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NUMERICAL SIMULATION OF IMPACT EFFECTS ON MULTILAYER FABRICS

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Abstract. High strength fabrics provide lightweight impact protection and are employed in a wide range of applications. Examples include body armor for law enforcement and military personnel and orbital debris shielding for the International Space Station. Numerical simulation of impact effects on fabric protection systems is difficult, due to the complex woven structure of the fabric layers and the typical application of fabrics in a multilayer configuration. Recent research has applied a new particle-element method to the simulation of impact effects on multilayer fabrics, applicable over a wide range of impact velocities, for use in body armor and orbital debris shielding design applications.

Keywords: Impact dynamics, numerical methods.
PACS: 62.50.+p, 46.15.-x.

NUMERICAL METHOD

Most Lagrangian frame shock physics simulations are performed using pure finite element methods or pure particle methods. In recent years a number of coupled particle-element and hybrid particle-element methods have been introduced, in an attempt to combine the best features of finite element methods and particle methods, in a unified numerical formulation. One such approach is the hybrid particle-element formulation developed by the first author and co-workers [1,2]. This formulation employs particles and elements in tandem. Ellipsoidal particles are used to model inertia, contact-impact, and thermodynamics in compressed states, with Euler parameters providing a singularity-free description of particle rotations. In 'intact' materials, the particle motions are coupled by elastic-plastic elements, which model tension and elastic-plastic shear. The graphics in Figure 1 illustrate the formulation. The top figure shows a collection of particles, which in this method describe inertia and thermomechanical compression of a solid body. The middle figure shows a collection of hexahedral elements, with vertices located at the particle mass centers. These elements quantify interparticle forces due to tensile and shear deformation of the modeled solid body. The lower figure superimposes the particle and element models (the particle size is reduced for clarity), illustrating the hybrid formulation. This numerical approach offers several advantages in shock physics applications: (1) slidelines, rezoning, mass and energy discard of finite element methods are avoided, (2) strength modeling and mass diffusion issues of Eulerian methods are avoided, (3) tensile instability and numerical fracture issues of particle methods are avoided, and (4) no particle-to-element mapping algorithms or particle-to-element contact-impact models are introduced

Note that the transition from an intact to a fragmented body is modeled in a seamless fashion, by failure of the elements due to tensile, shear, or thermal loading.

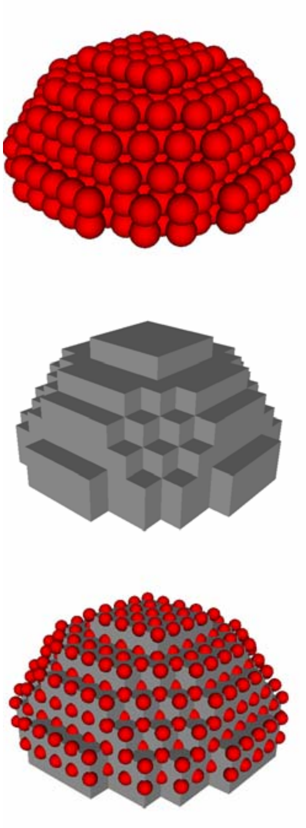

Figure 1. Graphical representation of the hybrid particle-finite element formulation.

The particle-element formulation just described is developed using an energy based modeling approach, which facilitates the systematic use of a hybrid kinematic scheme. The system kinetic energy is described as a function of the translational and angular momenta of the particles (there is no element mass matrix). The system potential energy depends on the equations of state for the particles and the constitutive models for the elements. The introduction of entropy or internal energy as a generalized coordinate allows the thermomechanical problem to be formulated using Hamilton's equations or Lagrange's equations. In this formulation the evolution equations for the internal state variables are nonholonomic constraints on the system level model. Internal state variables include normal and deviatoric damage variables, which model the transition from an intact to a comminuted medium once element failure criteria are satisfied, and plastic variables described by an additive decomposition of the deviatoric Lagrangian finite strain tensor into elastic and plastic parts. The final system level model consists of explicit first order state equations.

