

Influence of the Medium and Structural Parameters on the Formation Effect of Linear Explosively Formed Projectiles

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Abstract

The linear explosively formed projectile (LEFP) is a special type of linear shaped charge (LSC) and is developed on the basis of the explosively formed projectile. Known for their excellent penetration performance and directional destruction capacity, LEFPs are widely utilized in explosion dismantlement, petroleum exploration, concrete crushing, metal cutting, and penetrator interception. LEFPs can also induce multi-mode damage—combining penetrator impact, shock waves, and bubble effects—during underwater detonations. Thus, they are employed in applications including subsea pipeline disruption and effective neutralization of underwater vehicles. Adequate formation effect is a criterion for a desirable penetration performance of shaped charges. Therefore, investigating the formation characteristics of LEFPs in different media and optimizing the structural parameters are important tasks. In this study, the arbitrary Lagrangian–Eulerian (ALE) method is adopted for numerical simulation, and the efficacy of the ALE method is verified by the consistency between numerical and experimental results. Then, the formation effects of LEFPs in pure air medium, water medium, and water with air cavity are investigated separately. The results show that the stabilized velocity of the penetrator in air is 1355 m/s, while the velocity is only 423.6 m/s in water. Furthermore, the liner cannot be completely closed in water and cannot form a slender penetrator as in air. After the addition of the air cavity, the stabilized velocity of the penetrator increases to 966.6 m/s, and its morphology is significantly enhanced. Moreover, explosive material, liner material, and liner thickness are chosen as the primary factors for orthogonal optimization. The optimized factor combination is RDX–Copper–1 mm. The peak velocity of the penetrator, the velocity before penetration, the velocity after penetration, and the length of penetration increase by 50.8%, 44.9%, 26%, and 10.3%, respectively.

Keywords Linear explosively formed projectile; ALE; Penetrator formation; Underwater explosion; Orthogonal optimization

1 Introduction

In recent years, the linear explosively formed projectile (LEFP) has been proposed and developed on the basis of

the explosively formed projectile (EFP) configuration to increase the effective damage range (Gou and Zhang, 2011; Mao et al., 2024). The conventional EFP has a cylindrical structure with a conical liner, as shown in Figure 1(a); it can form a high-speed and concentrated metal penetrator, which results in extremely deep penetration into structures (Ding et al., 2017; Cardoso and Teixeira-Dias, 2016; Zu et al., 2016). Furthermore, this shaped charge configuration demonstrates strong potential for implementation in explosive damage scenarios in underwater environments (Gu et al., 2023; Cao et al., 2024; Zhang et al., 2025a, 2025b). The generated high-velocity penetrator can first induce a penetration hole in the target structure. Subsequently, under the joint action of shock wave loading and bubble pulsation (Zhang et al., 2023; Zhang et al., 2024a), the structure undergoes substantial plastic deformation, which leads to efficient and multi-mode damage effects. However, the penetrator with a highly concentrated mass along the central axis also results in the relatively small radius of the penetration hole, which does not contribute effectively to overall damage to the targets (Liu et al., 2020; Zhang et al., 2022). To solve this problem, a linear shaped charge

Article Highlights

- The formation characteristics of linear explosively formed projectiles (LEFPs) are explored through 3D numerical simulations based on the arbitrary Lagrangian–Eulerian method.
- The influence of the medium on the formation characteristics of the LEFP penetrator is investigated.
- The orthogonal optimization method is used to improve the formation effect of the LEFP.

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(LSC) with tensile structure is proposed and developed (Mehmannavaz et al., 2021), as depicted in Figure 1(b). Compared with the EFP, the LSC can form a linear penetrator with higher penetrator mass, kinematic energy, and hit rate (Ahmed and Malik, 2017; Vigil, 1989).

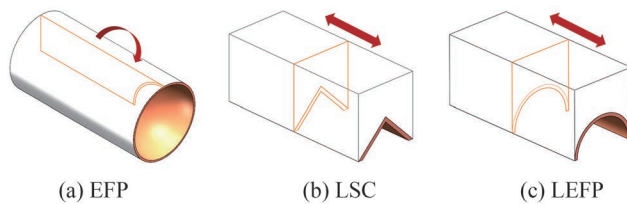


Figure 1 Geometrical structures of EFP, LSC, and LEFP

An LSC generally has a chevron liner that can form a blade-shaped jet. Focused on the formation effect of the LSC, Lim (2013) establishes an analytical expression that explains the nonlinear nature of the jet formation process of the LSC. Johnston and Lim (2012) report a numerical observation of the jet characteristics and particle distribution of the LSC during the formation process. Moreover, they validate the penetration performance of the LSC against the mild steel target. Sterbentz et al. (2023) optimize the placement of multiple detonators, the distribution of metal inclusions within the high explosive (HE), and the time delay between detonators. The optimization aims to modify the behavior of the HE detonation wave to improve the formation effect of the LSC. Yang et al. (2011) reveal the propagation process of the detonation wave in the LSC on the basis of the smoothed particle hydrodynamics (SPH) method. They determine the effect of ignition mode on the jet characteristics. Feng et al. (2013) propose a modified SPH model and assess the influence of the metal case on the properties of the jet. Wang et al. (2015) probe into the jet formation process and penetration performance of the LSC when the liner materials are copper, steel, and aluminum separately. Works conducted by several researchers demonstrate that relevant factors such as geometric configuration, structural parameters, material properties, and ignition mode significantly impact the jet formation effect, which directly reflects the penetration capacity (Cheng et al., 2018; Deng et al., 2022). As a result, considerable research has been conducted on the optimization of these factors to improve the penetration performance of LSCs. However, the limitations of the formation mechanism cause the susceptibility of the jet of conventional LSCs to standoff distance and its proneness to localized fracture during the formation process; these conditions lead to insufficient post-penetration effect (Cheng et al., 2018; Deng et al., 2022; Gou and Zhang, 2011b).

An LEFP with a semicircular or segmental liner is proposed and developed, as shown in Figure 1(c), to completely improve the jet formation effect through structural design. Gou and Zhang (2011a), Gou et al. (2012), and Gou (2014) reveal the formation mechanism and test the pene-

tration capacity of LEFPs in different initiation modes, determine the influence of the curvature radius of the liner on the formation effect of the penetrator, and assess the bifurcate fracture phenomenon during the formation process. Liu et al. (2013) record the jet morphology of the LEFP during the formation process by X-ray radiography technology and test the velocity of the penetrator. Ma et al. (2022a, 2022b) design and modify the structural parameters of LEFPs under air explosion conditions. Some studies have also been conducted on the effectiveness of the LEFP on penetrator interference (Joo et al., 2017). However, for the existing research on LEFPs, scholars pay close attention to the air explosion condition. Few papers have been published on the formation effect and performance of the penetrator of LEFPs in water or other media. In addition, the research on the penetrator morphology and velocity evolution laws of LEFPs in different media is still insufficient.

Accordingly, the formation effect and penetration performance of LEFPs in different media are investigated in this study. The numerical simulations are based on the arbitrary Lagrangian–Eulerian (ALE) method and are calculated using an LS-DYNA solver. First, the formation effect of the LSC in the air medium and the damage to the target plate are simulated. The numerical results are compared with the experimental data to confirm the validity and accuracy of the ALE method. Then, the numerical models of LEFPs in air medium, water medium, and water with air cavity are separately established. The influence of the medium on the formation effect of the penetrator is explored. Finally, the orthogonal optimization is conducted for the materials of the explosive and the liner, as well as the liner thickness. The optimized factor combination is determined, and the damage effect of the LEFP configuration on the target plate before and after optimization is compared and explored.

2 Theory and numerical verification

2.1 Basic ALE equations

Two classical algorithms are generally used to calculate fluid–structure interaction (FSI) problems for shaped charges: the Lagrange algorithm and the Euler algorithm. The Lagrange method accurately captures free surfaces and interfaces. The reason is that the grid describing the material transforms synchronously with the deformation of the material. However, this method struggles to describe the large distortion of the computational domain. The Lagrange method is widely utilized in structural mechanics (Hu et al., 2017). For the Euler method, the grid is fixed in place, and the material can move through the grid. This method can solve large deformation problems, but it cannot precisely define material interfaces. The Euler method is extensively adopted in fluid dynamics (Agu et al., 2018).

The ALE algorithm integrates the advantages of the Lagrange and Euler algorithms. The finite element mesh and material structure in the ALE method exist independently, and the ALE grid transforms properly according to the parameters defined during the calculation process (Kim and Shin, 2008). Therefore, the ALE method not only effectively tracks the boundary motions of materials but also avoids the termination of computation induced by large mesh distortion; this method has been extensively used to simulate high pressure, high strain rate, and nonlinear deformation characteristics in shaped charge problems. (Gu et al., 2022; Barras et al., 2012; Pischevar and Amirifar, 2010; Yu et al., 2023).

The structured ALE (S-ALE) method is employed in this study to enhance computational efficiency and reduce the time and memory consumption of simulations. This approach preserves the core principles of the ALE algorithm while adopting predefined strategies to simplify mesh motion, material modeling, and interface tracking. This feature improves computational flexibility and simulation speed. The governing equations in the ALE method are presented as follows (Nobile and Formaggia, 1999). Equations (1) to (3) define the mass conservation, momentum, and energy, respectively (Nobile and Formaggia, 1999):

$$\frac{\partial \rho}{\partial t} = (-\rho) \operatorname{div}(\mathbf{v}) - (\mathbf{v}_i - \mathbf{u}_i) \frac{\partial \rho}{\partial x_i} \quad (1)$$

where ρ denotes the density of the fluid; t is the time; $\mathbf{v}_i$ and $\mathbf{u}_i$ signify the velocity of the fluid and the mesh, respectively; x_i represents the Eulerian coordinate in the i direction (Kim et al., 2008):

$$\rho \frac{\partial \mathbf{v}_i}{\partial t} = \sigma_{i,j} - \rho (\mathbf{v}_i - \mathbf{u}_i) \frac{\partial \mathbf{v}_i}{\partial x_j} \quad (2)$$

where σ is the stress tensor and x_j is the Eulerian coordinate in the j direction (Kim and Shin, 2008):

$$\rho \frac{\partial e}{\partial t} = \sigma_{ij} \epsilon_{ij} - \rho (\mathbf{v}_i - \mathbf{u}_i) \frac{\partial e}{\partial x_j} \quad (3)$$

where e denotes the energy (Kim and Shin, 2008):

2.2 Equation of state (EoS) and constitutive model

2.2.1 EoS of explosives

The Jones–Wilkins–Lee (JWL) EoS is used in this study to describe the pressure–volume–energy characteristics of the detonation products during the penetrator formation process. The pressure of exploding gas can be expressed as (Kim and Shin, 2008):

$$P = A(1 - \frac{\omega}{R_1 V}) e^{-R_1 V} + B(1 - \frac{\omega}{R_2 V}) e^{-R_2 V} + \frac{\omega E}{V} \quad (4)$$

where A and B are the linear coefficients; ω , R_1 , and R_2 represent the nonlinear coefficients; V denotes the ratio of the volume of detonation products to the initial volume of the

explosive; E refers to the detonation energy per unit volume. Detailed parameters for the explosives used in this study are listed in Table 1 (Dobratz, 1974; Elbeih et al., 2018; Fu et al., 2013).

