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Exploring the role of shear in oblique impacts: A comparison of experimental and numerical results for planar targets

A.M. Stickle*, P.H. Schultz

Department of Geological Sciences, Brown University, Providence, RI 02912, USA

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ABSTRACT

Oblique impacts produce asymmetric damage patterns due to asymmetric, directed shock waves; these patterns are seen for both laboratory and planetary scale craters [1,2]. Previous laboratory and computational studies of impact-induced damaged have focused mainly on tensile failure following hypervelocity impacts. Though extension plays a significant role in impact-induced damage, it is widely accepted that shear failure also occurs during hypervelocity impacts. Shear failure occurs over a variety of scales both during and after impacts [3–5]. Here we examine this process in more detail for oblique impacts. Experiments not only provide a general view of small-scale processes (including damage patterns in their final form), but also can be difficult to relate to larger impacts with confidence, even though similarities can be documented [e.g. 1]. Detailed computer models provide complementary information. Although they detail underlying processes during crater formation, they do not always contain adequate constitutive models, thereby requiring simplifying assumptions. A comprehensive model taking into account deformation following failure of rocks is still unavailable, which limits conclusions based solely on numerical simulations. Consequently, a combination of models and experiments must be used. Impact experiments into planar polymethylmethacrylate (PMMA) targets at small scale are examined in an attempt to constrain the sequence, location and style of failure. Two- and three-dimensional CTH models (with identical conditions to the experiments) were computed using a variety of failure criteria in order to determine the parameter set that best matches the experimental results. High-speed imaging recorded the sequence and location of failure within various PMMA targets, which was then compared with results from theoretical models. The CTH models provide critical details about specific failure style and indicate only minimal failure due to extension following the impact except for tensile failure at the base of the block. Instead, shear failure dominates below the crater. While the CTH hydrocode models generally match the extent of the damaged region, some differences remain. Projectile properties (density, composition, size) for impacts with the same kinetic energy affect the extent, style, and growth of damage in a given target. This includes differences in degree of uprange damage, subarcuate fractures, and sub-parallel failure planes. Comparisons between experiment and hydrocode results reveal that projectile failure (even at hypervelocity) contributes to the observed differences.

1. Introduction

Oblique impacts produce asymmetric damage patterns due to directed shock waves; these patterns are seen for both laboratory and planetary scale craters (e.g., [1,2,6–12]). Previous computational studies of impact-induced damaged focused primarily on tensile failure following hypervelocity impacts. Specifically, Smooth Particle Hydrodynamics (SPH) hydrocode models (as well as CTH models) focused on primarily extensional processes and failure (i.e.,[13–15]). Senft and Stewart [16] examined the possible locations of shear failure using the CTH hydrocode, whereas other studies by Ivanov et al. [17] used the SALE-2D code to examine tensile failure around impact craters, as well as of the projectile.

Although extension plays a significant role in impact-induced damage, shear failure also must contribute [4,5,18]. Results of SALE-2D hydrocode calculations indicate large regions fail in shear during an impact, whereas only small regions near the surface of the target fail in tension [17]. Separate studies by Senft and Stewart [16] using the CTH hydrocode indicate regions dominated by shear failure beneath vertical impacts. Experimental results also support the presence of shear-dominated failure regions [2,3,19–21]. Though previous studies have discussed this failure in broad terms,

* Corresponding author. Tel.: +1 401 8633594; fax: +1 401 8633978.
E-mail address: angela_stickle@brown.edu (A.M. Stickle).

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here we examine this process in more detail for oblique impacts in order to constrain their location and sequence, as well as extent of damage directly following hypervelocity impacts.

Experiments allow documenting processes at small scales and reveal damage patterns in their final form, which then can be compared with features at large scales, while detailed computer models provide extrapolation to large scales. Because such models do not always contain sufficiently sophisticated constitutive models, however, simplifying assumptions must be made. For example, a comprehensive model that takes into account deformation following failure of rocks is still unavailable, thereby limiting some conclusions drawn just from numerical simulations. Consequently, comparing results from both models and experiments more fully reveal details of the process.

2. Experimental Approach

The modes of failure due to a hypervelocity impact (and how this failure is manifested at large scales) can present a challenge for hydrocodes. The most recent version of the CTH hydrocode [22] includes adaptive mesh refinement in order to minimize computational time while resolving small-scale structures. This improvement provides a strategy to test conclusions about failure modes and dominant processes drawn from small-scale laboratory experiments. Here impact experiments into planar polymethylmethacrylate (PMMA) targets at small scale are compared with CTH models in an attempt to constrain the sequence, location and style of failure.

The transparency of PMMA allows a clear view of the evolving failure patterns within the target (e.g., [1]). Fortunately, room temperature PMMA also has mechanical properties similar to those of brittle rocks in the upper crust [23]; this makes it an ideal material for comparison to geologic materials. In addition to its mechanical properties, PMMA exhibits birefringence, which permits analog studies of dynamic failure processes in rock [23–28]. These experiments were performed at room temperature, taking advantage of the brittle nature of PMMA. To determine how these results apply to more ductile materials, future studies may be done on heated PMMA or on other transparent plastics that are ductile at room temperature (i.e., Polycarbonate).

