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Modeling finite thickness slab perforation using a coupled Eulerian–Lagrangian approach

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ABSTRACT

A coupled Eulerian–Lagrangian (CEL) method can be used to model many types of dynamic events. Projectile penetration through solids is particularly well-suited to a CEL method. In this study the CEL method in the commercially-available code Abaqus was used to model a near rigid projectile perforating finite thickness concrete slabs. A near rigid projectile can be modeled as a Lagrangian material with distinct material interfaces, while the solid target can be modeled as an Eulerian material capable of large deformations. An improved concrete constitutive model is also described that was implemented into Abaqus as a user material model. A simplified stochastic model was also implemented to capture some of the heterogeneous nature of concrete. The CEL simulations are compared to experimental data to demonstrate the utility of this method for this type of perforation event.

1. Introduction

Penetration of a projectile into soil, rock or concrete is a problem of interest to the military and civil communities. Methods to predict penetration into brittle materials have seen significant developments since World War II, with much effort focused on synthesis of empirical data with analytical tools (White, 1946; Kennedy, 1976; Backman and Goldsmith, 1978; Wilkins, 1978; Jonas and Zukas, 1978; Aptukov, 1990; Ben-Dor et al., 2005).

Modern computational capabilities have spurred increased interest in numerical first-principles approaches to penetration calculations in concrete targets. Most computational approaches have focused on either Lagrangian finite element (FE) or Eulerian finite difference (FD) methods (Anderson, 1987). One advantage of the Lagrangian FE method is that the interface between the penetrator and the target is well defined and readily tracked. Behavior at material contact interfaces is enforced through spatial slide surfaces, which must be defined *a priori*. A disadvantage of this method is that severe distortion of the mesh in high-velocity impact problems causes computational difficulties resulting in very small time steps and numerical errors. Rezoning the mesh in areas of high distortion has been used to overcome these problems. However, the rezoning process must often be repeated many times resulting in considerable computational overhead (Brown et al., 2002). Other techniques like element erosion (Belytschko and Lin, 1987; Johnson and Stryk, 1987; Sewell et al., 1990) have also been proposed to overcome the problem of mesh distortion in these high-velocity impact problems. Recent advancements in Lagrangian meshfree methods for large deformation and fragmentation problems (Chen et al., 1996; Johnson et al., 1996, 2000; Guan et al., 2011) have provided new capabilities for penetration modeling due to their ability to model large distortion, material separation, and evolving contact conditions.

Eulerian FD methods accommodate large distortions readily, and no *a priori* definition of contact surfaces is required. However, the material interfaces are not distinct, and heuristics must be introduced to prevent the smearing of the boundary between the penetrator and target (Anderson, 1987).

A coupled Eulerian–Lagrangian (CEL) method provides a natural approach to a usable, general-purpose penetration model (Brown et al., 2002). The penetrator is modeled using a Lagrangian formulation, while the target is modeled using an Eulerian formulation. The Lagrangian domain moves through the Eulerian mesh, and heuristics are required to couple the responses of the two domains. The most common approach involves applying the Eulerian pressures to the Lagrangian mesh, and applying the Lagrangian nodal velocities as boundary conditions on the Eulerian mesh. The boundary of the Lagrangian domain is used to define the boundary between the penetrator and target. Conditions must be satisfied to ensure that the two materials do not occupy the same space at each time step (Benson, 1992).

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All numerical penetration model approaches for high velocity impacts in concrete require adoption of a brittle material constitutive law. The constitutive law must be able to predict the salient characteristics of the material response resulting from impact, penetration and perforation. Forrestal and Luk (1992) developed relationships to predict the penetration of ogive-nose projectiles into soils after normal impact based on a spherical cavity expansion model incorporating three stress-dependent constitutive models. However, Forrestal et al. (1994) recognized that penetration studies often lack the material characterization data required to properly calibrate these constitutive models. To this end, they proposed a semi-empirical method to predict the depth of impact in a concrete target that required only the unconfined compressive strength of the concrete and a dimensionless empirical constant that is used to modify the unconfined compressive strength and density of the concrete.

A number of models have been proposed and implemented in various codes. The material property data required for calibration of these constitutive models must be obtained from appropriate laboratory material characterization tests (Cargile, 1999). One of the most common constitutive laws used in both Lagrangian and Eulerian formulations was developed by Holmquist et al. (1993) and is commonly referred to as the Holmquist–Johnson–Cook (HJC) model. The model was formulated for large strains, high strain rates, and high pressure simulations. Material damage, rate effects, and crushing were accommodated as a function of the stress state and air void ratio.

In this paper, a CEL approach is used to model penetration and perforation of a brittle concrete target by a high-velocity, ogive-nose steel projectile. A constitutive model is adopted similar to the HJC model that also includes third-invariant dependency in the failure surface, which was shown to be important in perforation problems (Fossum and Brannon, 2006). For this study, a variation of the Advanced Fundamental Concrete (AFC) model (Adley et al., 2010) was used to model the concrete. The model will be discussed in the subsequent section.

