Orthogonal Analysis of Linear Shaped Charges Jet Penetrating Layered Targets

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Abstract. This paper reports on the linear shaped charges (LSCs) jet penetrates into double layer spaced targets. The distance between the LSCs and the first layer target is 0.2 times width of the LSCs, the distance between the LSCs and the second layer target is 25 times width of the LSCs. The mechanism of LSCs penetrate into the double layer spaced targets causing less collateral damage in terms of jet residues has been studied by experiment and numerical simulation. After the LSCs has been crashed by detonation wave, a linear metal jet formed and penetrates into the first layer plate, then the jet is separated into jet tip and slug. The jet tip penetrates into the second layer plate and consumed, then a strip pit formed on the surface of the back plate. The slug penetrates into the second layer plate subsequently and consumed. Due to the stress concentration and tensile fracture, the second layer target is broken and less residue of jet pass it. Experiments were made and the results indicated that the numerical simulation results agreed fully with the physical principle. A verification plate was used in the experiment to test the collateral damage of residual jets. When the space between verification plate and back plate of the layered target is 500mm, both of the experimental results and simulation results show that there is no obvious damage to people. The relationship between the performance of jet and the parameters of LSCs has been analyzed by an orthogonal method (significance test and interaction effect analysis). A good teamwork should be done for all the key parameters of LSCs which can break the spaced targets with less collateral damage.
1. Introduction

Linear shaped charges (LSCs) have the ability for the instantaneous penetrating of the structures and have been used in the field of military and civilian. LSCs are used in the separation of the capsule of the anti-submarine rockets and the separation system of the cluster bomb, for example. In the civilian application domains, LSCs have been used in the demolition of the big structures as buildings, heavily reinforced bridges, large ships and so on [1].

George [2] presented a model to describe the LSCs liner collapse and the jet/slug formation, the jet and slug are massive, rod-like fragments, and the jet wings have separated into somewhat symmetrical fragments, a velocity gradient exits between different parts of the jet. The jet tip has the highest velocity and the slug has the lowest velocity. Zeng [3] proposed a theory of linear jet formation with a 3-Dimension model, this theory is different to the formation process of conical shaped charges (CSCs) jet.

His research presented a detailed theoretical model of the formation process of linear jet after the detonation wave sweeps the liner. Lim [4-6] proposed a simplified steady-state motion equation to express the jet formation of LSCs. The analytical approach was later advanced to a nonlinear equation by an arc-shaped deformation of the liner prior to collapse. He provides a clue how to calculate the level of arc deformation during projection of the liner. The understanding of the formation and kinematics of the liner collapse line (LCL) is important because the LCL provides a fundamental of the jet flight pattern. Lim first assumed a steady-state LCL, a reasonable result in a limited configuration was presented, then the geometrical configuration of the LCL is investigated based on the arc deformation of the LSCs liner prior to collapse [7, 8], the nonlinear nature of LCL delivers a skewed jet at longer flight distance.

The efficiency of LSCs is determined based on the penetration depth to the target. Due to a significant number of factors (liner material, geometrical parameters of liner, casing material and thickness, stand-off distance) affect the cutting efficiency of the LSCs, the optimization is very complex. Most of optimization analyses are related to CSCs but less to LSCs. Miyoshi simulated the jet formation and penetration on the steel target with different stand-off distance and how to find the optimal stand-off distance was discussed too [9]. In Bohanek research [10], the factors like explosive mass, liner material and stand-off distance are studied by experiment, the relationship between the penetration depth and various factors is established.

Most of the research about LSCs focus on penetrating into a semi-infinite target or single layer target, but less published paper presents the research on the spaced armor, such as the vehicle door, the airplane door and the civilian anti-theft door. The type of double layer spaced targets in this research present a general characteristic of double layer plate that is used in engineering (the door of car or airplane, the civil anti-theft door). The stand-off between the first layer target and LSCs is small (2 times of the width of LSCs) and the stand-off between the second layer target and LSCs is much bigger (25 times of the width of LSCs). The stand-off is too bigger to use a traditional shaped charge jet due to the particle of jet, explosively formed projectile (EFP) always be used for the big stand-off distance but the performance of the EFP to penetrate the target in case of small stand-off is not very good [1]. In the fights against terrorism or in the accident [11, 12], how to quick demolish the anti-theft door is an important problem and the LSCs can meet the requirement. The mechanism of linear jet penetrate into double layer spaced targets with less collateral damage behind the second layer plate has
been illustrated in this research. The relationship between the performance of jet and the geometrical parameters of liner (liner angle \( \alpha \), liner thickness \( T \), linear length \( l \) and sectional area of charge \( S \)) is established with orthogonal method (significance test and interaction effect analysis). A type of LSCs with optimal penetration capability and less collateral damage to specially appointed double layer spaced targets is presented.

