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Dynamic fragmentation using phase-field modelling of fracture

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Abstract

Dynamic fragmentation is a process during which a material or structure subjected to intense loads fails catastrophically through the initiation, propagation and coalescence of a multitude of cracks. It is a key topic in many fields of engineering, as for instance in aerospace industry, where the outcome of destructive re-entry is of great concern. Robust numerical models are direly needed to develop a fundamental understanding of such events, in particular to be able to predict the statistical distributions of fragment sizes, shapes and velocities resulting from destructive events. A well established way to address this problem is to use finite elements solid mechanics models coupled with cohesive elements [1]. Cohesive cracks give an explicit representation of crack surfaces and simplify the treatment of contacts between fragments, a crucial factor to predict debris velocities. However, the cohesive approach is known to suffer from mesh dependency, with crack paths that depend on the underlying mesh, resulting in non-robust predictions of fragments shapes. Phase-field modelling of fracture belongs to a different family of methods using diffuse crack approaches. Unlike cohesive models, phase-field crack paths are independent of the underlying mesh. This method has shown promising results in various problems, not only in quasi-statics but also in dynamics, where complex mechanisms such as crack branching are observed. However, in dynamic regimes, a load-dependent widening of the cracks occurs, which hinders the interpretability of fragmentation simulations involving extreme events like impacts or explosions [2]. Under these conditions, the damage width representing the cracks becomes so large that a significant portion of the geometry is degraded, limiting the accurate determination of fragment shapes. In this work, we explore alternative strategies to alleviate this issue and compare them to commonly used phase-field models. Specifically, we investigate approaches utilizing mass degradation [3], strength criteria [4], or local viscoelasticity. The fracture propagation dynamics and branching behaviour are examined, and these models are further validated against 1D fragmentation tests, where analytical solutions serve as benchmarks. [1] M. Vocialta, N. Richart, J.-F. Molinari, 3D dynamic fragmentation with parallel dynamic insertion of cohesive elements, International Journal for Numerical Methods in Engineering, 109, (2017), 1655-1678. [2] S. Durussel, G. Molnár, J.-F- Molinari, Origins of phase-field crack widening in dynamic fragmentation explained, arXiv preprint arXiv:2512.18022, (2025). [3] C.-H. Chen, E. Bouchbinder, A. Karma, Instability in dynamic fracture and the failure of the classical theory of cracks, Nature Phys, 13, (2017), 1186–1190. [4] F. Vicentini and J. Heinzmann and P. Carrara and L. De Lorenzis, Variational phase-field modeling of cohesive fracture with flexibly tunable strength surface, Journal of the Mechanics and Physics of Solids, 207, (2026), 106424.

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