Hypervelocity impact and fragmentation of brittle materials

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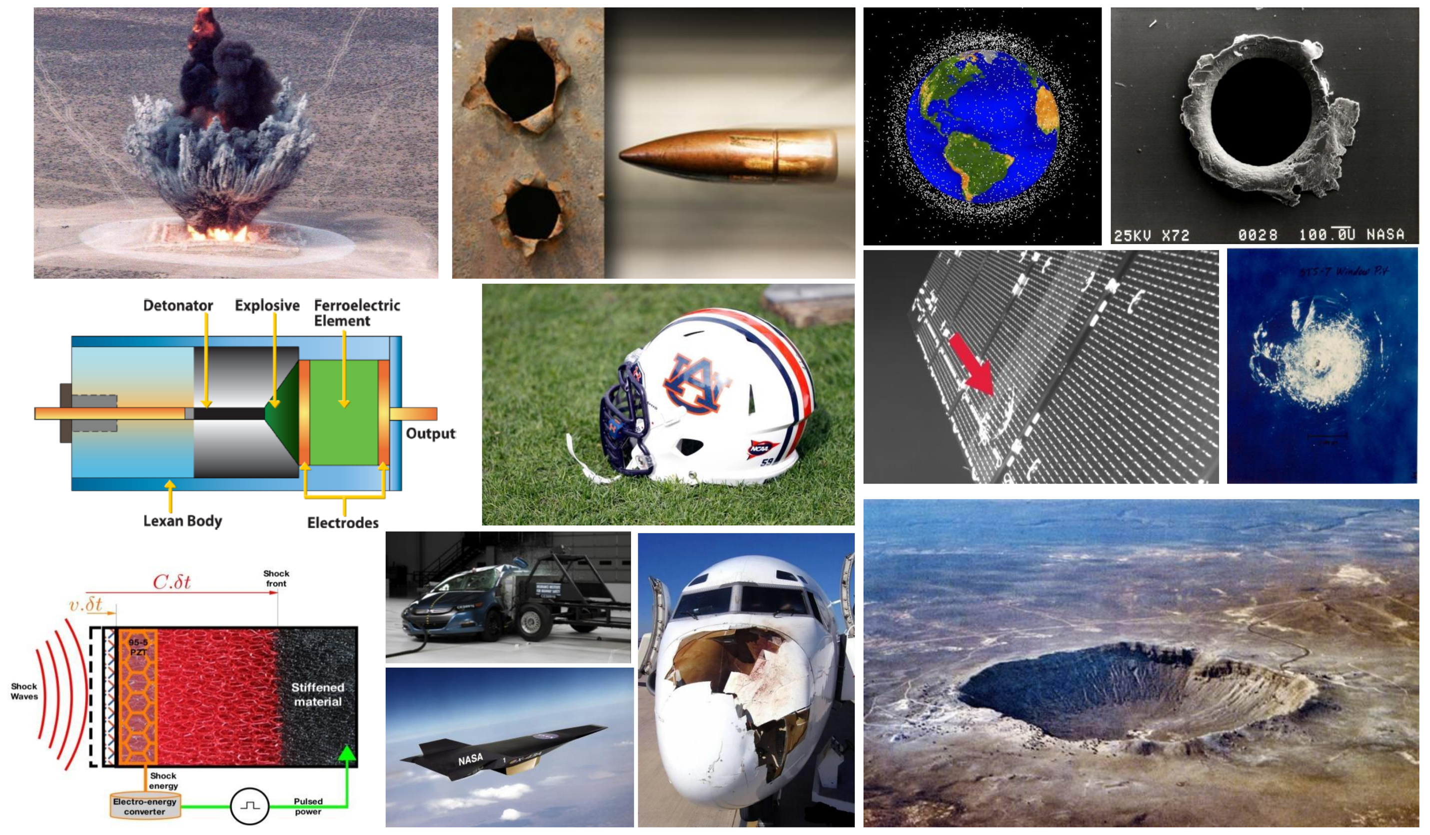
Introduction