2. Experiment

2.1. LSCs specimen and layered targets
The schematic illustration and photograph of the LSCs are shown in Figure S1. \( L \) is the length of the LSCs, \( W \) is the width of the liner, \( T \) is the liner thickness, \( H_2 \) is the length of the charge, \( H \) is the stand-off distance, \( l \) is the liner slant length, \( \alpha \) is the apex angle of liner. The LSCs was made with two parts: the casing and the liner, both manufactured from oxygen-free high thermal conductivity (CU-OFHC). The liner is glued to the casing after the explosive was poured into it.

The anti-theft door is shown in Figure 1a, the thickness of the front plate and back plate both are 1 mm, the space between them is 75 mm.[13] All the plate made of medium-carbon steel. An equivalent target which has the same primary dimensions and material to the anti-theft door was used in order to cost saving, the equivalent target is shown in Figure S2, two types of steel plate were used in the manufacture of equivalent target, one is 200×200×1 mm and another one is 500×500×1 mm.

2.2. Experiment arrangement and results
Three types of experiments were conducted. One is the LSCs penetrate an anti-theft door, the length of LSC is 150 mm, as shown in Figure 1b. The anti-theft door was laid down on the ground. The double layered plates have been penetrated successfully and the experiment result is shown in Figure 2. The length of the gap on the back plate is 150 mm, which is the same length to the LSCs, the biggest width of the gap is 15 mm. The space between the anti-theft door and the ground is 100mm, not much jet residues were found on the ground.

![Figure 1](image.png)

Figure 1. Photograph of: (a) anti-theft door; (b) experimental setup.
The second type of experiment was the LSCs penetrate an equivalent target. The length of the LSCs is 100 mm and the length of target’s sides is 200 mm. The experimental arrangement shows in Figure S3. A verification plate was used to test the collateral damage, the distance between the back plate and the verification plate is 500 mm. both of the front plate and back plate was penetrated successfully. The crack was regular edges and the maximum width of crack is 15 mm. The length of the crack is 100 mm, which is the same to the length of the LSCs, as shown in Figure 3b. Only a few minor scratches on the surface of the verification plate, no obvious residual metal jets and collateral damage can be found on the surface of the verification plate, as shown in Figure 3c.

In the third experiment, four LSCs were used and the length of each LSCs is 500mm, All LSCs be linked together and was ignited by one detonator, the experimental arrangement was shown in Figure S4. The back plate of the equivalent target was penetrated successfully and a rectangular hole formed on it (Figure 4). Experimental results shows that the detonation wave can propagate smoothly from one LSCs to another one.

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**Figure 2.** Penetration result of the anti-theft door: (a) front view; (b) back view.

**Figure 3.** Penetration result of the equivalent targets (200×200×1 mm) : (a) front view; (b) back view; (c) verification plate.

**Figure 4.** Penetration result of the equivalent targets: (a) front view; (b) back view.
3. Numerical simulation

3.1. Numerical model

ANSYS LS-DYNA 2-D was used for the calculation. The command “CONSTRAINED LANGUAGE IN SOLID” was used to provide the mechanism for coupling interaction between the Lagrangian geometric entity to a Eulerian geometric entity\textsuperscript{[14]}. The explosive, copper liner and surrounding air mass were modeled using a Eulerian mesh. These three materials were modeled with default material properties that available in the material library\textsuperscript{[15]}. The Jones-Wilkins-Lee (JWL) Equation of State (EOS) was used for the explosive and the equation is shown in Eq.S\textsuperscript{1}\textsuperscript{[16]}, and the value is given by Table S\textsuperscript{1}\textsuperscript{[17]}, $V_0$ is the initial relative volume. The copper liner was modeled using Steinberg-Guinan Strength constitutive model. The air around the JPC was modeled using ideal gas EOS. The target was modeled using Lagrangian 2-D solid elements and the Johnson-Cook constitutive model, this equation can be used to model the strength behavior of materials subjected to large strains, high strain-rates and higher temperature\textsuperscript{[18]}. The parameter values are shown in Table S\textsuperscript{2}\textsuperscript{[19]}.

