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An Optical Design Theory for Focused Fragmentation Warhead

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ABSTRACT

Focusing the dispersing direction of fragments with high-accuracy is one key issue in the design of advanced focused fragmentation warhead for the application of aerial defence and antimissile. The similarity of mechanism between the focusing of geometrical optics and focusing of fragments is analysed in details, and it is proved that the driving direction of warhead fragment can be controlled according to the theory of geometrical optics. A new design model and method for Focused fragmentation warhead is obtained. The design is preliminary proved to be efficient by some tests, and it is found that 85 per cent of total fragment of the warhead can be focused within the designed focusing zone, which is an improvement to the 70 per cent obtained by other methods.

Keywords: Focused fragmentation warhead, geometrical optics, explosion driving, aerial defence, antimissile

NOMENCLATURE

n, n'	Refractive index of mediums
r	Radius of spherical surface
$\alpha_{1,2,3,\ldots,n}$	Incidence angles
$\beta_{1,2,3,\ldots,n}$	Refraction angles
L	Intercept distance
U	Aperture angle
I	Incidence angle
I'	Refraction angle
$\Delta\theta$	Rotating angles with clockwise
Δx	Width of cylindrical warhead parts
δ_x	Deflected angle
l	Warhead length
φ_1	Included angle between the normal direction of charge surface and x-axis
De	Detonation rate
V_{0x}	Initial velocity of fragment
A_1, A_2	Correction factors
$\beta(x)$	Mass ratio of charge and shell within a cylindrical warhead part
$w(x)$	Charge mass
$m(x)$	Shell mass
$d(x)$	Charge diameter
k	Coefficient of usable explosive energy
φ_2	Included angle between normal direction of detonation wave and x-axis

1. INTRODUCTION

For the focused fragmentation warhead which are mainly applied to aerial defence and antimissile campaign，the high-density fragment zone (focusing fragment zone) is constructed by controlling the distribution of fragments within a small fragment dispersion angle. The focusing fragments can penetrate and form a lot of densely destroyed holes within a certain zone of the aerial target. Then a damage effect like shearing failure is obtained. The design methods related to the focused fragmentation warhead mainly include the method of parallel fragment dispersion proposed by Held[1] and the method that a shape controller of detonation wave adopted by Liu[2]. An annular focusing fragment zone can be achieved by these methods, and the ratio of the fragments within the focusing zone to the total fragments is approximately 70 per cent in general[3]. However, the focusing zone of fragments formed by these methods is a little wide and the distance between most adjacent holes is too large. Therefore, obvious shearing failure effect cannot be produced on the target.

According to literature[4,5], in which the optimization design method and application of aspheric geometry optical imaging was investigated, it can be considered that the movement law of fragment driven by explosion is a little similar to the focusing principle of ray. The theory of geometrical optics can be used to investigate the focusing mechanism of fragments, and a new design method for the focused fragmentation warhead conforming to objective laws is proposed. Firstly, it is assumed that the initiating causes the detonation wave to transmit along the normal direction of the charge's curved surface according to the condition of instant detonation. Secondly, to control the dispersing direction of each fragment, a method which can amend the influence of transmitting direction of detonation wave to the movement of fragments is studied, while the focusing position of fragments, the initiation position, and the charge structure is specified. Finally, the basic design method of focused fragmentation warhead is presented, by which the high-density fragment zone is constructed at the given lethal range and the shearing failure effect on the target is achieved[6]. The validity of the above method is proved by some experiments, and it shows that the target subject to a combined loading

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of high-density fragment zone and shock wave will produce structural damage.

2. METHODS

2.1 Focusing Theory Based on Geometrical Optics

According to the theory of geometrical optics, a refraction takes place on a single spherical surface when a ray reaches the spherical interface between two different transparent mediums. The light passes through the center of the spherical interface without any refraction when the transmitting direction of incident light is perpendicular to the spherical interface. As shown in Fig. 1, all incident rays (l_1, l_2, l_3, l_4, l_5, …) focus on C_1, the centre of the spherical interface, while their incident

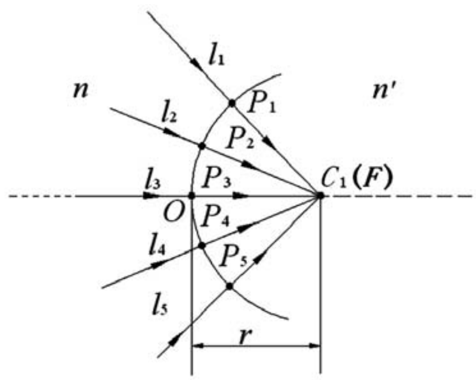


Figure 1. Refraction at a simple spherical surface.

direction is the same as the normal direction of the spherical interface. The spherical surface is the interface between the two different mediums with refractive indexes n and n'. C_1 is the centre of the sphere, while OC_1 is the radius of spherical surface expressed by r.

