Hypervelocity Impact of Spaced Plates by a Mock Kill Vehicle

James Wilbeck, Stephen Herwig, Jon Kilpatrick
ITT Industries, Inc., Advanced Engineering & Sciences Division
Huntsville, Alabama

Douglas Faux
Lawrence Livermore National Laboratory
Livermore, California

Eugene S. Hertel
Sandia National Laboratories
Albuquerque, New Mexico

Robert Weir
Sandia National Laboratories
Albuquerque, New Mexico

Milan Dutta
U.S. Army Space and Missile Defense Command
Huntsville, Alabama

Summary – In support of the National Missile Defense (NMD) program, a series of Light Gas Gun (LGG) lethality tests were conducted at the Arnold Engineering Development Center (AEDC). A new projectile was designed for this test series that would be representative of aspects of a generic NMD system kill vehicle. A series of projectile development tests were performed during the design phase of the projectile. This paper reports the results from the second development shot, in which the projectile impacted normally against two thin aluminum target plates, spaced approximately 5.5 diameters apart. Results reported include the documentation of the damage to the first and second plates, the debris generated behind the first plate, and correlation of these with analytical and numerical predictions. Hydrocodes used for analyses included ALE3D, run by the Lawrence Livermore National Laboratory, and CTH, run by the Sandia National Laboratories. The purpose of the hydrocode analyses was to help in assessing the ability of these codes to predict the debris formation process and the target damage.
IMPACT CONDITIONS

This test was conducted using the large two-stage light gas gun at AEDC. This gun, having a 14 inch (35.6 cm) diameter pump tube and a 3.3 inch (8.4 cm) launch tube, is the largest two-stage LGG in the United States. The pump tube of this gun can be seen on the left side of the photograph presented in Figure 1. The projectile had an overall length of 13.32 cm and an outside diameter of 8.38 cm and was made of Lexan, Figure 2. The mass of this projectile was held to 439 grams by drilling holes in the Lexan to lower its effective density.

TEST SET-UP

The target set-up is shown in Figure 3. The target plates were hung normal to the shotline, and were free to swing. The first two plates were 0.25 in (0.64 cm) thick Aluminum 6061-T651, and the third plate was a 1.00 in (2.54 cm) thick steel witness plate. Due to the limited room in the target chamber, each of the plates was limited to a width and height of 4 feet. This was felt to be insufficient to prevent cracks from running to the edge, but was unavoidable. The plates were spaced 18 in (45.7 cm) apart, and were held with cable in the top two corners. Both vertical and horizontal X-rays were taken with 450 KEV X-ray heads. The X-rays cassettes were held in trays that were permanently placed 2 feet (61 cm) off shotline. Because of the location of the X-ray cassettes in the target chamber, the centers of the plates had to be offset a few inches from the shotline.

TEST RESULTS

For this test, the measured impact velocity was 6.502 km/s. Laser photographs and X-rays of the projectile in flight, examples of which can be seen in Figures 4 and 5 respectively, showed the projectile to be in one piece at impact. The orientation of the projectile at impact of the first plate was extrapolated from the X-rays taken in flight. These values were found to be 5.2° pitch down and 12.6° yaw right.
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
As stated earlier, vertical and horizontal X-rays were taken of the debris cloud behind the first aluminum plate, prior to its impact of the second aluminum plate. The time of the X-rays was about 45μs after impact of the first aluminum plate. These X-rays were studied to determine the amount of projectile erosion caused by the first plate and the residual projectile that would subsequently impact the second plate. Copies of both X-rays are presented in Figure 6.

The damaged target plates were recovered and extensive measurements were made of the two aluminum plates. A photograph of the first plate is presented in Figure 7. The hole in the first plate was nearly circular, with an average diameter of 4.826 in (12.258 cm). (The chunk cut out of the hole in the lower left side was originally assumed to be caused by a late-time impact by a piece of gun piston, and was not included in the circular area.)

The pieces of the second plate were reassembled and photographed, with the results seen in Figure 8. Petaling and extensive bending of the plate were observed. In order to quantify the observed damage to the plate, each section of the plate was thoroughly measured. These measurements were then used to digitally reconstruct a flattened image of the plate. Figure 9 illustrates the results of this effort. Further quantification of damage to the second plate was made by studying the small holes and craters in the plate that were observed around the larger hole in the middle of the plate. Based upon the size of the holes and depths of the craters, two regions of damage were formulated. These regions can be seen in Figure 8, where white tape has been used to delineate the bounds of the regions.