To reduce the runtime of simulation while maintaining the accuracy, the simulations were conducted in three phases. The first phase (detonation) is conducted in 2-dimensional and a plane-symmetry model is used. The casing is deleted after the linear jet formed. The second phase is the forming jet penetrates into the front plate, when the jet tip and slug left the front plate and move toward the back plate, the front plate is deleted. After the back plate is broken by the impact of the slug, the third phase is over. Model of the LSCs and the double layer spaced targets is shown in Figure 5. A “T” shape of air zone was used to reduce the time consumption. Flow out boundary condition was used to simulate the infinite region of the detonation products and air. Fixed boundary condition was used to the bottom/top edge of the front/back plate.

![Figure 5. Model of LSCs penetrates double layer spaced targets.](image)

3.2. Mesh sensitivity

Simulation with fine meshes produces more accurate solution with the cost of longer time consumption. In order to study the mesh sensitivity on the jet penetration, the mesh sensitivity study was performed. In this analysis where five different Eulerian mesh sizes of 0.05, 0.1, 0.2, 0.3, and 0.5mm were applied to examine the variation of the jet characteristics with the mesh density. Mesh sensitivity for jetting analysis is shown in Figure S5, where the relation between the cumulative jet mass and its axial X-position is shown. It can be observed that predicted curves of five different mesh sizes have nearly the same shape at the beginning of the jet formation. Then, noticeable variations among five curves occur for different mesh sizes. However, with the decrease of mesh size from 0.5 mm to 0.05 mm, the convergence of the solution is observed, so 0.1×0.1 mm cell is used in analyses. According to reference\textsuperscript{[14]}, the same mesh size of the Lagrangian mesh for targets is used.
3.3. Numerical results

30 μs after the detonation of the explosive, the liner has been collapsed and the metal jet begins to take shape, as shown in Figure 6a. After the jet formed (54 μs after the detonation of the explosive, Figure 6b), the front plate was broken by the jet. The break time of jet is delayed by the penetration process, as shown in Figure 7a. Without the front plate, the linear jet will break into particles and after a long distance movement towards the back plate, the penetration capacity will be seriously harmed (Figure 7b). 102 μs later, the front plate has been broken, the linear jet breaks up into jet tip, slug and some copper fragments like a wing (Figure 6c). The wing has no penetration ability, this phenomenon is the same as the model proposed by George [2]. The velocity of the jet tip is bigger than that of the slug and wing. 230 μs after the ignition of the explosive, the jet tip, slug and the wings are separated completely and the space between them become much bigger with the time increasing (Figure 6d).

![Figure 6](image_url)  
**Figure 6.** Jet formation and penetration procedure at different times: (a) t=30μs; (b) t=54μs; (c) t=102μs; (d) t=230μs.

![Figure 7](image_url)  
**Figure 7.** Relationship between linear jet and front plate: (a) with the plate; (b) without the plate.

The Jet tip firstly impacts on the second layer target, as shown in Figure 8a. When the jet tip consumed completely, a strip crack formed on the surface of the back plate, then the slug impact on the back plate at the same area (Figure 8b). After the slug is consumed, all the kinetic energy of slug transfers to the back plate and the plate keeps in motion, then tensile fracture will occurs on the back
plate and it is pulled apart in the end. The edge of the crack on the back plate is much thinner than other parts of plate ($T_2<T_1$), the pressure on the stretch zone is much lower than any other place of the plate (Figure 9b). Due to the tensile fracture, less residual of jets can pass the back plate. The failure model of the first layer plate is the same as a high-speed projectile penetrates into the thick plate. The projectile has a very high residual velocity after penetration. The edge of the crack on the front plate is much thicker than other parts of plate ($T_2>T_1$, Figure 9a). Figure 9 presents two different penetration model, one is the high-speed penetration of thin plate and another one is a tensile fracture of the thin plate. Figure 10 presents the two different penetration model of experiment, the edge of the front plate is regular and much thicker (see Figure 10a), the edge of the back plate is much thinner than the initial thickness of plate (see Figure 10b). The simulation results agree well in line with the experiment results (see Figure 9 and Figure 10).

