HYBRID PARTICLE-ELEMENT SIMULATION OF COMPOSITE MATERIAL IMPACT PHYSICS

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Abstract

In this paper, previous and ongoing computational research employing a hybrid particle-element method is summarized and presented for the following advanced composite material systems: reinforced carbon-carbon composites, Kevlar-epoxy composites, multi-layered Kevlar woven fabrics, aluminum-Kevlar orbital debris shields, and porous tile thermal protection systems.

1 Introduction

Advances in composite materials and structures have substantially improved the design and performance of impact protection systems such as body armor, orbital debris shields for spacecraft, and blast protection for military vehicles. The ability of the advanced protection systems to mitigate impact threats arising from striking projectiles has been enhanced by employing high-strength and lightweight composite materials and structures including fiber-reinforced resin composites, fabric-resin laminates, and multilayer ceramic-fabric-metal composite structures [1].

As advanced materials are utilized, the development of reliable computer-aided virtual prototyping tools becomes more significant because purely experimental research is often high-cost and time-consuming. As a virtual prototyping methodology, the hybrid particle-element method, first developed by the second author for the simulation of hypervelocity impact phenomena in metallic materials [2], has been extended to simulate the ballistic and hypervelocity impact physics of composite materials and structures for use in various impact protections systems.

2 Hybrid Particle-Element Method

A hybrid particle-element method [2,3] is an energy-based Lagrangian method which uses particles and elements simultaneously, but not redundantly. Elements describe material deformation, strength effects, and the structured connectivity of inertial particles carrying thermodynamic properties and particle shape functions for a contact-impact algorithm. The translational and rotational kinematics of the modeled particles are described by their center-of-mass coordinates and singularity-free Euler parameters, respectively. Once this hybrid particle-element geometric model is established, a total Largrangian or Hamiltonian can be expressed in terms of the generalized coordinates, i.e., the kinematic state variables, thermodynamic state variables, and internal state variables (e.g. plastic strain tensor, normal and shear damage variables).

The hybrid particle-element formulation yields a strong form of the first-order system dynamics equations consisting of extended Lagrange's or Hamilton's equations as well as the time-evolution equations for entropy (or internal energy) and the internal state variables. The nonintegrable time-evolution equations are treated as nonholonomic constraints in the energy formulation. Various types of material constitutive equations and equations of state for compressed materials can be incorporated into the hybrid particle-element formulation, in a thermodynamically consistent fashion. This unique hybrid methodology allows the hybrid particle-element method to avoid: (a) the mass and energy discard algorithms in Lagrangian finite element methods, (b) the mass diffusion in Eulerian finite volume methods, and (c) tensile instability (causing numerical fracture) in pure particle methods.

A hybrid particle-element method has shown high accuracy in simulating various impact protection problems involving composite materials and structures, under both high-velocity and hyper-velocity impact loading conditions [4-8].

3 Modeling Composite Material Impact Physics

3.1 Reinforced Carbon-Carbon Composites

A reinforced carbon-carbon (RCC) composite has been used for the Space Shuttle leading edge and nose by virtue of its high thermal-shock resistance. The impact resistance of RCC-based composite structures in these applications is also a material property of interest, due to potential damage associated with orbital debris impacts. Investigation of the impact resistance of the RCC composite panel has become more important in the wake of the loss of the Space Shuttle Columbia in 2003. The disaster was caused by damage to RCC on the left wing leading edge which was struck by a piece of foam insulation. Fahrenthold and Park [5] and Fahrenthold Hernandez [4] developed a computational model to simulate the damage of the RCC panel by striking projectiles. Figure 1 depicts a simulation of a foam corner impact on the RCC edge at 775 ft/s [4]. An approximately 15 cm long crack was predicted for this corner impact case; the simulated crack size was close to the experimental value 14 cm.

Fahrenthold and co-workers [4,5] also have performed computational research studying the effect of impact obliquity and the geometry of the orbital debris on coating spallation and RCC panel damage. Figure 2 shows a simulation of a 0.35-g aluminum disc impact at a striking velocity of 7 km/s and at an obliquity of 45° on the RCC panel (which has silicon carbide coating to prevent the oxidation of RCC). Hybrid particle-element simulations have been used to predict the ballistic limit, the degree of coating spallation, and the size of RCC panel perforation.