NIH-Image software was employed to digitally measure the area and center of the actual hole. Next, an area-equivalent circle was calculated and overlaid on the digital image with its center coincident to the actual hole center. This resulted in a circle centered 3.2 in (8.13 cm) to the right and 2.3 in (5.84 cm) below the plate center, with a radius of 7.1 in (18.03 cm). This
hole is outlined in red in Figure 9 and represents a reasonable axi-symmetric approximation of
the primary plate damage.

Secondary and tertiary damage rings were also measured and photographed. These are
outlined respectively as yellow and blue bands in Figure 9. For the purposes of this analysis,
secondary damage was defined as particle damage resulting in individual craters that fully
perforated the plate. Tertiary damage was defined as particle damage that resulted in deep
individual craters that did not fully perforate the plate. It was observed that a reasonable
approximation of the secondary damage radius was 9 inches, with a tertiary damage ring radius
of 13 inches. These damage bands correspond to those outlined in white tape on the actual plate
in Figure 8.

COMPARISONS WITH ANALYSES

Efforts were made to compare the data obtained from this test with various analytical and
numerical models. Two sets of comparisons will be presented in this paper. The first looks at an
analysis of the size of the hole in the first plate. The measured value was compared with a
variety of existing models and good correlation was found with two. Secondly, hydrocodes were
run by two DOE laboratories to look at the early time impact event, and predictions of damage to
the first two plates and the debris generated behind the first plate were compared with the test
results.

ANALYTICAL STUDIES

This section compares the predictions of two established hole size models against the
observed average hole diameter generated after impact with the first thin aluminum plate.
Although it is known that the impact conditions included significant projectile pitch and yaw, for
computational simplicity, none of the following models were modified to account for these
effects. All computations assumed a normal impact and utilized the following constants:
One of the better-known hole-size models was developed at GM Delco in the 1960's [Ref. 1]. Based upon experimental observations and a great deal of small fragment data, the model took the form

$$D/d = 0.45 \frac{V}{d}^{2/3} + 0.90$$

(1)

A second model developed in a similar fashion for NASA in the 1960's [Ref. 2] took the form

$$D/d = 3.4 \left(\frac{t}{d}\right)^{0.333} \left(\frac{V}{c}\right)^{0.333} (1 - 0.0308 \left(\frac{\rho_t}{\rho_p}\right))$$

(2)

Both of these models have been successfully compared with data from the hypervelocity impact of small fragment against thin plates. The fact that they differ so greatly in form lead to concerns as to their applicability to the reported case of a large Lexan projectile. However, both gave very good agreement with the test. Using the values given above, the results of the predictions are as follow:

<table>
<thead>
<tr>
<th>Predicted Hole Dia.</th>
<th>Average Value from Test</th>
<th>GM Model Prediction</th>
<th>NASA Model Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12.26 cm</td>
<td>11.96 cm</td>
<td>11.97 cm</td>
</tr>
</tbody>
</table>

The small under-prediction of diameter can easily be attributed to the pitch and yaw of the projectile which would cause an increase in the area of projectile overlap of the target.
HYDROCODE STUDIES

Hydrocode studies were conducted by both the Sandia National Laboratories (SNL) and the Lawrence Livermore National Laboratory (LLNL). The primary focus of their analyses was predictions of early time debris formation and resulting plate damage. Predictions of debris behind the first plate were correlated with X-rays from the test. Predictions of early time plate damage were correlated with the observed hole damage in the tested plates. Late-time structural response of the plates was not considered. The efforts by both laboratories were quite good. Both laboratories ran 3-D versions of their respective codes to account for projectile pitch and yaw.

LLNL Results with ALE3D

An ALE3D simulation was performed on the second NMD development shot discussed above. ALE3D [3] is a 3-D, arbitrary-LaGrange-Eulerian, finite element code that treats fluid and elastic-plastic response of materials on an unstructured grid. The major components of the code are explicit and implicit continuum-mechanics, thermal diffusion, and chemistry. All components of the code participate in advection and operate with slide surfaces. The ALE3D code employs a relaxation scheme that allows the mesh to move into areas of high gradients and concentrate zones in regions of interest. This methodology allows for a more accurate simulation with fewer zones than the traditional Eulerian approach.

