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Simulation Study on Hypervelocity Penetration of Lab Scaled Shape Charge Mechanism

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Highlights:

- Small scale Shape charge mechanism parameters is successfully fabricated to produce hypervelocity detonation.
- Hypervelocity penetration is achieved of up to 6000m/s.
- A numerical simulation using Euler meshing techniques has successfully proven the experimental results of a hypervelocity shape charge penetration.

Abstract. Shaped charge (SC) is a mechanism used by defence industries as anti-armored weapon to penetrate armored plates. Numerous studies have been conducted on the shaped charged effects. However, experimental studies are limited due to great safety requirement and limited access to high grade explosive. Due to these limitations, an experimental study on a small-scale shaped charge mechanism (SCM) penetration blast test was conducted against five (5) types of target materials. The experimental data is then verified by simulation to proof that it can be used to predict the SC penetration data. This paper intent to present a comparative study on the effect of shaped charge blast conducted by simulation with the actual experimental results. In order to conduct this study, a 2D AUTODYN software were used to develop the SC blast model against five (5) types of target materials. This study concludes that the 2D AUTODYN simulations results can predict the hypervelocity penetration for all target materials compared to the experimental test with an average difference of 9.1 %.

Keywords: *2D Autodyn; defence technology; hypervelocity penetration; shaped charge; shaped charge mechanism.*

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1 Introduction

A basic shaped charge consists of a casing filled with explosive material shaped at the target end using cone liner. The application of shaped charge mechanism (SCM) in the anti-tank weapon has greatly increased the penetration capability against hardened metal plates or barrier. Upon detonation of the SCM, energy from the detonation moved towards the cone liner symmetrically forcing the cone to melt and moved towards the target in a form of a focused intense and localized jetting force travelling at hypervelocity speed of above 1000 m/s [1,2]. The mechanics of hypervelocity penetration is a complex sequence which involved elastic-plastic deformation of the target materials that takes place when a strike velocity exceeds a critical value, typically above 1,500m/s. Depending on the VoD of the high explosive used, a typical SCM can produce a converging jet of molten liner materials with a tip velocity that can reach up to 6-12 km/s [3,4].

Though the SC penetration can be measured, the actual visualization of the mechanics of SC hypervelocity penetration experimentation is very difficult to be observed. In addition, SC experimentations using actual SC ammunitions are also very expensive and difficult to be carried out due to numerous safety precautions and procedures. Numerical simulations therefore are known to be an efficient method and capable of executing quantitative measurement of an explosive blast properties [4,5]. An explosive blast can be analysed using single method such as Lagrange, Euler or the mixture between both called Arbitrary Lagrange Euler (ALE), or mesh free Lagrangian commonly known as Smooth Particle Hydrodynamics (SPH) method. The numerical simulation on deformation of structure under shock and impact loadings, may utilized any of the technique which has its own advantages and limitations [6,7]. The Euler processor can be used to model the extremely high pressures and strain rates conditions during material deformations (of casing and liner material) and gases explosions [8]. The Lagrangian framework in the other hand is suitable for the SC structure to cater for material motion and distortions.

Based on previous simulations conducted by researches, the SC hypervelocity penetration effect can be simulated using AUTODYN 2D or 3D using both or either the Euler and/or Lagrangian framework. Combining the Euler and Lagrangian framework for a shaped charge simulation allows AUTODYN to readily model the venting of the explosive gases between the structural elements which can provide an accurate and efficient results [8]. The explosive detonation can be conducted using the Eulerian method while the target can response through the Lagrange method [9, 10].

This paper intent to discuss the comparison between the SC penetration as predicted by simulation compared to results from blast experiments of a smaller scale SC device [11, 12]. This is to prove that the simulation model developed can be used to predict SC penetration of a metallic materials with available mechanical properties. In these study, series of simulations were conducted to determine shaped charge penetration of various target plates based on parameters used in the blast test. Prior to developing the simulated SC penetration, series of hypervelocity penetration blast test have been conducted using a small-scale Shaped Charge Mechanism (SCM) against few metallic targets. A military grade plastic explosive no.4 (PE-4) which is C4 equivalent were used throughout these tests. Preliminary test was also conducted to identify mechanical properties of various target materials.

