J. Eng. Technol. Sci., Vol. 54, No. 6, 2022, 220613

Simulation Study on Hypervelocity Penetration of Lab-Scale Shaped Charge Mechanism

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Highlights:

- Small-scale shaped charge mechanism parameters were successfully determined to produce hypervelocity detonation.
- Hypervelocity penetration was achieved up to 6,000 m/s.
- Numerical simulation using Euler meshing successfully proved the experimental results of hypervelocity shaped charge penetration.

Abstract. Shaped charge (SC) is a mechanism used by defence industries in anti-tank weapons to penetrate armored plates. Numerous studies have been conducted on shaped charge effects. However, experimental studies on this topic are limited by the great safety requirements and limited access to high-grade explosives. Due to these limitations, an experimental study on a small-scale shaped charge mechanism (SCM) penetration blast test was conducted against five types of target materials. The experimental data were then verified by simulation to prove that they can be used to predict SC penetration data. This paper presents a comparative study on the effect of shaped charge blasts conducted by comparing simulation results with actual experimental results. In order to conduct this study, the Autodyn 2D software was used to develop an SC blast model against five types of target materials. This study concluded that Autodyn 2D simulation 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.*

Received October 4th, 2022, Revised December 8th, 2022, Accepted for publication December 9th, 2022.

DOI: 10.5614/j.eng.technol.sci.2022.54.6.13

1 Introduction

A basic shaped charge consists of a casing filled with explosive material shaped using a cone liner at the target end. The application of the shaped charge mechanism (SCM) in anti-tank weapons has greatly increased the penetration capability against hardened metal plates or barriers. Upon detonation of the SCM, the energy from the detonation moves towards the cone liner symmetrically, forcing the cone to melt and move towards the target in the form of a focused, intense, localized jetting force traveling at hypervelocity speed of above 1000 m/s [1,2]. The mechanics of hypervelocity penetration is a complex sequence, which involves elastic-plastic deformation of the target materials that takes place when the strike velocity exceeds a critical value, typically above 1.500 m/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 to 12 km/s [3,4].

Although SC penetration can be measured, the actual mechanics of SC hypervelocity penetration are very difficult to observe. In addition, SC experimentations using actual SC ammunitions are very expensive and difficult to carry out due to the numerous required safety precautions and procedures. Numerical simulations therefore are known to be an efficient method to execute quantitative measurement of explosive blast properties [4,5]. An explosive blast can be analyzed using a single method such as Lagrange, Euler, a mixture of both called Arbitrary Lagrange Euler (ALE), or using a meshfree Lagrangian method commonly known as Smooth Particle Hydrodynamics (SPH). Numerical simulation of the deformation of a structure under shock and impact loadings may utilize any of these techniques, each of which has its own advantages and limitations [6,7]. A Euler processor can be used to model the extremely high pressure and strain rate conditions during material deformation (of the casing and the liner material) and gas explosions [8]. The Lagrangian framework, on the other hand, is suitable for the SC structure to allow for material motion and distortions.

Based on simulations conducted in previous studies, the SC hypervelocity penetration effect can be simulated using Autodyn 2D or 3D using the Euler and/or the Lagrangian framework. Combining the Euler and the 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 accurate results efficiently [8]. The explosive detonation can be conducted using the Eulerian method while the target's response can be modeled with the Lagrange method [9,10].

This paper provides a comparison between SC penetration as predicted by simulation compared to results from blast experiments with a smaller-scale SC device [11,12]. This was done to see if the developed simulation model can be used to predict SC penetration of metallic materials with available mechanical properties. In this study, a 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, a series of hypervelocity penetration blast test was conducted using a small-scale shaped charge mechanism (SCM) against several metallic targets. Military-grade Plastic Explosive No. 4 (PE-4), which is C4 equivalent, was used throughout these tests. A preliminary test was conducted to identify the mechanical properties of various target materials.

