Structure Design of Shaped Charge for Requirements of Concrete Crater Diameter

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Abstract: When shaped charge penetrats into concrete, crater diameter must meet certain requirements. By using theories of shaped jet formation and crater diameter growth during jet penetrating concrete, we revealed the thresholds of the velocity and diameter of jet head, and therefore obtained the related structure parameters of top liner, so that shaped charge structure was developed. We built a ∅60 mm copper liner and a ∅142 mm Ti-alloy liner which followed the rules of 0.6 cal and 0.7 cal in-crater diameter. respectively. X-ray experiment and penetration test results showed that the parameters of jet head were consistent with the results of theoretical analysis. The in-crater diameter of ∅60 mm shaped charge reached 36 mm, and the ∅142 mm one reached 100 mm. They both met the design requirements.

Key words: shaped charge; crater diameter; structure design

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0 Introduction

As the application area of shaped charge is expanding to some special fields, including precursory charge of tandem warhead[1], and petroleum perforation bullet[2], other than shaped charge penetration depth requirements, additional condition that penetration crater diameter must be as large as possible is also demanded. Enlarging penetration crater diameters can increase damage power of shaped charge.

Many scholars at home and abroad have focused on structural design and optimization for shaped charge to increase jet penetrating crater diameter. Huerta et al.[3] used numerical simulation to structurally design and optimize single cone shaped charge and verified it by experiments. Xiao et al.[4] designed double material composite of jet shaped charge to increase crater diameter. Zhou Quan[5] conducted multi-objective optimization design based on orthogonal test to reach two objectivs of penetration depth and crater diameter, and the latter was selected as the main objective function. Ma Jianfu[6] investigated the influence of structure and materials of shaped charge on penetration depth and crater diameter in the process of jet penetraton.

We developed a structure of top liner to increase crater diameter based on the theory of shaped jet formation and crater diameter growth theory during jet penetration. Then we designed shaped charge structure and and tested it. The experiments verified that the method could be applied to structure design of large crater diameter shaped charge.

1 Theoretical Analysis

1.1 Structure design

Szendrei/Held equations provided the relationship between penetration crater diameter and velocity & diameter of shaped charge jet[7-11]

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$$D_c = \sqrt{\frac{A}{B}} \tag{1}$$

$$A = \frac{1}{(1+\gamma)^2} v_j^2 D_0^2, \quad B = \frac{2R_t}{\rho_t}$$

where D_c is the penetration crater of jet, v_j the velocity of jet, D_0 the diameter of jet, $\gamma = \sqrt{\frac{\rho_t}{\rho_j}}$, where ρ_t is the density of target, ρ_j the density of jet, R_t the penetration resistance of target.

Eq. (1) shows that the velocity and diameter of jet head should satisfy the following relations

$$v_T D_T = (1+\gamma)\sqrt{\frac{2R_t}{\rho_t}} D_{Tc} \tag{2}$$

where v_T is the velocity of jet head, D_T the diameter of jet head, and D_{Tc} the crater diameter of concrete.

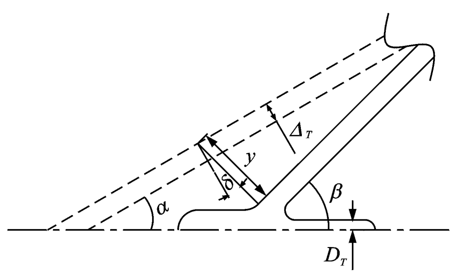

Fig. 1 Schematic of liner collapse

Fig. 1 deliberates the schematic of liner collapse. Since the distance between the elements at the top of the liner and charge axis is short, elements are quickly crushed to the axis driven by explosive detonation. Considering scattering angle $\delta \approx 0°$ and collapse angle $\beta \approx \alpha$, based on the formation theory of shaped charge jet, the velocity and the mass of jet head can be simplified as[12]

$$v_T = v_{T_0} \cot \frac{\alpha}{2} \tag{3(a)}$$

$$m_T = m_{T_0} \sin^2 \frac{\alpha}{2} \tag{3(b)}$$

where α is the half cone angle of charge element, v_{T_0} the collapse velocity of elements at the top of the liner, and m_{T_0} the mass of elements at the top of the liner.

