Perforation of Metal Plates: Laboratory Experiments and Numerical Simulations*

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Abstract

The Naval Explosive Ordnance Disposal Technology Division has a requirement to establish a modeling capability to simulate render safe procedures for unexploded ordnance. To aid in establishing this capability, the Navy has initiated a research and development program that includes modeling studies, research on applicable impact related material parameters, and comparison of the modeling results with experimental results. This paper presents a summary of the progress during the first six months of this effort including a selection of laboratory experiments and their numerical simulation.

Introduction

The Naval Explosive Ordnance Disposal Technology Division has a requirement to establish a modeling capability to simulate render safe procedures for unexploded ordnance. To aid in establishing this capability, the Navy has initiated a research and development program that includes modeling studies, research on applicable impact related material parameters, and comparison of the modeling results with experimental results. This paper presents a summary of the progress during the first six months of this effort including a selection of laboratory experiments and their numerical simulation.

The Naval Explosive Ordnance Disposal (NEOD) Technology Division has conducted more than 90 plate impact experiments to support the initial phase of this research and development effort. The target plates include three thicknesses: 0.125, 0.25 and 0.5 inch (3, 6, and 12 millimeters), three materials: A36 Steel, 6061-T65 Aluminum and C2600 Brass, three projectile types: 0.5 Caliber, PAN Steel, and PAN Aluminum slugs, at impact speeds between 240 and 3400 feet/second (70 to 1050 meters/second). The nominally normal projectile impact data includes: pre and post impact projectile speeds and orientations, post-test deformed projectiles, plate deformed profiles, plate plug masses for perforated plates, flash X-ray images, and post-test photographic documentation.

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The numerical technique selected to model these experiments is the Smooth Particle Hydrodynamics (SPH) particle technique as implemented in LS-DYNA. The SPH technique offers the advantages of a Lagrangian method without the necessity to select ad hoc erosion criteria to remove highly deformed elements. The plate impact simulations were performed independent of the experiments and without knowledge of the experimental results, i.e. blind predictions. Overall the modeling was quite successful, however a trend was noted that the model results under predict the measured residual projectile velocities as the projectiles became more deformed. An understanding of this trend in the modeling is the subject of continuing research and development.

Plate Impact Experiments

More than 90 flat plate impact experiments were performed under the direction of the Naval Explosive Ordnance Disposal Technology Division. The plates had a free span area of 8 by 8 inches (203 by 203 mm) and were fixtured as shown in Figure 1. Three plate thickness were used in the experiments: nominal thicknesses of 0.125, 0.25, and 0.5 inches (3, 6, and 12 mm) and three plate materials were tested: A36 Steel, 6061-T651 Aluminum and C2600 Brass.

The plates were nominally center impacted by three types of blunt projectiles launched from different devices that produced impact speeds ranging from between 240 and 3400 feet/second (70 to 1050 meters/second). The orientation of the projectile impacts were intended to be normal to the target, but in 12 of the tests an angle-of-attack greater than or equal to 5 degrees was observed. The projectiles are basically right circular cylinders with a short lengths of reduced diameter (shoulders) at the rear of the PAN projectiles. The PAN projectiles also have a slight taper from their front (impact end) to the start of the shoulder at the aft end. The overall dimensions of the blunt projectiles are given in Table 1.

