SPECIALIZED PARTICLE-ELEMENT METHODS FOR ORBITAL DEBRIS IMPACT SIMULATION

Kwon Joong Son(1), Roque J. Hernandez(2), Eric P. Fahrenthold(3)

(1)Department of Mechanical Engineering, The University of Texas at Austin, 1 University Station C2200, Austin, TX 78712, USA, Email: iammrson@mail.utexas.edu
(2)Department of Mechanical Engineering, The University of Texas at Austin, 1 University Station C2200, Austin, TX 78712, USA, Email: roquehernandez@mail.utexas.edu
(3)Department of Mechanical Engineering, The University of Texas at Austin, 1 University Station C2200, Austin, TX 78712, USA, Email: epfahren@mail.utexas.edu

ABSTRACT

Improved computational methods for hypervelocity impact problems can assist in the design of spacecraft shielding and the development of orbital debris mitigation guidelines. Recent research has extended hybrid particle-element methods, developed specifically for hypervelocity impact simulation, to address problems of particular interest in orbital debris impact research.

1. INTRODUCTION

The 2007 demonstration of a Chinese anti-satellite capability and the very recent collision [1] of an Iridium satellite with a defunct Russian spacecraft have focused attention on the orbital debris threat to NASA spacecraft, military spacecraft, and to civilian spacecraft operated in support of the Department of Defense. Examples of DoD reliance on low earth orbit spacecraft are the Iridium constellation, which has supported DoD for more than five years [2], weather satellites located at 800-850 km, and a significant portion of the imaging and electronic surveillance satellites operated by the National Reconnaissance Office. Although the number of large, catalogued objects in earth orbit is measured in the thousands, it is estimated that tens of millions of uncatalogued, sub-centimeter sized debris particles are present, capable of damaging or disabling spacecraft [3]. Collision velocities lie in the range of five to fifteen kilometers per second. To date the problem of orbital debris has been of primary concern only for manned spacecraft, since the rather low probability of debris impacts has discouraged the introduction of dedicated satellite debris shielding. Despite this fact, NASA research has shown [4] that some relatively inexpensive modifications to commercial satellites can significantly reduce their vulnerability to orbital debris impact damage.

To account for the orbital debris threat, the spacecraft designer must: (a) describe the debris environment, specifically the size, velocity, and spatial distribution of particles in orbit, (b) estimate the probability of impact for each location on the spacecraft, as a function of orbit altitude, orbit inclination, and spacecraft orientation, and (c) quantify the expected damage for all potential impacts, as a function of structural geometry and material composition. Research on the first two tasks is, relatively speaking, well advanced and is imbedded in the computer code BUMPER, maintained by NASA. However a significantly increased research effort is needed to properly address the third task, namely quantifying the damage associated with orbital debris impacts.

Predicting the damage associated with orbital debris impacts is complicated by three factors: (a) spacecraft are produced in small quantities and often incorporate a wide range of complex and expensive materials, (b) approximately one third of the impact velocity range of interest lies outside the capabilities of light gas guns, which are currently limited to less than ten kilometers per second at the projectile sizes of interest, and (c) conventional numerical methods, such as Eulerian hydrocodes, are ill suited to address important features of the orbital debris impact simulation problem.

2. ORBITAL DEBRIS IMPACT SIMULATION

The inability of current experimental methods to reach the entire velocity range of interest in orbital debris applications has encouraged the development of new impact simulation codes for survivability analysis and shielding design, funded by both NASA [5] and the European Space Agency [6]. Note that a purely experimental approach to the shielding design problem, possible in principal for low velocities only, calls for a very large number of impact tests, since each test investigates only one of many different possible combinations of: (a) projectile mass, material, geometry, velocity, and impact obliquity, (b) structural material and geometry, and (c) shielding design (if applicable). The relatively high cost and limited production of many spacecraft materials and structures means that there is considerable benefit in the development of computer aided design tools for simulation of orbital debris impact problems at all velocities.

Proc. '5th European Conference on Space Debris', Darmstadt, Germany
30 March – 2 April 2009, (ESA SP-672, July 2009)

A number of different numerical methods and codes have been used in hypervelocity impact applications. The available codes are in general one of four types: Lagrangian finite element [7], Eulerian finite volume [8], smoothed particle hydrodynamics (SPH) [9], or some particle-element formulation [10]. The present paper describes extensions of a parallel hybrid particle-element method and code [11] developed under previous NASA, NSF, and ONR support. This numerical method and code has several advantages in the present context [12]. Unlike pure finite element methods it is capable of simulating large deformations in comminuted media, very important in the analysis of spacecraft fragmentation. Unlike finite volume methods it can represent strength effects in a Lagrangian frame, important in the accurate prediction of structural failure. Finally, unlike pure particle methods and alternative particle-element formulations, it is not subject to tensile instability or numerical fracture. The unique Hamiltonian method used to develop this hybrid particle-finite element formulation is well suited to model fragment transport and contact-impact of all intact and failed material, as well as the history dependent material failure process. As a result, the numerical method used here provides an explicit description of fragment mass, shape, velocity, temperature, etc. (consequently a "fragmentation model" based on internal state variables [13] is not required).

