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NUMERICAL–EXPERIMENTAL ANALYSIS OF EXPLOSIVELY FORMED PROJECTILE PENETRATION CHARACTERISTICS

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***Abstract**: Within this paper, a comparative analysis of the results obtained by numerical simulation and experimental testing of the penetration of an explosively formed projectile (EFP) was performed. The mentioned type of projectile is characterized by a complex process of penetrator formation. Understanding the dynamics of penetrator formation and its interaction with the target material is of key importance for analyzing the performance and comparing the construction parameters of these systems. The numerical model was developed with the aim of simulating the detonation process, projectile formation and studying its penetration. Experimental tests were conducted under strictly controlled conditions to determine the basic penetration parameters and validate the numerical model. The analysis includes a comparison of key parameters, including the geometry of the explosively formed projectile, the speed of movement and the depth of penetration in the target material. The obtained results indicate a significant agreement between the numerical and experimental data, thus confirming the adequacy of the applied numerical approach. Observed deviations were analyzed in the context of the simplification of the numerical model and limitations of the experimental methodology. The research results contribute to a better understanding of the mechanism of explosively formed projectile penetration and confirm the importance of numerical simulations as a reliable tool for evaluating their performance.*

***Keywords:** explosively formed projectile, numerical simulation, experimental testing, penetration, model validation.*

1. INTRODUCTION

An explosively formed projectile (EFP) is a specific type of warhead in which a metal casing is transformed into a compact, high-velocity projectile under the action of a detonation wave [1,2]. Unlike a conventional cumulative shaped charge, in which the metallic liner is typically conical and its collapse produces a high-velocity cumulative jet, an EFP (Explosively Formed Projectile) uses a shallow concave metallic liner, typically with a spherical or similar profile [1,2]. Under the influence of the detonation products, the EFP liner undergoes plastic deformation and forms a compact penetrator. Unlike a cumulative jet, which achieves its highest effectiveness within a specific and relatively limited range of stand-off distances and gradually loses coherence during flight, an EFP penetrator can maintain its integrity over significantly greater distances and achieve substantial penetration at longer stand-off distances from the target.

Its penetration characteristics depend not only on the velocity and mass of the projectile, but also on the penetrator geometry, mass distribution, stability in flight, and mechanical properties of the target material [3, 4]. The development of EFP research over the past few decades has been accompanied by advances in experimental techniques and numerical methods. Early research showed that projectiles with similar velocities can achieve different penetration depths depending on the projectile shape and characteristics of the target material, confirming that their performance cannot be reliably assessed based on a single ballistic parameter [3]. The development of three-dimensional numerical models has enabled the analysis of the complete process, from the formation and flight of the projectile to its interaction with the target. Comparison of numerical and experimental results has shown that reliable validation requires simultaneous analysis of the projectile geometry, its velocity, and the achieved penetration depth [4, 5].

Particular attention in modern research is paid to the influence of structural and material parameters on the process of formation and penetration of EFPs. The results show that the choice of liner material, its geometry and thickness distribution significantly affect the final shape, stability and penetration characteristics of the projectile [6, 7]. In addition, by changing the configuration of the liner, using a two-layer liner and detonation wave deflectors, it is possible to control the formation process and increase the length-to-diameter ratio of the penetrator [8]. Research on

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sintered liners has further indicated the importance of microstructure and manufacturing methods for preserving the integrity of the projectile during formation [9].

Modern approaches increasingly combine numerical simulations and experimental tests to more reliably assess the behavior of the projectile and the target. Experimental and numerical studies of penetration into different target materials have shown that measuring the penetration depth alone is not sufficient for a complete model assessment, but it is also necessary to analyze the geometry of the projectile and the characteristics of the resulting damage [10]. Validated numerical models are also used for design optimization, including the geometry of the cladding, projectile stabilization, and material selection, which significantly reduces the number of required experimental tests [11].

Based on the analyzed literature, it can be concluded that there is a need for further validation of numerical models through the simultaneous comparison of several characteristic parameters and different target configurations.

The aim of this paper is a comparative analysis of the results obtained by numerical simulation and experimental testing of the penetration of an explosively formed projectile. A numerical model was developed to simulate the detonation process, projectile formation and its interaction with the target material, while experimental tests were conducted under controlled conditions to determine the basic penetration parameters. By comparing the geometry of the formed projectile, its velocity and penetration depth, an analysis of the agreement between the numerical and experimental results was performed.