2 Numerical Simulation Method

A stand-alone ANSYS AUTODYN software Version 13 for 64-bit Windows processor is used to conduct the hypervelocity penetration blast simulation of a SCM. In addition to SCM parameters, some target materials parameters used for the simulation are Ultimate Tensile Stress, Shear Modulus and Poisson ratio are taken from preliminary test conducted using Ultimate Testing Machine (UTM). These data input is inserted into AUTODYN simulation settings. Results from simulation will be compared with actual hydrodynamics penetration test. The percentage of differences between those two methods will be discussed. The actual SCM designed for this study is shown in Figure 1.

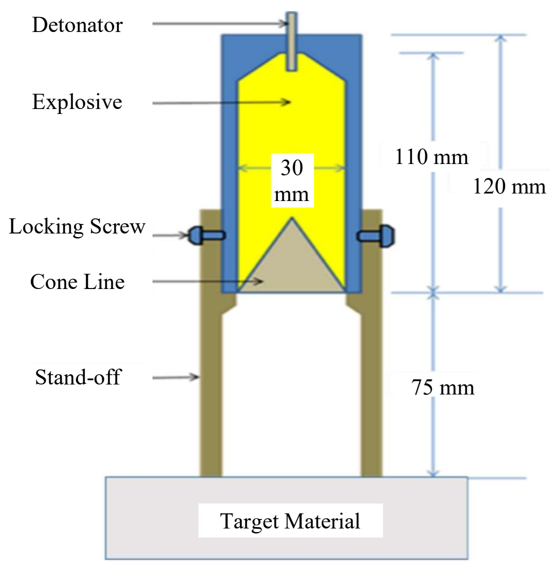

Figure 1 Shaped Charge Mechanism [10].

2.1 Meshing Techniques

The Euler and Lagrange Meshing technique can be used in AUTODYN to simulate the effect of blast loads against structural elements [1,2].

In this study, only Euler algorithm was used to simulate the explosive, air, and steel. The explosive and air were modeled with Euler mesh where by the shock wave resulted from the blast will propagates through the cells without causing any deformation to the mesh. The Euler processor used for the air sub-grid was filled with material model using an ideal gas equation of state to simulate the model domain of the blast wave propagation. Fixed gauges placed just in front of the inside face of the elements are assigned to the Euler mesh to record the pressure on the elements. The air domain on the other hand was modeled using stationary Euler mesh where no deformation takes place in it [2]. The main variables involved in the Euler equation are the Cartesian velocity components, pressure, density, total enthalpy and total energy are denoted by u, v, P, ρ, H and E, respectively. Boundary condition is set to flow-out so that when the blast wave hits the boundary layer, it will travel through it instead of reflecting back on the blast center.

2.2 Mesh Convergence analysis

A mesh convergence analysis is conducted to ensure the results of an analysis are not affected by changing the size of mesh [13]. VoD is used as the main parameters related to Shaped Charge. The convergence analysis is carried out to get the convergence curve to identify a consistence peak VoD in relation to a consistence number of mesh elements [8]. Figure 2 shows the layout of the simulation.

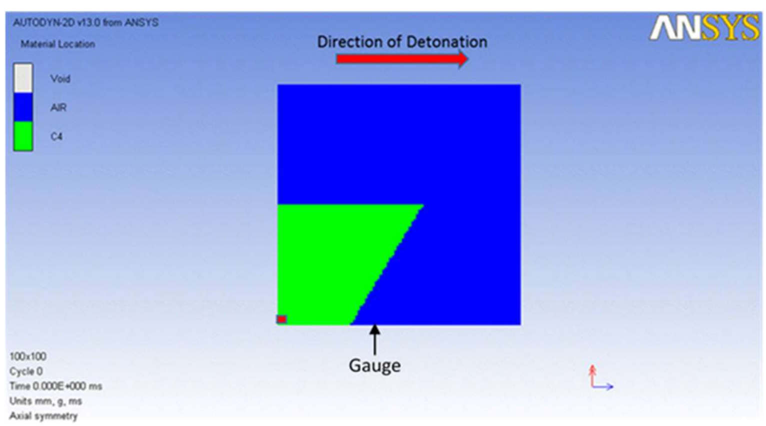

Figure 2 Shaped charge simulation layout.

