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High-Obliquity Impact of a Compact Penetrator on a Thin Plate: Penetrator Splitting and Adiabatic Shear

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Abstract

Computational simulations were performed of the impact of a compact, nonideal penetrator on a thin plate at high obliquities. These computations simulated two series of experiments at velocities of 1.5 km/s and 4.1 km/s, respectively, with obliquities of 55–70°.

The experimental results indicated penetrator splitting at obliquities between 55 and 65°. Preliminary three-dimensional simulations with the CTH code, using either maximum tensile stress failure or the Johnson-Cook model, captured some aspects of fragment splitting but in a less than satisfactory manner. Simulations utilizing the Silling shear band model were also performed, with somewhat more realistic results.

In addition to graphical descriptions of the target hole geometry and debris cloud, numerical histories of the target hole area and up-range/down-range partitioning of mass, momentum, and energy were extracted for comparison with the experiments.

Acknowledgment

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1. Introduction

A generic problem arising in penetration mechanics is the impact of a compact, nonideal penetrator on a thin plate or shell at high obliquity. We are concerned generally with impacts for which $\theta \geq 55^\circ$, $1.5 \text{ km/s} \leq V \leq 5 \text{ km/s}$, $t/d < 1$, $l/d < 3$, where θ is the obliquity, V the impact speed, t the plate thickness, and l and d the penetrator length and diameter. Ballistic impact under these conditions has been studied relatively little as compared with the large volume of extant work concerned with rigid penetrators and/or low obliquities. Consequently, analytic penetration/debris models and algorithms that are acceptably accurate for encounter conditions of the latter sort may not be so for those considered here. High-obliquity impact on thin targets may produce very asymmetric debris clouds, whereas current penetration algorithms often assume the debris cloud is axisymmetric. Moreover, in thin-target impacts, the relative strength of shear loading as compared with pressure loading increases dramatically at high obliquity so that the operative material failure mechanisms may be quite different from those that apply at the same impact speed but low obliquity.

The work reported herein represents our preliminary effort to include in numerical simulations some of the critical material failure mechanisms which we believe underlie the complex penetration phenomena observed experimentally for encounter conditions described in the previous paragraph. Therefore, we restrict attention to a single prismatic penetrator and single-element target configuration. Geometric variation is primarily with respect to obliquity; we also present results arising from combined effects of penetrator obliquity, θ , and rotation about the shot line, ϕ . Because this study is exploratory, we restrict attention to impact speeds near the extrema of the test matrix.

2. Experimental Motivation

Our simulations were motivated by two series of experiments. The first series was performed at the University of Alabama-Huntsville (UAH) Light Gas Gun for the U.S. Army Missile Command (MICOM); we received a summary of the experiments from Mr. Mike Cole of MICOM. In all shots, the penetrator was a $1.4 \times 2 \times 2$ cm rectangular prism of 4130 steel (density 7.9 g/cm^3 , mass 44.2 g)

hardened to Rockwell C43. The target was a $0.476 \times 150 \times 300$ cm plate of 304 stainless steel. In the experiments, the penetrator orientation (pitch, yaw and θ) varied widely. Rather than attempting to match the geometry of each shot exactly, we performed simulations at each combination of (V, θ) represented in the experiments; at the extreme values of (V, θ) we also varied θ . Figure 1 illustrates the initial geometry used in the simulations. The penetrator faces are parallel and perpendicular to the shot line, and it travels to the right and down. Note that in all the simulations $y = 0$ is exploited as a symmetry plane. Table 1 summarizes the matrix of simulations for the UAH shots.

A similar series of experiments were conducted (Bjerke, Luther, and Scheffler 1994) at the U.S. Army Research Laboratory (ARL) (also for MICOM) in which the same penetrator impacted a laminate target at $V \approx 2.2$ km/s and $55^\circ \leq \theta \leq 70^\circ$; yaw and pitch at impact were negligible. The ARL target consisted of a thin, ($t \approx 1.5$ cm), mild steel layer in front, a middle layer of very low-density material, and finally the same stainless plate used in the UAH experiments. For obliquities between 55° and 65° , the penetrator split so that a substantial fragment penetrated the target (and was captured in a witness pack), while other large fragments ricocheted down the front surface of the target. Similar behavior has also been observed for mild steel cube and sphere penetrators against single mild steel and stainless steel plates (Finnegan et al. 1993; Finnegan and Schulz 1992). It appears that this *splitting* mode of penetration is not due primarily to the laminate nature of the ARL target but is dependent upon material strength-related failure mechanisms. In particular, the larger penetrator fragments retained sharp edges and appeared to have suffered little gross plastic deformation. Thus, we chose to examine this phenomenon with simulations at low velocity ($V = 1.5$ km/s, $\phi = 0$) and the same obliquities as in the UAH series. However, we employed several different material models for the penetrator, as noted in Table 2.

3. Simulation Methodology

All simulations were performed with the Eulerian wavecode, CTH (McGlaun and Thompson 1990). The SESAME Mie-Grüneisen EOS model and parameter values for 304 stainless steel were used for the target plate. The deviatoric response was modeled with an elastic-perfectly plastic