3.2 Multilayer Kevlar Fabrics

Kevlar, a type of para-aramid fiber, is widely used in impact protection applications such as body armor, ballistic helmets and jet engine containment systems because of its flexibility and high strength-to-weight ratio. Kevlar is used in single- or multi-layered woven fabrics and composites. Rabb and Fahrenthold [6] have developed a yarn-level hybrid particle-element model to simulate projectile impacts on multi-layered woven Kevlar fabrics. Figure 3 depicts a .22 caliber steel fragment simulating projectile (FSP) impact on four layers of Kevlar fabric, with two fixed edges, at a striking velocity of 400 m/s [6]. The hybrid particle-element model in this simulation incorporates contact-impact at the yarn level and rate-dependent frictional interactions between neighboring yarns and between the projectile and the yarns. The hybrid particle-element method can model the evolution of fabric deflection, the inter-yarn interaction, yarn fracture, yarn pull-out, and the transport of fragmented debris from the fabric and projectile. This work can be extended to model a dissipation augmented Kevlar composite, such as a Shear Thickening Fluid (STF)-treated Kevlar fabric composite. This numerical research may also be also extended to model fabrics made of other synthetic fibers such as ballistic nylon and nano-augmented carbon fibers.

3.3 Kevlar-Epoxy Composite

Kevlar-epoxy composite is widely used in engineering applications such as spacecraft impact shielding systems, helicopter rotor blades, and containment systems for jet engine fan blades. Figure 3 shows a hybrid particle-element simulation of a 0.22 caliber steel FSP impact on a 0.3 cm-thick Kevlar-epoxy composite panel at 1 km/s and an obliquity of 30° [7]. Complex impact dynamics (e.g. shear and normal contact-impact interactions between material particles, kinematics of fragmented particles, damage and fracture in finite elements, the time evolution of thermodynamics properties of compressed materials, etc.) of high-strength fabrics and fabric composites are well described by the hybrid particle-element method.

3.4 Aluminum-Kevlar Orbital Debris Shield

Figure 5 depicts a hybrid particle-element simulation of an aluminum sphere impact on multi-layered aluminum-Kevlar orbital debris shield [8]. Debris from the shattered projectile and the outmost sacrificial aluminum plate will in general strike and damage the structural layers to follow. Because the hybrid particle-element method does not discard the failed mass particles, as is done in many finite element simulations, the protective performance of the shield can be more accurately predicted.

3.5 Porous Silica Tile Composite

Advanced Thermal Protection Systems (TPS) may be based on ceramic tiles, with a composite structure consisting of: the Toughened Unipiece Fibrous Insulation (TUFI) coating, advanced ceramic tile such as LI-900 and LI-2200 silica tiles, a strain insulation pad (SIP), and a titanium alloy (Ti-6Al-4V) plate. The development of a numerical method to estimate orbital debris impact effects on TPS at velocities outside the experimentally achievable range is important due to the limitations and high-cost of hypervelocity testing techniques. A hybrid particle-element model for hypervelocity impact simulation on ceramic tile TPS is currently under development. In particular, the development of the geometric model and material constitutive equations for a porous ceramic tile, well suited to the hybrid particle-element methodology, must be performed. Figure 6 illustrates research to date on the hybrid particle-element simulation of a spherical projectile impact on a porous silica tile [8]. The simulation results can describe the contact-impact interactions between modeled particles as well as the damage and spallation of the individual material subsystems.

4 Conclusions

The incorporation of advanced materials into modern impact protection systems has motivated the development of an experimentally validated computational method to assist current design processes, which rely heavily on experimental approaches. This paper has described completed and ongoing numerical research performed to investigate the impact physics of composite materials and structures under the threat of striking projectiles, at ballistic velocities and at hypervelocities. The three-dimensional energy-based numerical model described in the present paper can simulate the transient thermomechanical behavior of composite structures impacted by projectiles of various types over a very wide range of striking velocity and obliquity. The long-term objective of this research is to develop reliable virtual prototyping tools for designing TPS and orbital debris shielding for spacecraft, lightweight and flexible body armor systems, and other impact damage mitigation systems. To achieve this goal, further modeling and simulation work on composite materials and structures will be needed in the future.