If y is the distance from element of the top liner to the axis and Δ_T the wall thickness of element, the relationship between jet head diameter and wall thickness of the top liner can be obtained by geometry as

$$D_T = \sin \frac{\alpha}{2} \sqrt{\frac{\Delta_T}{\cos\alpha}\left(2y + \frac{\Delta_T}{\cos\alpha}\right)} \tag{4}$$

Suppose that the move of element is only driven by explosive one-dimensional projection, and that the influence of lateral rarefaction waves and effect of elements can be ignored. Since the metal is not rigid body, surface pressure of projectile is actually not so high and detonation wave oblique impacts liner, collapse velocity of element at top liner is

$$v_{T_0} = \frac{1}{8}(\cos\varphi + 0.68)\frac{\rho_e l_T}{\rho_j \Delta_T} D \tag{5}$$

where φ is the angle form detonation wave front to tangent plane of liner element, l_T the length effective charge corresponding to liner element, ρ_e the density of the explosive, and D the detonation velocity.

To charge in top liner, we have

$$l_T = \frac{R_k - y}{2\cos^2\left(\frac{\alpha}{2}\right)} \tag{6}$$

where R_k is charge radius.

Substitute Eqs. (5, 6) into Eq. (3(a)), the velocity of jet head can be obtained. Then substitute Eqs. (3(a), 4) into Eq. (2), we obtain

$$\frac{1}{16}\frac{\rho_e (R_k - y)}{\rho_j \cos\left(\frac{\alpha}{2}\right)}(\cos\varphi + 0.68) D \sqrt{\frac{1 + 2y\cos\alpha}{\Delta_T \cos^2\alpha}} = (1+\gamma)\sqrt{\frac{2R_t}{\rho_t}} D_{Tc} \tag{7}$$

When D_{Tc} is the crater diameter, the relationship of Δ_T, α, φ and y should satisfies Eq. (7). If any three of them are known, the fourth can be calculated. Therefore, by using the parameters of the top liner, structure can be designed, so as to obtain the required crater diameter on concrete.

1.2 Calculation verification

1.2.1 Cooper liner structure

The diameter of shaped charge is ∅60 mm and crater diameter on concrete is 0.6 times the charge diameter, that is $D_{Tc} = 36$ mm. The explosive is JH-2, with $\rho_e = 1.7$ g/cm^3, $D = 8.4$ mm/μs. The martial of liner is OFHC with $\rho_j = 8.93$ g/cm^3. Concrete is C35 with $\rho_t = 2.4$ g/cm^3 and $R_t = 68$ MPa[13].

The charge structure is K type. Half cone angle is $\alpha = 60°$. The distance from element at the top liner to axis y is 1.6 mm. The diameter of waveform regulator is ∅52 mm and the angle of incidence of detonation wave is $\varphi = 0°$.

We can get $\Delta_T = 1.74$ mm by Eq (7). Through parameters of element at the top liner, $v_T = 5.35$ mm/μs and $D_T = 2.4$ mm can be obtained by Eq. (3(a)) and Eq. (4) respectively. To simplify the calculation during inverse design of the top structure of liner, we approximately set $\delta \approx 0$, $\beta \approx \alpha$, so jet head velocity of the actual charge structure should be lower than the calculated value, and the head diameter is higher than calculation values.

According to the structure of liner top by inverse design, ∅60 mm shaped charge structure is shown in Fig. 2.

