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Damage rheology model: from local quasi-static to non-local dynamic formulation

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Many damage models attempt to quantify material deformation beyond the reversible elastic regime using continuum and discrete approaches, scalar and tensorial damage state variables, linear and nonlinear elasticity, and other categories of ingredients and formulations. In previous studies, we developed a nonlinear visco-elastic continuum damage rheology for evolving elastic properties of rocks sustaining irreversible brittle deformation. The model accounts for three general aspects of brittle rock deformation: (1) Dependency of the effective elastic moduli on the existing crack density (damage) and loading conditions; (2) Evolution of the crack density and elastic moduli with the ongoing deformation; (3) Macroscopic brittle instability at a critical level of damage. The previous formulation assumes local relation between the energy function and material damage, leading to complete localization during failure, and may be classified as "quasi-static" since it does not allow a detailed analysis of dynamic events associated with macroscopic instability. We present a new non-local and dynamic formulation of the damage rheology model that eliminates these major shortcomings. The model accounts for strong micro-crack interaction in a highly damaged region prior to the total macroscopic failure by incorporating the spatial derivative of the damage as an additional state variable. This leads to a definition of an internal length scale that does not exist in elasticity and in local damage models. The new model predicts a finite width of a newly-created highly-damaged zone. Accounting for the dynamics require two additional modifications: (1) Incorporating the strain rate tensor in the state variables provides a thermodynamic formulation for the Kelvin-Voigt visco-elastic model and produces some damping during the dynamic processes; (2) We suggest that the loss of convexity signifies a phase transition from a highly damaged solid to a granular material. In the vicinity of the critical level of damage, we expect a formation of a mixture zone of partially solid and granular media similar to the mushy region discussed in a context of the Stefan problem of classical thermodynamics. We discuss briefly key relevant aspects of granular mechanics and suggest a simplified approach to characterize the transition between damaged solid and granular material. We demonstrate that the new damage formulation allows a self-consistent analysis of the dynamic rupture process.