Table 1 Parameters in JWL EoS for explosives (Dobratz, 1974; Elbeih et al., 2018; Fu et al., 2013)

Materials	TNT	HMX	RDX	8701
ρ (g/cm ³)	1.63	1.89	1.76	1.72
A (GPa)	373.8	778.3	750.0	581.7
B (GPa)	3.747	7.071	7.60	6.815
R_1	4.15	4.20	3.84	4.10
R_2	0.9	1.0	1.26	1.0
ω	0.35	0.30	0.47	0.35
D (m/s)	6930	9110	8424	8425
E (GJ/m ³)	6.0	10.5	10.1	9.0
P_{CJ} (GPa)	21.00	42.00	30.20	29.95

2.2.2 EoS of air

The linear polynomial EoS is utilized to describe the air. The pressure is given by (Ma et al., 2022a):

$$P = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_5 \mu + C_6 \mu^2) E_0 \quad (5)$$

where C_0 , C_1 , C_2 , C_3 , C_4 , C_5 , and C_6 denote the correlation coefficients of the linear polynomial equation; $\mu = \rho/\rho_0 - 1$, where ρ and ρ_0 refer to the current density and the initial density of air, respectively; E_0 is the internal energy. The parameters for air are presented in Table 2 (Ma et al., 2022a).

Table 2 Parameters in the linear polynomial EoS for air (Ma et al., 2022a)

ρ (g/cm ³)	C_0	C_1	C_2	C_3	C_4	C_5	C_6	E_0 (GPa)	V_0
0.00125	0	0	0	0	0.4	0.4	0	0.00025	1.0

2.2.3 EoS of water

The EoS of water follows the Mie–Gruneisen model, and the pressure of water in compression is given by (Zhang et al., 2017; Steinberg, 1987):

$$P = \frac{\rho_0 C_0^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2} \right) \mu - \frac{a}{2} \mu^2 \right]}{\left[1 - (S_1 - 1) \mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2} \right]} + (\gamma_0 + a\mu)e, \mu > 0 \quad (6)$$

When the water is in an expansion state, the pressure can be expressed as (Zhang et al., 2017; Steinberg, 1987):

$$P = \rho_0 C_0^2 \mu + (\gamma_0 + a\mu)e, \mu < 0 \quad (7)$$

where ρ_0 is the initial density; C_0 refers to the sound velocity; μ signifies the compressive factor, which is denoted by $\mu = \eta - 1$, where η is the ratio of the current density to the initial

density; γ_0 represents the Gruneisen coefficient; α denotes the first-order volume correction to γ_0 ; e suggests the specific energy per unit volume; S_1 , S_2 , and S_3 imply the coefficients of the slope of the u_s-u_p curve, where u_s and u_p represent the shock and particle velocity, respectively. The relevant parameters are displayed in Table 3 (Zhang et al., 2017).

Table 3 Parameters in the Mie–Gruneisen EoS for water (Zhang et al., 2017)

ρ_0 (g/cm ³)	C_0 (m/s)	γ_0	α	S_1	S_2	S_3	e (J/kg)
0.998	1480	0.5	0	2.56	1.986	1.2268	357.1

2.2.4 Material models of copper, iron, and titanium

The liner involved in this study is made separately from copper, iron, and titanium. The material model utilized is the Johnson–Cook model, which is suitable for calculating the high-rate deformation of metals. The yield stress is defined as (Ma et al., 2022b):

$$\sigma_y = (A + B\varepsilon_p^n)(1 + C \ln \dot{\varepsilon}^*) \left[1 - (T^*)^m \right] \quad (8)$$

where A , B , C , m , and n represent the material parameters determined from experiments. ε_p and $\dot{\varepsilon}^*$ refer to the effective plastic strain and effective strain rate, respectively. $\dot{\varepsilon}^* = \dot{\varepsilon}_p / \dot{\varepsilon}_0$, where $\dot{\varepsilon}_0 = 1 \text{ s}^{-1}$. The homologous temperature T^* can be expressed as $T^* = (T - T_r) / (T_m - T_r)$, where T , T_m , and T_r refer to the current, melting, and room temperature, respectively.

The Mie–Gruneisen EoS described above is also utilized for liner materials, given that the liner exhibits fluid characteristics at high pressure and temperature during the formation process. The detailed parameters for the material models are depicted in Table 4 (Zhang et al., 2020).

Table 4 Parameters for the material models of the liner (Zhang et al., 2020)

Material	Copper	Iron	Titanium
ρ_0 (g/cm ³)	8.930	7.896	4.650
G (GPa)	46.0	81.8	41.0
A (MPa)	90	350	797
B (MPa)	292	275	574
n	0.31	0.36	0.11
C	0.025	0.022	0.000
m	1.09	1.00	0.65
γ_0	2.02	2.17	1.29
C_0	3940	4569	5031
S_1	1.49	1.49	1.50

2.2.5 Material model of Q235 steel

During the penetration process, stress exceeding the yield strength of the Q235 steel is generated. Thus, the material model should have the capability to simulate the nonlinear stress–strain behavior. Accordingly, the plastic–kinematic model is employed to describe the dynamic behavior of

Q235 steel, and the Cowper–Symonds model is adopted to describe the strain rate effect. These models can be expressed as (Wang et al., 2022):

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{P}} \right] (\sigma_0 + \beta E_p \varepsilon_p^{\text{eff}}) \quad (9)$$

$$E_p = \frac{E_t E}{E - E_t} \quad (10)$$

where σ_0 , $\dot{\varepsilon}$, $\varepsilon_p^{\text{eff}}$, and β are the initial yield stress, strain rate, effective strain rate, and hardening parameters, respectively. C and P represent the strain rate coefficients. E_p , E , and E_t signify the initial yield stress, elastic modulus, and tangent modulus, respectively. The parameters are displayed in Table 5 (Wang et al., 2022).

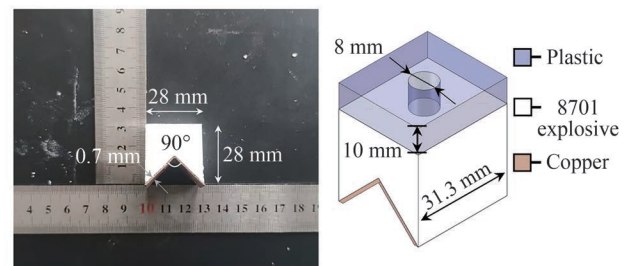
Table 5 Parameters in the plastic–kinematic model for Q235 steel (Wang et al., 2022)

ρ (g/cm ³)	E (GPa)	M	σ_0 (MPa)	E_t (MPa)	C/s^{-1}	P	F_s
7.85	210	0.3	235	250	40.4	5	0.28

2.3 Numerical verification

The size of the penetration hole, especially the penetration length, is an important parameter for cutting thin-walled structures. Thus, the penetration length test on the steel plate is performed to determine the penetration capacity of a traditional LSC with a chevron liner and verify the accuracy of the ALE method.

The LSC is mainly composed of the main charge, a liner, and an initiation device, as shown in Figures 2 and 3. The main charge is made of 8701 explosive, has a mass of 30.0 ± 0.1 g, and is manufactured using the compression modeling method. The thickness of the liner is 0.7 ± 0.02 mm. A plastic detonator holder is stuck to the upper surface of the LSC to locate and fix the electric detonator for improved initiating conditions. Detailed geometric parameters of the LSC and the detonator holder are displayed in Figure 2.



(a) Geometric parameters of the LSC (b) Preparation of the LSC

Figure 2 Geometric parameters of the LSC and the detonator holder

The size of the target plate is $(500.0 \pm 0.5) \text{ mm} \times (500.0 \pm 0.5) \text{ mm} \times (3.0 \pm 0.5) \text{ mm}$ (length $\times$ width $\times$ thickness), as depicted in Figure 3. Several bolt holes are preset on the outside of the plate for subsequent installation.

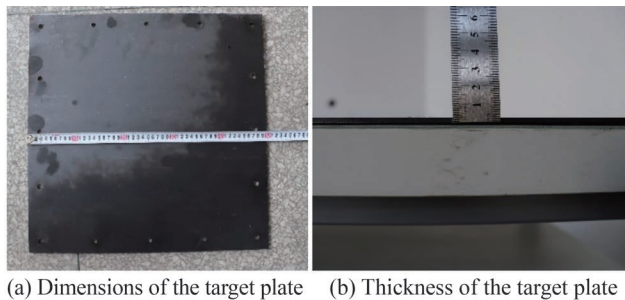


Figure 3 Geometrical parameters of the target plate

The experimental setup is illustrated in Figures 4(a) and (b). First, the target plate with a locating mark is bolted on the steel flange to exploit the enforcement of a rigid fixed boundary condition. Then, the cardboard box with a height of 42.0 ± 0.5 mm is adhered to the surface of the target plate. The cardboard box can realize a standoff distance of 1.5 times the height of the charge for the jet formation without negatively influencing the formation effect due to its own structural strength. Finally, the LSC is placed on the midspan of the cardboard box, and an electric detonator is inserted into the detonator holder.

The experimental results are presented in Figure 4(c). A

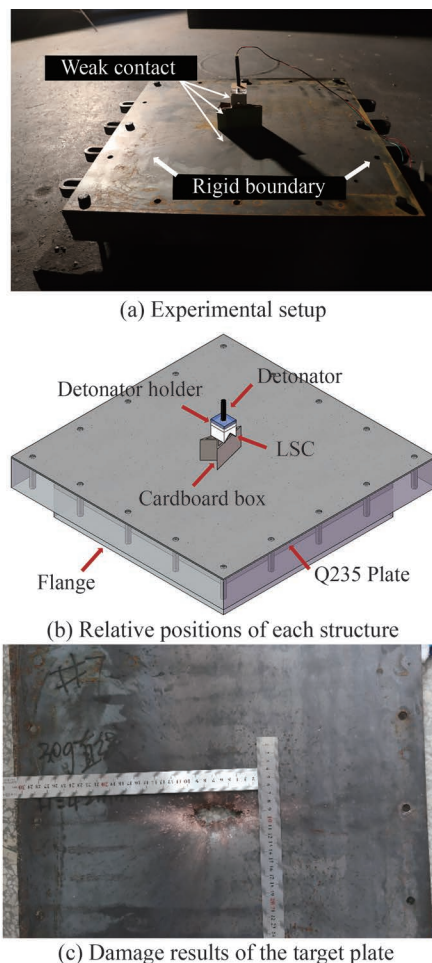


Figure 4 Experimental arrangement and results

penetration hole is created into the target plate, which has a length of 60.0 ± 0.5 mm and a width of 20.0 ± 0.5 mm. The apparent shear failure mode suggests that the liner of the LSC has formed into a high-speed metal jet, which rapidly penetrates through the target plate. The plastic deformation region of the target plate measures nearly $(81.0 \pm 0.5) \text{ mm} \times (45.0 \pm 0.5) \text{ mm}$.

The numerical model corresponding to the experimental setup is further established, as shown in Figure 5, to verify the accuracy of the ALE method. Considering the geometric symmetry of the numerical model, a half-scale model is established to increase computational efficiency. The computational domain measures $100 \times 100 \times 200$ mm (length $\times$ width $\times$ height), with symmetry defined along the YZ plane. Accordingly, a symmetry boundary condition is implemented on the YZ plane, while nonreflecting boundary conditions are applied on the remaining boundaries to remove the influence of shock wave reflections on the simulation results. The target plate dimensions are set to exceed the experimentally observed damage region, and all the edges are rigidly constrained. The plate thickness and the geometrical parameters of the shaped charge are identical to those set in the experiments. The target plate is discretized using uniform hexahedral elements with a mesh size of $0.5 \times 0.5 \times 0.5$ mm, which results in a total of 16 000 000 elements. The same mesh generation approach is used for the solid target and the fluid domain, with a shared-node treatment method implemented at the interface. Meanwhile, FSI is considered.