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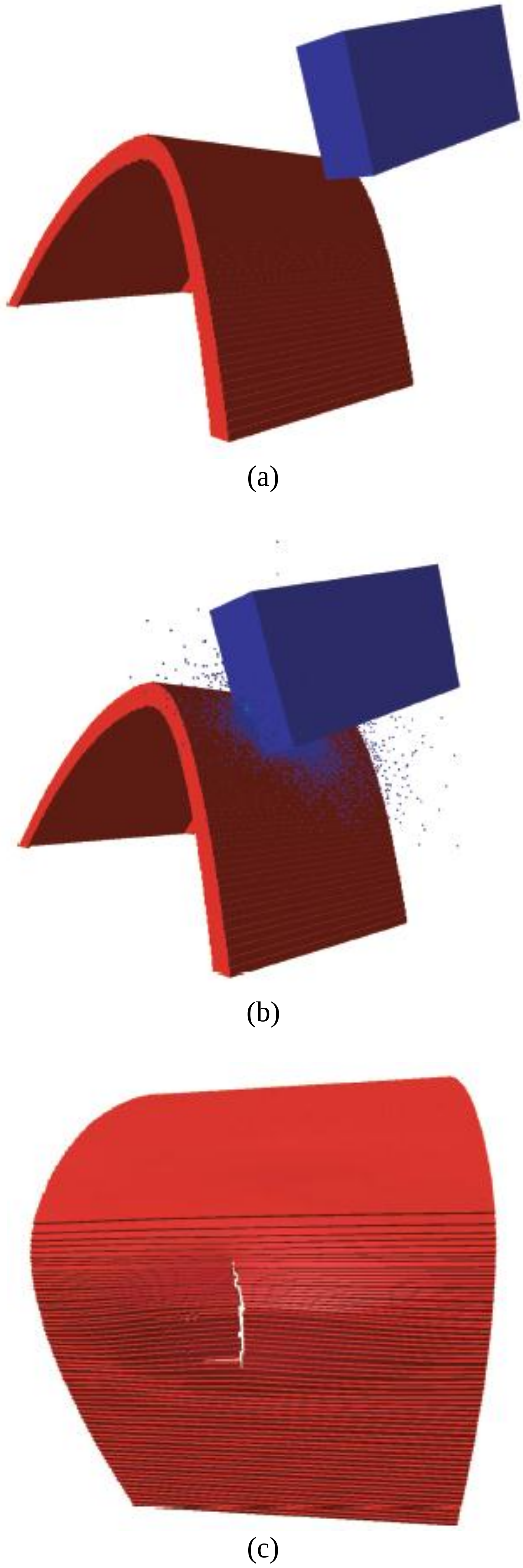


Fig.1. Simulation of a foam corner impact on the reinforced carbon-carbon panel [4]