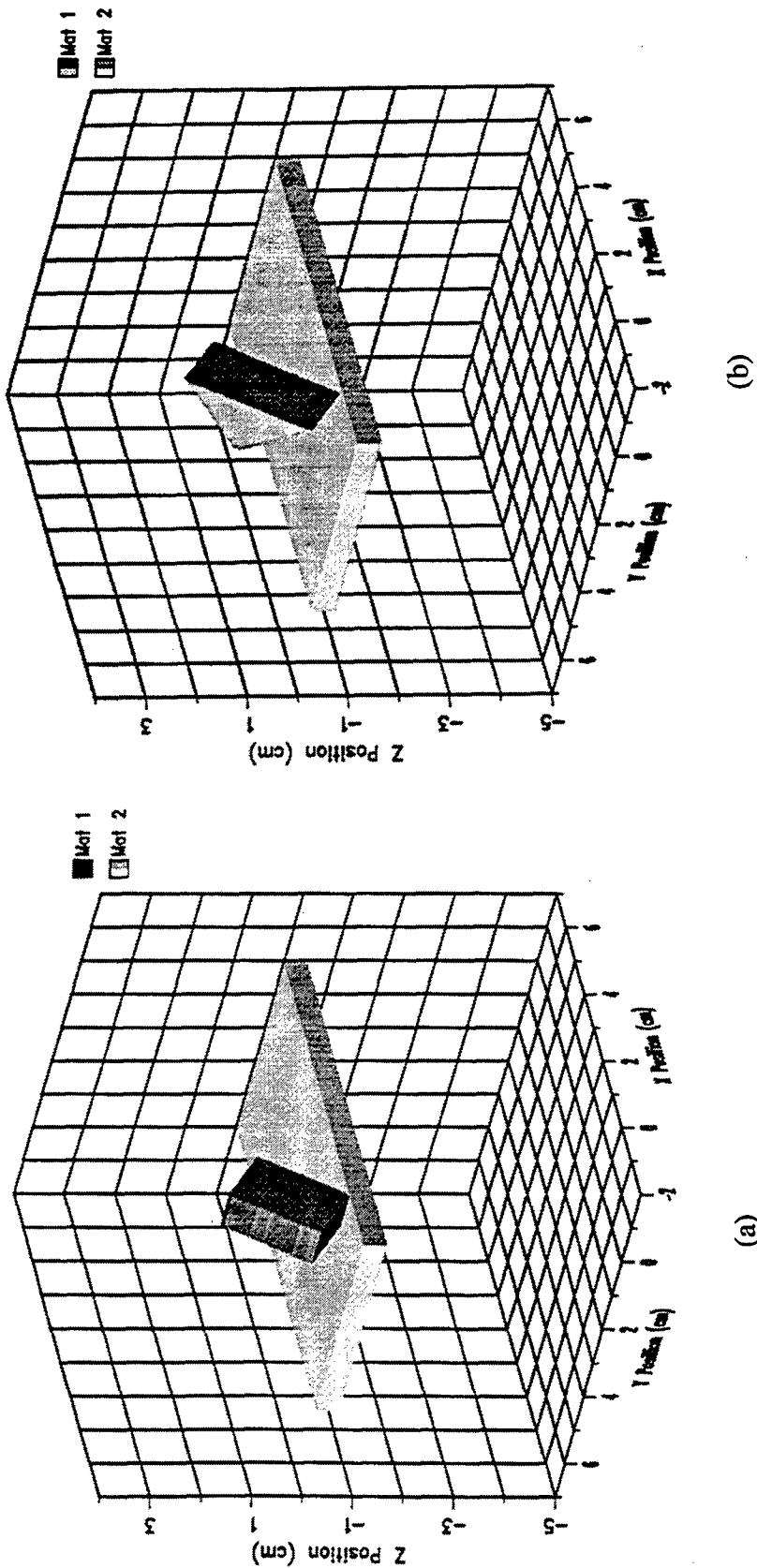


Figure 1. Computational Domain for $\theta = 55^\circ$ Showing Symmetry Plane at $y = 0$. (a) Shot Line Rotation $\phi = 0^\circ$; (b) Shot Line Rotation $\phi = 45^\circ$. Pitch and Yaw Relative to the Shot Line Are Always Zero.

Table 1. Summary of Three-Dimensional (3D) Simulations Performed for UAH Shots

ID	q	w	g	e	m	k	b	r	c	d	a	v
V (km/s)	4.16	4.16	4.19	4.10	4.16	4.16	3.19	3.19	3.12	3.07	3.11	3.11
θ (deg.)	55	55	60	65	70	70	55	55	60	65	70	70
ϕ (deg.)	0	45	0	0	0	45	0	45	0	0	0	45

Table 2. Summary of 3D Simulations Performed for ARL Shots

ID	θ (deg.)	Penetrator Material Model
x	60	Johnson-Cook flow and failure, $\epsilon^{pf} = 0.6$.
z	60	Johnson-Cook flow and failure, $\epsilon^{pf} = 0.15$.
0	60	Elastic-perfectly plastic, fracture stress = $1.5 Y_0$.
1	60	Elastic-perfectly plastic, fracture stress = $0.375 Y_0$.
3	55	Elastic-perfectly plastic, fracture stress = $1.5 Y_0$.
4	65	Elastic-perfectly plastic, fracture stress = $1.5 Y_0$.
5	70	Elastic-perfectly plastic, fracture stress = $1.5 Y_0$.

(EPP), von Mises yield surface with low-density and high-temperature strength reduction (EPP); the initial yield strength $Y_{02} = 0.34$ GPa was obtained from the Steinberg-Guinan-Lund viscoplasticity model database distributed with CTH. In all UAH simulations, the penetrator was also treated with the Mie-Grüneisen EOS (using parameter values for Vascomax-250 steel) and the EPP strength model. The initial yield strength $Y_{01} = 1.16$ GPa was obtained by converting the measured R_c hardness to Brinell (BHN 400) and using a handbook value for oil-quenched and tempered 4130 steel (Brades 1978).

An important factor in the use of CTH is the numerical fracture algorithm. Since strength effects were believed significant in the experiments, we used the maximum principal stress criterion,

$p_f = \max(0, \sigma_{\max}^d - \sigma_f)$, in which σ_f is the smallest (user input) tensile *fracture stress* in the cell, $\sigma_{\max}^d$ the maximum principal deviatoric stress, and p_f is the cell *fracture pressure*. If the cell pressure falls below p_f , void is introduced to raise the pressure. Use of an experimentally determined spall strength for the fracture stress may not produce good results in all problems; no fracture stress values are supplied in the CTH material libraries. As a baseline value we used $\sigma_f = 1.5 Y_0$ for both materials. The yield strength for mixed cells is given by a volume average over the materials with strength (void volume is not counted). The penetrator-target interface is treated as a contact (continuous velocity). All 3D simulations used a uniform space mesh of 0.075-cm cubes; the mesh and target are longer in the x-direction than indicated in Figure 1.