When the incident rays (l_1, l_2, l_3, l_4, l_5…) radiate from the same point A, the light refraction on the single spherical surface will occur. As shown in Fig. 2, the incidence angles (α_1, α_2, α_3, α_4, α_5…) are the angles between the incident direction of the rays and the normal direction of the spherical interface. Therefore the refracted rays do not focus on the centre of sphere C_1 but deflect from the normal direction of the spherical

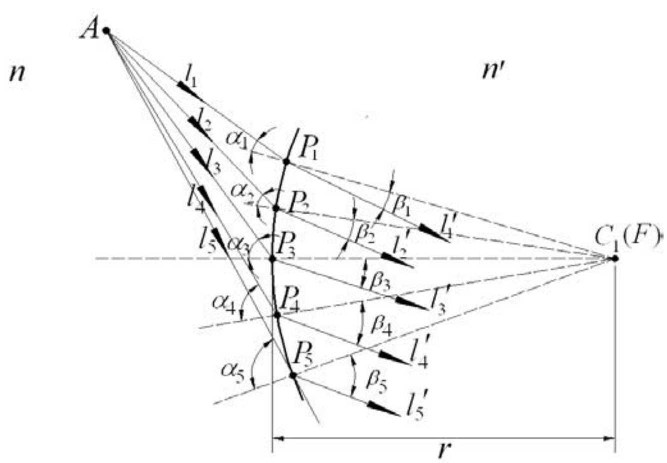


Figure 2. Refraction of multiple lights at a simple spherical surface.

interface with different refraction angles (β_1, β_2, β_3, β_4, β_5...).

According to the refraction theorem, the refraction angles of all the refracted rays can be calculated as follows:

$$\beta_i = \arcsin(\frac{n}{n'}\sin\alpha_i), \quad i = 1, \cdots, n \tag{1}$$

For the convenience of analysis, the refraction phenomenon on the single spherical surface for one ray is shown in Fig. 3. AP is the incident ray, PA' is the refracted ray and P is the incident point. According to the Cartesian symbolic rule, the location of the incident ray is determined by the intercept distance L and the aperture angle U. After the incident ray passes through the spherical surface, the refracted ray will intersect the optical axis at the point A′. Similarly, the location of the refracted ray is determined by the intercept L' and the aperture angle U'. PC is the normal line of the spherical surface at the point P. I is the incident angle between PC and the incident ray, I' is the refraction angle between PC and the refracted ray.

If the incident ray AP deflects from PC with angle I,

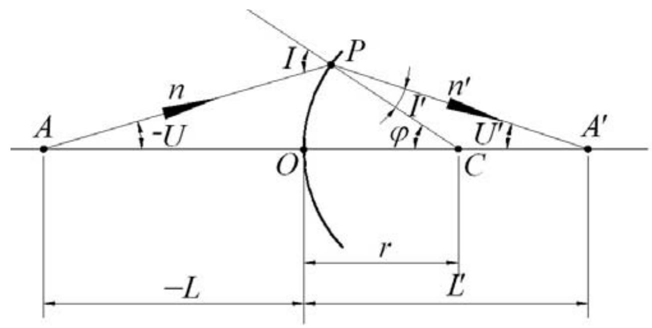


Figure 3. Geometrical representation of refraction of a simple spherical surface.

the refracted ray PA' will deflect from PC with the angle I'. According to the refraction theorem, I' can be calculated as follows:

$$I' = \arcsin(\frac{n}{n'}\sin I) \tag{2}$$

In order to make sure the refracted ray PA' pass though the focus point C_1, the spherical interface must rotate along the clockwise direction for a certain angle $\Delta\theta$, as shown in Fig. 4. Then the new incident angle I_2 and refraction angle I'_2 can be