The AFC model is discussed in Section 2 along with additional features included that were not implemented in the original version of AFC given in Adley et al. (2010). In Section 3 the experimental penetration problems, which were modeled by the CEL method, are described. The setup of the CEL simulations is discussed in Section 4. Section 5 discusses the simulation results, and Section 6 provides concluding remarks.

2. Material model

The AFC model, developed by the U.S. Army Engineer Research and Development Center, is a three-invariant plasticity model that includes hydrostatic crushing, material yielding, plastic flow, and damage effects. A material fit was produced for WES5000, a 38.2 MPa compressive strength concrete, by Adley et al. (2010) and was used in this study. In the AFC model the hydrostatic and deviatoric responses are assumed to be decoupled. The hydrostatic response is composed of three separate regions, as shown in Fig. 1. The first region (zone I in Fig. 1) is the low-pressure elastic portion that extends to the initial crushing pressure defined by two constants, C_6 and C_7, which are the initial crushing pressure and initial crushing volumetric strain, respectively. The second region (zone II in Fig. 1) is a nonlinear crushing region given by

$$P = K_1 + K_2\mu^2 + K_3\mu^3, \tag{1}$$

where K_1, K_2, and K_3 are material constants, and μ is volumetric strain. The third region (zone III in Fig. 1) describes the response of the fully crushed material. Once the volumetric strain reaches a predefined locking strain, C_9, the model assumes linear locking of fully crushed and compacted material defined by a locking bulk modulus, C_8. Upon unloading in the linear locking region, the response follows the locking bulk modulus, C_8. The compression failure surface is defined by

$$S_Y^{comp} = (C_1 - (C_2 + (C_1 - C_2)d)e^{A_n I_1} - C_4 I_1(1 + C_3\ln(\dot{\varepsilon}_n)), \tag{2}$$

where C_1, C_2, C_3, C_4, and A_n are material constants and d, I_1, and $\dot{\varepsilon}_n$ are the damage, first stress invariant, and a normalized strain-rate, respectively. The strain-rate in Eq. (2) is normalized by the reference strain-rate of 0.0001 s^{-1}. Fig. 2 shows the compression failure surface for loading at both a quasistatic (0.001 s^{-1}) strain rate and a strain rate of 100 s^{-1}. Expansion of the failure surface due to the model's strain rate dependence is shown. The tensile failure surface is defined by

$$S_Y^{tens} = (C_1 - (C_2 + (C_1 - C_2)d)(1 + C_3\ln(\dot{\varepsilon}_n))(T_{max} - I_1/)T_{max}, \tag{3}$$

where T_{max} is the maximum allowed tensile pressure, and the tensile failure surface evolves according to the same damage term as used for the compression surface. An important enhancement of the AFC model over similar constitutive models is inclusion of the third stress invariant for calculation of the extension failure surface. The extension failure surface is obtained by using the third stress invariant to calculate the Lode angle using a Willam–Warnke Lode function (Fossum and Brannon, 2006). A reduction factor is then computed that is multiplied by Eq. (2) to obtain the extension failure surface (Adley et al., 2010). A final constant in the failure surface definition is C_5, which is the maximum allowable principal stress on the failure surface.

The damage portion of the AFC model will now be discussed. In the original AFC model by Adley et al. (2010), evolution of the compression and tensile failure surfaces occurs according to the single damage parameter, d. As a consequence the original AFC model tensile behavior has a sharp discontinuity that is not desirable for numerical simulations that are driven by the tensile response (i.e., finite thickness slab perforation). Although typical, use of this single damage parameter does not account for the different failure mechanisms that occur during tensile and compression failure in the continuum. Therefore, a bi-scalar damage description was proposed for the AFC model (Chen et al., 2011; Roth et al., 2011) that is based on a multiscale two-parameter damage model (Ren et al., 2011). In the AFC bi-scalar damage description, separate damage evolution terms are defined for compression and tension. The compression damage, d_c, evolves according to

$$d_c = \sum[\Delta\varepsilon_p/(-I_1 D_1) + \Delta\mu_p/(1.5C_9)], \tag{4}$$

which is the evolution function described by the original AFC damage evolution algorithm. In Eq. (4), D_1 and C_9 are material constants, and $\Delta\varepsilon_p$ and $\Delta\mu_p$ are the plastic strain increment and volumetric strain increment, respectively. The damage value is allowed to increase only to a value of 1.0.

Tensile damage evolution in the AFC bi-scalar damage description is defined by a microcrack-informed damage model (MIDM) proposed by Ren et al. (2011). The MIDM was proposed to improve the description of softening behavior of brittle solids by replacing the continuum-scale phenomenological description of tensile damage with a damage evolution function that is derived from a model of fracture in the concrete microstructure. A representative microcell is used to describe the material microstructure, and brittle failure is explicitly modeled in the concrete substructure according to the fundamental laws of fracture mechanics. To provide the linkage to the continuum scale, the averaged microcell stress and strain are homogenized to the continuum, and equivalence is established between the Helmholtz free energy (HFE) of the cracked microcell and the HFE of the continuum (Ren et al., 2011). Conventional damage mechanics is then used to obtain a