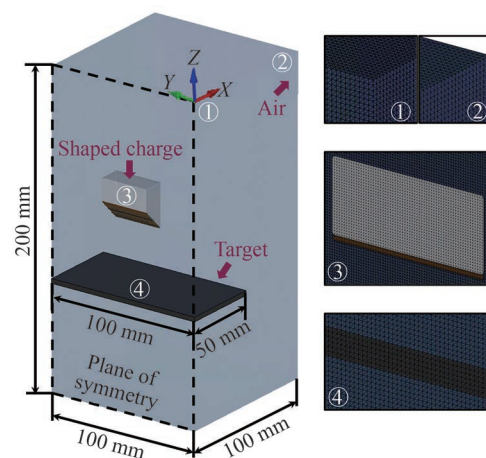


Figure 5 ALE model for numerical verification

The jet formation and penetration processes are reproduced, as presented in Figure 6. Under detonation waves, the liner gradually becomes compressed and deformed. Then, a fan-shaped jet with high velocity is generally formed, along with the slug that trails behind. For traditional LSCs, the majority of the liner by mass goes into the slug. As depicted in Figures $t = 1.5 \mu\text{s}$ to $t = 27 \mu\text{s}$, the jet and the slug undergo extensive fragmentation before the penetration process, which is detrimental to the penetra-

tion performance and post-penetration effect of the LSC. As for the penetration process, the jet creates an initial penetration hole into the target plate. Then, the size of the hole is gradually increased due to the effect of the penetrator and detonation byproducts. The comparison between structural damage dimensions and deflection contour plots with experimental results is presented in Figure 6(b).

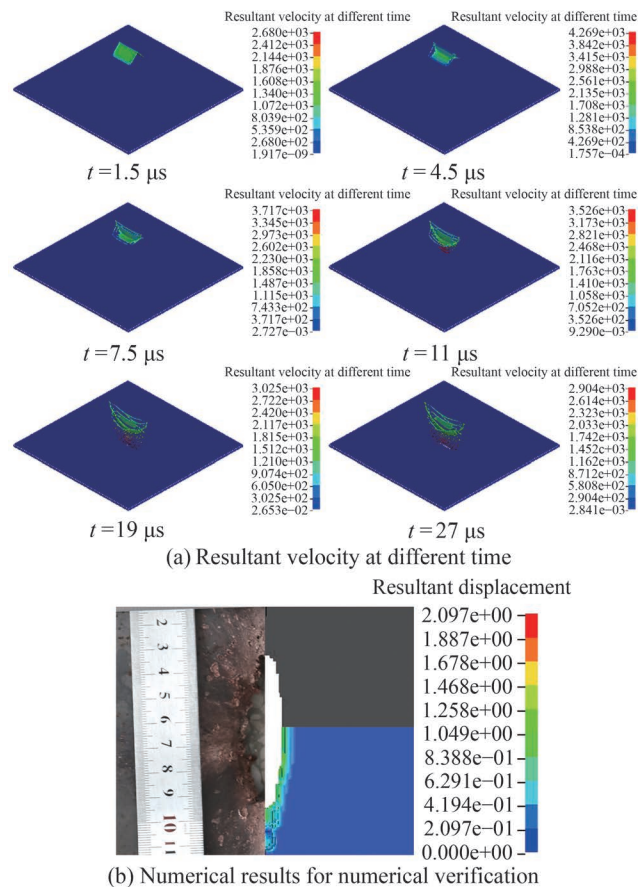


Figure 6 Damage results from numerical simulation: $t = 1.5 \mu\text{s}$ to $t = 27 \mu\text{s}$ represent the formation and penetration process of the LSC, and (b) refers to the comparison between experimental data and simulation results

The damage mode of the plate in numerical simulation is similar to that observed in the experiment. The target plate is characterized by shear failure at the center, which is caused by penetration. Localized plastic deformation is also observed around the penetration hole. The degree of deformation gradually decreases from the center toward both sides.

The penetration hole generated in the simulation has the dimensions of $62.6 \times 17.5 \text{ mm}$. The errors in the length and width of penetration are 4.3% and -12.5%, respectively. The error in the width of penetration is primarily attributed to the incomplete perpendicularity of the LSC to the target plate. The maximum deflection of the target plate in the experiment is measured to be $13.7 \pm 0.5 \text{ mm}$, while the value obtained from numerical simulation is 12.6 mm, which results in an error of -8.0%. The plastic deformation region of the target plate measures around $80 \times 34 \text{ mm}$, with errors of -1.2%

and -24.4%, respectively. Overall, the numerical damage results of the LSC agree well with the experimental data. Therefore, the 3D ALE method is proven to be effective and accurate in solving the shaped charge problems in this study.

This study extends previous works by further investigating the application of LSCs for efficient damage to thin-walled structures. An airburst experiment is performed to determine the damage effects of the LSC on flat Q235 steel plates. The results demonstrate that stretch-formed charges possess distinct advantages over conventional cylindrical charges in achieving super-aperture perforation. A long penetration hole with an L_p/W_p ratio of 3.58 is generated in the simulation, where L_p and W_p represent the length and width of penetration, respectively. However, experimental observations and numerical simulations reveal pronounced penetrator fragmentation during the formation and penetration process. The resulting slug also tends to be relatively bulky and exhibits lower effective mass, which adversely affects the overall damage performance.

Compared with LSCs, the LEFP offers superior efficiency and precision in structural damage applications. By replacing the conical liner with a hemispherical (or spherical-cap) design, LEFPs can generate penetrators with greater mass concentration, improved aerodynamic stability, decreased sensitivity to standoff distance, and more pronounced post-penetration effects. Given the geometrical similarity between LSCs and LEFPs—both of which are derived from the longitudinal extension of the charge section—the longitudinal length of the formed penetrators remains comparable. The resulting damage patterns are also consistent. Therefore, the damage characteristics found in the LSC experiments provide important reference data for understanding the formation and penetration behavior of LEFPs with similar geometries. The experimental validation also supports the feasibility and accuracy of the ALE-based simulation methodology utilized in this study. It lays a solid foundation for the subsequent numerical investigation on the formation and damage mechanisms of LEFPs.

3 Influence of the medium on the formation characteristics of LEFPs

3.1 Numerical model and convergence tests

The numerical model of the LEFP based on the ALE method is shown in Figure 7. The mass of the main charge made of TNT is 55 g, and detailed parameters of the LEFP are displayed in Table 6. Considering that the numerical model is symmetric, a half-scale model is used for calculation to enhance computational efficiency and visualize the penetrator formation characteristics more intuitively. The size of the calculation domain is $100 \times 80 \times 200 \text{ mm}$ (length $\times$ width $\times$ height). A nonreflecting boundary condi-

tion is implemented on all surfaces of the fluid domain to eliminate the effect of reflected shock waves.

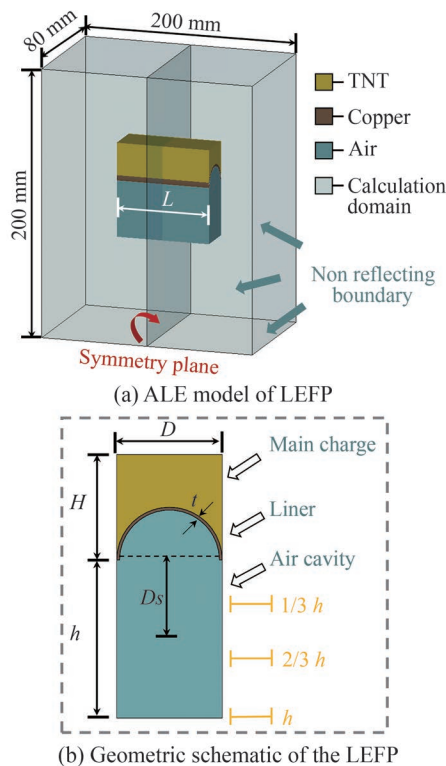


Figure 7 Numerical model of the LEFP

Table 6 Detailed parameters of the LEFP

D (mm)	H (mm)	h (mm)	t (mm)	L (mm)
28	28	42	1.5	70

The uniform hexahedral meshing is applied to discretize the computational domain. Convergence tests need to be conducted because the quality of meshing directly affects the accuracy of the results. The convergence analysis of an air explosion, which is performed with the calculation domain filled with air, is conducted. The velocities of the penetrator at 16 μ s under different numbers of cube elements are presented in Table 7.

Table 7 Velocity of the penetrator

Number of grids (million)	6	8.6	10.4	12.8	16	20
Mesh size (mm)	0.64	0.57	0.54	0.50	0.46	0.43
Velocity of the penetrator (m/s)	965.0	1153.0	1463.0	1606.0	1625.0	1696.0

First, the velocity of the penetrator increases rapidly with the number of grids until the number reaches 12.8 million, which corresponds to an element size of $0.5 \times 0.5 \times 0.5$ mm. At this point, the penetrator velocity reaches 1606 m/s, after which the velocity gradually levels off. The difference in the penetrator velocity between the grid numbers of 12.8 and 20 million is only 5.3%, which suggests that the penetrator

velocity has converged at the element size of 0.5 mm. The size of the grid is set to 0.5 mm in subsequent numerical simulations to ensure computational efficiency.

3.2 Formation effect of LEFPs in air

The formation characteristics of the LEFP in an air domain are investigated. The numerical model and corresponding material models have been introduced in Sections 2.2 and 2.3, respectively. In this case, the calculation domain and the air cavity area are filled with air. The formation process of the penetrator is depicted in Figure 8.

At the initial stage of the formation process, the detonation wave propagates at an extremely high speed along the vertical direction of the charge. As a result, a dynamic high-pressure region is formed on the surface of the liner, which causes the liner material to undergo plastic flow. The top portion of the liner is the first to be impacted, which causes its deformation. Subsequently, other areas of the liner are gradually compressed. This phenomenon leads to the material rapidly converging toward the central axis. Overall, the liner gradually overturns, as displayed in Figures 8(a) and (b). After the reversal of the liner, a penetrator is gradually generated and elongated under the effect of the velocity gradient, as presented in Figures 8(c) to (d). During the formation process, the back of the penetrator has a radial component of the momentum and, therefore, gradually becomes closed. At approximately 50 μ s, the penetrator is completely closed and presents a long and slender morphology.

The evolutions of the penetrator velocity, displacement, and side dimensions are illustrated in Figures 9 and 10 for quantifying the formation effect of the LEFP. Notably, the velocity of the penetrator always refers to the velocity of the penetrator head, which is a significant formation characteristic that reflects the penetration capability of the LEFP. Under the continuous expansion of the detonation products, the penetrator head is subjected to a net forward thrust. This stage is dominated by the explosive energy, which results in a rapid accumulation of kinetic energy and a sharp augmentation in the penetrator velocity. As the detonation products expand, their internal pressure decreases rapidly, which causes the penetrator to lose its primary driving force. Simultaneously, aerodynamic drag—proportional to the square of the velocity of the penetrator—begins to play an important role, particularly during the early stages of jet formation. At the same time, the velocity gradient within the penetrator facilitates the redistribution of its speed, which further depletes the kinetic energy of the penetrator. This depletion results in a gradual decrease in velocity, which lasts until the penetrator reaches a dynamic equilibrium between inertia and resistance. At this point, the velocity stabilizes. The evolution curve of velocity shown in Figure 9 indicates that the velocity of the penetrator increases initially and decreases thereafter, and then, it peaks at 1935 m/s at around 8 μ s. Then, the velocity gradually levels off, and

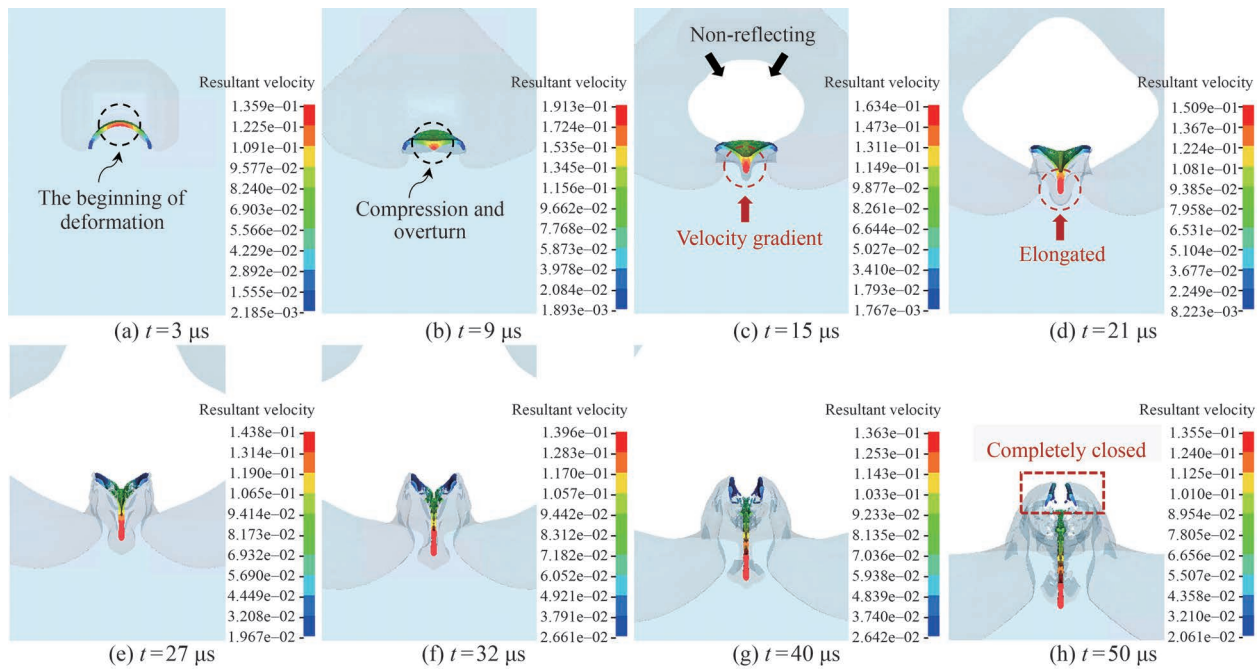


Figure 8 Formation process of the penetrator in air

finally, it stabilizes at 1355 m/s at 50 μ s.

