Improvement of penetration performance of linear shaped charges

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Abstract

Experiments and simulations of linear shaped charges (LSCs) have been conducted to improve the penetration performance and minimize collateral damage by fragments. Annealed tough pitch copper was selected for an appropriate liner material. The penetration depth increased by 50 %, compared to current LSCs. The detonation effects of the explosive change the liner into the jet and slug. But, the case is also transformed into fragments, which creates undesirable collateral damage. Polyvinyl chloride was adopted as the case material to reduce damage by fragments. No fragments were generated when the newly-designed LSCs were shot. For the simulation of the jet formation and target penetration, the Euler solver of AUTODYN on the two-dimension planar was selected, and the liner, case and explosive were filled on the Euler solver plane. The calculation results gave us significant information about determining the optimal stand-off distance and allow us to design effective cutting plans for use with LSCs.
Keywords: linear shaped charges, target penetration, stand-off distance, Euler solver.

1 Introduction

Liner shaped charges (LSCs) have the ability for the instantaneous cutting of the structures and have been used in the separation of the first and second stages, and the command destruction of solid rocket boosters (SRB) in the H-2A rocket. In the field of the military, LSCs are used the separation of the capsule in the antisubmarine rockets. In the civil engineering area, LSCs have been used in the demolition of the big structures such as buildings, iron bridges and cranes.

At best, the penetration performance of conical shaped charges (CSCs) is usually 8.0 times the cone diameter (CD), while LSCs have a maximum performance at 1.2 times of the charge width. Improvement of the penetration performance is needed to conduct more effective cutting.

Appropriate setting of the stand-off, which is the distance between the liner base part of LSCs and the surface of the target, needs to be precisely controlled to obtain the optimal penetration performance.

The collateral damage by the fragments from the case of the LSCs should also be eliminated to conduct the cutting plans reliably and safely.

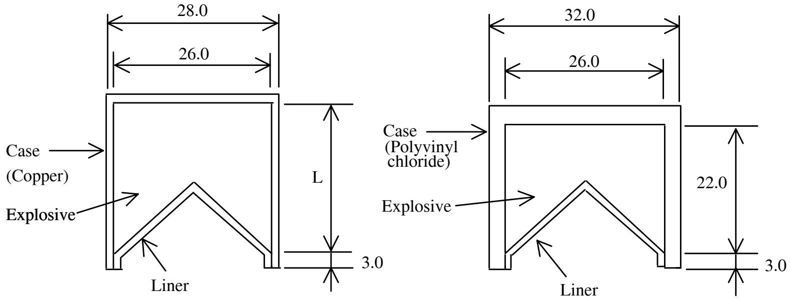
Miyoshi *et al* [1] presented that simulations using AUTODYN are useful for understanding the process of jet formation and target penetration. Moreover, an appropriate stand-off can be determined from the calculation results. The Euler solver of AUTODYN on the two-dimension planar was used, and the liner, case and explosive were filled on the Euler solver plane.

In this paper, we present our effort for improving the penetration performance, minimizing fragments and obtaining an appropriate stand-off. The simulation results proved very useful in predicting test results and in meeting our objects.

2 Design and manufacture

2.1 Liner and case

LSCs consist of the liner, case and explosive, as shown in fig. 1. Copper is most commonly used as the liner material. A tough pitch copper plate was cut to the required dimensions for the liner and case. The copper plates were angled at prescribed forms.



L = 31.0, 26.0 and 21.0

Liner thickness =1.0

Figure 1: Dimensions of LSCs.

Dimensional accuracy was acceptable, but the remaining stress due to the bending work was anticipated. Annealing conditions were at 400 degree C for two hours in a vacuum. Assembly of the liner and case was conducted by two methods, silver brazing and soldering. The treating temperature was about 750 and 250 degree C, respectively. The temperature of silver brazing method was too high to invalidate the annealing effect. Since the recrystallization temperature of copper is 650 degree C, silver brazing makes the particle size of copper larger and constitutes a limiting factor between good jet formation and the troublesome jet break-up. The specimens utilizing soldering were expected to lead to good penetration results and were used for the first step experiment, the stand-off test.

In order to reduce damage by fragments, polyvinyl chloride was adopted as the case material. Two types of LSCs were manufactured, a copper case type (CC) and a reduced fragments (RF) type.

Table 1: Explosive loading data.