Figure 8. Jet tip and slug penetrate the back plate: (a) $t=996\text{us}$; (b) $t=1046\text{us}$.

Figure 9. Two different penetration models of simulation: (a) front plate; (b) back plate.

Figure 10. Two different experimental penetration models.
4. Orthogonal analyses

An Orthogonal table L9(3^4)\(^{[20, 22]}\) is shown in Table 1, four factors (Angle of liner a, liner thickness T, liner length l and LSCs cross-section area S) and three different levels of each factor are listed in the table. Table 1 can be used in the significance test and interaction effect analysis \(^{[21]}\). With the significance test, the relationship between factors and the jet performance (volume, velocity and kinetic energy of the jet) and its penetration ability could be analyzed. The interaction between different factors can be figure out with the interaction effect analysis.

As shown in Figure 6c, 102 μs after detonation of the explosive, the velocity of jet tip and slug are tending towards stability. The volume, the velocity of the jet tip/slug after 200 μs were used in the analysis. The nominal thickness of mesh size is set as 1, so the volume of jet and the relative kinetic energy of jet can be calculated. A simple calculation method for the relative kinetic energy is shown in Eq.S2. The volume, velocity and relative kinetic energy of jet tip/ slug about simulation NO.1 and NO.2 (Table 1) are listed in Table S3. Each simulation was made twice and recorded like NO.1 and NO. 1’. For brevity, only the simulation of NO.1 and NO.2 (Table 1) are listed in Table S3.

| Group | Angle of liner (°) | Thickness of liner (T/mm) | Length of liner (l/mm) | LSC cross-section area (S/mm²) |
|-------|--------------------|---------------------------|------------------------|-------------------------------|
| 1     | 75                 | 0.55                      | 2.2                    | 22                            |
| 2     | 75                 | 0.60                      | 2.5                    | 24                            |
| 3     | 75                 | 0.65                      | 2.8                    | 26                            |
| 4     | 80                 | 0.55                      | 2.5                    | 26                            |
| 5     | 80                 | 0.60                      | 2.8                    | 22                            |
| 6     | 80                 | 0.65                      | 2.2                    | 24                            |
| 7     | 85                 | 0.55                      | 2.8                    | 24                            |
| 8     | 85                 | 0.60                      | 2.2                    | 26                            |
| 9     | 85                 | 0.65                      | 2.5                    | 22                            |

4.1. Significance test

As shown in Table 2, the relative kinetic energy of full jet (jet tip and slug) is set as the index and 18 results are presented (9 groups of simulation and each one was made twice). The sum of all 18 results S is 4489.56 and the total average \(μ\) of them is 498.84. \(A_1\) is the average value of all 6 results of the simulation with the first level of factor A, the methods of computation is shown in Eq.1 \(^{[21]}\). SD\(_A\) is the total sum of squares of deviations. Use the same method, the value of SD\(_B\), SD\(_C\) and SD\(_D\) is calculated and listed in Table 2. By comparing SD\(_A\), SD\(_B\), SD\(_C\) and SD\(_D\), the most influential factor on the relative kinetic energy of full jet is factor C, followed in turn by factor A, D and B. The effect E of each level of factors (A, B, C, D) is listed in Table 3, the methods of computation is shown in Eq.1. The optimal combination is \(A_3B_3C_3D_3\) and the engineering average of this combination is 598.41.
Table 2. Orthogonal table (relative kinetic energy of full jet).

| Group | A   | B   | C   | D   | NO.1 | NO.1' |
|-------|-----|-----|-----|-----|------|-------|
| 1     | 1   | 1   | 1   | 1   | 356.30| 365.44|
| 2     | 1   | 2   | 2   | 2   | 471.34| 466.34|
| 3     | 1   | 3   | 3   | 3   | 516.89| 512.79|
| 4     | 2   | 1   | 2   | 3   | 530.94| 565.25|
| 5     | 2   | 2   | 3   | 1   | 529.86| 514.06|
| 6     | 2   | 3   | 1   | 2   | 472.16| 487.25|
| 7     | 3   | 1   | 3   | 2   | 585.53| 594.30|
| 8     | 3   | 2   | 2   | 1   | 505.43| 477.28|
| 9     | 3   | 3   | 2   | 1   | 515.11| 512.85|

\[
A_1 (448.19) \quad B_1 (499.63) \quad C_1 (443.98) \quad D_1 (465.60)
\]
\[
A_2 (516.59) \quad B_2 (494.05) \quad C_2 (510.31) \quad D_2 (512.82) \quad S=4489.56
\]
\[
A_3 (531.75) \quad B_3 (502.84) \quad C_3 (542.24) \quad D_3 (518.10) \quad \mu=498.84
\]
\[
SD_A (3963.85) \quad SD_B (39.56) \quad SD_C (5024.95) \quad SD_D (1671.00)
\]