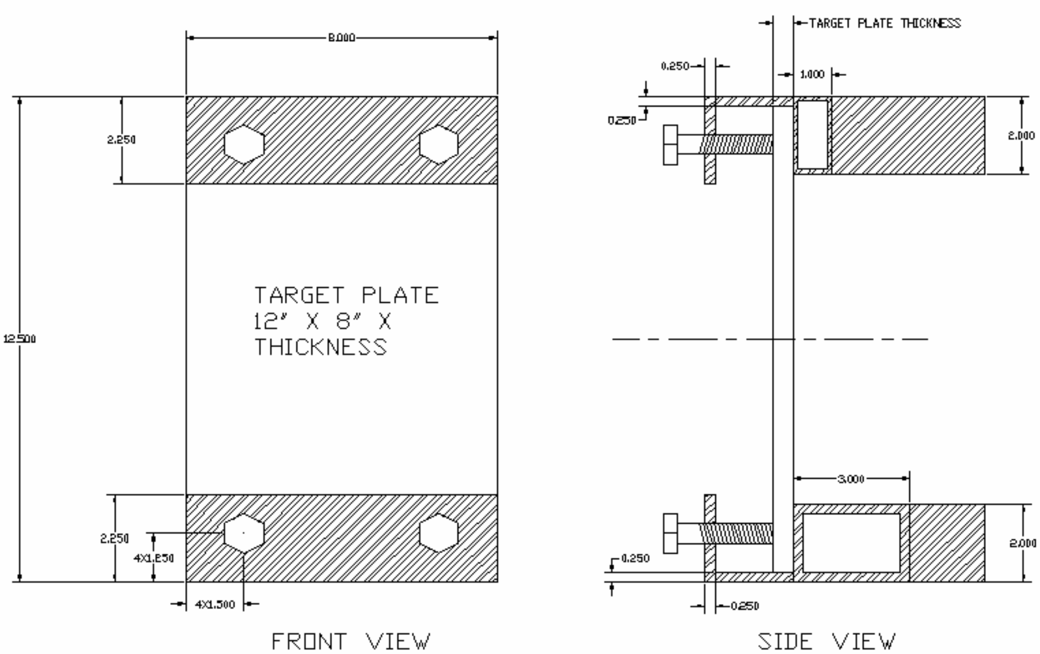

Figure 1 Schematic impact plate configuration and fixture.

Table 1 Summary of projectile dimensions.

Projectile	Length (inches)		Diameter (inches)		
	Overall	Shoulder	Fore	Taper	Aft
0.5 Caliber	3.0		1.0	1.0	1.0
PAN Steel	1.100	0.125	0.664	0.647	0.516
PAN Aluminum	0.974	0.125	0.660	0.645	0.520

The key experimental data included the impact and residual velocity of the projectiles. Additional photographic data documented the pre and post-impact orientation of the projectiles, post-test plate and projectile deformed shapes and estimates of the plate plug masses from the plates that were perforated.

Ballistic Limit Estimations

Recht and Ipson [1] proposed an analytical expression, based on conversation of energy and momentum, that can be fit to residual perforation velocities and provides an estimate of the ballistic limit; this is a useful technique when the available data do not include the ballistic limit. The analytical expression that is fit to the velocity data is

$$v_r = a\left(v_i^p - v_{bl}^p\right)^{1/p}$$

v_r residual projectile velocity

v_i initial projectile velocity

v_{bl} ballistic limit velocity

where the parameter a is related to the mass of the projectile and the mass of the 'plug' that results from a perforated plate, i.e.

$$a = \frac{m_p}{m_p + m_{plug}}$$

and $p = 2$. For the present purposes of estimating the ballistic limit, the parameters a and v_{bl} are determined from a non-linear regression fit of the data, with the constraint that $a < 1$. A unique determination of these two parameters requires a minimum of two residual perforation velocities. In addition to providing an estimate of the ballistic limit, the Recht-Ipson equation provides a convenient way to display and represent both the experimental and numerical velocity results.

Sample Data and Recht-Ipson Parameters

Figure 2 illustrates the type and nature of the principal data obtained from the plate impact experiments, and the Recht-Ipson fits to the laboratory data. The data was obtained from two independent facilities, i.e. the indicated METS data is from NEOD's laboratory and a laboratory facility at Battelle also performed tests as requested by NEOD. The data consists of velocity pairs with the projectile's impact velocity plotted on the abscissa, as the independent variable, and the projectile's residual velocity plotted along the ordinate. The impactor was the 0.5 Caliber projectile and the target plates were three thicknesses of A36 steel plate. Note: Additional NEOD data for higher and lower velocities was inadvertently omitted when the parameters, and subsequent numerical comparisons, were determined; however this data is consistent with the subset presented in Figure 2, and subsequently in Figure 6.