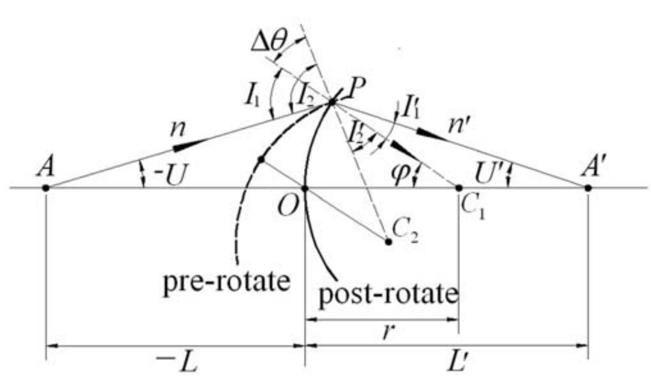


Figure 4. Geometrical representation of refraction after spherical face was rotated by Δθ.

calculated as follow:

$$\begin{cases} I_2 = I_1 + \Delta\theta \\ I_2' = \Delta\theta = \arcsin(\frac{n}{n'}\sin I_2) \end{cases} \tag{3}$$

Since the refractive index on both sides of the spherical interface is a fixed value, it follows:

$$\Delta\theta = f(I_1) = arcctg(\frac{n'/n - \cos I_1}{\sin I_1}) \tag{4}$$

Therefore, in order to make the refracted rays focused on the point C_1, the spherical interface must be divided into a number of segments, where each of them rotates along the clockwise direction with the angle:

$$\Delta\theta_i = f(\alpha_i) = arcctg(\frac{n'/n - \cos\alpha_i}{\sin\alpha_i}) \tag{5}$$

The original sphere interface between two mediums turn to be non-spherical after rotating each part with a certain angle, and it makes all rays focused on the same point.

2.2 Focusing Mechanism of Fragments-based on Theory of Optics

The fragmentation warhead is mainly composed of charge, blaster and shell. The elementary charge structure of focused fragmentation warhead is shown in Fig. 5. The surface of charge is a spherical shape to which the preformed fragments are adhered tightly. There are end covers on the two ends of charge. The ignition position locate at point *O*. Assuming the charge is composed of several parallel cylindrical parts with width Δx, all charge parts will explode at the same time according to the instant detonation theory. The ignition produces a detonation wave and it transmits along the normal direction of the charge surface. Following the focusing principle of light refraction on the single spherical surface, the fragments are then driven away along the same direction, as shown in Fig. 1.

As shown in Fig. 5, without the sparse influence of the detonation of charge on the warhead end[7], all preformed fragments will be driven away and focused on the point $C_3(x_f, y_f)$ which is the centre of the sphere.

However, in reality, the charge of warhead cannot detonate simultaneously. The initiation point is usually located at one end or the centre, even in the off-centre position. The propagation of detonation wave is directional. When one end initiation is taken, the propagation of detonation wave and the dispersion direction of detonation products are similar to the refraction of multiple rays, which from an incidence ray and pass through the spherical surface as shown in Fig. 2. The dispersing direction of each fragment is deflected away from the normal direction of charge surface by an angle δ_x(similar to β_i in Fig. 2) [8,9], which leads to the deviation of fragments from the focus position. Therefore the charge surface form needs to be revised according to the method, shown in Fig. 4 and Eqn (5), to make the fragments focus on the point of $C_3(x_f, y_f)$.

In practical engineering applications, the design of focused fragmentation warhead is restricted and interfered by many conditions and factors. For instance, the focus point may not be at the geometric centre of charge. These factors will distinctly affect the focusing effect of fragments so that some pertinent methods should be taken to revise the form of the charge surface.

2.3 Basic Design Method of Focused Fragmentation Warhead

The design of focused fragmentation warhead mostly obeys the idea of rotating the spherical interface with a certain angle as shown in Fig. 4. By amending the charge curved surface according to the initiation position, the dispersion direction of each fragment can be controlled and driven to the focus point.

The design method for focused fragmentation warhead based on the theory of optics is presented as follows: Firstly, the circular arcs of charge surface and the initiation point are drawn out according to the initial power parameters of warhead, such as the number of fragments and the initial velocity; Then the optic rotation angle $\Delta\theta_x$ of each charge curve segment can be calculated according to the pre-determined position of focusing point; Finally, the charge curve and the warhead structure satisfying the focusing requirement is obtained.