The material loaded are air and C4/PE4 explosive, set in a 100 x 100 mm box setup. A Quad command is used to create shaped charge with the following coordinates; X1, Y1 (30,0), X2, Y2 (60,50), X3, Y3 (0,50) and X4, Y4 (0,0). A detonation point is set at (0,0) and a velocity gauge is set at (40,0).

2.3 Setting up the Simulation

A standalone AUTODYN 2D hydrocode is used for numerical simulation of shaped charge jet formation and target penetration to validate the penetration depth obtain from experimental results. The 2D model is used because it reduces computational time and easier to modeled. For ease of process and to reduce processing time, a Euler solver of the AUTODYN is used for both jet formation and penetration simulation. A SCM model were prepared with 2D symmetry and arranged to penetrate target materials in accordance with series of experiments conducted. A Euler box of 550 mm x 19 mm is created according to the actual shaped charge arrangements as shown in Figure 3. The boundary condition is set to be "flow-out" to replicate the explosive flow into the surroundings. The boundary condition is set at the location depicted in light brown color in Figure 3. It is set from the upper edge of explosive to the beginning of target material.

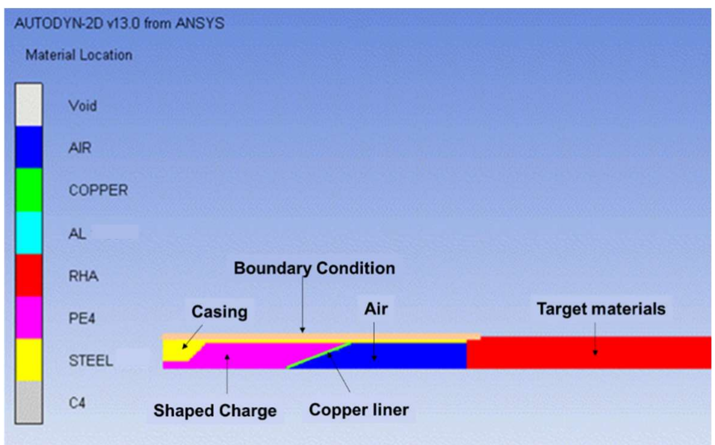

Figure 3 Material Setup for Simulation in Euler Box.

The Euler box as shown in Figure 3 is fill with materials at certain coordinates to become a shaped charge model. The fill parts become the shaped charge, target and copper liner. The materials are differentiated by colors assigned to the materials. The target location is fixed and replaced with defined target materials namely RHA Class 3A, Mild Steel, Brass and Aluminum.

2.4 Material Models

The SCM model was created according to the real geometry and dimensions. The explosive used in the SCM is C4 which is equivalent to PE4, with measured average Density, D = 1.474 g/cm^3. All material models for the target materials are taken from actual experimental results for material properties and velocity of detonation blast test. Other common material models data are selected from AUTODYN list of material. The boundary condition is inserted into certain locations. A point of velocity of detonation, VoD = 8193 m/s is defined and located at point (0,0). All units are set to be in gram, millisecond and millimeter. The simulation is set to run at certain cycle times to obtain penetration results.

The list of material models selected are air, Aluminium, Brass, Copper, Mild Steel, RHA, Hardox-500 and PE4. Materials properties required by the Autodyn model are Yield Strength, Ultimate Tensile Strength, Shear Modulus and Hardness. The rapid expansion of high explosive detonation model is taken from the Jones Wilkins Lee (JWL) Equation of State (EOS). The pressure for the expanding gas is given by:

$$P = A\left(1 - \frac{\omega\eta}{R_1}\right)\mathrm{e}^{-\frac{R_1}{\eta}} + B\left(1 - \frac{\omega\eta}{R_2}\right)\mathrm{e}^{-\frac{R_2}{\eta}} + \omega\rho\mathrm{e} \quad (1)$$

From Eq. (1); A, B, R_1, R_2, ω are empirical constants, ρ = density, ρ_0 = reference density, $\eta = \rho/\rho_0$, and e = specific internal energy [11].

