Analysis of Long Rod Penetration at Hypervelocity Impact

John J. Misey*
Ballistic Research Laboratory, Aberdeen Proving Ground, Md.

The hypervelocity impact (>3 km/sec) of a long rod penetrator against thin targets of like material was studied analytically with the aid of the HELP code, a two-dimensional, finite-difference Eulerian computer code. The results were compared with experimental data. The analytical examination of the effect of strength showed no perturbation. The computations of projectile residual speed deviated by no more than 3% from the experimental data; of residual mass by no more than 16%; of final rod length by no more than 5%; and of target exit diameter by no more than 8%. This agreement demonstrated that the HELP code can serve as a useful analytical tool for the study of kinetic energy projectile penetration of hypervelocity impact.

Introduction

THE study of the dynamic response of materials to intense impulsive loading may be approached from three distinct points of view: experimental, analytical, and numerical. In the experimental approach tests are conducted to deduce relationships between various parameters from the observed results. Generally many data points (therefore many tests) are required, so that this approach becomes both time consuming and expensive, especially in the hypervelocity regime (striking velocities>3 km/sec). To obtain some knowledge of the physics of the deformation process and at the same time reduce the number of tests, recourse is made to analytical methods. Simplifying assumptions are introduced into the governing equations of continuum physics, and these are reduced to a set of partial differential equations which characterize the elastic-plastic hydrodynamic response of a material or structure. Very often the resulting differential equations are mathematically intractable and further approximations must be introduced to obtain an approximate analytical solution, at the expense of reducing the scope of the problem. With the present availability of large digital computers, however, there now exists the realization that systems of differential equations never attempted before can be solved. The main advantage of computer utilization is that parameters can be varied easily and quickly in any problem and their effects noted and compared. Furthermore, even if only a part of the problem can be formulated correctly, several methods of complete formulation can be assumed and a determination of which is the best or most sensible solution can be made.

The objectives of this study were twofold: to ascertain the effect of material strength on target and projectile deformations with varying target thickness, and to determine the applicability of the HELP code to study hypervelocity (HV) impact of long rod kinetic energy penetrators by validating, if possible, the numerical results with experimental data.

Approach

The modeling of the hypervelocity impact by a long rod kinetic energy penetrator was done with the aid of the HELP code,[1] a two-dimensional multimaterial Eulerian code for solving material flow problems in the hydrodynamic and elastic-plastic regimes. Although the code is basically Eulerian, material interfaces and free surfaces are propagated in a Lagrangian manner through the calculational mesh as discrete interfaces across which material is not allowed to diffuse. The material model employed in HELP includes the Tillotson equation of state, modified to give a smooth transition between condensed and expanded states; a deviatoric constitutive relation; a yield criterion defined to account for the increase in strength at high pressures and decrease at elevated temperatures; and failure criteria. Failure in tension is based on relative volume. When the relative volume in a cell reaches a certain value greater than a specified maximum distension, that cell is said to fail, and any computed tensions are zeroed out. Recently,[2] a failure criterion based on a maximum allowable value of plastic work has been incorporated to model plugging failure. When the material ahead of the slip surface has been subjected to that value of plastic work, the slip surface is advanced to the next row of cells and the material in those cells through which the slip surface passes is said to have failed. For this problem the plugging failure model was not used.

The problem selected for study was that of a blunt aluminum cylinder impacting a target of like material at normal incidence. The input parameters of the problem are shown in Table 1.

A computational mesh 30 cells wide by 90 cells long was used to model the problem. In the region of impact and perforation the cell dimensions were 0.4×0.4 mm to provide an aspect ratio of 1, but to incorporate the entire projectile-target configuration the aspect ratio was varied up to 3 for the 25.4 mm target. Elsewhere the cell dimensions were increased at the ratio of 10% for the same reason. Thus, the finest zoning was restricted to the region where the greatest deformation occurs. For cases 3-5 the aspect ratio in this region was increased to 1.5. The problems were run on a

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*Physicist, Terminal Ballistics Division.