LSC type	*Charge height (mm)*	*Mass (g)*	*Weight (g)*	*Density (g/cm^3)*	*Remarks*
CC-A-1	31	473	228	1.80	
CC-A-2		474	230	1.81	
CC-A-3		472	229	1.80	
CC-B-1	26	406	180	1.80	
CC-B-2		409	183	1.83	
CC-B-3		413	189	1.87	Case became deformed
CC-C-1	21	341	134	1.80	
CC-C-2		342	134	1.80	
CC-C-3		---	---	---	Measurement mistake
RF-1	22	274	148	---	Density was not calculated
RF-2		282	157	---	
RF-3		271	146	---	

2.2 Explosive loading

In the experimental design the use of explosive octol 75/25 was planed, but small gas bubbles in the explosive were not able to be removed. Defoaming and warming in vacuum were ineffective. Therefore, octol 70/30 was loaded.

Copper case types were loaded with explosives, and then defoamed and warmed in a vacuum. Small gas bubbles were able to be removed. After gradually cooling and solidification, small porosities were generated.

Preloading warming in a vacuum was not applied to the reduced fragments hardware. Loading in the atmosphere was conducted, and the explosive was gradually cooled and became solidified. Gas bubbles and porosities were observed to be minimal.

Explosive loading data of the LSCs is shown in table 1. The final number 2 in the LSC type means the soldering method, and all the others used silver brazing. All of LSCs were 200 mm in length.

3 Experiments

3.1 Stand-off test

The aim of the test is to obtain the relationship between the stand-off distance and the penetration depth, and to therefore determine the optimal stand-off distance.

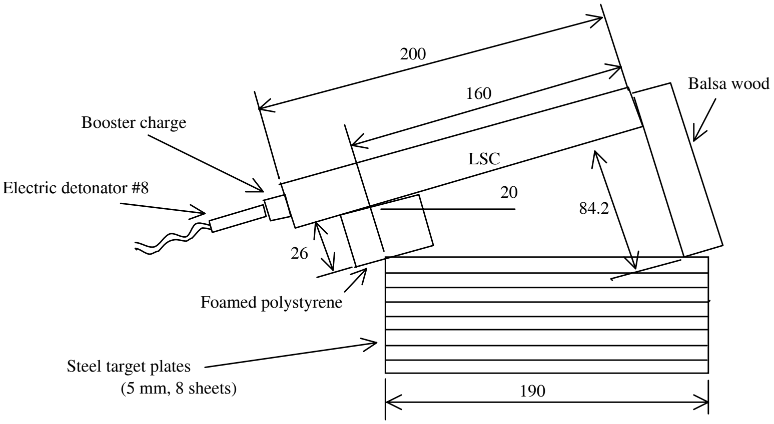


Figure 2: Stand-off test setup.

Determination of an appropriate stand-off distance is very important to obtain high cutting performance in LSCs. Fig. 2 shows the setup of the stand-off test. From the items showed in table 1, CC-A-2, CC-B-2, CC-C-2, and RF-2 were selected for testing.

3.2 Fragmentation test

The aim of the test is to observe the damage to the witness plate in when using the polyvinyl case, compared to the copper case. Two witness steel plates, 3.2 and 1.6 mm thick, were placed at 2 m point from a LSC.

3.3 Penetration test

The penetration performance of LSCs against the steel targets was evaluated by using the data from the stand-off test, and the fragmentation test was conducted at the same time. The setup of the penetration test was similar to fig. 2, except that a LSC was placed parallel to the steel target plates.

These tests were conducted in the dome-type explosion test facility, located in the Yoshii plant. The facility has the enclosed space of 8 m diameter and 5 m height. For protection from fragments and blast waves, the inner wall consists of reinforced concrete several meters thick, a steel plate 25 mm thick, and three steel plate 3.2 mm thick.

4 Results

4.1 Stand-off test

4.1.1 Penetration angle against the target

The penetration angle of the jet front against the target is shown in fig. 3. The eqn (1) was obtained.

$$\sin\theta = V_j / U \tag{1}$$

V_j : Velocity of the jet front, U : Detonation velocity.

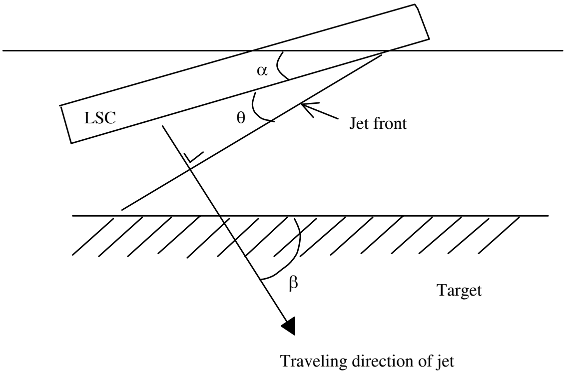


Figure 3: Penetration angle of jet.