3 Result and Discussion

Series of hydrodynamics penetration blast test were succesfully conducted using SCM on Aluminium 6061, Brass C3604BE (Aloy 380), Mild Steel ASTM A36/G250, Hardox-500 and RHA Class 3A plate. The penetration results are shown in Table 1 [10]. A simulated SC blast was developed using 2D Autodyn and results from both were compared for results proximities. Figure 4 to Figure 8 shows the simulation before and after a simulated shaped charge penetration blast for all five target materials used. Summary of the simulation results for hydrodynamics penetration depth are compared with the experimental results.

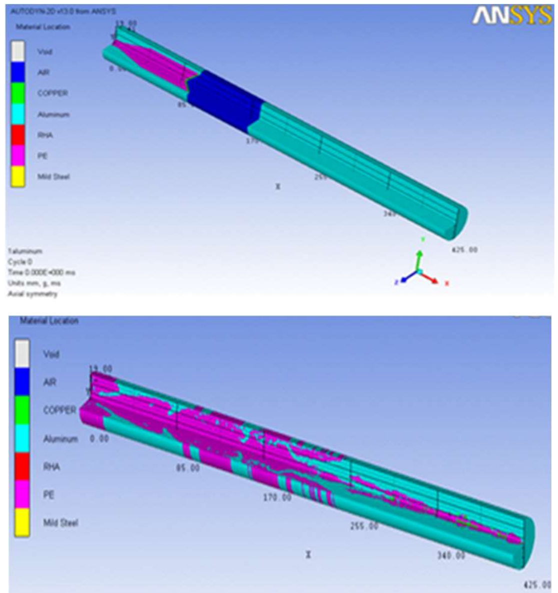

Figure 4 Aluminum before and after blast.

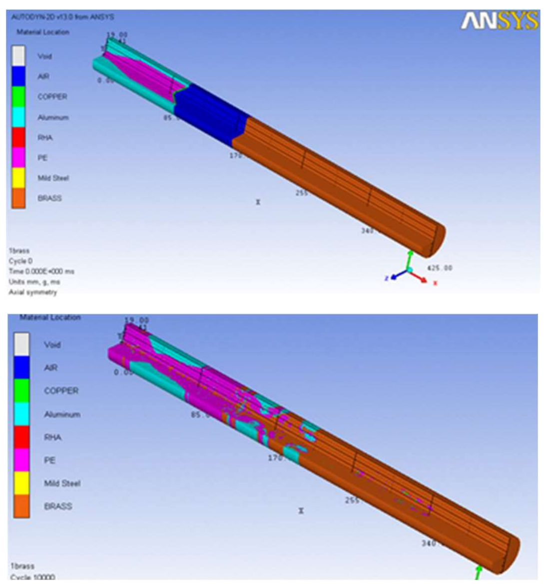

Figure 5 Brass before and after blast.

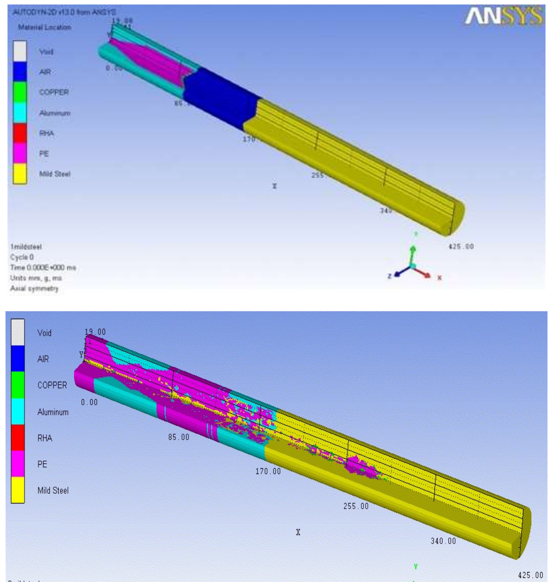

Figure 6 Mild Steel before and after blast.

