Study on effective protective area of ceramic composite target

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Abstract. In order to study the difference of ballistic performance in different area of ceramic composite spaced targets, penetration experiment of two targets is conducted. Based on the experiment results, simulation method is used with the dynamic analysis software ANSYS/LS-DYNA, by which the process and mechanism of armour protection is discussed, as well as the effect of unit shape on ballistic performance of targets. It is revealed that the segmentation degree of ceramic cone accounts for the difference in ballistic performance. Besides, the critical points of effective protection is calculated, and the effective protective area of both targets is measured.

1. Introduction

Strengthening the protective capability of armoured vehicles is the key to improve the viability and combat effectiveness, while it is hard for traditional plate armour to meet the requirements of protection and maneuverability at the same time [1]. A form of composite armour is designed by combining the ball-proof ceramic, which possesses the advantage of high strength, high hardness and low density, with ductile materials such as metal and fiber. The ductile backboard is able to provide support for the brittle ceramic panel, and make the utmost of ballistic performance which provides an effective solution to the contradiction between protective capability and the self weight of armoured vehicles.

Space is set in composite spaced armour between the ballistic structural units and baseboard, which gives play to the yaw effect of space, as well as improve the protective ability over multiple bullets. While the ballistic performance of connecting region is not reliable enough, it is necessary to do further research in this aspect and measure the effective protective area of the composite armour.

Wilkins [2] and Hetherington [3] conducted ballistic experiments and obtained the best thickness ratio of ceramic panel to aluminum alloy backboard, which is between 1.5 to 3. Weber [4] pointed out that compared with the diameter of projectile body, the bigger the of ceramic panel is, the more lateral self constraint will be given by the panel, which is able to reduce the degree damage of ceramic panel, and improve the ballistic performance. Shao [5] analyzed the effective protective area of different shapes of structural units by simulation, whose result shows that when the diameter of circular unit is equal to the side length of square units, the effective protective area of square unit is higher than circular unit.

This paper conducts the penetration experiment of 12.7mm-caliber armour-piercing projectile with two targets of the same match, though there is difference in the shape of units between them. Based on the results of experiment, simulation is adopted to analyze the ballistic performance of the units as well as measuring the effective protective area.
2. The penetration experiment

We conduct a penetration experiment into the ceramic composite targets with ogive nose kinetic energy projectiles of 12.7mm caliber. The test range is 75 meters long, and the designed ballistic speed is $V_{25}=810-825\text{m/s}$. The ballistic structural units are composed of ceramic panels of 13mm thickness and 2A12 aluminum alloy backboard of 6mm thickness, which are glued by epoxy glue. The baseboard is a 15mm-thick armoured aluminum plate. Between the units and the baseboard, there is designed space of 25mm in normal direction.

![Diagrammatic drawing of ceramic composite targets](image)

Figure 1. Diagrammatic drawing of ceramic composite targets.

Figure 1 shows the vertical structure of composite targets, as well as the horizontal arrangement of Target A and Target B. The shape of units is set as the unique variable. Target A adopts regular hexagon units with 50mm side length, which is $6487.5\text{ mm}^2$ in acreage; Target B adopts square units with 80mm side length, which is $6400\text{ mm}^2$ in acreage. The targets have the same theoretical areal density, which is $107.43\text{kg/m}^2$.

2.1. Experiment results

There are 2 valid strikes on Target A and 3 valid strikes on Target B. According to the record on experiment spot, the detailed results of experiment are shown in Table 1.

| Name | Number | Shape of units | Shot position | $V_{25}$ (m/s) | Backboard damage | Baseboard damage |
|------|--------|----------------|---------------|----------------|------------------|-----------------|
| Target A | 1 | Regular hexagon | Eccentric area | 820 | Local deformation, tear and perforation | Local deformation, no perforation |
| | 2 | | Fringe area | 818 | Local deformation, tear and no perforation | |
| | 1 | | Eccentric area | 806 | Local deformation, tear and perforation | Tiny local deformation, no perforation |
| Target B | 2 | Square | Central area | 819 | Local deformation, tear and perforation | Tiny local deformation, no perforation |
| | 3 | | Central area | 805 | Local deformation, tear and perforation | Tiny local deformation, no perforation |

2.2. Analysis of results

As the result shows, there is difference in ballistic performance between different area of units. Under the adopted structural match, the central and eccentric area is able to realize effective protection over 12.7mm-caliber kinematic energy bullets, while the fringe area is too weak to defend
penetration, and the critical point of effective protection is not clear. By further study, the effective protective area of the composite targets can be measured.

3. Numerical simulation of ballistic performance

The model of projectile-target effect is built according to the actual size with software ANSYS/LS-DYNA, which is meshed with SOLID164 unit into units with 1mm-side length. The initial speed of projectile is set as 800m/s. Some of the mesh structures are depicted in Figure 2.