The penetration angle is shown in eqn (2), and the jet velocity is represented as eqn (3).

$$\theta = \frac{\pi}{2} - \alpha - \beta \tag{2}$$

$$V_j = U\cos(\alpha + \beta) \tag{3}$$

When the target is penetrated by the jet, some vestiges generated by the jet are observed on the cutting surface of the target, as shown in fig. 4.

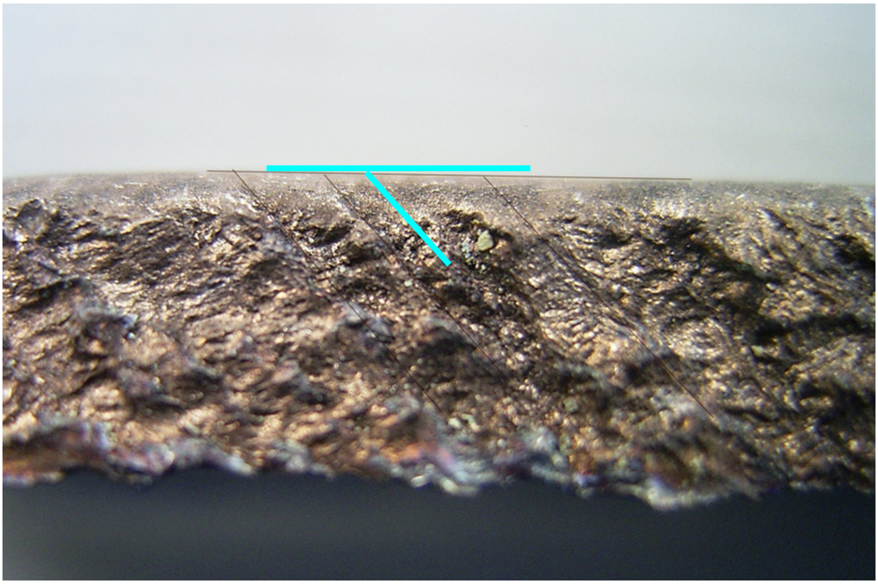


Figure 4: Cut surface of the target.

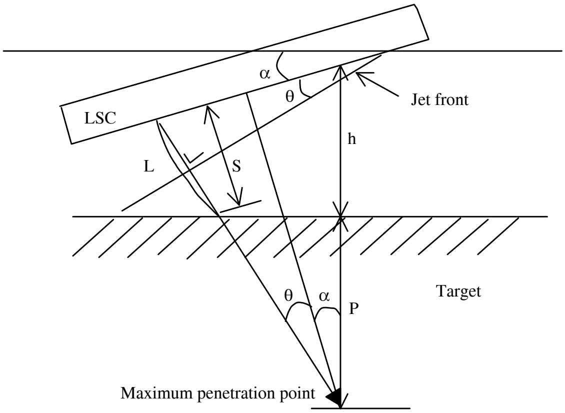


Figure 5: Optimal stand-off calculation.

The angle is 47 degree, and the detonation velocity is 8,400 m/s. By using eqn (1), the jet velocity was calculated to be about 3,300 m/s.

4.1.2 Maximum penetration point

The explanation drawing of the optimal stand-off calculation is shown in fig. 5. The optimal stand-off *S* is calculated by using eqn (4) and (5).

$$L = \frac{(h+P)\cos\alpha}{\cos\theta} - \frac{P}{\cos(\alpha+\theta)} \tag{4}$$

$$S = L\cos\theta \tag{5}$$

From the test results, the most significant part of the penetration was determined to be located at about 69 mm from the left end of the steel target. The parameter of eqn (4) and (5) was obtained, that is, *h* is 50 mm, *P* 30 mm, alpha 20 degree and theta 23 degree. Therefore, the optimal stand-off was determined to be 40mm.

4.2 Fragmentation test

As shown in fig. 6, no fragments were generated when the reduced fragments type was shot. Contrary, to take a single example, a copper case type generates 141 penetration holes on a steel plate 1.6 mm thick, and 87 holes on a plate 3.2mm thick.