2 Numerical Simulation Method

ANSYS Autodyn standalone version 13 for 64-bit Windows was used to conduct the hypervelocity penetration blast simulation of an SCM. In addition to the SCM parameters, some of the target material parameters used in the simulation (ultimate tensile stress, shear modulus and Poisson ratio) were taken from the preliminary test conducted using an Ultimate Testing Machine (UTM). These data were inserted into the Autodyn simulation settings. The results from the simulation were compared with an actual hydrodynamics penetration test. The percentage of difference between the two methods will be discussed below. The actual SCM designed for this study is shown in Figure 1.

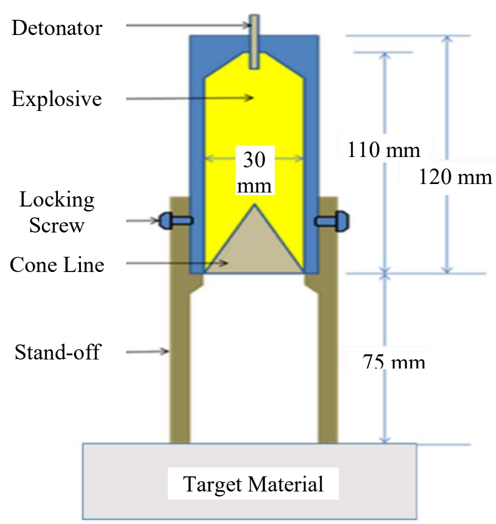

Figure 1 Shaped charge mechanism [10].

2.1 Meshing Techniques

Euler and Lagrange meshing techniques can be used in Autodyn to simulate the effect of blast loads against structural elements [1,2].

In this study, only the Euler algorithm was used to simulate the explosive, air, and steel. The explosive and air were modeled with a Euler mesh, whereby the shock wave produced by the blast propagates through the cells without causing any deformation to the mesh. The Euler processor used for the air sub-grid was filled with a material model using an ideal gas equation of state to simulate the model domain of the blast wave propagation. Fixed gauges placed right in front of the inside face of the elements were assigned to the Euler mesh to record the pressure on the elements. The air domain on the other hand was modeled using a stationary Euler mesh, in which no deformation takes place [2]. The main variables involved in the Euler equation are the Cartesian velocity components, pressure, density, total enthalpy, and total energy, denoted by u, v, P, ρ, H and E, respectively. The boundary condition was 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

Mesh convergence analysis was conducted to ensure that the results of the analysis were not affected by a change in mesh size [13]. VoD was used as the main parameter related to the shaped charge. Convergence analysis was carried out to get the convergence curve to identify a consistent peak VoD in relation to a consistent number of mesh elements [8]. Figure 2 shows the layout of the simulation.

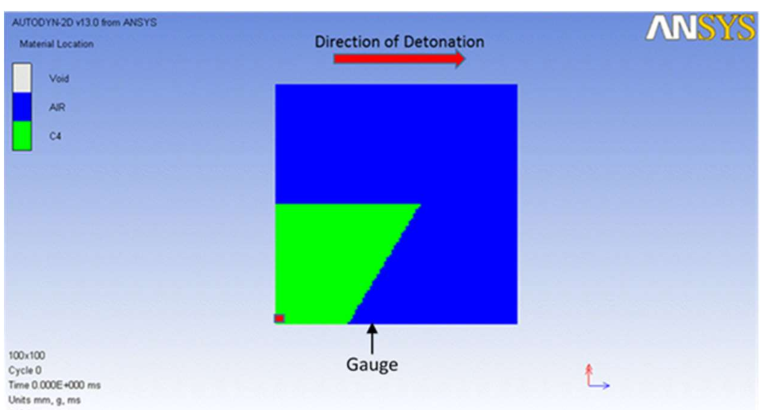

Figure 2 Shaped charge simulation layout.

