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EXPERIMENTAL AND NUMERICAL STUDY OF PRECURSOR SHAPED CHARGE PERFORMANCE

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Abstract: *The shaped-charge effect remains one of the most effective mechanisms for defeating armored targets. Tandem shaped-charge warheads provide enhanced effectiveness against explosive reactive armor systems, where the precursor charge is used to initiate the reactive armor prior to the arrival of the main charge. The present study investigates the performance of a small-diameter precursor shaped-charge warhead with a charge diameter of 50 mm. A 60° conical copper liner with a thickness of 1 mm is accelerated by the detonation products of an explosive charge and subsequently transformed into a high-velocity jet. The experimental program included three explosive materials—TNT, RDX, and HMX—as well as variations in standoff distance. A high-strength alloy steel cylinder was used as the target. In parallel, a numerical model of jet formation and target penetration was developed using the commercial finite element software Abaqus/Explicit and a purely Eulerian formulation. Comparison of the experimental observations and numerical predictions demonstrated good agreement in terms of penetration depth and cavity geometry, while also providing insight into the underlying penetration mechanisms and the influence of key design parameters. The validated numerical model provides a reliable basis for further analysis and optimization of shaped-charge warhead performance.*

Keywords*: precursor shaped charge, shaped charge jet, penetration depth, experimental investigation, numerical simulation*

1. INTRODUCTION

More than a century after its discovery, the shaped-charge effect remains one of the most effective mechanisms for armor penetration and continues to serve as the basis for numerous modern warhead designs. Its operating principle relies on focusing explosive energy and converting it into a high-velocity metal jet through the collapse of a metallic liner [1–5]. Defense applications have driven the continuous improvement of shaped-charge performance through extensive experimental, analytical, and numerical investigations.

The shaped-charge mechanism may be divided into the following phases [1,2]: (i) propagation of the detonation wave through the explosive charge, (ii) acceleration of the liner material by the detonation products, (iii) liner collapse and jet formation, (iv) jet evolution and stretching, (v) jet impact on the target and subsequent penetration, and (vi) process termination, either by target perforation or by arrest of penetration in a sufficiently thick target. Table 1 summarizes representative values of the characteristic parameters of shaped-charge warheads and jets, together with the corresponding performance metrics.

In the present study, an experimental investigation of the performance of a small-diameter (50 mm) shaped-charge warhead was conducted. Subsequently, comprehensive numerical simulations of the complete shaped-charge process were performed. The objective of the research was to develop and validate a numerical model capable of

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accurately reproducing the experimental observations, thereby providing a reliable basis for further optimization of the warhead design and enhancement of its performance.

Table 1. Typical ranges of characteristic parameters and performance metrics for shaped-charge warheads and jets [1,2].

Liner base diameter	CD = (40…700) mm
Detonation velocity	D = (7.0…10.0) km/s
Liner thickness	(0.02…0.04) CD, for copper
Jet diameter	≈ (0.03…0.15) CD, variable
Jet length	≈ (6…15) CD, before breakup
Cavity diameter	≈ (0.1…0.3) CD, variable
Jet tip velocity	≤ 1.4 D
Jet tail velocity	≈ (0.2…0.5) D
Optimum standoff	≈ (2…7) CD
Penetration depth	(4…10) CD, in steel target

2. EXPERIMENTAL INVESTIGATION

The subject of the experimental investigation was a small-diameter shaped-charge warhead shown in Fig. 1. The warhead is primarily intended for use as a precursor charge in a tandem-warhead configuration; however, it may also be employed as a standalone warhead carried by an unmanned aerial vehicle (UAV) intended for top-attack engagement of lightly armored targets.