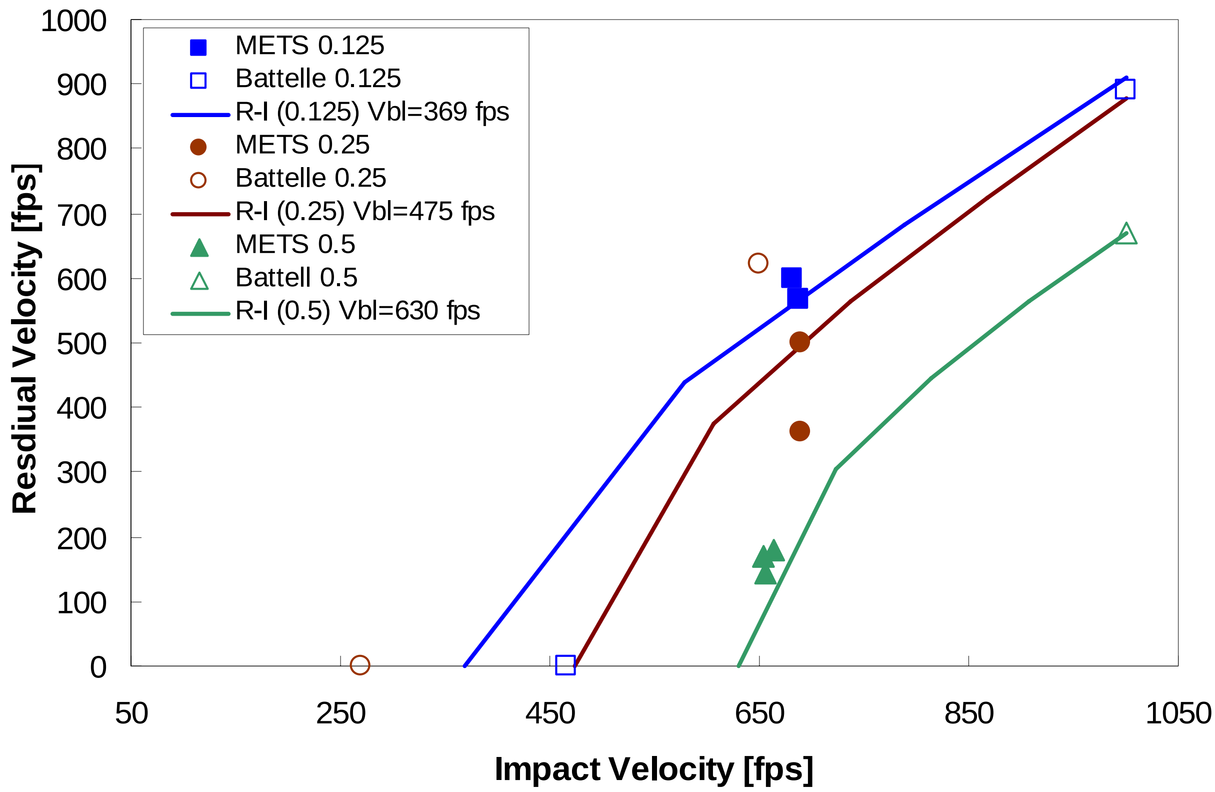

Figure 2 Summary of measured (METS & Battelle) 0.5 Caliber projectile impact and residual velocities with comparison to Recht-Ipson fits of the data.

Table 2 summarizes the Recht-Ipson parameters for the three plate thicknesses. In addition to the projectile velocities, some of the perforated plate plugs were recovered and weighed. For the 0.5 inch thick steel plate, in the present example, one such plug was reported to have a mass of 48 grams. With a calculated 0.5 Caliber projectile mass of 302 grams, the corresponding non-dimensional Recht-Ipson parameter, a, has a value of 0.86 which is identical to the value reported in Table 2. This correspondence is likely due to some serendipity, and the close correspondence of the Recht-Ipson analysis to the present experiments.

Table 2 Summary of Recht-Ipson parameters for three plate thickness with 0.5 Caliber projectile.

Thickness (in)	Recht-Ipson Parameters	
	a	v_{bl} (ft/sec)
0.125	0.98	369
0.25	1.0	475
0.5	0.86	630

Plate Impact Simulations

A total of 34 plate impact simulations were performed as *blind predictions* to span the planned experimental data. This series of predictions focused on the three thickness of the steel target plate impacted by the three different types of projectiles. An additional 13 simulations were performed for three thicknesses of an aluminum target plate and 2 simulations using a brass target plate. Although these latter 15 simulations were performed after the data was released, no 'tuning' of the model was performed other than using published material model parameters for the two target plates.

