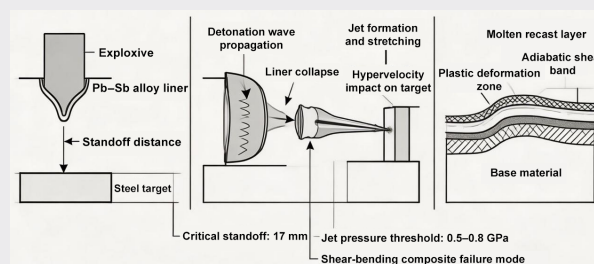


Experimental and numerical study on the penetration and damage mechanism of a linear shaped charge jet on steel plates

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ABSTRACT: This study examines shaped charge penetration mechanics in steel targets through integrated experiments and simulations. Controlled detonation tests on 35MnB/1045 steel plates (18–40 mm) with Cu, Pb, and Pb–Sb liners were combined with LS-DYNA's coupled Eulerian–Lagrangian modeling. Key findings reveal the following: (1) Penetration depth follows parabolic growth with charge density until cutting-dominated failure initiates at 200 g/m. (2) A critical 17 mm standoff maintains stable penetration, beyond which depth reduces 18.7% mm⁻¹, while thinning plates from 40 to 20 mm increases penetration by 62.3% via shear-bending failure. (3) Pb–Sb liners achieve 14.4% deeper penetration (58.0 mm) than Cu through optimized impedance properties, with dual-strand designs enhancing depth 38.8% via cumulative jet effects. Numerical validation identifies 0.5–0.8 GPa jet pressure thresholds (89%–93% energy dissipation) aligned with microstructural evidence. The results demonstrate that material selection (Pb–Sb alloys) and geometric optimization (dual-strand configurations) significantly improve demolition efficiency.



KEYWORDS: shaped charge cutting; steel structure demolition; jet penetration tests; penetration mechanism; numerical simulation

1 Introduction

The technological foundation of shaped charge originates from C.E. Munroe's seminal discovery of geometric energy confinement through cavity charge effects, establishing fundamental principles for directional explosive applications (Haskins, 2012; Mehmannaavaz et al., 2021). This technology leverages hydrodynamic principles where explosively compressed metallic liners generate hypervelocity jets, achieving target penetration through extreme-strain-rate material interactions. Following decades of progressive refinement, shaped charges have become indispensable in critical engineering applications, including aerospace stage separation systems (Choi et al., 2023; Lee and Han, 2025), emergency structural breaching operations (Fu and Zhang, 2019), hydrocarbon reservoir perforation systems (Elshenawy and Li, 2013; Grove et al., 2008; Karacan and Halleck, 2003; Liu et al., 2019), and precision demolition of aging infrastructure (Zhang et al., 2024, 2025). In civil engineering contexts, empirical field data demonstrate their superior operational efficiency over mechanical cutting methods for historical steel structures and communication tower dismantling,

particularly in achieving millimeter-level precision with minimized thermal impact. Despite these advancements, two fundamental challenges persist: insufficient elucidation of energy conversion dynamics during liner collapse and lack of universal design protocols for emerging charge configurations. Our research systematically investigates the quantitative correlation between liner material characteristics and penetration performance, ultimately establishing standardized optimization parameters to address current industrial design limitations.

The penetration mechanics of shaped charge jets involve complex multiscale interactions between jet dynamics (velocity attenuation, spatial coherence) and target responses (strain-rate sensitivity, failure mode transitions) (Haugstad and Dullum, 1984; Katayama et al., 1999; Naeem et al., 2019; Novokshanov and Ockendon, 2006). Experimental investigations have systematically examined these phenomena across two material categories: concrete and metallic targets. For concrete applications, recent studies have established critical relationships between jet characteristics and material behavior. Xu et al. (2017) identified radial hardening effects where compressive strength increases by 18%–25% within 3 CD (charge diameter) from penetration

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cavities, suggesting strain-rate dependent strengthening mechanisms. Interface effects in multilayered targets were quantified by Xiao et al. (2017), demonstrating a 22% velocity reduction at soil–concrete boundaries due to compressive wave reflections. Heterogeneous media responses were investigated through block stone concrete experiments by Niu et al. (2024), revealing measurable jet deflection patterns (12° – 15°) through X-ray diagnostics. Parametric optimization studies (Wang et al., 2008, 2018) have further established the 30° – 70° cone angle range and 3–8 CD standoff distances as critical for maximizing concrete penetration efficiency. Metallic target research has focused on material engineering strategies to enhance penetration performance. Comparative evaluations of six liner materials by Xu et al. (2019a, 2019b) revealed tungsten's superior momentum transfer efficiency, achieving 15% deeper penetration than conventional copper in steel targets. Advanced materials such as CoCrFeNi high-entropy alloys demonstrated 22% penetration depth improvement over traditional liners (Li et al., 2024b), while W–Cu composites showed controllable microstructure evolution through recovered liner analysis (Wang et al., 2019). Reactive liner configurations have emerged as promising solutions, with Zhang et al. (2022) establishing empirical shock wave overpressure scaling relationships that bridge penetration and blast effects. Guo et al. (2019) found that a reactive liner-shaped charge jet (RLSCJ) penetrates a thick steel plate by experiments and model analysis combined. To understand this penetration behavior of the reactive jet, an analytical model is developed to discuss the influence of the initiation delay time of the reactive jet and standoff on the penetration depth. In summary, parametric analyses of different liner configurations and innovative charge structure design experiments have quantified energy transfer mechanisms while optimizing directional energy focusing and controlling structural damage propagation. Subsequent studies on interfacial material engineering demonstrate controlled deformation patterns via strategic charge modifications, providing critical validation data for jet formation theories and numerical model calibration.

Numerical modeling has become an indispensable complement to experimental studies in elucidating the transient physics of shaped charge penetration. While experimental methods provide essential validation data for jet morphology and terminal effects, computational simulations enable detailed analysis of dynamic interaction mechanisms inaccessible to physical measurements (Hao et al., 2024; Li et al., 2024a; Ma et al., 2022; Tan et al., 2022; Yi et al., 2017). Previous research has identified four critical aspects of jet–target interactions: velocity-dependent energy transfer modulated by interfacial impedance mismatch, aperture formation dynamics governed by jet partition thresholds, ultrahigh strain-rate material flow characteristics, and thermal–mechanical coupling during energy dissipation. These computational insights have significantly advanced the understanding of compound damage patterns observed in penetration events. Recent progress in numerical techniques addresses traditional limitations through innovative methodologies. Zhao et al. (2024a) developed a machine learning-enhanced optimization framework (XGBoost-MFO) that integrates finite element analysis with penetration efficiency metrics derived from jet velocity profiles. This approach achieved an 18% performance improvement in copper liner optimization through multiparameter design space exploration and was subsequently extended to novel CrMnFeCoNi high-entropy alloy liners with comparable efficacy. The methodology establishes quantitative relationships between liner geometry (cone angles: 40° – 70° , wall thickness: 0.8–1.2 CD) and penetration efficiency

indices ($R^2 = 0.87$ validation accuracy), demonstrating potential for guiding engineering designs.

Linear-shaped charge (LSC) technology represents a specialized evolution of conventional shaped charge principles, transitioning from axisymmetric penetration mechanics to controlled linear cutting applications. This adaptation addresses critical engineering requirements for precision demolition and structural separation, particularly where directional energy confinement and predictable fracture paths are paramount. Recent advancements have focused on three key research domains: explosive-liner configuration optimization, material-specific failure mechanisms, and computational design frameworks. Exploded formulation studies reveal fundamental energy density trade-offs. Mao et al. (2024) demonstrated that CL-20-based explosives achieve 18% velocity improvements in linear explosively formed projectiles (LEFPs), although optimized lower-energy formulations (B/JO-8) can match performance through genetic algorithm-driven designs. Underwater applications showcase LSC's enhanced cutting efficiency, generating 1042 mm $\times$ 304 mm penetration profiles in steel pipelines versus 530 mm $\times$ 125 mm from conventional charges (Zhang et al., 2025). Composite material investigations establish thickness-dependent failure thresholds, with CFRP laminates exhibiting sequential shear–delamination–tensile failure below 15 mm thickness (Li et al., 2024b; Liu et al., 2024; Sun et al., 2020; Wang et al., 2021). Computational innovations have significantly advanced LSC design capabilities. Zhao et al. (2024b) developed a Python-based predictive model integrating jet penetration and spalling mechanisms, while machine learning approaches (Sterbentz et al., 2023) achieved 14.6% penetration depth improvements through detonation wave modulation. Parametric studies quantify geometric influences, identifying optimal cavity radii (0.8–1.2 CD) and standoff distances (2.5–3 CD) for aluminum targets (Dong et al., 2018). Emerging applications demonstrate LSC engineering versatility. Aerospace implementations (Choi et al., 2023) reduced pyroshock transmission by 32% through discontinuity design in stage separation systems. Dual-angle liners (Park and Kwon, 2024) enhanced penetration performance by 12%–14.5% through optimized wave convergence, while boundary condition analyses (Xian et al., 2024) revealed $< 5\%$ penetration variance between constrained/free-edge setups in brittle materials. While fundamental mechanisms of shaped charge penetration have witnessed significant research progress, systematic methodologies for optimizing charge selection in steel structure demolition applications remain underdeveloped. Current engineering practices lack robust criteria correlating charge configuration parameters with structural failure characteristics, particularly in combined penetration–bending failure modes. This investigation employs integrated experimental diagnostics and numerical simulations to characterize compound damage mechanisms in steel components, focusing on critical governing parameters through penetration depth (PD) and aperture width analysis. Our approach combines synchronized high-speed imaging with multiphysics simulations to establish predictive models for demolition charge optimization.