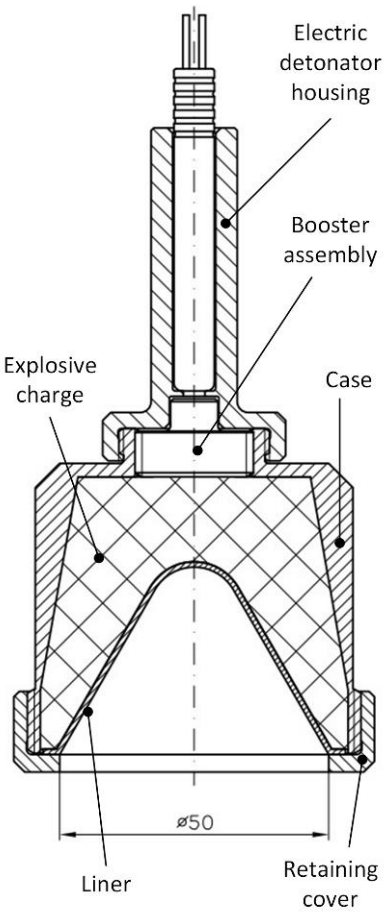


Figure 1. Assembly drawing of the 50 mm shaped-charge warhead configuration employed in static tests, showing its main components.

As a part of a broader experimental campaign, a series of field tests was conducted at the proving ground of Poliex in Berane, Montenegro. In the static tests, the explosive train was initiated using an EDK-8 electric detonator manufactured by Poliex. The detonation impulse was transmitted to a PETN booster charge, ensuring reliable initiation of the main explosive charge. Various explosive formulations were investigated as the main charge material, including phlegmatized RDX, HMX, and TNT. The explosive charges were manufactured by pressing the explosive compositions to the prescribed density.

The conical liner was manufactured at Forging Center LLC Valjevo by cold forging from copper bars supplied by Copper Mill Sevojno, Serbia. The material was DNP-Cu (Class A), a phosphorus-deoxidized copper grade with a copper content of 99.95 wt.% and a phosphorus content below 0.015 wt.%. Following forging and subsequent machining, the liner was placed in a furnace preheated to 300 °C and held at this temperature for 15 minutes. It was then removed from the furnace and allowed to cool in air. The hardness measured immediately after forging, prior to machining and annealing, was 105 HBW 5/250. Due to the small wall thickness of the liner and the limitations of the available hardness testing equipment, its hardness after annealing was not measured.

The warhead case was manufactured from glass-fiber-reinforced polyamide in the baseline configuration, while aluminum and steel were considered as alternative casing materials. The present paper considers only the baseline configuration. The explosive pressing operations, fabrication of individual components, copper liner annealing, and final warhead assembly were all conducted at the Poliex manufacturing facilities. Photographs of the individual components and assembled warheads are presented in Fig. 2.

As a practical substitute for standard rolled homogeneous armor (RHA) steel plates, cylindrical targets made of quenched and tempered Č.4732 steel were employed owing to their availability, cost-effectiveness, and suitability for longitudinal sectioning, which facilitated detailed post-test examination of the penetration cavity. Equivalent designations of this steel in other standards include 42CrMo4 (EN), AISI 4140, and 1.7225 (W.Nr.). The targets had a diameter of 80 mm and lengths of 150 mm and 200 mm.

The standoff distance between the base of the conical liner and the target was controlled using a machined polystyrene spacer designed to ensure accurate alignment and positioning of the warhead relative to the cylindrical target. Adhesive tape was additionally used to secure the assembly during the tests. Photographs of the setup used in the field tests are presented in Fig. 3.

The primary diagnostic parameters considered in the field tests were: (i) penetration depth, (ii) the geometry of the penetration cavity, including the entry and possible exit holes, and (iii) damage to the supporting structure. The experimental results are presented and discussed in Section 4 through comparison with the corresponding numerical predictions.

3. NUMERICAL SIMULATIONS

The numerical investigation of shaped-charge jet penetration was performed using the finite element software Abaqus [6] and its explicit solver. This software has been widely employed for the simulation of transient, high-energy, and high-strain-rate phenomena, including shaped-charge jet formation and penetration into metallic targets [7–11].

