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THREE-DIMENSIONAL PARALLEL SIMULATION OF DYNAMIC FRACTURE AND FRAGMENTATION USING A HYBRID DG/COHESIVE METHOD

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ABSTRACT

It has long been of interest in the scientific community to gain a better understanding of the fracture and fragmentation behavior of materials subject to high-rate deformation. In general, fragmentation is a very difficult physical phenomenon to model since it depends sensitively on small-scale stochastic processes (e.g. inclusion microcracking, defect interaction, etc.), geometric imperfections and stress wave propagation and interaction. However, in recent years a promising method based on the cohesive zone approach has emerged as a possible computational tool for predicting fragmentation. This approach takes the form of specially formulated interface finite elements governing the separation of crack faces at element boundaries with a phenomenological traction-separation law. Of the two main types of cohesive laws that have been formulated, those of the so-called "rigid" type implemented with on-the-fly insertion show promise over "initially elastic" cohesive laws for predicting fragmentation since they avoid the severe restriction on the time step attendant to proper wave propagation for the latter approach. Indeed, in previous studies the rigid cohesive law has been used successfully to simulate several experimental fragmentation tests [1,2]. Although the results from these studies seem to validate the method in many aspects, a few key issues remain yet unresolved. The first of these is the issue of convergence.

In order to ensure that a numerical fracture solution with cohesive elements is not mesh dependent, it has recently been suggested that one should observe convergence of the fracture energy with successive mesh refinement [3]. To study the energy convergence, the authors considered the problem of an expanding ceramic ring posed in a 1D setting. They found that in the best case scenario, convergence is achieved with approximately 10^4 elements, which scaling up, is equivalent to 10^8 in 2D and 10^{12} in 3D. Since previous multidimensional studies use fewer elements than this, it can be concluded that energy convergence in multiple dimensions probably has not been achieved.

Restricting our attention to 3D problems, it immediately becomes clear that mesh densitites approaching the scaled value are not computationally possible absent the ability of massively-parallel simulation. Moreover, coordinating on-the-fly insertion in a 3D parallel architecture in the continuous Galerkin (CG) framework is extremely complex as it requires the creation and coordination of new elements (and nodes) at various locations in the mesh, at possibly every step in the calculation. As a result of this complexity, a 3D parallel capability for this method under the CG framework is currently unavailable.

A possible solution to this difficulty is to utilize the alternative discontinuous Galerkin (DG) formulation of the non-linear solid dynamics problem. Developed recently in [4], the explicit DG framework for this problem uses interface elements from the start of the calculation to track small discontinous nodal displacements at all interior element boundaries. Therefore, on-the-fly insertion of cohesive elements using DG does not require the creation of new elements. Rather, the already-existing interface elements are simply converted to cohesive elements wherever the fracture criterion is met. Toward this end, a DG/cohesive hybrid FEM algorithm with parallel capabilities has recently been implemented [5]. This research code allows for the first time, massively parallel 3D fracture simulation using rigid cohesive elements.

Given this new capability the purpose of this work is multifold. First, 3D simulation of two common fragmentation tests - the expanding ring test from [1] and the ball/plate impact test from [2] will be demonstrated using the DG/cohesive code. Subsequently, these numerical tests will be used to investigate the energy convergence and the scalability of the method. In addition, certain physical phenomena characteristic of these tests including the fragment size distribution for the ring test and conical and radial cracks for the plate impact test will be demonstrated. In preliminary work, fracture and fragmentation of expanding ring specimens has been simulated successfully in parallel with mesh sizes up to 100,084 elements. Also, the formation of multiple simultaneous necks, a physical hallmark of this test, has been demonstrated as an initial validation of the method.

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