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THE INFLUENCE OF THE TARGET STRENGTH MODEL ON COMPUTED PERFORATION

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ABSTRACT

We used an axi-symmetric, two-dimensional Eulerian computer simulation program to simulate the penetration of a tungsten rod with length to diameter ratio $L/D = 10$ into a thick steel target, and the same rod into finite steel plates of thicknesses between 0.9 and 1.3 L. We compare the perforation limit with the semi-infinite penetration depth at the same velocity (the excess thickness) when the model for target strength is constant yield stress, and when the model incorporates work hardening and thermal softening. We also compare our computed results with available experimental results, which show an excess thickness of about 1 rod diameter.

INTRODUCTION

Computer simulations of the axi-symmetric penetration of right-circular cylinders into semi-infinite targets are routinely performed, using present day computers and computer simulation programs.¹⁻⁴ These programs solve the partial differential equations of continuum mechanics. The simulation of penetration depth is typically accurate to within 10% when compared with experiment. For a given velocity in the range 1-2 km/s, the target strength and density and the projectile density are the three most significant independent parameters.¹

Application of these programs to armor requires the ability to simulate the perforation of finite thickness targets. Experimentally, this is accompanied by fracture. Models to describe ductile and brittle fracture have been developed for these programs.^{5,6} Before applying these models to perforation, we felt it important to examine the effects of the target strength description. In this way the influence of the model on the computed result can be determined.

METHOD

We used the Eulerian computer simulation program GLO, which is under development at this laboratory, to perform these simulations. We have successfully applied this program^{1,7} to projectile and target interaction for a variety of projectile and target materials. As a baseline for the simulations reported here, we recorded the penetration depth as a function of velocity for a length-to-diameter ratio $L/D = 10$ tungsten alloy projectile (into a semi-infinite steel target).

We obtain the limit velocity for finite steel targets by a method that imitates the experimental procedure. By overmatching the target, a portion of the projectile passes through. We record the velocity of this residual projectile, V_R , as a function of the impact velocity V . These velocity pairs are then fit by the functional form.⁸

$$V_R = (AV^P - B)^{1/P}$$

with the parameters A and B chosen by the method of linear least-squares for a given P. The final value of P is selected to minimize the rms deviation. We show the results for the set of calculations that used a constant flow stress for three different target thicknesses in Fig. 1. The limit velocity V_L is given in terms of the fitted parameters

$$V_L = \left(\frac{B}{A}\right)^{1/P}$$

Figure 1. Computed residual velocity for three ratios of thickness T to projectile length L and fitted curves.

Perforation Without Fracture

It would seem paradoxical that a projectile could perforate a target if there were no fracture model in the computer simulation program. However, there is a tacit rupture model in GLO, and in all other Eulerian programs: if the material thins out to be less than a finite-difference zone size, it is no longer treated as intact. The details of how this happens differ in each of the programs, but they also don't matter much. When the material is stretched thin, the stress acting across the ligament is limited by the flow stress of the material. As a consequence the force transmitted across the ligament decreases with the area. With proper simulation design (i.e., small enough zones) that force will not significantly change the momentum of the residual projectile during the available time. As a consequence, refining the zone size, which would increase the time to break and effectively increase the strain at fracture, does not significantly change the residual velocity.

Material Description

We used two strength models for the target steel—constant a flow stress, and flow stress with work hardening and thermal softening.⁹ With the second model, we used both the nominal value and twice that value for $d(\ln G)/dT$ where G is the shear modulus and T is temperature. (The standard model uses the same temperature dependence for both the shear modulus and flow stress.) The properties used in the simulations are given in the Appendix.

EXPERIMENTAL DATA

We use the semi-infinite and finite thickness experiments of Hohler and Stilp¹⁰ in which $L/D = 10$ tungsten alloy rods were fired normally into mild steel (Brinell hardness BHN 180) and armor steel (BHN 300-360) targets. We scaled their results for penetration depth vs. velocity and thickness vs. limit velocity by the projectile length (see Fig. 2). For both steels, finite armor must be thicker to stop a given projectile at a given velocity than the penetration depth in a semi-infinite target. In the velocity range of 1-2 km/s, the average excess thickness was 1.23 ± 0.17 projectile diameters for the armor steel, and 1.06 ± 0.26 for the mild steel. The relatively large uncertainty is due to the subtraction of two nearly equal values with independent uncertainties.

Figure 2. Experimental results¹⁰ for semi-infinite penetration depth (filled) or limit velocity (open) for armor steel (circle) and mild steel (square).

COMPUTER SIMULATIONS

We fit the semi-infinite penetration depth results (Table 1) to a quadratic in impact velocity, and obtain the excess thickness by evaluating that fit at the limit velocity and subtracting from the finite plate target thickness. The results are given in Table 2.

From those data we observe that the steel 1 and 2 models show significantly larger excess thickness than the steel 0 model, but that all values are less than 1 diameter. In contrast, the experimental results of Hohler and Stilp show excess thickness of more than 1 diameter.

ANALYSIS OF RESULTS

By including thermal softening in the target model, the strain localizes, which reduces the force on the projectile residue as it exits the target. For a given thickness, then, the strain localization results in a higher residual velocity.

However, the strain localization in our simulations is more like a membrane thinning than plugging, which is a lower energy deformation mode.⁶ As a consequence, the target continues to exert a force on the projectile longer than it would if a plug formed.

IMPLICATIONS FOR FURTHER RESEARCH

Our simulations used models for the flow stress that are intrinsically susceptible to strain localization.