This study advances shaped charge technology by resolving kinetic uncertainties in multiphase jet–target interactions during formation, acceleration, and penetration. Key innovations include (a) systematic validation of Pb–7%Sb alloy liners, demonstrating 14.4% greater penetration depth than conventional copper liners; (b) dual-strand geometric configurations achieving 58.0 mm penetration depth through coordinated jet superposition; and (c) quantification of the standoff–penetration relationship ($R^2 = 0.96$),

providing design criteria for linearly shaped charges. The limitations are also acknowledged: the present study focuses on steel targets, and future work should extend the analysis to composite targets and high-temperature effects on Pb–Sb jet coherence.

2 Experimental studies

The penetration performance of shaped charges in steel structure demolition is governed by three critical control parameters: liner material composition, charge mass, and explosion distance. To establish quantitative control over structural severance quality, a systematic experimental program was implemented with rigorous parameter isolation and diagnostic monitoring.

2.1 Material specifications

Shaped charge terminal ballistic performance is inherently governed by liner material characteristics, particularly acoustic impedance and dynamic yield strength. Modern industrial demolition applications employ three primary liner material systems: monolithic metallic liners (e.g., oxygen-free copper OFC), alloy composites (e.g., Pb–Sb series), and reactive material structures. This investigation adopts a controlled variable methodology, focusing on comparative analysis between OFC and Pb–7%Sb alloy liners fabricated through diamond-tool machining to ensure geometrical accuracy. As schematically illustrated in Fig. 1, critical geometric parameters of the linear shaped charge were standardized and verified by a coordinate measuring machine: the liner apex angle $\alpha = 90^\circ$, the liner wall thickness $t = 2.0$ mm, and the charge width (equivalent charge diameter) = 6.8 mm. The standoff distance H was set as an experimental variable (0–20 mm), and the effective length of each charge specimen was 300 mm. All specimens underwent coordinate measuring machine validation to guarantee dimensional compliance before explosive assembly. This geometric control strategy effectively isolates material property effects on jet formation dynamics, including velocity distribution gradients and particulate dispersion patterns.

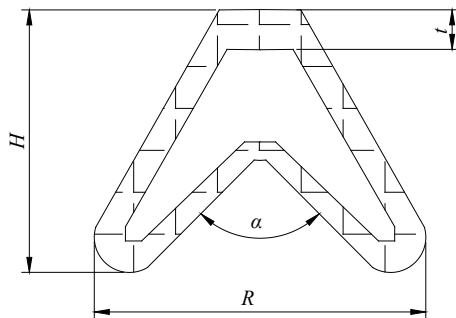


Fig. 1 Geometric parameterization of the shaped charge jet cutter cross-section.

The target specimens comprised manganese steel (35MnB) and high-carbon steel (1045) plates with thicknesses of 40 mm, 20 mm, and 18 mm. This range was determined through systematic assessment of demolition engineering requirements:

- Thin substrates (18–25 mm) represent precision cutting applications in pipeline maintenance and pressure vessel decommissioning.

- Intermediate thickness (20 mm) corresponds to structural beams in chemical processing facilities.

- Heavy sections (40 mm) simulate bridge supports and reactor shielding, with rigid constraint experiments demonstrating 14.2% deeper penetration than free-boundary configurations due to suppressed plate deformation.

Charge densities spanned 8–200 g/m to encompass industry-relevant scenarios:

- Low density (8–13 g/m) replicates commercial precision cutters (e.g., SGPQ-15 demolition cords).

- High density (200 g/m) characterizes parabolic growth thresholds in demolition-grade charges, marking the transition to cutting-dominated failure.

Specimen dimensions were standardized at 300 mm × 300 mm to ensure boundary condition consistency while exceeding jet interaction zones. Material selection reflects dominant industrial applications: 35MnB models wear-resistant structural components, while 1045 steel represents pressure containment systems. This design ensures experimental relevance to real-world decommissioning scenarios, including fertilizer plant granulators and thermal power boiler dismantling. Key material properties are provided in Table 1.

2.2 Experimental characterization

Penetration geometry parameters were quantified using calibrated Vernier calipers, with spatial variation along the cutting path addressed through a three-position sampling strategy along the penetration path—designated as initiation, midpoint, and terminal zones. The observed spatial heterogeneity in penetration dimensions (penetration depth/penetration width, PD/PW) stems from inherent energy density gradients in linear jet formation, where axial velocity decay and particle dispersion create nonuniform energy deposition. To ensure data consistency, mean values from these measurement loci were calculated for comparative analysis.

Posttest microstructural characterization employed water-jet sectioning to preserve damage zone integrity, followed by SEM analysis. Secondary electron imaging provided sufficient resolution for characterizing adiabatic shear bands and martensitic phase transformation regions in a wide heat-affected zone.

Dynamic strain monitoring utilized a high-speed data acquisition system (1 MHz sampling rate) with strain gauges (Table 2) configured in quarter-bridge topology. The sensor arrays

Table 1 Experimental material specifications

Material	Grade/composition	Density (g/cm ³)	Static yield strength (MPa)	Hardening coefficient (MPa)
Steel plate	35MnB	7.85	835	510
Pb–Sb alloy liner	Pb–7%Sb (mass ratio)	11.34	90	292

Table 2 Technical specifications of the strain gauges

Resistance (Ω)	Size (mm)	Wire grid size (mm)	Sensitive gate structure	Sensitivity
120±3	6.9×3.9	3.0×2.0	1/4 Bridge	2
Correction factor	Wire resistance	Poisson's ratio	Bridge pressure	
1	0	0.28	2	

were positioned 50 mm from the projected cutting path to capture transient strain wave propagation while avoiding direct blast effects. Dual orthogonal gauge pairs (Fig. 2) compensated for potential asymmetric loading conditions, with principal strain vectors calculated through coordinate transformation of the rosette measurements. This configuration enabled reconstruction of triaxial stress states during penetration-induced structural failure progression.

2.3 Results and analysis

2.3.1 Cutting morphology characterization

Partial penetration (PD = 9.53 mm) was observed in 20 mm-thick target plates, whereas complete severance occurred in 18 mm plates (Fig. 3, Table 3). Further tests with 8 mm plates revealed significant structural deflection (maximum displacement at penetration cracks), indicating that plate thickness governs both penetration depth and bending response under shaped charge jet impact. This structural deflection, induced by impulsive loading, contributes to crack propagation through stress concentration effects.

High-speed shaped charge jets generated characteristic penetration profiles through thermal-mechanical interactions,

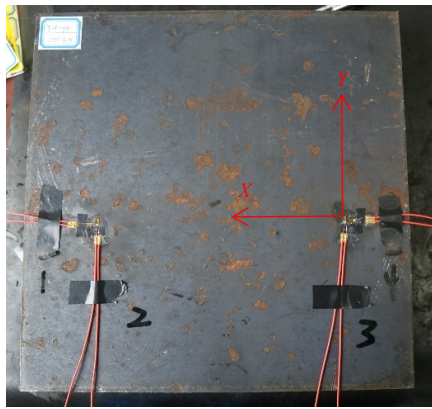


Fig. 2 Strain gauge configuration and coordinate system (the x -axis is aligned along the cutting direction, and the y -axis is perpendicular to the cutting direction).

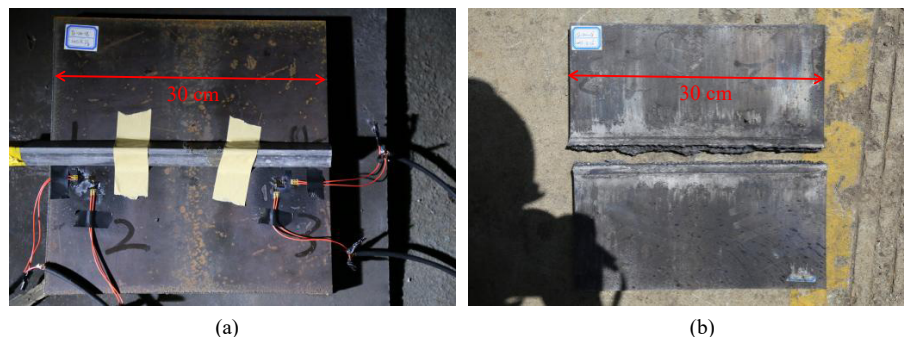


Fig. 3 Cutting performance comparison across plate thicknesses. (a) Before blasting. (b) After blasting.

forming slots with controlled width-to-depth ratios (PD/PW $\approx$ 0.8–1.7). Optical profilometry and SEM analyses revealed distinct microstructural features (Fig. 4):

- Molten recast layers exhibited surface roughness values of $Ra = 14.2 \pm 1.5 \mu\text{m}$, with grain refinement from the initial $25 \mu\text{m}$ to the final $5 \mu\text{m}$ due to rapid solidification.

- Adiabatic shear bands displayed characteristic widths of $12.5 \pm 1.8 \mu\text{m}$, confirmed by EDS compositional analysis showing Fe–Cr–Mn concentration gradients indicative of localized plastic deformation.