Set the relative kinetic energy of the slug as the index (Table S4) and set the relative kinetic energy of the jet tip as the index respectively (Table S5). Using the same method of analysis shows above, when the relative kinetic energy of slug was set as the index, the most influential factor on the relative kinetic energy of slug is factor C. The optimal combination is A_3B_3C_3D_3 and the engineering average of this combination is 169.93. In the analysis of the relative kinetic energy of jet tip, the most influential factor on the relative kinetic energy of jet tip is factor B. The optimal combination is A_3B_2C_3D_2, the engineering average of this combination is 325.3119. Table 4 summarizes the order of factors that affect the relative kinetic energies of the full jet, jet tip and slug. NO 1 means it has the greatest effect, followed in turn by 2, 3, and 4.

Table 3. The effect of different levels of factors.

| Level | Value       | Level | Value       |
|-------|-------------|-------|-------------|
| A_1   | E_{A_1}(-50.65) | B_1   | E_{B_1} (0.79) |
| A_2   | E_{A_2} (17.75)  | B_2   | E_{B_2} (-4.79) |
| A_3   | E_{A_3} (32.91)  | B_3   | E_{B_3} (4.00)  |
| C_1   | E_{C_1} (-54.86) | D_1   | E_{D_1} (-33.24) |
| C_2   | E_{C_2} (11.47)  | D_2   | E_{D_2} (13.98)  |
| C_3   | E_{C_3} (43.40)  | D_3   | E_{D_3} (19.26)  |

\[
\bar{A}_1 = \frac{(356.30 + 365.44 + 471.34 + 466.34 + 516.89 + 512.79)}{6}
\]
\[
SD_A = \sum_{i=1}^{3} (\bar{A}_i - \mu)^2
\]
\[ F_{A_1} = \bar{A}_1 - \mu \]  

(1)

**Table 4.** Orders of the factors that could influence the index.

| Item                      | A  | B | C | D |
|---------------------------|----|---|---|---|
| Kinetic energy of full jet| NO.2 | 4 | 1 | 3 |
| Kinetic energy of slug    | NO.2 | 4 | 1 | 3 |
| Kinetic energy of jet tip | NO.4 | 1 | 2 | 3 |

4.2. *Interaction effect analysis*

The interaction between different parameters can be evaluated by the interaction effect analysis. All 18 interaction groups between different parameters with three different indexes (relative kinetic energy of all jet, slug and jet tip respectively) are listed in Table S6. Take the relative kinetic energy of jet tip as the example to analyze the interaction between parameters, as shown in Table S5 and Table S7. The interaction between parameter A and B be selected, this is NO 13 which is listed in Table S6. Table 5 presents the calculation results of interaction analysis and the calculation methods are listed in Eq. S3.

As shown in Table 5 and Eq. 2, factors A and B have remarkable influence on the kinetic energy of slug. The interaction between factor A and B is remarkable. The effect of A×B at different levels were calculated and shown in Table S8. The optimal engineering average is \( u_{optimal} = \mu + A_3B_1 + C_3 + D_3 = 305.7016 \), the combination is \( A_3B_1C_3D_3 \). This type of combination shows a conclusion that the length of liner is bigger, the cross-section area of charge is bigger, the angle of liner is bigger and the thickness is smaller, jet tip has the highest kinetic energy after the front plate was broken.

\[ F_A \sim F_r - 1, rs(t-1) = 16.86 > F_{ar-1}, rs(t-1), a = 0.01, 0.05 \]

\[ F_B = 2111.16 > F_{ar-1}, rs(t-1), a=0.01, 0.05 \]

\[ F_{AxB}=26.99 > F_{ar-1}, rs(t-1), a=0.01 \]

(2)