For 3D numerical simulation, penetrators are formed not only vertically but also longitudinally. The longitudinal size of the penetrator directly determines its length, and its longitudinal structure observed from the side is also a crucial factor in assessing the formation effect.

Figure 10(a) shows that the initial morphology of the penetrator is fan-shaped. At approximately 22 μ s, localized damage occurs at the back of the penetrator, as shown in Figure 10(b).

It gradually develops into large-scale fragmentation, as presented in Figure 10(c). The fragmentation extends from

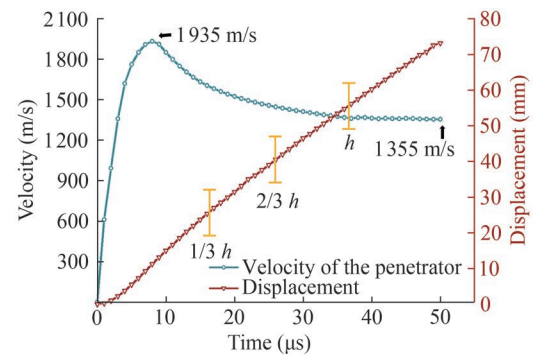


Figure 9 Velocity of the penetrator during the formation process in air

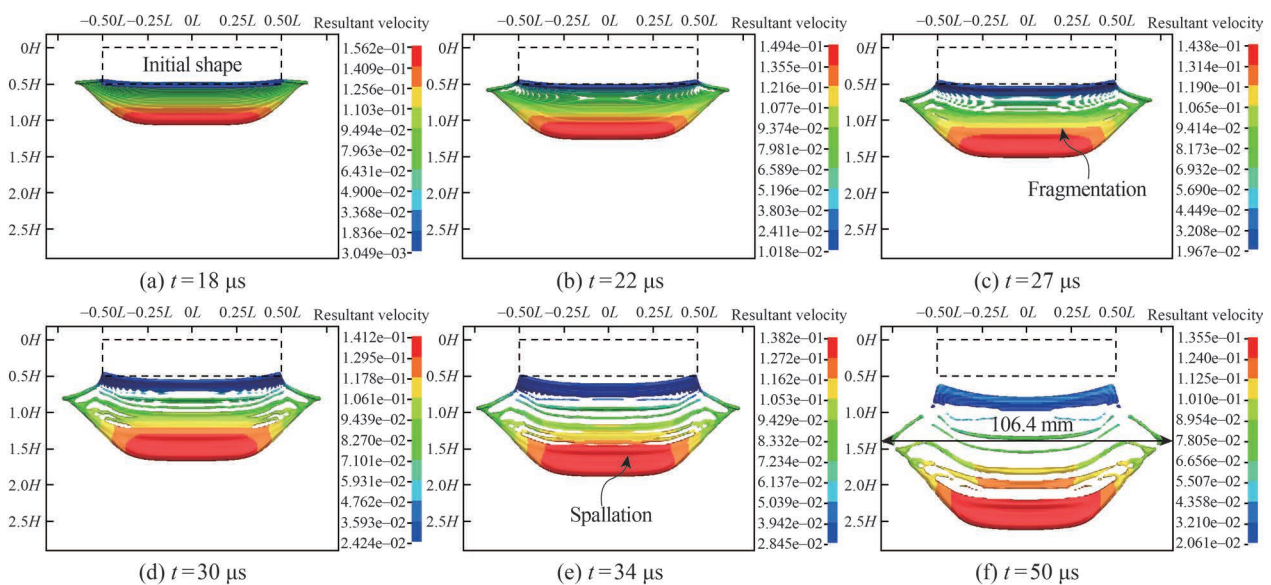


Figure 10 Profile of the penetrator during the formation process in air

back to front and from the outside to the inside, as displayed in Figures 10(d) and (e). Finally, the coupled effects of the velocity gradient and rarefaction waves induce the delamination of the penetrator, which leads to a decrease in effective mass and a significant reduction in penetration capacity. At around 50 μs , the longitudinal size of the penetrator reaches 106.4 mm, which corresponds to 1.52 times the length of the LEFP.

3.3 Formation effect of LEFPs in water

For the underwater explosion of the LEFP—when the computational domain is filled with water—the formation of the penetrator is significantly less effective than that in air, as illustrated in Figure 11. Owing to the much higher density of water than that of air, the expansion of the detonation products is severely restricted, which results in reduced energy transmission to the liner surface and a substantial decrease in effective pressure. Consequently, the collapse velocity of the liner decreases, which prevents the liner from fully converging into a slender penetrator. The penetrator head becomes blunt due to insufficient kinetic energy. Furthermore, after the penetrator head enters the water, it experiences hydrodynamic drag that is proportional to the square of its velocity. This condition further intensifies the bluntness and mass accumulation at the head. As the penetrator moves axially and the tail undergoes deformation, the cross-sectional shape transforms from a W-profile to a V-profile. The water resistance disrupts the continuity required for the tail to close, which hinders effective convergence of the trailing metal and leads to an open-ended morphology. As presented in Figure 12, the velocity of the

penetrator has a maximum of 947.5 m/s at around 4 μs . Then, the velocity continues to decrease, with only 423.6 m/s at 50 μs . Considering the low compressibility of water, the degree of initial compression and deformation of the liner is inadequate, which results in a relatively low overall velocity of the penetrator.

Meanwhile, lower velocity of the penetrator causes the liner to turn over later, as depicted in Figures 13(a) and (b), compared with the air explosion presented in Figure 10. However, it also leads to a smaller velocity gradient, which is conducive to the integrity and continuity of the penetrator morphology without internal damage. In addition, the resistance of water limits not only the vertical formation of the penetrator but also the longitudinal formation. At 50 μs , the longitudinal size of the penetrator is 85.4 mm, which corresponds to 1.22 times the length of the LEFP, as displayed in Figure 13(c).

Overall, the morphology of the penetrator after formation in air is elongated and homogenous, with a higher velocity and greater degree of expansion. By contrast, the morphology in water is flat and wide, with a lower velocity but a more concentrated mass. The results above suggest that a positive medium condition is essential for the formation of the penetrator, especially for its initial formation. Thus, an air cavity is added in front of the liner to improve the formation effect of the LEFP in water. Considering that the velocity and morphology of the penetrator have been stabilized at 36 μs , as indicated in Figures 9 and 10, the distance from the head of the penetrator at this time to the bottom of the LEFP is set as the length of the air cavity. In this way, the penetrator can be adequately formed. Geometrical parameters of the air cavity are depicted in Figure 7.

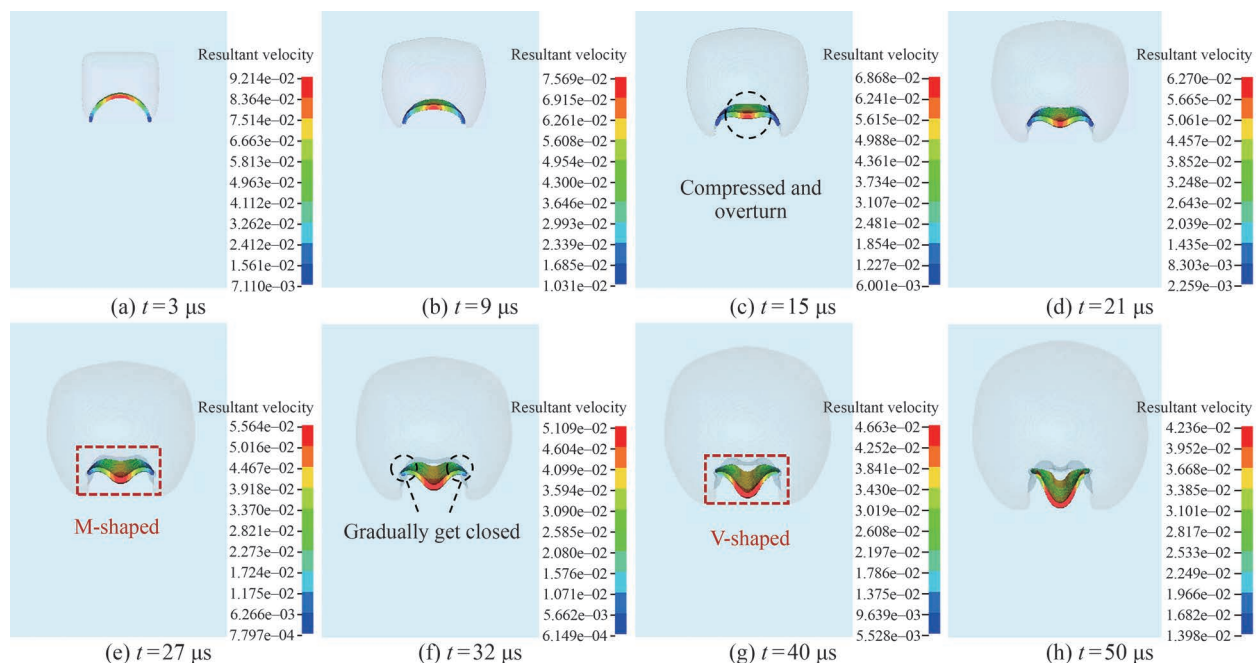


Figure 11 Formation process of the penetrator in water

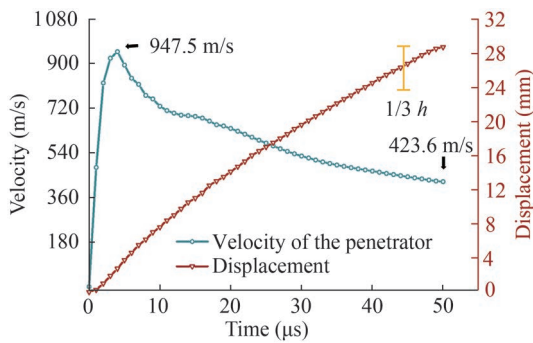


Figure 12 Velocity of the penetrator during the formation process in water

3.4 Formation effect of LEFPs in water with an air cavity

The timescale of liner collapse dominated by the detonation wave is much shorter than that of hydrostatic pressure compressing the air. Thus, the air cavity remains in a low-pressure state during the initial stage of penetrator formation, which provides relatively stable medium conditions

for the formation process. Figures 14(a) to (e) show similarities with the formation process in pure air medium presented in Figure 8. The penetrator is normally elongated, and its back gradually becomes closed. At the initial forming stage before 15 μ s, the detonation products intrude into the air cavity because of the relatively large internal pressure, as shown in Figure 14(c). It also partially encapsulates the outside of the liner. Then, the air cavity is cut off from the middle by the fast-moving penetrator. The volume of the air gradually decreases under the coupling effect of hydrostatic water pressure, the penetrator, and the expanding bubble.