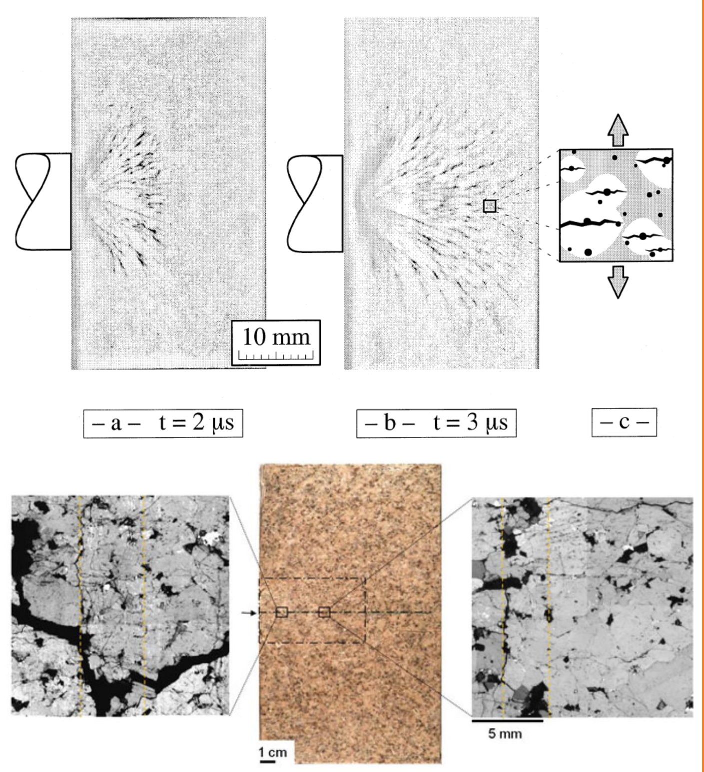
- Material is said to be under extreme environment if it undergoes large pressure and temperature changes over a short period of time.
- High velocity impact is a typical example of extreme environment where shock waves are generated in the material.
- Extreme environments are found in planetary collisions, micrometeorite impact on satellites, ballistic impact, and even day to day environments like crashes and collisions.
- We study shock wave propagation brittle materials.



Some examples of extreme environments – ballistic impact, bullet impact, orbital debris impact, crashes, collisions, crater formation and planetary evolution, and pulsed power generators.

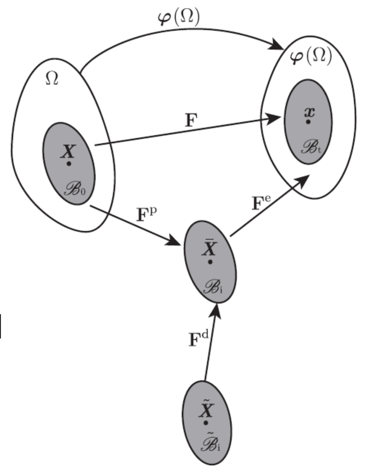
Brittle materials

- Geological materials: rocks, ice, etc.
- Infrastructural materials like concrete and glass.
- General progression of damage:
  - Void and microcrack nucleation
  - Growth and propagation of microcracks under mode I loading
  - Coalescence of microcracks to form bigger cracks.
- Under shock loading, the progression of damage is violent and catastrophic.
- This is called dynamic fragmentation.



Continuum Damage Mechanics

- We use the ideas of Continuum Damage Mechanics (CDM) to model damage within the system.
- Here the damage is introduced as an auxiliary configuration along with damage tensor $\boldsymbol{F}_d$.
- $\boldsymbol{F}_d$ degrades the moduli of the material in its equation of state $\mathcal{E} = \mathcal{E}\left(\tilde{\boldsymbol{E}}_e, a(\boldsymbol{B}_d)\right)$, $\boldsymbol{B}_d = \boldsymbol{F}_d\boldsymbol{F}_d^T$

