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Representing ductile damage with the dual domain material point method

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Abstract

In this paper, we incorporate a ductile damage material model into a computational framework based on the Dual Domain Material Point (DDMP) method. As an example, simulations of a flyer plate experiment involving ductile void growth and material failure are performed. The results are compared with experiments performed on high purity tantalum. We also compare the numerical results obtained from the DDMP method with those obtained from the traditional Material Point Method (MPM). Effects of an overstress model, artificial viscosity, and physical viscosity are investigated. Our results show that a physical bulk viscosity and overstress model are important in this impact and failure problem, while physical shear viscosity and artificial shock viscosity have negligible effects. A simple numerical procedure with guaranteed convergence is introduced to solve for the equilibrium plastic state from the ductile damage model.
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1. Introduction

Lagrangian finite element methods are the traditional choice to model solid deformations involving void growth and material failure. However, difficulties arise when the material experiences large deformation resulting in heavily skewed elements. To avoid this numerical difficulty, we use the dual domain material point (DDMP) method [1] for these types of problems. The DDMP method is an improved version of the material point method (MPM) [2], which is the particle-in-cell (PIC) method [3] reformulated using the concept of virtual work for history-dependency in constitutive modeling. Since the concept of virtual work is also the starting point of the finite element method (FEM), many numerical properties are similar between the material point methods (both DDMP and MPM) and the FEM. The most significant difference between the material point methods and the FEM is that material point methods retain Lagrangian capabilities using an Eulerian mesh, rather than a Lagrangian mesh as in FEM. The Lagrangian capability

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of the material point method relies on the Lagrangian particles, also called material points, that are free to move about the Eulerian mesh, and thus can be used to carry the history dependent quantities in ductile material models without the difficulties of numerical diffusion. At each time step, data from the moving particles is transferred to the underlying grid where numerical analysis can be readily performed.

Material point methods avoid mesh distortion difficulties associated with Lagrangian methods and numerical diffusion difficulties associated with Eulerian methods because these methods use both an Eulerian mesh and Lagrangian particles. However, the MPM is far from problem free for cases involving large material deformations because the MPM uses gradients of shape functions at particle locations to calculate the nodal force. When a particle crosses a cell boundary, numerical noise is created since the gradient is discontinuous across cell boundaries [4]. Several schemes [4,5] have been explored to avoid this numerical noise. All of the schemes introduce the concept of a particle domain, which is equivalent to modifying the shape functions in the MPM. To conserve mass and momentum, these particle domains are required to cover the entire domain occupied by the material without overlap or gap. A rigorous enforcement of this requirement brings back mesh distortion difficulties of the finite element method. In practical uses of these schemes, this requirement is relaxed [4,5] by accepting errors in mass and momentum conservation.

The DDMP method [1] takes a different approach to avoid the numerical noise by modifying the gradient of the shape function to make it continuous across cell boundaries, without changing the shape function of the MPM. In this way the concept of particle domain is not needed. As a consequence, the influence of a particle is different for the momentum and force calculations. Therefore the method is named as the "dual domain" material point method. The method has been shown to rigorously conserve mass and momentum, while the error in energy conservation is second order in both temporal and spatial discretization.

The DDMP method has been applied to many large deformation problems [6,7] with success. In the present work we use the DDMP method to perform continuum mechanics calculations of a flyer plate experiment using a ductile damage model. The present work has three objectives. The first objective is to evaluate whether the DDMP method can represent the major physics involved in this problem, including plastic flow, porosity growth, material damage, and failure. The second objective is to understand the numerical properties of the DDMP method in materials with ductile damage and strain softening. The third objective is to use the numerical capability of DDMP to evaluate the relative importance of different physical mechanisms and numerical treatments often used in modeling this impact and failure problem. The noise reduction provided by the DDMP method is important in this flyer plate problem. In the region where the material is about to fail, the softening of the material leads to localized strain and large displacement of the particles causing them to move across cell boundaries.

The basis for the flyer plate problem is straightforward: A plate is traveling at high velocity and strikes another stationary plate. These are referred to as the flyer plate and the target plate, respectively. The target plate has a thickness double that of the flyer plate. Upon impact, a compression shock travels through both plates to opposite surfaces, and the reflected tensile expansion fans collide at the center of the target plate, if the flyer and the target plates are made of the same material. For a critical value of initial velocity of the flyer plate, voids are created in a typical ductile material leading to softening and eventually failure along the center line of the target plate as shown in Fig. 1. This problem is physically well defined, while presenting numerous challenges for numerical techniques, including shock propagation, material softening and failure, and history dependence. Therefore we choose this problem to test the DDMP method. The DDMP method is described briefly in the next section. Readers interested in the method are encouraged to Ref. [1] for further details.

2. Dual domain material point method

As shown in Fig. 1, the target plate develops a highly porous region near the center line in the experiment. It is not practical to numerically consider the individual pores and cracks, and we employ the work of Addessio and Johnson [8,9], who developed a ductile damage model based on the continuum description to capture the effects of void growth in aggregate. Our starting point is the macroscopic continuum description of the material. The momentum equation can be written as

$$\rho \frac{d\mathbf{v}}{dt} = \nabla \cdot \boldsymbol{\sigma}, \tag{1}$$

where ρ is the density of the bulk material, $\mathbf{v}$ is the velocity, and $\boldsymbol{\sigma}$ is the stress tensor, which depends on the history