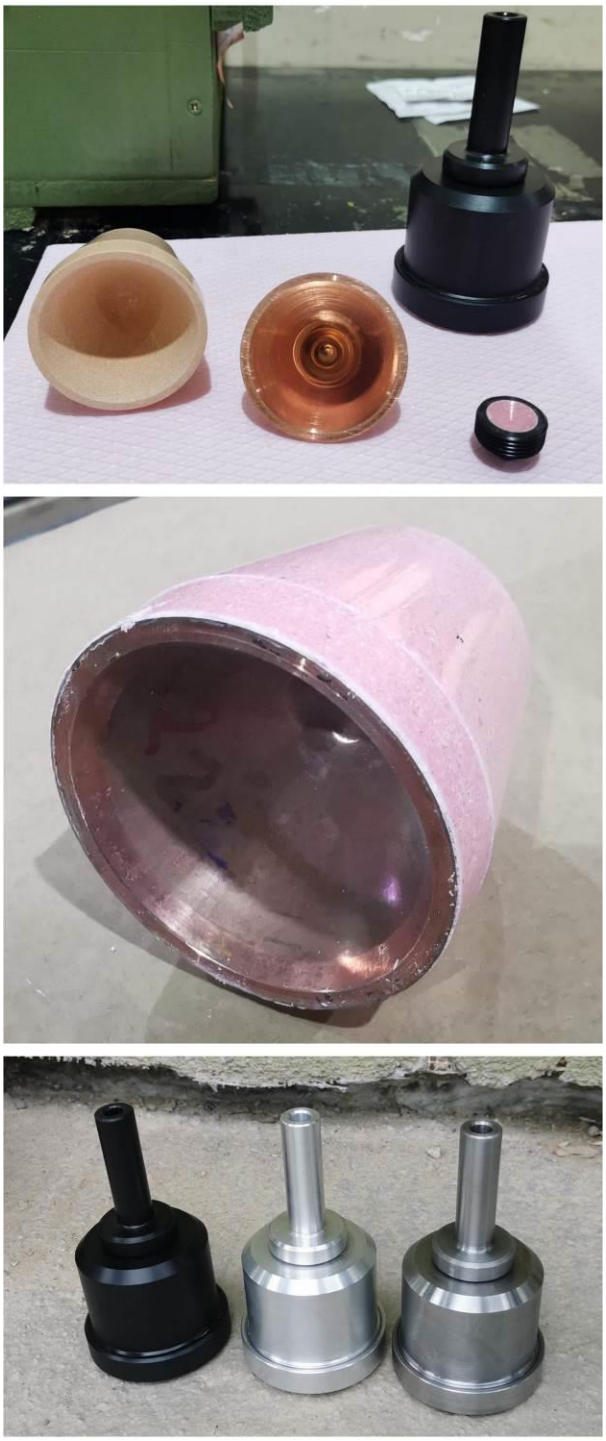


Figure 2. Photographs of the main stages of warhead preparation: (top) individual warhead components, including the RDX explosive charge, liner, booster, and casing; (middle) assembly of the liner and HMX explosive charge; and (bottom) completed warheads with polyamide, aluminum, and steel casings.



Figure 3. Experimental setup: (top) warheads and cylindrical targets configured with various standoff distances; (bottom left) assembled warhead–target configuration before testing and a recovered target showing the penetration cavity; and (bottom right) warhead fitted with an EDK-8 detonator and prepared for testing.

Owing to the severe material deformation associated with the penetration process, a purely Eulerian formulation was employed. A quasi-axisymmetric 15° wedge model was adopted, reproducing the actual geometry of the shaped-charge warhead and target configuration (Fig. 4). Appropriate boundary conditions were applied to enforce symmetry. Following a mesh convergence study, a uniform element size of 0.5 mm was used in the axial direction, while the element size in the radial direction gradually increased from 0.2 mm to 0.8 mm. The total number of Eulerian EC3D8R elements was on the order of 500,000, depending on the model configuration, particularly the target thickness and standoff distance.

Accurate representation of material behavior under highly dynamic loading conditions is of crucial importance for the reliability and predictive capability of the numerical model. The shaped-charge liner and target were modeled using material parameters representative of the copper grade (DNP-Cu, Class A) and Č.4732 steel employed in the experiments, respectively. The dynamic plastic response of both materials is described using the Johnson–Cook constitutive model [12], together with a linear shock-wave equation of state. Material failure is modeled using the Johnson–Cook damage model [13]. The warhead casing was made of glass-fiber-reinforced polyamide (PA-GF), corresponding to the configuration

used in the experimental tests. In the numerical model, the casing material was represented by a simplified isotropic elastic-plastic model with a density of 1350 kg/m³, Young's modulus of 8 GPa, and Poisson's ratio of 0.35. The plastic behavior and ductile damage initiation were described using tabulated parameters estimated based on available literature [14]. Experimental observations and numerical analyses conducted by the authors within broader research program indicated that variations in casing material had a relatively limited influence on the penetration performance of the investigated shaped-charge configurations.