As shown in Fig. 6, suppose that the point (x_f, y_f) is the focusing point and (0, 0) is the initiation point. All fragments within the length *l* will converge at the focus point. Assuming the charge detonates instantly without the consideration of the

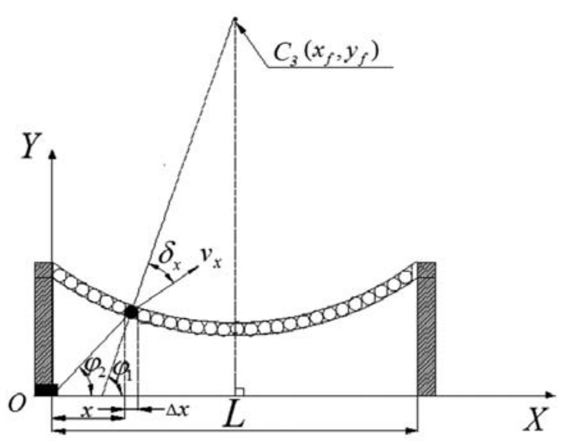


Figure 5. Elementary charge structure of focused fragmentation warhead.

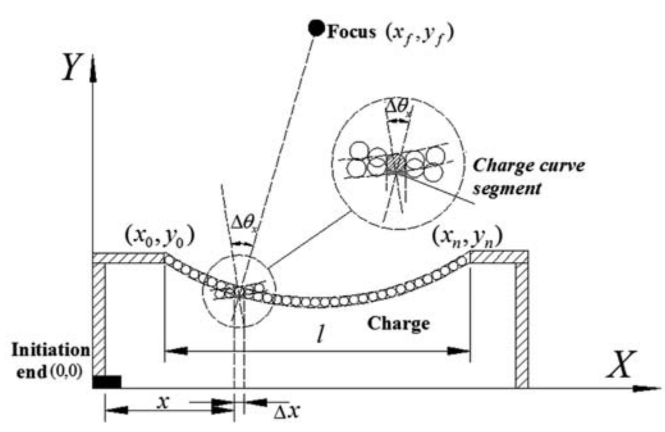


Figure 6. Design drawing of focusing warhead.

initiation position, the generator of charge curve is the circular arc S_1 with the centre point (x_f, y_f) and boundary points (x_0, y_0) and (x_n, y_n). It can make the fragments converge to the focusing point.

The representation equation of circle S_1 is as follows:

$$(x-x_f)^2+(y-y_f)^2=(x_f-x_0)^2+(y_f-y_0)^2 \tag{6}$$

To simplify the calculation, the fitted quadratic parabola equation of Eqn (6) is:

$$y_1=a_1x^2+b_1x+c_1 \tag{7}$$

while equation of slope is:

$$y_1'=2a_1x+b_1 \tag{8}$$

Then the new curvilinear equation of S_2 can be given below:

$$g(x)=\int(y_1'+\Delta\theta_x)dx+k = -\frac{x}{m}-\frac{1+m^2}{2am^2}\ln\left|2amx+bm-1\right|+k \tag{9}$$

where $m = \tan\Delta\theta_x$, $\Delta\theta_x$ is the rotation angle of charge curved surface shown in Fig. 6. According to the Shunshan[10], with the condition of one end initiation, $\Delta\theta_x$ can be calculated as:

$$\begin{cases}\Delta\theta_x=\arctan[\dfrac{\frac{V_{0x}}{2De}\cos(\frac{\pi}{2}-\phi_1+\phi_2)}{1-\frac{V_{0x}}{2De}\cos(\frac{\pi}{2}-\phi_1+\phi_2)}, & \phi_1>\arctan(y_f/x_f)\\ \Delta\theta_x=\arctan[\dfrac{\frac{V_{0x}}{2De}\cos(\frac{\pi}{2}-\phi_1+\phi_2)}{1+\frac{V_{0x}}{2De}\cos(\frac{\pi}{2}-\phi_1+\phi_2)}], & \phi_1<\arctan(y_f/x_f)\\ \Delta\theta_x=0, & \phi_1=\arctan(y_f/x_f)\end{cases} \tag{10}$$