Using the method shows above. Some of the interaction groups listed in Table S6 were analyzed. The results were drawn as the 3-dimensional curved surfaces shown in Figure S6. The X-axis, Y-axis and Z-axis represent the first factor, second factor and the index of the interaction analysis respectively. For example, as shown in Figure S6b, the X, Y and Z axis represent factor A (angle of liner a), C (length of liner l) and the index (relative kinetic energy of full jet) respectively. In order to get the maximum value of the relative kinetic energy of full jet, The best combination is the angle of liner a is 80° and the length of liner l is 2.5 mm. Figure S6b proposes a suggestion that how to choose the angle of liner a and the length of liner l in the design of the LSCs.
Table 5. Variance table.

| Source | SS (sum of squares) | df (degrees of freedom) | MS | F |
|--------|---------------------|-------------------------|----|----|
| A      | $S_A$ (3922.12)     | r-1, (2)                | $S_A$(1961.06) | $F_A$ (16.86) |
| B      | $S_B$ (49125.96)    | s-1, (2)                | $S_B$(24562.98) | $F_B$ (211.16) |
| $A \times B$ | $S_{A \times B}$ (12559.99) | (r-1)(s-1), (4) | $S_{A \times B}$(3140.00) | $F_{A \times B}$ (26.99) |
| Error  | $S_E$ (1046.92)     | rs(t-1),(9)             | $S_E$ (116.32) |

$F_{0.01}(2, 9) = 8.02; F_{0.05}(2, 9) = 4.26; F_{0.01}(4, 9) = 6.42$

4.3. Discussion

The radio between the thickness of liner and the width of liner is much bigger than the traditional LSCs \([1]\). The mass of liner should be big enough because lots of jet material be consumed during two times of penetration. The radio between the mass of liner and the mass of charge is much smaller, more explosive should be used, the kinetic energy of jet tip change a little with the increase of mass of the explosive but the kinetic energy of slug will be much bigger, so much more energy could transmit to the second layer plate when the slug impact on it. In traditional LSCs, slug has no value but in this research, slug acts a very important role in the penetration.

The structure of the double layer spaced targets is almost the same, which are consisted of a thin front plate, a thin back plate and a big space between them. In order to design a LSCs to penetrate a given structure of double layer spaced targets with less collateral damage. The penetration mechanism presented and all the relationship between the parameters of LSCs and the performance of jet (volume, velocity and penetration ability) were presented in this section will be very helpful for the LSCs design work.

5. Conclusions

The results of numerical simulation and experiment indicated that after the detonation wave sweep the liner, a jet formed and penetrating into the front plate. After the plate was broken, the complete metal jet breaks into three parts: a high-speed jet tip, a low-speed slug and some fragments like a wing. The jet tip reaches the back plate firstly and impact on the plate and consumed in the end, then a cave formed on the back plate. After the slug impact on the back plate, all the kinetic energy of slug deliver to the back plate. The plate keeps on moving and tensile fracture occurs, the plate was pulled apart in the end.

During the jet penetrate into the first layer plate, the penetration process can delay the break time of jet. In the process of penetrating the back plate, the slug of the traditional LSCs has not any value in penetration, but the slug of the shaped charge jet (SCJ) in this design plays an important role in penetrating the back plate.
Traditional EFP can be used in big stand-off distance (>10 times of the diameter of charge) and traditional CSCs jet only can be used in the small stand-off distance (<6 times of the diameter of SCJ). The LSCs studied in this paper can penetrate the double layer spaced targets with both of the big and small stand-off conditions, which has the feature both of the EFP and SCJ. With less residual of jets pass the second layer plate, the LSCs presented in our research can be used in engineering domain and reduce injury.

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Supporting Information

Orthogonal analysis of linear shaped charges jet penetrating into spaced targets

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Figure S1 Structure: (a) photograph of the object; (b) schematic illustration with geometrical parameters.

Figure S2 Equivalent targets: (a) photograph of the object; (b) schematic illustration with geometrical parameters.
Figure S3 Experimental arrangement: a LSCs penetrate the equivalent targets with collateral damage test.

Figure S4 Arrangement: (a) photograph of the object; (b) schematic illustration with geometrical parameters.

Figure S5 The cumulative jet mass versus the jet axial coordinate obtained from the different mesh sizes of jetting analysis.
Figure S6 Interaction effect analysis of different factors group listed in Table S6.

