Penetration Evaluation of Explosively Formed Projectiles Through Air and Water Using Insensitive Munition: Simulative and Experimental Studies

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***Abstract*—The process of formation, flying, penetration of explosively-formed projectiles (EFP) and the effect of water on performance of the charge for underwater applications is simulated by Ansysis Autodyn 2D-Hydro code. The main objective of an explosively formed projectile designed for underwater applications is to disintegrate the target at longer standoff distances. In this paper we have simulated the explosively formed projectile from OFHC-Copper liner for 1200 conical angle. The Affect of water on the penetration of EFP is determined by simulations from Ansysis Autodyn 2-D Hydrocode and by varying depth of water from 1CD-5CD. The depth of penetration against steel target is measured experimentally. Flash X-Ray Radiography (FXR) is used to capture EFP jet formation and its penetration against target is measured by depth of penetration experiments. Simulation results are compared with experimental results. The difference in simulated and experimental results for depth of penetration is about 7 mm, which lies within favorable range of error. The jet formation captured from FXR is quite clear and jet velocity determined from Flash X-ray radiography is the same as the ones obtained by using other high explosives. Therefore, it is indicated that Insensitive Munition (8701) can be utilized instead of Polymer Bonded Explosives (PBX) for air and underwater environments with great reliability and without any hazard.**

Keywords-Explosively Formed Projectiles; Liner; Jet formation; Jet Penetration; Depth of Penetration.

I. INTRODUCTION

Explosively Formed Projectiles have become the most lethal device to defeat armor, masonry and other underwater moving objects including ships and submarine vehicles. In order to accomplish the objective, the EFP must be aerodynamically stable, so as to hit the target with small velocity decay rate and with small angle. In the last few decades, efforts have been made to optimize the liner shape and initiation mechanism of EFP's which affect the formation and penetration properties of EFP [1-3]. The formation of EFP is a complex process involving high pressure and high temperature. In this work EFP jet is formed in air. To examine the effect of water on the velocity and penetration of the EFP, water with varying depths is introduced after the jet has traversed into air for 3CD. Experimental results for 120^o angle are compared with simulated results. Flash X-Ray Radiography is used to capture the images of jet formation. The cross-sectional view of the charge without casing with conical angle 120^o and geometry of the model used for simulation is shown in Figure 1.

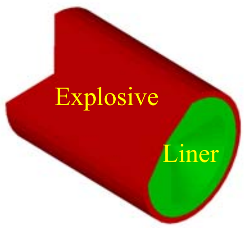

Fig. 1. Cross-sectional view of the standard Shaped

II. DIMENSIONS AND MATERIAL MODEL

The shapes of the liner and charge are shown in Figure 1. The shape of the liner is conical. The diameter of the liner is 54 mm. Charge diameter is kept 60 mm for convenience. The length of charge is 84 mm for numerical simulations. The explosive, air, water and liner are meshed with 0.2 mm along x-axis. Along y-axis for 0-20 mm the mesh size is 0.2 and for 20-40 mm the mesh size is 0.4. The Euler solver is used to model the explosive liner and air. The target is modeled using Lagrange solver. To avoid the interaction problem with Euler and Lagrange solver, Euler/Lagrange coupling method is used. Point detonation method is chosen for initiation of the charge. The materials models of air, charge, liner and target are described in Table I. The material parameters of 8701 explosive, OFHC- copper liner and target, steel-45 are listed in Tables II, III and IV respectively.

The JWL Equation of State is used to describe the detonation of EFP Charge, which in generalized form is given below:

$$P = A\left(1-\frac{\omega}{R_1V}\right)e^{-R_1V} + B\left(1-\frac{\omega}{R_2V}\right)e^{-R_2V} + \frac{\omega E}{V}$$

TABLE I. MATERIAL MODELS

Part Name	*Material*	*Equation of State*	*Strength Model*
Explosive	8701	JWL	None
Liner	Cu-OFHC	Gruneisen	Steinburg Guinan
Air	Air	Ideal Gas	None
Target	Steel-45	Shock	Johnson Cook
Water	Water	Shock	None

TABLE II. JWL PARAMETERS OF 8701

ρ[g/cm3]	1.695
D	8.425e+3
A	8.544e+08
B	2.049e+0724
R1	4.6
R2	1.35
ω	0.25
E	9.5e+06

TABLE III. SHOCK PARAMETERS FOR OFHC-COPPER (LINER)

ρ[g/cm3]	G	C_1[Km/sec]	C_2	S_1	S_2
8.93	2.02	3.94	0.0	1.489	0.0

TABLE IV. MATERIAL PARAMETERS FOR STEEL-45 (TARGET)