where φ_1 is the included angle between the normal direction of charge curved surface at the distance of x to initiation point and x-axis, φ_2 is the included angle between the normal direction of detonation wave front at this position and the x-axis, δ_x is the included angle between the fragment dispersion direction and the normal direction of charge curved surface at this position, *De* is the transmitting velocity of the detonation wave, V_{0x} is the initial velocity of fragment at the distance of *x,* which can be calculated by the modified Gurney formula[11] as:

$$V_{0x}=K[1-A_1e^{-Bx/d(x)}][1-A_2e^{-C(L-x)/d(x)}]\cdot \sqrt{2E_g}\cdot\sqrt{\beta(x)/[1+0.5\beta(x)]} \tag{11}$$

where B and C are the constants determined from experiment, A_1 and A_2 are correction factors about the influence of end effect, $\beta(x) = w(x)/m(x)$ is the ratio mass of the cylindrical part of charge with width Δx at the distance of x, $w(x)$ is the charge mass, $m(x)$ is the shell mass, $d(x)$ is charge diameter, k is the coefficient of effective explosive energy. The value $B = 1.11$, $C = 3.03$, $A_1 = 0.20$, $A_2 = 0.08$ are given by Feng[11].

It should be declared that an error exists in the calculation of dispersion direction of fragments near the two ends of warhead due to the leaking of detonation gas along the x-axis in reality. Therefore, the further revision should be investigated for the rotation angle of charge curved surface at the ends.

As a result, the generatrix equation of charge curved surface for the focused fragmentation warhead is as follows:

$$g(x)=k-\frac{x}{\tan\Delta\theta_x}-\frac{1+\tan^2\Delta\theta_x}{2a_1\tan^2\Delta\theta_x}\cdot \ln\left|2a_1x\tan\Delta\theta_x+b_1\tan\Delta\theta_x-1\right| \tag{12}$$

The above curve $g(x)$ can be formulated as a new quadratic parabola equation:

$$y_2=a_2x^2+b_2x+c_2 \tag{13}$$

In summary, the key point for the design of focused fragmentation warhead is the calculation of $\Delta\theta_x$ according to the pre-determined position of focusing point and the initiation position of charge. Then the specific expressions of charge can be generated by the Eqns (6)-(13) , which is the most important work.

3. EXPERIMENTAL RESULTS

3.1 Design of Experiment

Based on the above design theory, two schemes of focused fragmentation warhead (W-A and W-B) are proposed. For the W-A scheme as shown in Fig. 7, the horizontal and longitudinal ordinates of focus point are 50 mm and 300 mm respectively. The generatrix equation of charge surface is marked. Similarly, for the W-B scheme as shown in Fig. 8, the horizontal and longitudinal ordinates of focus point are 80 mm and 300 mm respectively. The generatrix equation of charge surface is marked too. The same charge composed of 35 per cent TNT and 65 per cent RDX was used in both schemes. Steel spheres with a diameter of 3 *mm* are used as the fragments, and the initiation position of charge is located at (0,0) of the coordinate system. As shown in Fig. 9, the warhead model of W-A and W-B are prepared for experiment.

To avoid the influence of shell fragments, both schemes have no casing. The dispersing direction of all the fragments can be distinguished easily by analysing the penetrating holes in the target. However, we can use a thin aluminum alloy (about 2 mm) as a shell to adhere all the pre-made fragments in practical engineering applications.

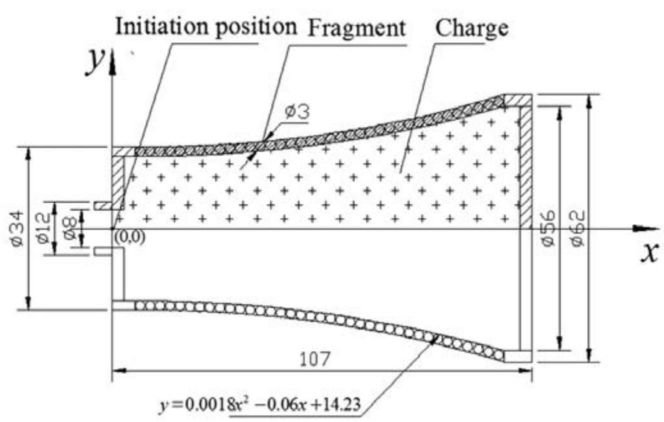


Figure 7. W-A scheme of focused fragmentation warhead.