2. EXPERIMENTAL

In the following, preliminary warhead model has been designed and for it, the ANSYS Autodyn is used to simulate its EFP formation process. Used materials for each part of the EFP warhead and steel target are listed in Table 1.

Table 1. Materials used in numerical simulation

Component		Material	model	equation of state
Warhead - EFP	explosive	Octogen (HMX)	-	JWL
	liner (disc)	Cu-OFHC (Oxygen-Free High-Conductivity Copper)	Johnso-Cook	-
	case	EN AW-6061T6	Steinberg Guinan	-
	deviator	Polyethylene (PE)	-	-
Steel target		Armor steel (hardness up to 340HB)	Johnson-Cook	-

In accordance with the results obtained by numerical simulation, warheads were manufactured. All the components of the polygon tests (warhead, steel target) were in agreement with the numerical model. Used materials in accordance with the respective standards are listed in Table 2.

Table 2. Materials of components for the experimental set up

Component		Material
Warhead – EFP	explosive	phlegmatized octogen (HMX)
	liner (disc)	phosphorus-deoxidized copper (CW024A)
	case	EN AW-6061 T6
	deviator	Polyethylene (PE)
Steel target		Armor steel (hardness up to 340HB)

2.1 Numerical simulation

The numerical simulation applied in this research was developed with the aim of analyzing the formation process of an explosively formed projectile and its interaction with the target material (armour steel target). The simulation includes the detonation process of the explosive charge, the deformation of the liner (disk), the formation of the projectile, its movement through the air space and penetration into the steel target. The obtained results represent the basis for comparison with experimental tests and assessment of the ability of the numerical model to faithfully reproduce the physical processes that determine the performance of the EFP system [3, 4].

Due to pronounced deformations, high deformation rates and short duration of the process, the numerical model is based on the combined Euler–Lagrange approach. In this approach, the explosive charge and airspace are modeled in the Eulerian domain, while the liner (disc), warhead shell, and steel target are modeled in the Lagrangian domain. Such a formulation enables efficient modeling of the movement of detonation products while at the same time a precise description of the deformation of solid bodies and their mutual interaction, which is why it represents a standard approach in simulations of explosive processes [5, 10].

2.1.1 The geometry of EFP warhead model

The geometry of the numerical model of the warhead is defined in accordance with the geometric characteristics of the real experimental sample in order to ensure identical conditions for numerical simulation and experimental tests. Figure 1 shows a schematic representation of the geometry of the EFP warhead.

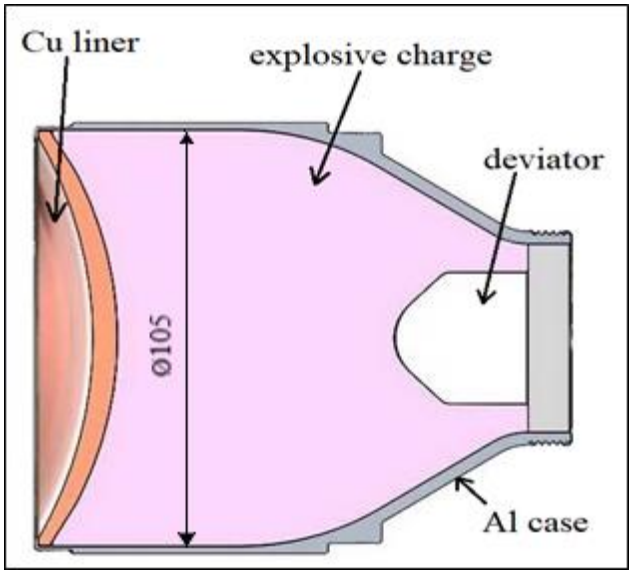


Figure 1. Geometric shape of the EFP warhead

2.1.2 Numerical models for description of EFP warhead elements and penetration process

To describe the material behavior of EFP warhead components, constitutive models and equations of state were used, which enable the simulation of processes characteristic of explosive loads, including large plastic deformations, high deformation rates and the spread of detonation products [3, 6].