Since orbital debris shielding designs, such as shielding deployed on the International Space Station, may very well include Kevlar or other fabrics, it is important to take note of the literature in this field. Virtually all computational work on fabrics has employed finite element techniques. Although finite element methods have been applied with success to model a single layer of woven material [14], significant numerical difficulties (such as mass and energy discard) have been encountered in modeling multi-layer configurations, so that practical debris shields (which contain a dozen or more layers) are not accurately represented using pure finite element models. Recent research has demonstrated the ability of the method and code used in this research to model the complex contact-impact dynamics and failure of multi-layer woven fabrics under fragment impact.

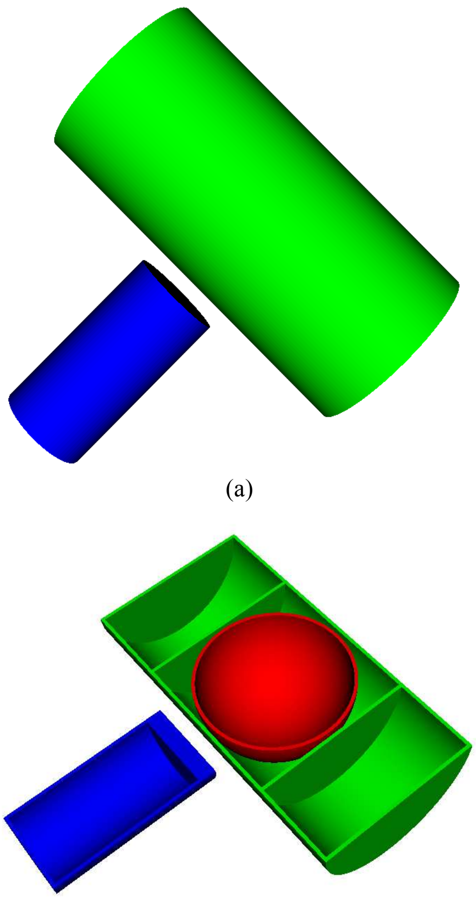
3. HYBRID PARTICLE-ELEMENT METHOD

Fig. 1 depicts projectile and target models broadly representative of spacecraft structures. The target is a cylindrical body (green) with an internal tank (red), whereas the interceptor is a cylinder with a thick end cap (blue). The graphics in Fig. 2 depict an impact sequence, at a velocity of 3.5 km/s, performed over a period of 100 microseconds. As the sequence illustrates, the modeled breakup includes large fragments, such as the back end of the target and tank, as well as numerous small fragments (individual particles) ejected at or near the point of collision.

The preceding example illustrates the development of improved hybrid particle-element methods to account for the geometric complexity of spacecraft. Additional research has focused on the requirement to model the many complex materials involved in spacecraft design, including fabric impact protection systems and tile thermal protection systems.

Fig. 3 shows a simulation of an aluminum sphere impact on a type LI-900 Space Shuttle tile.