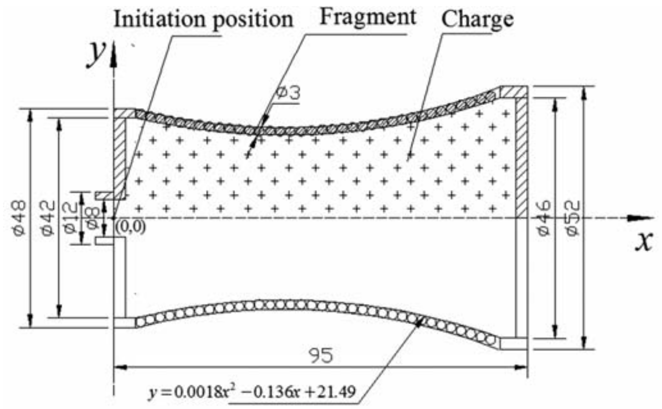


Figure 8. W-B scheme of focused fragmentation warhead.

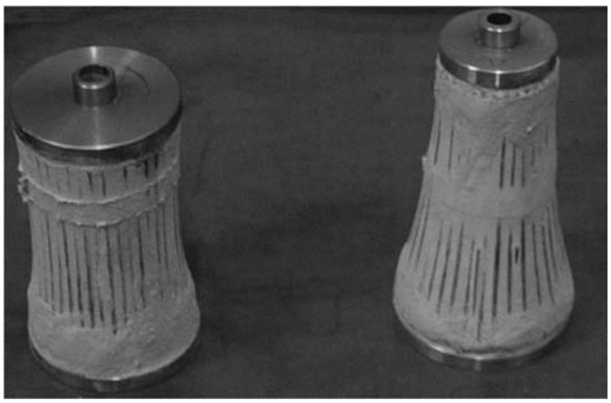


Figure 9. Work-pieces of W-A and W-B schemes.

3.2 Measurement of Experiment

To observe the focusing effect of the fragmentation warhead and its damage to the target plate with combining effect of focusing fragment and shock wave, the test method is designed and shown in Fig. 10.

The target, which made of steel plate with a thickness of 3 mm, a length of 400 mm and a width of 400 mm, is used to gain the focusing effect of focused fragmentation warhead. The centre of the target located in the same horizontal plane with the warhead, and the distance from the centre of warhead is 300 mm. The pulsed x-ray high speed camera is used to measure the initial velocity of fragments and the angle of disperse direction. Sensitometer strip of x-ray was laid on the left side of the specimen.

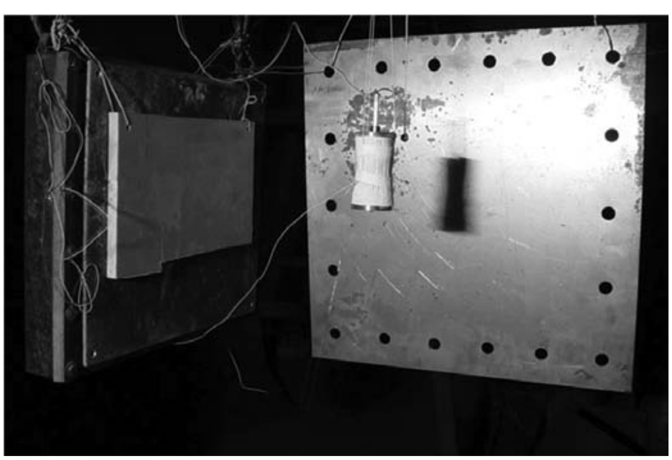
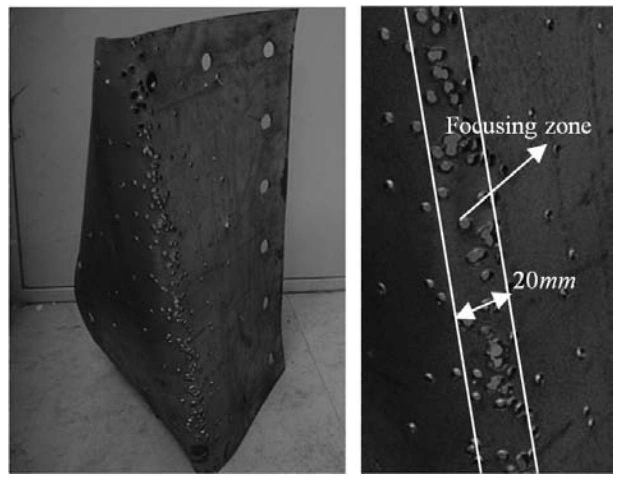


Figure 10. Method of experiment.