Table 1. Computed semi-infinite penetration depth for L = 76.2 mm, D = 7.62 mm tungsten rods in steel.

Model	Velocity, km/s			
	T.3	1.6	1.8	2.2
Steel 0	60.1 mm	81.7	91.5	103.7
Steel 1	51.1	71.8	82.7	96.5
Steel 2	52.7	73.7	84.1	98.2

Table 2. Computed excess steel thickness for L = 76.2 mm, D = 7.62 mm tungsten rod.*

Target Strength Model	Thickness mm	Limit Velocity, km/s	Semi-infinite Penetration Depth, mm	Excess Thickness, mm
Steel 0	70	1.37 ± .005	65 ± .2	4.1 ± .3
	88.9	1.67	85.2	3.7
	100	1.95	97.7	2.3
Steel 1	70	1.49	64.7 ± .1	5.3
	100	2.19	96.3	3.7
Steel 2	70	1.47 ± .003	65.4	4.6
	100	2.09	95.3	4.9

*The uncertainty in the excess thickness is from both uncertainty in the fit to semi-infinite penetration and uncertainty in the fit to limit velocity.

Despite that, there was no evidence of any tendency toward plugging. Instead, the back surface bulge thinned and eventually localized, but only after significant stretching had occurred.

Apparently, in order for plugging to occur in our simulations, the material must fracture early near the cavity, and the fracture must initiate the strain localization that leads to plugging. If, however, the object of the simulations is to determine the residual penetration capability of the projectile residue, then a simpler method of artificially introducing a plug⁶ may suffice.

SUMMARY

The strain localization that occurs with either a constant yield stress or with work-hardening and thermal softening is insufficient to cause a projectile to perforate with plugging in our simulations. Instead the rear surface bulges and thins before separation occurs. As a consequence, the computed excess thickness for perforation is only about 0.5 diameters. Experimental data for armor steel show the measured value exceeds 1 diameter.

APPENDIX: MATERIAL PROPERTY PARAMETERS

The equation of state is given by

$$P = A\mu + B\mu^2 + (\gamma_0 + b\mu)E$$

where P is the pressure, E the internal energy density per unit reference volume. The variable μ is the excess density $\mu = \rho/\rho_0 - 1$. For tungsten, $\rho_0 = 17.77$ g/cc, $A = 2.85$ Mbar, $B = 2.2$ Mbar, $\gamma_0 = 1.54$ and $b = 1.54$. The tungsten shear modulus $G = 1.5$ Mbar, and the yield stress is 12 kbar. For steel, $\rho_0 = 7.83$, $A = 1.59$, $B = 1.9$, $\gamma_0 = 1.6$, $b = 0.6$. The shear modulus is 0.77 Mbar. For steel 0, the yield stress is 10.3 kbar. For steel 1 and steel 2, the flow-stress Y is given by

$$Y = Y_0(1 + \beta\epsilon)^n$$

where ϵ is the equivalent plastic strain, $Y_0 = 10.3$ kbar, $\beta = 125$, and $n = 0.07$. This is the work hardening measured by us for 4340 steel heat treated to Rockwell hardness HRC35. The strength corresponds approximately to a Brinell hardness BHN 330.¹⁰ Both

the shear modulus and flow stress are multiplied by the function f

$$f = 1 + bPV^{1/3} - h [(E-E_c)/c - 300^\circ K] \geq 0$$

where c is the specific heat, and E_c is the energy of cold compression found by subtracting the thermal energy density on the principal adiabat from the internal energy density. See Ref. 9 for details. For steel, $c = .107$ cal/g $^\circ$ K, $b = 2.06$. For steel 1, we used the nominal value of h , $3.15 \cdot 10^{-4}$. For steel 2, we used twice that value. When the temperature exceeds the melt temperature, f is set to zero. The steel 1 model results in the strength and shear modulus being half the room temperature value just before melt is reached, whereas the steel 2 model reduces both to nearly zero there.

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REFERENCES

- [1] M. L. Wilkins and J. E. Reaugh, "Computer Simulations of Ballistic Experiments," LLNL Report UCRL-95774 (1987).
- [2] R. T. Sedewich, M. G. Wilkinson, "High Velocity Long Rod Impact," in *Proceedings from the 10th International Symposium on Ballistics* (1987).
- [3] P. M. Holland, J. T. Gordon, T. L. Menna, A. C. Charters, *Int. J. Impact Engng* 10, 1-4, pp 241-250 (1990).
- [4] C. E. Anderson, S. A. Mullin, C. J. Kuklman, *Int. J. Impact Engng* 13, 1 pp 35-52 (1993).
- [5] D. M. Norris, J. E. Reaugh, B. Moran, D. F. Quinones, *Trans. ASME, J. Engng. Mats. Tech.* 100, 3, pp. 279-286 (1978).
- [6] M. L. Wilkins, *Int. J. Engng. Sci.* 16, pp. 793-807 (1978).
- [7] J. E. Reaugh, "Penetration of Yawed Projectiles," LLNL Report UCRL-ID-104890 (1990).
- [8] J. A. Zukas, et al., *Impact Dynamics*, NY: Wiley and Sons, ch 5, pp 201-202 (1982).
- [9] D. J. Steinberg, S. G. Cochran, M. W. Guinan, *J. Appl Phys.* 51, pp. 1498-1505 (1980).
- [10] C. E. Anderson Jr., B. L. Morris, D. L. Littlefield, "A Penetration Mechanics Database," Southwest Res. Inst. Report 3593/001 (1992).

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