because the damage evolution depends on the deformation mechanisms and failure strength of the material. Especially at early times, the stress state is dominated by compressive and shear stresses. Impact experiments into basalt targets at the NASA Ames Vertical Gun Range (AVGR) [e.g., 6] illustrate that significant damage accumulates early in the impact process and thus a realistic damage model should capture material behavior under multiple stress states.

Experimental Methods: During an impact event, material elements will experience various stress states. We perform dynamic failure experiments that determine the dynamic material response of basalt under more general stress states. Brazilian disk tests [e.g., 7] provide a means to determine the dynamic tensile strength using a compressive Kolsky bar. During the excavation stage, shear stress becomes increasingly important, and thus dynamic torsion experiments using a torsion Kolsky bar [8] illustrate material response under pure shear.

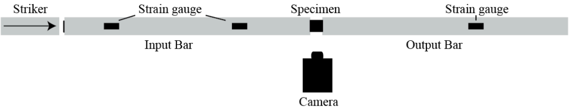

Fig. 1 Schematic configuration for the Kolsky bar used in dynamic compression and tension experiments.

Brittle materials experiencing confining pressure have markedly different behavior and failure strength than unconfined materials [e.g., 9,10]. Dynamic experiments varying the magnitude of confining stress for both bi-axial and radial confinement better constrain these differences. Using results from these experiments, a failure envelope for basalt at high-rates can be determined. This data can also be used to fit existing material models used in impact simulations.

The compressive strength of basalt was measured over a range of strain rates for both uniaxial and biaxial stress states. Quasistatic compression experiments were conducted using a MTS servohydraulic uniaxial testing machine, and the dynamic experiments were performed using a Kolsky bar (also called a Split Hopkinson Pressure Bar) (Fig. 1). The specimens were loaded until failure, while the damage evolution was tracked using high-speed photography. Impact experiments at the AVGR [with a setup as described in 11] provide information about damage evolution and a means to test the accuracy of new material models.

Results and Discussion: The strength of brittle materials is highly rate-dependent [12-17]. Fig. 2 shows a comparison of the measured compressive (top) and tensile (bottom) strength of basalt over a range of strain rates, and it is clear that the strength increases markedly with increasing rate. This dependence is seen for both terrestrial and meteorite materials [e.g., 12-14,16,18]. The rate dependence of the strength of geophysical materials can be captured using a scaling law with a 2/3 power [19].

Impact cratering is a dominant physical process throughout the solar system, and numerical models provide one of the best means to study large-scale cratering processes. Laboratory experiments provide information about impact processes at small scales, however extrapolating to larger scales is often difficult and requires the use of scaling laws [e.g., 19-21, etc] or sophisticated numerical models. These models must be validated with observational evidence in order to provide confidence that they accurately represent what occurs following an impact. Further, predictive models for damage evolution following planetary impacts also require accurate, sophisticated constitutive models. The accuracy of these models relies heavily on validation with detailed laboratory experiments. One of the best means to validate these models is to quantitatively compare damage and deformation in the target material [e.g., 22], and these suites of dynamic experiments provide data that can be used for comparison.

During the impact process the stress state changes. For example, near the impact point compression, shear stress states, and high-rates dominate. As the process continues, though, pressures decay, rates drop, and shear stress becomes increasingly important. Reflections from interfaces or free surfaces can induce tensile stress in the material. Therefore, the data provided by a suite of dynamic failure experiments under specific stress states provides a means for significant advances in understanding of the impact process via the deformation behavior of materials.

High-speed imaging from impact experiments at the NASA AVGR, combining with imaging and strength measurements from dynamic failure experiments provide one example of benchmarks for numerical calculations. Initial work by Tonge et al. [23] indicates that constitutive models incorporating micromechanical deformation mechanisms [24] and dynamic strength data, as shown here, can reasonably replicate damage zones seen in impact experiments at the AVGR [e.g., 23].

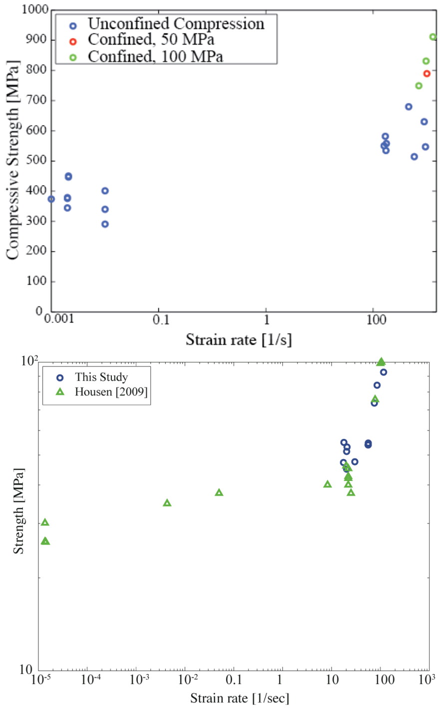

Fig. 2 Rate dependence of compressive (top) and tensile (bottom) strength for basalt, including data from [7]. The gap in data between strain rates 10^{-2} and 10^2 is due to limitations of the testing equipment. Although both tensile and compressive strength is rate-sensitive, failure strength and critical strain rate are different between stress states.

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