At nearly 32 μ s, the penetrator pierces the air cavity, which causes its head to contact the surrounding water and become blunted. Subsequently, the air becomes entrained around the penetrator and is carried along for a certain distance, as displayed in Figures 14(f) to (h).

A drop in velocity due to the exposure of the penetrator to water can be clearly found in Figure 15. Specifically, the velocity instantly drops from 1778 to 1401 m/s. Moreover, the maximum velocity is 2037 m/s at approximately 8 μ s, which is 102 m/s greater than that in air explosion at

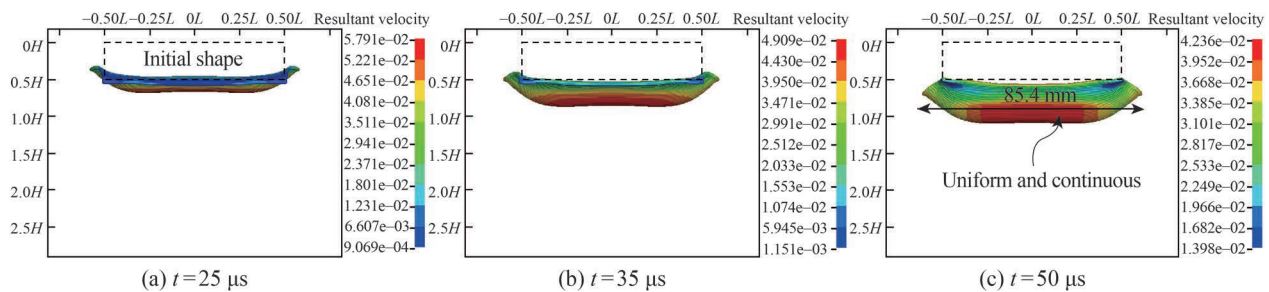


Figure 13 Profile of the penetrator during the formation process in water

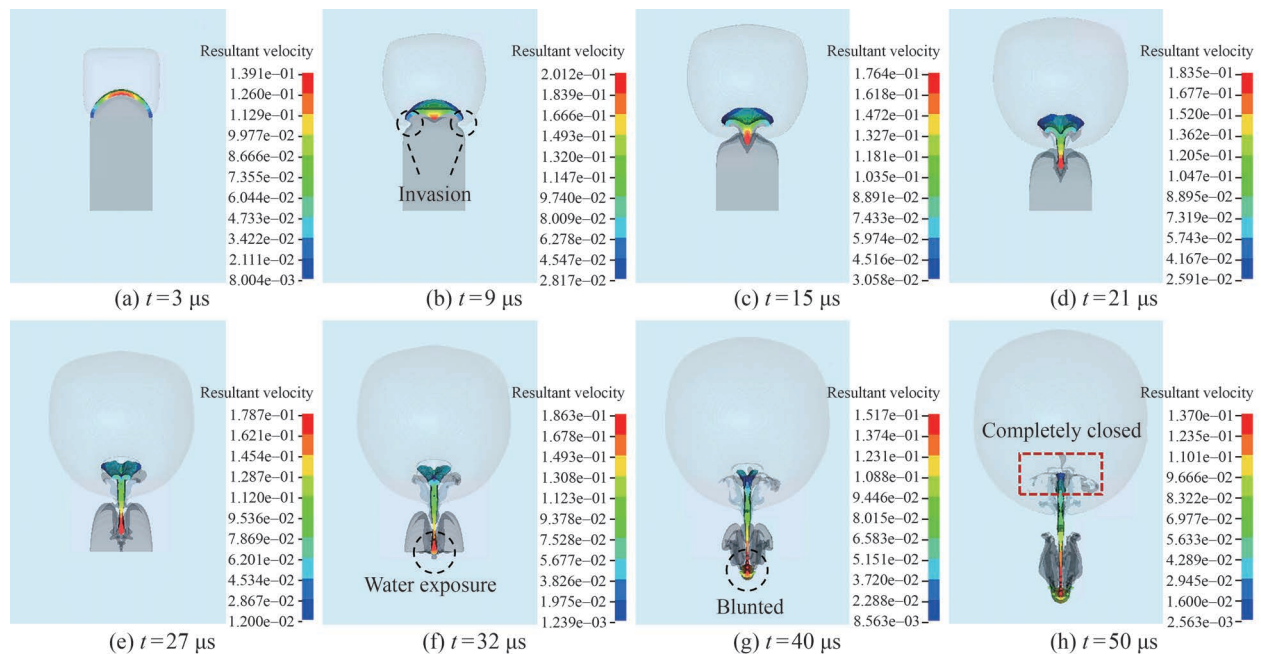


Figure 14 Formation process of the penetrator in water with an air cavity

the same time. This result is primarily attributed to the lower detonation energy entering the water. Then, the velocity gradually decreases due to the water resistance, which remains 966.6 m/s at 50 μ s.

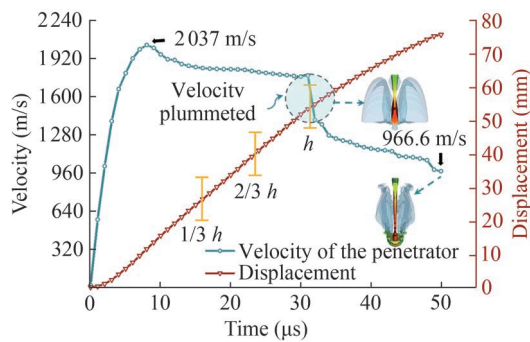


Figure 15 Velocity of the penetrator during the formation process in water with an air cavity

The process of overall deformation and destruction of the penetrator is displayed in Figure 16. An initial break occurs in the middle of the penetrator and gradually propagates in the longitudinal direction, as depicted in Figures 16(b) and (c). At around 32 μ s, a curved crack appears in the anterior part of the penetrator, as displayed in Figure 16(d). Different from the explosion in air or water, the penetrator under such medium conditions does not show a flat section at the

bottom but is completely bent. As a result, the mid-head part of the penetrator is the first to contact with water and gets blunted, as illustrated in Figures 16(e) and (f). This condition leads to local depression at the bottom. Subsequently, the penetrator exhibits a three-part pattern of destruction, with a delamination of the penetrator head, half-breaks at the back, and internal breaches at both sides, as indicated in Figures 16(g) and (h). Finally, the longitudinal size of the main penetrator reaches 64.4 mm, as presented in Figure 16(i).

Overall, water significantly constrains the formation effect of the penetrator longitudinally and vertically. Introducing an air cavity augments the velocity of the penetrator, improves its morphology, and enhances the focus of the metal liner. All these advances are beneficial for increasing the penetration capacity of the LEFP.

4 Orthogonal optimization analysis

4.1 Orthogonal optimization design

On the basis of the calculation results in the previous section, orthogonal optimization is further performed in terms of geometric parameters and materials of the LEFP

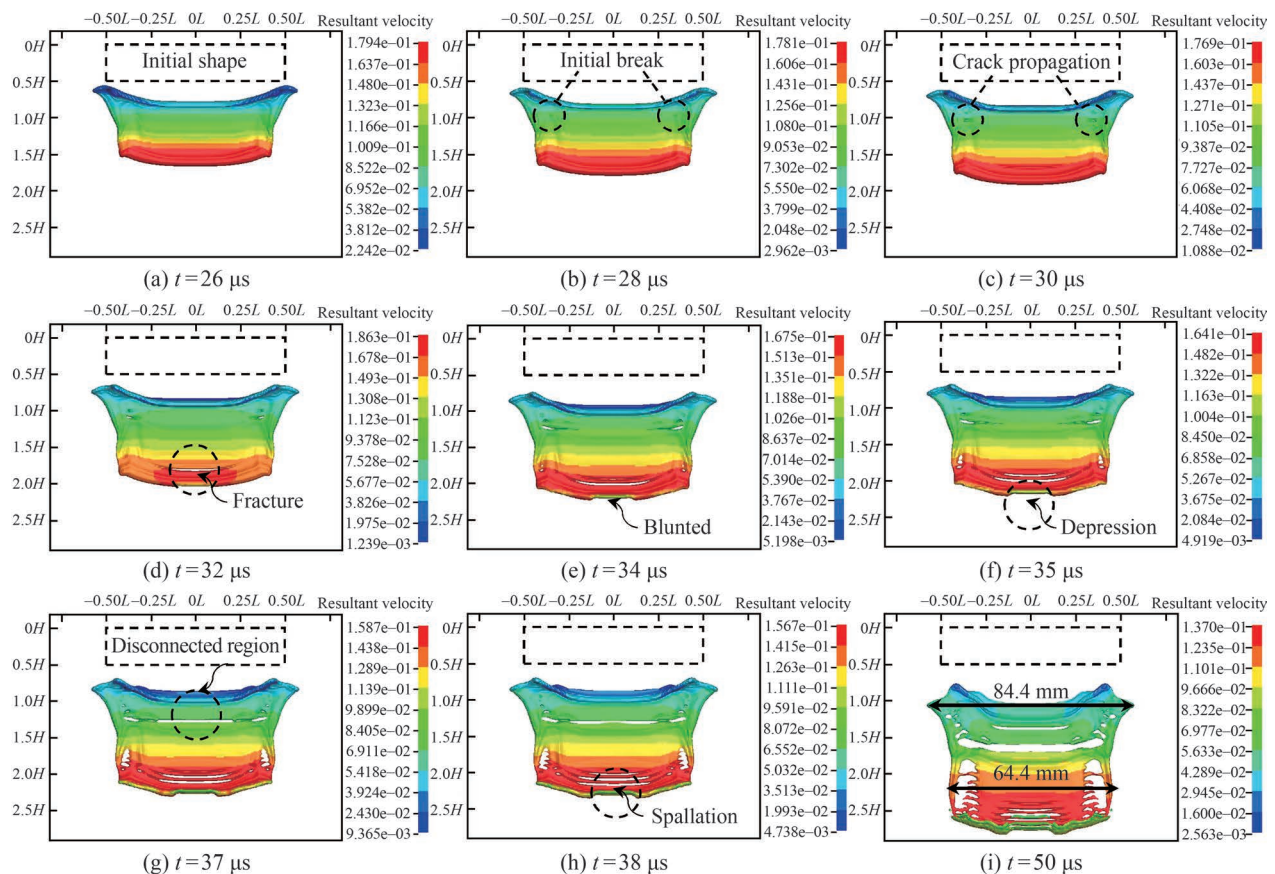


Figure 16 Profile of the penetrator during the formation process in water with an air cavity

to improve the formation effects and penetration performance of the penetrator in water with an air cavity.

As for the LEFP, materials of the explosive (Zhang et al., 2024b) and the liner (Tian et al., 2025), as well as the thickness of the liner (Duan and Du, 2010), have appreciable influence on the formation effects of the penetrator. Thus, they are chosen as the three dependent factors for optimization. The initial configuration of the optimized LEFP, including the explosive dimensions and the curvature of the liner, is fixed throughout the optimization process. The levels for each factor are determined based on previous research on rationality (Duan and Du, 2013; Wu et al., 2013; Li et al., 2023). The chosen parameter levels in this study can adequately characterize the formation characteristics of LEFPs under various combinations of liner mass and explosive energy. The parameter space covers typical variations in the morphology of the penetrator, including its breakup caused by insufficient liner mass and its incomplete formation due to inadequate explosive energy. The selected parameter space is thus considered to be representative, which is presented in Table 8.