![Mesh structures of calculation models](image)

Figure 2. Mesh structures of calculation models

The ceramic adopts MAT-JOHNSON-HOLMQUIST-CERAMICS model; aluminum alloy, elastic core and lead sleeve adopt MAT-PLASTIC-KINEMATIC model; warhead shell adopts JOHNSON-COOK model. The corresponding material parameters come from reference [6].

The contact between the projectile and target adopts ERODING-SURFACE-TO-SURFACE. The contact between the ceramic panel, the aluminum alloy backboard and the aluminum alloy backboard adopts TIED-SURFACE-TO-SURFACE.

3.1. Verification of simulation results

Three calculation models are created on the basis of three typical examples in experiments, corresponding to the situation when the spot of impact is located in the central area of square panel, the eccentric area of regular hexagon panel and the fringe area of regular hexagon panel. The contrast between experiment results and simulation results is shown in Figure 3.

![Contrast between experiment results and simulation results](image)

Figure 3. Contrast between experiment results and simulation results.
The results of experiment and simulation are roughly the same. In central and eccentric area, the backboards are deformed, teared and perforated, and the damage of baseboard is tiny. While in fringe area, the backboard is teared and the baseboard is perforated. By contrast, the simulation result and calculation model can be confirmed as valid.

3.2. Analysis of simulation results

The simulation results reproduce the process of penetration, which can be concluded into four main stages. In the first stage, the warhead shell hits the ceramic panel, while the speed and shape of bullet core remains unchanged. In the second stage, the bullet core begins to penetrate the panel, and get abraded by the ceramic with high hardness. Around the point of impact, the ceramic crushes and crack grows along hoop direction and radial direction. Ceramic cone forms under the combined action of tensile stress wave and compressive stress wave, which is pushed by the bullet core until their speed is equal. When it comes to the third stage, the bullet core and ceramic cone impact the backboard together, making the backboard out of shape and damaged. In the last stage, the rest of the bullet hits the baseboard, and the speed falls to 0, or the baseboard is penetrated.

There are two extreme cases in fringe area, the commissure and the intersection point. Figure 4 reveals the time history curves of kinematic energy of the projectile, which shows the ballistic performance in different area of square units.

![Figure 4. Time history curves of kinematic energy of the projectile.](image)

As is shown in Figure 4, during the second stage of penetration, the kinematic energy of bullet core declines sharply, indicating that this stage plays a crucial part in ballistic performance. When the point of impact is located in central or eccentric area of the panel, the decline of kinematic energy of bullet core is continuous, as during the time when the bullet crosses the space, the backboard keeps deforming and wasting the remaining energy of bullet. When the bullet strikes the weak fringe area, the time that the second stage lasts is short, and the decline of kinematic energy is far less than that in other area. Besides, there is a break between the second and third stage, which means that the backboard deformation is not sufficient and the ballistic performance is not revealed enough.

The ceramic cone plays an important part in the bullet-proof process. Figure 5 reveals the form of ceramic cone when the point of impact is located in central area and commissure respectively. Comparing with the complete ceramic cone in central area, the ceramic cone of commissure is fragmented, which accounts for the difference in ballistic performance.

![Figure 5. Form of ceramic cone.](image)
Figure 6 shows the contrast between square unit and regular hexagon unit. In central and commissure area of unit, the ballistic performance of two shapes is roughly the same. While in intersection point, the reduce of kinematic energy of square unit is less than regular hexagon. The reason is that for square units, the intersection point is shared by four segments, while for regular hexagon units, the intersection point is shared by three segments. It can be concluded that the segmentation degree of ceramic cone has an influence on the ballistic performance.

3.3. Study of effective protective area

In order to explore the critical point of effective protection, situations on different point of impact are modeled, the arrangement of which is shown in Figure 7. Considering the effect of adjacent panels on the ballistic performance in fringe area, those panels are included in modeling [7]. The judgement criteria of effective protection is the remaining speed of projectile, as well as the damage of baseboard. Only when the speed is reduced to 0, and there is no tear or perforation on the baseboard, the protection can be judged as effective.

According to the results of calculation, the critical points of effective protection are found, along which the border of effective protective area is drawn as Figure 8. By calculation, the effective protective area of Target A accounts for 58.65% of total area; while the effective protective area of Target B accounts for 63.72% of total area.
4. Conclusion

According to the results of experiments and simulation, the segmentation degree of ceramic cone accounts for the difference in ballistic performance in different area of targets. The ballistic performance of square unit and regular hexagon unit is basically the same in central and eccentric area, while in intersection points of panels, the hexagon units have better performance.

The critical points of effective protection is calculated, based on which the effective protective area is measured. For Target A, the effective protective area accounts 58.65% of total area, while for Target B, the value is 63.72%.

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