3.3 Experimental Data Analysis

The focusing effect of fragment is analysed by checking the dispersing positions of fragments. For the W-A scheme, there are 244 spherical fragments adhered toward the side of target. After the explosion, there are 220 fragments penetrating the target effect. It can be counted clearly that about 153 fragments focus on the zone with a width of 20 mm, as shown in Fig. 11.



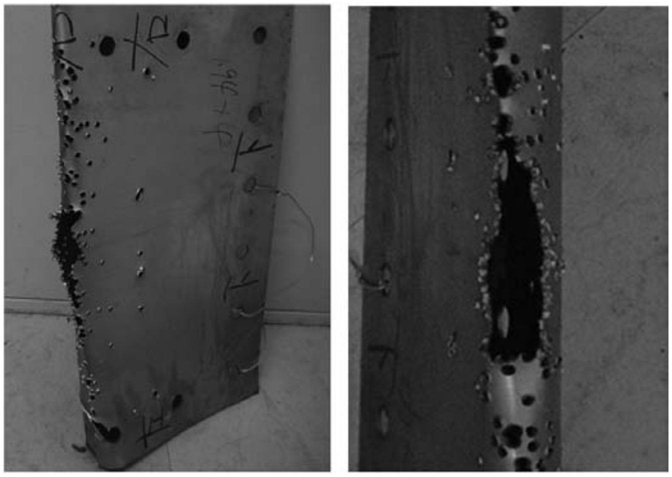
(a) (b)

Figure 11. Distribution of fragments for W-A scheme: (a) Full view of target; (b) Detail of target.

It was observed that there are two lines in upside and downside direction of the focusing zone which are linked by the penetrating hole on the target. The distribution of these holes on the lines can be proved to be stricken by spherical fragments near the two ends of warhead. This phenomenon is caused by the rarefaction effect of detonation wave near the two ends. It indicates that the focusing effect influenced by the end of the warhead is necessary to consider in the design.

There are 244 spherical fragments adhered toward the side of target, and the number of effective fragments designed to focus would be 179 without the consideration of end influence. As 153 fragments are found to focus on the zone with a width of 20 mm, the focusing rate of the W-A scheme is 153/179, i.e. 85.5 per cent.

For the W-B scheme, there are 204 spherical fragments adhered toward the side of the target. After the explosion, there are about 200 fragments penetrating the target effect. It can be counted clearly that about 148 fragments focused on the zone, as shown in Fig. 12. Similarly, due to the rarefaction effect of detonation wave on the two ends, there are two lines located upside and downside direction of the focusing zone which are linked by the hole on the target. The number of effective fragments designed to focus would be 175 without the consideration of end influence. As 148 fragments are found to focus on the zone, the focusing rate of the W-B scheme is 148/175, i.e. 84.6 per cent.



(a) (b)

Figure 12. Distribution of fragments for W-B scheme:(a) Full view of target and (b) Detail of target.

It needs to be noted that the focusing effect of fragments is influenced by the shape of the flat target. For the focusing zone with a length of 120 mm and a width of 30 mm for W-B scheme, the focusing zone would be formed with the length equal to that of the target if the target is taken as the cylindrical target.

It is noted that the serious bending effects at the target occurred in the focusing zone with high density penetration of fragments. This effect is related to the combining effects of focusing fragments and shock wave, and this will be investigated further in another publication.

4. CONCLUSION

Based on the theory analysis, the similarity of mechanism between the focusing of geometrical optics and focusing of fragments is investigated. It is shown that the driven direction of fragments of warhead can be analysed based on the theory of geometrical optics. A new design model and method for focusing fragment of warhead is obtained. The design has proven to be relatively efficient according to the results of two static tests of warheads, and it is found that 85 per cent of total fragments of the warhead can be focused within the designed focusing zone, while usually only 70 per cent can be achieved by the classical methods. The optical design theory for Focused fragmentation warhead can be applied to the design of advanced aerial defence and antimissile fragment warheads.

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