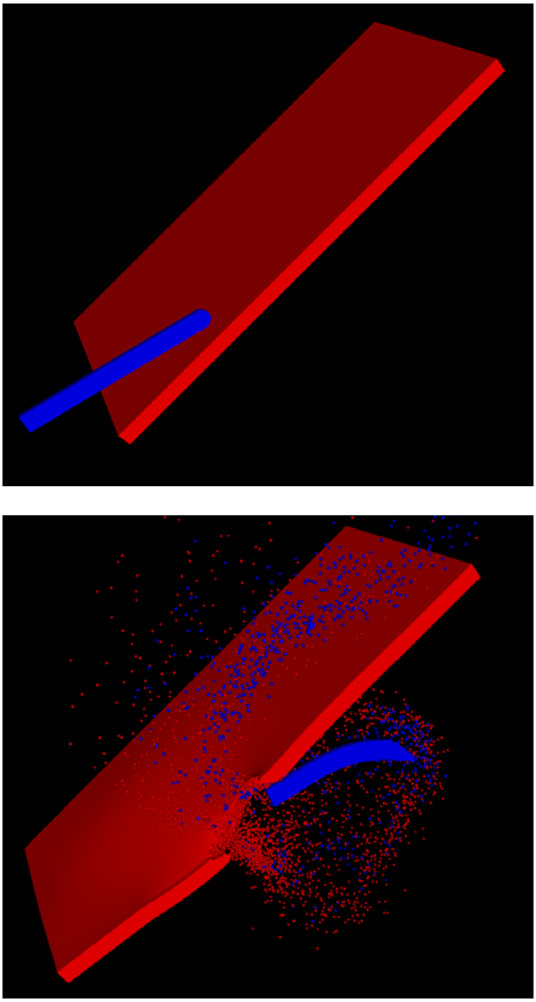

Figure 2. Long rod impact, sectioned particle-element plots at impact and at 100 microseconds after impact.

Figure 2 depicts an example impact simulation, which illustrates application of the method. The simulation models the oblique impact of a 0.767 cm diameter, L/D = 10, uranium alloy rod (velocity 1.21 km/s) on a 0.64 cm thick steel plate (velocity

0.217 km/s). The simulation employed approximately one million particles and elements. The simulation results for residual rod length (5.48 cm) and residual rod velocity (1.07 km/s) show good agreement with the corresponding experimental data (5.55 cm and 1.07 km/s) [3].

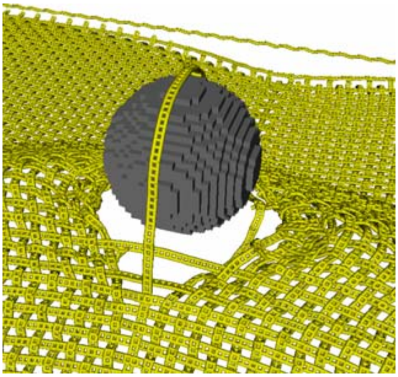

Figure 3. Simulation of a 0.22 caliber steel sphere impact on a single layer of Kevlar fabric at 250 m/s.

FABRIC MODELING

High strength fabrics are employed, in a multilayer configuration, in a variety of impact protection applications. Soft body armor is composed of 20-30 layers of Kevlar; a typical threat is a 0.20-0.30 caliber steel fragment with an impact velocity of 500 m/s. Some orbital debris shields deployed on the International Space Station incorporate 7-12 layers of Nextel/Kevlar; a typical threat is a centimeter size aluminum fragment with an impact velocity of 7-15 km/s. Simulation of impact effects on multilayer fabric targets is a difficult task. Fabric has a relatively complex internal structure, with both yarn-level (0.75 mm) and fiber level (12 micrometer) subscales. Numerous parameters (fiber type, weave type, yarn count, crimp, stitching patterns) affect fabric ballistic performance. Dynamic response to impact loads involves multiple intra-layer and inter-layer friction and contact-impact processes. Previous impact modeling work on fabrics has employed a variety of numerical methods. Simulations for body armor and turbine blade containment applications have most often employed a hexahedral finite element based approach [4] while hypervelocity impact simulation work has most often employed a particle based SPH approach [5]. Some disadvantages of a finite element based approach include mass or energy discard, excessive bending stiffness in hex models of the yarns, and difficulties with slideline modeling of very complex contact-impact effects. Some disadvantages of an SPH approach include tensile instability and numerical fracture problems. For multilayer impact modeling over a wide range of impact velocities (100 m/s - 15 km/s), an approach which combines the best features of finite element and particle methods is needed.

