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A review of mechanisms and models for dynamic failure, strength, and fragmentation

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ABSTRACT

Modeling of catastrophic disruption requires understanding the processes of dynamic failure and fragmentation. This paper summarizes current mechanisms and models for dynamic failure, strength, and fragmentation, reviewing these from a mechanics perspective and with an emphasis on making links to the developing advances in these areas in the engineering and computational mechanics communities. We describe dynamic failure processes, examine size and rate effects, articulate the scaling concepts that arise naturally from these processes, and examine the influences of these processes on effective strength and fragmentation.

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1. Introduction

There is evidence throughout the solar system of catastrophic disruption, particularly as the result of large impacts into asteroids (Williams, 1989; Zappal et al., 1995; Binzel and Xu, 1993; Burbine et al., 2001) and comets (Podolak and Prialnik, 1996; Chapman, 1975). Missions in recent decades (e.g., NEAR, Deep Impact, Hayabusa, Dawn, Rosetta, and soon OSIRIS-REx) have revealed new and interesting details about the nature of small bodies in the solar system. Many asteroids have been observed to have impact craters with diameters comparable to the body size (Bottke Jr. et al., 2002), suggesting that very large impacts can be below the disruption threshold. In addition, internal structure and damage has been observed on the surface of most small bodies, as is evident from large-scale fractures observed on Ida (Sullivan et al., 1996), Eros (Veverka et al., 2000), and Vesta (Le Corre, 2012; Schenk et al., 2012; Scully et al., 2012). It appears that much of this structure is the consequence of impact-dominated processes.

Our understanding of impact processes is typically limited by two things: first, our understanding of the dynamic material properties and failure processes of the planetary materials that are involved in the impact, and second, our ability to capture these complex processes within computational simulations of these extreme events. Laboratory experiments have been very useful in improving our understanding of impact processes and catastrophic disruption (e.g., Gault, 1973; Gault and Wedekind, 1969; Fujiwara and Tsukamoto, 1980; Nakamura and Fujiwara, 1991; Martelli et al., 1994). Laboratory-scale experiments, however, are orders of magnitude smaller than most of the collisions in the solar system. Thus computational simulations (e.g., Melosh et al., 1992; Benz and Asphaug, 1994; Jutzi et al., 2010) and scaling relationships (Holsapple, 1993; Davis et al., 1994; Housen et al., 1983) are critical in understanding large-scale impacts. Hydrocode-based simulations have been shown to be capable of handling many of the complexities of the major impact event, particularly with respect to shockwave propagation and interactions with boundary conditions, and are typically benchmarked against laboratory experiments. Improvements to such simulations and the development of new scaling relationships should result from advances in the understanding and modeling of the failure processes that occur during impact events.

Most of the impact events of interest to planetary science represent extreme dynamic events, which are characterized by the deposition of large amounts of energy in very short times. Because the speeds at which energy can propagate away from the location of deposition are finite (e.g., shock speeds), the local energy density rises very rapidly, and so the material seeks new internal

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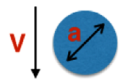

~5τ ~10-100τ Time

Domain	Source	Shock	Strength/Flow	Structure/ Interior
Pressure, Pa	10^{11}	10^{9}	10^{7}	10^{6}- 10^{7}
Strain Rate, s^{-1}	10^{5}	10^{4}- 10^{2}	10^{1}- 10^{-2}	10^{-6}
Temperature, K	10^{4}- 10^{3}	10^{2}	10^{2}	10^{2}- 10^{1}
Critical Processes	Strong Shocks, Jetting	Propagating Shocks, Excavation flow	Collapse mechanisms, Post-shock strength,	Interactions of cracks and waves with internal structure
Failure Mechanisms	Melting, Vaporization, Phase Transitions	Massive Cracking Massive Shear banding Massive Void Growth	Shear zones Collapsed bands Comminuted flow	Cracking
Kinds of Models	Equation of State	Plasticity Dynamic failure mechanics	Plasticity, flow of disordered media	Structural deformation and failure

Fig. 1. Schematic of mechanistic domains and associated mechanisms in catastrophic disruption and asteroid impact. Note that $\tau_i \sim a/V$ is an impactor-dependent timescale.

pathways to dissipate the energy (e.g., fracture, melting, and vaporization). These internal energy pathways are typically referred to as "mechanisms." Which mechanisms are available depends on the materials involved, and which of these mechanisms are exercised depends also on the severity of the impact, and the generalized loading conditions (e.g., impact parameters such as obliquity).

A schematic of the main variables, failure mechanisms and processes in planetary impact events is presented in Fig. 1 in terms of the conventional domains associated with a major impact. Consider an impactor of diameter a impacting a much larger target body at a high velocity V. One characteristic timescale for the event is then given by $\tau_i = a/V$, and the likely phenomena can then be categorized in terms of time after impact, described in terms of multiples of τ_i. This type of domain decomposition can also be performed in terms of length scales using multiples of the impactor diameter. Four domains can be identified, denoted generally as the source, strong shock, strength/flow and structural domains. Within each of these domains, we can identify the expected pressures, strain rates, and temperatures. These variables typically characterize the conditions that are developed in those domains. For example, the domain just under the impactor (called the contact domain) perceives the highest pressures, strain rates and temperatures. For each domain, we also identify critical macroscale processes, the deformation and failure mechanisms, and the kinds of models needed to describe these mechanisms. The material models that are used should be able to account for this range of pressure, strain rate and temperature histories, be able to incorporate these deformation and failure mechanisms in an effective way, and provide the key parameters necessary for the modeling of the critical processes in each domain.

The domains of primary interest to us in this paper are in the shaded region in Fig. 1. The materials in this region are under pressures of the order of 10 MPa–1 GPa, deforming at intermediate strain rates of 10^{-6}–$10^{4}\ s^{-1}$, and undergoing massive failure through the collective behavior of cracks, voids and shear bands. Modeling the response of the material involves the coupling of these damage mechanisms with the rapidly varying stress states associated with the propagating shock, the development of rarefaction fans and subsequent spall from shock release down isentropes, massive fragmentation at intermediate strain rates, fragmentation-induced dilatation ("bulking") and the overall rates of deformation. In practice, few simulation approaches are able to handle all of these phenomena within the same simulation with high fidelity, with particular difficulties often arising from the fragmentation and bulking components.

This paper summarizes current mechanisms and models for dynamic failure, strength, and fragmentation, reviewing these from a mechanics perspective and with an emphasis on making links to the developing advances in these areas in the engineering and computational mechanics communities. Note that the background of the authors is that of experiments and modeling in dynamic mechanics of solids, rather than planetary science, and so it is likely that we cannot adequately represent the extensive literature in this area in planetary science. We therefore do not attempt to capture all of the excellent work already published within the planetary science literature in this area, providing instead representative examples of related work. Finally, we note that reviews such as this are inevitably biased towards the works that are most familiar to the authors, and we apologize in advance to any who feel that their work has been slighted: this is certainly not our intention.

2. Dynamic failure mechanics

The specific failure processes that are developed within any given region of the target depend primarily on the material class (e.g., brittle versus ductile) and the current stress state. Fig. 2 provides some of the typical failure processes that are developed within each material class as a function of the multiaxial stress state. Note, e.g., that the influence of confining pressures on failure processes can also be dramatic. Confining stresses can reduce available driving forces for some failure processes like fracture. However, confining stresses can also change the *mode* of failure. For example, Hu et al. (2011) demonstrated that the application of a biaxial confining stress can re-orient the principal direction of crack growth during compression, producing diffuse shear-dominated

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