CTH calculations reveal that shear failure dominates failure in PMMA at laboratory scales [18,29]. Shock-induced tensile failure in PMMA at laboratory scales can be shown to resemble failure in basalt, although shear failure is significantly reduced. Nevertheless, hydrocode models reveal that shear becomes more important at larger scales [29]. Consequently, PMMA provides an ideal analog material to look at the effect of shear damage during hypervelocity impacts, as well as the interaction between shear and tensile stresses. Planar targets allow calibration of the relative role of various processes, thereby providing a benchmark between the theoretical models and experimental data. Such comparisons also provide a basis for the comparisons between experiments and CTH models of more complicated processes, e.g., within spherical bodies [18,29].

Experiments were performed at the NASA Ames Vertical Gun Range (AVGR) at the NASA Ames Research Center in order to address the style and sequence of failure occurring underneath oblique impacts. The AVGR is a two-stage hydrogen light gas gun, which can launch projectiles at velocities up to 7 km/s (mass$<$ 0.1 g) over a range of impact angles from 15° above horizontal to vertical, (in 15-degree intervals) while leaving particulate targets horizontal. For this study, experiments used $15 \times 15 \times 6$ cm and $15 \times 15 \times 5$ cm blocks of PMMA with projectiles impacting at an angle of 30° above the horizontal with velocities ranging from $\sim$3.8–$\sim$6.3 km/s. High-speed imaging (250,000–500,000 frames/sec) documents the sequence and location of failure due to impact. The PMMA targets rested on a Styrofoam block in order to minimize free-surface effects at the base of the block. Evolution of the damage growth was measured through the side of the target over a range of azimuths extending from the point of impact (Fig. 1, Fig. 4). Material was considered "damaged" within the opaque region.

Corresponding three-dimensional CTH models were computed using identical conditions to the experiments. The calculations use a Mie-Grüneisen equation of state (EOS) for the Pyrex impactor [30], PMMA target and Styrofoam base (both available within the CTH package). PMMA has a shock-induced phase transition at $\sim$25 GPa, and the Mie-Grüneisen EOS is a good representation for PMMA below this transition. At pressures above the transition, the EOS still provides rough agreement and it can be used with confidence up to pressures of $\sim$100 GPa. Because we are concerned with material away from the impact point at much lower pressures, this EOS provides a valid representation of our material. Two separate failure criteria were used. The Johnson-Cook Fracture model illustrates the relative roles of shear failure and extensional failure ("spallation"). Extensional failure occurs when the stresses exceed the tensile strength of the material. Shear failure occurs when the stresses exceed the yield strength of the material and the material exceeds a specified amount of plastic strain. The models used in these calculations assume linear, isotropic elasticity, and von Mises plasticity with an associated flow rule that the plastic strain rate is always normal to the yield surface.

The Pyrex projectile was assumed to behave like a geologic material, with a pressure yield surface that incorporates thermal softening and density degradation. Currently, this is sufficient in modeling the basic behavior of the projectile breakup during impact. A slightly more complicated strength model was needed to model impact damage into the PMMA. Unfortunately, it is difficult to model both shear and tensile failure of PMMA concurrently in CTH today. Therefore, two separate strength models for PMMA are considered. Damage by extensional failure occurs when the maximum allowable tensile stress is exceeded; spallation is represented with this model. Shear-induced damage follows the Johnson-Cook Fracture (JCF) model. JCF is a scalar damage model for predicting the failure of materials where the failure criterion is based on equivalent plastic strain as a function of pressure, temperature, strain rate and loading path. While this model only predicts damage involving shear deformation, it is typically used in conjunction with the spall model for predicting failure of damaged material or due to excess hydrostatic tension. However, for increased understanding of PMMA failure, we find it useful to treat shear and extensional failure separately and not try to convolve the two phenomena. In the JCF model, a scalar damage parameter, D, is calculated in each cell: D ranges from 0 (pristine, undamaged material) to 1 (completely damaged material) and failure occurs when $D = 1$. The damage parameter is calculated according to:

$$\frac{dD}{dt} = \frac{\dot{E}}{E_F} \tag{1}$$

where $\dot{E}$ is the equivalent plastic strain rate and E_F is the local value of strain to fracture, which is calculated by:

$$E_F = \left(D_1 + D_2 Exp\left(\frac{-D_3 p}{Y}\right)*(1 + D_4 Ln(\dot{E}))*(1 + D_5 T_{\text{hom}}\right) \tag{2}$$

where D1-D5 are constants, p is pressure, Y is the local yield stress and T_{hom} is the homologous temperature, defined by:

$$T_{\text{hom}} = \frac{T - T_{room}}{T_M - T_{room}} \tag{3}$$

where T_M is the melting temperature of the material. Once the material has failed, the yield strength is then assumed to be zero.