A model development activity preceded the present impact simulations, that also served as a proof-of-concept demonstration for the somewhat novel modeling approach used in the present work. There is a very nice body of experimental and numerical plate impact work reported by Borvik and co-workers, e.g. Borvik, et al [2 & 3], that was used in developing the plate impact model.

Geometric Modeling

Figure 3 illustrates the geometry, and relative size comparison, of the three projectile types used in the present plate impact study; the projectile dimensions were provided previously in Table 11. The impactors are modeled using single-point integration hexahedra solid elements.

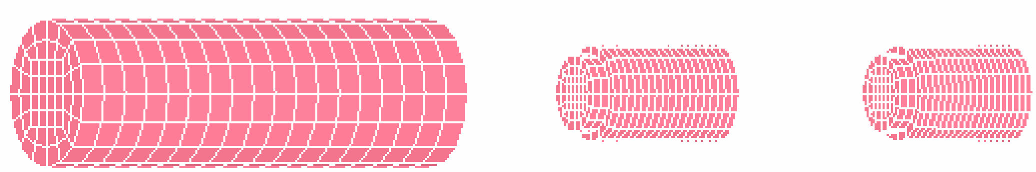

Figure 3 Projectile models: 0.5 Caliber (left), PAN Steel (center) and PAN Aluminum (right); models are approximately to the same scale.

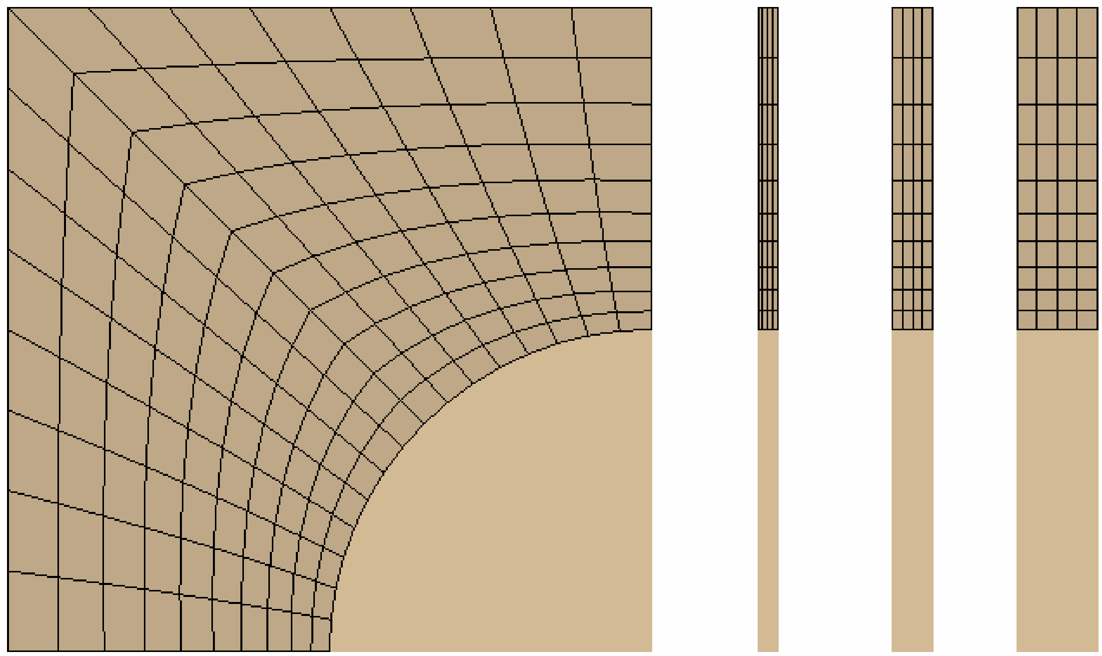

Figure 4 Quarter symmetry plate model (plan view) and three plate thicknesses: 1/8, 1/4 & 1/2 inches.