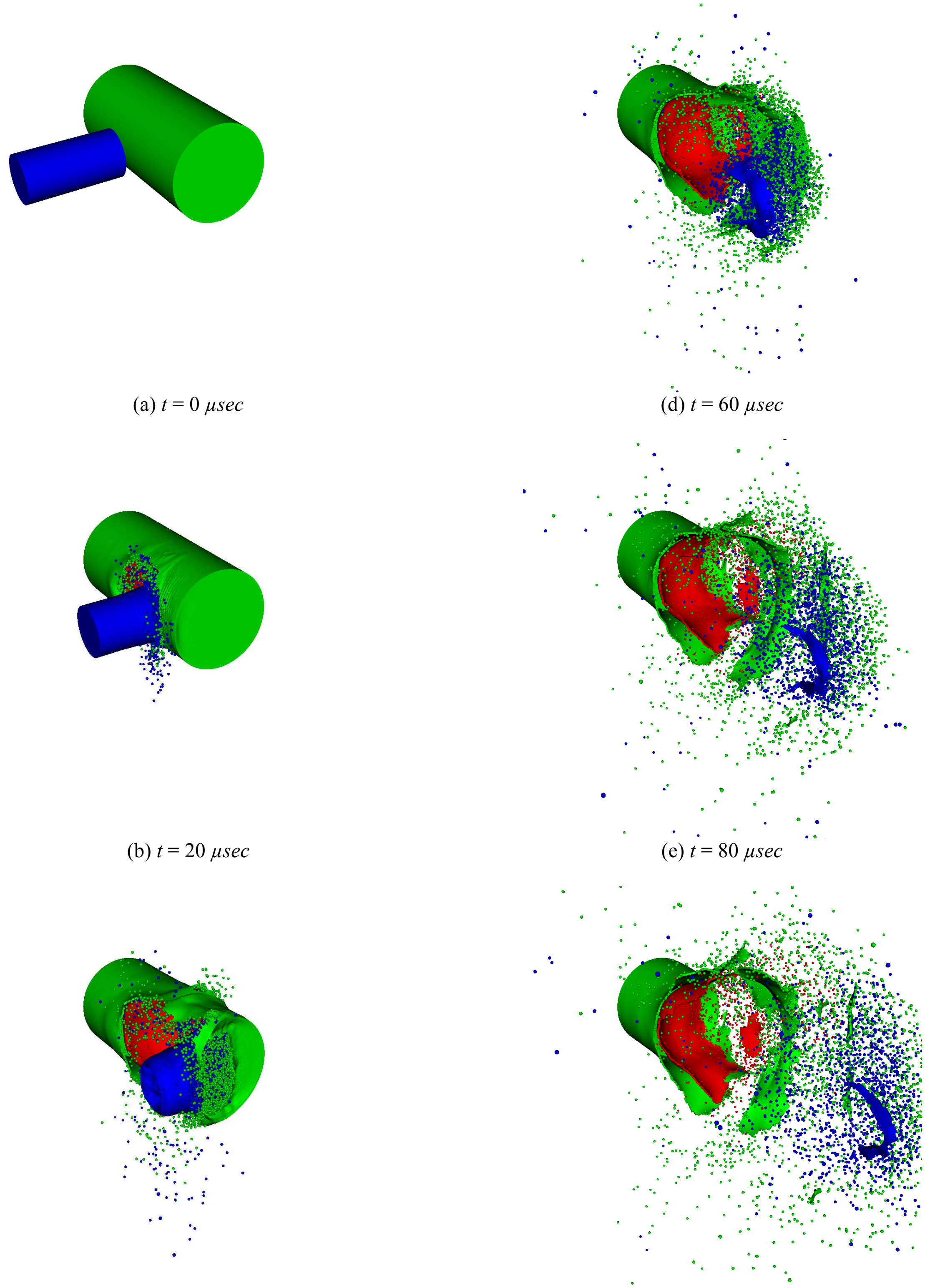
Fig. 4 shows a simulation of an aluminum sphere impact on multi-layer aluminum-Kevlar orbital debris shield.



(a)

(b)