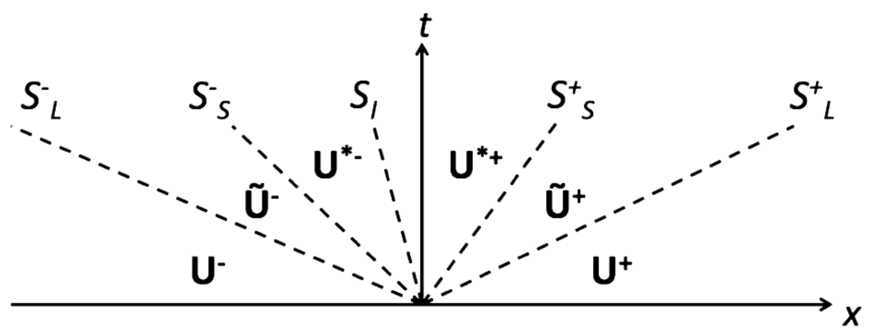


EOS and evolution laws

- The equation of state or the constitutive law comprises of a bulk part, a shear part and a thermal part.
- $\mathcal{E}(\boldsymbol{B}_d = \boldsymbol{I}, \tilde{\boldsymbol{E}}, \zeta) = \frac{a_0^2}{2\alpha}(\eta^\alpha - 1)^2 + C_v T_0 \theta(\eta)\left(e^{\bar{\zeta}} - 1\right) + 2\, b^2(\eta)\varepsilon$ where η and ε are functions of invariants of strain.
- The evolution of damage is prescribed by a Grady-Kipp evolution law. $\boldsymbol{F}_d = \sqrt{1-D}\,\boldsymbol{Id}_3$ where $\frac{dD^{1/3}}{dt} = (m+3)\alpha^{1/3}\epsilon^{m/3}$.
- The inelastic deformations are governed by a plastic evolution law $\boldsymbol{L}_p = \dot{\lambda}_p\, dev\, \boldsymbol{\Sigma}/||dev\, \boldsymbol{\Sigma}||$, where $\dot{\lambda}_p = \dot{\lambda}_0 \exp\left(\frac{1}{c_3}\left[\frac{\sqrt{\frac{3}{2}}||dev\, \bar{\bar{\Sigma}}||}{Y(p).f(T)} - 1\right]\right)$
- The yield strength and shear modulus of the material is influenced by the pressure in the material.
- The moduli, a_0 and $b^2(\eta)$ degrade with damage in the system.

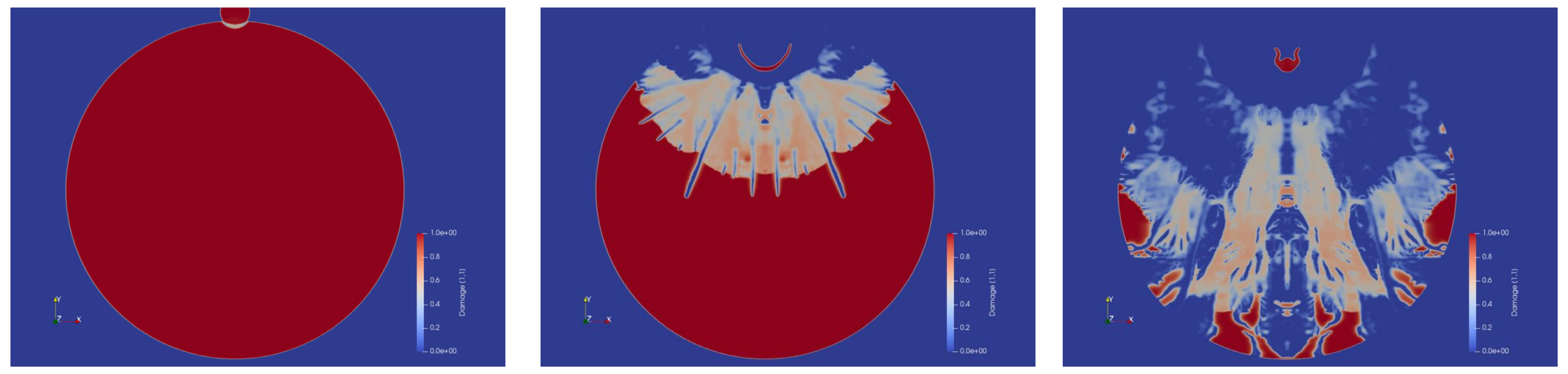
Computational framework

- AMROC - Eulerian computational framework with adaptive mesh refinement capability.
- Moving level sets for tracking interfaces accurately.
- Multi-material Riemann solver
- Central idea revolves around solving a Riemann problem for a state enveloped by two waves.
- Compute wave speeds from initial states
- For more than one material, we have a contact discontinuity