One reason for performing this calculation was to evaluate the equation of state used for Lexan. The ALE3D set-up for this simulation is shown in Figure 10. The ALE3D model contained 4.5 million elements and was run with 160 processors on the IBM SP2 massively parallel supercomputer at LLNL. It took 58 CPU hours to run this simulations out to 150 microseconds. An initial orthogonal mesh was used and the projectile and plates where overlayed onto the mesh. The projectile was pitched and yawed about its center of gravity (CG).
The CG was located at the Y=0 plane and the Z=0 plane. An initial velocity of 6.502 km/s was applied to the projectile in the positive X direction. The projectile and plates had a material weighting factor greater than the background air resulting in the mesh relaxing (moving) into the materials. A Mie-Gruneisen equation of state was used for the Lexan and aluminum and the Steinberg-Guinan High Rate model was used for the constitutive response of each material.

Figure 11 is a series of material plots showing a side view (XY plane) at 25, 45, 65, 90, 120 and 150 microseconds after impact. The projectile expands laterally at a rate of 0.12 cm/μs as it traverses the space between the witness plates resulting in a debris radial spread half angle of 22.5 degrees. Figure 12 is a 2-D material plot at Z=0 cm showing mesh location. This illustrates the advantage of the ALE technique by concentrating zones where they are needed.

X-rays were taken at 45 μs after projectile impact of the first aluminum plate. A three-dimensional view of the projectile at 45 μs after impact is shown in Figure 13. Pseudo-radiographs were then produced from the ALE3D dump file for comparison to experimental x-rays. Figure 14 shows a comparison between the x-ray at about 45 μs and the ALE3D pseudo-radiographs at 45 μs. The projectile impacted with significant yaw introducing asymmetry into the problem which can only be captured with a three-dimensional simulation. Very good agreement between x-rays and simulation are observed.

As discussed earlier, Figure 8 presented a photograph of the damaged second aluminum plate. It is apparent from this figure that the impact caused extensive fracturing, generated multiple petals, and entirely sheared off a large portion of the lower-right quadrant of this plate. Figure 9 showed a visual reconstruction of the plate with all petals bent back flat. Figure 15 compares this sketch with the ALE3D simulation of the damage to the second aluminum plate. To conserve problem size and code run time, only a subsection of the full plate was modeled. The primary (red) and secondary (yellow) experimental damage rings are overlaid onto the
simulation showing very good agreement. The simulated center of damage is centered 1.988 in (5.05 cm) to the right and 0.811 in (2.06 cm) below the plate center. The second aluminum witness plate was hung off center to make room for the x-ray film packs (1.125 in left and 1.4375 in up). The corrected simulated debris hole center is 3.114 in (7.91 cm) right and 2.248 in (5.71 cm) down as compared to 3.378 in (8.58 cm) right and 2.299 in (5.84 cm) down for the experiment. It is important to note that the ALE3D simulation does not account for fracture and was only run to 150 microseconds, thereby not exhibiting later-time structural deformations of the plates.

Finally, the hole size in the first aluminum witness plate is compared with the experimental hole size, Figure 16. The average hole diameter in the first witness plate for the experiment was 4.826 in (12.26 cm) and for the simulation the average diameter was 4.7 in (11.94 cm). It is interesting to note that the hole pattern in the first witness plate does not exhibit fracture and petaling of the aluminum; thereby, agreeing quite well with the simulation. A second point to note in the figure is that the ALE3D run predicts extensive plastic deformation in the region where a tear occurred in the actual target plate. From this, it has been deduced that the tear may have been due to the asymmetry of the initial impact, in which a small area failed due to the excessive plastic flow. This failure caused a notch of material to rip out of the plate, with the inertia of the tab causing the tear to be greater than the predicted plastic zone.

**Sandia Results with CTH**

The second NMD development shot was simulated by Sandia in two ways; the automatic mesh refinement (AMR) option in CTH was used to simulate a two-dimensional impact of the AEDC projectile with a spaced plate array and the standard multiprocessor version of CTH was used to simulate the shot in three-dimensions. CTH is an Eulerian shock physics analysis package, or hydrocode, which solves the conservation of mass, momentum and energy equations.
using a finite volume scheme over a spatially fixed computational mesh. When the AMR option in CTH is invoked, computational mesh is added and removed as the simulation progresses. Mesh is added when material activity (material with non-zero velocity) changes. The method uses a patch based refinement scheme, where a “patch” of additional mesh is added in a hierarchical fashion with a 2:1 refinement ratio. In the version used for this study, patches are added and removed depending on material activity.