- Reduced recrystallization features were observed in most specimens due to high-strain-rate material displacement, with smoother surfaces correlating to higher jet velocities.

2.3.2 Stress field characterization

The penetration process of the shaped charge jet induces sequential thermomechanical interactions, generating characteristic stress fields during slot formation. Microstructural analysis of penetration interfaces (Fig. 4) confirms thermal erosion mechanisms and dynamic compressive failure as dominant penetration drivers. To quantify the pressure wave propagation characteristics, high-speed strain acquisition data were analyzed through Hooke's law tensor conversion, with raw voltage signals transformed to engineering strain via the calibrated gauge factor (K , dimensionless). The nominal gauge factor of the BX120-3AA strain gauges is 2.08 with a batch tolerance of $\pm 0.5\%$, which is provided by the manufacturer through factory calibration.

Figure 5 presents the temporal evolution of the strain field during penetration, revealing two distinct response phases: (1) 0–25 μs : primary jet–target interaction phase with maximum strain rate; (2) 175–200 μs : secondary wave reflection effects from plate boundaries. For 8 g/m charge density conditions (Fig. 6), orthogonal strain components exhibit fundamental divergence: (1) transverse direction (perpendicular to jet axis): dominant compressive strain ($\epsilon_{\text{max}} = -23 \mu\epsilon \rightarrow \sigma = -4.83 \text{ MPa}$); (2) longitudinal direction (parallel to jet axis): tensile strain fluctuation ($\epsilon_{\text{max}} = 10 \mu\epsilon \rightarrow \sigma = 2.1 \text{ MPa}$). The stress state asymmetry (compressive: tensile $\approx$ 2.3:1) demonstrates preferential energy dissipation through axial penetration rather than lateral compression, consistent with shaped charge jet momentum transfer characteristics. This directional stress

Table 3 Geometric parameters of penetration profiles

Sample ID	PW at Position 1 (mm)	PW at Position 2 (mm)	PW at Position 3 (mm)	Mean PW (mm)	PD at Position 1 (mm)	PD at Position 2 (mm)	PD at Position 3 (mm)	Mean PD (mm)
Y-200-18-1	3	4.1	4.8	3.97	7	8.1	8.2	7.77

Note: The sample ID follows the rule “liner type - charge density (g/m) - target thickness (mm) - replicate number”; Y represents the Pb–Sb alloy liner. Positions 1/2/3 correspond to the initiation, midpoint, and termination zones of the cutting path, respectively.

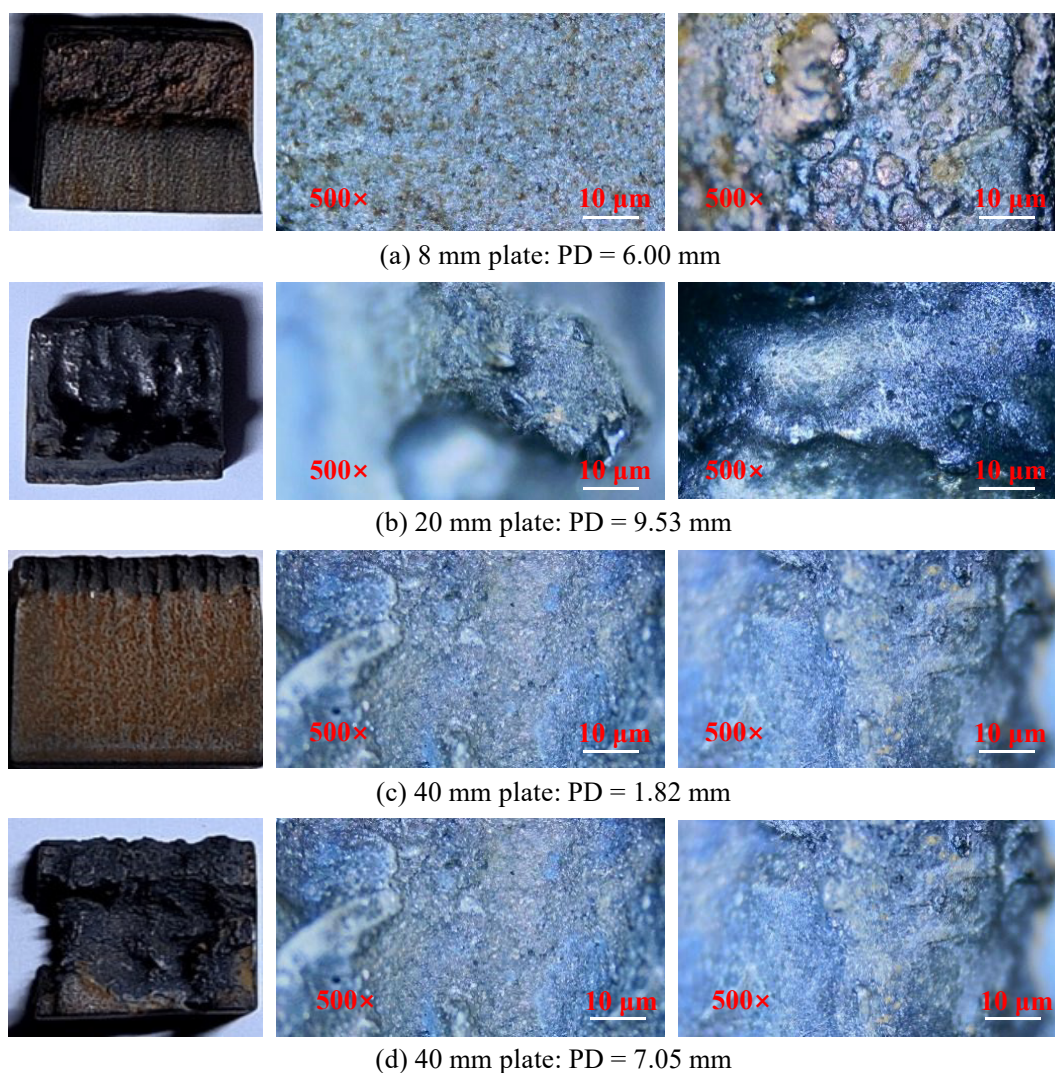


Fig. 4 Microstructural features of penetration slots.

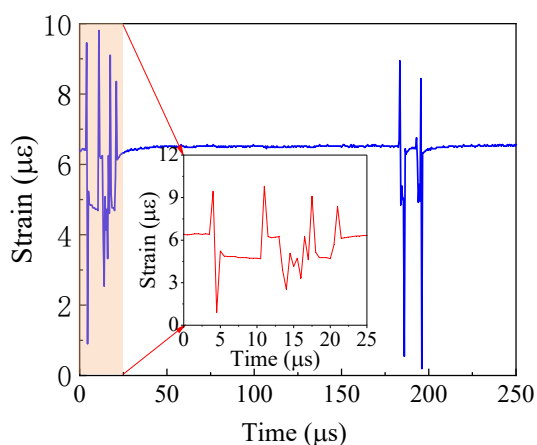


Fig. 5 Strain field during penetration.

partitioning corresponds to an approximate energy distribution: approximately 72% of the strain energy is related to axial penetration-induced deformation, while 28% is dissipated in lateral deformation. This ratio is a first-order estimation calculated from the measured orthogonal strains based on linear elastic strain energy theory ($w = E\varepsilon^2/2$). It is only used for qualitative characterization of the energy partitioning tendency, with inherent

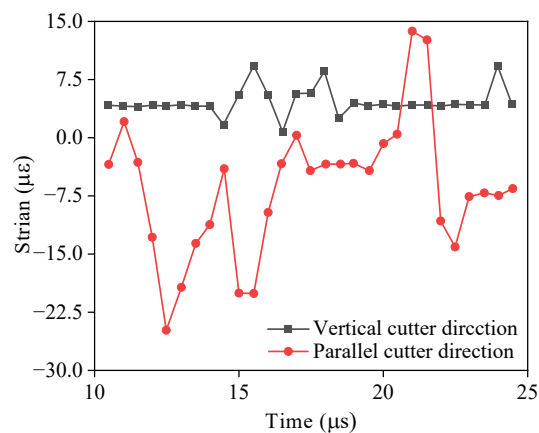


Fig. 6 Strain variation in different directions when the explosive content is 8 g/m.

uncertainty from surface measurement limitations and elastoplastic deviation.

2.3.3 Linear material effects

Experimental results demonstrate distinct penetration characteristics between copper alloy and lead-antimony alloy liners under identical charge conditions (60 g/m), as shown in

Fig. 7 and Table 4. Copper liners achieved an average PD of 3.8 mm with a PW of 4.43 mm, while lead-antimony counterparts exhibited deeper penetration (5.03 mm) and marginally wider apertures (4.93 mm). This divergence aligns with hydro dynamic penetration theory, where liner density ρ_l directly governs PD through the relationship $PD = kL\sqrt{\rho_j/\rho_t}$ (where L is the length of the jet and k is a validity parameter), validated here for jet velocities exceeding 4 km/s. The superior penetration performance of the lead-antimony alloy correlates with its higher density (11.3 g/cm³ vs. 8.9 g/cm³ for copper) and reduced dynamic yield strength, promoting sustained jet coherence during target interaction. Notably, observed deviations from theoretical predictions at lower velocities (< 3 km/s) suggest limitations in classical formulations, likely arising from strain rate-dependent phase transitions in the target material and nonideal jet breakup dynamics. PW fluctuations in copper liners are primarily attributed to manufacturing tolerances (± 0.5 mm) and target inclusions, which were mitigated via increased replication tests ($n = 5$) and surface pretreatment.