The Johnson-Cook flow law and failure models (Johnson and Cook 1985) were used for some of the 3D ARL simulations and with the explicit shear band calculations. The flow stress is given by

$$\sigma = [A + B(\epsilon^p)^n] [1 + C \ln(\max(1, \dot{\epsilon}))] [1 - T^{*m}], \quad (1)$$

where ϵ^p is the equivalent plastic strain, $\dot{\epsilon}$ the strain rate and T^* the homologous temperature. The equivalent plastic strain at failure is given by

$$\epsilon^{pf}(p, \sigma, T^*, \dot{\epsilon}) = [D_1 + D_2(-D_3 p / \sigma)] [1 + D_4 \ln(\max(1, \dot{\epsilon}))] [1 + D_5 T^*], \quad (2)$$

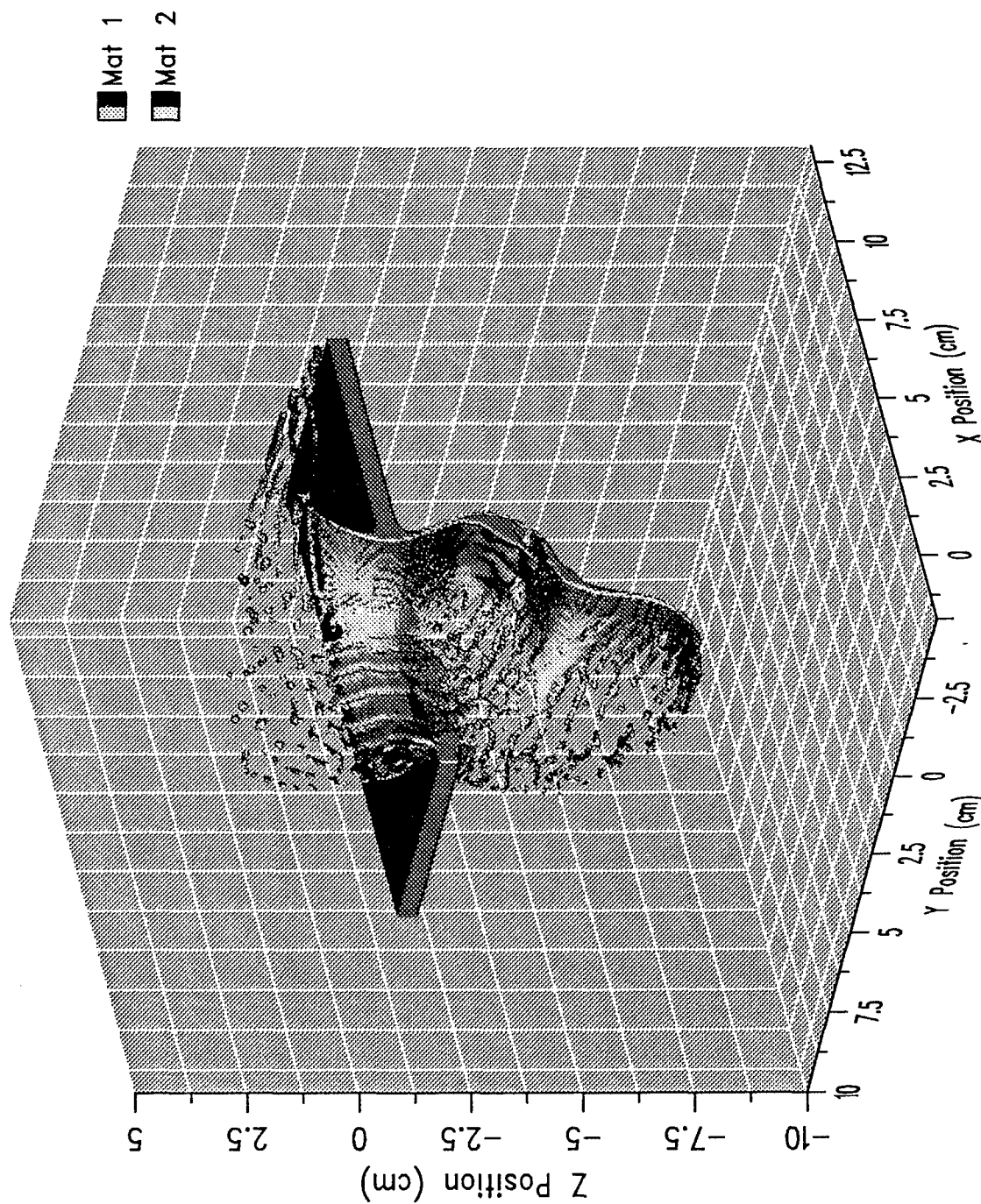
where p is the pressure and $D_1, \dots, D_5$ are constants. Damage accumulates according to $D = \int (\epsilon^{pf})^{-1} d\epsilon^p$; failure occurs when $D = 1$, at which point (in CTH) the stress deviator and fracture stress, p_f , are set to zero. Material constants were obtained by taking published values for 4340 steel and adjusting A, B, D_1, D_2 so that the yield strength, ultimate strength and ϵ^{pf} in a quasi-static tension test matched handbook values (Brades 1978) for the penetrator.

4. Results of Simulations

The UAH results are typified by Figure 2. The flow is pressure-dominated and results in considerable fragmentation, although large sections of the debris bubble are still intact. The rotation, ϕ , has a mild effect on the bubble at $\theta = 55^\circ$ but a much stronger effect at 70° . In both cases the edge strike produces a considerably stronger initial shock, which contributes to debris bubble asymmetry. Although little penetrator mass has traveled downrange at 70° , the plate is perforated nonetheless; in all cases, the target hole is still growing at 26 μs . At 65° and 70° , a large section of plate has been accelerated and deformed by the penetrator, but it is unclear whether these areas will ultimately fragment, tear off as intact petals, or remain attached. Shearing-induced flow instabilities appear to influence the fragmentation significantly, but mesh size dependence of this aspect of the simulations has not yet been explored. Note that although initial shock pressures at $\theta = 55^\circ$ approach 50 GPa (not shown) the impact geometry results in poor focusing of release waves, so there is essentially no shatter of the penetrator. Apparently for the same reason, the well-known α - ϵ phase transition at 13 GPa has no significant effect. By using the CTHED post-processor to sum material masses over subregions of the computational domain, the uprange/downrange partitioning of penetrator mass and target hole growth can be calculated as in Figures 3 and 4.

Figure 5 shows the effect of varying the material failure model at 1.5 km/s. The penetrator fragments in all cases, but only after suffering very extensive plastic deformation, contrary to the experimental results of Bjerke, Luther, and Scheffler (1994). Tensile stresses occur because the penetrator material is flowing laterally against the target. The Johnson-Cook model does not encourage fragmentation, because plastic strain must be accompanied by significant tension in order that damage may accumulate rapidly. During early shock release wave interaction, there is little plastic strain and at later times (as in this figure) the tensile stresses are weak.