CTH has models for material strength and failure, volumetric changes due to pressure and temperature, high explosive detonation and initiation, and energy sources. It has the capability to run on a variety of serial, distributed data parallel, and shared memory parallel computing platforms. The user interface is identical for serial and parallel execution. CTH has been validated against a large class of experimental data and is widely used in the Department of Defense and Department of Energy laboratory complex. Typical simulations include shock propagation, penetration and perforation of armor, warhead mechanics, and high explosive initiation and detonation.

The AMR option in CTH can provide much higher local mesh resolution than the standard version of CTH due to its ability to automatically adjust the local zone size. By weighting the local zone size with material activity in the mesh, a minimum local zone size of 0.068 cm in the 2D computational mesh (52.5 cm x 70 cm) for this problem can be provided by a mesh size varying between 10,000 and 300,000 zones. This minimum zone size results in ~9 zones through the thickness of the aluminum plates. The standard version of CTH, for the same problem with a cell size of 0.068 cm, requires 794,766 zones in the 2D mesh, or roughly 2.5 times larger.

During this analysis, for both the standard and AMR option in CTH, the projectile was modeled using a polycarbonate sesame EOS for the Lexan, elastic/perfectly plastic strength
model, and fracture. The aluminum plates were modeled using a pure aluminum sesame EOS, elastic/perfectly plastic strength model, and fracture. The AMR option in CTH was run on a Sun Ultra60 workstation for a 2D axis-symmetric representation of the impact. The case run with the standard version of CTH was done entirely 3-dimensionally with no planes of symmetry due to the projectile pitch and yaw and was run in parallel on the Sandia ASCI multi-processor teraflops computer using 118 nodes.

Figure 17 shows the 2D simulation of the debris cloud generated by the projectile impact at 6.5 km/s using the AMR option in CTH. The simulation shows a jet forming by the portion of the aluminum plate constrained by the projectile’s forward cup. The impact hole measures 12 cm (4.7”) in diameter and the exit hole measures 36.5 cm (14.4”) in diameter.

Figure 18 shows the standard CTH 3D simulation of the debris cloud generated by the projectile impact at 6.5 km/s. The 3D simulation was made over a 52 cm x 52 cm by 80 cm mesh with a uniform cell size of a 0.25 cm cube. This results in a mesh of 13,844,480 zones. The figure shows a 2D slice through the computational space at the y=0 plane and at t=0, 30, 90, and 150 μs.

Figures 19 and 20 compare the experimental and code predicted (simulated) x-ray of the projectile taken approximately 45 microseconds after impacting the first aluminum plate. Major features of the projectile are replicated in the CTH calculation: overall shape and orientation, the jet of material preceding the body of the projectile, the mushrooming of the body, and the trailing debris on the edges. The CTH calculation shows a more pronounced spall-cap on the end of the projectile. The similarities between the calculated and test projectiles at this stage after impact is a source of confidence that CTH is modeling the material response well.

Figures 21 and 22 show the calculated holes in the first and second aluminum plates at 150 μs. The first plate has a roughly circular entry hole 12-13 cm (4.7”- 5.1”) in diameter with an
asymmetry reflecting the pitch and yaw of the projectile. The hole in the second plate is roughly 41 cm (16.1 in) in diameter; a ratio of roughly 4 between the two hole diameters. The similarity in the hole sizes between the finely resolved calculation done with the 2D AMR option in CTH and the coarser calculation done with standard 3D CTH version increases the confidence the resolution in the 3D calculations are providing realistic simulations.

The holes in the plates that resulted from the development shot were shown previously in Figures 7 and 8. As with the ALE3D run, CTH predicted a protrusion in the region where a notch of material was torn out. The reported hole size is 4.8” in diameter, which compares well to the calculated hole size for both the AMR and standard CTH simulations.

The exit hole in Figure 8 is much larger than that predicted by CTH, but this is due to the hole shown in Figure 22 being taken at 150 microseconds. The hole will grow with time after impact as structural response to the momentum imparted to the plate becomes dominant. A better comparison of penetration damage is possible by comparing the prediction of Figure 22 with the digitally reconstructed second plate as shown in Fig 9. The stated size of the exit hole is on the order of 18” in diameter, which was of the order calculated by both the AMR option and standard CTH simulations.