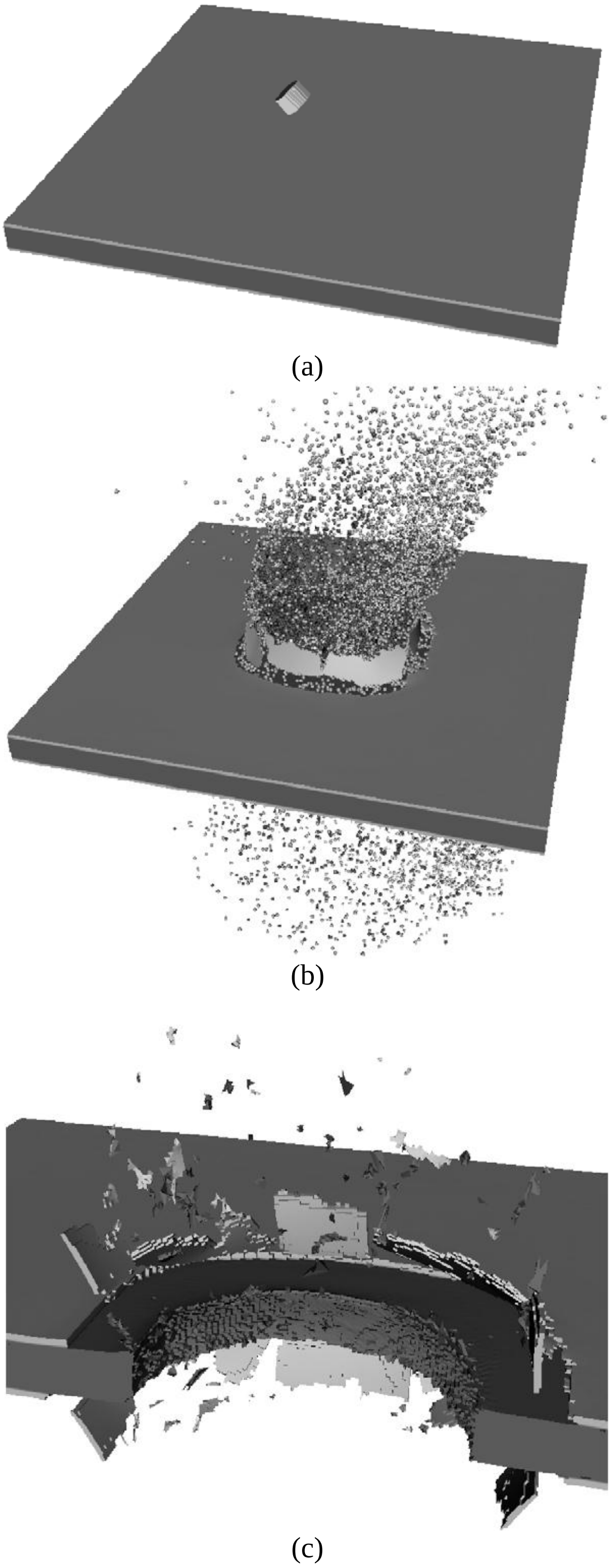
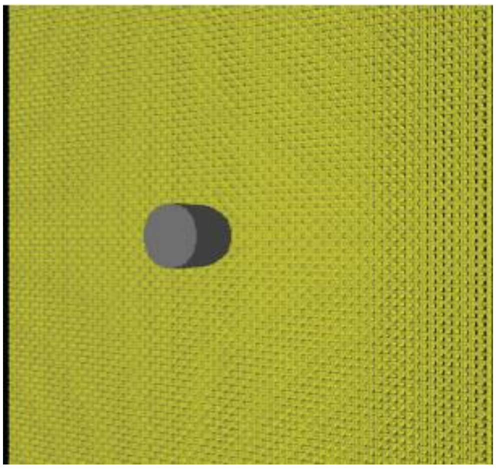


Fig.2. Simulation of hyper-velocity impact on the reinforced carbon-carbon composite panel [5]



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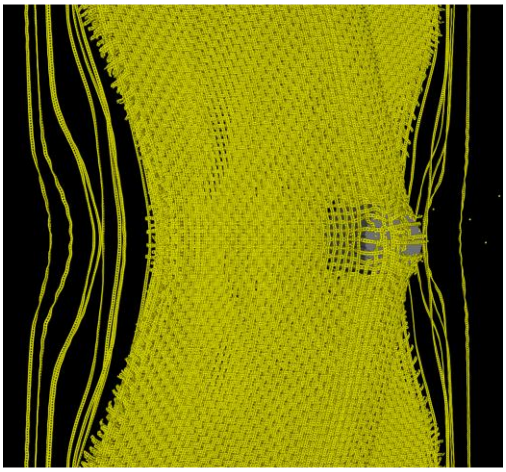

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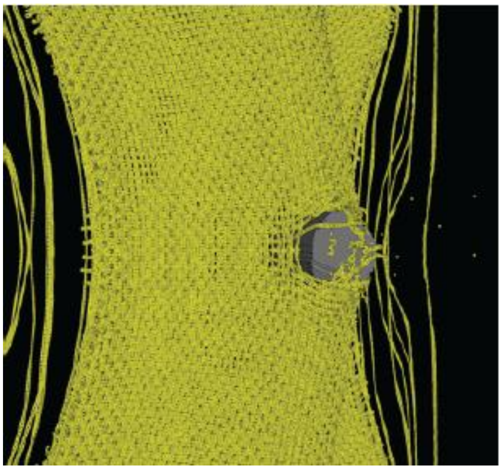