To obtain better fragmentation behavior, we have also employed in two dimensions a model intended to capture effects of *adiabatic shear band* formation (Silling 1992). In our version, shear bands are assumed to nucleate (at preassigned locations identified by *Lagrangian tracer particles*)



(a)

Figure 2. Combined Effects of Obliquity, θ , and Rotation, ϕ , on Debris Cloud Evolution at 4.1 km/s and 26 μ s; Impact Velocity Vector Lies in x-z Plane. Plot Volumes Are $9 \times 9 \times 9$ cm, Centered at $(x, y, z) = (4.5, 4.5, -2.5)$. ID = q: $V = 4.16$ km/s, $\theta = 55^\circ$, $\phi = 0^\circ$.

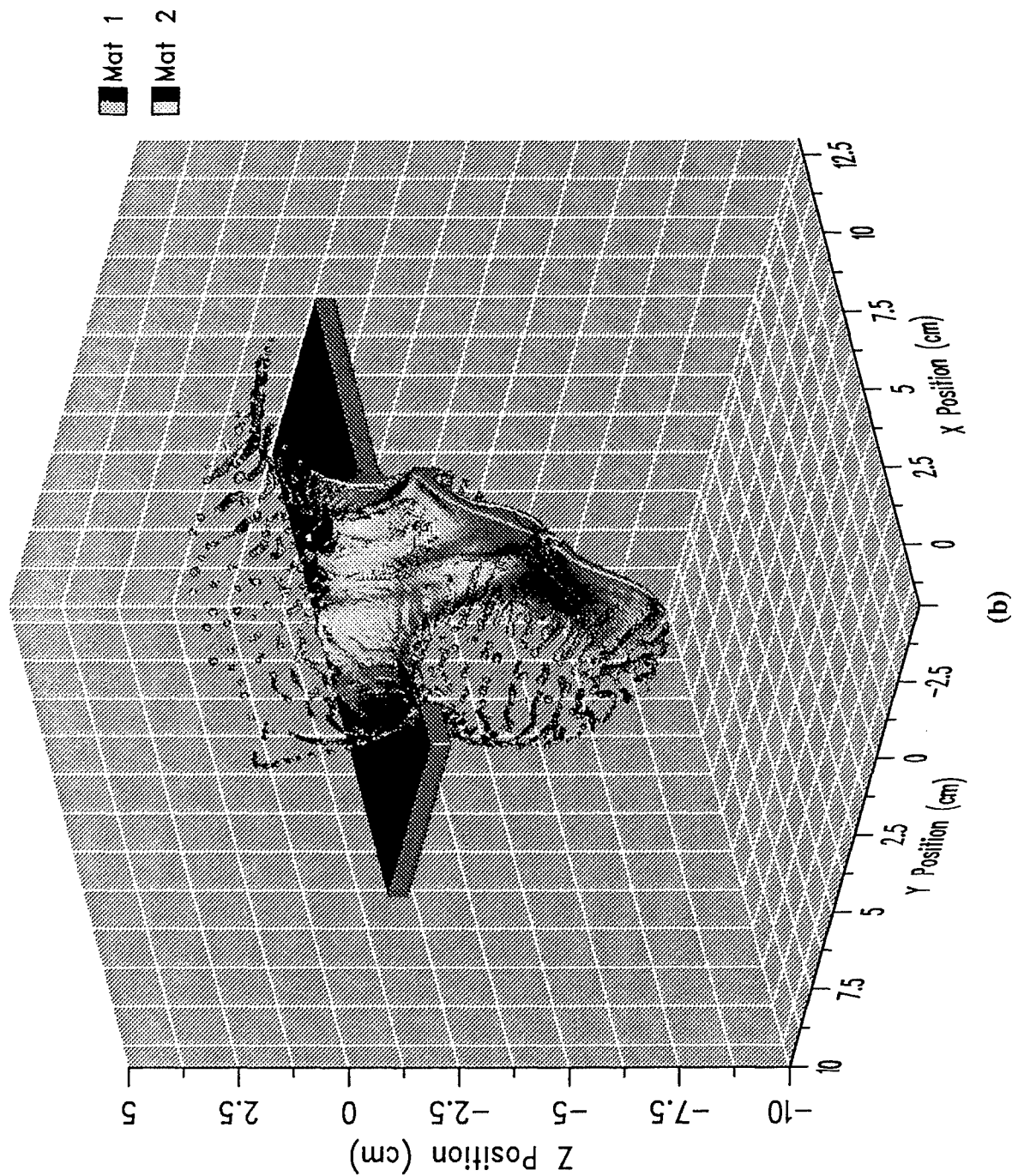


Figure 2. Combined Effects of Obliquity, θ , and Rotation, ϕ , on Debris Cloud Evolution at 4.1 km/s and 26 μ s; Impact Velocity Vector Lies in x-z Plane. Plot Volumes Are $9 \times 9 \times 9$ cm, Centered at $(x, y, z) = (4.5, 4.5, -2.5)$. ID = w: $V = 4.16$ km/s, $\theta = 55^\circ$, $\phi = 45^\circ$ (continued).