Equation S1 The Jones-Wilkins-Lee (JWL) Equation of State (EOS) used for the explosive TNT

\[ P = A \left( 1 - \frac{\omega}{R_1 e^{R_1 V}} \right) + B \left( 1 - \frac{\omega}{R_2 e^{R_2 V}} \right) + \omega E \]

Equation S2 Simple calculation method for the relative kinetic energy.

\[ E_{\text{relative kinetic energy}} = \frac{1}{2} \frac{V_{\text{volume of jet tip/slug}} \times v^2}{\text{velocity of jet tip/slug}} \]

Equation S3 Calculation methods for the participate used in the interaction effect analysis.

\[ \bar{X} = \frac{1}{rst} \sum_{i=1}^{r} \sum_{j=1}^{s} \sum_{k=1}^{t} X_{ijk} \]

\[ \bar{X}_{ij} = \frac{1}{t} \sum_{k=1}^{t} X_{ijk}, \quad i = 1, 2, ..., r, \quad j = 1, 2, ..., s, \]

\[ \bar{X}_{i.} = \frac{1}{st} \sum_{j=1}^{s} \sum_{k=1}^{t} X_{ijk}, \quad i = 1, 2, ..., r, \]
\[ X_{ij} = \frac{1}{rts} \sum_{i=1}^{r} \sum_{j=1}^{s} X_{ijk}, \quad j = 1, 2, \ldots, s, \]

\[ S_A = \frac{1}{st} \sum_{i=1}^{r} \sum_{j=1}^{s} (X_{ij} - \bar{X})^2, \quad S_B = \frac{1}{rt} \sum_{j=1}^{s} (X_{j} - \bar{X})^2, \]

\[ S_E = \sum_{i=1}^{r} \sum_{j=1}^{s} \sum_{k=1}^{t} (X_{ijk} - \bar{X}_{ijk})^2, \]

\[ S_{A \times B} = \frac{1}{t} \sum_{i=1}^{r} \sum_{j=1}^{s} \sum_{k=1}^{t} (X_{ijk} - \bar{X}_{i} - \bar{X}_{.j} + \bar{X})^2, \]

\[ \bar{S}_A = \frac{s}{r-1}, \quad \bar{S}_B = \frac{s}{s-1}, \]

\[ \bar{S}_{A \times B} = \frac{s_{A \times B}}{(r-1)(s-1)}, \quad \bar{S}_E = \frac{s_{E}}{rs(t-1)}, \]

\[ F_A = \frac{\bar{S}_A}{\bar{S}_E}, \quad F_B = \frac{\bar{S}_B}{\bar{S}_E}, \quad F_{A \times B} = \frac{\bar{S}_{A \times B}}{\bar{S}_E}. \]

**Table S1** The JWL constant and detonation characteristics of the explosive [17].

| \( \rho_e \) (kgm\(^{-3} \)) | A (Gpa) | B (Gpa) | R\(_1\) | R\(_2\) | \( \omega \) | C-J V\(_{det}\) | C-J e | C-J P (Gpa) |
|----------------|--------|--------|-------|------|-------|---------------|-------|-----------|
| 1717           | 524.23 | 76.78  | 4.2   | 1.1  | 0.34  | 7980         | 8.5e6 | 29.5      |

**Table S2** The input parameters of target materials [19].

| \( \rho \) (g/cm\(^3\)) | A (Mpa) | B (Mpa) | n     | \( \varepsilon_0 \) (s\(^{-1}\)) | C | m | T\(_{\text{melt}}\) (K) |
|----------------|--------|--------|------|----------------|---|---|----------------|
| 7.83           | 250    | 477    | 0.18 | 2.86e-2       | 0.012 | 1 | 1811           |

**Table S3** Data of volume and velocity got from numerical simulation.

| Group | Volume of jet tip (2.5e-3 mm\(^3\)) | Velocity of jet tip (m/s) | Kinetic energy of jet tip | Volume of slug (2.5e-3 mm\(^3\)) | Velocity of slug (m/s) | Kinetic energy of slug |
|-------|-----------------------------------|--------------------------|--------------------------|----------------------------------|------------------------|------------------------|
| 1'    | 150                               | 1078                     | 87.15                    | 705                              | 559                    | 110.15                 |
| 1    | 125                               | 1090                     | 74.26                    | 718                              | 570                    | 116.64                 |
| 2    | 350                               | 1222                     | 256.90                   | 858                              | 554                    | 131.67                 |
| 2'   | 356                               | 1214                     | 249.49                   | 866                              | 554                    | 132.89                 |