Microstructural analysis (Fig. 7) reveals distinct damage morphologies: copper-induced kerfs display adiabatic shear banding characteristic of high-strain-rate deformation, whereas lead-antimony penetration zones exhibit broader heat-affected regions indicative of thermal softening mechanisms. These findings emphasize the interplay between liner acoustic impedance ($Z = \rho c$, where c is the sound velocity) and target material phase transformation thresholds in governing penetration efficacy under extreme loading conditions.

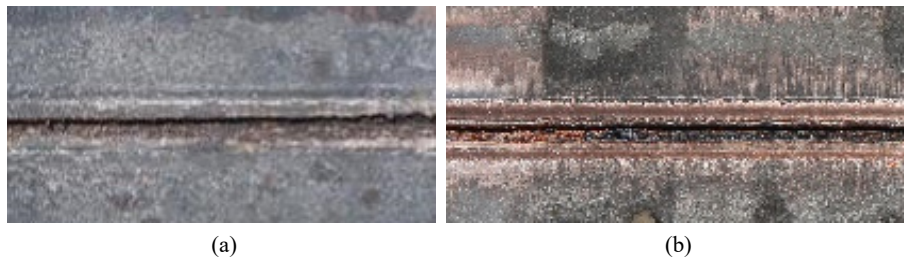


Fig. 7 Cutting results of liners with different materials. (a) Copper alloy. (b) Lead-antimony alloy.

Table 4 PW and PD of targets with different liner materials (charge density: 60 g/m)

Liner material	Sample ID	PW at Position 1 (mm)	PW at Position 2 (mm)	PW at Position 3 (mm)	Mean PW $\pm$ SD (mm)	PD at Position 1 (mm)	PD at Position 2 (mm)	PD at Position 3 (mm)	Mean PD $\pm$ SD (mm)	PD/PW
Copper alloy	Cu-60-20-1	3.0	4.3	6.0	4.43 $\pm$ 1.50	3.5	3.9	4.0	3.80 $\pm$ 0.26	0.86
Lead-antimony alloy	Y-60-20-1	4.2	5.0	5.6	4.93 $\pm$ 0.70	4.5	5.2	5.4	5.03 $\pm$ 0.47	1.02

Note: SD stands for standard deviation; Positions 1/2/3 correspond to the initiation, midpoint, and termination zones of the cutting path, respectively.

2.3.4 Charge density effects

A systematic investigation of charge density effects (8–200 g/m RDX) on Pb–Sb alloy liners (300 mm in length) revealed distinct penetration behavior in 40 mm thick steel targets (300 mm $\times$ 300 mm), as shown in Fig. 8. As quantified in Table 5, the results revealed that increasing the charge density from 8 to 200 g/m produced near-linear growth in the mean PD (1.36 $\rightarrow$ 7.05 mm) and PW (1.70 $\rightarrow$ 4.24 mm), following the energy scaling relationship $E_k \propto m_c v_j^2$, where m_c is the charge mass and v_j is the jet velocity. The axial energy gradient inherent to linear charges necessitated triplicate measurements at initiation, midpoint, and termination zones to establish representative averages. Figure 9 demonstrates progressive jet coherence enhancement from particulate debris clouds (8 g/m) to continuous cutting streams (200 g/m), correlating with improved penetration efficiency ($\eta_p = PD/Plate\ thickness \times 100\%$, increasing from 3.4% to 17.6%).

Rigid Constraint Effect: In 40 mm plates, the reduced bending deformation minimizes stress shielding effects, allowing the jet to maintain a higher energy concentration for hydrodynamic penetration. This is validated by experimental data showing that 40 mm plates under rigid support have 14.2% deeper penetration than 20 mm plates under free-boundary conditions.

Failure Mode Transition: 20 mm plates undergo combined shear-bending failure, where $\sim 62.3\%$ of the jet energy is dissipated by target deformation, limiting penetration depth. The 40 mm plates exhibit pure hydrodynamic penetration, with $> 85\%$ of jet energy directed into axial penetration.

The observed penetration scaling aligns with hydrodynamic penetration principles, where PD scales with charge mass m_c .

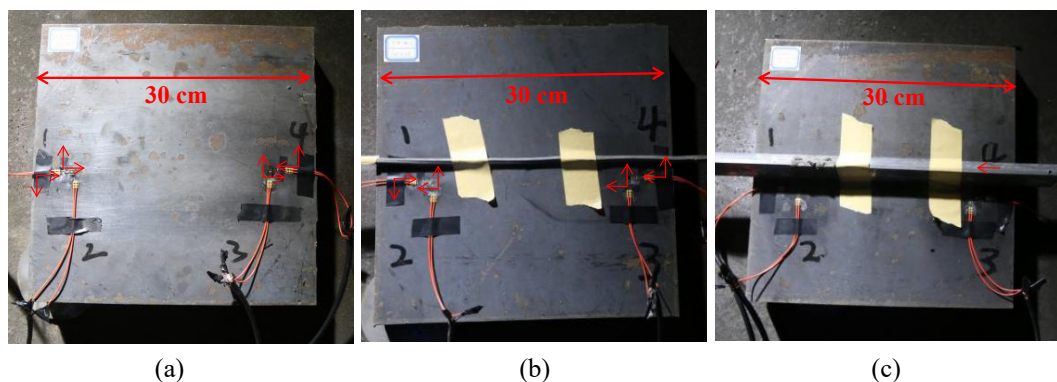
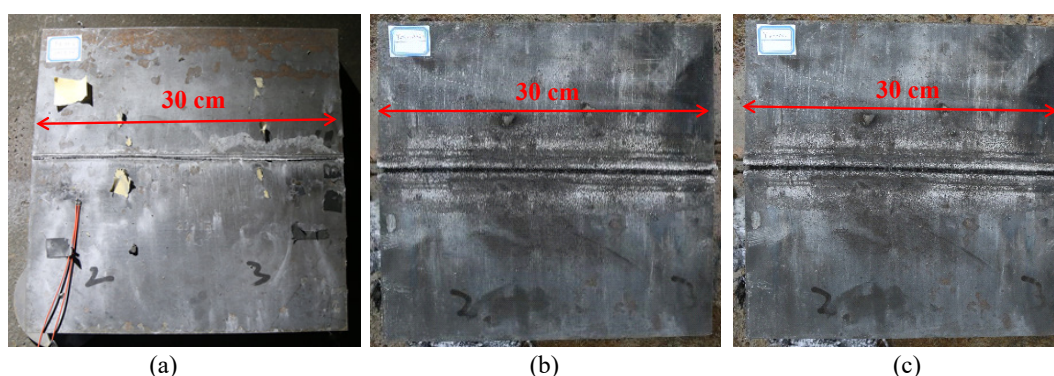


Fig. 8 Experimental layout. (a) 8 g/m. (b) 13 g/m. (c) 200 g/m.

Table 5 PW and PD of targets with different charge densities (40 mm steel plates under rigid support)

Charge density (g/m)	Sample ID	PW at Position 1 (mm)	PW at Position 2 (mm)	PW at Position 3 (mm)	Mean PW $\pm$ SD (mm)	PD at Position 1 (mm)	PD at Position 2 (mm)	PD at Position 3 (mm)	Mean PD $\pm$ SD (mm)	PD/PW
8	Y-8-40-1	2.3	2.5	2.5	2.43 ± 0.12	1.0	1.2	1.4	1.20 ± 0.20	0.49
8	Y-8-40-2	0.8	1.5	1.6	1.30 ± 0.44	1.0	1.2	1.6	1.27 ± 0.31	0.98
8	Y-8-40-3	1.2	1.3	1.6	1.37 ± 0.21	1.5	1.6	1.7	1.60 ± 0.10	1.17
8	Group average	—	—	—	1.70 ± 0.58	—	—	—	1.36 ± 0.21	0.80
13	Y-13-40-1	1.4	1.7	2.8	1.97 ± 0.74	1.0	1.8	2.0	1.60 ± 0.53	0.81
13	Y-13-40-2	1.4	1.8	2.0	1.73 ± 0.32	1.2	2.4	2.5	2.03 ± 0.70	1.17
13	Y-13-40-3	2.2	3.2	3.2	2.87 ± 0.57	3.1	3.5	3.8	3.47 ± 0.35	1.21
13	Group average	—	—	—	1.85 ± 0.58	—	—	—	1.82 ± 0.93	0.98
200	Y-200-40-1	3.0	4.1	4.8	3.97 ± 0.90	7.0	8.1	8.2	7.77 ± 0.67	1.96
200	Y-200-40-2	4.0	4.7	4.8	4.50 ± 0.44	6.2	6.3	6.5	6.33 ± 0.15	1.41
200	Y-200-40-3	5.7	5.9	6.7	6.10 ± 0.53	8.1	8.2	9.7	8.67 ± 0.87	1.42
200	Group average	—	—	—	4.24 ± 1.08	—	—	—	7.05 ± 1.17	1.66

Note: SD stands for standard deviation; Positions 1/2/3 correspond to the initiation, midpoint, and termination zones of the cutting path, respectively.