CONCLUDING REMARKS

This paper reports a single test at high velocity in which the impact conditions are well defined, the debris generated at impact are well characterized, and the damage to the target plates are well documented. It is hoped that this data can be used by various hydrocode and structural code modelers to validate their capabilities to predict real impact tests.

A couple of empirical hole size models developed in the 1960’s were shown to give a very good prediction of the hole size in the first target plate.
The extensive work by LLNL using ALE3D and Sandia with CTH appears to have demonstrated both qualitatively and quantitatively their ability to predict the complex response of both projectile and target to the early time impact conditions. However, these hydrocode studies also demonstrated the need for structural analysis efforts to predict the late time plate damage.

REFERENCES


Figure 1 – AEDC Two-Stage Light Gas Gun Facility

Figure 2 – CAD Drawing of the Lexan Projectile
X-ray preferences:
1) 2, orthogonal x-ray heads
2) x-ray film pack as close to centerline/plates as possible
3) 3 pairs (lexan, alum) step wedges located on each film pack as shown
4) hang projectile and take set-up x-rays to adjust x-ray energy
5) Horizontal x-ray at 35 microseconds after impact
6) Vertical x-ray at 65 microseconds after impact

Figure 3 - Approximate Test Setup for the Second Development Shot
Figure 4 – Laser Photograph of the Projectile in Flight

Figure 5 – X-ray of Projectile in Flight
Figure 6 – Horizontal and Vertical X-rays of Debris Between Aluminum Plates, T = 45μs

Figure 7 – Hole in Front Plate Target
Figure 8 – Photographs of the Damaged Second Aluminum Plate
Figure 9 – Digitally Reconstructed View of the Second Aluminum Plate with Petals Folded In
Figure 10 - ALE3D set-up for Development Shot #2 simulation: a) Side view (XY plane) red: projectile, green: first aluminum plate, blue: second aluminum plate, b) Side View close up showing projectile pitch of 5.2° nose down, c) Top View (XZ plane) close up showing projectile yaw of 12.6° nose right.
Figure 11 - ALE3D Simulation of Development Shot #2: Side Views (XY plane) at various times, a) 25 b) 45, c) 65, d) 90, e) 120 and f) 150 microseconds after impact.
Figure 12 - ALE3D Simulation of Development Shot #2: Two-dimensional slice at 45 microseconds of XY plane at Z=0.0 cm. Plot illustrates the ALE technique by moving zones into regions of interest. The Lexan (red) and front aluminum plate (green) have weighting factors greater than the background air.

Figure 13 - ALE3D Simulation of Development Shot #2: Three-dimensional view of the projectile and first aluminum plate at 45 microseconds. The Lexan (red) and front aluminum plate (green) are shown.
Figure 14 – Comparison of the experimental x-rays and ALE3D pseudo-radiographs of the projectile at 45 microseconds. a) vertical x-ray plane b) horizontal x-ray plane (projectile travels right to left)
Figure 15 - Comparison of ALE3D simulation and experiment for the second witness plate. Top figure is a digitally reconstructed view of the second witness plate from the experiment. Primary (red) and secondary (yellow) damage rings are shown. The experimental center of damage was 3.11 inches right and 2.25 inches down versus 3.37 inches right and 2.30 inches down for the simulation.
Figure 16 - Comparison of ALE3D simulation and experiment for the first witness plate. Top figure is a photograph of the first aluminum plate and the bottom picture is the ALE3D simulation showing hole size at 45 microseconds. Average hole diameter for the experiment was 4.8 inches versus 4.7 inches for the simulation.
Figure 17. 2D AMR option in CTH simulation of Development Shot #2: Side Views (XZ plane) at various times, a) 0 b) 45, c) 100, and d) 150 microseconds after impact (domain plotted from x = -20 to x=20).
Figure 18. 3D CTH simulation of Development Shot #2: Side Views (XZ plane) at various times, a) 0 b) 30, c) 90, and d) 150 microseconds after impact.
Figure 19 - X-ray of AEDC projectile at 45 μseconds after impact

Figure 20 - Simulated x-ray of CTH Calculation at 45 μseconds after impact

Figure 21 - CTH Prediction of Hole in First Target Plate

Figure 22 - CTH Prediction of Hole in Second Target Plate