Table 8 Levels for each factor

Level	Material of the explosive	Material of the liner	Thickness of the liner (mm)
1	TNT	Copper	2.0
2	HMX	Iron	1.5
3	RDX	Titanium	1.0

The L9 (3^4) orthogonal design scheme is shown in Table 9. All the cases are based on constant charge volume and configuration. The numerical model can be found in Figure 7.

Table 9 Case setting for orthogonal optimization

No. of cases	Material of the explosive	Material of the liner	Thickness of the liner (mm)
1	TNT	Copper	2.0
2	TNT	Iron	1.5
3	TNT	Titanium	1.0
4	HMX	Copper	1.5
5	HMX	Iron	1.0
6	HMX	Titanium	2.0
7	RDX	Copper	1.0
8	RDX	Iron	2.0
9	RDX	Titanium	1.5

4.2 Simulation results and analysis

As shown in Figure 7, D_s is defined as the distance from the head of the penetrator to the bottom of the LEFP. $D_s = 1/3 h$, $D_s = 2/3 h$, $D_s = h$ are chosen as three characteristic moments for analyzing the formation effect of the LEFP during the formation process.

The evolution of the velocity of the penetrator for each case is displayed in Figure 17. For improved comparative

analysis, nine cases are divided into three groups. The three cases within a group correspond to the same material of the explosive.

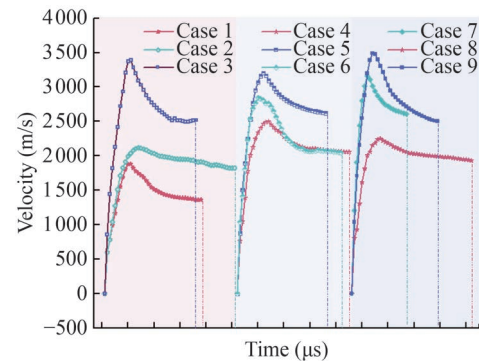


Figure 17 Evolution of the velocity of the penetrator for each case

The velocity distributions of the penetrators in cases 1 to 3 are depicted in Figure 18. The penetrator in case 3 has the largest peak velocity (3389 m/s) and stabilized velocity (2521 m/s). Meanwhile, the penetrator in case 2 has the best morphology because of its uniform and continuous nature. However, the middle front part of the penetrator in case 2 exhibits a necking effect, which will negatively influence the penetration capacity of the LEFP. The penetrators in cases 1 and 3 appear to be wide and short, which is due to local fragmentation in the middle of the penetrators.

Among cases 4 to 6 displayed in Figure 19, the peak and stabilized velocity of the penetrator in case 5 are the largest, which are 3207 and 2623 m/s, respectively. The penetrator in case 5 is the most disadvantaged because its back suffers extensive fragmentation and delamination. The penetrator in case 6 is extremely short and broad, with the lowest stabilized velocity being 2045 m/s. Overall, the penetrator in case 4 has the best formation effect. However, it still suffers from the necking problem and exhibits multiple and discontinuous cavities at the back.

As for cases 7 to 9 presented in Figure 20, the penetrator in case 9 has the largest peak velocity of 3489 m/s, while that in case 7 exhibits the highest stabilized velocity of 2611 m/s. Therefore, the penetrator in case 7 has excellent speed retention capacity. Meanwhile, the morphology of the penetrator in case 7 is slender and homogenous. Considering the necking problem in case 8, as well as structural fracture along with insufficient closure of the penetrator in case 9, the penetrator in case 7 has the best formation effect. In addition, although the back of the penetrator in case 7 shows local delamination, the front main part of the penetrator is still uniform and uncracked, which has little effect on the damage results of cutting thin-walled structures. As mentioned earlier, the longitudinal size of the penetrator is also a crucial component in evaluating formation effects. Accordingly, the quantified formation characteristics for the penetrators in each case are organized and depicted in Figure 21.

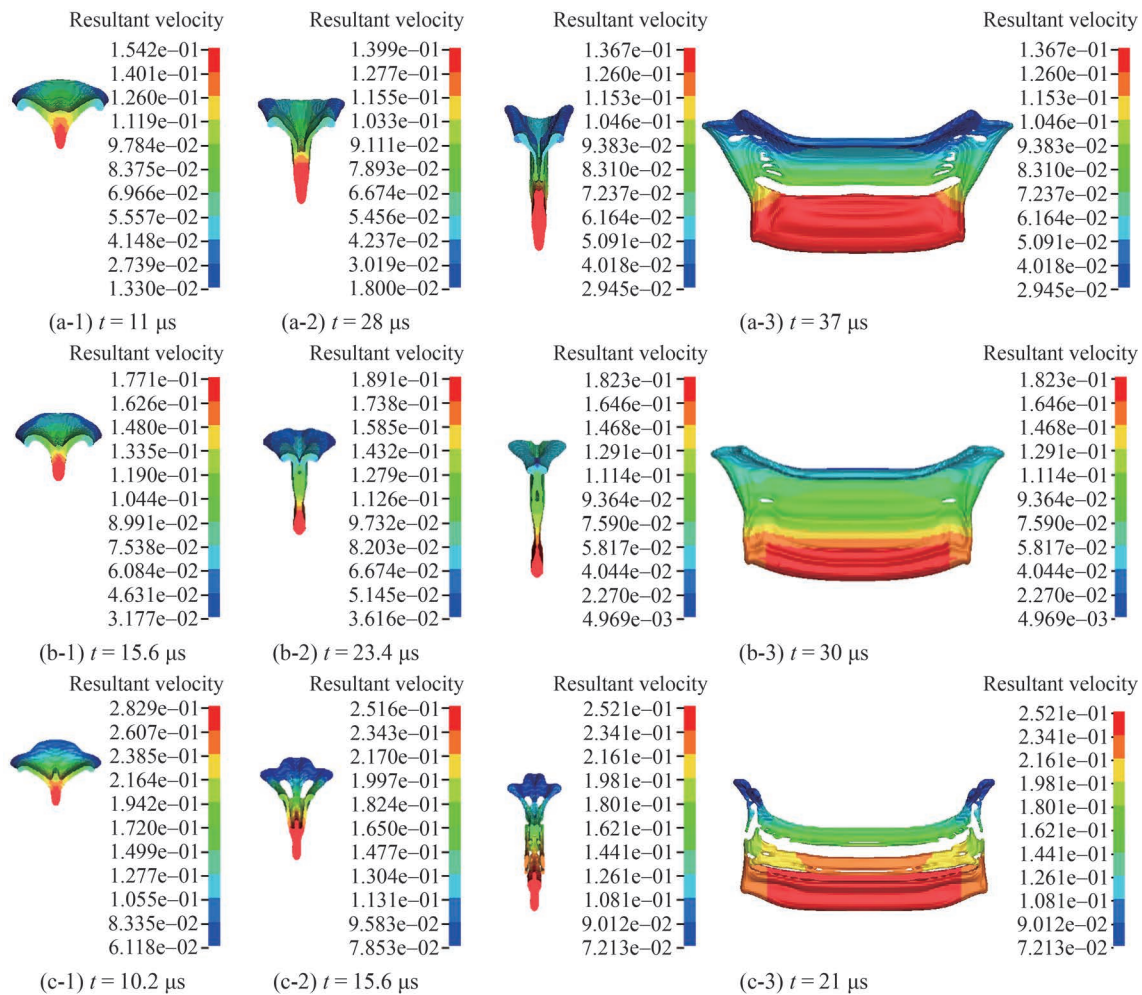


Figure 18 Velocity distribution of the penetrator when $D_s = 1/3h$, $D_s = 2/3h$, and $D_s = h$: (a-1) to (a-3) for case 1, (b-1) to (b-3) for case 2, and (c-1) to (c-3) for case 3

In Table 10, A, B, and C refer to the explosive material, liner material, and liner thickness, respectively. The effect of the three parameters on the penetrator velocity is in the following descending order: C (liner thickness) > A (explosive material) > B (liner material). Subsequently, an ANOVA is performed, as displayed in Table 11.

SST, SSE, SSA, SSB, and SSC refer to the total sum of squares, the error sum of squares, and the sum of squares attributed to factors A, B, and C, respectively. DF, DFE, DFA, DFB, and DFC represent the total degrees of freedom, the error degrees of freedom, and the degrees of freedom associated with each factor. Correspondingly, MSE, MSA, MSB, and MSC are the mean square values for the error and for each factor. FA, FB, and FC denote the F-values for factors A, B, and C.

Based on the critical value of the F-distribution at a significance level of 0.1%, $F_{0.001}(2, 2) = 999$, all three factors exhibit statistically significant effects on the penetrator velocity. The significance is in the following order: C (liner thickness) > A (explosive type) > B (liner material).

The optimal factor combination is identified as RDX–

Titanium–1 mm. Given that this specific combination is excluded in Table 9, an additional simulation (Case 10) is required. The corresponding formation performance of the LEFP at $D_s = h$ under this condition is depicted in Figure 22.

As illustrated in the velocity contour in Figure 22, the velocity of the penetrator in case 10 reaches 3256 m/s, which is 24.7% higher than that in case 7. This finding confirms a noticeable increase in head velocity. However, the penetrator formed in case 7 presents a slender and more uniform cross section. Meanwhile, the penetrator in case 10 exhibits significant fragmentation, which can inevitably impair the penetration capability. Moreover, the continuous length of the penetrator in case 7 is 21.4% greater than that in case 10. Therefore, a comprehensive analysis of penetrator morphology, head velocity, and axial continuity indicates that case 7 demonstrates the most favorable formation performance among all the cases, which corresponds to the factor combination of RDX–Copper–1 mm.

Additional cases are investigated to further analyze the applicability of the optimized LEFP configuration under varying charge quantities. Specifically, in cases 11 and 12,

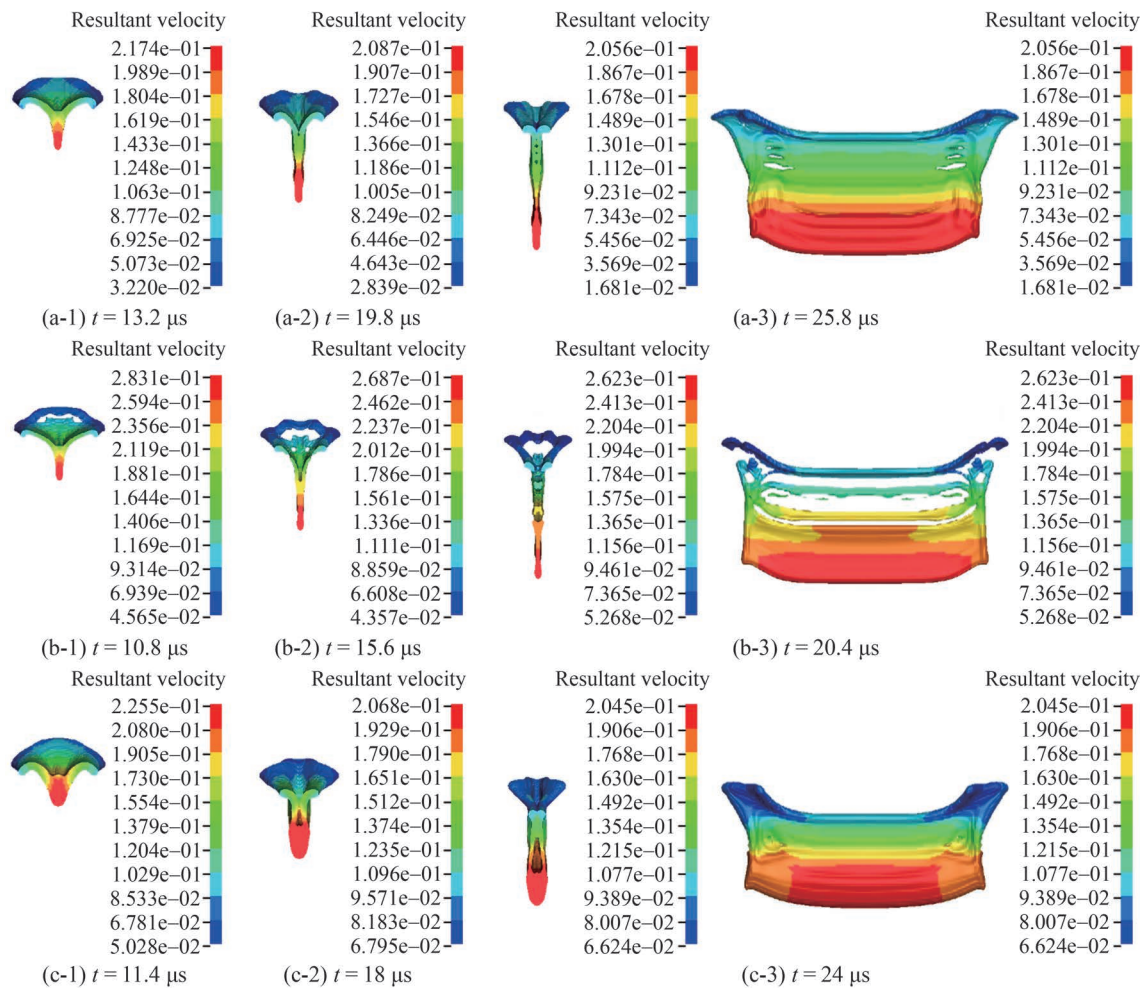


Figure 19 Velocity distribution of the penetrator when $D_s = 1/3h$, $D_s = 2/3h$, and $D_s = h$: (a-1) to (a-3) for case 4, (b-1) to (b-3) for case 5, and (c-1) to (c-3) for case 6