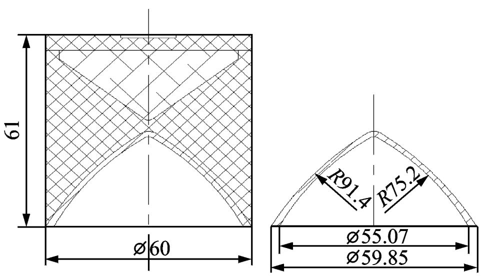

Fig. 2 Inversion structure of ∅60 mm shaped charge liner

1.2.2 Ti-alloy liner structure

The diameter of shaped charge is ∅142 mm and crater diameter on concrete is 0.7 times the charge diameter, that is $D_{Tc} = 99$ mm. The explosive is Octol, with $\rho_e = 1.78$ g/cm^3 and $D = 8.48$ mm/μs. The martial of liner is Ti-alloy with $\rho_j = 5.6$ g/cm^3. Concrete is C40 with $\rho_t = 2.4$ g/cm^3 and $R_t = 80$ MPa[13].

The charge structure is K type. The half cone angle is $\alpha = 48°$. The distance from element at the top liner to axis y is 6 mm. The diameter of waveform regulator is ∅132 mm and the angle of incidence of detonation wave is $\varphi = 0°$.

$\Delta_T = 6.48$ mm can be calculated by Eq. (7). With parameters of element at the top liner, $v_T = 7.65$ mm/μs and $D_T = 6$ mm can be obtained by Eq. (4(a)) and Eq. (6), respectively.

According to the structure of liner top by inverse design, ∅142 mm shaped charge structure is shown in Fig. 3.

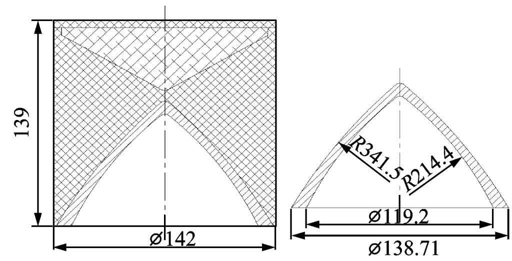

Fig. 3 Inversion structure of ∅142 mm shaped charge liner

2 Experiment and Analysis

2.1 X-ray experiment

X-ray experiment site layout for ∅60 mm shaped charge is shown in Fig. 4. Experiments were conducted four times, and the results are shown in Figs. 5—8.

Fig. 4 X-ray experiment site

Fig. 5 X-ray of the first charge (50 μs, 80 μs)

Fig. 6 X-ray of the second charge (40 μs, 100 μs)

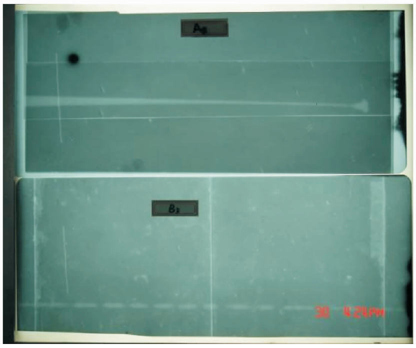

Fig. 7 X-ray of the third charge (60 μs, 155 μs)

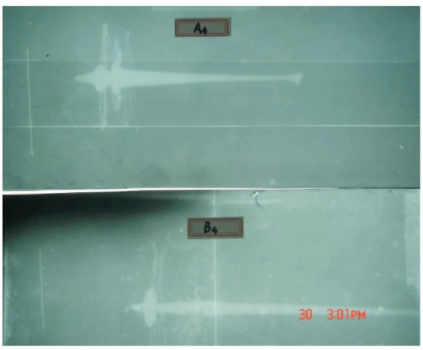

Fig. 8 X-ray of the fourth charge (30 μs, 60 μs)

Head velocity of shaped charge jet was about 5 000 m/s. Head diameter was about 3.5 mm. The tail velocity was about 1 265 m/s and the tail diameter was about 14.5 mm by measuring. X-ray showed that the calculation result was basically consistent with the basic X-ray experimental results. Compared with inverse design theoretical results, calculated value of head velocity was higher and head diameter was smaller which is in accordance with the results of the analysis because the theoretical analysis ignores flying angle and crushing angle changes of element at top liner.