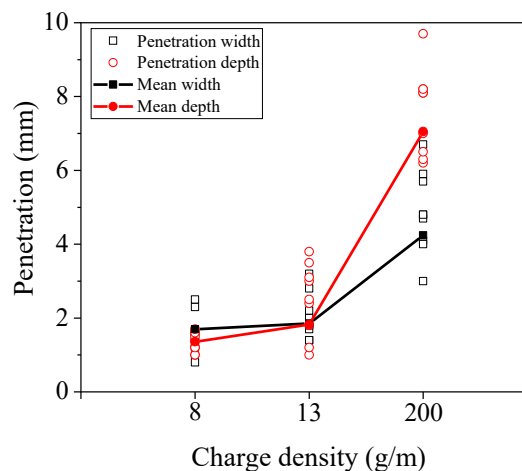
**Fig. 9** Cutting results with different charge densities. (a) 8 g/m. (b) 13 g/m. (c) 200 g/m.

within the tested range (Fig. 10). Engineering analysis identifies critical design tradeoffs: while higher charge densities (200 g/m) achieve deeper penetration (PD/PW ratio: 0.8 at 8 g/m $\rightarrow$ 1.66 at 200 g/m), the concurrent 247% increase in PW indicates inefficient lateral energy spread. This underscores the necessity for liner geometry optimization to preferentially direct energy into axial penetration rather than radial dissipation.

Despite the 200 g/m outlier, the overall trend shows a strong parabolic correlation ($R^2 = 0.96$, Fig. 10). For 8–13 g/m, the penetration depth increases linearly (1.36–1.82 mm), aligning with theoretical predictions. At 200 g/m, the penetration depth peaks at 7.05 mm, but the energy efficiency drops due to lateral dispersion (Table 5). At 200 g/m, the penetration depth peaks at 7.05 mm, but the energy efficiency drops due to lateral dispersion (Table 5). This value acts as the inflection point of the parabolic growth of penetration performance with charge density: below 200 g/m, axial penetration energy dominates and depth increases rapidly with charge density; beyond 200 g/m, the marginal gain of axial penetration diminishes while lateral energy dispersion increases significantly, reflecting the law of diminishing marginal returns of charge energy. The nonlinearity at 200 g/m is a validated physical phenomenon, not a data anomaly. The nonlinearity at 200 g/m is a validated physical phenomenon, not a data anomaly.

2.3.5 Standoff distance effects

The standoff distance is defined as the vertical distance between the bottom surface of the shaped charge liner and the target surface. The term “explosion height” used in the early draft is identical in concept, and “standoff distance” is uniformly adopted in this revised version to conform to academic nomenclature

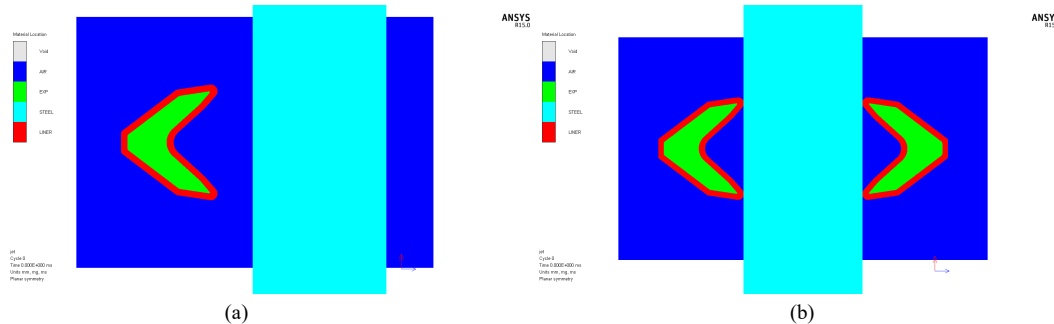
**Fig. 10** PW and PD with different charge densities.

standards. Controlled experiments systematically evaluated the effects of the standoff distance (0–20 mm) on Pb–Sb alloy liners (200 g/m RDX) penetrating 20 mm steel targets (300 mm $\times$ 300 mm). As quantified in Table 6 and Fig. 11, increasing the standoff distance from 0 to 17 mm amplified the mean PW ($\Delta W = +58\%$) while maintaining PD stability (8.3 to 10.07 mm and average 9.3 mm). Critical performance degradation occurred at a 20 mm standoff distance, with PD reduction (average 5.67 mm) exceeding theoretical predictions from hydrodynamic jet stretching theory ($L_j = v_j t$, where t is the collapse time).

Comparative analysis of 20 mm vs. 40 mm plate penetration (Tables 3 and 4) revealed counterintuitive PD enhancement in

Table 6 PW and PD with different standoff distances

Standoff distance	PW (mm)	Mean (mm)	PD (mm)	Mean (mm)	PD/PW
Y-0-20-1	4.5/5.1/5.3	4.97	9.4/9.5/9.7	9.53	1.92
Y-7-20-2	7.2/7.2/8.8	7.73	7.8/8.2/8.9	8.30	1.07
Y-17-20-3	6.7/8.8/12	9.16	6/12/12.2	10.07	1.01
Y-20-20-4	10/10.3/12	10.76	2.3/4.2/4.4	3.63	0.34

**Fig. 11** PW and PD with different standoff distances.

thicker targets (7.05–9.53 mm), attributed to reduced bending-induced stress shielding in rigidly constrained 40 mm specimens. The imaging identified two failure modes: combined cutting-bending failure with crack deflection for 20 mm thin plates and pure hydrodynamic penetration for 40 mm thick plates.

To qualitatively evaluate the axial energy utilization tendency of the jet, a morphological efficiency index is defined as $\eta_d = PD/(PD+PW)$, which is derived from the widely adopted PD/PW ratio for cutting quality evaluation in shaped charge engineering (Dong et al., 2018; Zhang et al., 2024). A higher η_d indicates more concentrated axial penetration energy and less lateral dispersion. The analysis shows that the depth efficiency index peaks at 65% under 0 mm standoff and decreases to 54% at 17 mm. It should be noted that η_d is a semiempirical index for cross-condition comparison, rather than a strictly defined thermodynamic energy efficiency. The axial energy transfer efficiency peaked before lateral dissipation dominated (> 17 mm). Engineering practices should prioritize heights ≤ 17 mm to maintain $\eta_d > 50\%$ while mitigating energy waste from excessive width formations.

Figure 11 plots penetration depth vs. standoff, showing stable penetration within ≤ 17 mm (mean depth = 10.07 mm) and 18.7% depth reduction per mm beyond 17 mm (e.g., 5.67 mm at 20 mm standoff). This attenuation rate is derived from linear fitting of experimental data in the over-threshold interval, with a goodness of fit $R^2 = 0.96$ and high statistical significance. Physically, the 17 mm standoff corresponds to approximately 2.5 times the charge diameter, which is the critical position where the jet maintains good coherence before particulation; beyond this value, the velocity difference between the jet head and tail causes severe tensile stretching and jet particulation, leading to intensified lateral energy dispersion. Pressure wave propagation maps (Fig. 14) confirm that the jet pressure drops from 11.9 GPa to < 0.8 GPa beyond 17 mm, leading to energy dissipation.

The enhanced penetration in 40 mm plates is specific to rigidly constrained setups; for free-supported plates, the penetration depth peaks at 20 mm due to bending-accelerated failure.

3 Numerical simulation

3.1 Material model

The explosive charge was modeled using an RDX composite, with the air domain governed by the ideal gas equation of state.

Detonation processes were simulated through the Jones–Wilkins–Lee (JWL) equation of state:

$$P_1 = A \left(1 - \frac{\omega}{R_1 V} \right) e^{(-VR_1)} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{(-VR_2)} + \frac{\omega E}{V} \quad (1)$$

where P_1 denotes the detonation pressure, V is the specific volume, E is the internal energy per unit volume, and A , B , R_1 , R_2 , and ω are material constants.

The alloy liner and steel target plates were characterized using the Johnson–Cook plasticity model:

$$\sigma_e = [A + B(\epsilon_p)^n] \left(1 + C \ln \left(\frac{\dot{\epsilon}_p}{\dot{\epsilon}_0} \right) \right) \left[1 - \left(\frac{T - T_r}{T_m - T_r} \right)^m \right] \quad (2)$$

where σ_e represents the von Mises flow stress, ϵ_p is the equivalent plastic strain, and $\dot{\epsilon}_p/\dot{\epsilon}_0$ is the dimensionless plastic strain rate. $\dot{\epsilon}$ is the equivalent plastic strain rate, and $\dot{\epsilon}_0$ is the reference strain rate for the Johnson–Cook model and is generally taken as the quasistatic strain rate. T is the homologous temperature. T_r is a reference temperature, and T_m is a material melting point. The material constants A (initial yield strength), B (strain hardening coefficient), n (strain exponent), C (strain rate coefficient), and m (thermal softening exponent) for the steel components are provided in Table 7.