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

2.3 Setting up the Simulation

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

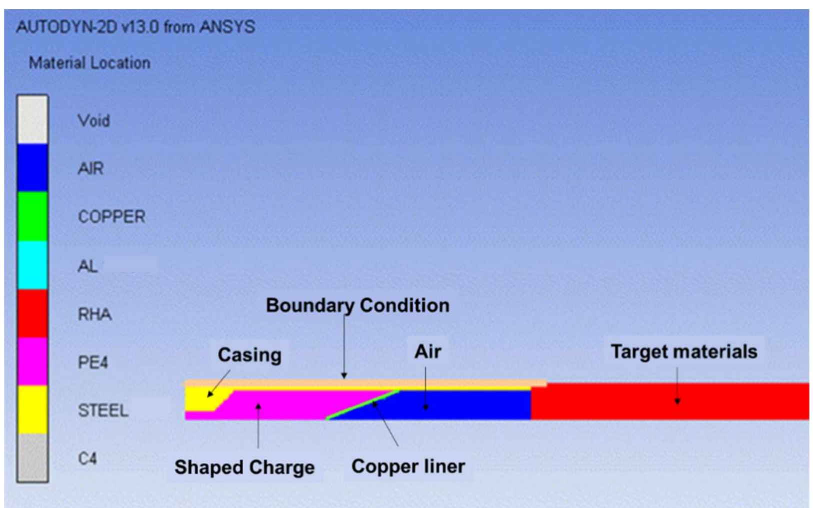

Figure 3 Material setup for the simulation in a Euler box.

The Euler box shown in Figure 3 is filled with materials at certain coordinates to get the shaped charge model. The filled parts are the shaped charge, the target end, and the copper liner. The materials are differentiated by colors assigned to the materials. The target location was fixed and replaced with defined target materials, i.e., 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 was C4, which is equivalent to PE4, with measured average density, D = 1.474 g/cm^3. All material models for the target materials were taken from the actual experimental results for the material properties and the velocity from the detonation blast test. Other common material models data were selected from the Autodyn list of materials. The boundary condition was inserted into certain locations. Point of velocity of detonation (VoD) = 8193 m/s was defined and located at point (0,0). All units were set to grams, milliseconds and millimeters. The simulation was set to run at certain cycle times to obtain the penetration results.

The list of material models selected were air, aluminium, brass, copper, mild steel, RHA, Hardox-500, and PE4. Materials properties required by the Autodyn model were Yield Strength, Ultimate Tensile Strength, Shear Modulus, and Hardness. The rapid expansion of the high explosive detonation model was taken from the Jones Wilkins Lee (JWL) equation of state (EOS). The pressure for the expanding gas was given by:

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

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

A 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 Autodyn 2D and the results from both were compared to see the proximity of the results. Figures 4 to 8 show the simulation before and after the simulated shaped charge penetration blast for all five target materials used. A summary of the simulation results for hydrodynamics penetration depth was compared with the experimental results.

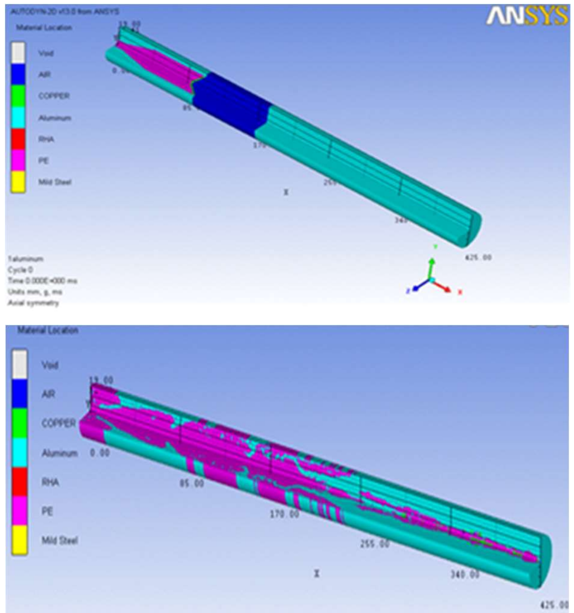

Figure 4 Aluminum before and after the blast.

