VIRTUAL EXPERIMENTS TO DETERMINE BEHIND-ARMOR DEBRIS FOR SURVIVABILITY ANALYSIS

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ABSTRACT

When a projectile perforates the armor of a vehicle, the residual projectile entering the vehicle is accompanied by a much wider cloud of behind-armor debris (BAD) generated by stress wave interactions. BAD plays an important role in the evaluation of survivability of crew and components in a vehicle under fire. Survivability/vulnerability analysis codes (e.g., MUVES) require an input of BAD characteristics of the armor for each threat projectile. This data is currently generated by conducting laboratory experiments in a standard set-up in which each threat projectile is fired on the actual armor and the BAD pattern is captured on witness plates. Conducting survivability analyses of vehicles in the design phase, before the armor is actually built, poses a challenging problem. To solve this problem, we have come up with an innovative approach to determine BAD characteristics by conducting virtual experiments of the standard set-up. We do this by conducting physics-based three-dimensional (3-D) computer simulations with the CTH wave code. We obtain BAD characteristics for impacts of kinetic energy rods and shaped-charges on metal and ceramics plates, including some yawed rod impacts. An additional advantage of these simulations is that they provide important details of the debris field that are difficult to obtain in laboratory experiments. The expected impact of this work would be to improve the timeliness, accuracy, and cost of survivability analyses for Army's decision makers.

1. INTRODUCTION

A projectile perforating a vehicle's armor produces a large ellipsoidal cloud of behind-armor debris (BAD) resulting from multiple stress-wave reflections in the target armor. BAD is an important factor in producing crew injuries and component damage in vehicles impacted by projectiles. The vulnerability analysis suites of codes (e.g., MUVES) require as an input the BAD characteristics of the armor under consideration for each threat projectile, e.g., a kinetic energy (KE) rod. In the conventional method, BAD characteristics are determined by conducting laboratory experiments with a standard set-up in which the projectiles are fired on the actual armor plate and BAD is captured on a witness plate placed some distance behind the target plate. The resulting BAD pattern on the witness plate is analyzed to obtain parameters that are then input into vulnerability analysis codes (e.g., MUVES) to determine system survivability/vulnerability. Conducting survivability analysis of vehicles in the system design phase, before the armor is actually built, poses a challenging problem. To solve this problem, we present an innovative methodology in which we conduct virtual experiments of the standard set-up by performing physics-based numerical simulations with the CTH finite-difference code on Army's high performance computers. In addition to providing the BAD pattern on witness plates, these simulations give quantitative information on time evolution of the debris field which is difficult to obtain in laboratory experiments.

CTH is an Eulerian wave-code which uses material properties as an input. The equations of continuum mechanics are integrated over a spatial mesh in small time steps. We used the Johnson-Cooke model of plasticity. The simulations were conducted in three-dimensions (3-D), using 10-20 million Cartesian cells, on the high performance computers at the Major Shared Resource Center (MSRC) on Aberdeen Proving Ground. We present results of our virtual experiments to obtain the BAD pattern on witness plates for impacts of KE rods and shaped-charge on arbitrary metal and ceramic armor.

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2. VIRTUAL EXPERIMENTS OF KE ROD IMPACTS

We present results of two virtual experiments to determine BAD generated by impact of a KE rod on rolled-homogeneous armor (RHA). In the first one, the impact is normal with zero yaw; in the second, the impact is with high yaw. This will enable us to see how the BAD pattern changes when a specific yaw is given to the impacting rod. In both simulations, a witness plate is positioned behind the target plate and parallel to it. Figure 1 shows the cross-sectional view of an early stage of a 3-D simulation in which a rod of length (*L*) *12.45* cm, diameter (*D*) *0.4* cm, strikes a steel armor plate of thickness *11.45* cm with a velocity of *1.6* km/s normal to the plate. A thin witness plate is placed at a distance of *11.45* cm behind the plate. After the rod perforates the armor plate, the behind armor debris impinges upon the witness plate. The BAD distribution on the witness plate obtained by simulation is shown in Figure 2.

Figure 3 shows the distribution of velocities of debris fragments as a function of radial distance (measured along the back surface of the target) from the impact axis, obtained by our virtual experiment. This is a significant new result, as it is presently not practical to obtain this velocity distribution by experimental measurements (Prakash, 2003). In the laboratory, it is difficult to keep track of each individual fragment in a time sequence of x-ray shadowgraphs. The current survivability analyses simply make assumption about the shape of the BAD velocity distribution.