the cross-sectional dimensions of the charge are kept consistent with those in case 7, while the charge lengths are adjusted to $0.8L$ and $1.2L$, respectively. Meanwhile, cases 13 and 14 employ geometric scaling factors of 1.2 and 1.4. The detailed geometrical configurations of these validation cases are displayed in Figure 23.

The formation profiles and associated parameters of the penetrators under each case when $D_s = h$ are presented in Figure 24 and reviewed in Table 12.

A comparison of cases 7, 11, and 12 demonstrates that LEFPs with varying charge lengths present highly consistent formation characteristics. The velocities of the penetrators are nearly identical across the three cases, and their lateral and vertical morphologies are comparable. The continuous penetrator length remains approximately 1.7 mm in all cases, with longitudinal fracture positions occurring at similar positions. In addition, the ratio of longitudinal penetrator length to charge length differs by less than 2% between cases 11 and 12. These results imply that, under identical charge cross-sectional parameters, LEFPs maintain a stable formation behavior over a certain range of

charge lengths.

By contrast, the comparison of cases 7, 13, and 14, which involve different geometric scale ratios, suggests that increasing the overall charge quantity—while keeping the standoff distance constant—results in higher velocities of the penetrator head, improved morphology of the penetrator, and reduced susceptibility to fragmentation. However, such configurations also require appropriate adjustment of the standoff distance to guarantee sufficient energy transfer and effective penetrator formation. Overall, the parameter combination derived from orthogonal optimization reveals robust applicability to LEFP configurations with varying charge quantities when geometric compatibility and detonation conditions are properly coordinated.

4.3 Comparison of results before and after optimization

In this part, the effectiveness of the orthogonal optimization is verified, and the penetration performance of the LEFP is investigated. Accordingly, comparative calculations of the

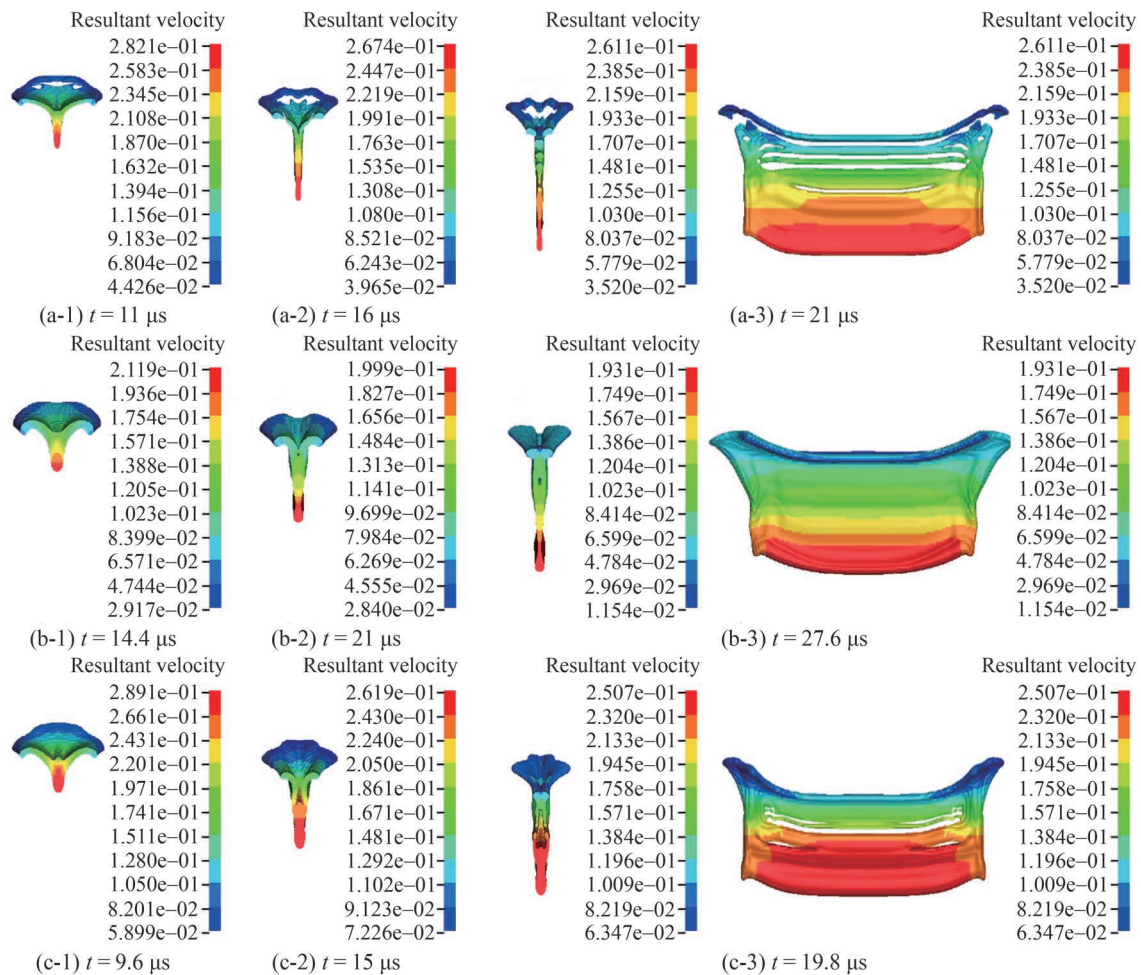


Figure 20 Velocity distribution of the penetrator when $D_s = 1/3h$, $D_s = 2/3h$, and $D_s = h$: (a-1) to (a-3) for case 7, (b-1) to (b-3) for case 8, and (c-1) to (c-3) for case 9

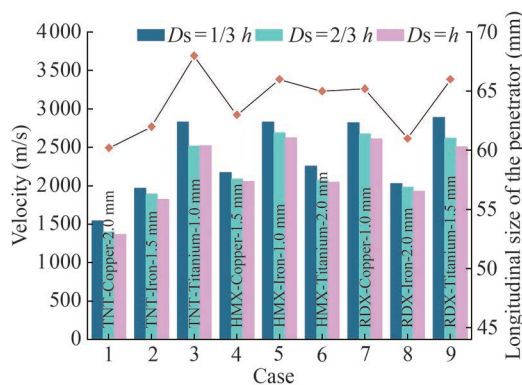


Figure 21 Evolution of the velocity and longitudinal dimension of the penetrator during the formation process

Table 10 Range analysis

Level	A	B	C
1	1903.7	2011.3	1781.0
2	2241.3	2125.7	2128.7
3	2349.7	2357.7	2585.0
range	446.0	346.4	804.0

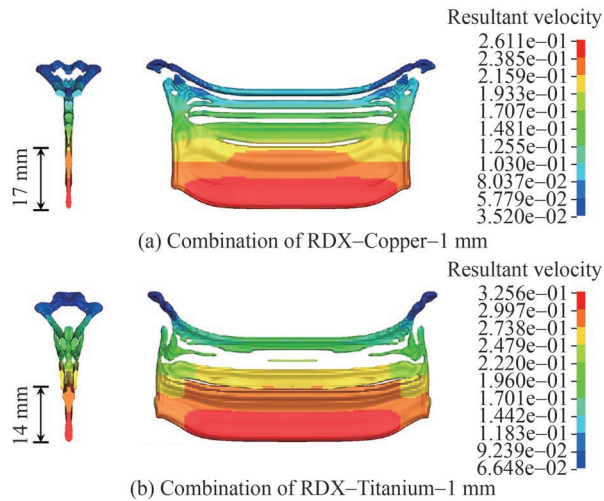
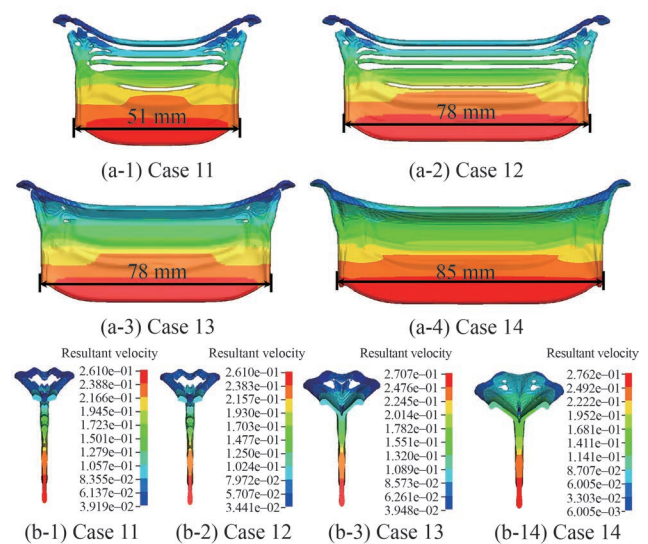
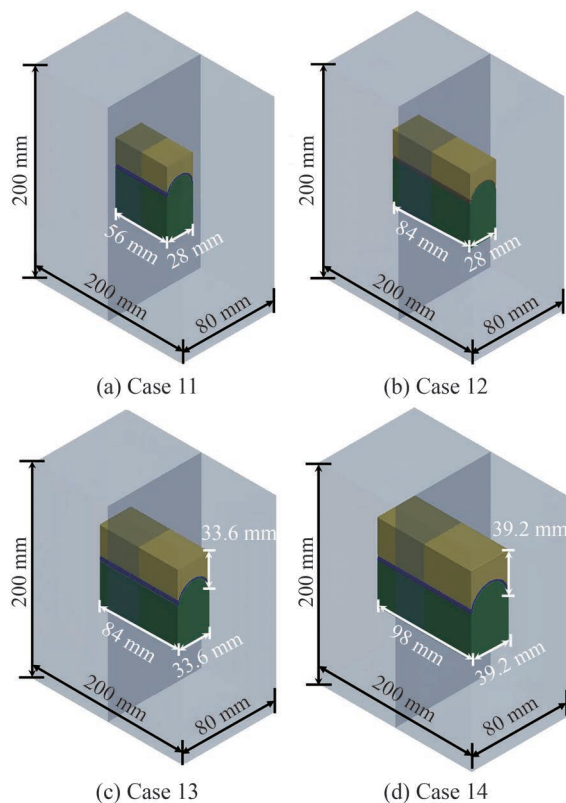
LEFP penetrating a Q235 plate with a thickness of 5 mm before and after optimization are conducted. The medium condition is similar to that in Section 4.2, and the standoff distance is set as 42 mm, which corresponds to 1.5 times the height of the LEFP. The size of the target plate is $320 \times 150 \times 5$ mm (length $\times$ width $\times$ height). The distribution and evolution of the penetrator velocity are depicted in Figures 25 and 26, respectively.