ρ[g/cm3]	G	C1[Km/sec]	C2	S1	S2
7.83	2.17	4.56	0.0	1.33	0.0

III. SIMULATION OF PENETRATION PERFORMANCE OF EFP (JET FORMATION AND PENETRATION)

For penetration against rocks and other armor piercing applications the jet with larger diameter is essential to obtain the better penetration depth. Also the EFP jet must be stable and with minimum velocity gradients to avoid the jet break up while approaching the target surface [6]. The jet formation for liner angle 120 at time t= 0, 20, 40, 60 and 72 microseconds (µsec) is shown in Figure 2. The target is made of steel -45 with a width of 100 mm. The penetration picture for Explosively Formed Projectile for 1200 conical liner after 250µsec traversing through 3CD air and 3CD water against steel target obtained from simulation code is shown in Figure 3.

IV. SIMULATION RESULTS

The kinetic energy behavior of the EFP jet emerged from conical liner angle 1200 is predicted. The jet formation is accomplished in air. The effect of water depth on kinetic energy of the jet during penetration through water for a standoff distance of 1-Charge diameter (1CD) to 5-charge diameter (5CD) and steel target is determined using 2D-Hydrocode. By taking time along x-axis and kinetic energy along y-axis, it is observed from simulation that when water depth increases, the kinetic energy decay rate is slow. This is also clear from Figure 4.

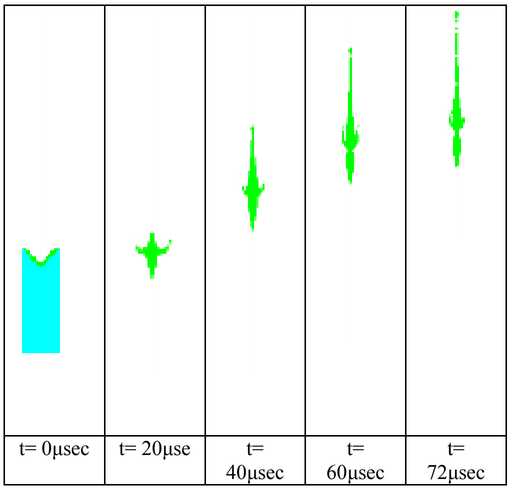

Fig. 2. Jet Formation at different time steps

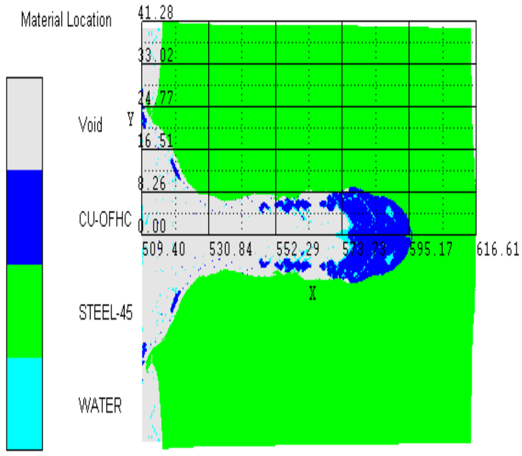

Fig. 3. Numerical simulation of the jet penetration against steel target.

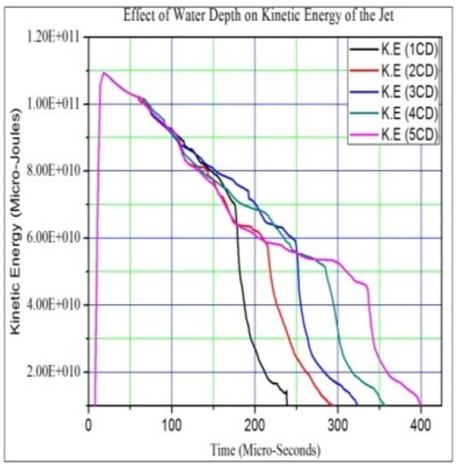

Fig. 4. Kinetic Energy behavior of the copper liner during jet formation and Penetration

V. EXPERIMENTAL SETUP

A. Flash X-Ray Radiography (FXR) Setup

To radiograph the EFP jet formation, the FXR experiment method was used. The EFP charge and other armor were hanged by a cotton rope. Passive detonation technology was utilized in the experiments to visualize the jet deformation accurately and to avoid the discrepancies attributable to detonator. The pictorial representation of the FXR setup is shown in Figure 5. Two 450 kV flash x-ray tubes were installed for registration of the jet after interaction. The protected cassette films were positioned to capture the fragments after interaction. The schematic of the FXR setup is shown in Figure 6.