Figure 4 shows the plan view of the quarter symmetric target plate and three edges views corresponding to the three plate thickness, i.e. 1/8, 1/4 and 1/2 inches thick. The outer portion of the plate is comprised of standard single-point integration hexahedra (Lagrange elements) while the inner circular region is comprised of Smooth Particle Hydrodynamics (SPH) nodes, as implemented in the general purpose analysis code LS-DYNA [4]. The Lagrange portion of the model remains constant, only the model thickness changes for each plate. Four Lagrange elements are used through the thickness of the plate models to capture plate bending and inelastic responses.

The circular SPH region of the model has a radius of 2 inches (50.8 mm) which is constant for all three plate thicknesses. Note the projectiles have a radius of 0.5 inches for the 0.50 caliber slug and 0.33 inches for the two PAN projectiles. Thus the 2 inch radius for the SPH region is a compromise between the projectile radius and the edge of the target plate. The number of SPH particles in each plate model depended upon the plate thickness, see Table 3. There are several SPH modeling 'Rules-of-Thumb' that were considered in constructing the SPH portion of the model:

- At least two SPH particles should be used for every Lagrange element at the interfaces between SPH particles and Lagrange elements, e.g. at the circular boundary between the SPH and Lagrange portions of the model.
- A uniform spatial distribution of particles is preferred.
- The simulation CPU time is *not* a linear function of the number of SPH nodes, i.e. the 'nearest neighbor' SPH search algorithm's CPU time increases with the number of SPH nodes, as $n \log n$, in addition to the increase in CPU due to the addition of more SPH particles.

Table 3 Summary of SPH particle distribution for three plate thicknesses.

Plate Thickness (inches)	Number of Particles		Particle Spacing (mm)
	Radial	Thickness	
1/8	96	6	0.5292
1/4	80	10	0.6350
1/2	64	16	0.7937

Material Modeling

Two constitutive models are used in the plate impact simulations:

1. The Johnson-Cook model for the target plate, and associated Equation-of-State,
2. A simple von Mises model, for the projectiles.

The Johnson-Cook model parameters for 1018 steel were obtained from Vural, et al. [5] and the steel and aluminum model parameters for the projectiles were obtained from the on-line material database www.matweb.com. As mentioned above, the steel target plate simulations were performed before the experimental program, where it had been planned to use 1018 steel for the target plate, however this steel was not available in the required forms when the experiments were executed. Readily available A36 steel plates were substituted for the target plates; no A36 steel Johnson-Cook model parameters could be located in the open literature, so it was decided to use the documented 1018 steel Johnson-Cook model parameters. Laboratory characterizing and constitutive model parameter determination for A36 steel are planned as part of a future modeling effort.

Sample Simulations and Results Comparisons

Figure 5 shows the deformed configuration of the 0.5 Caliber impactor and 0.25 inch thick steel target plate at the end of the simulations with initial impactor velocities of 250, 650, and 1000 feet/second, respectively. For the simulations illustrated in Figure 5 the residual velocities predicted by the simulations are -12.8 (rebound), 509 and 857 feet/second, respectively. Recall from the above presentation of the experimental results that the Recht-Ipson fit to the 0.25 inch thick data provided an estimated ballistic limit of 475 feet/second for the 0.5 Caliber projectile, which is consistent with these simulations results which bracket the ballistic limit between 250 and 650 feet/second.