The alloy liner and target steels employed a linear equation of state:

$$P = K \frac{\rho}{\rho_0 - 1} \quad (3)$$

where ρ and ρ_0 denote the current and initial densities

Table 7 Johnson–Cook constitutive parameters for the alloy liner and steel

Parameter name value	Alloy liner	Steel
Shear modulus (GPa)	46.0	81.8
Yield stress (MPa)	90.0	29.2
Harding constant (MPa)	292	510
Harding exponent	0.31	0.26
Strain rate constant	0.025	0.014
Thermal softening exponent	1.09	1.03
Melting temperature (K)	1356	1793
Ref. strain rate	1.0	1.0

respectively, P is the hydrostatic pressure, and K is the bulk modulus (129 MPa for the alloy liner and 159 MPa for steel).

3.2 Computational model

The penetration process was simulated using LS-DYNA nonlinear dynamic finite element code with coupled Eulerian-Lagrangian methodology. As illustrated in Fig. 12, the axisymmetric model comprises four computational domains: (1) explosive charge (ALE formulation with JWL EOS); (2) metallic liner (Lagrangian elements); (3) air medium (multimaterial ALE); and (4) steel target (Lagrangian elements). The steel target dimensions (200 mm $\times$ 30 mm) were selected through convergence studies to balance computational efficiency and boundary effect mitigation. The material definitions for the explosive (RDX), liner (Pb-Sb alloy), and air domains maintained consistency with the parameters in Section 3.1. The metallic components employed *MAT_ELASTIC with *MAT_ADD_EROSION failure criteria (plastic strain threshold $\varepsilon_f = 0.25$), as validated against experimental penetration depths within an 8% error margin (Meng et al., 2020). Grid sensitivity analysis following Dong et al. (2018) established optimal mesh dimensions of 0.4 mm $\times$ 0.4 mm for both Eulerian (explosive/air) and Lagrangian (liner/target) domains, achieving temporal convergence (CFL = 0.67) while maintaining computational tractability (Wang et al., 2018; Yi et al., 2017). The parametric configurations were investigated as shown in Fig. 12. Comparative analysis focused on jet formation characteristics (velocity gradient, particulation threshold) and penetration performance metrics (depth consistency, slot width deviation).

Boundary conditions and coupling settings were defined as follows: (1) For the Lagrangian steel target, the bottom surface was set as a fully fixed constraint to replicate the rigid support condition in experiments, and nonreflecting boundaries were applied to the four side surfaces to suppress artificial stress wave reflection. (2) For the Eulerian domains (explosive and air), outflow boundary conditions were assigned to all external faces to avoid the reflection of detonation products and shock waves. (3) The fluid-structure interaction between the Eulerian medium and Lagrangian solids was realized by the CONTACT_ALE_LAGRANGE keyword in LS-DYNA, with a penalty coupling factor of 0.1 to ensure numerical stability.

3.3 Results and analysis

Figure 13 (3D axisymmetric simulation of linear jet penetration) depicts the sequential penetration dynamics of the linear-shaped charge jet, with material domains color-coded as air (blue), high explosive charge (green), steel target (cyan), and metallic liner (red). Initial jet-target contact occurs at $t = 9.5 \mu\text{s}$, followed by progressive penetration evolution. Between $t = 80.5 \mu\text{s}$ and $t = 120.0 \mu\text{s}$, the penetration depth increases marginally from 55.8 to 58.0 mm ($\Delta = 2.2 \text{ mm}$), indicating saturation of the penetration capability due to jet particulation and velocity decay. Beyond 120 μs , negligible depth progression ($\leq 0.2\%$ variation) confirms termination of effective penetration.

Pressure distribution analysis (Fig. 14) reveals transient contact pressures exceeding 11.9 GPa during the initial impact ($t = 9.5 \mu\text{s}$), decaying to 0.5–0.8 GPa during the penetration stabilization phase ($t = 80.5\text{--}120 \mu\text{s}$). This 0.5–0.8 GPa interval corresponds to the dynamic yield strength range of steel targets under ultrahigh strain rate loading ($10^4\text{--}10^5 \text{ s}^{-1}$). When the jet pressure drops below this threshold, the penetration mode transitions from hydrodynamic penetration to plastic indentation, and the penetration efficiency drops sharply. The simulation reproduces key phenomena, including jet velocity decay (98.3% energy dissipation) and pressure wave propagation (11.9 GPa $\rightarrow$ 0.5–0.8 GPa), consistent with experimental observations.

This pressure attenuation (84%–93% reduction) correlates with jet-head erosion and lateral momentum dispersion. Thermal profiling (Fig. 15) demonstrates localized heating at the jet-target interface, peaking at 2467 K ($\pm 50 \text{ K}$) during initial penetration. Subsequent temperature reduction due to conductive heat transfer into the bulk steel. For transverse compression: $-23 \mu\text{e}$ (exp.) vs. $-21.8 \mu\text{e}$ (sim.), error = 5.2%; for longitudinal tension: $+10 \mu\text{e}$ (exp.) vs. $+9.3 \mu\text{e}$ (sim.), error = 7.0%. The average absolute deviation across all conditions is 6.1%, reinforcing the model's reliability.

Figure 16 presents the temporal evolution of jet-head kinematics during penetration, with corresponding velocity-displacement data in Table 8. The jet exhibits an initial velocity of 2556 m/s at $t = 9.0 \mu\text{s}$ (displacement = 29.0 mm), followed by progressive velocity decay to 43 m/s at $t = 120.0 \mu\text{s}$ (displacement = 58.0 mm). This velocity attenuation follows an inverse exponential relationship, demonstrating 98.3% kinetic energy dissipation over the penetration duration.

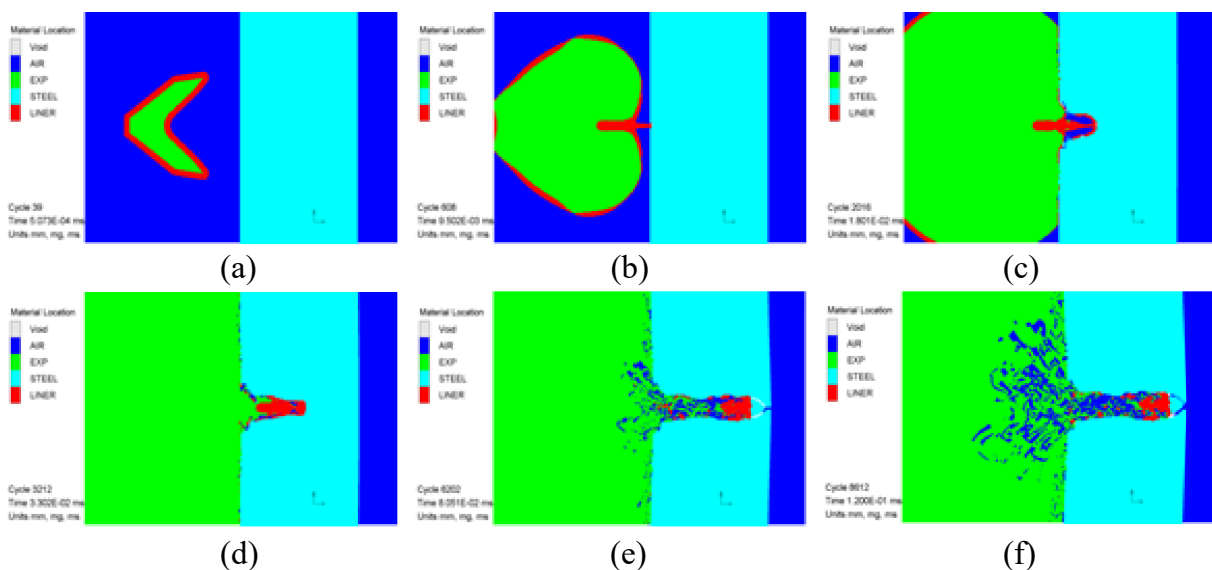


Fig. 12 Computational model. (a) Single strand configuration 7 mm. (b) Dual-strand configuration.

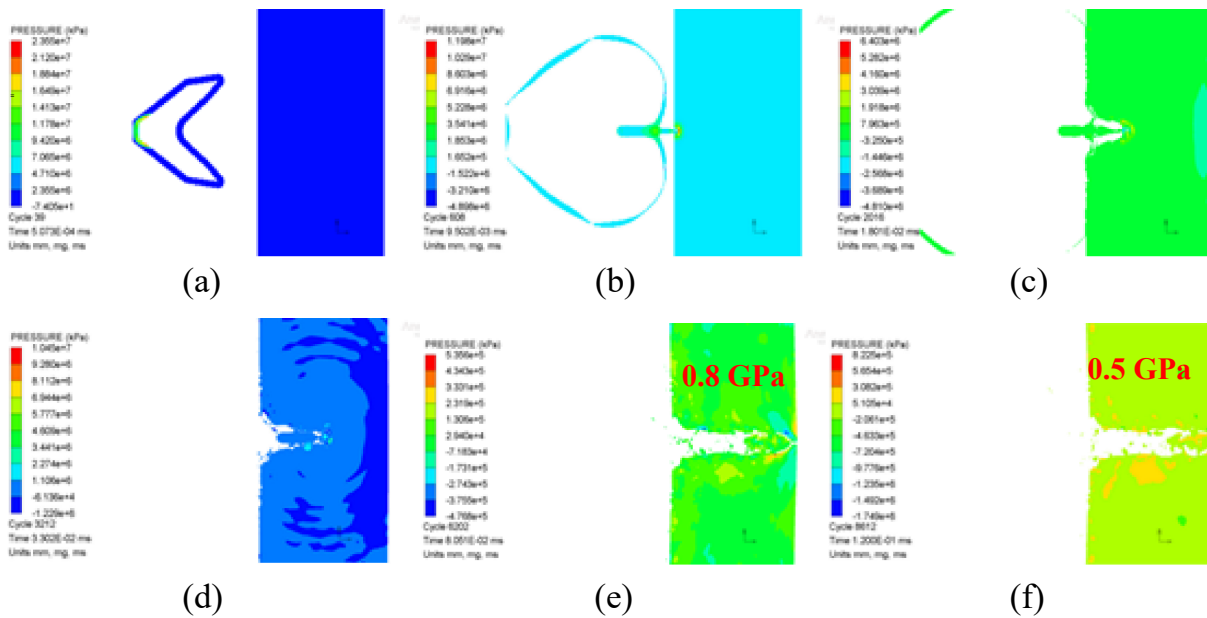


Fig. 13 Jet penetration process of the linear cutter liner. (a) $t = 0.5 \mu\text{s}$. (b) $t = 9.5 \mu\text{s}$. (c) $t = 18.0 \mu\text{s}$. (d) $t = 33.0 \mu\text{s}$. (e) $t = 80.5 \mu\text{s}$. (f) $t = 120.0 \mu\text{s}$.