The behavior of metal components is modeled using the Johnson–Cook constitutive model, which describes the dependence of yield stress on plastic strain, strain rate, and temperature. The Johnson-Cook constitutive relation is expressed as:

$$\sigma = (\mathrm{A} + B\varepsilon^{n})(1 + C\ln\dot{\varepsilon})\left(1 - \left|\frac{T - T_r}{T_m - T_r}\right|^{m}\right) \qquad (1)$$

Where σ is the equivalent flow stress; A, B, C, n and m are material constants; ε is the equivalent plastic strain; $\dot{\varepsilon}$ is the equivalent plastic strain rate; T is the current temperature; T_m is the melting temperature; T_r is the reference temperature [3, 6].

Due to its ability to realistically describe the behavior of metallic materials under dynamic loading, this model is one of the most commonly used in the analysis of explosive processes and high-speed impacts [3, 4, 6, 7].

To describe the behavior of the explosive charge, the Jones–Wilkins–Lee (JWL) equation of state was applied. The JWL equation relates the pressure of the detonation products to their relative volume and specific internal energy and can be expressed as:

$$P = A\left|1 - \frac{\omega}{R_1 V}\right| e^{-R_1 V} + B\left|1 - \frac{\omega}{R_2 V}\right| e^{-R_2 V} + \frac{\omega E_0}{V} \qquad (2)$$

Where P is the pressure of the detonation products; V is the relative volume; A, B, R_1, R_2 и ω are material constants; E_0 is the specific internal energy in explosiv [3, 6].

Due to its reliability in modeling detonation processes, the JWL equation represents a standard in numerical analyzes of explosive charges [6, 7].

The parameters of the used models were taken from the available literature and appropriate databases, with the values selected for the materials used in this research.

2.2 Experimental setup - Static penetration test

Experimental tests (static penetration tests in real conditions) were conducted with the aim of determining the penetration characteristics of an explosively formed projectile and validating the results obtained by numerical simulation. The experimental setting was defined so that the warhead was placed at a standoff distance of 1,5 m in relation to the armored target.

A schematic representation of the experimental setup for penetration tests is shown in Figure 2, and the materials of the target and warhead components are listed in Table 2.

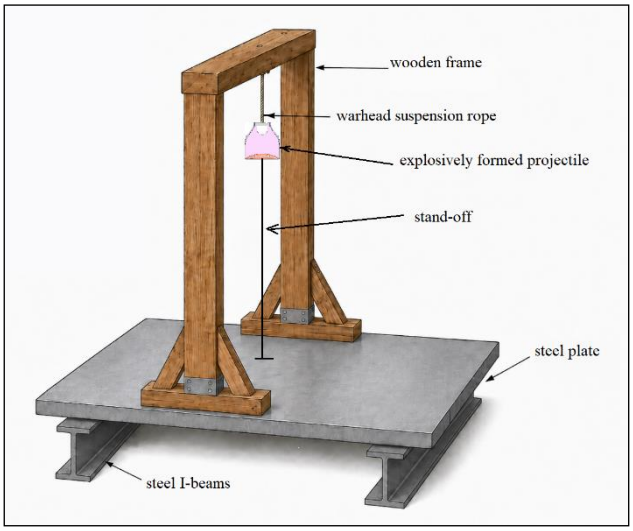


Figure 2. Setup for static penetration test

For the purposes of numerical simulation, the chosen explosive is octogen (HMX), while for the needs of real explosive charging, this explosive was used with the addition of phlegmatizer in a small mass fraction (an inert component that enables safe pressing of HMX). The presence of the inert component was neglected for the purposes of the numerical simulation.

Experimental tests included static penetration tests with two different target configurations. In configuration I, penetration through a 50 mm thick steel plate was analyzed, while in configuration II, penetration through a 100 mm thick steel plate was tested. The change in plate thickness was performed in order to see the full penetration effect, i.e. to estimate the depth of penetration. In this way, it was possible to analyze the behavior of an explosively formed projectile upon impact with a homogeneous obstacle. The obtained experimental results represent the basis for assessing the accuracy of the numerical model and analyzing the degree of agreement between the numerical and experimental approaches.

Table 3. Parameters for static penetration test

Parameter	
Stand-off	1,5 m
Configuration I	Armor steel, thickness 50 mm
Configuration II	Armor steel, thickness 100 mm
Result	Penetration depth - 85 mm

3. RESULTS AND DISCUSION

3.1. Process of explosivly formated projectile

The numerical model was developred asa a 2D axisymmetric model, with one quarter of the model considered due to the axis symmetry of the problem. A Lagragian formulation was applied to both the liner and the target. The liner was discretized with 201 elements, while the target mesh consisted of 400 elements. Numerical simulation was then used to analyze the process of forming an explosively formed projectile after the initiation of the explosive charge. During detonation, intense plastic deformation of the copper disk occurs, forming a compact projectile capable of maintaining stability during flight and achieving significant penetration when hitting a target.