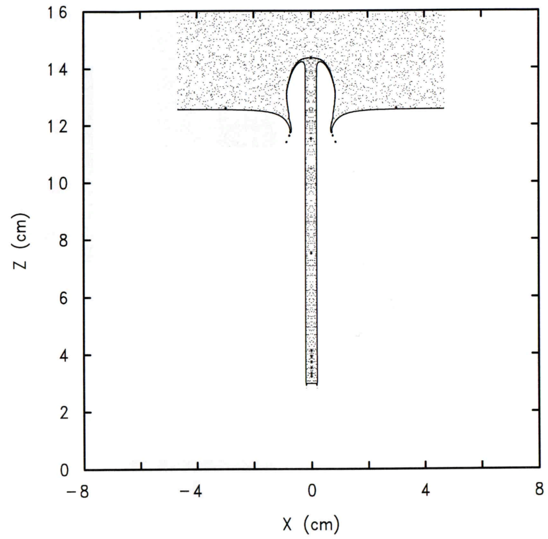

Figure 1. The simulated impact of a long rod on a thick armor plate to determine the characteristics of behind armor debris (BAD).

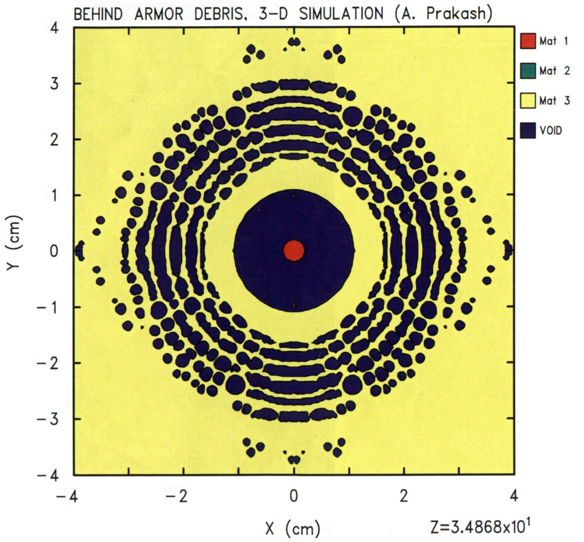

Figure 2. Result of a virtual experiment to determine behind armor debris (BAD) pattern captured on a witness plate placed behind a steel armor plate which was perforated by a rod impacting with zero yaw.

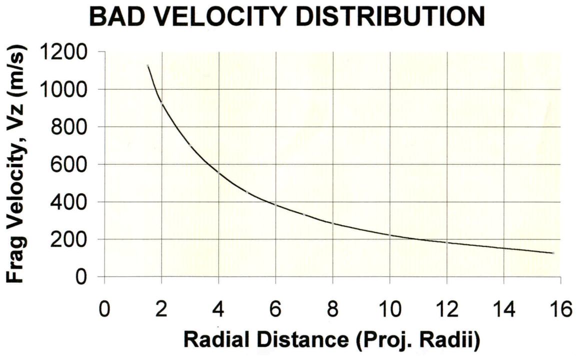

Figure 3. Velocity of debris fragments as a function of radial distance of the point of origination of the fragment from the impact axis, measured along the back surface of the target.

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To investigate how the introduction of yaw in the incident rod would alter BAD, we conducted 3-D simulations of impact of an $L/D = 30$ rod, moving at 1.6 km/s with 15^o yaw. The target thickness was taken to be $t = 0.34L$, and a thin witness plate was positioned behind the plate at a separation equal to the target thickness. Figures 4a,b show an early (20 μs) stage and a late stage of penetration. We find that the yawed rod exits the back surface of the target with a lateral shift from the line of initial impact. The BAD distribution captured on the witness plate by the simulation is shown in Figure 4c. The dark region is the portion of the witness plate that is affected by the impinging debris. Rod and target fragments arriving at the witness plate at this time (190 μs after rod impact on the target) are distinguished by color/shades. The debris pattern shows marked differences from the case of impact with zero yaw (Figure 2). Again, it is difficult to conduct a laboratory experiment to determine BAD pattern generated by a rod with a pre-specified yaw at such high velocities.

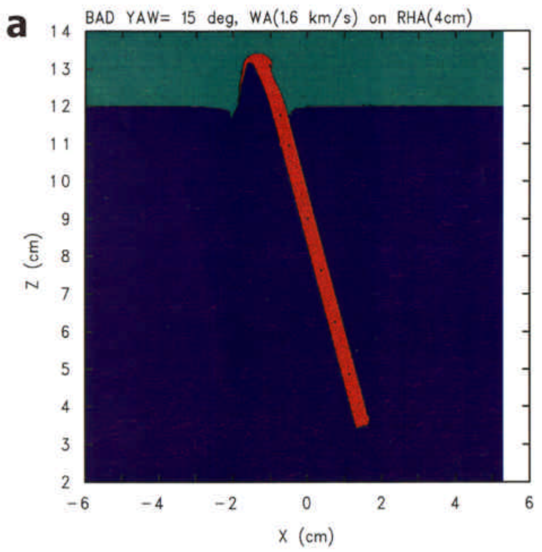

Figure 4a. An early stage of penetration of a yawed rod in the simulation.