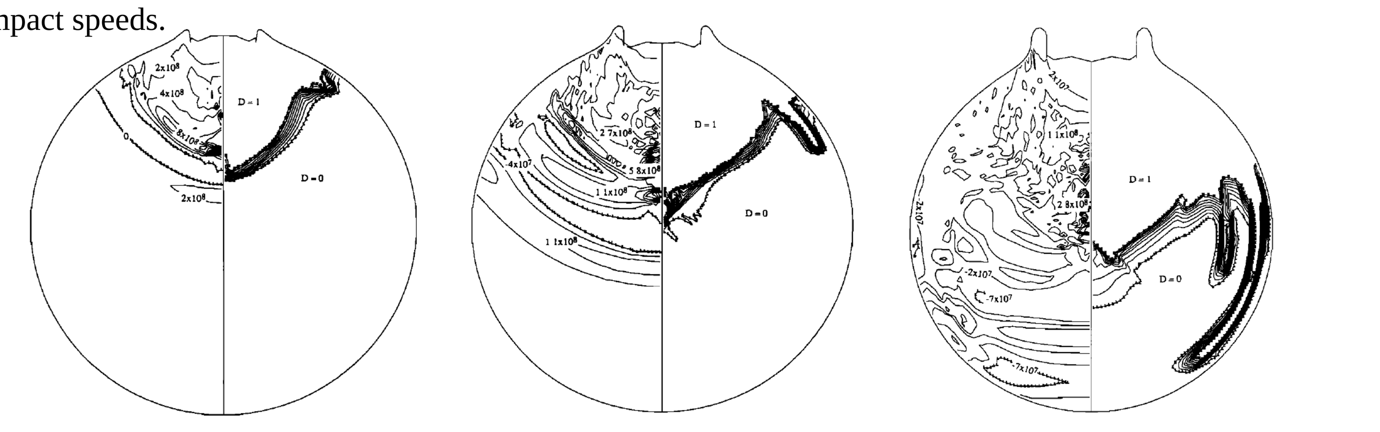


Results

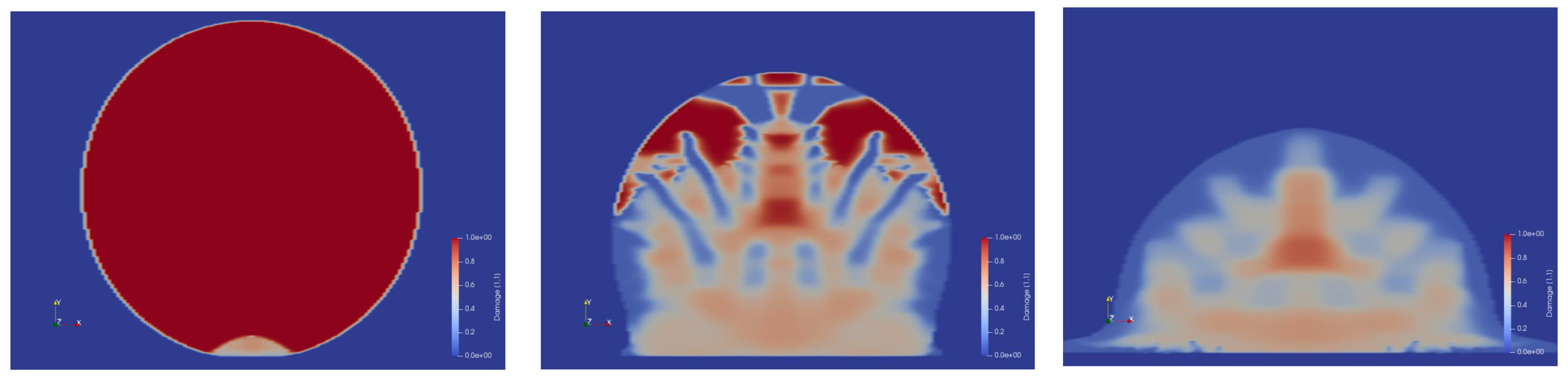
- Impact of an Aluminum sphere on Basalt sphere.
- Aluminum is purely elastic while Basalt has high plastic yield strength with Grady Kipp fragmentation model.