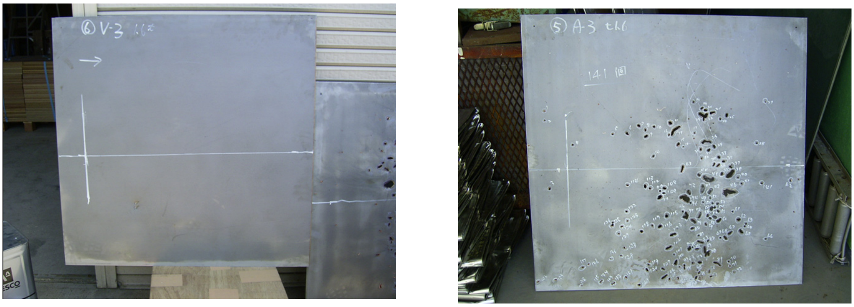


Figure 6: Zero and 141 holes.

4.3 Penetration test

The test results are shown in table 2.

The penetration 76 holes of CC-A-1 (*) were not representative, because the plate was not correctly set. A few pieces of holes of RF-1 (**) were generated by the fragments from the target cutting. In the case of RF-3 (***), the fragments from the target were deflected by some wood boards.

Table 2: Test results.

LSC	*Charge height (mm)*	*Target (mm)*	*Cutting result*	*Steel plate (mm)/ penetration holes (pcs)*
CC-A-1	31	35	Complete cut by penetration	1.6/ 136, 3.2/ 76*
CC-A-3		40	Complete cut by penetration	1.6/ 141, 3.2/ 87
CC-B-1	26	35	Complete cut , but rupture of small part	1.6/ 104, 3.2/ 53
CC-B-3		40	Complete cut by penetration	1.6/ 108, 3.2/ 38
CC-C-1	21	35	Complete cut, but rupture of small part	1.6/ 64, 3.2/ 34
CC-C-3		40	Incomplete cut at detonation point	1.6/78, 3.2/ 53
RF-1	22	25	Complete cut, but rupture of large part	1.6/ 2, 3.2/5 **
RF-3		30	Completer cut, but rupture of large part	1.6/ 0, 3.2/0***

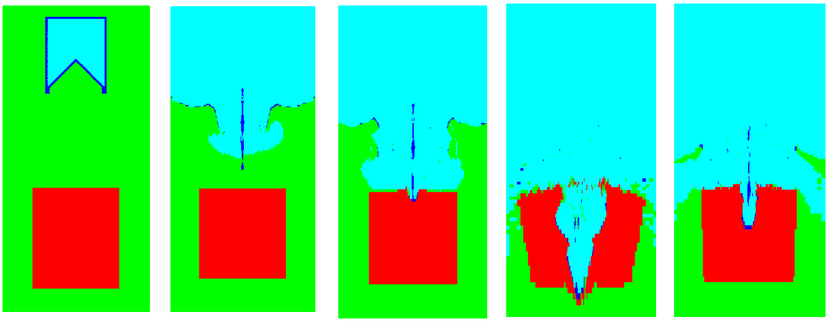


Figure 7: Penetration process simulation.

5 Simulations

Simulations were conducted with AUTODYN-2D to verify the optimal stand-off and the maximum penetration depth. The Euler solver on the two-dimension planar was selected, and the liner, case, explosive, air, and steel target were filled on the Euler solver plane. For the copper liner and copper case, the shock Hugoniot equation of state (EOS) and Steinberg-Guinan strength model, and for the steel target, the shock Hugoniot EOS and Johnson-Cook strength model were used. For the explosive the JWL EOS, and air the Ideal gas EOS were used. For the RF type, we substituted polyethylene for polyvinyl chloride, since polyvinyl chloride was not registered in the data library of AUTODYN. The EOS of polyethylene was used in the shock Hugoniot EOS.

The jet formation and target penetration process were obtained as a form of moving images. Fig. 7 shows the snap shots at 0, 15.4, 21.4, 33.2 and 73.4 micro-second from the mpeg files as test examples. The charge height, stand-off distance, and target thickness were changed in concert with the setup of the experiments.

6 Discussions

The flash x-ray system is usually used as a diagnostic tool for evaluating of shaped charge jet. But in the case of LSCs, perceiving of the jet behaviour from the x-ray photos is extremely difficult, because the jet is thin and the photo contrast is low. The AUTODYN simulation gives us significant information about the jet and slug profile, as shown fig. 8.