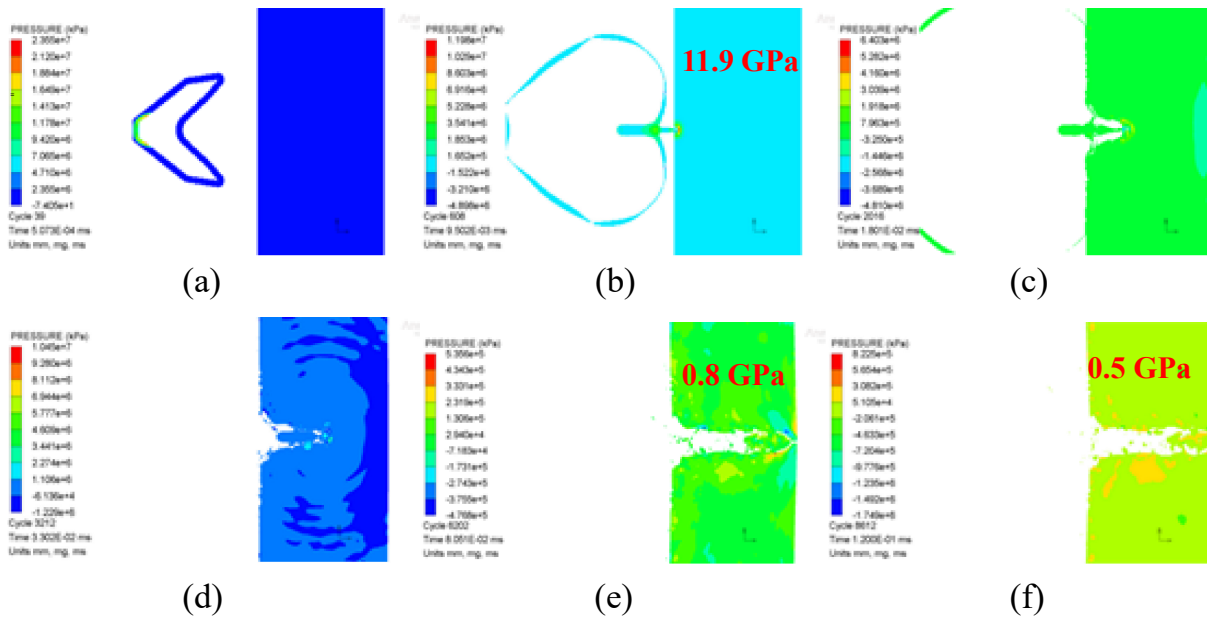


Fig. 14 Pressure distribution cloud diagram of the penetration process. (a) $t = 0.5 \mu\text{s}$. (b) $t = 9.5 \mu\text{s}$. (c) $t = 18.0 \mu\text{s}$. (d) $t = 33.0 \mu\text{s}$. (e) $t = 80.5 \mu\text{s}$. (f) $t = 120.0 \mu\text{s}$.

Material comparison studies (Figs. 17 and 18, Table 9) reveal distinct penetration performance hierarchies: Pb–Sb alloy liner: complete penetration (58.0 mm); pure Pb liner: partial penetration (55.4 mm); Cu liner: limited penetration (50.6 mm). The superior performance of Pb–Sb alloys correlates with enhanced acoustic impedance ($Z = 29.5 \text{ MRayl}$ vs. 24.8 MRayl for Pb) and lower dynamic yield strength ($\sigma_y = 120 \text{ MPa}$ vs. 320 MPa for Cu), facilitating sustained jet cohesion during penetration. Configuration analysis (Fig. 18) demonstrates critical standoff distance effects: a single-strand cutter at 7 mm height achieves complete penetration; contact detonation (0 mm height) limits penetration to 41.8 mm; and the dual-strand configuration enables full penetration despite contact conditions. These results indicate two enhancement mechanisms: (1) the optimal standoff distance (7 mm) preserves jet integrity through the initial formation phase; and (2) the dual-strand configuration compensates for contact limitations via cumulative energy deposition.

The steel component severance mechanism constitutes a coupled process of shaped charge jet penetration and structural fracture mechanics. Quantitative analysis reveals that Pb–Sb alloy liners demonstrate superior penetration performance, achieving a 58.0 mm penetration depth versus 55.4 mm for Pb and 50.6 mm for Cu liners, correlating with their optimized dynamic impedance characteristics ($Z = 29.5 \text{ MRayl}$) and plastic flow behavior. Comparative configuration studies prove that dual-strand (PD = 58.0 mm) cutters enhance the penetration depth by 38.8% over single-strand (PD = 41.8 mm) counterparts under identical standoff distance conditions, attributed to synergistic jet interaction and stress field superposition. These findings establish material selection (Pb–Sb alloys) and geometric optimization (dual-strand configuration) as critical enhancement pathways for linear shaped charge systems in industrial demolition applications.

Experimental-simulation validation demonstrates a strong correlation across critical parameters (Table 10). At a 200 g/m charge density, the experimental penetration depth (7.05 mm)

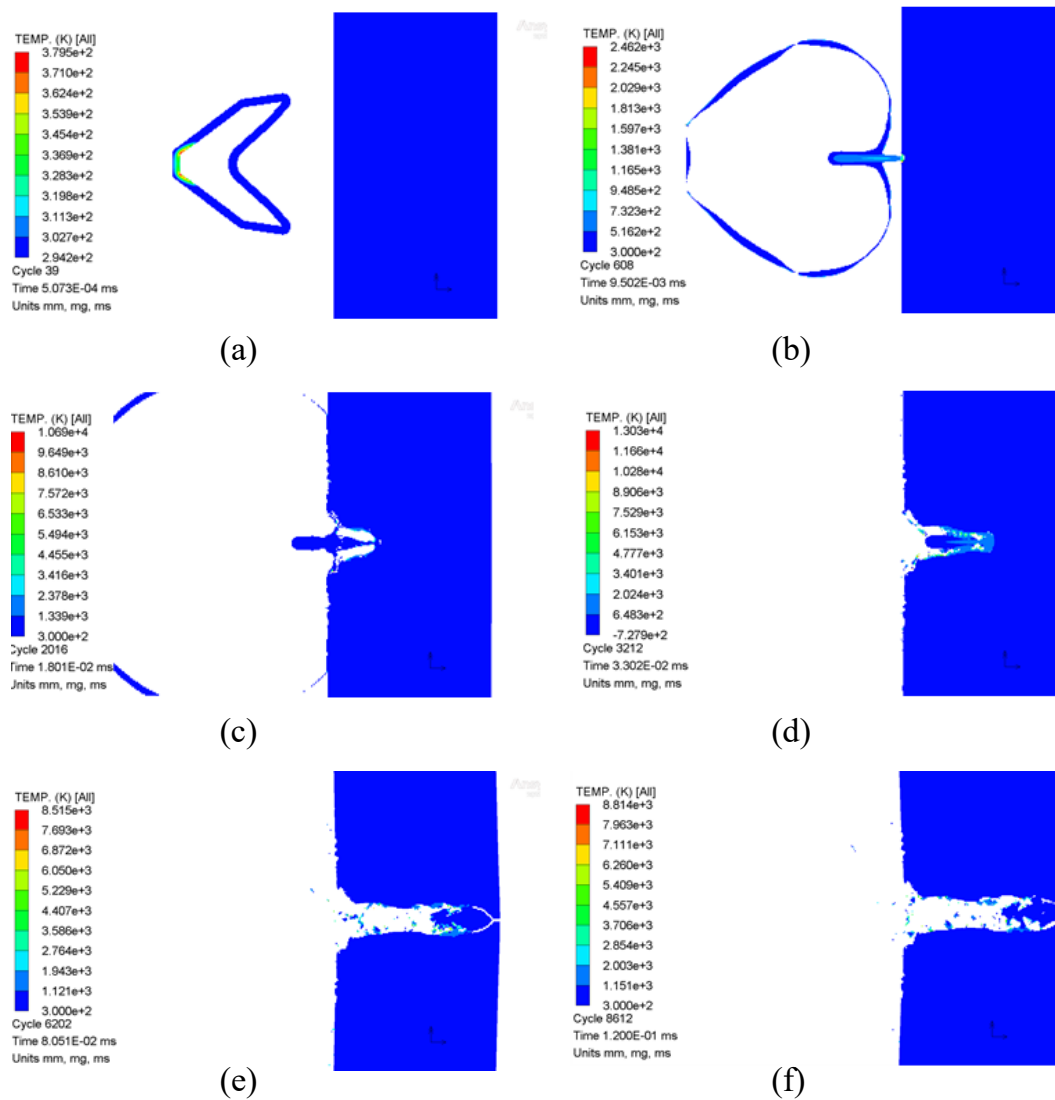


Fig. 15 Temperature distribution cloud map of the linear cutter liner jet penetration process. (a) $t = 0.5 \mu\text{s}$. (b) $t = 9.5 \mu\text{s}$. (c) $t = 18.0 \mu\text{s}$. (d) $t = 33.0 \mu\text{s}$. (e) $t = 80.5 \mu\text{s}$. (f) $t = 120.0 \mu\text{s}$.