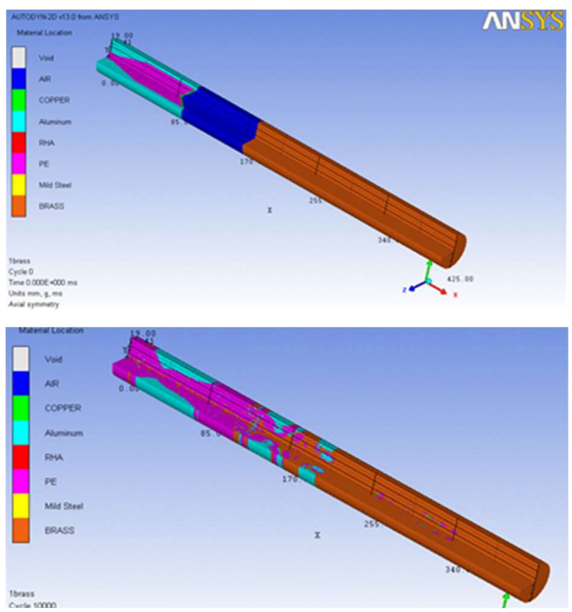

Figure 5 Brass before and after the blast.

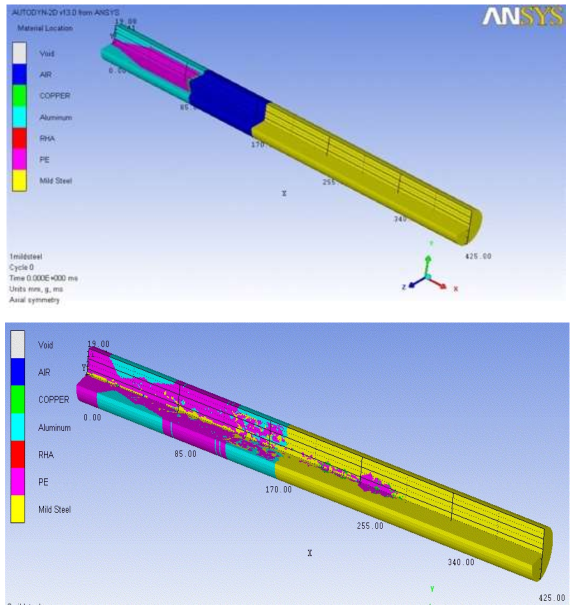

Figure 6 Mild Steel before and after the blast.

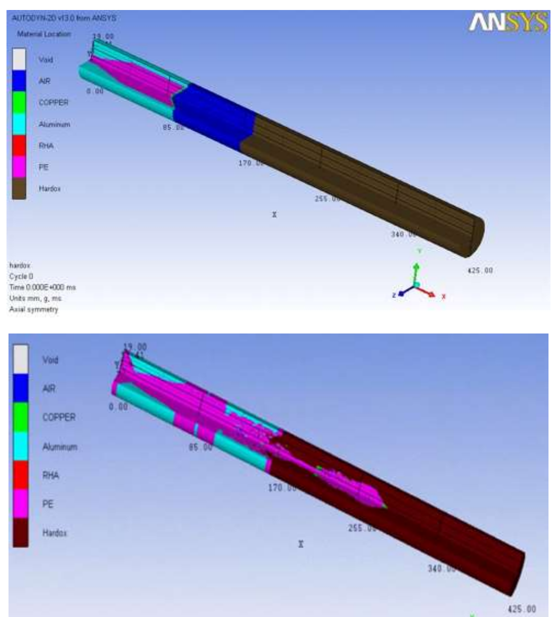

Figure 7 Hardox-500 before and after the blast.