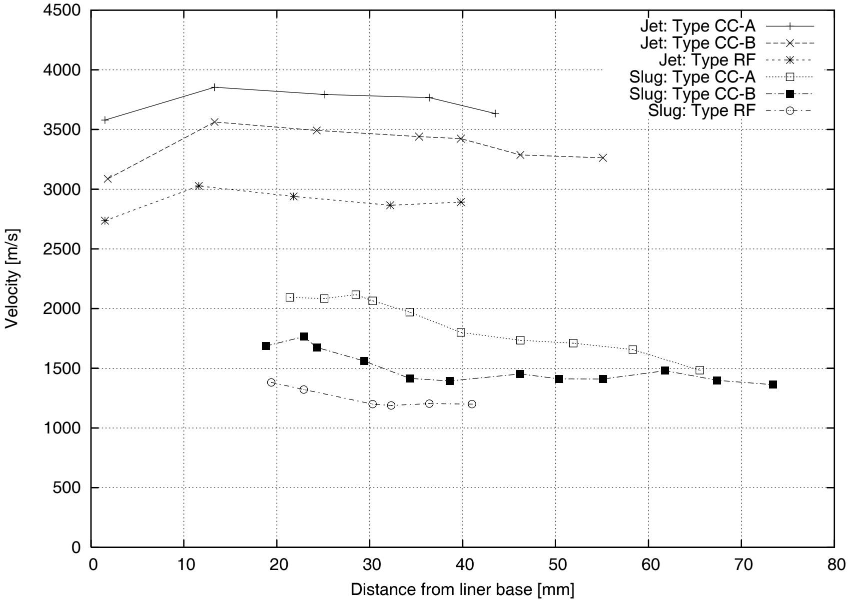


Figure 8: Jet and slug tip velocity.

From the simulations the average jet velocity was determined to be about 3,500 m/s. The result agrees with our assumption showing in 4.1.1. The penetration depth was compared with experiments and calculations. The maximum penetration depth was estimated to be 47 mm on a CC-A type LSC and was equivalent to 1.81 times of the charge width of 26 mm. As the maximum penetration depth of a current LSC is 1.2 times at a maximum, the performance of one of the newly-designed LSC increased by about 50 %.

Stand-off effects were clearly confirmed by the simulations. The optimal stand-off was determined to be 40 mm and a series of experiments was conducted with use of this data. For the type CC-B, the penetration depth was calculated to be 43.5 mm. When the stand-off was set as 20 and 40 mm, the penetration depth was calculated to be 29.0 and 21.6 mm, respectively.

The penetration velocity profile was also obtained from the simulations and a two-tiered penetration process was confirmed. For the type CC-A, two-third thickness of the target steel was penetrated by the jet and the residue was decoupled by the slug. As shown in fig. 8, the slug has the velocity of more than 2000 m/s, and has the ability for cutting the steel target.

By changing from copper to polyvinyl chloride, the generation of fragments from the case was completely inhibited. The reduced fragment type LSCs have a highly utility value at cutting work, when fragile and expensive items are located nearby. As polyvinyl chloride has no confinement effects, lowering of the penetration depth was projected. Experimental results show a slight difference between the CC-C type and RF type. Additional experiments and simulations should be conducted to evaluate the confinement effects.

Explosive loading for a narrow and long space was crucial, because the penetration performance is greatly influenced by precise loading conditions. Special loading tools should be designed and used to ascertain equable conditions of explosives.

The simulation results, especially moving images, are intuitively able to confirm the process of jet formation and target penetration. By selecting an appropriate EOS, strength model, and failure model of the materials, AUTODYN may be used as an adequate tool for predicting and evaluating the performance of LSCs.

The three-dimension simulation of LSCs should be crucial for evaluating the overall LSC performance. The SPH (Smooth particle hydrodynamics) solver is a useful procedure to demonstrate the shaped charge jet behaviour. We have plans to conduct the three-dimension simulation as soon as possible.

7 Conclusions

The live fire stand-off tests, fragmentation tests and penetration tests were conducted. Simulations by using AUTODYN were also performed. Through this present study we have demonstrated the following conclusions:

1) The procedures for obtaining the optimal stand-off distance were confirmed.
2) Adopting polyvinyl chloride for the case material drastically decreases fragments from the case.
3) Simulations based on the experimental results indicate that newly-designed LSCs have 1.5 times the tration ability, compared to current products.

4) AUTODYN is a useful tool for predicting and evaluating the overall performance of LSCs.

AUTODYN simulations should be used for designing effective cutting plans when using LSCs.

References

[1] Miyoshi, H., Ohba, H., Kuroiwa, M., Inoue, T., Kitamura, H., & Hiroe, T., The jet penetration performance of linear shaped charges. *Science and Technology of Energetic Materials*, **65(2)**, pp. 173 179, 2004. (in Japanese)