The explosive charge is described using the Jones–Wilkins–Lee (JWL) equation of state [15], coupled with a programmed burn model. The material parameters used in the Abaqus simulations are summarized in Tables 2 and 3.

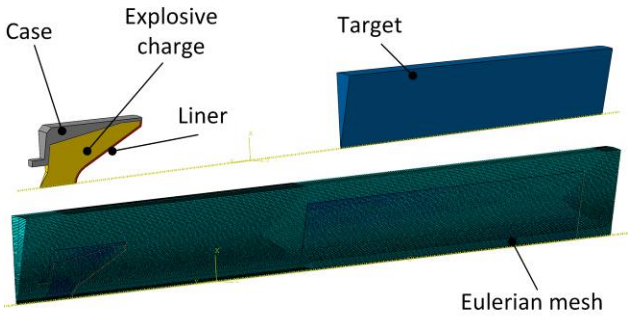


Figure 4. Geometry and Eulerian finite element mesh of the quasi-axisymmetric numerical model.

The total duration of the simulated process, from explosive initiation to the end of jet penetration, is approximately 150–250 μs.

Table 2. Material parameters used in the Abaqus simulations for the copper liner and steel target [12, 13].

	COPPER	Č.4732
Density (kg/m³)	8960	7850
JOHNSON-COOK PLASTICITY MODEL		
A (MPa)	90	792
B (MPa)	292	510
C	0.025	0.014
n	0.31	0.26
m	1.09	1.03
T_{melt} (K)	1356	1800
T_{trans} (K)	300	300
LINEAR U_s – U EQUATION OF STATE		
c_0 (m/s)	6940	4578
s	1.49	1.33
Γ	2.0	1.67
JOHNSON-COOK DAMAGE MODEL		
d_1	0.54	0.05
d_2	4.89	3.44
d_3	3.03	2.12
d_4	0.014	0.002
d_5	1.12	0.61

Table 3. Material properties and Jones–Wilkins–Lee (JWL) equation-of-state parameters for TNT, RDX, and HMX [15–17].

PROPERTY	HMX	RDX	TNT
PHYSICAL AND DETONATION PROPERTIES			
Density (kg/m³)	1760	1600	1550
Det. velocity (m/s)	8667	8112	6800
Det. energy (MJ/kg)	5.55	5.43	4.29
JWL EQUATION OF STATE PARAMETERS			
A (GPa)	674.9	611.3	335.7
B (GPa)	6.130	10.65	2.90
R_1	4.20	4.40	4.15
R_2	1.00	1.20	0.95
ω	0.30	0.32	0.30

4. RESULTS AND DISCUSSION

Figure 5 presents a representative numerical simulation of an HMX-based shaped charge at a standoff distance of 2.6 charge diameters (CD). The sequence of snapshots illustrates the complete process from jet formation and evolution to target penetration and the attainment of the final penetration depth, providing insight into the temporal development of the shaped-charge jet and its interaction with the target.

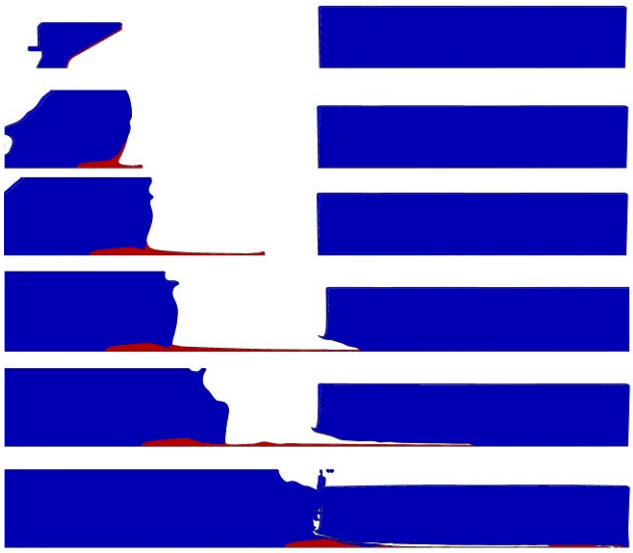


Figure 5. Numerical simulation of shaped-charge jet formation and penetration into a steel target. The snapshots illustrate the temporal evolution of the process at 0, 15, 30, 45, 90, and 240 μs after initiation.