The penetration process of the LEFP before and after optimization is similar, as displayed in Figure 26. After the Q235 plate impacts the target, it is rapidly punctured, which forms a long penetration hole. This hole gradually becomes enlarged due to the coupling effect of the penetrator and detonation products.

For the penetrator before optimization, its velocity immediately drops off as soon as it contacts the target plate. The velocity decreases from 1800 to 959 m/s. Then, it slowly recovers to 1100 m/s at $32 \mu\text{s}$ because of the internal propulsion from the middle part of the penetrator. Next, the velocity gradually decreases to 858 m/s at $74 \mu\text{s}$ due to the resistance of water. As for the penetrator after optimization, its veloc-

Table 11 Variance analysis

SST	SSE	SSA	SSB	SSC	DF	DFA	DFB	DFC	MSE	MSA	MSB	MSC	FA	FB	FC
1487184.9	142.9	324670.9	186842.9	975528.2	8	2	2	2	71.5	162335.5	93421.5	487764.1	2270.4	1306.6	6821.9

**Figure 22** Formation effects of the penetrators**Figure 24** Formation effects in cases 11 to 14: (a-1) to (a-4) exhibit the longitudinal formation of the penetrators, while (b-1) to (b-4) display the vertical formation characteristics**Figure 23** Numerical model of the validation case for evaluating the applicability of the LEFP optimization results

ity first decreases from 2608 to 1065 m/s because of the impact. Then, it recovers to 1695 m/s, and finally decreases to 1081 m/s at 74 μ s.

The phenomenon of velocity fluctuation can be found in

Table 12 Formation characteristics of the penetrators in cases 7 and 11–14

Case	7	11	12	13	14
Charge mass (kg)	58.7	46.9	70.4	101.4	161.0
Penetrator velocity (m/s)	2611	2610	2610	2707	2762
Penetrator longitudinal size (mm)	64	51	78	78	85
Ratio of penetrator longitudinal size to charge length	0.914	0.911	0.929	0.929	0.867

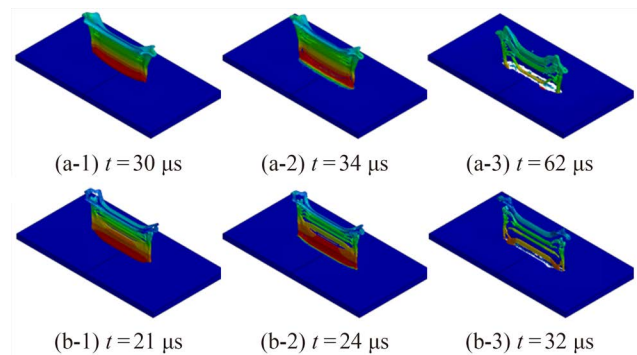
**Figure 25** Penetration performance of the penetrator: (a-1) to (a-3) for the LEFP before optimization and (b-1) to (b-3) for the LEFP after optimization

Figure 26, which is primarily due to the increase in head velocity caused by fragmentation and local shedding. After optimization, the peak velocity of the penetrator, the velocity before penetration, and the velocity after penetration

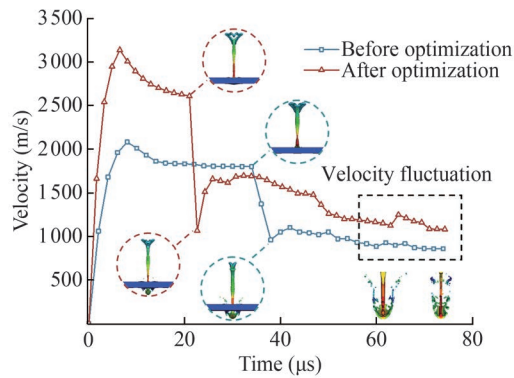


Figure 26 Evolution of the velocity of the penetrator during the formation process before and after orthogonal optimization

increase by 50.8%, 44.9%, and 26%, respectively.

The damage results are presented in Figure 27. The length and width of penetration before optimization are 63.8 and 13.0 mm, respectively. The size of the penetration hole after optimization reaches 70.4×12.2 mm. The optimization results in a 10.3% rise in the length of penetration and a 6.2% decline in its width, which enables accurate and efficient target cutting.

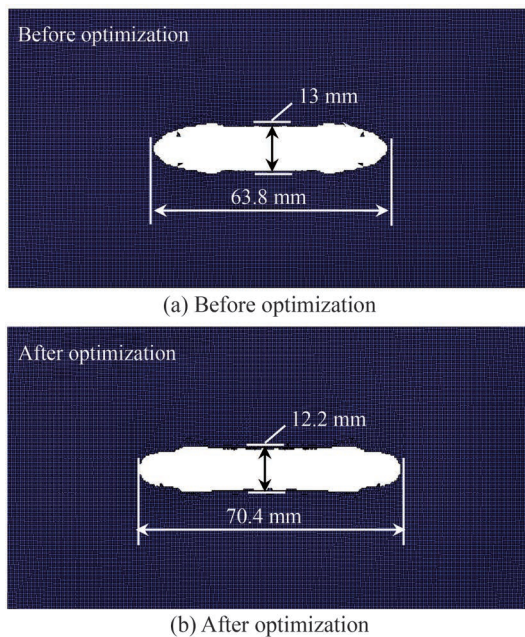


Figure 27 Penetration performance of the LEFP after optimization

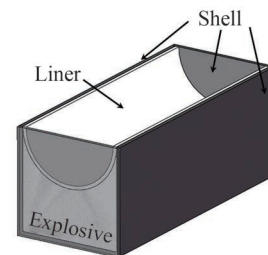
The orthogonal optimization performed in this study is based on three key parameters: explosive material, liner material, and liner thickness. The resulting configuration depicts the optimized LEFP design. However, in practical applications, LEFPs are equipped with a metallic shell in some cases. This shell provides physical confinement, which limits the radial expansion of explosive detonation products. It also leads to the concentration of more energy along the axial direction, which enhances the collapsing efficiency of the

liner. A comparative analysis is conducted between the optimized configurations with and without a casing to further determine the influence of the shell on LEFP formation. The shell is made of #45 steel, with a thickness similar to that of the liner (1 mm). The material model and parameters adopted for the shell are based on a previous study (Li et al., 2023).

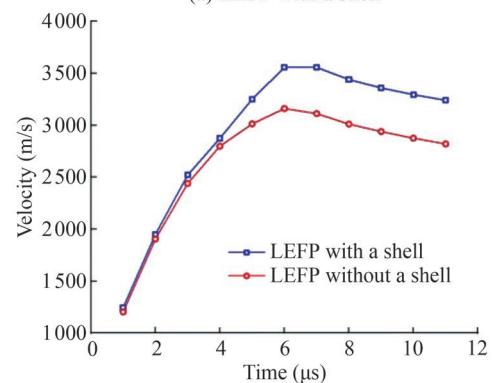
The geometric model is illustrated in Figure 28(a). The conclusions in Section 3 indicate that the initial formation characteristics of the penetrator are essential to the overall formation process and subsequent damage performance. Therefore, this study explores the formation behavior prior to 11 μ s. At this stage, the D_s for the uncased LEFP is $1/3 h$. The corresponding velocity profiles are depicted in Figure 28(b).

Table 13 Material parameters for #45 steel (Li et al., 2023)

$\rho_0/(\text{g}\cdot\text{cm}^{-3})$	E (GPa)	A_1 (GPa)	B_1 (GPa)	n	C_1	m	$\dot{\epsilon}_0/\text{s}^{-1}$
7.80	200	0.507	0.320	0.28	0.064	1.06	1
T_m (K)	T_r (K)	$D1$	$D2$	$D3$	$D4$	$D5$	a
1795	300	0.1	0.76	1.57	0.005	-0.84	0.46
$C/(\text{m}\cdot\text{s}^{-1})$	S_1	S_2	S_3	γ_0	E_0	V_0	
4569	1.49	0	0	1.69	0	1	



(a) LEFP with a shell



(b) Velocity evolution curves

Figure 28 Velocity evolution curves of LEFP penetrators with and without a shell

The head velocity trends of the two LEFP configurations are largely consistent. However, the LEFP with a shell shows a significantly higher velocity. At 11 μ s, its head velocity reaches 3241 m/s, which is 14.9% higher than that of the uncased LEFP. As presented in the formation process depicted

in Figure 29, the penetrator separates from the shell at around 6 μ s and then gradually forms independently. The resulting slug presents a relatively small lateral dimension, which suggests a more concentrated mass distribution and a more uniform penetrator morphology. At 11 μ s, the longitudinal length of the penetrator reaches 69 mm, which is 9.5% greater than that of the uncased LEFP. These results imply that the presence of a shell plays a positive role in improving the formation quality of the LEFP penetrator. This study provides useful insights for future explorations and experimental works on underwater applications of LEFPs.

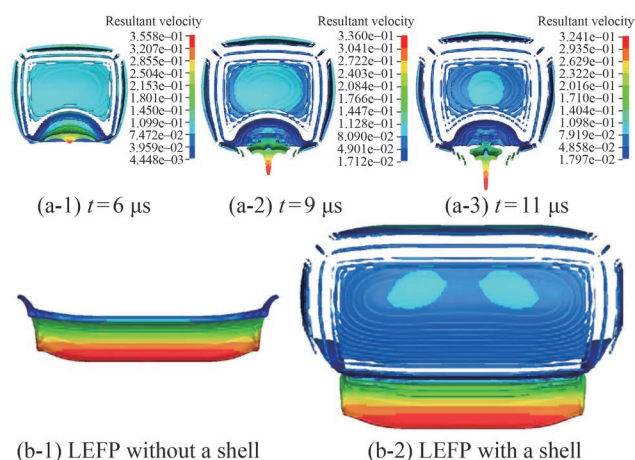


Figure 29 Formation process and characteristics of LEFPs with and without a shell

5 Conclusion

In this study, 3D ALE models are constructed to analyze the formation characteristics of LEFPs. An experiment on the damage of a Q235 plate subjected to a traditional LSC associated with near-field air explosion is conducted to validate the accuracy and efficacy of the ALE method. Then, the influence of the medium on the formation characteristics of the penetrator is investigated. Moreover, the orthogonal optimization method is used to enhance the formation effect of the LEFP. Finally, comparative calculations of the LEFP penetrating target plates are performed to confirm the effectiveness of the orthogonal optimization and determine the penetration performance of the LEFP. The main conclusions can be drawn as follows:

1) The errors in the length and width of penetration between the simulation results based on the ALE method and the experimental data are only 4.3% and -12.5%, respectively. The agreement between the results confirms the efficacy and accuracy of the ALE method employed in this study.

2) Water constrains the formation effect of the LEFP in vertical and longitudinal directions. The low velocity and stubby morphology reflect the inadequacy of the penetrator formation. The integration of an air cavity significantly

enhances the formation effect of the LEFP in water, which increases the velocity of the penetrator from 423.6 m/s to 966.6 m/s. It also improves its morphology.

3) Materials of the liner and the explosive, as well as the thickness of the liner, are chosen as the three dependent factors for orthogonal optimization. When comprehensively considering the morphology, velocity, and longitudinal dimension of the penetrator, the optimal factor combination is RDX-Copper-1 mm.

4) Comparative calculations of the LEFP penetrating a Q235 plate with a thickness of 5 mm before and after optimization are conducted. After optimization, the peak velocity of the penetrator, the velocity before penetration, the velocity after penetration, and the length of penetration increase by 50.8%, 44.9%, 26%, and 10.3%, respectively. Meanwhile, the width of penetration decreases by 6.2%, which realizes accurate and effective cutting of the target structures.

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