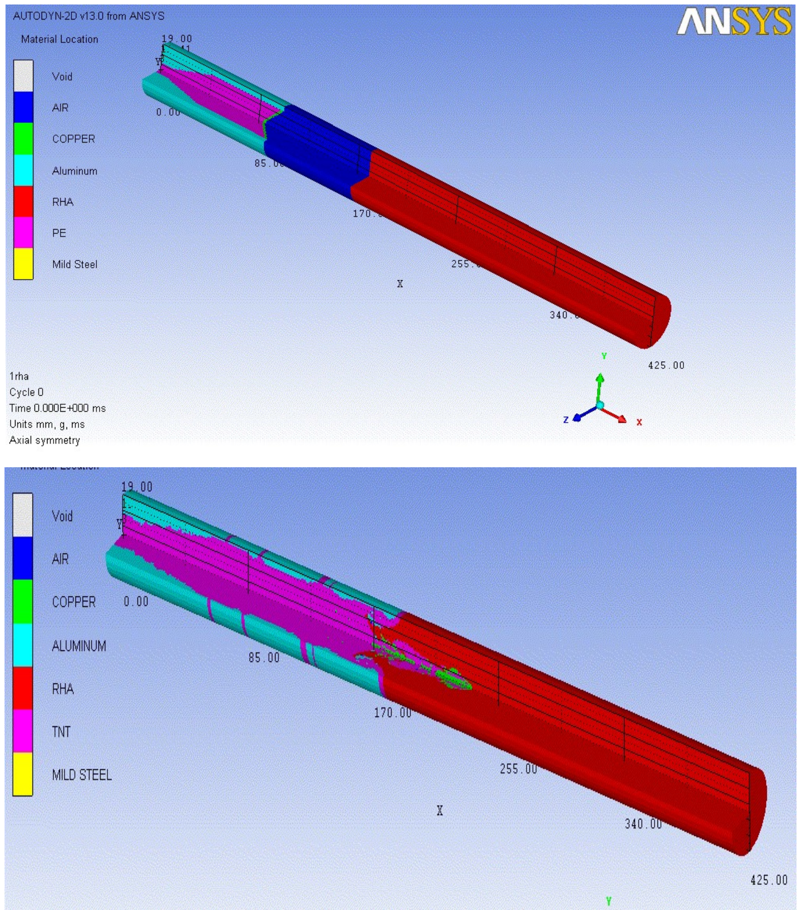

Figure 8 RHA before and after the blast.

The SC penetration results from the penetration blast test [10] and from the simulation in 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 the experimental and simulated results were small, with an average difference of 9.1%. However, the simulated result for Hardox-500 was high, i.e., 26 mm, which resulted in a 22% difference. This large difference may be due to the fabrication of SCM, which is largely influenced by the cone liner and explosive materials, for which consistency is difficult to maintain. The cone liners are hand-fabricated and the explosive used varies in years of storage. The results showed that the simulation could produce a good penetration approximation with a reasonably low error. The plot in Figure 9 shows a very good correlation between the simulation and the experimental results for SC penetration with R^2 values of 0.9845.

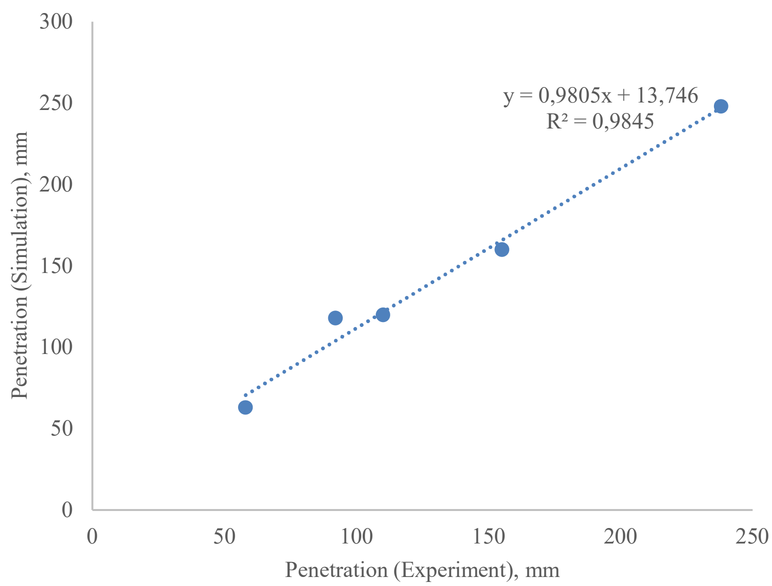

Figure 9 Correlation between simulation and experiment of SC penetration.

4 Conclusion

This study proved that Autodyn 2D simulation can be utilized 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 produced results with a 9.1% average difference with the experimental values. Based on the penetration depth resulted from the hypervelocity penetration tests for all targets, the experimental values were lower than the simulated values. The small average difference is within an acceptable range as the simulations are done within a specified boundary and do not consider factors such as gravity, air circulation inside the apparatus, and other materials properties.

Acknowledgement

The data of the results were performed and collected in the Fabrication Lab, Faculty of Engineering, National Defence University, Malaysia. The authors would like to thank UPNM for Research Grant UPNM/2020//GPJP/TK/6.

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