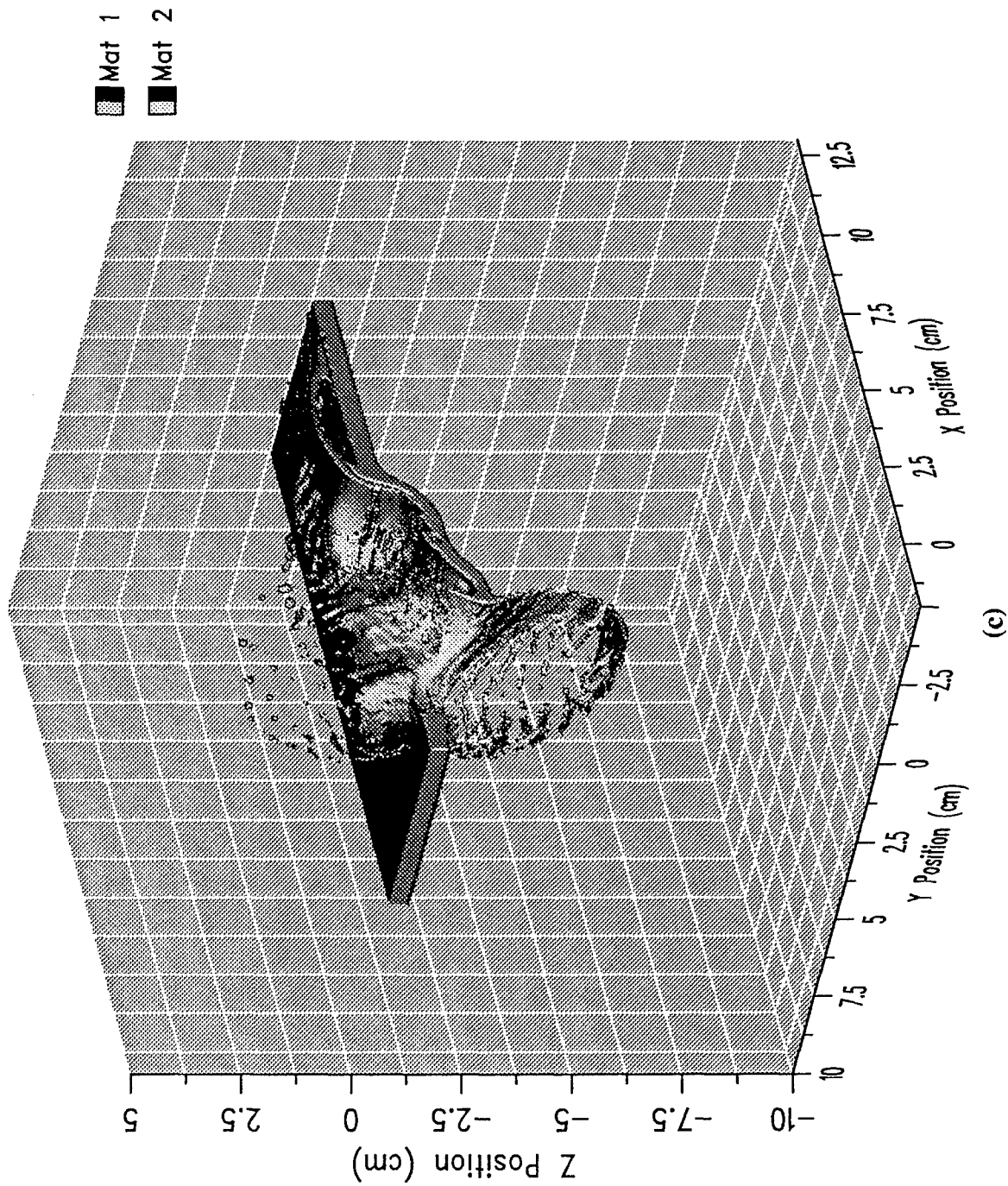


Figure 2. Combined Effects of Obliquity, θ , and Rotation, ϕ , on Debris Cloud Evolution at 4.1 km/s and 26 μ s; Impact Velocity Vector Lies in x-z Plane. Plot Volumes Are $9 \times 9 \times 9$ cm, Centered at $(x, y, z) = (4.5, 4.5, -2.5)$. ID = m: $V = 4.16$ km/s, $\theta = 70^\circ$, $\phi = 0^\circ$ (continued).

