Simulation of Granular Ceramic Armor Under Impact from Bullets

James G. McLean, Seth Frutiger, Robert Dabek, and Jeremy Reeves
State University of New York at Geneseo, Department of Physics and Astronomy, Geneseo, NY 14454

Abstract

Ballistic impact is studied for a novel form of armor, granular ceramic armor. Ceramic granules, in the millimeter size range, are closely packed and bonded together using a relatively soft polymer. This composite layer rests on a rigid backing. In field tests such panels have already shown the capability to stop armor piercing rifle rounds. The goal of the study is to determine the detailed mechanisms of energy and momentum dissipation. Because of the granular structure, the armor performance depends on the exact impact position. We are particularly interested in determining the weakest points for further design improvements. Mapping of exit velocities indicates that some of the stronger and weaker points are at surprising impact positions due to grain tumbling.

Introduction

The concept of using ceramic materials in armor systems for defeating projectiles is well known. Ceramic materials are attractive for armor applications due to their high compressive strength and high hardness as well as their low density compared to other typical armor materials such as steel. Products are currently available utilizing this idea, such as Dragon Skin® [1]. Current composite ceramic armor designs generally consist of ceramic plates, arranged in a mosaic pattern and backed with a more compliant material. Ceramic tile armor systems have been heavily studied, and the dynamics of its response to ballistic impact, as well as its failure mechanisms, are relatively well understood.

Ceramic armor tiles are brittle by nature, which degrades their multi-hit capability. An alternative aiming to alleviate this deficit is granular ceramic armor, consisting of an array of relatively small ceramic elements bonded together on a rigid backing. For instance, this has been suggested by Ko et al. [2, 3]. The small ceramic elements can give the system three advantages. First is a smaller critical flaw size. Smaller dimensions mean fewer flaws and higher failure stresses. Second is the scattering of destructive shock waves, which contribute to an important damage mechanism in ceramic tile armor designs. The surfaces of the ceramic grains act to scatter waves more efficiently than flat tile surfaces. Third is the ability to direct the force of impact laterally. As the bullet penetrates, the grains are forced in the lateral direction. This response is very different from that of an armor tile, in which tensile cracks initiate on the non-impact side.

Model

The specific design studied in this work is based on vehicle armor panels currently under development by Armor Dynamics [4]. The ceramic elements are off-the-shelf alumina grinding pellets, 13mm by 13 mm cylinders in shape with a beveled edge. These are packed in a regular hexagonal array presenting their circular face. In order to close up the inter-granular gaps, the cylinders are then tilted by 30°. The ceramic cylinders are bonded together by a relatively soft urethane material, the function of which is to hold the assembly in place rather than to provide protection. This construction does not provide the flexibility that would be required for body armor, but it does allow for relatively easy molding to contoured surfaces such as vehicle wheel wells.

In order to function, this ceramic assembly must be backed by a rigid layer, which absorbs the distributed projectile momentum. Performance field tests on prototypes have shown the capability to defeat armor piercing rounds. The design also seems to be superior to conventional steel plate armor in preventing ricochets.

To better understand the performance of this armor, we have used LS-DYNA® to model impacts on it by 7.62mm M61 armor piercing rounds. Of particular interest is the question of weak spots, which might be expected, for instance, in between the ceramic elements. This problem is particularly suited to modeling, as it is difficult to target specific points in field tests.

All parts are simulated using a Lagrange mesh of 8-node solid elements in LS-DYNA® run on an MPP cluster. The ceramic elements use the Johnson-Holmquist Ceramic material model [5] with parameters for alumina obtained from Ref [6]. The armor piercing core of the bullet is modeled using the Johnson-Cook material model with a Linear-Polynomial equation of state, while the lead components (front and rear filler) are modeled with the Plastic-Kinematic material model. The rigid backing used was a 9.5mm thick plate of 2024-T3 Aluminum modeled using Johnson-Cook.

Due to extreme strains some element erosion appears to be necessary to allow the simulations to proceed to conclusion. Despite the non-physical nature of simulated erosion, there is some physical basis for this in that post-mortem dissection of field tests reveals parts of the bullet and ceramic to in fact be “eroded,” that is, no longer be present. This is true both for parts of the ceramic elements, which have been ground to a dust, and for the bullets, especially the lead components, which presumably have evaporated.

Results

A representative result is given here, with further details to be presented in conference.

In simulation, the armor panels did not stop bullets as effectively as field tests have indicated, with all simulations resulting in penetration of the aluminum backing plate. Reasons for this discrepancy are still under investigation. Despite this, and the significant level of erosion required, we believe that the simulation results remain useful in comparing the strength or weakness of various impact points on the armor.

Figure 1 illustrates the remaining total kinetic energy for all bullet parts after penetrating the backing plate. The bubbles represent energies ranging from 313J to 604J (compare to the initial kinetic energy of 3150J).

Some of the results are to be expected. For instance, the minimum exit energy (and thus greatest protection) occurs for impacts directly on the center of a ceramic element (site A). Relatively

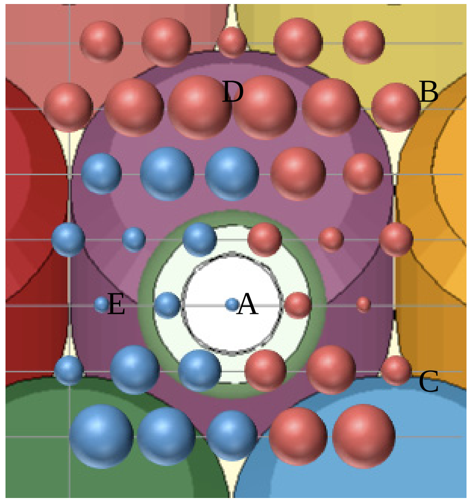

Fig. 1 Exit kinetic energies for non-eroded parts of the bullet obtained from simulations for various exit parameters. The green circle in the center is the bullet. Blue bubbles show direct simulation results; red bubbles are duplicates of those results based on the symmetry of the armor panel.

larger exit energies occur for impacts at site B, which is near an inter-granular gap where first impact is between two ceramic elements.

However, some of the results are more surprising. Inter-granular site C, where first impact is with a single ceramic element, has a significantly lower exit energy than is the case for site B. The greatest penetration occurs near site D, significantly displaced from a gap. Perhaps most surprising is the low exit energy for impacts at site E, very near the contact point of two ceramic grains.

Further analysis, to be presented at conference, suggests ways to modify the elements of the armor to improve upon its weaknesses.

References

[1] http://www.pinnaclearmor.com/body-armor/dragon-skin/, Pinnacle Armor, Fresno, CA.
[2] Yu, J. Z., Lei, C., Ko, F. K., "lmpact Responses of Gradient Designed Textile Structural Composites under Low and High Impact Velocities," ANTEC (1994).
[3] Ko, F., Yu, J. Z., Song, J. W., "Characterization of Multifunctional Composite Armor," Proceedings of the American Society for Composites, 947–956 (1996).
[4] http://www.armordynamics.com/, Armor Dynamics, Inc., Kingston, NY.
[5] Johnson, G. R., Holmquist, T. J., "An Improved Computational Constitutive Model for Brittle Materials," High-Pressure Science and Technology – 1993 American Institute of Physics Conference Proceedings 309, 981–984 (1994).
[6] Cronin, D. S., Bui, K., Kaufmann, C., McIntosh, G., Berstad, T., "Implementation and Validation of the Johnson-Holmquist Cermaic Material Model in LS-DYNA," 4th European LS-DYNA Users Confernce, 47–60.