Table 1 Problem parameters

Projectile		
Material		Al 2024-T3
Length		29.19 mm
Diameter		3.175 mm
Mass		0.647 g
Stroking velocity		4.718 km/sec
L/D ratio		9.2
Target (Al 2024-T3)		
Case no.	t/d[a]	thickness, mm
1	1	3.175
2	2	6.350
3	4	12.700
4	6	19.080
5	8	25.400

[a] t/d = target thickness/projectile diameter.

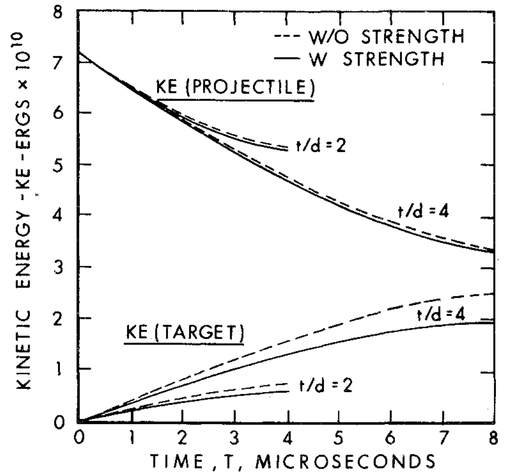


Fig. 1 Influence of strength effects for a HV impact at 4.73 km/sec (HELP code).

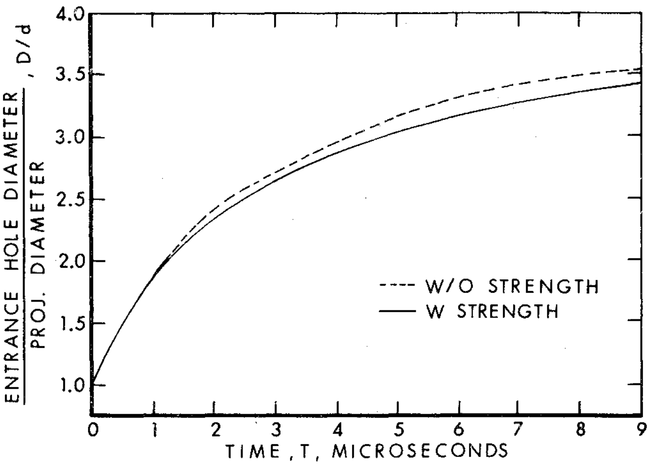
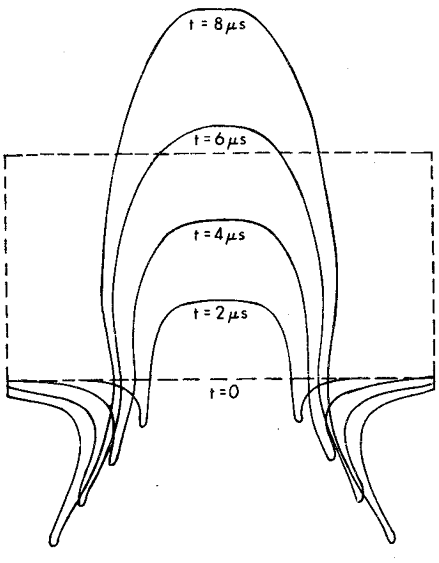


Fig. 2 Normalized entrance diameter growth for HV impacts.

Fig. 3 Target hole growth expansion history for $t/d = 4$.