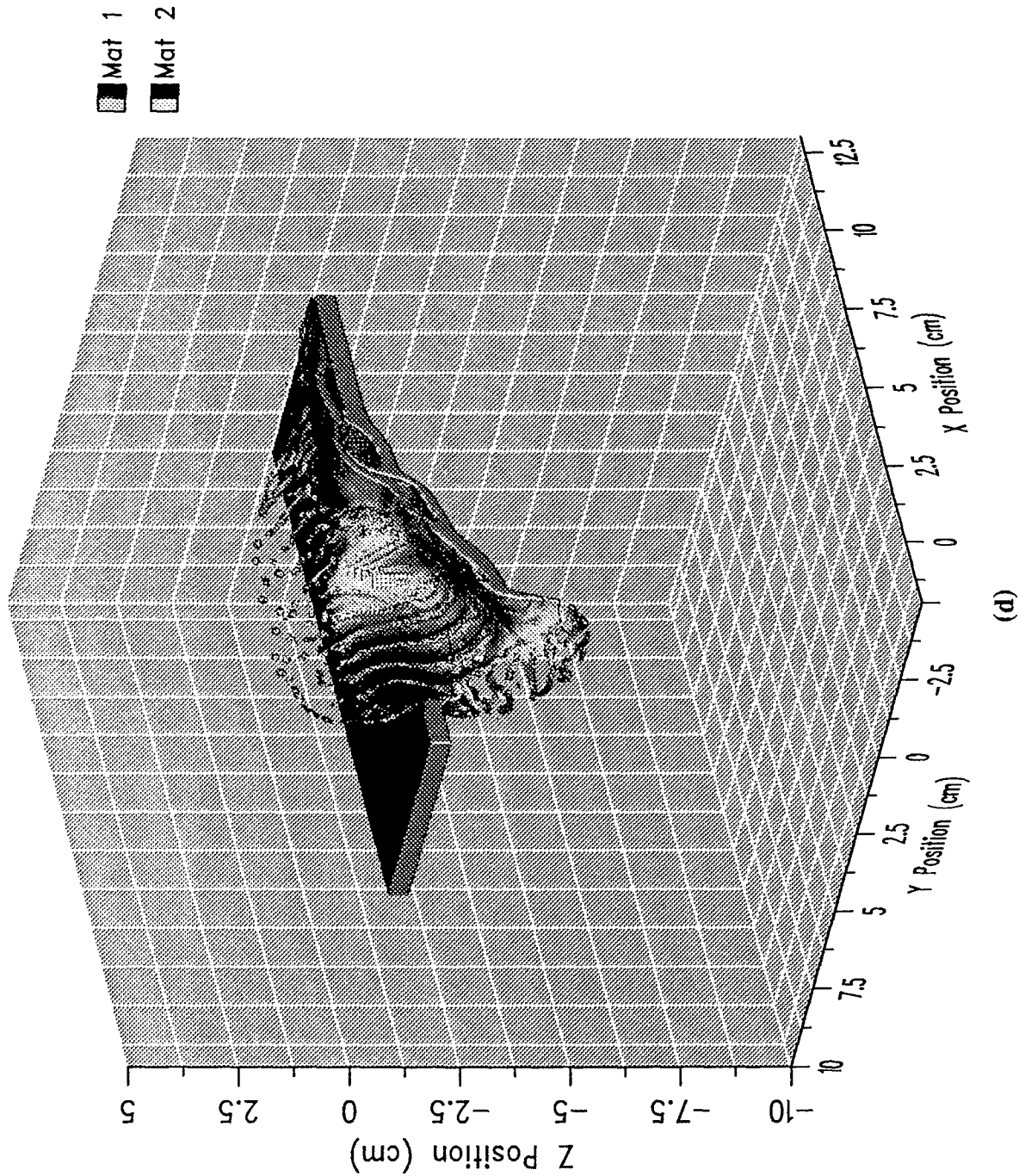


Figure 2. Combined Effects of Obliquity, θ , and Rotation, ϕ , on Debris Cloud Evolution at 4.1 km/s and 26 μ s; Impact Velocity Vector Lies in x-z Plane. Plot Volumes Are $9 \times 9 \times 9$ cm, Centered at $(x, y, z) = (4.5, 4.5, -2.5)$. ID = k: $V = 4.16$ km/s, $\theta = 70^\circ$, $\phi = 45^\circ$ (continued).

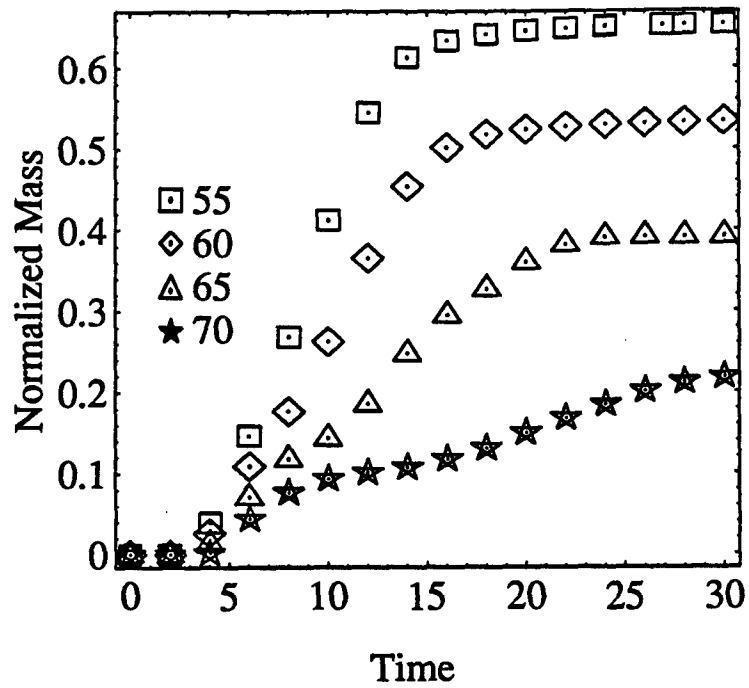


Figure 3. Time History of the Penetrator Mass Fraction Exiting the Bottom of the Target at 4.1 km/s.

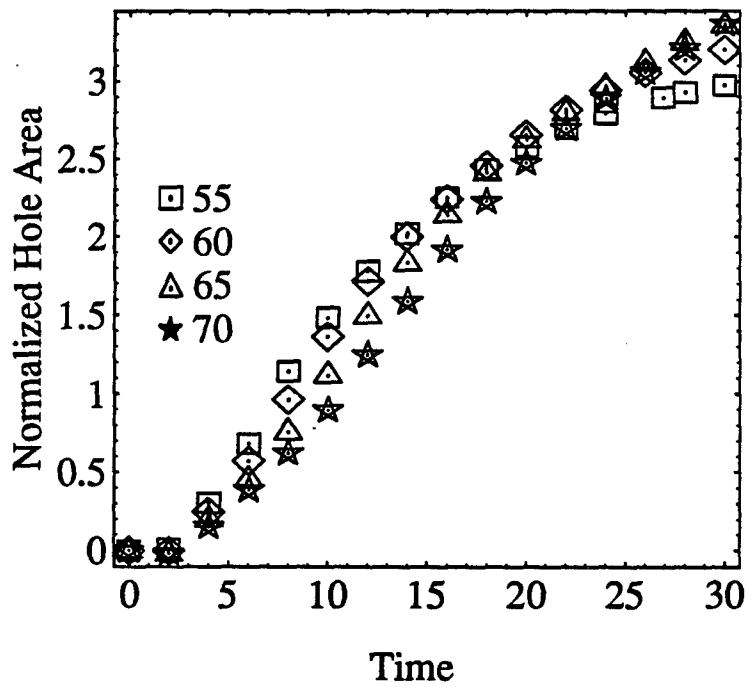


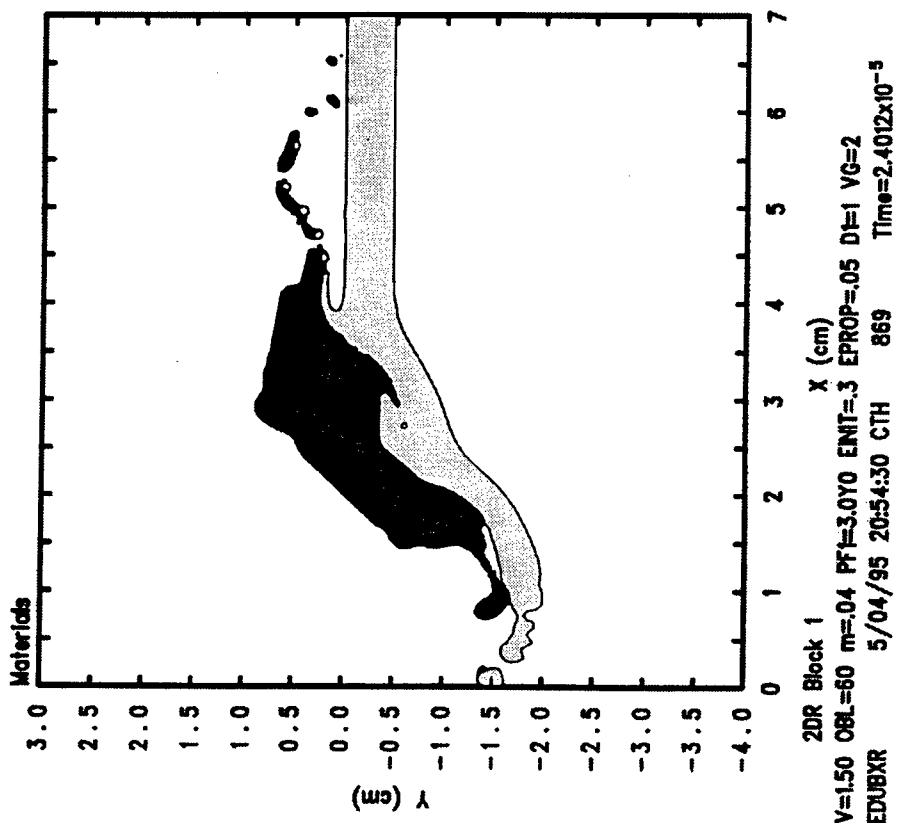
Figure 4. Time History of Target Hole Area Normalized by Sphere-Equivalent Penetrator Area at 4.1 km/s.