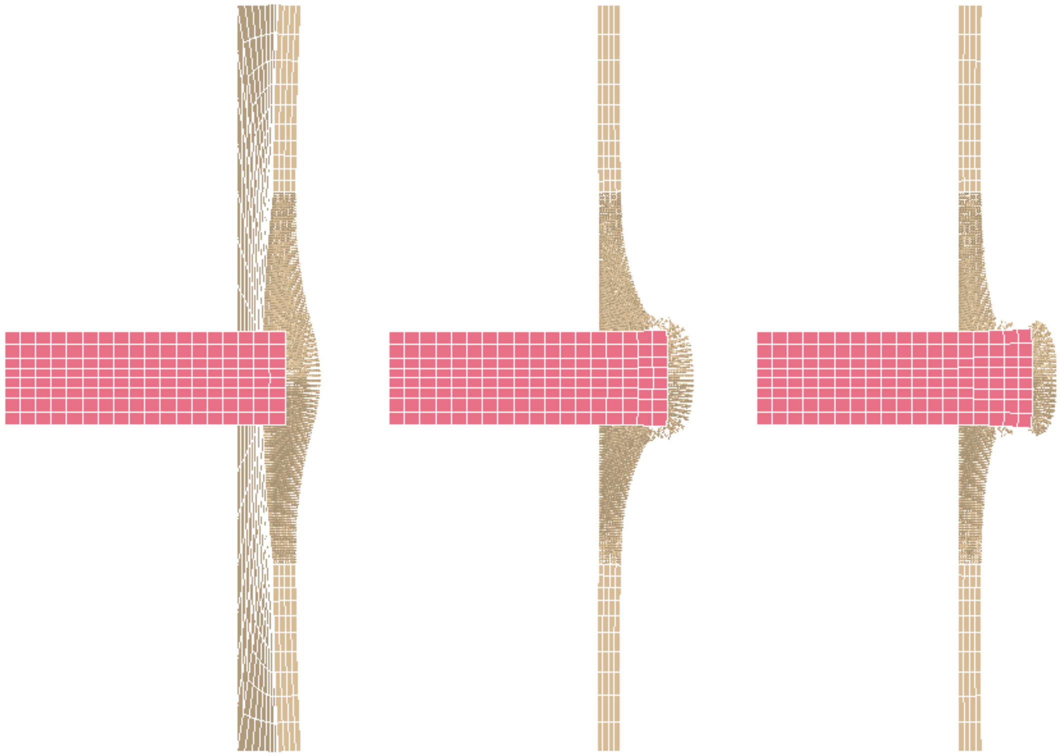

Figure 5 Deformation of 0.25 inch thick plate, and 0.5 Caliber projectile, for impact velocities of 250 (left), 650 (center), and 1000 (right) feet/second.

All 11 simulation results for the 0.5 Caliber projectile impacting the three thickness of steel target plate were also fit to the Recht-Ipson equation and the results are summaries in Table 4.

Table 4 Summary of Recht-Ipson parameters from simulations of three target plate thickness impacted by a 0.5 Caliber projectile.

Thickness (in)	Recht-Ipson Parameters	
	a	v_{bl} (ft/sec)
0.125	0.97	207
0.25	0.91	307
0.5	0.82	577

A graphical comparison of the experimental data and the Recht-Ipson fits to the simulations results is shown in Figure 6. Recall the target plate material used in the experiments was A36 steel and in the simulations a Johnson-Cook model of 1018 steel was used. Although different steels were used in the experiments and simulations, a cursory view of Figure 6 indicates that all the data can be plotted within the same range of velocities, i.e. it all fits on the same page. Further, for the most part the data and numerical results agree fairly well, especially given the discrepancy in the target plate materials.