Fig. 5. Image of the Experimental test Setup with vertically hanging shaped charges.

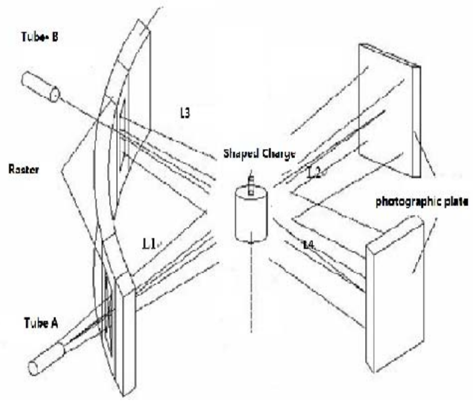

Fig. 6. Schematic of the test set up of 60 mm shaped charge in front of double flash X-Ray tube.

B. Jet formation and jet velocity calculation through fxr.

The jet tip and tail velocities are measured simultaneously measured using a multi Channel Flash X-ray system. The exposures obtained from X-ray at 30 µsec and 50 µsec after ignition are shown in Figure 7. The X-ray exposure Magnification is 2.0. The jet tip velocity obtained from X-ray exposure is 4.614 km/sec.

In the experiments, the distance from the first marked line on X photographic plate to the ground is 137mm and the distance from the second marked line on X photographic plate to the ground is 120mm. L1=142 mm, L2=83 mm, L3=149 mm, L4=88 mm.

$$k_A = \frac{L_1}{L_1 + L_2} = \frac{142}{142+83} = 0.631$$

$$k_B = \frac{L_3}{L_3 + L_4} = \frac{149}{149+88} = 0.6287$$

$$\Delta s_4 = 221.15 \cdot 0.6287 - 74.09 \cdot 0.6311 = 92.28\text{mm}$$

$$v_4 = \frac{\Delta s_5}{\Delta t} = \frac{92.28}{50-30} = 4614.0\text{m/s}$$

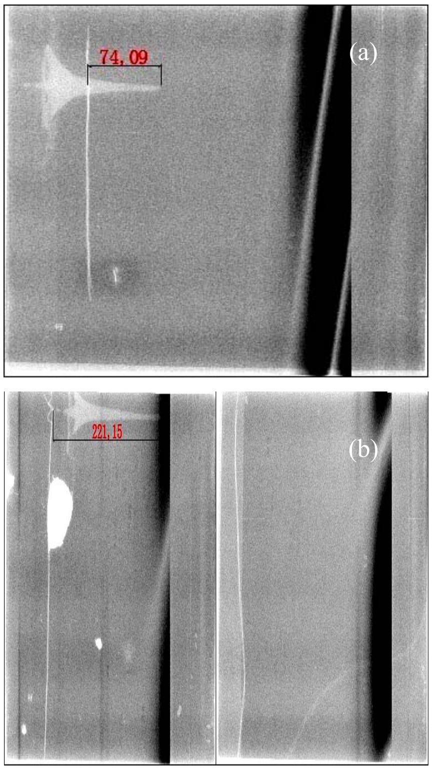

Fig. 7. (a) Jet Formation at 30 micro-Seconds (b)Jet Formation at 50 micro-Seconds

C. Depth of penetration setup

The penetration performance of the Explosively Formed projectiles is determined by its penetration against target made of 45-steel. The charge is placed at a standoff distance of 3CD air and 3CD water from the target. The target is made of three cylindrical blocks having 100 mm height and 100 mm diameter. The experimental set up for the depth of penetration before experiment is shown in the Figure 8.

Fig. 8. (a) EFP change at rest (b) steel Target with 3CD water (c) setup for DOP Experiment

D. Depth of penetration (dop) results

The penetration produced by the jet after initiation and interaction with the steel target is shown if Figure 9.

Fig. 9. EFP Jet Effect on the 45-steel Target

VI. CONCLUSIONS

Simulations were carried out to predict the effect of water on the kinetic energy and penetration of Explosively Formed projectiles in underwater environments. Jet velocity of the EFP has been calculated via the Flash x-Ray technique, a high speed diagnostic technique used to record micro-second phenomena. The penetration performance is determined through DOP experiments against steel targets. The depth of penetration measured from simulation and experiments are 79 mm and 72 mm respectively which shows a variations of about 7 mm, which is an within an acceptable range. From this comparison we can conclude that simulation and experimental are in reasonable agreement. This comparison also shows that from simulation we can predict the performance of EFPS against underwater targets very effectively. The Insensitive Material (8701-Explosive) has been used first time as the energetic material for the underwater application. This material can be utilized well in naval and other underwater applications.

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