Folowing the initiation of the explosive charge, the pressure of the detonation produts causes deformation and acceleration of the liner, leading to EFP formation. The stage of projectile formation at different time instants are shown in Figure 3. Figure 4 shows a ilustration of the formed penetrator.

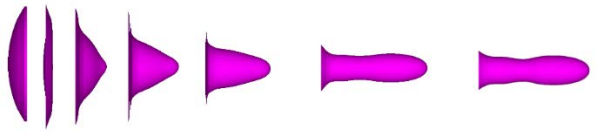


Figure 3. Penetrator formed over numerical simulation

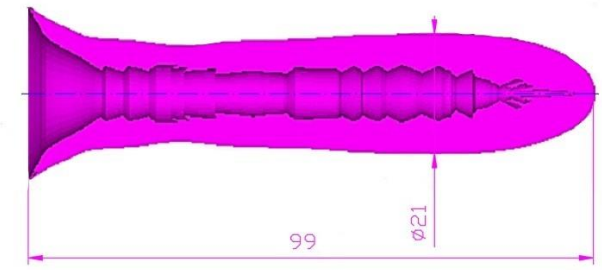


Figure 4. Penetrator formed over numerical simulation

Based on the results of the numerical simulation, the basic geometric and ballistic characteristics of the formed projectile were determined, including its shape, characteristic dimensions, mass and speed immediately before hitting the target. These characteristics represent the basis for the analysis of the penetration process and comparison with the test results in real conditions.

Table 4. Caharacteristics of EFP from numerical simulation

Parameter	Value
Projectile length	99 mm
Projectile diameter	21 mm
Projectile mass	295 g
Projectile speed	2050 m/s
Penetration depth	90 mm

3.2. Penetration of the EFP

Penetration characteristics of the explosively formed projectile were analyzed by numerical simulation and experimental through static penetration tests.

The results of the numerical simulation showed that an explosively forming projectile of a given geometry achieves penetration through a steel target (homogeneous armor plate) of approximately 90 mm, which was also confirmed in the real conditions of the penetration test (of about 85 mm).

By comparing the results of numerical simulation and experimental tests, a very good agreement can be observed regarding the achieved penetration depth. The obtained agreement between the numerical and experimental results confirms that the applied numerical model can reliably predict the penetrating characteristics of the explosively formed projectile under the analyzed test conditions. Minor deviations that may occur between numerical and experimental results can be attributed to the idealization of the numerical model, the limitations of the applied material models and experimental uncertainties, which is in accordance with the observations of other authors who were involved in the validation of numerical models of explosively formed projectiles [4, 5, 10].

4. CONCLUSIONS

In this paper, a comparative analysis of the results obtained by numerical simulation and experimental testing of an explosively formed projectile was performed. The analysis included the formation of the projectile, the determination of its basic geometric and ballistic characteristics, as well as the comparison of the achieved penetration depth in numerical simulation 90 mm through real static penetration tests.

The results of the numerical simulation showed that the applied model successfully describes the formation process of an explosively formed projectile and enables reliable determination of its basic characteristics. A comparative analysis with the results during real static penetration tests showed a high degree of agreement, whereby a penetration depth of about 85 mm was achieved. With a 100 mm thick steel plate, the projectile did not achieve complete penetration, while with a configuration with a single 50 mm thick steel plate, it completely penetrated the plate and continued to penetrate the soil base, with the total depth of penetration remaining practically unchanged.

The scientific contribution of this work is reflected in the validation of the numerical model through real static penetration tests. The confirmed agreement between numerical simulation and static penetration tests indicates that numerical simulations can be successfully used for the analysis and optimization of the construction of explosively formed projectiles, thereby reducing the need for a large number of complex and expensive polygon tests in the initial stages of their development.

The results presented in this paper represent the basis for further research aimed at the optimization of the disk geometry, the choice of materials and the improvement of numerical models, with the aim of increasing the efficiency and reliability of explosively formed projectiles in different application conditions.

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