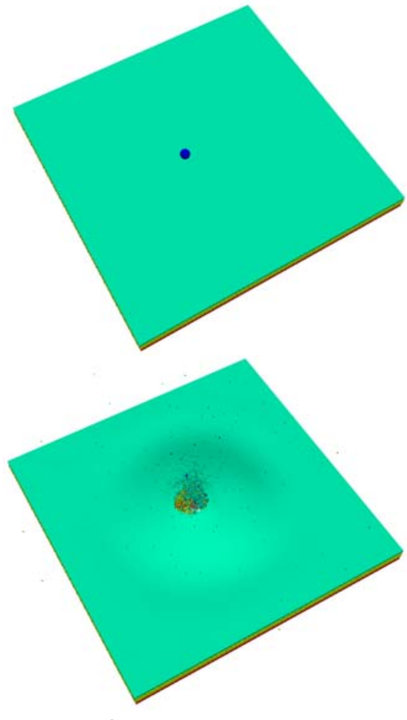

Figure 4. Orbital debris impact simulation, initial configuration and simulation results at 50 microseconds.

The authors are currently developing both yarn and membrane level numerical models of high strength fabrics, for application to body armor and orbital debris shielding design problems. The models employ the hybrid-particle element technique previously described, replacing the hex elements with bar elements which account for yarn or membrane tension. Figure 3 depicts a yarn level simulation of a 0.22 caliber steel sphere impact on a single layer of Kevlar fabric at 250 m/s. Note the explicit modeling of yarn level friction and contact-impact effects, and the high flexibility of the yarns. Although accurate accounting for such mesomechanical physics is a computationally difficult task, yarn level models may be required in order to accurately predict fabric performance in body armor applications.

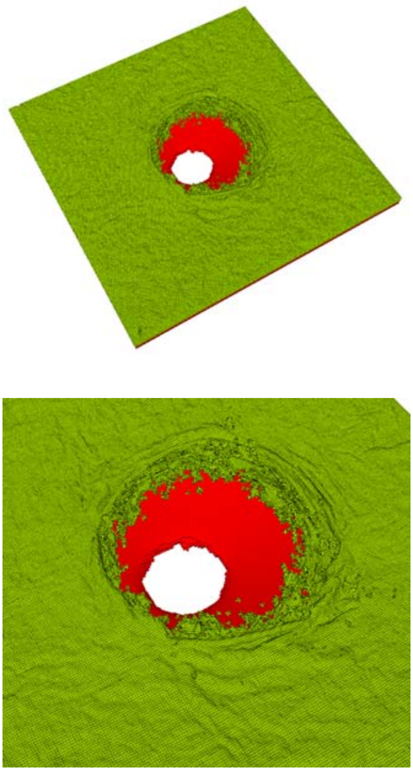

Figure 5. Orbital debris impact simulation, perforation detail for the Kevlar and lower aluminum target layers at 50 microseconds after impact.

In hypervelocity impact applications the authors are investigating the accuracy of membrane level particle-element models of fabric, which may reduce computational cost. Figures 4 and 5 depict the oblique (30 degree) impact of a 3.2 mm aluminum sphere on a layered aluminum-Kevlar target at 7 km/s. The upper and lower aluminum plates are 1 mm in thickness, and the total standoff is 5 mm. The intermediate target layer consists of six Kevlar panels. Work in progress is validating the computational model by comparison with experiments conducted at NASA Johnson Space Center.

CONCLUSIONS

A hybrid particle-finite element method is being applied to simulate multilayer fabric impact response, for impact velocities as low as 100 m/s and as high as 7 k/m. Initial work suggests that the method is well suited to model fabrics. The numerical method provides a unique combination of modeling advantages; its primary disadvantage is high computational cost .

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