when the equivalent plastic strain, ϵ^p , reaches an assigned value, ϵ_{init} . Each nucleator spawns four shear band tips that propagate at speed v_g in the directions of maximum shear stress if ϵ^p exceeds another value $\epsilon_{prop} < \epsilon_{init}$ in the CTH cell containing the band tip. When the tip moves to a new cell, a tracer is inserted and the stress deviator set to zero. On the time scale of our simulations, shear bands are hot and thus weak in tension as well as shear. To account for this, we use (2) with $D_1 = 1$ and $D_2 = \dots = D_5 = 0$, so that when $\epsilon^p \geq 1$, $p_f = 0$. The results in Figure 6 were obtained with $v_g = 2 \text{ km/s}$, $\epsilon_{init} = 0.3$, $\epsilon_{prop} = 0.05$. In spite of the crude shear band kinetics currently employed, the model does capture a crucial feature of the ARL experiments: the penetrator fractures without the individual fragments having first suffered large plastic deformation. This is particularly evident at the higher obliquities. Among several improvements we intend to make to the physics in this model are:

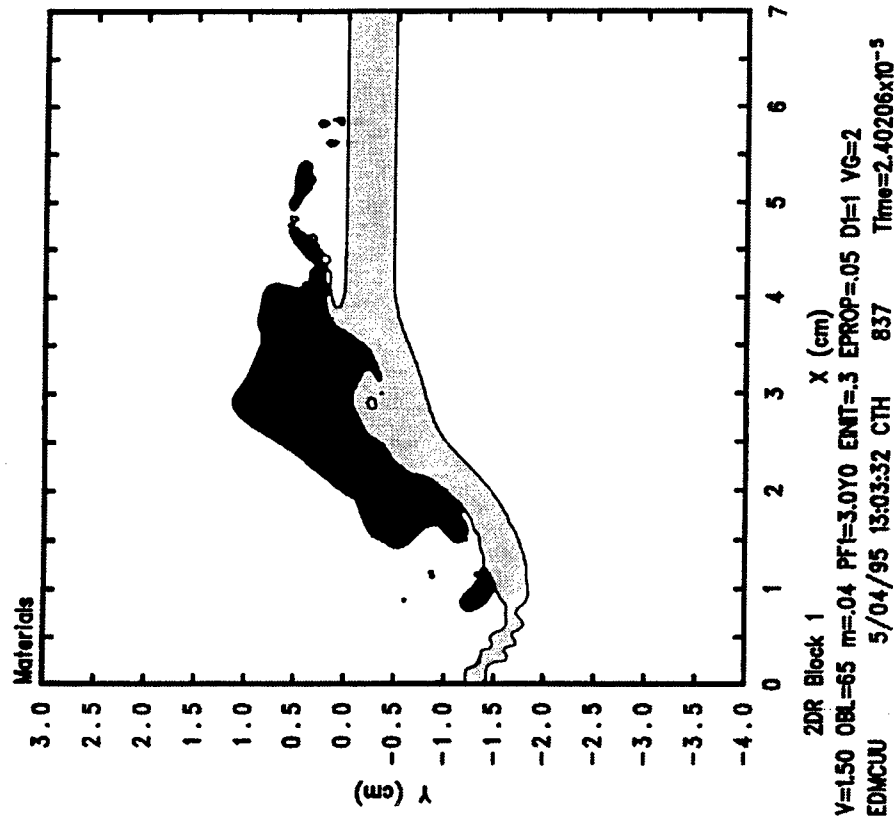
- a. Directly modify the fracture pressure in shear-banded cells [rather than use equation (2)] to prevent nonphysical softening in unbanded cells.
- b. Allow partial rather than total loss of shear strength in banded cells using results from one-dimensional (1D) analyses of adiabatic shear bands (Walter 1992; Wright 1995) .
- c. Allow random band nucleation with spacing determined from 1D analyses (Wright 1995).

5. Discussion

This work is part of an ongoing effort within the Weapons and Materials Research Directorate to provide improved analytical modeling of high-obliquity impacts. In achieving this end, direct simulation with wavecodes is a critical adjunct to experimentation, provided the simulations include appropriate models for operative material flow and failure mechanisms. In order to maximize the utility of these simulations, one further capability that is required is a statistical description of the debris evolution. This sort of information has traditionally not been available from wavecodes and the current version of CTH is no exception. At present, the CTHED post-processor can sum mass