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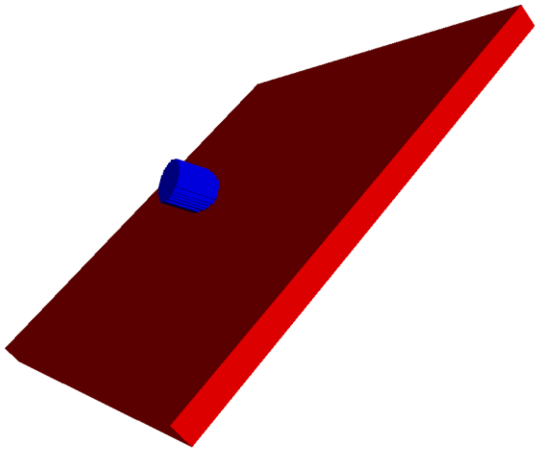
Fig.3. Simulation of a 0.22 caliber FSP impact on four layers of Kevlar with two fixed edges at 400 m/s [6]



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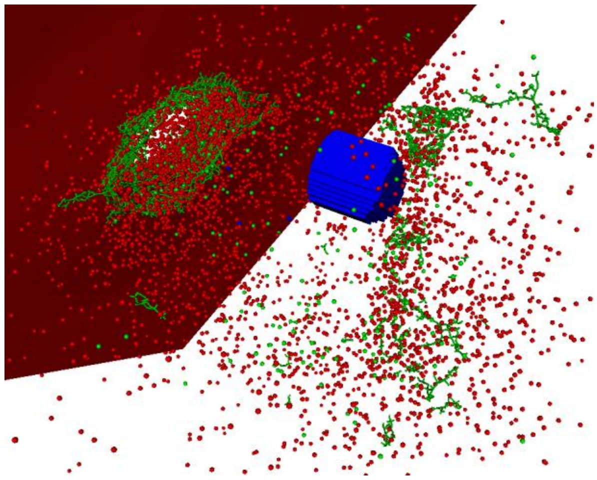

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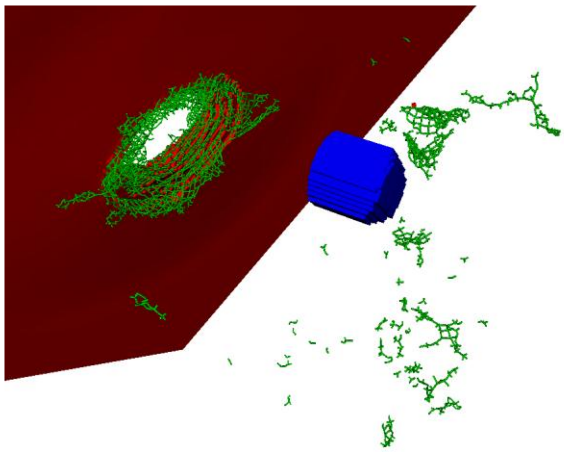

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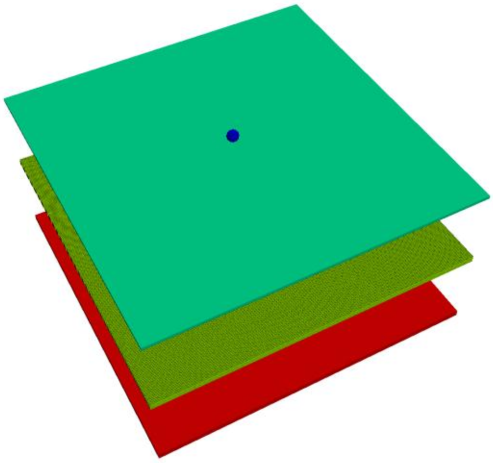
Fig.4. Simulation of a 0.22 caliber FSP impact on a Kevlar-epoxy composite at 1 km/s [7]