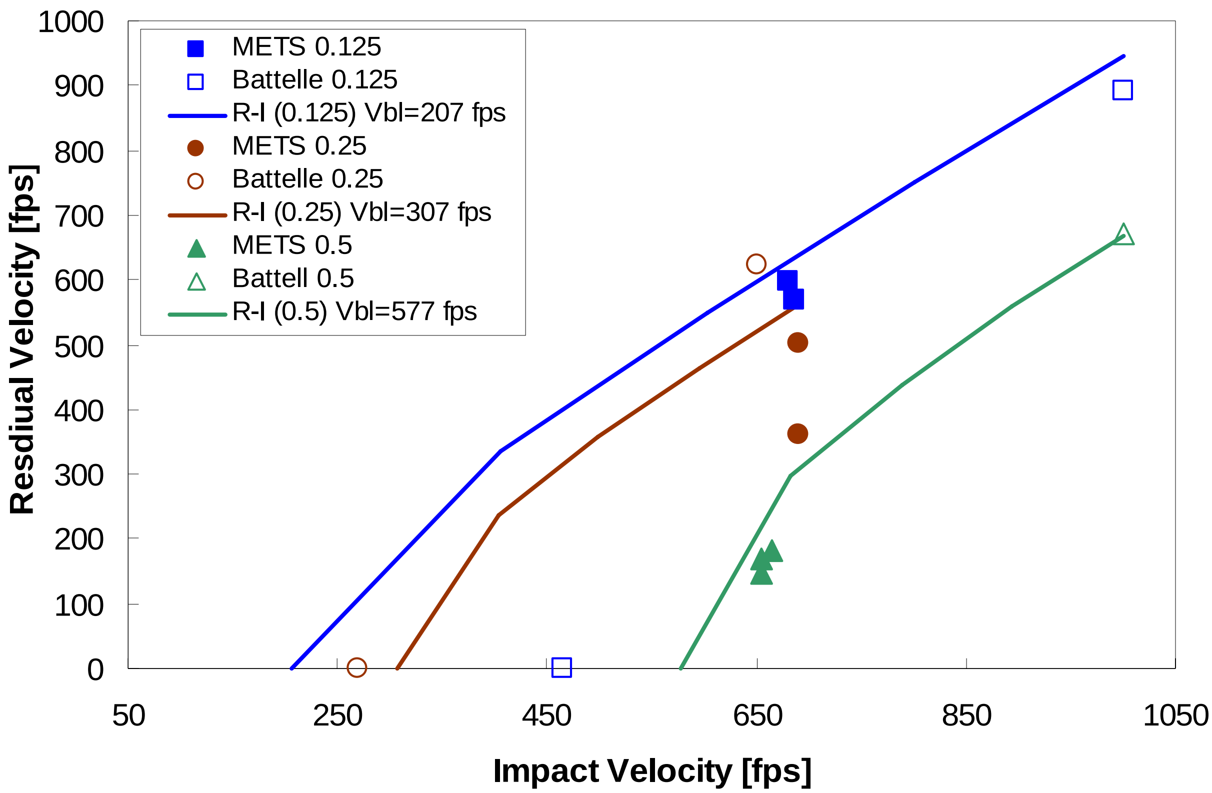

Figure 6 Summary of measured (METS & Battelle) 0.5 Caliber projectile impact and residual velocities with comparison to Recht-Ipson fits of the simulation results.

The comparison for the 0.125 inch thick plate results are quite good, with the Recht-Ipson fit to the numerical results providing a slight upper bound on the measured residual velocities. The Battelle data point at an impact of 465 fps, with no perforation, is the only data point that is not well characterized by the numerical results. This could be caused by a failing of the numerical simulation to under predict the ballistic limit velocity for thin plates, i.e. where bending and membrane stretching dominate the response. An overall average RMS error of 50 fps is obtained for the three METS measurements compared with the Recht-Ipson fit, and a value of 138.4 fps if the Battelle point is included in the RMS error average.

The comparison for the 0.25 inch thick plate results are also quite good, with the Recht-Ipson fit to the numerical results providing a dividing line between the METS and Battelle measurements. An indication of the scatter in the experimental results is shown by the two METS measurements with impact velocities of 690 fps, but residual velocities of 361 and 501 fps. The projectile for the former measurement had an estimated angle of obliquity of 7 degrees, while the later had an estimated 4 degree angle of obliquity. An overall average RMS error of 121 fps is obtained for the two METS measurements, and higher velocity Battelle measurement, when compared with the Recht-Ipson fit; the Recht-Ipson fit does not apply to values below the estimated ballistic limit.

The comparison for the 0.5 inch thick plate results are excellent, with the Recht-Ipson fit to the numerical results matching the Battelle measurement, and agreeing with the METS measurements in the critical ‘knee’ of the Recht-Ipson fit, i.e. close to the estimated ballistic limit. An overall average RMS error of 70 fps is obtained for the three METS and one Battelle measurement when compared with the Recht-Ipson fit.

Sources of Simulation and Experimental Discrepancies

The numerical results provided in this manuscript were compiled without knowledge of the experimental results, i.e. so called 'blind predictions.' Four potential sources for discrepancies between the experimental and simulations results are discussed briefly.