**Table S4** Orthogonal table (relative kinetic energy of slug).

| Group | A | B | C | D | NO.1 | NO. 1' |
|-------|---|---|---|---|------|--------|
| 1    | 1 | 1 | 1 | 1 | 110.15 | 116.64 |
| 2    | 1 | 2 | 2 | 2 | 131.67 | 132.89 |
Table S5 Orthogonal table (relative kinetic energy of jet tip).

| Group | A  | B  | C  | D  | NO.1 | NO. 1' |
|-------|----|----|----|----|------|--------|
| 1     | 1  | 1  | 1  | 1  | 87.15| 74.26  |
| 2     | 1  | 2  | 2  | 2  | 256.90| 249.49 |
| 3     | 1  | 3  | 3  | 3  | 257.03| 244.53 |
| 4     | 2  | 1  | 2  | 3  | 132.15| 158.33 |
| 5     | 2  | 2  | 3  | 1  | 284.56| 268.67 |
| 6     | 2  | 3  | 1  | 2  | 243.72| 235.39 |
| 7     | 3  | 1  | 3  | 2  | 191.33| 214.83 |
| 8     | 3  | 2  | 1  | 3  | 269.72| 262.09 |
| 9     | 3  | 3  | 2  | 1  | 225.39| 215.50 |

\[
A_1(132.69) \quad B_1(139.13) \quad C_1(128.36) \quad D_1(139.18)
\]
\[
A_2(143.05) \quad B_2(141.82) \quad C_2(143.15) \quad D_2(143.15)
\]
\[
A_3(150.22) \quad B_3(145.02) \quad C_3(154.46) \quad D_3(146.20)
\]

\[
S=1277.91 \\
\mu=141.99
\]

Table S6 Arrangement of interaction analysis.

| Index                        | AB | AC | AD | BC | BD | CD |
|------------------------------|----|----|----|----|----|----|
| Relative kinetic energy of full jet | 1  | 2  | 3  | 4  | 5  | 6  |
| Relative kinetic energy of slug | 7  | 8  | 9  | 10 | 11 | 12 |
| Relative kinetic energy of jet tip | 13 | 14 | 15 | 16 | 17 | 18 |

Table S7 Interaction analysis using kinetic energy of jet tip as index.

| B_1 | B_2 | B_3 | SUM |
|-----|-----|-----|-----|
|     |     |     |     |
\[ A_1 \]
\[
\begin{array}{l}
X_{111} (87.15) & X_{121} (256.90) & X_{131} (257.03)
\end{array}
\]
\[
A_1
\]
\[
\begin{array}{l}
X_{112} (74.26) & X_{122} (249.49) & X_{132} (244.53) & X_{1..} (1169.36)
\end{array}
\]
\[
X_{11} (161.41) & X_{12} (506.39) & X_{13} (501.56)
\]
\[
X_{211} (132.15) & X_{221} (284.56) & X_{231} (243.75)
\]
\[
A_2
\]
\[
\begin{array}{l}
X_{212} (158.33) & X_{222} (268.67) & X_{232} (235.39) & X_{2..} (1322.86)
\end{array}
\]
\[
X_{21} (290.48) & X_{22} (553.23) & X_{23} (479.14)
\]
\[
X_{311} (191.33) & X_{321} (269.72) & X_{331} (225.39)
\]
\[
A_3
\]
\[
\begin{array}{l}
X_{312} (214.83) & X_{322} (262.09) & X_{332} (215.50) & X_{3..} (1378.88)
\end{array}
\]
\[
X_{31} (406.16) & X_{32} (531.82) & X_{33} (440.90)
\]
\[
SUM
\]
\[
\begin{array}{l}
X_{..1} (858.06) & X_{..2} (1591.44) & X_{..3} (1421.90) & X_{...} (3871.10)
\end{array}
\]

**Table S8** The effect of A*B at different levels.

|      | A1B1 | A1B2 | A1B3 | A2B1 | A2B2 | A2B3 | A3B1 | A3B2 | A3B3 |
|------|------|------|------|------|------|------|------|------|------|
| SUM  |      |      |      |      |      |      |      |      |      |

-42.14 8.12 34.02
-3.18 5.96 -2.78
45.32 -14.08 -31.23