2.2 Experiment on crater ability

2.2.1 Cooper liner

Standard C35 concrete target used in test has two kinds of thickness, 0.5 and 1 m. The standoff is 100 mm (1.7 Cal.). Test site layout is shown in Fig. 9. Test was conducted three times. The first and the second target plate thicknesses were 500 mm. The third one was 1 000 mm, and the holes on the concrete are shown in Figs. 10—12.

Fig. 9 Test site layout of ∅60 mm shaped charge penetrating concrete

Fig. 10 In-crater of the first ∅60 mm shaped charge

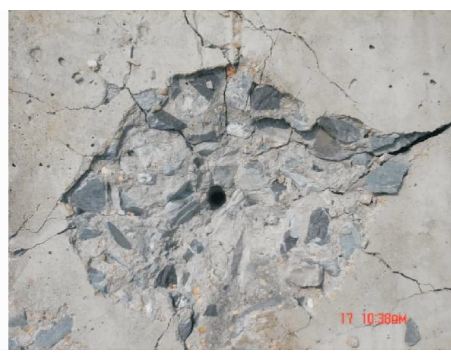

Fig. 11 In-crater of the second ∅60 mm shaped charge

Fig. 12 In-crater of the third ∅60 mm shaped charge

The first in-crater diameter was 35 mm, and the out-crater diameter was 15 mm. The second in-crater diameter was 36 mm, and the out-crater diameter was 15 mm. The third target thickness was 1 000 mm. The penetration depth was 650 mm, and the in-crater diameter was 35 mm.

The test results are shown in Table 1.

Table1 Test results of ∅60 mm shaped charge

No.	Target thickness/mm	In-crater diameter/mm	Out-crater diameter/mm	Penetration depth/mm
1	500	35	15	Penetration
2	500	36	15	Penetration
3	1 000	35		650

When stand-off was 100 mm, the penetration depth of ∅ 60 mm shaped charge penetrating standard C35 concrete was 650 mm(about 10. 8 Cal.) and in-crater diameter was 36 mm (0. 6 Cal.), which agreed with the inverse design goal that ∅60 mm shaped charge penetrating diameter on concrete is larger than 0. 6 Cal.

2. 2. 2 Ti-alloy liner

The thickness of standard C40 concrete target used in test was 1. 2 m. The stand-off is 307 mm (2. 2 Cal.). The in-crater hole on the concrete is shown in Fig. 13.

Fig. 13 In-crater of ∅142 mm shaped charge

The 1. 2 m thick concreter target was penetrated. The in-crater diameter was 100 mm(0. 7 Cal.), and the out-crater diameter was 70 mm (0. 5 Cal.)which reached the inverse design goal that ∅142 mm shaped charge penetrating diameter on concrete is larger than 0. 7 Cal.

3 Conclusions

We analyzed the velocity and the diameter of the jet head when shaped charge jet crater diameter met certain requirements by using the theories of shaped jet formation and crater diameter growth during jet penetrating concrete. The structure parameters of ∅60 mm and ∅142 mm shaped charge were investigated with the required crater diameter. The structure of shaped charge was designed, and the head velocity and diameter were obtained by calculation.

By ignoring flying angle and crushing angle change, the calculated head velocity was higher than the actual value and the calculated head diameter was lower than the actual value, which was confirmed by X-ray experiments. The penetration power experiment indicated that when stand-off was 100 mm, the penetration depth of ∅60 mm shaped charge penetrating standard C35 concrete was 650 mm(about 10. 8 Cal.) and in-crater diameter was 36 mm (0. 6 Cal.), and ∅142 mm shaped charge penetrated 1. 2 m standard C40 concrete and in-crater diameter was 100 mm(0. 7 Cal.). The experiment validated our design.

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