Figure 1. Schematic of a representative spacecraft collision model



(a) $t = 0$ *μsec*

(d) $t = 60$ *μsec*

(b) $t = 20$ *μsec*

(e) $t = 80$ *μsec*

(c) $t = 40$ *μsec*

(f) $t = 100$ *μsec*

Figure 2. Simulation of spacecraft collision

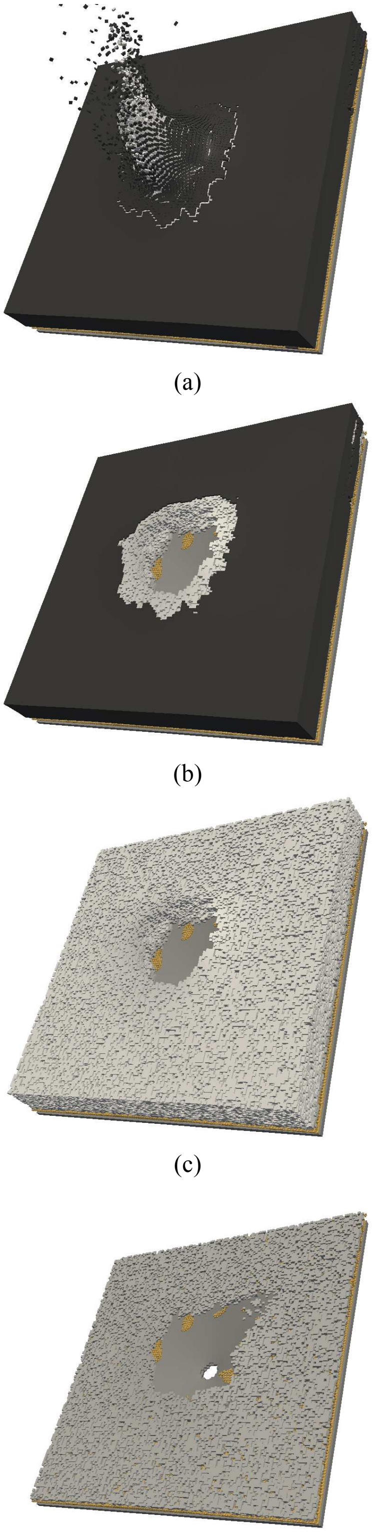

(a)
(b)
(c)
(d)

Figure 3. Simulation of orbital debris impact on a type LI-900 porous silica tile

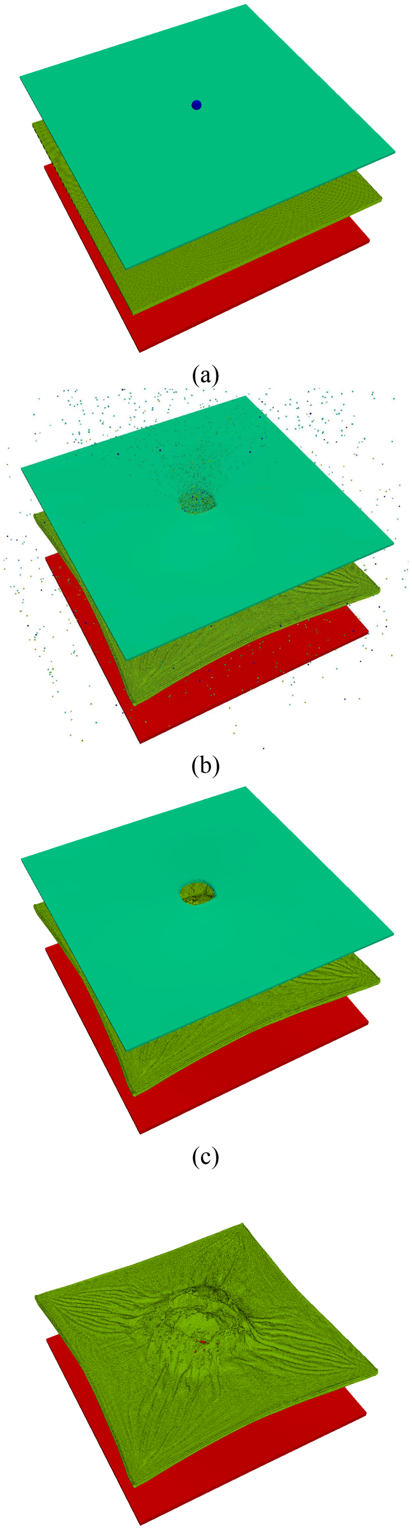

(a)
(b)
(c)
(d)

Figure 4. Simulation of orbital debris impact on an aluminum-Kevlar orbital debris shield

4. CONCLUSIONS

The simulations described in this paper illustrate work completed or in progress. Additional work is needed to develop, implement in parallel, and validate against experiment new particle-element computational models and new thermomechanical material models for the simulation of hypervelocity impact effects on three classes of materials of primary interest in spacecraft design. They are carbon fiber composites, metal-composite honeycomb, and membrane materials. Each of these materials presents distinct modeling challenges.

The motivation for research on the aforementioned classes of materials, and the principal associated modeling challenges, are as follows:

- Carbon fiber composites: these are important spacecraft structural materials, and reinforced composites have in some cases been employed as debris shielding; the most important modeling challenge is the development of equations of state and material constitutive models which reflect the variation of impact performance with fiber volume fraction.
- Metal-composite honeycomb: these are again important spacecraft structural materials; the most important modeling challenge is the development of numerical models which reflect the channeling of impact debris observed in hypervelocity impact experiments.
- Membrane materials: these are employed in solar panels, in antennas, and as thermal insulation blankets; the most important modeling challenge is the development of numerical models which simultaneously reflect their low bending stiffness, their complex contact-impact dynamics in a multi-layer configuration, and their sometimes very weight efficient debris shielding performance.

The long-term objective of this research is the development of an experimentally validated computational tool for use in virtual prototyping of new spacecraft designs.

5. ACKNOWLEDGEMENTS

This work was supported by NASA Johnson Space Center and the Office of Naval Research.

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