SPH Analysis Formulation – Some confidence was established in the LS-DYNA SPH analysis formulation, used in the present simulations, by simulation of similar known experimental results, i.e. Borvik et al. [3] plate impact experiments and simulations. It was found that the SPH analysis formulation works well at velocities greater than the ballistic limit for the two plate thicknesses simulated, i.e. 6 and 12 mm (0.23 and 0.46 inches). The SPH analysis formulation results become suspect when there is significant bending and membrane stretching of the target plate, i.e. relative thin plates impacted at or below the ballistic limit. In this response range of the target plates, the SPH analysis technique suffers from the so called 'tensile instability[†]' and the simulated plate appears to have less ballistic resistance than the corresponding experiment.

Johnson-Cook Material Model – There is a considerable body of literature describing successful application of the Johnson-Cook constitutive model for impact and perforation simulations. A minimal parameter study of the various Johnson-Cook input parameters (not reported here) showed little sensitivity to parameter changes and the computed response. However, the present results are based on Johnson-Cook constitutive mode parameters for 1018 steel, as provided by Vural [5], while the steel used in the experiments is an uncharacterized (commercially obtained) A36 steel. The lack of appropriate constitutive model parameters for the steel plate used on the experiments is thought to be a significant source of discrepancies between the experiment and numerical results, particularly in the regime where the projectile velocities approach the target's ballistic limit.

Deformable Projectiles – In the comparisons with the Borvik experimental and numerical results, cited above, the projectiles were assumed to be rigid (hardened tool steel). In the present simulations significant deformation of the PAN steel and PAN aluminum projectiles were predicted, and later observed. The simple constitutive model parameters for these materials were obtained from generic material property data, i.e. the materials used in the experiments are uncharacterized. The interaction of these significantly deformed projectiles with the plates is thought to affect the penetrability of the plates, especially near the ballistic limit.

Experimental Results – The quality of the experimental results needs to be assessed separate from the numerical simulations. In particular, repeatability of the experimental results and estimates of the non-normality of the projectiles at impact, i.e. pitch and yaw angles.

[†] See for example Monaghan [6].

Conclusions

The comparative results of residual velocity and projectile deformations (not reported here) for the 0.5 Caliber projectile are very good. However, the same is not true for the other two projectile types. The calculated projectile deformations for the PAN Steel and PAN Aluminum projectiles indicate these model components are not reproducing the experimental measurements.

An assessment of the modeling of these components, both constitutive and spatial (mesh), was performed. The two projectile modeling aspects investigated were the material constitutive model and spatial discretization. The objective of the study was to assess the effect of projectile modeling changes on target plate perforation, i.e. velocity reduction, with the goal of adopting modeling changes that improved the correlation between the experimental and simulation results for future simulations.

The constitutive modeling investigation was based on replacing the simple von Mises constitutive model for the projectile material with available Johnson-Cook material models for a similar material. For 0.5 Caliber projectile the AISI 6150 Steel von Mises constitute model was replaced by an S-7 Tool Steel Johnson-Cook constitutive model, with minimal changes in velocity reduction obtained from the simulations. The AISI 12L14 PAN steel projectile von Mises constitute model was replaced by a 1006 Steel Johnson-Cook constitutive model. In this case, the impact end of the projectile eroded, due to the damage parameter portion of the Johnson-Cook model, for all three plate thicknesses. While the experimental projectiles deform significantly, especially the PAN projectiles, they remain integral, i.e. they do not fragment. It was decided to stop the Johnson-Cook constitutive modeling portion of the parameter study at this point. While the simple von Mises constitutive models may not accurately represent the projectile response, e.g. no strain-rate effects are included, the selection from available Johnson-Cook models as replacement materials for the projectiles is, in this case, even less accurate.

The discretization modeling investigation used a hybrid projectile model that combined SPH particles at the impact end of the projectile and Lagrange solid elements at the aft end. The objective of this modeling change was to better model the severe deformation at the impact end of the projectile via the SPH particles. The Lagrange solid elements used to model the projectiles, in additional simulations not reported here, were highly distorted (PAN projectiles only) and may not have accurately represented the projectile deformation. The concern here is that over estimation of the projectile deformation may lead to increased velocity reduction, i.e. lower projectile residual velocity, since the increased diameter of the significantly deformed projectile will interact with a larger area of the target plate. Additional hybrid projectile simulation results generally indicate no significant change in velocity reduction between the all Lagrange solid element projectile models and the hybrid models, especially for the PAN projectiles.

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