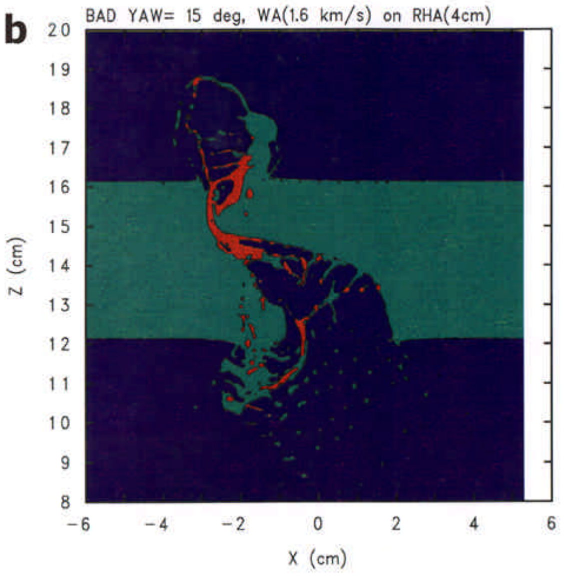

Figure 4b. A late stage of the simulation showing perforation of the target plate by a yawed rod that is moving upward. Notice that exit point is displaced laterally.

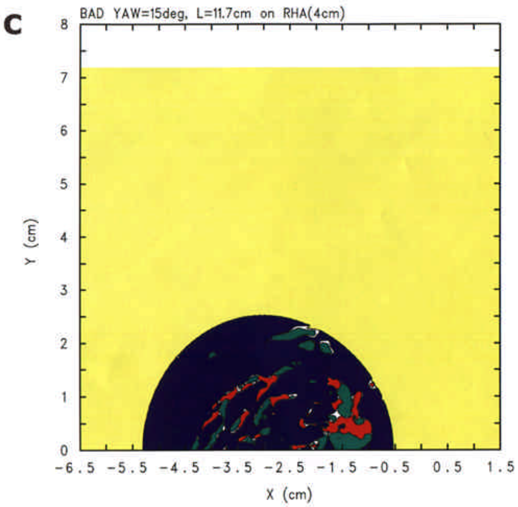

Figure 4c. Simulated behind armor debris (BAD) produced by the yawed rod impact. The dark portion is the region of the plate affected by BAD. The red and green pieces are the rod and target fragments, respectively (at 190 µs).

3. VIRTUAL EXPERIMENT OF SHAPED-CHARGE IMPACT ON CERAMIC ARMOR

The following figures show the results of a virtual experiment to determine BAD characteristics of a hypothetical ceramic armor perforated by a copper shaped-charge (red) impacting at *8* km/s. The target consists of *.5*" SiC (green) backed by *.5*" Ti (light-blue). The left side of Figure 5 shows the pressure contours of stress waves in the target during perforation, at *7.5* µs after impact. Figure 6 shows the developing holes forming in pulverized ceramic at the entrance and in titanium plate at the exit, at *87.5* µs after impact. Finally, the virtual BAD pattern captured on a witness plate (dark-blue) placed *8*" behind the target is shown in Figure 7.

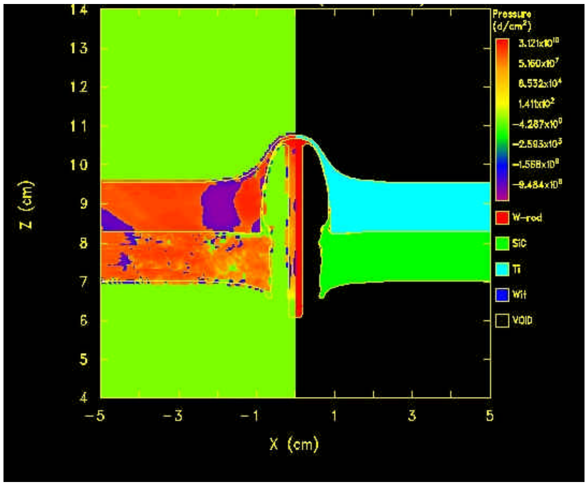

Figure 5. Simulated shaped-charge penetration in ceramic armor, at 7.5 µs.