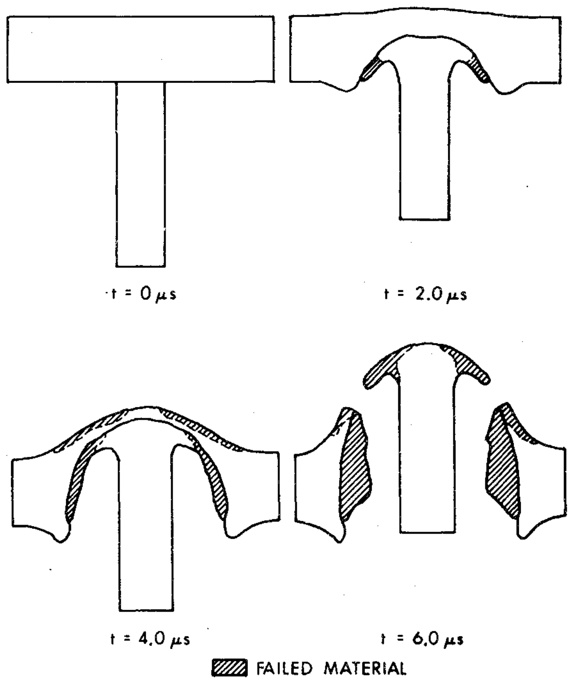


Fig. 4 Projectile-target deformation of a HV impact, $t/d = 2$.

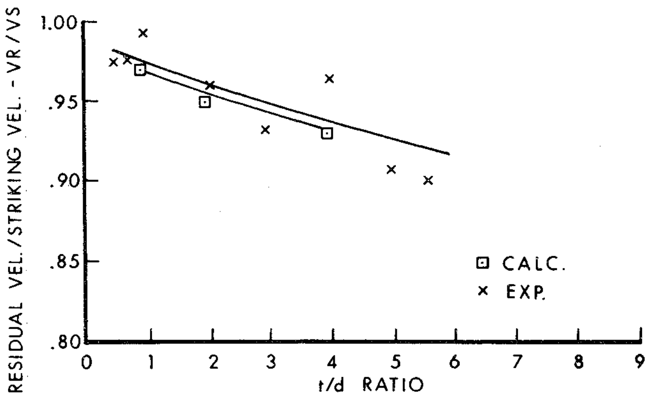


Fig. 5 Residual velocity vs t/d ratio for aluminum-aluminum HV impact.

UNIVAC 1108, EXEC 8 computer. Computer run time was dependent on the target thickness, varying from 5 min/μ sec of real time for the 3.175-mm target to more than 20 min/μ sec for the 25.4-mm target. The run times were shorter when the strength phase of the code was turned off.

The computations for the five cases were divided in two groups. In the first group the problem of material response was treated as purely hydrodynamic in nature and the influence of deviation stresses was not considered. In the second group the material response was considered to be strength dependent and the stress deviations were included. The termination of each computation was to be controlled by the average projectile velocity. When this velocity approached a constant minimum value the rod was considered to have perforated the target and the computation was stopped. In some cases the computations were stopped prior to this condition, but the problems were sufficiently advanced to obtain reasonable results.

The experimental data used to validate the numerical results of the computations were the work of Baker.[3] Slight variations in striking velocities, L/D ratios, and aluminum composition of the projectiles were noted.

Results

A comparison of the results from the computation of the two groups to determine the influence of strength effects at hypervelocity impact gave some interesting results, as shown in Figs. 1 and 2. In all five cases the penetration depth and the kinetic energy in the projectile, both as a function of time, remained relatively unchanged. When strength effects were included the average projectile velocity, the kinetic energy in the target, and the hole growth were only slightly lower,