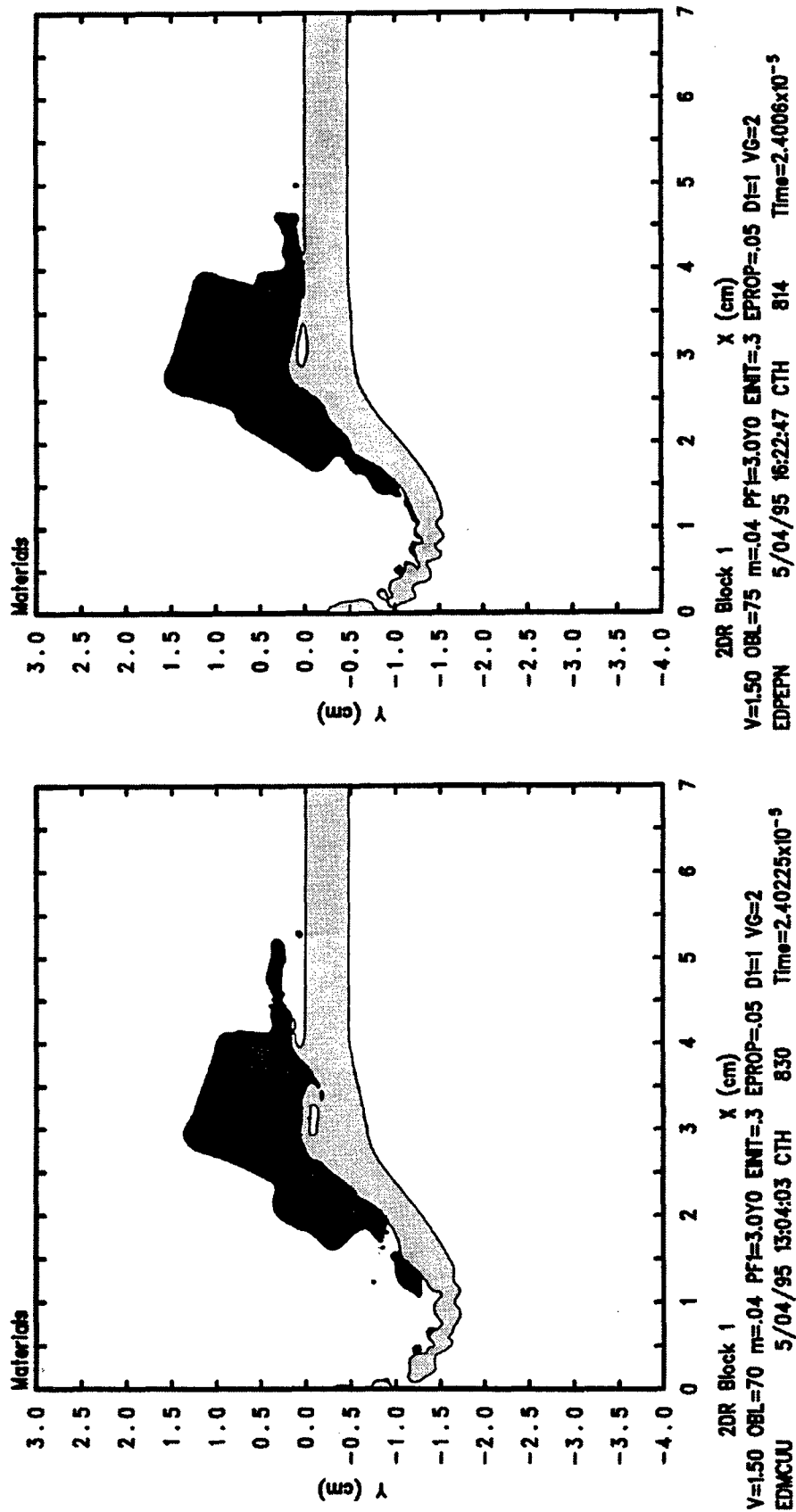


(a)



(b)

Figure 6. Behavior of the Two-Dimensional (2D) Explicit Shear Band Model at 1.5 km/s and 24 μ s. The Black Curves Running Through the Darker Penetrator Material Are the Shear Bands. The Bands Nucleated From Three Tracers Along the Short Edge and Five Along the Long Edge Meeting at the Penetrator Vertex That First Impacted the Target. (a) Obliquity = 60°; (b) Obliquity = 65°.



(c)

(d)

Figure 6. Behavior of the Two-Dimensional (2D) Explicit Shear Band Model at 1.5 km/s and 24 μ s. The Black Curves Running Through the Darker Penetrator Material Are the Shear Bands. The Bands Nucleated From Three Tracers Along the Short Edge and Five Along the Long Edge Meeting at the Penetrator Vertex That First Impacted the Target. (c) Obliquity = 70°; (d) Obliquity = 75° (continued).

over rectangular subregions of the mesh, but more detailed information is not available. More fundamentally, the fragment size produced by the numerical fracture algorithm is generally dependent on the size of the computational cells, although the overall distributions of mass, energy, etc., are less strongly affected by the mesh.

In conclusion, we have presented results that indicate a significant effect of penetrator shape on the debris cloud at high velocity and obliquity. At lower velocity, we have shown that a crude adiabatic shear band model can account for experimentally observed penetrator splitting and that simpler failure models do not.

6. References

- Bjerke, T. W., L. A. Luther, and D. R. Scheffler. "Single Fragment Impact With Laminate Targets." ARL-MR-132, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1994.
- Brades, B. P. (ed.). *Metals Handbook: 9th edition*. Vol. 1, p. 422, 1978.
- Finnegan, S. A., L. F. Dimaranan, O. E. R. Heimdahl, and J. K. Pringle. "A Study of Obliquity Effects on Perforation and Ricochet Processes in Thin Plates Impacted by Compact Penetrators." *Proceedings of the 14th International Symposium on Ballistics*, Quebec Canada, 1993.
- Finnegan, S. A., and J. C. Schulz. "Fragmentation Processes for High-Velocity Impacts." *Shock-Wave and High-Strain-Rate Behavior in Materials*. New York: Marcel Dekker, pp. 705-712, edited by M. A. Meyers, L. E. Murr, and K. R. Staudhammer, 1992.
- Johnson, G. R., and W. H. Cook. "Fracture Characteristics of Three Metals Subjected to Various Strains, Strain Rates, Temperatures and Pressures." *Engineering Fracture Mechanics*, vol. 21, pp. 31-48, 1985.
- McGlaun, J. M., and S. L. Thompson. "CTH: A Three-Dimensional Shock Wave Physics Code." *Journal of Impact Engineering*, vol. 10, pp. 351-360, 1990.
- Silling, S. A. "Shear Band Formation and Self-Shaping in Penetrators." SAND92-2692, Sandia National Laboratory, Albuquerque, NM, 1992.
- Walter, J. W. "Numerical Experiments on Adiabatic Shear Band Formation in One Dimension." *International Journal of Plasticity*, vol. 8, pp. 657-693, 1992.
- Wright, T. W. "Scaling Laws for Adiabatic Shear Bands." To appear in the *International Journal of Solids and Structures*, vol. 32, pp. 2745-2750, 1995.

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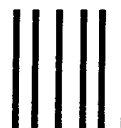
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