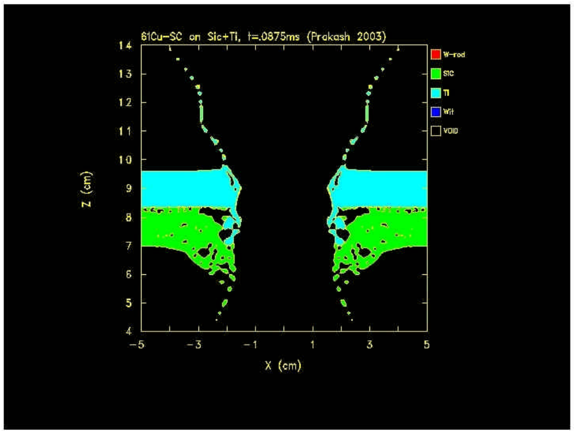

Figure 6. Entrance (bottom) and exit holes forming in SiC+Ti armor shortly after perforation by shaped-charge.

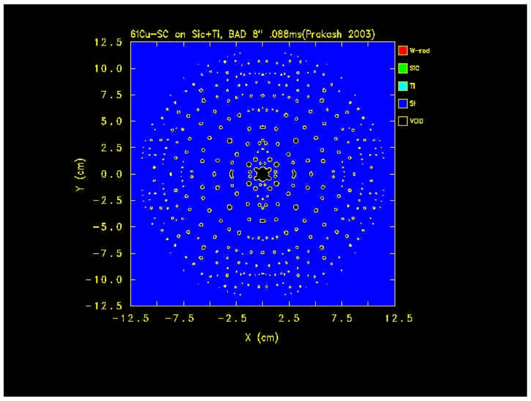

Figure 7. Simulated pattern of behind-armor debris (BAD) from shaped-charge impact on ceramic armor, collected on a witness plate eight inches behind the target.

As a validation, we have compared the above results of the virtual experiments with those of an actual experiment conducted in the laboratory (personal communication from John Abell and Richard Saucier, 2003). As shown in the Table, the hole sizes and 95% cone angles show good agreement with the experimental results, however, the distribution of fragments does not show similarly good agreement. While results to date are promising, we are doing additional work to determine if CTH can provide a better prediction of actual fragmentation distributions within the spall cone.

Table 1. Validation Data

	VIRTUAL EXPT.	RANGE EXPT.
Entrance hole diameter	2.36"	2.6"
Exit hole diameter	1.57"	1.3"
95%BAD cone half-angle	32° (true origin)	34° (assumed origin)

4. DISCUSSION OF RESULTS

We have presented results of virtual experiments of behind armor debris (BAD) produced in impact of kinetic energy rods and shaped-charge on vehicle armor, by conducting three-dimensional numerical simulations with the wave code CTH. Results of these virtual experiments showing BAD distributions captured on witness plates placed some distance away from the armor have been presented. These simulations shed light on features of BAD that are difficult to obtain experimentally. For example, the velocity distribution of fragments as a function of position on the back surface of the target plate has been obtained. Moreover, our simulations yield BAD patterns for high velocity KE rod impact with large yaw. These are shown to be drastically different from conventional BAD produced by rods impacting with zero yaw. For example, it is shown that the position on the back surface of the target plate where the rod fragments emerge is laterally shifted from the point of impact. It would be difficult to conduct such an experiment in the laboratory. It would also be difficult to make a simple analytical model to obtain these features. Our virtual experiment on BAD from a shaped-charge impact on a complex ceramic target was subjected to a validation test by comparing the results with an actual laboratory experiment. The comparison showed good agreement for the size of hole in the armor and for the 95% debris cone angle, however, the distribution of fragments does not show similarly good agreement. More work is needed to determine if CTH can provide a better prediction of actual fragmentation distributions within the spall cone. The simulations capability described here is at present the only possible avenue for conducting BAD vulnerability analysis of vehicles in the design phase (before the armor is built).

5. CONCLUSION

The virtual experiments to determine behind-armor debris characteristics by performing physics-based 3-D numerical simulations with the CTH code presented here demonstrate a new way to enable survivability analysis of conceptual or actual armor. The expected future impact of this capability is three-fold. First, it would make it possible to conduct BAD vulnerability analyses of vehicles in the design phase, before the armor is actually built. One could thus compare the relative performance of conceptual armor candidates. Second, it would make it possible to obtain quantitative information on various physical characteristics of BAD that are difficult to determine in laboratory experiments (e.g., the velocity distribution of debris fragments). Third, it would improve timeliness and accuracy of survivability analysis products for decision makers and provide cost savings in systems development.

REFERENCES

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