The numerical simulations provide detailed information on the penetration process that cannot be obtained directly from the experiments. For example, the predicted jet tip velocity is approximately 5350 m/s. This relatively low value can be attributed to the large cone angle of the liner, which favors the formation of a heavier but slower jet.

The predictive capability of the numerical model was assessed by comparing the calculated penetration depths for several representative cases with the corresponding experimental measurements, as summarized in Table 4.

Table 4. Comparison of experimentally measured and numerically predicted penetration depths for various explosive charge materials and standoff distances.

Explosive charge	Standoff (CD)	Penetration depth (mm)	
		Simulation	Experiment
HMX	2.6	194	188
RDX	1.2	122	118
TNT	1.2	98	93

Overall, very good agreement between the numerical predictions and the experimental measurements was achieved, with the relative error in penetration depth not exceeding 5%. Interestingly, even the TNT-filled charge provides a significant penetration capability, making it potentially suitable not only for precursor-warhead applications but also as a standalone warhead against lightly armored targets. As expected, the numerical model consistently predicts slightly greater penetration depths, primarily due to the idealized axisymmetric representation of the process, including perfectly symmetric initiation, explosive charge geometry, and liner configuration. These assumptions result in a more coherent and continuous shaped-charge jet than that produced under experimental conditions.

Figure 6 compares the entry holes produced by the HMX-based warhead listed in Table 4, as obtained experimentally and predicted numerically. The comparison demonstrates good agreement between the experimental observations and numerical predictions, confirming the ability of the numerical model to reproduce the principal features of the target response in the vicinity of the entry hole.

After testing, the targets were sectioned longitudinally using wire electrical discharge machining (wire EDM). A comparison between the experimentally obtained penetration cavity profile and its numerical prediction is presented in Fig. 7. The numerically predicted cavity is slightly narrower than that observed experimentally, particularly in the entrance region and over approximately the first third of the penetration depth. This discrepancy can be attributed primarily to the idealized nature of the numerical model, which assumes perfect geometric and loading symmetry and consequently produces a more coherent and better-focused jet. In contrast, the experimental process is inevitably affected by minor geometric and manufacturing imperfections, as well as small asymmetries in initiation and jet formation, which promote jet dispersion and result in a somewhat larger cavity diameter. The agreement improves with increasing penetration depth, indicating that the numerical model captures the overall penetration mechanism and cavity evolution with satisfactory accuracy.

The good agreement between the experimental observations and numerical predictions demonstrates the capability of the numerical model to accurately capture the jet formation and penetration processes, thereby providing a sound basis for further optimization of the shaped-charge warhead design.