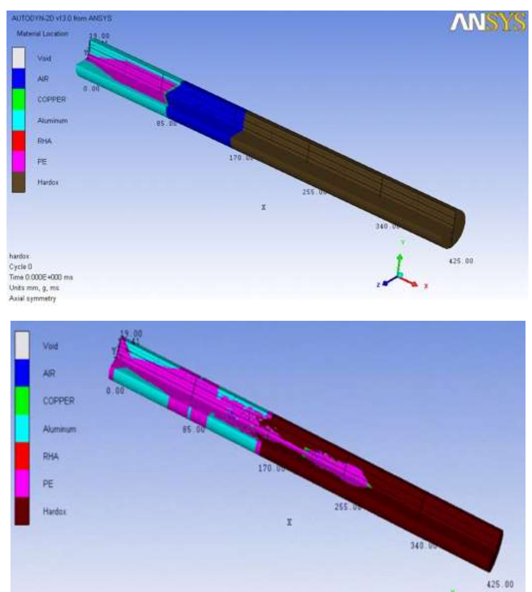

Figure 7 Hardox-500 before and after blast.

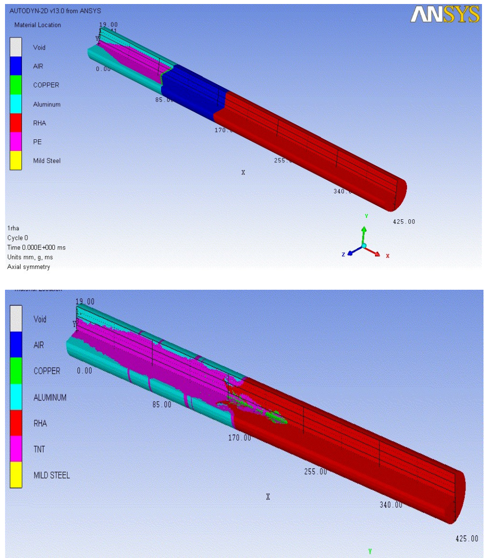

Figure 8 RHA before and after blast.

Both SC penetration results from penetration blast test [10] and simulations from this study are tabulated in Table 1.

Table 1 Comparison of Penetration Results between Simulation and Experiment.

Target Specimen	Penetration (Experiment), mm	Penetration (Simulation), mm	Differenc e, %
RHA	58	63	7.94
Hardox-500	92	118	22.03
Mild Steel	110	120	8.33
Brass	155	160	3.13
Al	238	248	4.03

It is noted that the differences between experimental and simulated results are small with an average difference of 9.1 %. However, the simulated results for Hardox-500 is high which is 26 mm which has resulted in a 22% percentage differences. These larger differences may be due to fabrication of the SCM which is largely influence by the cone liner and explosive materials. These are two SCM characteristics whereby its consistency is difficult to maintain. The cone liners are hand fabricated and the explosive used varies in years of storage. Results shows that the simulation can produced good penetration approximation with reasonably low error. The plot in Figure 9 shows a very good correlation between simulation and experiment results of SC penetration with R^2 values of 0.9845.

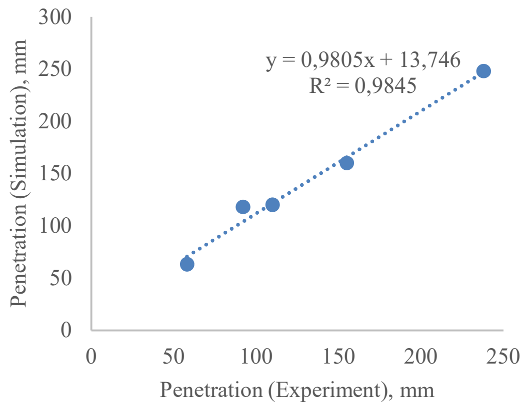

Figure 9 Correlation between Simulation and Experiment of SC Penetration.

4 Conclusion

The study proves that the 2D AUTODYN simulation can be utilised to predict the SC hypervelocity penetration by SCM based on limited mechanical properties namely Yield Strength, Ultimate Tensile Strength, Shear Modulus and Hardness. The simulation has produced results with an average of 9.1 % difference with the experimental values. Based on the penetration depth resulted from hypervelocity penetration tests for all targets, the experimented values are lower than the simulated values. The small average difference is in acceptable range as simulations are done within its specified boundary and does not consider factors such as gravity, air circulation inside the apparatus and other materials properties.

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