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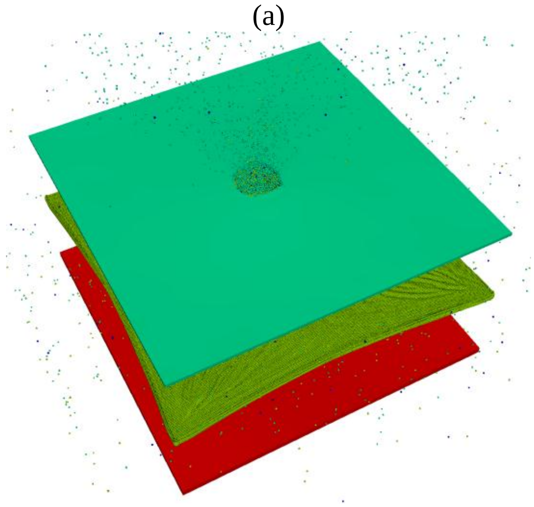

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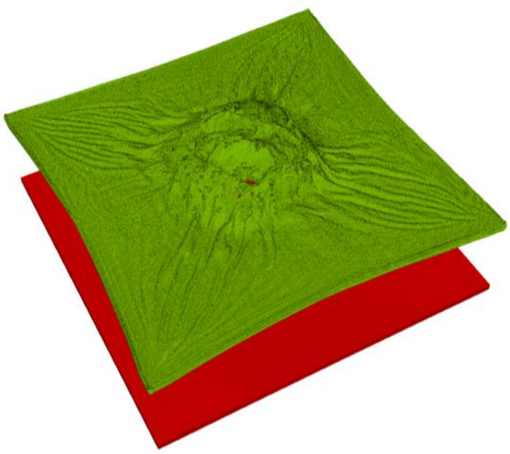

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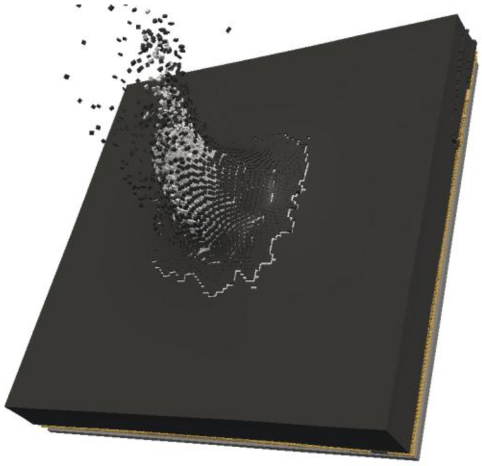
Fig.5. Simulation of a spherical projectile impact on an aluminum-Kevlar orbital debris shield [8]



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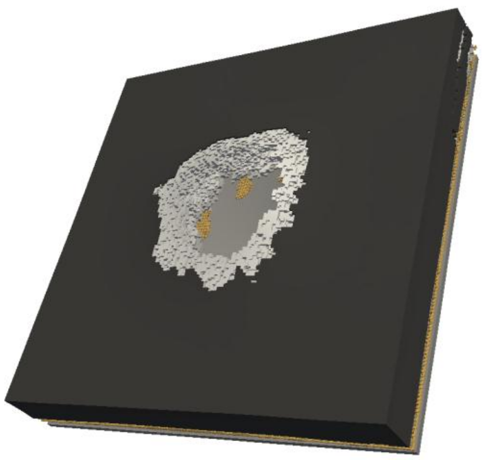

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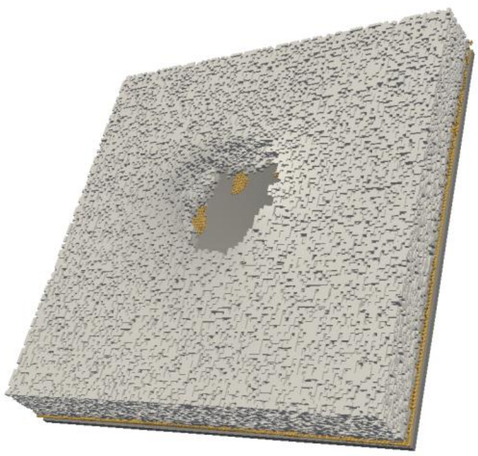

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Fig.6. Simulation of a spherical projectile impact on a porous silica tile [8]