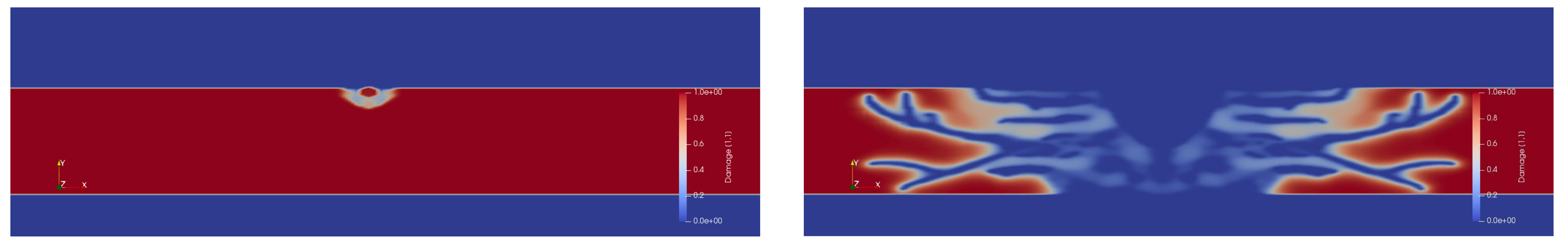
[Above] Evolution of damage and associated crack propagation when a small Aluminum sphere impacts a large Basalt sphere at 5 km/s impact speed. [Below] Simulations performed by Melosh and collaborators with similar geometry at 3km/s impact speeds.



- Other test geometries: Taylor impact experiment of brittle material and micrometeorite impact on plate.



[Above] Evolution of damage and associated crack propagation when a basalt sphere is launched onto a rigid wall at 500 m/s impact speed. This is a classic Taylor impact test. [Below] Evolution of damage when a spherical Al impactor strikes basalt plate at 5km/s speed.



Future Work

- Degradable yield strength $Y_p = (1-D)Y_i + DY_d$, where Y_i and Y_d denote yield strength of intact and damaged material.
- $Y_i = Y_0 + \mu_1 p/1 + (\mu_1 p/Y_\infty - Y_0)$ and $Y_d = \mu_2 p$
- Combined tensile and shear damage $D = D_t + D_s$
- D_t is governed by Grady-Kipp law and D_s depend on plastic strain evolution in the material.
- Stochastic anisotropic damage laws (DFH)

$$\frac{d^{n-1}}{dt^{n-1}}\left(\frac{1}{1-D_i}\frac{dD_i}{dt}\right) = \lambda_i\left(\sqrt{2EY_i}\right)n!\, S(kC)^n$$

- Gradient damage for regularization and avoiding damage localization

$$\mathcal{E}_{new} = \mathcal{E} + \frac{\eta_0}{2}|\nabla D|^2$$

- Viscoelasticity and phase transitions: $\boldsymbol{F} = \boldsymbol{F}_e\boldsymbol{F}_i$ where $\boldsymbol{F}_i$ is inelastic deformation tensor associated with viscoelasticity and phase transitions.
- Shock induced phase transitions and long time effects such as viscoelastic behavior will be included.

References

- Agrawal V., Ortega A.L. and Meiron D., Dynamic fragmentation of geological materials (*in preparation*)
- Barton P., *et al.*, *J. Comp. Phys.*, 240 (2013) 76-99.
- Barton P. and Drikakis D., *J. Comp. Phys.*, 229 (2010), 5518-5540.
- Ortega A.L. *et al.*, *J. Comp. Phys.*, 257 (2014), 414-441.
- Melosh J. *et al.*, *J. Geophys. Res: Planets*, 97 (1992), 14735-59.
- Denoual C. and Hild F., *Comp. App. Mech. Eng.*, 183(2000), 247-258.

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