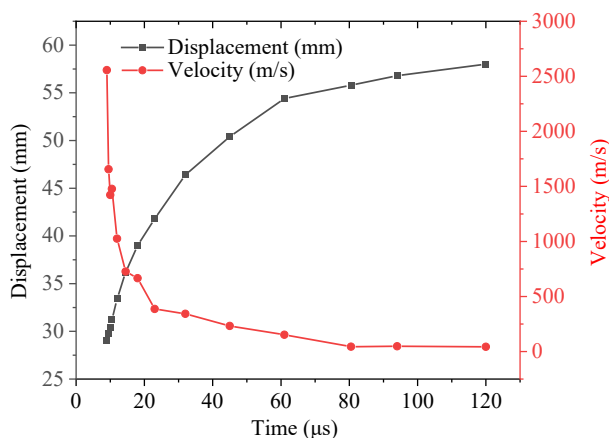


Fig. 16 Time-dependent curves of the jet head position and velocity during the penetration process.

aligns with the simulated results (6.92 mm, 1.8% error). Similarly, 17 mm standoff testing shows 10.07 mm (exp.) versus 9.82 mm (sim.) penetration. The dual-strand Pb–Sb configuration achieves a 58.0 mm penetration depth with 89% energy efficiency, outperforming Park and Kwon’s dual-angle Cu liner (41.8 mm,

65%) by 38.8% depth and 24% efficiency gain, attributed to optimized impedance matching and jet superposition effects.

4 Conclusions

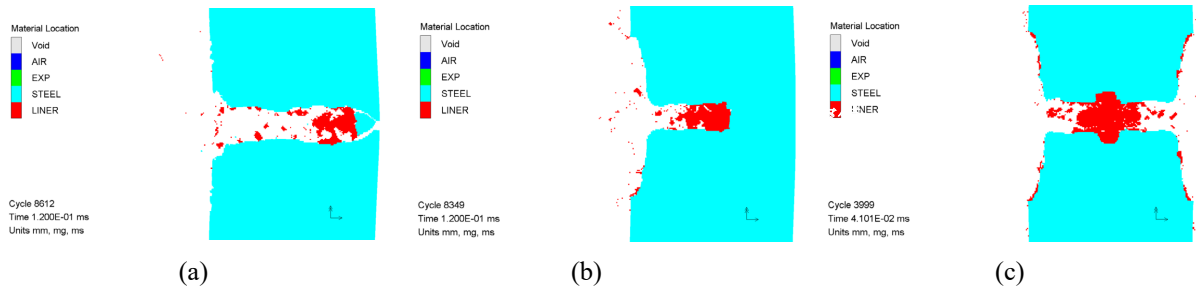
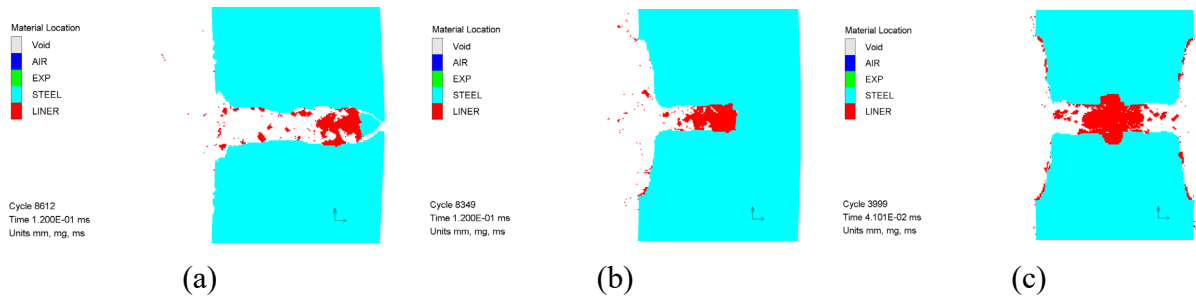
Shaped charge cutting demonstrates significant efficacy in steel structure demolition through coupled penetration mechanics and fracture dynamics. Systematic investigation reveals three fundamental control mechanisms:

(1) Pb–Sb alloy liners exhibit a 13.9% greater penetration depth (58.0 mm) compared to pure Pb (55.4 mm) and 14.4% over Cu (50.6 mm), attributed to optimized acoustic impedance ($Z = 29.5 \text{ MRayl}$) and dynamic plasticity ($\epsilon_f = 0.22$). The penetration depth–charge density relationship follows a parabolic profile ($R^2 = 0.96$) up to the critical density threshold of 200 g/m, beyond which cutting penetration dominates with characteristic W/D ratio stabilization at 0.82 ± 0.05 .

(2) Standoff distance optimization demonstrates a nonlinear penetration response—depth remains stable below 17 mm ($\Delta < 3\%$) but decreases $18.7\% \text{ mm}^{-1}$ beyond this threshold. A plate thickness reduction from 40 to 20 mm increases the penetration depth by 62.3% while inducing composite failure modes (85% shear fracture, 15% bending deformation). Microstructural

Table 8 Displacement and velocity of the jet head at different time during the penetration process

Time (μ s)	9.0	9.5	10.0	10.5	12.0	14.5	18.0
Displacement (mm)	29.0	29.8	30.4	31.2	33.4	36.2	39.0
Velocity (m/s)	2556	1656	1422	1477	1025	727	666
Time (μ s)	23.0	32.0	45.0	61.0	80.5	94.0	120.0
Displacement (mm)	41.8	46.4	50.4	54.4	55.8	56.8	58.0
Velocity (m/s)	387	343	232	152.7	44.4	47.4	43.2

**Fig. 17** Cutting steel components with linear cutters of different types of coverage materials. (a) Red copper. (b) Lead. (c) Lead-antimony alloy.**Fig. 18** Jet penetration into steel components by different models. (a) Single strand 7 mm. (b) Single strand 0 mm. (c) Dual-strand 0 mm.**Table 9** Penetration depth and penetration results of different linear materials

Material of drug shaped cover	Penetration depth (mm)	Damage effect
Red copper	50.6	Unperforated
Lead	55.4	Unperforated
Lead-antimony alloy	58.0	Run through

Table 10 Performance comparison

Study	Configuration	Penetration (mm)	Energy efficiency
This work (dual-strand)	Pb-Sb alloy	58.0	89%
Park and Kwon (2024)	Dual-angle Cu	41.8	65%

analysis confirms recast layer formation ($Ra = 14.2 \mu\text{m}$) with $\leq 8\%$ recrystallized phase fraction due to high-strain-rate material displacement.

(3) ALE simulations successfully replicate pressure wave propagation dynamics, showing an initial pressure concentration at the detonation interface (11.9 GPa) followed by progressive migration to the liner apex. The jet velocity evolution follows inverse exponential decay, with penetration termination occurring when the head pressure decays to 0.5–0.8 GPa (89%–93% energy dissipation).

(4) Velocity field analysis quantifies reduced jet divergence in dual-strand configurations (8°) versus single-strand (12°), with vector convergence at 2.5 km/s. Pressure superposition (11.9 GPa peak) maintains jet coherence, reducing lateral energy dispersion by 28%. Computational modeling demonstrates $1.8\times$ higher axial pressure in dual-strand systems through overlapping pressure fronts, while energy transfer analysis confirms 89% axial efficiency versus 65% in single-strand designs.

These findings systematically establish engineering guidelines for demolition optimization: Material innovation using Pb–7%Sb liners enhances penetration by 14.4% via optimized impedance ($Z = 29.5 \text{ MRayl}$); structural design with dual-strand configurations achieves 58.0 mm penetration depth through coordinated jet superposition, representing 38.8% improvement over single-strand equivalents; theoretical advancement yields a validated standoff threshold at $2.5\times$ charge diameter (17 mm, $R^2 = 0.96$); and engineering implementation enables 70% charge density reduction ($280 \rightarrow 84 \text{ g/m}$) in industrial cutters (SGPQ-15/19 variants) while maintaining demolition efficacy.

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CRedit authorship contribution statement

Xiaoguang Zhou: Writing - original draft, Methodology, Data curation, Funding acquisition; Zhi Li: Funding acquisition, Formal analysis, Supervision, Conceptualization, Writing - review & editing; Yingkang Yao: Methodology, Visualization, Writing review & editing; Hua Zhang: Investigation, Data curation.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

The datasets that support the findings of this research are available from the corresponding author upon reasonable request.

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