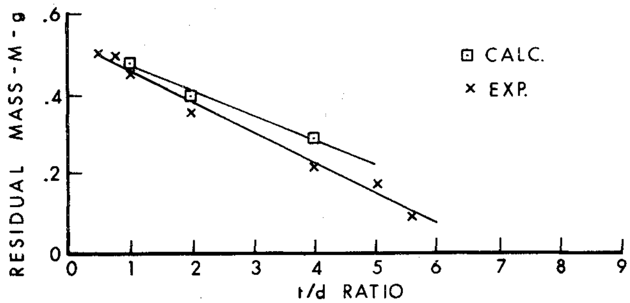


Fig. 6 **Residual mass vs t/d ratio for aluminum-aluminum HV impact.**

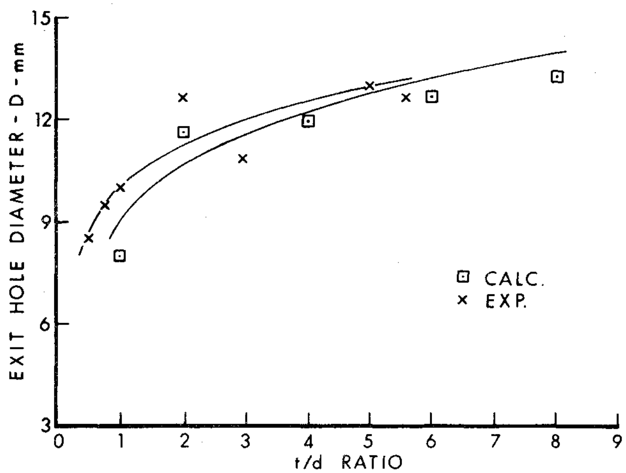


Fig. 7 **Hole diameter vs t/d ratio for aluminum-aluminum HV impact.**

indicating that for the given striking velocity the projectile greatly overmatched each of the targets. Figure 2 describes the normalized entrance diameter as a function of time for the hydrodynamics case. The inclusion of strength degrades the curve (represented by the solid line) but this degradation is relatively small. The hole formed by the kinetic energy round is cylindrical in shape, and therefore it is reasonable to consider the hole diameter by measuring either the exit or entrance diameter of the target. For comparison with the experimental data, the exit hole diameter was computed from the material package plot at the original location of the rear surface of the target. Figure 3 shows the computational growth of the hole becoming barrel-shaped, with the entrance diameter being slightly smaller than the exit hole.

The residual mass of the projectile was determined to be only the body of the projectile and to exclude the projectile material lining the target. Figure 4 represents deformation patterns for case 2 at 0, 2, 4, and 6 μsec. The shaded portions show areas where the material in the cells has failed as a result of high tensile pressures exceeding 35 kilobars. These patterns are typical for all cases.

Discussion

The comparison of experimental and analytical results is shown in subsequent figures. In Fig. 5 the residual velocities as a function of the t/d ratio are shown. While the scatter in the experimental data is somewhat pronounced, a least-squares fit with a correlation coefficient of 84% was obtained. The computed data points fall within 2% of the experimental curve. In Fig. 6 the residual mass is compared as a function of the t/d ratio. A correlation coefficient of 99.2% was calculated for a linear fit of both the experimental data and the analytical data. However, the discrepancy between the two curves may be attributed to the method used by the code for determining the residual mass. The inclusion in the code of not only a fracture criterion but also improved methods for tracking failed material regions may result in greater accuracy when computing the residual mass of the projectile. In Fig. 7 hole diameters are compared. The scatter in the experimental data is attributed to variations in the test conditions, but a least-squares fit gave reasonable correlation. A similar curve was generated for the analytical data. However, the analytical data points for $t/d=6$ and 8 are not the final exit diameters, because the code was stopped prior to complete penetration. With advances made in computer technology, cases 4 and 5 can be run to completion in shorter computer time and with not too significant an increase in cost.

Conclusions

For the cases studied, material strength effects proved to be negligible. Continued studies are planned, varying such parameters as target thickness, striking velocity, and projectile geometry. Because of the overall good agreement between the experimental and analytical results, it can be concluded that for the solution of hypervelocity impact problems where the material response is considered purely hydrodynamic, computer codes such as HELP can provide an efficient tool for both supplementing and reducing the number of experimental investigations.

References

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[2] Hageman, L. J., Sedgwick, Robert T., "Modification to the HELP Code for Modeling Plugging Failure," AFA Contract Rept. 3SR-1109, Eglin Air Force Base, Fla., May 1972.

[3] Baker, J. R., "Rod Lethality Studies," NRL Rept. 6920, Nval Research Laboratory, Washington, D.C., July 1969.