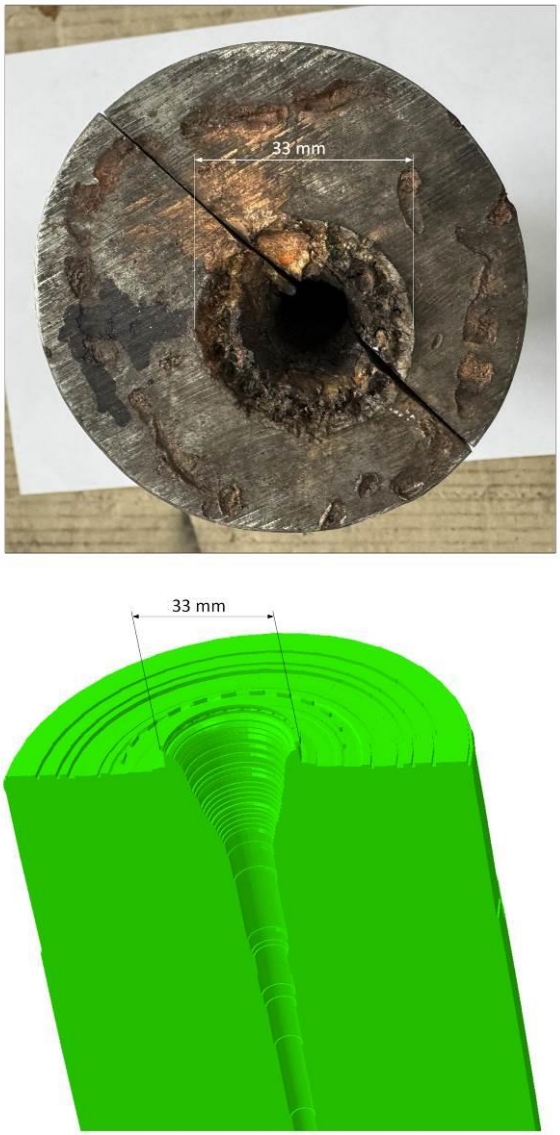


Figure 6. Comparison of experimentally obtained (top) and numerically predicted (bottom) entry holes for an HMX-filled shaped-charge warhead at a standoff distance of 2.6 CD.

5. CONCLUSION

This paper presents an experimental and numerical investigation of a small-diameter shaped-charge warhead with a charge diameter of 50 mm. The field tests examined the effects of explosive charge material and standoff distance using steel cylindrical targets. In parallel, a numerical model of shaped-charge jet formation and target penetration was developed in Abaqus/Explicit using a purely Eulerian formulation.

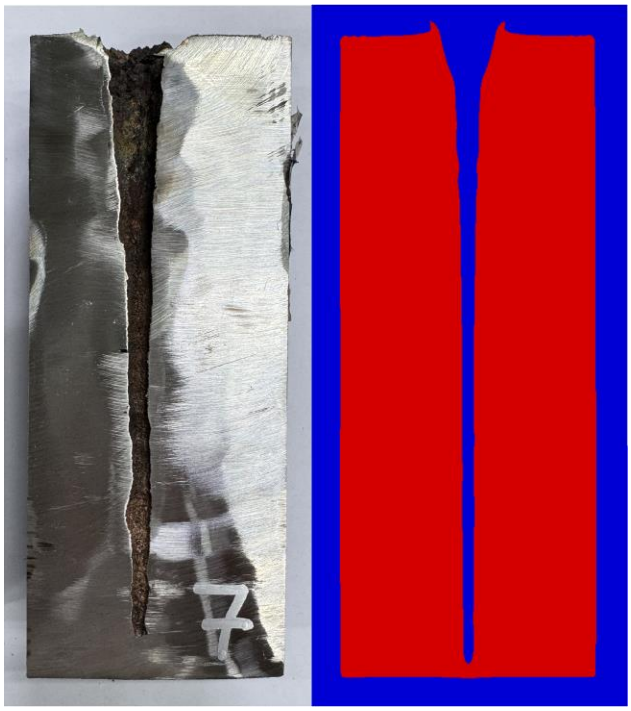


Figure 7. Comparison of experimentally observed (left) and numerically predicted (right) penetration cavity profiles produced in a steel target by an HMX-filled shaped-charge warhead at a standoff distance of 2.6 CD.

Comparison of the experimental observations and numerical predictions demonstrated good agreement in terms of penetration depth, penetration cavity geometry, and entry-hole characteristics. The results indicate that the proposed numerical model is capable of accurately reproducing the essential features of jet formation and penetration, providing a reliable tool for further analysis and optimization of shaped-charge warhead performance.

The present investigation represents the initial stage of an ongoing research effort. Future work will focus on a more comprehensive experimental and numerical assessment of the factors affecting warhead performance, including: (i) the influence of standoff distance on penetration effectiveness, (ii) the effects of liner mass and geometric tolerances, (iii) the influence of explosive charge density, (iv) the effects of case and booster-housing materials, and (v) the influence of initiation conditions on jet formation and overall warhead performance.

The validated numerical model provides a cost-effective framework for the analysis and optimization of shaped-charge warheads, reducing the need for extensive experimental testing during the design process.

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